$B^0_s \rightarrow J/\psi (\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$

DECAY AND SENSITIVITY TO
THE $B^0_s$ MIXING PHASE AT LHCb

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Abstract

The LHCb experiment is one of four main experiments to be setup at IP8 point of the proton-proton Large Hadron Collider (LHC) at CERN, Geneva. The data taking is scheduled to start end 2007. The LHCb detector is a forward single-arm spectrometer conceived to study CP violation and rare phenomena in the $b$-quark sector with very high precision. LHCb should provide a profound understanding of flavour physics in the framework of Standard Model (SM), so that the SM will be over-constrained, hopefully, it will exhibit some inconsistencies which may reveal a sign of New Physics beyond the SM.

The physics studies being considered by the LHCb collaboration offer the possibility of furthering in the SM description of CP violation. The SM provides the theoretical framework for the violation of the CP symmetry in neutral B mesons as well as in neutral K mesons. The neutral $B^0_s - \bar{B}^0_s$ system stays at a privileged position in the quest for CP violation evidences. The $B^0_s - \bar{B}^0_s$ mixing phase, $\phi_s$, has never been measured. This mixing phase has its origins in the interference between the decay and the mixing of those neutral mesons. $b \to \bar{c}c\bar{s}$ quark-level transitions decaying to CP eigenstates, may directly probe this electroweak phase by performing a time-dependent measurement of mixing-induced CP violation.

Among those quark level transitions, we have the golden-plated channel to perform such a measurement that is $B^0_s \to J/\psi \phi$ and that requires an angular analysis to disentangle its CP eigenstates components. On the other hand, $b \to \bar{c}c\bar{s}$ transitions to pure CP eigenstates provide another probe to the $\phi_s$, not requiring such angular studies. In this dissertation we will be consider the $B^0_s \to J/\psi (\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$ decays which are $b \to \bar{c}c\bar{s}$ transitions to pure CP even eigenstates.

The reconstruction and selection of those decays will be presented here using full Monte Carlo simulations. An annual event yield of $\sim 2000$ is assured with a background-over-signal level close to unity. The mass and proper time resolution will be also presented and some methods searching to improve those performances.

In the last chapter of the dissertation, we will also present a study of the statistical sensitivity of $B^0_s \to J/\psi (\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$ to the $B^0_s - \bar{B}^0_s$ mixing parameters, using a fast parameterised Monte Carlo simulation. Those simulations takes into account in a realistic manner the outputs from the full Monte Carlo simulations. Specifically, we will be simulate the background-over-signal levels, the time dependent acceptance efficiency and tagging and reconstruction performances for that decay mode. It will also take as inputs the event-by-event proper time errors obtained from the full MC. The likelihood fit performed to extract the physics parameters requires a flavour-specific control sample, $B^0_s \to D_s \pi$, which allows for the extraction of the $B^0_s - \bar{B}^0_s$ mixing frequency, $\Delta M_s$. The sensitivity achieved by our channel decay will be then combined to other $b \to \bar{c}c\bar{s}$ quark level transitions...
transitions to pure CP eigenstates and finally also to the $B^0_s \to J/\psi \phi$ decay to admixture of CP eigenstates. The sensitivity obtained from the pure CP modes is $\sigma(\phi_s) = 0.056$ rad whereas if we combine all decay channels into a single sensitivity measurement we achieve $\sigma(\phi_s) = 0.021$ rad. The contribution from the pure CP modes is non-negligible, $\sim 14\%$, so that it is expected that these channels will certainly help in the measurement of $\phi_s$.

**keywords:** LHCb, LHC, CERN, Standard Model, CP-violation, $B^0_s - \overline{B}^0_s$ system, $\phi_s$ weak mixing phase.
Résumé

L’Expérience LHCb constitue l’une des quatre principales expériences au LHC-CERN à Genève est située au point 8. La prise des premières données devrait commencer après l’été 2007. Le détecteur LHCb est un spectromètre à bras unique conçu pour étudier avec grande précision la violation CP et les phénomènes rares de la physique des quarks-b. LHCb devrait permettre une exploration approfondie du Modèle Standard, et ainsi révéler de possibles anomalies, signes d’une “Nouvelle Physique”.

Les études conduits par la collaboration LHCb offrent la possibilité de faire des tests avancés de la description de la violation CP dans le Modèle Standard. Celui-ci fournit la base théorique de cette violation exhibée par les mésons neutres B et K. Nous étudions ici les B_0^s. L’un des phénomènes sous-jacent de la violation est le mélange B_0^s − B_0^s. Sa phase, φ_s, n’a jamais été mesurée. Cette phase est à l’origine de l’interférence entre la désintégration et le mélange des mésons neutres. Les désintégrations des B_0^s en des états propres de CP suite aux transitions b → ccs au niveau des quarks sont des candidats potentiels pour déterminer cette phase électro-faible grâce à une mesure temporelle de l’instant de désintégration du B_0^s.

Parmi les transitions au niveau des quarks, le canal de référence pour une telle mesure est B_0^s → J/ψ φ. Ce canal nécessite cependant une analyse angulaire pour distinguer les états propres de CP finals. Les transitions pur les b → ccs dans des états propres CP fournissent une autre manière d’étudier la phase φ_s en s’affranchissant de l’analyse angulaire. Dans ce mémoire, nous considérerons les désintégrations B_0^s → J/ψ(μ^+ μ^-) η'(π^+ π^- η (γ γ)) qui sont des transitions b → ccs vers de purs états propres CP.

La reconstruction et la sélection de ces désintégrations seront présentées ici en utilisant des simulations de Monte Carlo réalistes. Le taux de production annuel d’événements est reproduit avec un rapport bruit-de-fond sur signal autour de 1. La résolution en masse et en temps propre sera aussi présentée ainsi que des recherches pour en améliorer les performances.

Dans le dernier chapitre, une étude sur la sensibilité statistique de la désintégration B_0^s → J/ψ(μ^+ μ^-) η'(π^+ π^- η (γ γ)) aux paramètres du mélange B_0^0 − B_0^0 sera décrite, utilisant des simulations Monte Carlo rapides. Celles-ci tiennent compte des résultats des simulations Monte Carlo réalistes mentionnées précédemment. Plus précisément, les simulations incluent de manière adéquate les niveaux de signal sur bruit-de-fond, la dépendance temporelle de l’acceptance ainsi que les performances de “tagging” et reconstructions pour ce canal de désintégration. Les calculs incluent la prise en compte des erreurs sur le temps propre au cas par cas pour chaque événement, ces erreurs ayant été,
obtenues lors des simulations Monte Carlo réalisées. L’ajustement de vraisemblance réalisé pour la détermination des paramètres physiques nécessite le canal de contrôle à la saveur spécifique, $B_s^0 \to D_s \pi$, qui permet d’obtenir la fréquence $\Delta M_s$.

Le niveau de sensibilité atteint dans notre canal de désintégration, sera ensuite combiné à ceux d’autres transitions $b \to c\bar{c} s$. La sensibilité obtenue pour les modes CP purs est de $\sigma(\phi_s) = 0.056$ rad après 1 année de prise de données tandis que la combinaison de tous les canaux de désintégration donne $\sigma(\phi_s) = 0.021$ rad. La contribution des modes CP purs est non négligeable, $\sim 14\%$: ces canaux devraient aider dans la mesure de $\phi_s$.

**Mots-clés:** LHCb, LHC, CERN, Modèle Standard, violation CP, mélange $B_s^0 - \bar{B}_s^0$, phase mélange faible $\phi_s$.
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Introduction

One of the unsolved theoretical questions in physics is why the universe is made chiefly of matter, rather than consisting of equal parts of matter and antimatter. It can be demonstrated that to create an imbalance in matter and antimatter from an initial condition of balance, the Sakharov conditions [1] must be satisfied, one of which is the existence of CP violation during the extreme conditions of the first moments after the Big Bang.

CP is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which reverses the sign of the spacial coordinates of a physical system.

The Big Bang should have produced equal amounts of matter and anti-matter if CP-symmetry was preserved; as such, there should have been total cancellation of both. This would have resulted in a sea of photons in the universe with no normal matter. Since this is quite evidently not the case, during the Big Bang, physical laws must have acted differently for matter and antimatter; and since CP-symmetry would dictate that physics would act identically to both classes of matter, it cannot hold in all cases.

CP violation was first discovered in 1964 in a kaon decay experiment [2]. Recently, a new generation of experiments, including the BABAR Experiment at the Stanford Linear Accelerator Center (SLAC) [3] and the Belle [4] Experiment at the High Energy Accelerator Research Organisation (KEK), Japan, have observed CP violation using B mesons. CP violation in the Standard model is incorporated through a complex phase in the CKM matrix. A necessary condition for the appearance of the complex phase, and thus for CP-violation, is the presence of at least three generations of quarks.

We will introduce in Chapter 1 the theoretical topics of CP violation in the Standard Model. The $B_s^0 - ar{B}_s^0$ system will be of special interest. In Chapter 2 will be described the experimental apparatus LHCb, being built at CERN, Geneva, for dedicated studies of CP violation. The following chapters will be dedicated to the presentation of the channel under study in this dissertation and some aspects about the simulations performed to obtain the data samples for our analysis. We will be specially concerned about $b \rightarrow c\bar{c}s$ quark-level transitions decaying into pure CP eigenstates as those provide direct access to the weak mixing phase, $\phi_s$. In Chapter 5 we present the selection of the decay channel $B_s^0 \rightarrow J/\psi \eta'$ and then the results obtained from it. The last chapter, is dedicated to the estimation of the statistical sensitivity to the $\phi_s$ and other parameters expected from our channel decay and combined with similar ones.
INTRODUCTION
Chapter 1

CP Violation

This chapter describes the CP symmetry operation and its violation within the Standard Model. Special emphasis is given to the $B^0_s$-meson system where new generation hadron colliders could shed light on the origin of this symmetry violation by the weak interactions and any possible sources of CP violation within New Physics models.

The violation of the CP symmetry is one of the fundamental and most exciting phenomena of modern particle physics. Although weak interactions are not invariant under P and C operations, it was believed for several years that the combined operation CP was preserved. However, in 1964, it was discovered through the observation of $K_L \rightarrow \pi\pi$ [2] that weak interactions are not invariant under CP transformations. In 2001, CP violation was also observed in decays of neutral B mesons [3, 4], which represents the beginning of a new era in the search for New Physics. Despite those discoveries, we still have few experimental insights into CP violation. In the Standard Model, the origin of the lack of symmetry is found in the flavour structure of weak charged-current interactions.

1.1 Weak decays and CP violation in the Standard Model

In the framework of the Standard Model, the massive fermions are grouped together in three families or generations. Each of them, consists of a doublet of left-handed particles (weak isospin $\pm 1/2$) and two singlets of right-handed particles (weak isospin 0). The weak interaction only acts on the left-handed particles, so the three families of quarks which are eigenstates of the weak interaction are

\[
\begin{pmatrix}
  u \\
  d'
\end{pmatrix}_L,
\begin{pmatrix}
  c \\
  s'
\end{pmatrix}_L,
\begin{pmatrix}
  t \\
  b'
\end{pmatrix}_L
\]

Where the weak eigenstates $d'$, $s'$, $b'$ are linear combinations of the mass eigenstates, i.e.:
\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} = V_{\text{CKM}} \cdot 
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}.
\tag{1.1}
\]

\(V_{\text{CKM}}\) is the unitary \(3 \times 3\) Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix introduced by Cabibbo 1963 [10, 11] and extended by Kobayashi and Maskawa [12] in 1973 to include a third generation of quarks. The CKM matrix can be written explicitly as

\[
V_{\text{CKM}} = 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\tag{1.2}
\]

where \(V_{ij}\) is the matrix element coupling the \(i^{th}\) up-type quark to the \(j^{th}\) down-type quark. The fact that the CKM matrix is unitary assures the absence of elementary FCNC vertices. Consequently the unitarity of \(V_{\text{CKM}}\) is at the basis of the GIM\(^{2}\) mechanism[8]. CP-violating effects may originate from the charged-current interactions of quarks, having the structure

\[
D \to U W^{-}.
\]

Here \(D \in \{d,s,b\}\) and \(U \in \{u,c,t\}\) denote down- and up- type quark flavours, respectively, whereas \(W^{-}\)is the usual \(SU(2)_{L}\) gauge boson.

If we express the non-leptonic charged-current interaction Lagrangian in terms of the mass eigenstates appearing in 1.1, we arrive at

\[
\mathcal{L}_{\text{int}}^{cc} = -\frac{g}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t})_{L} \gamma^{\mu} V_{\text{CKM}} \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix} W_{\mu}^{\dagger} + h.c., \tag{1.3}
\]

where \(g\) is the weak coupling constant that is related to the gauge group \(SU(2)_{L}\) and the \(W^{\mu(t)}\) field corresponds to the charged W bosons. Looking at the interaction vertices following from 1.3, we observe that the elements of the CKM matrix describe the generic strengths of the associated charged-current processes. The strengths of these couplings are not predicted by the SM and must hence be determined experimentally.

The CP conjugate of the charged-current \(D \to U W^{-}\) is \(\bar{D} \to \bar{U} W^{+}\). Since the corresponding CP transformation involves the replacement

\[
V_{UD} \leftrightarrow V_{UD}^{*},
\]

CP violation could be accommodated in the SM through complex phases in the CKM matrix.

The phase structure of the quark-mixing-matrix is not unique since we have the freedom of performing the following phase transformations which are related to phase transformations of the corresponding quark fields:

\[
V_{ij} \rightarrow \exp(i\zeta_{i}) V_{ij} \exp(-i\tilde{\zeta}_{j}).
\]

\(^{2}\)Glashow-Iliopoulos-Maiani mechanism
Using these transformations to eliminate unphysical phases, it can be shown that the parametrization of the general unitary $N \times N$ quark-mixing-matrix, where $N$ denotes the number of fermion generations, is described by $(N - 1)^2$ parameters consisting of

\[ \frac{1}{2}N(N-1) \]

Euler-type angles and

\[ \frac{1}{2}(N-1)(N-2) \]

complex phases [8].

In the case of $N = 2$ generations, we observe that only one rotation angle – the Cabibbo angle $\theta_C$ – is required for the parametrization of the $2 \times 2$ quark-mixing-matrix, which can be written as:

\[
V_{\text{CKM}} = \begin{pmatrix}
\cos \theta_C & \sin \theta_C \\
-\sin \theta_C & \cos \theta_C
\end{pmatrix}
\]

(1.4)

In the case of $N = 3$ generations, the $3 \times 3$ quark-mixing-matrix (CKM matrix) is parametrized by three angles, being the mixing angles between the generations and a single complex phase. This phase leading to an imaginary part of the CKM matrix is a necessary ingredient to describe CP in the Standard Model.

Many parametrizations of the $V_{\text{CKM}}$ have been proposed in the literature. Each emphasising a different aspect. The Particle Data Group [13] uses the "Kang-Chau"[14] representation, also called, ‘the standard parametrisation’:

\[
V_{\text{CKM}} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}
\end{pmatrix},
\]

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ control the mixing between the three $i,j$ generations ($i,j=1,2,3$) while $\delta_{13}$ is the CP violation phase. This parametrization highlights the rôle of the $V_{\text{CKM}}$ as an extension of the Cabibbo two-generation mixing mechanism. For numerical evaluations the use of the standard parametrisation is recommended.

Figure 1.1: Hierarchy of the quark transitions mediated through charged-current processes.
For phenomenological applications, it would be useful to have a parametrisation that makes the hierarchy of the mixing between generations explicit. This is introduced in the Wolfenstein parametrisation[15] in which each element of the matrix is expanded as a power series in the small parameter \( \lambda \equiv \sin \theta_C \) that has a value \( |V_{us}| \approx 0.22 \). The matrix only acquires a non-zero imaginary component at the 3rd order in \( \lambda \), specifically in the \( V_{ub} \) and \( V_{td} \) terms. The smallness of the Standard Model CP-violation is made explicit in this formalism. Couplings between first and second generations is \( O(\lambda) \) and between second and third it is \( O(\lambda^2) \), suggesting a suppression factor \( O(\lambda) \) between flavour changing decays. From the imaginary terms we see that CP violating effects involve transitions to the \( O(\lambda^3) \) and even smaller of \( O(\lambda^4) \).

\[
V_{CKM} = \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4),
\]

The precision of nowadays experiments demands to continue the Wolfenstein expansion up to \( O(\lambda^5) \).

\[
V_{CKM} = \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda + \frac{1}{2} A^2 \lambda^5 [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 (1 + 4A^2) & A\lambda^2 \\
A\lambda^3 [1 - (1 - \frac{1}{2} \lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2} A^2 \lambda^4 [1 - 2(\rho + i\eta)] & 1 - \frac{1}{2} A^2 \lambda^4
\end{pmatrix} + O(\lambda^6),
\]

### 1.1.1 Unitarity triangles

The unitarity constraint of the CKM matrix leads to six orthogonality conditions between any pair of columns or any pair of rows. Each orthogonality equation requires the sum of three complex numbers to vanish, and so can be represented as a triangle in the complex plane. The six triangles constructed this way are known as “unitarity triangles”. They have all the same area given by \( |J_{CP}|/2 = A^2 \lambda^6 |\eta| \) where \( J_{CP} \) is the “Jarlskog parameter”\(^3\)

\[
\begin{align*}
V_{us}V_{ud}^* + V_{cd}V_{cb}^* + V_{ts}V_{td}^* &= 0, \quad (sd) \quad (1.5) \\
V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* &= 0, \quad (sb) \quad (1.6) \\
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* &= 0, \quad (db) \quad (1.7) \\
V_{ucd}V_{cd}^* + V_{usb}V_{usb}^* + V_{ucb}V_{usb}^* &= 0, \quad (uc) \quad (1.8) \\
V_{cd}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* &= 0, \quad (ct) \quad (1.9) \\
V_{td}V_{ub}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* &= 0, \quad (tu) \quad (1.10)
\end{align*}
\]

The \((db)\) and \((tu)\) triangles have all their sides of the same order \( O(\lambda^4) \). They only differ at \( O(\lambda^5) \) and are the most useful unitarity relations in the studies of CP violation in the decays of B-mesons. Equation 1.7 relates to observables in the decays of B\(_d\) mesons, and equation 1.10 to B\(_s\) mesons decays.

We define the triangles’ interior angles of (1.7) as \( \alpha, \beta \) and \( \gamma \):

\[
\alpha \equiv \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right), \quad \beta \equiv \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{ub}^*} \right), \quad \gamma \equiv \arg \left( -\frac{V_{td}V_{ub}^*}{V_{cd}V_{cb}^*} \right).
\]

\(^3\)The “Jarlskog parameter” or “Jarlskog determinant” \( J_{CP} \) is derived from the unitary constraint on the CKM matrix and quantifies the “strength” of the Standard Model CP violation[16].
1.2. NEUTRAL MESON MIXING

At $O(\lambda^5)$ a phase is introduced into $V_{ts}$ such that the angles $\beta$ and $\gamma$ are shifted. From the stretched triangle (sb) given by the Eq. (1.6), we can define an interesting angle, $\chi$, essential for the $B_s^0$ system.

$$\chi \equiv \beta_s \equiv \arg\left(-\frac{V_{cb}V_{cs}^*}{V_{ub}V_{tb}^*}\right) \simeq \lambda^2 \eta \simeq \arg(V_{ts}) - \pi, \quad (1.11)$$

Figure 1.2: The six CKM “unitarity triangles”.

1.2 Neutral Meson Mixing

The phenomenon of oscillations between a neutral meson particle and its antiparticle is well established and is possible as a result of the non-conservation of flavour in the weak interaction. Mesons are colour-singlet bound states (flavour eigenstate) composed of a quark-antiquark pair ($B$-mesons contains one $b$-quark.) In absence of the weak force, they would remain stable. Gell-Mann and Pais, based on the observation that the flavour was not conserved under the weak interactions, proposed the possibility of neutral meson mixing. In this process, mesons would oscillate into its anti-particle partners continuously. The mixing is a second-order weak interaction, in which to leading order, in the SM, is dominated by box diagrams shown in Figure 1.4.

In these diagrams, the t (top) quark contribution dominates due to the hierarchy of the CKM matrix elements and also because the amplitude is proportional to the mass in the loop. The top quark being the more massive of them.

Due to the oscillation phenomenon, mass eigenstates are formed from a mixture of the flavour eigenstates, so that, after creation, the observed meson wavefunction can be
Figure 1.3: The two unsquashed unitarity triangles. These triangles have been normalised relative to the baseline of the (db) triangle so that $V_{cd}V_{cb}^* = -1$.

Figure 1.4: Box diagrams contributing to $B_q^0 - \overline{B_q^0}$ mixing ($q_1, q_2 \in u, c, t$).

described as

$$|\psi(t)\rangle = a(t)|B_q^0\rangle + b(t)|\overline{B_q^0}\rangle,$$  \hspace{1cm} (1.12) 

which is governed by the time-dependent differential Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$  \hspace{1cm} (1.13) 

Here the Hamiltonian matrix can be decomposed into the component mass $M$ and decay $\Gamma$ matrices respectively which are both Hermitian matrices, i.e.:

$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} = (M - \frac{i}{2} \Gamma) = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix},$$  \hspace{1cm} (1.14)
where the Hermitian matrices $\textbf{M}$ and $\Gamma$ are defined as

$$\textbf{M} = \frac{1}{2}(\textbf{H} + \textbf{H}^\dagger) \quad \Gamma = i(\textbf{H} - \textbf{H}^\dagger) \quad (1.15)$$

Invariance under the CPT transformation, assumed to hold in the S.M., implies that the mass and lifetime of the meson and its anti-meson are the same, and so the diagonal elements of the $\textbf{M}$ and $\Gamma$ matrices are equal too, i.e. $M_{11} = M_{22} \equiv M_0$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma_0$. Diagonalising $\textbf{H}$ leads to two stationary physical eigenstates:

$$|B^q_\pm\rangle = p|B^0_q\rangle \pm q|\bar{B}^0_q\rangle \quad (1.16)$$

where the admixture constants $p$ and $q$ are complex numbers following the normalisation condition $|p|^2 + |q|^2 = 1$. Since the physical eigenstates are characterised by their definite masses we can define the heavy $|B^q_H\rangle$ ($|\bar{B}^q_H\rangle$) and light $|B^q_L\rangle$ ($|\bar{B}^q_L\rangle$) states. The energy eigenvalues are then found by solving the characteristic equation by the standard procedure, yielding to:

$$E_{H,L} = M - \frac{i}{2} \Gamma \pm \sqrt{(M_{12} - \frac{i}{2} \Gamma_{12})(M^\ast_{12} - \frac{i}{2} \Gamma^\ast_{12})},$$

$$= (M \pm \frac{\Delta M}{2}) - \frac{i}{2}(\Gamma \pm \frac{\Delta \Gamma}{2})$$

$$= M_{H,L} - \frac{i}{2} \Gamma_{H,L}. \quad (1.17)$$

where we have defined here the masses of the two eigenstates as $M_{H,L}$ and their corresponding widths $\Gamma_{H,L}$. The mass difference $\Delta M$ and the width difference $\Delta \Gamma$ are defined as:

$$\Delta M \equiv M_H - M_L > 0,$$

$$\Delta \Gamma \equiv \Gamma_H - \Gamma_L > 0.$$

so the average values are:

$$M = \frac{m_H + m_L}{2},$$

$$\Gamma = \frac{\Gamma_H + \Gamma_L}{2}.$$

The mass difference is defined to be positive and since the “lighter” states lives longer, the width difference is also defined to be positive. The relationship between $p$ and $q$ can be extracted from the eigenvector equations, so the ratio $q/p$ is:

$$\frac{q}{p} = -\sqrt{\frac{M^q_{12} - \frac{i}{2} \Gamma^q_{12}}{M^q_{12} - \frac{i}{2} \Gamma^q_{12}}}, \quad (1.18)$$

relating the off-diagonal mass and decay matrix elements which are important to define the CP violation in the mixing.

The time evolution of the initial particle and antiparticle states, $|B^0_q(t)\rangle$ and $|\bar{B}^0_q(t)\rangle$, obtained by rearranging equations, and substituting for the time evolution of the states,

$$|B_{H,L}(t)\rangle = |B_{H,L}\rangle e^{-i(M_{H,L} \pm \frac{i}{2} \Gamma_{H,L})t},$$
are

\[ |B_q^0(t)⟩ = f_+(t)|B_q^0⟩ + \frac{q}{p}f_-(t)|\overline{B}_q^0⟩, \quad (1.19) \]
\[ |\overline{B}_q^0(t)⟩ = f_+(t)|\overline{B}_q^0⟩ + \frac{p}{q}f_-(t)|B_q^0⟩, \quad (1.20) \]

where the time varying parts of these equations has been separated out from the rest.

\[ f_\pm(t) \equiv \frac{1}{2}\left[ e^{-i(M_L-\frac{i}{2}\Gamma_L)t} \pm e^{-i(M_H-\frac{i}{2}\Gamma_H)t}\right]. \quad (1.21) \]

### 1.3 Time dependent decay rates of neutral B-mesons: CP violation

If we now consider the time dependent rates for neutral B-mesons to decay into a same final state \( f \), we first have to compute the amplitudes of these processes in which a initially created \( |B_q^0⟩ \) meson will follow the time evolution given by 1.19 and will decay occasionally into the final state \( f \), i.e.:

\[ A[|B_q^0(t)⟩ → f] = ⟨f|T|B_q^0(t)⟩ = f_+(t)A_f + \frac{q}{p}f_-(t)\overline{A}_f. \]

where \( A_f = ⟨f|T|B_q^0⟩ \) and \( \overline{A}_f = ⟨f|T|\overline{B}_q^0⟩ \) are the instantaneous decay amplitudes. Any difference between these two rates is clear proof of CP violation.

The same procedure could be applied to the anti-meson arriving to the following expression:

\[ A[|\overline{B}_q^0(t)⟩ → f] = ⟨f|T|\overline{B}_q^0(t)⟩ = f_+(t)\overline{A}_f + \frac{p}{q}f_-(t)A_f. \]

Hence, the associated decay rates are given by the squared amplitude modules, resulting in:

\[ \Gamma_f(t) ≡ \Gamma(|B_q^0(t)⟩ → f) = |A_f|^2\left\{ |f_+(t)|^2 + |\lambda_f|^2|f_-(t)|^2 + 2\Re\{\lambda_f f_+^*(t)f_-(t)\}\right\}, \]
\[ \Gamma_f(t) ≡ \Gamma(|\overline{B}_q^0(t)⟩ → f) = |A_f|^2\left\{ |f_-(t)|^2 + |\lambda_f|^2|f_+(t)|^2 + 2\Re\{\lambda_f f_+(t)f_-^*(t)\}\right\}, \quad (1.22) \]

where we have defined:

\[ \lambda_f \equiv \frac{q}{p}\overline{A}_f/A_f. \quad (1.23) \]

and we have also introduced:

\[ |f_\pm(t)|^2 = \frac{1}{4}\left[ e^{-\Gamma_Lt} + e^{-\Gamma_Ht} \pm 2e^{-\Gamma_Lt}\cos(\Delta m_q t)\right] \]
\[ = \frac{e^{-\Gamma_Ht}}{2}\left[ \cosh\left(\frac{\Delta m_q t}{2}\right) \pm \cos(\Delta m_q t)\right], \]
\[ f_+(t)f_-(t) = \frac{1}{4}\left[ -e^{-\Gamma_Ht} + e^{-\Gamma_Lt} + 2ie^{-\Gamma_Lt}\sin(\Delta m_q t)\right] \]
\[ = \frac{e^{-\Gamma_Ht}}{2}\left[ \sinh\left(\frac{\Delta m_q t}{2}\right) + i\sin(\Delta m_q t)\right]. \]
The first terms in the rates $\Gamma_f$ and $\Gamma_{\bar{f}}$ show that CP violation is generated if $|A_f| \neq |\bar{A}_f|$. This is called CP violation in the decay amplitudes. Even if there is no CP violation in the decay amplitudes, the second terms indicates that CP violation is generated if $|q/p| \neq 1$. This type of CP violation is called CP violation in the mixing and finally, even if there is not any of the previous CP violations sources present, CP violation can still arise due to the third term in the case:

$$Im\{\frac{q}{p} A_f \} \neq 0.$$ 

This type of CP violation is commonly referred to as CP violation in the interference between the mixing and the decay amplitudes.

Similarly we could compute the decay rates to the CP conjugated final state $\bar{f}$ given by:

$$\Gamma \left( B^0_q(t) \rightarrow \bar{f} \right) = \left| \frac{q}{p} \right|^2 \left\{ |f_-(t)|^2 + |\bar{f}_T|^2 |f_+(t)|^2 + 2 \Re \left[ \bar{f}_T f_+(t) f_+^*(t) \right] \right\},$$

$$\Gamma \left( \bar{B}^0_q(t) \rightarrow \bar{f} \right) = \left| \frac{q}{p} \right|^2 \left\{ |f_+(t)|^2 + |\bar{f}_T|^2 |f_-(t)|^2 + 2 \Re \left[ \bar{f}_T f_+(t) f_-^*(t) \right] \right\}. \quad (1.24)$$

### 1.4 The phenomenology of CP violation

We will now consider, in a model independent fashion, the three forms in which CP violating effects can be manifest:

- CP violation in the mixing between the neutral mesons, when the mass eigenstates are not CP eigenstates.
- CP violation in the decay which occurs when the amplitudes of a decay and its CP-conjugate counter-part partner have different magnitudes.
- CP violation in the interference of mixing and decay in which a meson that can decay to a CP final eigenstate directly or changing its flavour before decaying has associated amplitudes which interfere with each other.

#### 1.4.1 CP violation in meson mixing

CP violation in the meson mixing appears in the time evolution of the two neutral mesons described by the Schrödinger equation above. This CP source comes from a difference in rates $B^0 \rightarrow \bar{B}^0$ and $\bar{B}^0 \rightarrow B^0$. This fact is then represented by requiring the magnitudes of the off-diagonal elements in the effective Hamiltonian to be non-equal. i.e.:

$$\left| M_{12} - \frac{i}{2} \Gamma_{12} \right| \neq \left| M_{12}^* - \frac{i}{2} \Gamma_{12}^* \right| \quad (1.25)$$

and this is only due to a phase difference between $M_{12}$ and $\Gamma_{12}$. From Eq. 1.18 we can deduce a phase convention independent magnitude which is useful in phenomenological applications for CP violation in the mixing:

$$\left| \frac{q}{p} \right|^2 = \left| \frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}} \right|. \quad (1.26)$$
So the inequality in the magnitudes of the off-diagonal terms corresponds to:

$$\frac{|q|}{|p|} \neq 1$$

We note also that if CP is conserved in the mixing then the mass eigenstates have to be CP-eigenstates, that is to say, CP$$|B_{H,L}\rangle = \pm |B_{H,L}\rangle$$. If the mass eigenstates without mixing are defined as

$$|B_H\rangle = \frac{1}{\sqrt{2}} (|B^0_q\rangle + |B^0_{\bar{q}}\rangle)$$  \hfill (1.27)

$$|B_L\rangle = \frac{1}{\sqrt{2}} (|B^0_q\rangle - |B^0_{\bar{q}}\rangle)$$  \hfill (1.28)

The standard CP operation defined above applied over the mass eigenstates in then satisfied with the conventional $$|B^0_q\rangle = \text{CP}|B^0_q\rangle$$ and $$|B^0_{\bar{q}}\rangle = \text{CP}|B^0_{\bar{q}}\rangle$$ definitions.

### 1.4.2 CP violation in decay

CP violation can also take place in the interference between decay amplitudes, which causes a difference between decay rates of $$B^0_q \to f$$ and its CP-conjugate decay $$B^0_{\bar{q}} \to \bar{f}$$.

We may want to write the decay amplitudes of these processes as $$A_f \equiv \langle f | H_{\text{weak}} | B^0_q \rangle$$ and $$A_{\bar{f}} \equiv \langle \bar{f} | H_{\text{weak}} | B^0_{\bar{q}} \rangle$$. There are in these amplitudes two types of phases that can act in the Hamiltonian:

- the weak phases from the weak quark-mixing matrix ($V_{\text{CKM}}$), that are then due to complex parameters in the Lagrangian of the weak interaction, appear in complex conjugate form in the amplitudes, so with opposite signs. These are the phases that violate CP.
- the strong phases due to final state interactions mediated by the strong force. They appear in the amplitudes with the same sign and do not violate CP.

We therefore could write the amplitude as the product of its magnitude and its phases as:

$$A_f = \sum_i A_i e^{i\phi_i} e^{i\delta_i}, \quad A_{\bar{f}} = \sum_j A_j e^{-j\phi_j} e^{j\delta_j}$$

Considering the observable ratio of decay amplitudes which is a phase-convention independent quantity:

$$\left| \frac{A_{\bar{f}}}{A_f} \right| = \left| \frac{\sum_j A_j e^{j(\delta_j - \phi_j)}}{\sum_i A_i e^{i(\delta_i + \phi_i)}} \right|$$

If CP is conserved the weak phases are equal and, also the strong phases since we assume the strong force to be CP-invariant. Hence, if CP is conserved in the decay

$$\left| \frac{A_{\bar{f}}}{A_f} \right| = 1.$$  

Conversely, if the meson can decay by several mechanisms with different amplitudes, and at least two terms with different weak and strong phases, interference between the decay
amplitudes will occur causing the rates of the CP-conjugate amplitudes to be different. Then,

$$\frac{|\mathcal{A}_f|}{|A_f|} \neq 1. \iff \text{CP violation}$$

This type of CP violation is easily measured in decays of charged mesons since the mixing process is not present.

### 1.4.3 CP violation in the interference of mixing and decay: Mixing induced CP violation

Another kind of CP violation is possible when a neutral $B^0_q$-meson and its $\bar{B}^0_q$ anti-meson can both decay to the same final state $f$ (or $\bar{f}$), then CP violation can occur as a result of interplay between the mixing and decay amplitudes. The B-meson can decay directly or oscillate before decaying to the same common final state ($B^0_q \rightarrow B^0_q \rightarrow f$). This kind of CP violation is then a combination of the two previous ones, so the the complex ratios $\lambda$, $\bar{\lambda}$ are again defined for convenience.

$$\lambda = \left(\frac{q}{p}\right) \left(\frac{A_f}{|A_f|}\right) \quad \text{and} \quad \bar{\lambda} = \left(\frac{q}{p}\right) \left(\frac{\mathcal{A}_f}{|\mathcal{A}_f|}\right)$$

(1.29)

The ratio $q/p$ applies to the neutral meson mixing of the B-meson while $A$ and $\mathcal{A}$ are the decay amplitudes of the $B^0_q$ and $\bar{B}^0_q$ decaying to the same final state $f$ or $\bar{f}$. These quantities defined above are phase convention independents and are physically meaningful.

One can then observe CP violation in this scenario if $\lambda, \bar{\lambda} \neq 1$. This can be the case if CP is violated either in the mixing ($|q/p| \neq 1$) or the decay ($|A/A| \neq 1$) independently. But, as a more important case, it can also be violated even when neither mixing or decay CP violations are present, but, the phases of $q/p$ and $\mathcal{A}/A$ interfere to give a imaginary part $\Im\{\lambda, \bar{\lambda}\} \neq 0$. i.e. if CP is conserved:

$$\frac{|q|}{|p|} = 1;$$

$$\frac{|\mathcal{A}_f|}{|A_f|} = 1;$$

and furthermore the relative phases between the two quantities of interest vanishes. But even so, CP violation is observed provided that:

$$|\lambda_f| = 1, \quad \Im\lambda_f \neq 0.$$ 

This source of CP violation is not plagued with hadronic uncertainties which are difficult to compute as in the CP violation in the decay, so, this case is the most theoretically clean situation for extracting the values of the CKM parameters from experimental measurements.
1.5 CP violation in the B system: $\bar{b} \to \bar{c}c\bar{s}$ transitions to CP eigenstates

Unfortunately, at the $e^+ e^-$ B-factories operating at the $\Upsilon(4S)$ resonance (BaBar, Belle, CLEO[17]), no $B^0$-mesons are accessible, since $\Upsilon(4S)$ states decay only to $B(u,d)$-mesons, but not to $B^0$. On the other hand, the physics potential of the $B^0$ system is very promising for hadron machines (Tevatron, LHC), where plenty of $B^0$-mesons are produced. In some sense, $B^0$ physics is therefore the "El Dorado" for B experiments at hadron colliders.

In both the $B^0$ and $B^0_s$ systems, it can be argued that $|\Gamma_{12}| \ll |M_{12}|$ [5], i.e.:

$$\left| \frac{\Gamma_{12}}{M_{12}} \right| \ll 1$$

The strength of the $B^0 - \bar{B}^0$ mixing (where $q = d, s$ as before.) is described by the mass difference, $\Delta M_B$, that in this case, can be expressed in terms of the off-diagonal element of the neutral $B^0_q$-meson mass matrix, because of the property regarded above for the $B^0_q$ systems.

$$\Delta M_B = 2 |M_{12}|$$

That property of the $B^0_q$ system also leads to the following expression:

$$\frac{q}{p} = -\frac{M^*_{12}}{|M_{12}|} \left[ 1 - \frac{1}{2} \Im \left( \frac{\Gamma_{12}}{M_{12}} \right) \right], \quad (1.30)$$

Where the last expression has been expanded to next-to-leading order in $|\Gamma_{12}/M_{12}|$. The smallness of $\Im (\Gamma_{12}/M_{12}) \sim \mathcal{O}(10^{-3})$ render the ratio $q/p$ as a pure phase to an excellent approximation. So we can neglect CP violation effects in the mixing, and then write:

$$\left| \frac{q}{p} \right| = 1 \quad \text{that implies} \quad |\lambda_f| = \left| \frac{A_f}{A_f} \right|; \quad (1.31)$$

For the $B^0_s$ system, we use this approximation to transform the above time-dependent decay probabilities (1.22) into

$$\Gamma[B^0_q(t) \to f] = \frac{|A_f|^2 + |\bar{A}_f|^2}{2} e^{-\Gamma_q t} \left\{ \cosh \left( \frac{\Delta \Gamma_q t}{2} \right) + D_f \sinh \left( \frac{\Delta \Gamma_q t}{2} \right) \right. \right.$$  

$$+ C_f \cos (\Delta m_q t) - S_f \sin (\Delta m_q t) \left\}, \right.$$  

$$\Gamma[B^0_s(t) \to f] = \frac{|A_f|^2 + |\bar{A}_f|^2}{2} e^{-\Gamma_q t} \left\{ \cosh \left( \frac{\Delta \Gamma_q t}{2} \right) + D_f \sinh \left( \frac{\Delta \Gamma_q t}{2} \right) \right. \right.$$  

$$- C_f \cos (\Delta m_q t) + S_f \sin (\Delta m_q t) \left\}. \quad (1.32)$$

---

4 Belle has been recently running at the $\Upsilon(5S)$ resonance.

5 The upper bound on the CP asymmetry in semileptonic B decays ($A_{SL}$) implies that CP violation in the $B^0 - \bar{B}^0$ mixing is a small effect (we use $A_{SL}/2 \approx 1 - |q/p|$). $A_{SL} = (-3.0 \pm 7.8) \times 10^{-3} \implies |q/p| = 1.0015 \pm 0.0039$. The small deviation from 1 implies that, at present level of experimental precision, CP violation in B mixing is considered a negligible effect.
CP violation in the interference of mixing and decay is only possible in neutral B and K. Now, in the B\(_S^0\) system, we could consider decays in which their final states are CP-eigenstates since those simplify considerably the test of CP in hadronic experiments, i.e.:

\[ CP |f\rangle = \eta_{f,CP} |f\rangle, \]

being \(\eta_{f,CP} = \pm 1\) the eigenvalue of the final state.

Then a time dependent "CP" asymmetry is defined in this case in order to test CP violation in the B\(_S^0\) system.

\[ A_{CP}(t) = \frac{\Gamma[\bar{B}^0_s(t) \to f_{CP}] - \Gamma[B^0_s(t) \to f_{CP}]}{\Gamma[\bar{B}^0_s(t) \to f_{CP}] + \Gamma[B^0_s(t) \to f_{CP}]} \]  

The quantity \(\lambda_f\) containing essentially all the information needed to evaluate the asymmetry is given by

\[ \lambda_f = \frac{q A_f}{p \bar{A}_f} = e^{i\phi_s} \frac{\bar{A}_f}{A_f} \]

where \(\phi_s\) denotes the weak phase in the \(B^0_s - \bar{B}^0_s\) mixing. Generally several decay mechanisms with different weak and strong phases can contribute to the amplitudes. These are tree diagram (current-current), QCD penguin contributions and electroweak penguin contributions. If they contribute with similar strength to a given decay amplitude the resulting CP asymmetry suffer from hadronic uncertainties.

An interesting case arises when a single mechanism dominates the decay amplitude. Then the hadronic matrix elements and strong phases drop out and

\[ \frac{\bar{A}_f}{A_f} = -\eta_{f,CP} e^{-i2\phi_D} \]

is a pure phase with \(\phi_D\) being the weak phase in the decay amplitude. Consequently

\[ \lambda_f = -\eta_{f,CP} e^{i\phi_s} e^{-i2\phi_D} = -\eta_{f,CP} e^{i(\phi_s - 2\phi_D)} = -\eta_{f,CP} e^{i\phi_{CKM}}. \]

where \(\phi_{CKM} = (\phi_s - 2\phi_D)\) is the CKM phase.

Hence, assuming no CP violation in the mixing (\(|q/p| = 1\)) and that a single decay mechanism dominates, we obtain

\[ D_f \equiv \frac{2 \Re(\lambda_f)}{1 + |\lambda_f|^2} \equiv A_{\Delta\Gamma} \]

\[ C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \equiv A_{\text{decay}}^{CP} \]

\[ S_f \equiv \frac{2 \Im(\lambda_f)}{1 + |\lambda_f|^2} \equiv A_{\text{int}}^{CP} \]

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\[ D_f \equiv \frac{2 \Re(\lambda_f)}{1 + |\lambda_f|^2} \equiv A_{\Delta\Gamma} \]

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CP violation in the interference of mixing and decay is only possible in neutral B and K. Now, in the B\(_S^0\) system, we could consider decays in which their final states are CP-eigenstates since those simplify considerably the test of CP in hadronic experiments. i.e.:

\[ CP |f\rangle = \eta_{f,CP} |f\rangle, \]

being \(\eta_{f,CP} = \pm 1\) the eigenvalue of the final state.

Then a time dependent "CP" asymmetry is defined in this case in order to test CP violation in the B\(_S^0\) system.

\[ A_{CP}(t) = \frac{\Gamma[\bar{B}^0_s(t) \to f_{CP}] - \Gamma[B^0_s(t) \to f_{CP}]}{\Gamma[\bar{B}^0_s(t) \to f_{CP}] + \Gamma[B^0_s(t) \to f_{CP}]} \]  

The quantity \(\lambda_f\) containing essentially all the information needed to evaluate the asymmetry is given by

\[ \lambda_f = \frac{q A_f}{p \bar{A}_f} = e^{i\phi_s} \frac{\bar{A}_f}{A_f} \]

where \(\phi_s\) denotes the weak phase in the \(B^0_s - \bar{B}^0_s\) mixing. Generally several decay mechanisms with different weak and strong phases can contribute to the amplitudes. These are tree diagram (current-current), QCD penguin contributions and electroweak penguin contributions. If they contribute with similar strength to a given decay amplitude the resulting CP asymmetry suffer from hadronic uncertainties.

An interesting case arises when a single mechanism dominates the decay amplitude. Then the hadronic matrix elements and strong phases drop out and

\[ \frac{\bar{A}_f}{A_f} = -\eta_{f,CP} e^{-i2\phi_D} \]

is a pure phase with \(\phi_D\) being the weak phase in the decay amplitude. Consequently

\[ \lambda_f = -\eta_{f,CP} e^{i\phi_s} e^{-i2\phi_D} = -\eta_{f,CP} e^{i(\phi_s - 2\phi_D)} = -\eta_{f,CP} e^{i\phi_{CKM}}. \]

where \(\phi_{CKM} = (\phi_s - 2\phi_D)\) is the CKM phase.

Hence, assuming no CP violation in the mixing (\(|q/p| = 1\)) and that a single decay mechanism dominates, we obtain

\[ D_f \equiv \frac{2 \Re(\lambda_f)}{1 + |\lambda_f|^2} \equiv A_{\Delta\Gamma} \]

\[ C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \equiv A_{\text{decay}}^{CP} \]

\[ S_f \equiv \frac{2 \Im(\lambda_f)}{1 + |\lambda_f|^2} \equiv A_{\text{int}}^{CP} \]
\[ |\lambda_{f_{CP}}| = 1, \quad C_{f_{CP}} = 0, \quad S_{f_{CP}} = -\eta_{f_{CP}} \sin (\phi_{CKM}), \quad D_{f_{CP}} = -\eta_{f_{CP}} \cos (\phi_{CKM}), \quad (1.40) \]

**Figure 1.5:** Feynman diagrams contributing at quark level to the decay of a $B_0^q$ meson through a $b \rightarrow \bar{c}s$ transition ($q \in s,d$). The dashed lines in the penguin topology represent a colour-singlet exchange.

$B_s^0$ decays through $\bar{b} \rightarrow \bar{c}s$ transitions (See Fig.1.5) are penguin doubly-Cabibbo suppressed [18], i.e., no direct (at decay-level) CP violation is present. Furthermore, have their amplitudes been dominated by only one tree decay, hence, the decay phase $\phi_D \equiv \text{arg}[V_{cb}V_{cs}^*] \approx 0$.

Therefore, we still have mixing-induced CP violation which arise from the phase mismatch between $\phi_s$ and the phase of the decay amplitudes ratio $\phi_D$. I.e.:

\[ \phi_{CKM} = \phi_s - 2\phi_D \approx \phi_s. \]

The mixing phase can be related to angles of the unitarity triangle as follow:

\[ \phi_s \simeq -2\chi \simeq -2\lambda^2 \eta = \mathcal{O}(-0.04) \text{ rad} \]

Taking all the above considerations for the $\bar{b} \rightarrow \bar{c}s$ transitions which decay to CP eigenstates, we can write the time-dependent rates as follows:

\[
\Gamma[B_s^0(t) \rightarrow f_{CP}] = |A_{f_{CP}}|^2 \ e^{-\Gamma t} \ \left\{ \cosh \left( \frac{\Delta \Gamma s}{2} t \right) - \eta_{f_{CP}} \ \cos (\phi_s) \ \sinh \left( \frac{\Delta \Gamma s}{2} t \right) \right. \\
+ \eta_{f_{CP}} \ \sin (\phi_s) \ \sin (\Delta m_s t) \bigg\},
\]

\[
\Gamma[\bar{B}_s^0(t) \rightarrow f_{CP}] = |A_{f_{CP}}|^2 \ e^{-\Gamma t} \ \left\{ \cosh \left( \frac{\Delta \Gamma s}{2} t \right) - \eta_{f_{CP}} \ \cos (\phi_s) \ \sinh \left( \frac{\Delta \Gamma s}{2} t \right) \right. \\
- \eta_{f_{CP}} \ \sin (\phi_s) \ \sin (\Delta m_s t) \bigg\}.
\]

(1.41)

and hence the time-dependent CP asymmetry which results from these approximations.
allow us to directly determine \( \phi_s \) by only measuring this CP asymmetry.

In the case of the \( B^0_0 \) system, similar arguments can be followed. The time-dependent decay probabilities (1.32) for the \( B^0_0 \) system are further simplified as \( \Delta \Gamma_d \approx 0 \)

\[
\Gamma[B^0_0(t) \to f] = \frac{|A_f|^2 + |A_{f'}|^2}{2} e^{-\Gamma_d t} \left\{ 1 + C_f \cos (\Delta M_d t) - S_f \sin (\Delta M_d t) \right\},
\]

\[
\Gamma[B^{0\ast}_d(t) \to f] = \frac{|A_f|^2 + |A_{f'}|^2}{2} e^{-\Gamma_d t} \left\{ 1 - C_f \cos (\Delta M_d t) + S_f \sin (\Delta M_d t) \right\}.
\]

and if, we also consider decays to CP eigenstates common to \( B^0_0 \) and \( B^{0\ast}_d \), we obtain

\[
\Gamma[B^0_0(t) \to f_{CP}] = |A_{f_{CP}}|^2 e^{-\Gamma_d t} \left\{ 1 - \eta_{f_{CP}} \sin (\phi_d) \sin (\Delta M_d t) \right\},
\]

\[
\Gamma[B^{0\ast}_d(t) \to f_{CP}] = |A_{f_{CP}}|^2 e^{-\Gamma_d t} \left\{ 1 + \eta_{f_{CP}} \sin (\phi_d) \sin (\Delta M_d t) \right\}.
\]

Leading to a time dependent CP asymmetry for the \( B^0_0 \) system:

\[
A_{CP}(t) = -\eta_{f_{CP}} \sin (\phi_d) \sin (\Delta M_d t).
\]

where, if only Standard Model box processes contribute to the \( B^0_0 - B^{0\ast}_d \) oscillation, \( \phi_d \) is identical to \(-2\arg V_{td} = 2\beta\), i.e. \( \phi_d = 2\beta \).
Chapter 2

The LHCb Experiment

This chapter describes the Large Hadron Collider beauty (LHCb) experiment. It begins with a general description of the LHCb. Then, all its sub-detectors are introduced. Finally, the triggering system of the experiment is presented.

2.1 The LHCb experiment

The Large Hadron Collider beauty experiment (LHCb) is a single-arm forward experiment dedicated to precise measurements of CP violation and rare decays. However, other topics are being considered to be investigated to a lesser extend. The layout of the experiment is shown in Figure (2.1). LHCb is being installed at IP8 cavern at CERN ([19]), the site was occupied by Delphi during LEP times. A modification to the Large Hadron Collider (LHC) optics, displacing the interaction point by 11.25 m from the center, has permitted maximum use to be made of that existing cavern by freeing 19.7 m for the LHCb detector components. The choice of the geometry of the spectrometer is motivated by the fact that at high energies $b\bar{b}$ pairs are both predominantly emitted either in the same backward or forward cone. The second arm is missing, but this geometry allow for the use of the whole experimental area so that the length for measuring particles trajectories is double compared to central detectors. To reduce the material budget and to improve trigger performances, the detector layout suffered from some modifications of the original Technical Proposal TDR [20]. The changes are described in the Reoptimized Detector TDR [21]. The angular coverage ranges from 10 mrad to 300 (250) mrad in the bending (non-bending) plane. The key features of the LHCb detector are:

- Excellent vertex and proper time resolution;
- Precise particle identification (ID), specifically, hadron $\pi/K$ separation, and lepton $e/\mu$ ID;
- A versatile and efficient trigger scheme, in order to cope with a variety of modes with low branching fractions.

These main characteristics are accomplished by the use of the following subdetectors (systems):

- the vertex detector (VELO);
Figure 2.1: The LHCb spectrometer. Side view of the detector (non-bending plane). Also shown is LHCb reference system, which is chosen as the following: the \( z \) axis is along the beam pipe, with the origin close to the interaction point and pointed toward the detector. The \( y \) axis is in the vertical direction, which also coincides with LHCb magnetic field direction. The \( x \) axis is horizontal and is chosen to have a right handed coordinate system. Picture from [21].

- the upstream Ring-Imaging Cherenkov detector (RICH1);
- the Trigger Tracker (TT);
- the dipole magnet;
- the tracking stations (T1-T3). Decomposed in Inner Tracker (IT) and Outer Tracker (OT);
- the downstream Ring-Imaging Cherenkov detector (RICH2);
- the Scintillating Pad Detector (SPD) and Preshower (PS);
- the Electromagnetic Calorimeter (ECAL);
- the Hadronic Calorimeter (HCAL);
- the muon detector (M1-M5).

### 2.1.1 The beam pipe

The beam pipe needs to hold the Ultra High Vacuum in the region of the LHCb detector, hence, it has to be mechanically very strong to stand the difference in pressure between the high vacuum and the ambient. The design of the beam pipe is specially delicate since
2.1. THE LHCb EXPERIMENT

this vacuum chamber is located in a region of high rapidity of the LHCb in which the density of the particles is high. For this reason, attention needs to be paid in order to avoid as much as possible the number of secondaries created in the pipe that could reach the active elements of the detector, otherwise, the occupancy of the tracking chambers and RICH's would render the reconstruction of tracks and identification of particles not feasible. A large number of secondaries would also harm the electronics and produce tracks which do not originate from the collision point.

After the technical proposal [22], a reoptimization period\(^1\) was launched in order to investigate which material and shape would suit the best for the beam pipe. It can be seen on Fig.(2.2) that Beryllium is the most transparent material. The beam pipe is shaped in order to diminish as much as possible the interaction distance to the primaries. The position of the flanges and bellows is also crucial as these pieces are origin of secondaries that could be seen by the detector. From these considerations, it came out the following design. The beam pipe is composed of two conical sections, the first one, of 1840 mm length, is made of 1 mm thick Beryllium and has an aperture of 25mrad. It is welded downstream to the VeLO exit window and it is followed by short cylindrical section (250 mm length) and a cone of 10 mrad. Transition bellows connects the latter section to the second one constructed also from Beryllium and having an aperture of 10 mrad. It runs the full length of the detector with an increasing thickness of 1.0 to 2.4 mm. It is chopped in three sections due to coating restrictions that are joint together by well positioned flanges and transition bellows. Ports for pumping are foreseen at the downstream of this cone.

---

\(^1\)This reoptimization period was mainly motivated by the need to make the detector lighter without jeopardizing the physics goals of the experiment.
2.1.2 Vertex locator (VELO)

The distribution of production vertices around the nominal collision point spreads longitudinally within $\sim 5$ cm. The vertex locator subdetector [23, 24] is of main importance within the LHCb as it has to provide precise measurements of track coordinates close to the interaction region in order to be able to reconstruct accurately the production vertex as well as the B-meson decay vertex. The B-meson lives long enough to exhibit displaced vertices in the lab framework which are easy to separate as long as a very good vertex resolution is achieved. This is an important signature which allow us to enrich the B-decay content of the data via a high efficiency trigger system. The displacement of production and decay vertices is of the $O(1 \text{ cm})$ so sub-mm accuracy is needed to be able to resolve these vertices. The ability to reconstruct precisely those is of key importance for time dependent analyses such as $B^0 - \overline{B^0}$ mixing studies. For most of them, a proper time resolution of the order or better than $40 \text{ fs}$ is required. The VELO is also the first element in the chain which provides track information before the main tracking system. It is expected an off-line (online) vertex reconstruction resolution of $40 \mu\text{m (80}\mu\text{m})$ along the beam axis. The technology that can easily cope with the resolution and hard radiation requirements are silicon detectors with a small strip-pitch and low multiple scattering.

![Figure 2.2: Effect of beam pipe materials on particle fluxes on the inner part of the tracking chambers. This figure is taken from [23].](image)

Figure 2.2: Effect of beam pipe materials on particle fluxes on the inner part of the tracking chambers. This figure is taken from [23].

![Figure 2.4: Pile-up veto counter and VELO stations shown in the $y - z$ plane. The pile-up veto consists of two single planes of silicon situated at the lowest $z$ positions. The VELO is made of 21 stations, each consisting of two silicon planes. Picture from [23].](image)

Figure 2.4: Pile-up veto counter and VELO stations shown in the $y - z$ plane. The pile-up veto consists of two single planes of silicon situated at the lowest $z$ positions. The VELO is made of 21 stations, each consisting of two silicon planes. Picture from [23].

The LHCb silicon vertex locator system (VELO) surrounds the beam interaction region and its active element consist of 21 silicon disks stations placed transversely to the beam direction, as shown in Figure (2.4). The choice of this number of stations is motivated by the tradeoff between low material budget and tracking performance. For a track of a given
momentum, the error in the impact parameter is smaller if the extrapolation distance to the production vertex is short. This requires that detector stations have to be very close to the beam.

Figure 2.5: 3D view of the VELO vacuum vessel with the silicon sensors (TDR layout with 25 stations) and the corrugated RF-foils. Picture from [23].

Thanks to the forward design of LHCb the disc stations are built in two halves that can easily be placed at 8 mm from the beam during normal operation of data taking, but, in order to prevent from radiation damage during the filling and ramping of the LHC, these half-stations have to be moved out by 3 cm horizontally. The accuracy of the positioning is 0.05 mm. The two halves of each station are offset each other by 2 cm allowing a small overlap of the sensitive area and hence providing a mean for alignment. A data table taking into account possible misalignments will be provided at the beginning of each run in order to correct for hit positions.

The 21 stations are positioned along the beam for 1 m (8 of them are used for backward tracking). Two extra stations placed upstream will be used by the L0 trigger and mainly will help to veto multiple interactions per event within the Pile-Up Veto system.

Each half-station consist of two 220µm thick n-on-n single side silicon wafers bonded back-to-back, each sensor is isolated by p-doped guards. The first sensor wafer (R-sensor) has circular strips that increase with radial distance measuring the r-coordinate of the track hit, while the other (phi-sensor) primarily indicates the azimuthal coordinate of the hit but also gives a rough information about r, hence, they are used by the trigger system to make quick vertices. The radial strips of the latter sensor also increase with radius and are tilted by 5° from a pure radial design. The DAQ electronics of each sensor are placed on the outer most position of the wafers in order to avoid for radiation damage of the acquisition chips (so-called Beetle chips [25]).
In order to protect the sensors from RF currents induced by the beam bunches, a 0.3 mm aluminium alloy foil has been designed. It has some corrugations to give mechanical strength, to dissipate the induced currents and minimise material seen by the particles. This foil is placed in between the sensors as shown in Figure 2.5.

For minimizing the material between the interaction region and the detectors, the active elements of the VELO are within a thin aluminium box under a primary vacuum of less than $10^{-4}$ mbar. The sensors can then move freely out of the reach of the beam by the use of a system similar to a Roman Pot without risking the LHC vacuum.

The VELO main vacuum tank is bonded directly to the beam pipe so it stands the same LHC pressure. Electron-hole pairs created as charged particles pass through the wafers will drift to the strip readout points under a reverse bias voltage. The signal is then read out along double-metal strips which are routed out from the center of the sensor. The readout process is controlled by 16 Beetle chips [25] mounted on each sensor. In order to avoid thermal runaway, heat produced by electronics and power dissipation in the silicon bulk is removed by conduction through a cooling block that uses CO$_2$ as refrigerant.

2.1.3 Magnet

The magnet is a dipole type [26] with its magnetic field oriented vertically, that needs to be placed close to the interaction region in order to keep its size small and cope with most of the charged particles to be tracked down. Its geometry is therefore determined by the acceptance of B-mesons events. On the other hand, a low magnetic field has to be seen by the VELO detector to give low track curvature inside it, otherwise this would degrade the fast straight-track fitting that is essential to trigger performance. Henceforth, the magnet has been designed to be immediately downstream of the first RICH detector and just upstream of the first tracking stations. This should provide sufficient field integral before the tracking stations to give the desirable magnetic resolution of 0.4% for momenta up to 200 GeV/c. The bending power required to achieve this goal is 4Tm. A warm dipole magnet design has been chosen since it permits a fast ramping of the field and a polarity flipping that aims to reduce any systematics that could appear due to left-right asymmetries. A superconducting magnet was rejected due to its high cost, and mechanical risks. A very important issue for the design of the magnet has been also the uniformity of the field. The magnet provides a maximum central field of 1.1 T in the vertical direction.
2.1. THE LHCB EXPERIMENT

Figure 2.7: The LHCb magnet and surrounding iron yoke. The field mapping machine is mounted inside. This picture is taken from the “Press Office Photo Selection” of the CERN.

2.1.4 The Tracker System

The tracking system [22] consist of several distinct sub-detectors, namely, the VELO already seen above, the Trigger Tracker (TT) and the Tracking Stations T1-T3 as seen in Figure (2.1). The system as a whole aims to reconstruct the tracks of charged particles from which we can compute the particle momentum given the track curvature in the magnetic field. A particle momentum resolution of $\delta p/p \approx 0.4\%$ or better is expected for any charged end-particle issued from a B-decay in order to achieve the desirable mass resolution. After reoptimization of the LHCb, only four tracking stations were left without risking the tracking performance. Eleven stations were present in the original design from the Technical Proposal. The TT station will serve to veto any non-signal event at the second level of trigger (see below). Because it is located before the magnet, TT will see a similar high fluence of particles as in the VELO. Hence, the technology of detection that has been preferred is the silicon-based. The T1-T3 stations will have to cope with different fluences as we move out of the beam pipe, henceforth, two different regions named Inner Tracker and Outer Tracker has been defined in order to deal with the distinct fluxes using two kind of detectors. Matching the tracks to the calorimeter clusters allow association of the energy measurement to each track. In addition, linking tracks to RICH detector rings enables the particle identification.

2.1.4.a The Trigger Tracker

The trigger tracker (TT) [27, 28] is positioned between the first RICH sub-detector and the upstream side of the magnet. It aims to have a rough estimate of the transverse momentum of tracks with large impact parameter. In addition, it is also used by off-line analyses to track down low momentum particles which are not seen by other tracking stations since those particles are swept out of the acceptance by the magnet. Long-lived particles, such as $K^0_S$, decay after the VELO, thus, they will not be seen unless another tracking station is placed just after the decay vertex. The choice of silicon microstrips detectors as base technology for the TT and the Inner Tracker (IT) is motivated by some detector constraints that are, the ability to cope with high density of tracks, to be radiation-
hard, to have a fast response time, and to have a very good hit resolution. TT covers an area of about $130 \times 160 \text{ cm}^2$. It consists of a total of 4 layers distributed in pairs which are separated by 27 cm along the beam axis (so-called TTa and TTb). The silicon wafer is $410 \mu \text{m}$ thick having strip pitches of $198 \mu \text{m}$. Sensors are mounted on carbon composite ladders which facilitates the heat removal. The most upstream and downstream layers are disposed vertically (x-layers) whereas the inner ones are titled by $\pm 5^\circ$ (u-/v-layers).

2.1.4.b The Inner Tracker

The reduction of the number of tracking stations has been motivated by the effort to decrease the amount of material seen by a particle in the LHCb. At the technical proposal times [20], stations were optimised for a Kalman-like [29] algorithm that would follow track seeds at the trigger stations back to the interaction region. Several complementary tracking algorithms have been developed for the reoptimized detector layout that allow us to reconstruct the trajectories of charged particles using only three stations (T1-T3) plus the TT.

Each of the three inner tracking stations [28] consists of four detector boxes which are arranged around the beam pipe in a cross-shape fashion as shown in Fig.(2.9). The dimensions of the boxes are motivated by the need of reducing occupancies in the outer tracker regions. The cross extends over approximately 120 cm in width and 40 cm in height. This geometry is well adapted to the distribution of particle densities in the experiment which is highest within the horizontal bending plane of the magnet.

As for the TT stations, the technology that suits the best the requirements of good space resolution, ability to cope with high charged particle fluxes, fast signal collection, and excellent momentum resolution which is dominated by multiple scattering, is the silicon microstrip option. Silicon sensors are 11 cm long and 7.8 cm wide and they are $320 \mu \text{m}$ or $410 \mu \text{m}$ thick (left/right or top/botton boxes respectively) single side $p^+\text{-on}-n$ with a strip pitch of $198 \mu \text{m}$.

A detector box contains four detection layers with vertical or near vertical readout strips, as in the TT, following the $xuvx$ pattern, in which $u$ and $v$ are the stereo layers ($\pm 5^\circ$) sandwiched in between. Ladders hold the sensors in the foreseen positions and help in the removal of heat generated by leakage currents of the sensors. To achieve the actual performances for those support ladders, several studies on the mechanical stiffness of different prototypes as well as on their thermal features were carried out by the LHCb collaboration [30]. A summary of those studies can be found in Appendix C.

The ladder in which sensors are glued on consist of a sandwich-like structure made up of 4 layers: $25\mu \text{m}$ of kapton material used here for electrical insulation purposes, $200\mu \text{m}$ of heat conducting carbon fiber (Mitsubishi K13D2U) at $\pm 10^\circ$ from the ladder vertical axis, $1\text{mm}$ of foam (Airex R82) and once more $200\mu \text{m}$ of carbon fiber.

One-sensor ladders are used in the top/bottom boxes while two-sensors ladders are in the left/right ones. The different thickness of the sensors ensures sufficient signal in the presence of increased noise due to increased load capacitance for the long ladders.

Each of the detection layers consists of seven staggered silicon ladders which are mounted onto a common cooling rail that removes the heat from the front-end electronics. This arrangement allows for a small overlap between the ladders. All 28 ladders are housed in an enclosure that provide thermal, optical, an electrical insulation.

For the Velo, TT and the IT, the Beetle chip\textsuperscript{2} is used as front-end. The front-end readout

\textsuperscript{2}The Beetle DAQ is a 128 channel custom-made analog readout chip using commercial 0.25 $\mu \text{m}$ CMOS.
chip samples detector data at the LHC bunch crossing frequency of 40 MHz and stores them in an analog pipeline for a maximum latency of 160 clock cycles. The electronics allow for a fast shaping time which avoid the pile-up of events to be reconstructed.

The three tracking stations T1-T3 are placed at equidistant positions along the beam line in between the magnet and the second RICH sub-detector.

Dedicated Monte Carlo studies have shown that a tracking efficiency larger than 95% and a ghost rate smaller than 7% could be achieved for tracks with a momentum larger than 12 GeV/c. The momentum resolution ranges from 0.35% to 0.5% and the IP resolution reaches 140 \( \mu \text{m} \) for tracks with a large transverse momentum. The momentum and impact parameter (IP) resolutions are shown in Figure (2.12).

Figure 2.8: 3D view of the IT ladder. The Airex foam is sandwiched by two carbon-fibre layers. It is also shown the insulation layer of kapton material as well as the two silicon sensors and their front-end electronics

Figure 2.9: 3D view of one of the T stations.

Figure 2.10: Layout of \( x \)-layer in T2. Dimensions are given in cm. This figure is taken from [31].

Figure 2.11: Layout of \( u \)-layer in T2. Dimensions are given in cm. This figure is taken from [31].

and radiation hard technologies.
2.1.4.c The Outer Tracker

As already mentioned above, the Outer Tracker (OT) [32] covers an area of moderate track density. The boundaries of the OT have been defined so that it will only see up to a maximum in occupancy of 10%. For this reason, the track hit detector technology choice could be thought in terms of low cost and good spatial resolution. The latter calls for the use of drift cells as they provide with fast response signals, good spatial resolution, are easy to build, and do not need for special maintenance requirements.

The OT is built from 5 mm straw tubes, that are gathered in two layers packed in such a way that spatial resolution is less than the straw radius. These two layers form a plane (module). Each plane is made of rows of 64 or 96 straws depending in which region of the acceptance they are placed. Each straw is filled with a gas admixture that may be varied to fine-tune the drift time of charged ions. The preferred gas is the mixture of Ar(75%), CO₂(10%) and CF₄(15%).

The signal collected by the inner anode of each tube is read out by electronics cards located far away from the acceptance of the LHCb. Even thought the radius of the straws allows for fast signal collections, a maximum drift time of two cross bunches (50ns) is allowed since pattern recognition is able to track down hits within this time period. As in the TT, each station is formed by 4 layers of OT modules disposed as in the TT fashion, i.e., revealing the (xuvx) geometry.

Figure 2.12: Resolution of the parameters of the reconstructed tracks at the production vertex: a) momentum resolution as a function of the momentum, b) impact parameter resolution as a function of $1/P_T$. B-decay particle spectra ($p$ and $P_T$) are shown in the lower part of the plot. Picture from Ref. [23].
2.1.5 The RICH System

Hadron identification in LHCb is provided by two ring-imaging Cherenkov (RICH) detectors [23, 33, 34]. They have been specialised to improve selection of b-physics decays. Specifically, the ability to identify $\pi$ out of K tracks (or the other way around) is of vital importance in order to make precision b-physics studies on channels that have identical topologies but not same end products. 90% of $\pi$ and K issued from B-decays are well separated within a dynamic range of 1 to 150 GeV/c.

It is also crucial to be able to find kaons accompanying B-mesons of interest. By doing so, a B-meson flavour can be assigned to the reconstructed candidates (see below.)

RICH detectors are based on the Cherenkov effect [35] that occurs when a high energy charged particle traverses a dielectric medium (characterised by a refractive index n) with a velocity $\beta c$ greater than the speed of light in that medium, i.e., c/n. If this happens, the charged particle will create an arrangement of induced dipoles within the dielectric that build up forming a net dipole which originates instantaneous photon emission in a coherent way. Henceforth, an effective wavefront of Cherenkov light is emitted forming a cone that has an aperture angle of $\Theta_c$ with respect to the momentum vector of the particle. The cosine of the angle is then given by:

$$\cos(\Theta_c) = \frac{ct}{\beta ct} = \frac{1}{\beta n}$$

and can be understood from the Huygens’ construction of Fig 2.14, which neglects any particle recoil correction term. For typical high energy particles found in LHCb the energy loss per unit track-length in the radiator medium is negligible and is of the order of some hundreds of eV cm$^{-1}$ (see [36]). The usefulness of the Cherenkov effect lies in the fact that measurement of the above angle provides a direct measurement of the velocity of the particle. RICH detectors make use of spherical mirrors that are able to reflect the light

$^{3}\beta = v/c$ being the relativistic velocity fraction, where v is the velocity of the particle and c the speed of light in vacuum
arising from a series of cones produced by the same particle on to a single ring at the mirror’s focal length. The centre of the ring position at the focal length distance is given by the projection of the track and its radius depends only on the velocity of the particle. Thus, the combination of momentum measurement given by the track curvature, and the velocity obtained as explained above, allow an estimate of the particle mass and hence its identity.

The LHCB collaboration has chosen to split the RICH system into two detectors, RICH1 and RICH2 as well as make use of three distinct radiators in order to satisfy the requirements of particle identification and π-K separation over a wide range of particle momentum and polar angles.

RICH1 is placed close to the interaction point, directly clamped to the downstream face of VELO. Far away enough from the magnet to see straight tracks and close enough to the interaction point in order to cover the angular acceptance of low- to mid-momentum tracks that may get swept out of the detector as well as to keep its size small. It covers polar angles from 25mrad to 330mrad detecting particles with momentum ranging from 1-70GeV/c. The Cherenkov radiator gas is $C_4F_{10}$, with $n=1.0015$, to detect mid-momentum tracks. There is also present a 5 cm thick panel made of silica aerogel, with $n=1.03$, which is specifically designed to detect the low-momentum particles. They both provide $3\sigma$ π-K separation for the whole dynamic range. Alternatively, a mix of $C_3F_8$ and $C_5F_{12}$ that has the same refractive index as $C_4F_{10}$ is considered as the gas radiator. Cherenkov angles for some particles depending on their momenta can be seen in Fig. 2.15 for three different radiators.

The spherical mirrors are tilted in order to focus the light cones into rings out of the experiment acceptance. These rings are further moved away by secondary flat mirrors that allow to place photon detector arrays out of the acceptance of LHCB as well as to increase the track radiation-length.

The technology chosen to detect the light is pixel hybrid photon detector (HPD). The choice is motivated by their ability to detect single photon, good spatial resolution, and a fast response time.

RICH1 is 3x2 m$^2$ in the x-y plane and 1 m deep in the z-axis. The optics are arranged vertically to the top and bottom and the mirrors are made of beryllium to decrease material budget.

RICH2 on the other hand uses $CF_4$ gas with $n=1.0005$, as a single radiator, extending from 10-120 mrad. It identify particles from p 10-100GeV and its optics are placed...
2.1.6 The Calorimeter System

Any calorimeter system aims to estimate the total energy and impact coordinates of the secondaries issued from high energy interactions. Those informations are provided by total-absorption methods by which the incident particles interact in a large detector mass generating secondary, tertiary particles and so on. Thus, all or most of the incident energy is absorbed by the medium.

In addition, such devices are essential in recording the energy of neutral hadrons; and since the energy resolution varies as $E^{-1/2}$ precision is only achieved at high energies. Just as important, they provide fast energy signals which are of vital importance for quick decisions on event selection.

LHCb calorimeters [37] have been designed to fulfill all these standard requirements but additionally some others specific to the detector has been added. The LHCb calorimeter should therefore identify and measure energy of electrons and hadrons which are required by off-line event studies but mainly of the ones to be used for various trigger algorithms.

Furthermore, the electromagnetic calorimeter (ECAL) will let us know the energy of photons and neutral pions of B-decay channels containing a prompt photon or $\pi^0$. All these informations have to be provided with sufficient selectivity and chiefly in a very short time given by the collision rate.

The requirement of good background rejection, reasonable efficiency, shower separation and the selectivity demanded by the first trigger level adds to the latter conditions the longitudinal segmentation of the electromagnetic shower detection. The structure chosen consist of four elements described by the order that particles see them:

- The single layer scintillator pad detector (SPD) to differentiate between charged and neutrals like $\pi^0$ that are the main background to the electron trigger.

- Then, just after the SPD, a single preshower (PS) is positioned to reject the high background of charged pions by longitudinally segmenting the ECAL.
• The "Shashlik" electromagnetic calorimeter (ECAL).

• A scintillating tile hadron calorimeter (HCAL).

Geometric matching of acceptance and of lateral segmentation facilitates the combination of information from cells of the different sub-detectors mainly for the trigger processing but also for off-line reconstruction.

Acceptance starts at 30mrad and extends up to 300mrad horizontally and 250mrad vertically. The dynamic ranges extends up to 200GeV in the ECAL and 300GeV in the HCAL. Complications arising from the use of radiation-hard detection techniques do not worth the improvement of acceptance at low polar angles.

The rates of charged particles and neutrals at the front face of ECAL vary over the calorimeter surface by some orders of magnitude. To reach a low occupancy level per cell so that the number of readout channels required is dropped down, and keep reasonable position and momentum resolutions, the calorimeter should have a non-uniform granularity. For this reason, three areas of occupancy with different cell sizes have been defined for the ECAL, SPD and PS, so-called, inner, middle and outer regions.

![Figure 2.16: Transverse segmentation of the SPD, PS and ECAL cells. A square represents a “module”. One quarter of the detector front face is shown. Figure from [37].](image1)

![Figure 2.17: Transverse segmentation of the HCAL cells. A square represents a “module”. One quarter of the detector front face is shown. Figure from [37].](image2)

### 2.1.6.a The Scintillator Pad Detector (SPD)

The Scintillator Pad Detector (SPD) is meant to complete the calorimeter system and perform the $e^+ / \gamma$ separation at the very first triggering level.

The detector elements are 15mm thick scintillator pads which are arranged in a matrix-like layer. A groove machined on each of the tiles holds a helicoidal wave-length shifting (WLS) fiber that allow collection of the scintillation light produced by the passage of charged particles. Hence, electrons and photons can be distinguished at this early stage what cannot be done once showering has begun.

The light from both WLS fiber ends is sent by long clear fibers to multianode photo-multipliers (PMT) placed above or below the detector. This structure provides on average about 25 photoelectrons in the PMT in response to a minimum ionising particle (MIP)$^5$.

The discrimination is then done applying a threshold on the energy released within a SPD cell of 0.7 MIP energy. This value is 100% efficient for electrons while it rejects most of the photons. Hence, a particle that has been recognised as electromagnetic at the ECAL

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$^5$A MIP leaves on average 2.85MeV in the scintillator
can be further discriminated if the SPD cell in front of the ECAL cluster shows no signal (i.e. SPD logic value is 0). Henceforth, a photon has been detected at the ECAL. Whereas, charged particles induce light emission in the SPD what corresponds to a logic value of 1.

![Figure 2.18: 4x4 SPD/PS cell.](image)

### 2.1.6.b The Preshower Detector (PS)

The main purpose of the preshower detector is to achieve electron/hadron separation. (specifically, $e/\pi^\pm$ separation). In addition to this, energy corrections for electromagnetic showers occurring before the ECAL can be estimated using this sub-detector. The PS detector consist of a 12 mm-thick lead ($2.5 X_0$) converter layer followed by a layer of scintillator tiles as the one for the SPD. The PS uses the difference in interaction lengths for electrons and pions in lead to distinguish them. Electrons produce a shower that starts in the lead absorber whereas pions do not. The secondaries from the electron shower reach the scintillator depositing in it significantly more energy that the pions. Henceforth, a threshold cut 4 MIP (After Monte Carlo studies) seems to be sufficient to distinguish them efficiently. The optimization of the PS thickness results from a compromise between trigger performance generating and energy resolution.

### 2.1.6.c The Electromagnetic Calorimeter (ECAL)

The electromagnetic calorimeter aims to:

- Provide electron and photon identification at the trigger level and at off-line reconstruction as well as to measure their energy.
- Provide for $\pi^0$ identification.
The requirements for the ECAL, such as, good energy resolution, transverse granularity, fast response time and to be radiation-hard, calls for the use of the "Shashlik" technology that combine all these features at a reasonable cost and has been already tested by the HERA-B calorimeter modules of similar design.

The ECAL is built from three different type of modules, each of them based on the "Shashlik" technology. As electromagnetic showers are more collimated that hadronic showers, each ECAL module is made from 2mm-thick lead absorber tiles to encourage showering inter-spaced with 4mm-thick scintillator tiles as active material, with tile's short axes aligned along the beam direction. In total there are 66 lead/scintillator tiles of $12\times12\text{cm}^2$ side which correspond to $25\ X_0$ in depth. Each type of the modules only differ each other by the number of readout cells, being 3x3 cells the inner modules, 2x2 the middle ones, and 1x1 the outer ones. Henceforth, the number of scintillating tiles in each of the planes differ as well, i.e., the outer modules having less number of tiles than the inner ones. As in the SPD and PS, the light from the scintillating tiles are readout by photomultipliers at the back end of the modules. Helicoidal WLS fibers placed in the tile are routed out through small holes on each tile to reach the photon detectors.

The energy resolution provided by this calorimeter design is $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1.5\%$. Test-beam data using electrons confirm this result measuring: $\sigma(E)/E = (9.4 \pm 0.2)\%/\sqrt{E} \oplus (0.83 \pm 0.02)\%$.

The first term is the stochastic component and represents the statistics related fluctuations, such as the intrinsic shower fluctuation, the photoelectrons statistics, etc. The second term is due to the detector non-uniformity and calibration uncertainty; $\oplus$ means that the two terms have to be added in quadrature; $E$ is expressed in GeV.

Figure 2.19: ECAL modules for the outer, middle and inner sections.
2.1.6.d The Hadronic Calorimeter (HCAL)

The main purpose of the hadronic calorimeter (HCAL) is to provide data to be used in the first level of trigger. As for the ECAL, the hadronic calorimeter (HCAL) is a sampling calorimeter with an alternating structure of 16 mm-thick steel tiles and 4 mm-thick (on average) scintillator tiles (absorber and active material respectively.) The more lateral hadronic showers require that in order to improve the sampling, tiles are oriented parallel to the beam axis. This orientation is also motivated by the need of fast readings at 40MHz. Again, WLS fibers are used for the readout of the scintillating material, but now these fibers run along the edge of the tiles to bring the light from three rows of tiles to a single-anode photomultiplier. The HCAL is segmented in two sections of different tile sizes in order to cope with the different fluences, see Fig. (2.17).

The HCAL length is 1.2 meters, i.e. 5.6 interaction lengths. The energy resolution provided by the calorimeter is \( \sigma(E)/E = 80\%/\sqrt{E} \pm 10\% \). These performance figures have been also verified by test-beam data using pions.

2.1.7 The Muon System

The muon system [38] is the sub-detector placed furthest downstream of the LHCb. It performs a two-fold task:

- Muon identification and momentum measurement for off-line analyses
- Trigger formation at the early stage.

Muon identification is of key importance since muons are present in many of the benchmark CP-violating channels of LHCb as well as in rare decays studied by LHCb that are expected to be a probe of new physics. It plays also an important role in the first triggering stage in which \( P_T \) information from muons are combined with \( E_T \) measurements from the calorimeter via the so-called muon trigger. In addition, muons are used in the tagging procedure to identify the flavour of the B-mesons through semi-leptonic decays which muons charge is a clue to the flavour.

The Muon detector is composed of five stations (M1-M5) interleaved with 80 cm-thick iron plates to reduce background (muon filters). M1 is located just upstream of the SPD while the others are placed after the HCAL. M1-M3 serves for muon track-finding and momentum resolution, whereas, M4 and M5 provides muon identification. Every station is divided in 4 regions of increasing size that differ in pad granularity which contributes to keep \( \sigma(P_T)/(P_T) \) constant over the whole detector surface. The gap between the first and second muon stations is intended to provide a measurement of the muon \( P_T \). The ECAL and HCAL are therefore used as an additional filter that accounts for 30 radiation lengths so that muons are the only particles to reach the muon detectors and they must have at least an energy of 6 GeV.

The technology chosen for all of the five muons stations is multi-wire proportional chambers (MWPC) detectors. Each station is thus formed by a 5mm gap between two planes filled with Ar, \( CO_2 \), and \( CF_4 \) and having 30 \( \mu \)m anode wires at 1.5 mm from each other placed in the middle of the chamber. Rather than induce showering, muons produce about 50 electrons as they ionise the gas which are collected using a 3kV potential. Since, the innermost region of M1 has to cope with a higher flux, triple-GEM technology based on gas avalanches has been chosen instead.
The muon detector provides a 55% efficiency muon identification for inclusive B-decays at the trigger level. In addition, 99% is otherwise achieved at the off-line reconstruction stage.

### 2.1.8 The Trigger System

Due to the LHC bunch structure and low luminosity achieved after beam de-focussing at the LHCb interaction point, the active frequency of crossings with p-p interactions visible by the spectrometer reduces to 10 MHz. Even though, storage services will not be able to manage such a huge amount of data. Furthermore, accounting for the small b\bar{b} production cross-section, the hadronisation to B-mesons, the fraction of events that have all B-meson decay products contained in the acceptance of the spectrometer as well as the very low branching ratios of the decay channels that are of phenomenological interest, the number of events that are to be looked at only foreseen at a few hundreds of Hz.

Because all of the facts mentioned above, a system that reduces the number of recorded events while enhancing the quality of those to fulfill the phenomenological requests, has to be implemented. The LHCb trigger system [39] must hence be selective and highly efficient when saving this small amount of interesting data.

In order to reach these goals, the trigger is implemented as a multi-level trigger system, i.e. first triggering levels provide fast decisions that rely on rough estimates of tracks, energy and momentum, and afterwards more complex levels are at the end of the chain having more CPU time to take a decision on a low event rate. In LHCb trigger is divided into three levels; being Level 0 (L0), Level 1 (L1) and the so-called high-level trigger (HLT). L0 is implemented in hardware while L1 and HLT are software algorithms that share the PC farm located at the counting room to take the decision within a fixed interval of time.

#### 2.1.8.a L0

The L0 trigger aims to reduce the average acceptance rate to \(\sim 1\) MHz. For that, L0 uses the fact that heavy B-mesons decay into low-mass daughter particles with large transverse momentum. Events with high-\(P_T\) electrons, photons, hadrons are selected using rapid calorimeter informations, while events with high-\(P_T\) muons make uses of the muon system information. They are simultaneously classified in four trigger streams which provides independent informations to be used in the final decision on whether to save it or not.

Events with multiple p-p interactions occur in a high level for the given nominal LHCb luminosity. These events typically pass the high-\(P_T\) triggers and are difficult to reconstruct due to their high multiplicity. Henceforth, they need to be removed since they will not leave so much bandwidth available. At this stage, a pile-up veto need to be implemented. Two dedicated r-sensors planes are placed upstream the VELO’s sensors. The reconstruction of tracks going backwards by these two sensors allow to resolve for the number of primaries on each event. The L0 trigger is performed by dedicated electronics boards on selected sub-detectors. Each sub-detector has a pipeline buffer which is 168 bunch-crossings long that translates to a latency time of 4.2 \(\mu s\) to take the decision given by the L0 decision unit (L0DU). L0DU combines all informations available from the muon and calorimeter triggers as well as the pile-up veto. It accepts an event if the largest \(E_T\) measurement of all available is above a fixed threshold provided that the pile-up veto reconstruct less than three tracks from another primary vertex, or, when the sum of the \(E_T\) for the two most energetic muons in the transverse plane is above a threshold. In order
to avoid the triggering on beam halo muons\textsuperscript{7} a threshold on the total $E_T$ for the event is fixed to 5 GeV.

\subsection*{2.1.8.b L1}

The second trigger level L1 operates at the input rate of L0 and reduces the data even further at an average acceptance rate of 40 kHz. The software algorithm uses the previous L0DU summary data from the calorimeters and muon system as well as incorporates triggering information given by the VELO and the TT station. The triggering aims to refine the L0 trigger. Starting from L0 seeds in the calorimeter and muon systems, corresponding tracks are searched for in the VELO and TT. A more stringent low-cut on track $P_T$ can be applied at that level.

A key feature of $b$ quark events is the existence of displaced secondary vertices, and this is exploited by the L1 trigger using the vertex detector VELO. The event is required to have at least one track in the VELO with an impact parameter to the production vertex in the range 0.15-3 mm. The decision is weighted by the track momentum which is measured thanks to the fringe field of the magnet that exists between the VELO and TT. Henceforth, high $P_T$ particles with a large impact parameter associated to them are selected as good candidates to pass the next triggering level.

The Level-1 decision algorithm consists of two parts: in the first, a generic algorithm, computes a trigger variable based on the properties of the two tracks with highest transverse momentum and applies a cut in the form of a vertical-diagonal discriminant in the plane of $\sum \ln(P_T)$ vs $\sum \ln(IP)$. In the second, the specific algorithms, the trigger variable is computed as a bonus and is weighted according to the presence of dimuons, high-$E_T$ electrons, photons, etc. in the event. Events are therefore selected according to six trigger streams for which a global variable is defined so that if it pass a threshold level an event is successfully recorded to the next trigger level.

The streams are:

- **Generic**: Event pass level if $\sum \ln(P_T) > 14.34$ for the two largest $P_T$ (in MeV/c) tracks.
- **Single muon**: At least a muon with $P_T > 14.34$ GeV/c.
- **Dimuon General**: The invariant mass of the two muons have to be greater than 500 MeV/c and smallest positive $IP$ greater than 0.075 mm.
- **Dimuon $J/\psi$**: Invariant mass of the di-muon candidates within a mass window of 500 MeV/c with respect to the nominal $J/\psi$ mass. Invariant masses largest than that of $J/\psi$ are also selected.
- **Electron**: The largest $E_T$ electron within the event with $E_T > 3.44$ GeV and the $\sum \ln(E_T) > 13.2$ ($E_T$ in MeV).
- **Photon**: The largest $E_T$ photon within the event with $E_T > 3.06$ GeV and the $\sum \ln(E_T) > 13.2$ ($E_T$ in MeV).

\textsuperscript{7}The charged-particle flux associated with the beam halo in the LHC contains muons of a rather wide energy spectrum. In particular halo muons traversing the detector horizontally can cause a muon trigger. The number of beam halo muons depends strongly of the level of residual gas in the beam pipe.
The L1 algorithm is executed in the CPU farm and has a latency of \(\sim 50\) ms to process the event. This L1 timing allows for the various phases of the Level-1 to be run and only rejects a tiny fraction \((\sim 10^{-6})\) of the L0 accepted events.

### 2.1.8.c HLT

As it has already been said above, the high-level trigger (HLT) algorithm is entirely implemented in software. It has been nominally assigned a computing power of about 25% of the PC farm. At this stage, data from any sub-detector of LHCb is available to the HLT complex algorithms but even so, RICH information is currently unused due to the intensive computational calculus which would be required to perform the inversion of the RICH optics. Instead, particle identification (PID) information from the RICH is included only when an event has passed this trigger level.

The current implementation allows for a latency of processing of about 200 ms within which specific b-hadrons events are selected as well as integration of some other data streams that will allow a better knowledge of the systematic errors. The HLT receives data at an average rate of 40 kHz and accepts events at a nominal rate of 2 kHz.

It is mandatory here to perform a L1 confirmation on the event. Hence, we repeat the L1 reconstruction of VELO tracks and the primary vertex with the improved accuracy given by the pattern recognition algorithm available and the matching of these tracks to the TT and T1-T3 ones. The L1 cuts are then repeated as the momentum resolution has largely improved.

Additionally, a series of dedicated selection cuts is applied in order to keep the channels for core physics studies as well as the ones to control the systematics. The exclusive B-candidate events amounts up to a \(\sim 200\) Hz level rate. In this sample stream are included events which allow to estimate sidebands as well as control channels.

(a) Detailed description of the HLT trigger.

Figure 2.20: HLT highways. Figure from [40].
The extra 1.8 kHz are divided in three streams which are:

- **high mass dimuon candidates (600 Hz):** Which are selected with an invariant mass of the pairs above 2.5 GeV/c^2 and that will serve to study the systematic uncertainty on lifetime measurements, to test the tracking reconstruction performance as well as to provide with magnetic field calibrations.

- **D^* (300 Hz):** This stream allows for PID efficiency and misidentification estimations as well as to reconstruct D-decay events.

- **b-inclusive (900 Hz):** Events of this sample stream that includes high-P_T candidates and high-IP muons lead to estimates of trigger systematics.

Figure 2.21: Overview of the three trigger levels. [39].
Chapter 3

\( \mathbf{B}_s^0 \rightarrow J/\psi \eta' \) decay mode

3.1 Exploring CP Violation through \( \mathbf{B}_s^0 \rightarrow J/\psi \eta' \) at LHCb

3.1.1 Physics motivations for \( \mathbf{B}_s^0 \rightarrow J/\psi \eta' \) channel selection

CP violation effects in the B-system are expected to be much larger than in the neutral Kaon system. Recently, two dedicated B-physics experiments "Babar" [3] and "Belle" [41, 42] have reported first evidences for CP-violation in the B-system. Starting by the end of 2007, LHC and its dedicated experiment LHCb, will allow quite stringent tests of the \( \mathbf{B}_d^0 \), with an experimental reach far beyond those of BABAR and Belle. It will also have the unique source of \( \mathbf{B}_s^0 \) mesons worldwide. The challenge will be then to select those b-meson decays of interest for physics studies and constrain the angles of the unitarity triangles in a search for New Physics. \( \mathbf{B}_s^0 \rightarrow J/\psi \eta' \) aims to contribute in the extraction of \( \phi_s \) weak mixing phase without theoretical uncertainties by a simple measure of the CP-asymmetry. This asymmetry is expected to be small in the S.M., hence, a large value for this phase will be a strong evidence for New Physics.

What are then the physics motivations to select this decay channel? If we take the CP parities of the \( J/\psi \) and \( \eta' \) and consider that mesons are produced in a P wave with angular momentum \( \ell = 1 \),

\[ (+1)(-1)(-1)^\ell = +1, \]

we find that the final state of this transition is an eigenstate of the CP operator, with eigenvalue +1 (CP-even), i.e.:

\[ \text{CP}|J/\psi \eta' \rangle = +|J/\psi \eta' \rangle, \]

\( J/\psi \eta' \) is said to be a pure CP-eigenstate. This consideration leads to a simplification of the time-dependent CP-asymmetry since the final state \( f = \bar{f} \) and in turn \( \lambda_f = \lambda_{\bar{f}} \). (See section (1.5)).

As we have already discussed above, the B-meson system presents CP-violating effects in the pure mixing which are negligible compared to the interference between mixing and decay, in particular, in the interference between the \( \mathbf{B}_s^0 \rightarrow \mathbf{B}_s^0 \) mixing and its decay into the final state \( J/\psi \) by the \( \text{CP} \). As can be seen in Fig.3.1 \( \mathbf{B}_s^0 \rightarrow J/\psi \eta' \) originates from \( \bar{b} \rightarrow c\bar{c}s \) quark-level transitions, and receives contributions from tree and penguin topologies but is dominated by the tree decays since penguins are Zweig suppressed. (See section (1.5)). As a result, a single CKM phase dominates \( \phi_D \) which in the case of a \( b \rightarrow c\bar{c}s \) transition is
\[ \phi_D \equiv \arg[V_{cb} V_{cs}^*] \approx 0. \] Furthermore, \( \lambda_f \) is a pure weak phase resulting from a vanishing CP violation in the decay. On the other hand, we still have mixing-induced CP violation given by:

\[ \Im(\lambda_{B^0_s \to J/\psi \eta'}) = -\sin(\phi_s), \]

which is a small effect in the Standard Model, since \( \phi_s \sim O(-0.04) \) rad in the S.M. This mixing-induced CP violation dominates the time-dependent asymmetry for these \( \bar{B} \to \ell \ell s \) transitions, and hence a measurement of the asymmetry for this channel allows us to directly measure \( \phi_s = -2\chi \) provided that \( \Delta M_s \) is extracted from the \( B^0_s - \bar{B}^0_s \) fast oscillations in the \( B^0_s \) system.\(^1\)

### 3.1.2 Experimental motivations for \( B^0_s \to J/\psi \eta' \)

From the experimental side, this channel is quite appealing, even if the branching ratio is expected to be small compared to the Golden Channel which is \( B^0_s \to J/\psi \phi \). This latter channel is a vector-vector final state of mixed-CP that requires a large number of events to be selected due to the fact that in order to disentangle the CP-even and -odd contributions an angular analysis is needed. Since \( B^0_s \to J/\psi \eta' \) is CP-even such analysis is not demanded and a lower number of selected events is needed for the asymmetry studies.

An extra motivation, is the fact that \( B^0_s \to J/\psi \eta' \) has never been observed so a branching ratio measurement for this channel could be possible due to the high luminosity of LHC.

This thesis specifically focus on the decay channel \( B^0_s \to J/\psi (\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma)) \). LHCb has developed its trigger level giving priority to the selection of decays with muons. Muons are easy to detect since they go through the whole detector without interacting until they reach the muon chambers where are properly identified. Hence, this channel decay should benefit from a high trigger efficiency.

\( J/\psi \) and \( \eta' \) mesons are short lived so their vertices collapse together forming a single vertex at the \( B^0_s \) decay vertex. In the case of the benchmark channel \( B^0_s \to J/\psi \eta (\gamma \gamma) \), the \( \eta \) meson decays to two photons which do not help in the reconstruction of the decay vertex. For the channel under study in this thesis, \( \eta' \) decays to \( \eta \) as well but the two pions accompanying \( \eta \) will help to locate the decay vertex even if the photons from \( \eta \) do not contribute to this task. Because of the latter, a good proper time resolution of the \( B^0_s \) mesons is expected for this decay mode. On the other hand, channels which contains photons worsen their mass resolutions and selection efficiencies due to the poor performace of the ECAL at LHCb. The large multiplicity of this channel renders the full reconstruction of all final state particles of the decay quite difficult.

### 3.1.3 Branching fraction for \( B^0_s \to J/\psi \eta' \)

The experimental value of the branching ratio (\( BR \)) for this channel decay is not available as it has never been observed. Theoretical hypotheses need to be taken into consideration in order to foresee a most likely value for the \( BR \) of the \( B^0_s \to J/\psi \eta' \) mode.

**Quark-model:** Because of the SU(3)-breaking the physical \( \eta \) and \( \eta' \) are mixtures of the SU(3) octet and singlet states in the quark-model. So, in the presence of mixing we can

\[^1\text{Extraction of } \Delta M_s \text{ is realised using a flavor-specific channel, like, } B^0_s \to D_s^- \pi^\pm.\]
write the physical states as

\[ \eta = \eta_8 \cos \theta_P - \eta_1 \sin \theta_P \]  
\[ \eta' = \eta_8 \sin \theta_P + \eta_1 \cos \theta_P \]  

where \( \eta_1, \eta_8 \) are the singlet and octet wavefunctions respectively given in terms of their quark-content by

\[ \eta_8 = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s}) \]  
\[ \eta_1 = \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s}) \]  

and \( \theta_P \) is the pseudoscalar mixing angle. The physical eigenstates are hence related to the singlet and octet by a rotation through this angle.

This mixing angle and the \( \eta_1 - \eta_8 \)-mixing itself are still controversial issues which have important implications in the computation of the \( \mathcal{BR}(B^0_s \to J/\psi \eta') \).

Let us now focus on the \( \eta' \) wavefunction which can be brought to a form in which the \( 1^{st} \) generation quark content and the \( s\bar{s} \) content are isolated:

\[ \eta' \equiv N_{\eta'} (u\bar{u} + d\bar{d}) + S_{\eta'} (s\bar{s}) \]

The \( S_{\eta'} \) part takes the form:

\[ S_{\eta'} = -\frac{2}{\sqrt{6}} \sin \theta_P + \frac{1}{\sqrt{3}} \cos \theta_P \]  

(3.5)

The mixing angle is a constant of nature which needs to be determined experimentally. Distinct experimental methods lead to different values for the mixing angle. One obtains in any case values spanning the interval \([-10^\circ, -20^\circ]\)[13]. Rather than adopting some specific value, we will consider both outer limits as the \( \theta_P \)-dependence of \( S_{\eta'} \) is linear to a good approximation between those limits.

\( B^0_s \to J/\psi \eta' \) branching fraction: Assuming that the strong interaction dynamics are symmetric under SU(3) transformations (U-spin symmetry) lead us to consider the amplitudes for \( B^0_s \to J/\psi \eta' \) and \( B^0_d \to J/\psi K^0 \) transitions shown in Fig.(3.1) to differ only by CKM factors, kinematics and factors coming from the hadronic wavefunctions [43, 44]. Hence, we can estimate the \( \mathcal{BR}(B^0_s \to J/\psi \eta') \) in terms of that for \( \mathcal{BR}(B^0_d \to J/\psi K^0) \) as:

\[ \mathcal{BR}(B^0_s \to J/\psi \eta') = \mathcal{BR}(B^0_d \to J/\psi K^0) \left| S_{\eta'} \right|^2 \left( \frac{m_{B^0_s}}{m_{B^0_d}} \right)^3 \left( \frac{\lambda(m^2_{B^0_s}, m^2_{J/\psi}, m^2_{\eta'})}{\lambda(m^2_{B^0_d}, m^2_{J/\psi}, m^2_{K^0})} \right)^{3/2} \]  

(3.6)

where \( \lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz \), accounts for the kinematic factors.
3.1.4 Visible branching fraction and annual production yield

At this point we might want to compute the annual production yield expected for this specific mode at LHCb, i.e., the number of events of interest produced at the interaction point. To get this estimate, we need to know the average luminosity at LHCb, the production cross section of a $b\bar{b}$ pair, its hadronization probability to the expected $B^0_s$ meson and finally the branching fraction of the mode visible for this specific decay. As it has already been seen in the Chapter 2, the LHCb has some optics to get a low luminosity at the interaction point so that the number of primary vertices per event is reduced and hence the reconstruction efficiency is increased. The foreseen average luminosity at LHCb is $L_{av}^{LHCb} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

The production cross section for the $b\bar{b}$ pairs have been extrapolated from previous experiments running at lower center of mass energies. The obtained figure is $\sigma_{b\bar{b}}^{LHCb} \sim 630 \mu b$ but a conservative figure has been adopted by the collaboration which is $\sigma_{b\bar{b}}^{LHCb} = 500 \mu b$ [45]. A year of data taking is estimated to be about $10^7 \text{ s}$. The hadronization probability of a $b$-quark to form a $B^0_s$-meson is shown in Table (3.1).

<table>
<thead>
<tr>
<th>b-hadron</th>
<th>Production fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm$</td>
<td>39.7 ± 1.0</td>
</tr>
<tr>
<td>$B^0$</td>
<td>39.7 ± 1.0</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>10.7 ± 1.1</td>
</tr>
<tr>
<td>b-baryon</td>
<td>9.9 ± 1.7</td>
</tr>
</tbody>
</table>

Table 3.1: Production fractions to form a $b$-hadron from a $b$-quark [13].

From these figures we can estimate the number of $B^0_s$-mesons produced in one year at the interaction point as well as the number of $B^0_s \rightarrow J/\psi \eta'$ produced and how many of those decay to $B^0_s \rightarrow J/\psi (\mu^+\mu^-) \eta'(\pi^+ \pi^- \eta (\gamma \gamma))$.

For instance, the number of $B^0_s \rightarrow J/\psi \eta'$ produced in one year of data taken $(2 \text{ fb}^{-1})$ is computed as:

$$N^{2 \text{ fb}^{-1}}_{B^0_s \rightarrow J/\psi \eta'} = L_{av}^{LHCb} \cdot t_{\text{year}} \cdot \sigma_{b\bar{b}}^{LHCb} \times 2 \times \text{BR}(b \rightarrow B^0_s) \times \text{BR}(B^0_s \rightarrow J/\psi \eta').$$  \hspace{1cm} (3.7)

The number of events corresponding to our channel available for physics analysis is hence obtained by replacing the BR ($B^0_s \rightarrow J/\psi \eta'$) by the expected visible branching fraction. In order to compute the visible branching fraction we need to know the relevant subprocesses branching fractions which are shown in Table 3.2. The figures of the visible branching fractions for two distinct pseudoscalar mixing angles are also shown in this table. The number of signal decays obtained assuming two different pseudoscalar mixing angles: $\theta_p \in [-20^\circ, -10^\circ]$ is given in Table 3.3.

Assuming a $b\bar{b}$ production cross section of $\sigma_{b\bar{b}}^{LHCb} = 500 \mu b$ and the average luminosity at LHCb, we get the annual number of expected $b\bar{b}$ pairs in $4\pi$, which is equal to $1 \times 10^{12}$. 
3.1. EXPLORING CP VIOLATION THROUGH $B^0_s \rightarrow J/\psi \eta'$ AT LHC

### Table 3.2: Visible branching fractions ($\theta_p \in [-20^\circ, -10^\circ]$) together with some relevant sub-decay processes branching fractions.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \mu^+ \mu^-$</td>
<td>$(5.88 \pm 0.10) \times 10^{-2}$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu^+ \mu^- \gamma$</td>
<td>$(8.8 \pm 1.4) \times 10^{-3}$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu^+ \mu^- {\gamma}$</td>
<td>$(6.76 \pm 0.14) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \gamma \gamma$</td>
<td>$(39.43 \pm 0.26) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^+ \pi^- \eta$</td>
<td>$(44.3 \pm 1.5) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_p = -20^\circ$</td>
<td>$\theta_p = -10^\circ$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow J/\psi \eta'$</td>
<td>$(5.74 \pm 0.34) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow J/\psi(\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$</td>
<td>$(6.8 \pm 0.5) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

### Table 3.3: Number of signal decays for two different pseudoscalar mixing angles: $\theta_p \in [-20^\circ, -10^\circ]$.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Number of Annual Signal Decays in $4\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_p = -20^\circ$</td>
<td>$\theta_p = -10^\circ$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow J/\psi(\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$</td>
<td>$(1.4 \pm 0.2) \times 10^6$</td>
</tr>
</tbody>
</table>
Chapter 4

Simulation and reconstruction: LHCb software

This chapter describes the LHCb software in some detail. It is then exposed how events are simulated within the LHCb spectrometer, including the generation of p-p collisions and decays of unstable particles. Afterwards, a portrait of the software and methods of reconstruction is added together with the scheme of particle identification.

4.1 Computing Framework

The increasing complexity of the LHCb experiment and its numerous software implementations have demanded the use of a common software framework. Specifically, the motivations that have pushed the LHCb collaboration to build a framework for all required applications [46] are discussed hereafter.

Software implementations in LHCb have to withstand changes in requirements and technology over the expected lifetime of the experiment and previously during its conception period. Versions of the same application are likely to be produced; so a common framework will help in the evolution of a certain application without affecting others related to it. Besides, it will provide with interfaces which could link any application to already existing ones even if these are external to the LHCb project.

LHCb applications have to share many common tools, services, data, etc. so the use of a framework which collect all these routines and serve data as soon as it is demanded it is of great help.

With these goals in mind LHCb has conceived GAUDI [47, 48], a general Object Oriented framework, written in C++, designed to provide a common infrastructure and environment for the different software applications.

Classical Object oriented programming assumes objects own the functionalities to transform themselves, GAUDI however decouples the objects describing the data from the algorithms. This allows a longer stability for the data objects (the LHCb event model\(^1\)) as algorithms evolve much more rapidly.

Typical phases of Particle Physics data processing have been encapsulated in the vari-

\(^{1}\)The set of classes (and relationships between classes) that describe the LHCb event data, together with the conventions governing their design and organization, are known as the LHCb Event Model [46, 49]
ous LHCb applications. The applications are all based on the Gaudi framework. Experiment specific software as for example the Event Model and Detector Description are in the framework as core software components. Each application is a producer and/or consumer of data as shown in Figure (4.1). They share and communicate via the LHCb Event model and make use of the LHCb unique detector description. This not only ensures consistency between the applications but also allows algorithms to migrate from one application to another. The subdivision of the different applications have been driven by their different scopes, convenience as well as computer processing times constraints.

![Diagram](image)

**Figure 4.1:** The LHCb data processing applications and data flow. Underlying all of the applications is the Gaudi framework and the event model describes the data expected. The arrows represent input/output data. Figure taken from [46].

Just for completeness, it should be added that a Conditions Database is foreseen within the framework. This is a database facility that permits the handling of information regarding the running conditions of LHCb sub-systems that may vary with time. Alignment informations will be also included in this database.

The software architecture of Gaudi supports event data processing applications that run in different environments ranging from the real-time L1 and HLT triggers in the on-line system to final physics analysis performed off-line.

The different tasks required in the LHCb software will now be presented together with their corresponding Gaudi applications being described to some extent.

- **Simulation application** Gauss [50] is the Gaudi application that simulates the physics occurring at the interaction point as well as the behaviour of the spectrometer to allow understanding of the experimental conditions and performance. It integrates two independent phases. The first phase consists of the *event generation* of proton-proton collisions and the decaying of the hadrons in channels of interest for LHCb. It is interfaced to the external programs Pythia [51] for the event production and to a specialized decay package, EvtGen [52].

Pythia deals with the *pp collisions*, its output consists of the outgoing particles described by their four-momentum vectors. The majority of the physics occurring in a pp collision is dominated by QCD. Pythia includes both short-distance, perturbative, and long-distance, non-perturbative, effects. The scattering of partons (quarks and gluons) relies on the factorization hypothesis which decouples the two distinct
4.1. COMPUTING FRAMEWORK

regimes, i.e., the simulation of a pp collision is factorized into a hard scattering of the partons with a large momentum transfer and a soft scattering with low momentum transfer in which protons interact at long distance as a point-like particles. Since the outgoing quarks and gluons are coloured, they must fragment into colourless hadrons while they are in the interaction region. Unstable hadrons will further decay. The combined process of fragmentation and decay is commonly referred to as hadronisation.

**B production** at this point can take place. **PYTHIA** consider the following processes as mechanisms for the $b\bar{b}$ production (contributions considered by **PYTHIA** at $\sqrt{s} = 14$ TeV are shown within parentheses):

1. **Pair creation** ($\sim 15\%$) Two leading-order hard processes contribute to this category of heavy quark production, quark-antiquark annihilation ($q\bar{q} \rightarrow b\bar{b}$) and gluon fusion ($gg \rightarrow b\bar{b}$) of which the later appears to be the dominant one.

2. **Flavour excitation** ($\sim 60\%$) A virtual heavy b quark from one of the protons is put on its mass shell by scattering against a parton of the other proton, i.e. ($bq \rightarrow bq$ and $bg \rightarrow bg$). As the $b$ quark is not a valence flavour, and thus comes from the sea quarks, it must originate from a branching $g \rightarrow b\bar{b}$.

3. **Gluon splitting** ($\sim 25\%$) The $b\bar{b}$ pair is not created in the hard scattering of the partons, instead, it appears in the parton shower as a gluon that follows a $g \rightarrow b\bar{b}$ process.

The generator phase of Gauss also handles the simulation of the running conditions, the smearing of the interaction region and the change of luminosity during a fill due to the finite beam lifetime. Multiple pp collisions (pile-up) are produced for each event according to a probability function which takes into account the running luminosity.

**EVTGen** is the specialized decay package that takes care of the decay of $b$ hadrons into the desired decay for physics analyses. It implements mixing of neutral B mesons, angular correlations, etc. It has been calibrated taking into account observed data from different experiments.

The second phase of Gauss, the so-called **detector simulation**, look at the particles produced at the generator phase as they pass through the detector. Thus, three physical processes are regarded at this stage, namely: interactions of particles with matter, effect of magnetic field over charged particles, and decay of long-lived unstable particles. These simulating tasks are delegated to the **GEANT** [53] toolkit that has been adapted to the LHCb specialities. **GEANT** is linked to Gauss using some interfaces from **Gaudi**. Energy depositions, Cherenkov emissions, and photoelectron production in the HPD are among the many features that are simulated in **GEANT**. The geometry description is taken from a specific geometry database.

The output of **GEANT** in the form of hits produced in the sensitive areas as well as the Monte Carlo truth history is then converted back into the LHCb event model.

- **Digitisation application** The digitisation program is the final stage of the LHCb simulation. The **Gaudi**-based **Boole** [54] application is designed to mimic the digitisation. **Boole** simulates the detector response to the hits previously generated in the sensitive materials by the **Gauss** application, and includes both the physics of
CHAPTER 4. SIMULATION AND RECONSTRUCTION: LHCB SOFTWARE

(a) Geometry description of the Vertex Locator (VELO).

(b) Detailed RICH simulation showing the charged particles and the tracking of the emitted Cherenkov photons via the mirrors up to the photon detectors.

Figure 4.2: GEANT detector simulation of the LHCb geometry and the tracking through materials

the signal collection and the specific behaviour of any electronics in each subdetector (e.g. Electronics noise and cross-talk effects). Simulation of the response of L0 trigger hardware as well as Spill-over effects are also taken into account in this phase. We name Spill-over effects to any residual signals from previous bunch crossings which interfere with the generated by present pp collisions. This effects are simulated under BOOLE by determining the probability of one or more interactions occurring in the two preceding (-50ns, -25ns) and one following (+25ns) bunch crossings. BOOLE uses the instantaneous luminosity of the event to come up with the spill-over probability.

The L1 Buffer and Raw Buffer are the main output of the BOOLE application. Since those Buffers mimic the real data, they cannot contain explicit references to the MC hits, instead, Monte Carlo truth information is preserved in this stage by associating electronics channels encoded in L1 and Raw Buffers and the corresponding Monte Carlo truth.

- **Reconstruction application** BRUNEL [55] is the GAUDI-based application which carries out the duties of track reconstruction and identification of particles. It takes as input the Raw Buffer objects corresponding to all subdetectors from which it produces a DST (Data Summary Tape) for its use in physics analyses. Because it starts from these Raw Buffers, BRUNEL does not distinguish between real data coming from the DAQ or the simulated data resulting from the BOOLE digitisation. In particular, all access to Monte Carlo information will be switched off when processing real data. In physics selections studies, the same detector geometry and material description are used in order to ensure consistency between the simulated spectrometer and the one used for reconstruction. In addition, reconstruction with possible misalignments will be possible as it will compare the measurement positions to some nominal ones.

The reconstruction phase is followed by a **Relations Phase** in which specific algorithms navigate the event model relationships to associate reconstructed clusters to the MC Particles from which the hits and further clusters were built. The association tables between tracks, clusters and MC Particles are also stored on the DST.

- **Analysis framework** This is the stage in which physicists are interested the most. It
4.2 TRACK RECONSTRUCTION

is performed mainly by the GAUDI-based DAVINCI [56] package. In this final stage of data processing, the decays of interest are searched for among any event selected in the reconstruction phase. For that, in a first step, primary vertices are looked for and fitted, next, particles objects are constructed from tracks and calorimeter clusters. Those are the main ingredients on which lies any selection of events. Finally, DAVINCI algorithms will combine these particle objects to form high-level ones to which some selection cuts (e.g. B-mesons mass, lifetimes) might be applied, and thus, the application will end up with the selection of events of interest. The DAVINCI project includes many tools, and generic algorithms to ease the search of those cuts which are specific to the physics selections. In addition, it provides with a set of tools and algorithms to retrieve the MC truth information to assess reconstructions and selection efficiencies.

Besides, another analysis toolkit named LoKi is available to facilitate the coding of physics analyses. It is programmed in C++ and provides a set of high level utilities with physics oriented semantics.

4.2 Track reconstruction

In this section we will describe how the LHCb collaboration has envisaged the process of reconstruction of tracks. To this end, we first start by defining the types of tracks that will be encountered. Thereafter, we will show the strategy to find those tracks and we will end up telling how a track could be parametrised after been refitted. Some reconstruction performance figures are added to complete this section.

4.2.1 Types of tracks

Charged particles inside the detector will leave hits on the tracking system according to their initial decay vertices, trajectories and momenta. We might therefore classify those produced tracks inside the spectrometer depending on which subdetectors they have left hits. The following classes of tracks are defined, (see Fig. 4.4 for an schematic illustration.)
1. **Long track** These are tracks generated by charged particles which have enough momentum and a correct initial direction to traverse the whole tracking system, so they leave hits from the VELO down to the T-stations. This fact makes them the most valuable set of tracks for B-decay reconstruction as they benefit from better momentum and impact parameter resolutions.

2. **Upstream track** On the other hand, low momentum particles are swept out of the acceptance by the fringe-field so they do not traverse the magnet. Those constitute the set of the so-called upstream tracks which only leave hits on the VELO and TT-stations. Their poor momentum resolution makes them only useful to understand the photon background that they originate as they pass through the RICH1 subdetector.

3. **Downstream track** Long-lived particles, typically $K^0_S$ and $\Lambda$, decay outside the VELO acceptance, so their decay products only traverse the TT and T-stations.

4. **Velo track** These are tracks generated by decay products of particles decaying at production vertices having large polar angles, so that, they are not seen by any other subdetector. Many tracks lie on this category and they are useful for a precise reconstruction of primary vertices.

5. **T track** Finally, some secondary interactions will only leave hits on the T stations. Those tracks are the T ones and provide us with a handle for the RICH2 pattern recognition.

A typical B-event contains $\sim$26 long tracks, $\sim$11 upstream tracks, $\sim$4 downstream tracks, $\sim$26 VELO tracks and $\sim$5 T tracks.

![Figure 4.4: Typical types of tracks encountered in a event. This picture is from [57]](image)

### 4.2.2 Track finding

In order to successfully reconstruct a track, we first have to follow a pattern reconstruction process in which measurements from distinct tracking subdetectors are associated to possible track candidates. The strategy is then to form small track-segments called seeds from which the search of tracks is eased. The pattern recognition application consists of
4.2. TRACK RECONSTRUCTION

several algorithms which are run in a specific order to reach this goal. In the following, the individual algorithms in the track finding procedure are described:

- **VELO seeding** Tracks in the VELO are considered to be straight lines as the magnetic field in this region can be neglected. The reconstruction of VELO seeds starts from the identification of groups of three hits at the most upstream sectors of the VELO which are then matched to downstream ones by extrapolating the formers to the latters knowing that all these tracks originate from the interaction point.

- **Long Tracks: Forward tracking** This algorithm attempts to reconstruct long tracks from previously created VELO seeds and hits in T stations. VELO seeds are combined with a single measurement of a T station in order to have an initial track candidate from which a parametrization of a possible trajectory is obtained. The next step is hence to look for any other hits that confirm the track along the trajectory. When enough hits have been associated, the track is reconstructed. A likelihood function will confirm the hypothesis or will consider the track as a ghost track. The majority of long tracks (~ 90%) are reconstructed this way. For computing processing reasons, further algorithms will not take into account any of the hits already used in a forward track.

- **T seeding** As in the VELO region, the magnetic field in the T-stations is low enough to search for track seeds. Seeds are formed by firstly considering only the bending plane measurements and then joining hits in the T-stations stations as straight-lines. Secondly, the fringe field is taken into account refitting the tracks as a parabola. The stereo coordinates of the hits are added to confirm the track.

- **Long Tracks: Track matching** Most of the long tracks that have not been reconstructed by the forward technique are now recovered by this algorithm. It aims to match T seeds to VELO ones using the Runge-Kutta [58] method to extrapolate one another.

- **Upstream tracking** This algorithm [59] matches any of the remaining VELO seeds to the TT stations. In order to reduce the number of ghosts, hits in both TTa and TTb are required.

- **Downstream tracking** A two-fold method [60] is used in order to find downstream tracks. In the first method, the algorithm extrapolate the T seeds back to the TT stations using a technique similar to the forward tracking [61]. On the other hand, the second method estimates the momentum of the T seeds assuming them originated from the interaction point and taking into account the p-kick. From this estimation, a matching is possible between the T seeds and hits on the TT stations based on the $\chi^2$ of a Kalman fit.

- **VELO and T tracks** Any other VELO or T seeds that have not been used at this final stage are stored as VELO and T tracks respectively.

4.2.3 Track fitting

After tracks have been identified, their trajectories need to be refitted to determine the most accurate estimates of the track parameters together with the corresponding covariance matrices. The latter is crucial in a event reconstruction process in which tracks are
matched to RICH rings, calorimeter cluster, etc. in order to associate a Particle Id to the track. The technique used for this is the Kalman Filter [29]. After fitting the reconstructed trajectory will be represented by states vectors \((x, y, dx/dz, dy/dz, q/p)^2\) which are specified at a given z-position in the LHCb experiment. The Kalman filter takes naturally into account any material effects and the losses of energy. An initial state is obtained at the most downstream measurement and from this prediction, hits are searched for proceeding in the upstream direction, updating the state vector at each measurement plane. The Kalman filter takes into account any material encountered as it traverses the spectrometer. When all measurements are added to the track, the track states at the previous nodes are updated in reverse direction, such that the information from all measurements is properly accounted in every node, resulting in a smooth track. After this final step, the best estimates of all track states along the trajectory are known.

4.2.4 Reconstruction performance

At this point we might want to evaluate the performance of the track reconstruction algorithms and the quality of the reconstructed tracks after fit. The former is estimated by defining some reconstruction efficiencies for each type of track as well as the level of non-real tracks, also called ghosts. The latter by calculating momentum and space residuals. Some of the tracks will present technical difficulties for the reconstruction as they do not leave enough hits to be properly identified. So firstly we have to choose a sample of tracks to which apply those criteria. The sample is defined according to the MC truth information. Hereafter are only listed the definitions which are of interest for this dissertation. As it will be seen in Chapter 5, only long tracks are used for the selection. The reconstruction performance and the quality of these tracks shown below, allow an optimal reconstruction of the \(B^0\) mesons:

- a VELO track is said to be reconstructible if the particle generates at least 3 \(r\) and 3 \(\phi\) hits in the VELO.
- a T track is said to be reconstructible if the particle give at least 1 \(x\) and 1 stereo hit in each T1-T3 station.
- for long tracks, the particle must be reconstructible as a VELO and T track.

A long track is considered as successfully reconstructed if the VELO and T tracks that form the track have each at least 70\% of their hits originating from the same single MC particle. Any reconstructed tracks failing those requirements of association are considered as ghosts.

The reconstruction efficiency is defined as the fraction of reconstructible tracks that are successfully reconstructed, and the ghost rate as the fraction of reconstructed tracks that are ghosts.

Although the quality of the reconstructed tracks could be monitored by the \(\chi^2\) of the fit and the pull distribution of the track parameters, the momentum and impact parameters resolutions of the reconstructed tracks provide with more intuitive measurements of the accuracy of the track parameters.

For long tracks with momentum over 10 GeV/c^2 the average reconstruction efficiency is 94\% whereas for final states of specific B decays the observed efficiencies reach \(\sim 95\%\). Although the average ghost rate reach the 9\%, most of the ghosts have a low transverse mo-

\(^2\)See [62] for more information about the track states
momentum and since the majority of B tracks of interest have a large $p_T$ ($p_T > 300\text{MeV}/c^2$), the effective ghost rate drops to 3\% [23]. The efficiency of long track reconstruction is plotted in Figure 4.5 as well as the corresponding ghost rates as function of the track momentum and transverse momentum respectively.

The momentum and impact parameter resolutions of the reconstructed long tracks as a function of the track momentum and $1/p_T$ respectively are shown in Fig. 2.12

![Graphs showing reconstruction efficiency and ghost rate](image)

Figure 4.5: Reconstruction efficiency for long tracks as a function of the momentum of the generated particle (4.5(a)) and ghost rate for long tracks with reconstructed momentum greater than $p_{\text{cut}}$ (4.5(b)).

### 4.3 Particle Identification

If we wish to successfully select events of interest for physics analyses, a powerful particle identification system is required in the spectrometer. In addition, excellence in particle identification will help us both in trigger algorithms as well as in reconstruction of the initial flavour of the B-mesons. Particle identification (PID) at LHCb is performed by the RICH counters, the Calorimeter system and the Muon subdetector.

The RICH subdetectors are mainly responsible for the identification of charged hadrons ($\pi^\pm, K^\pm, p$). However, they can also help in the lepton identification, so the information from the various subdetectors is combined to improve the identification. The rings observed in the RICH photodetectors are compared to those expected under a given set of mass hypotheses for the reconstructed tracks passing through the RICH. A likelihood function is determined from this comparison which give us the probability for the particle to be under a certain hypothesis. As already mentioned earlier, the ability to identify $\pi$ out of $K$ tracks is of vital importance if we want to distinguish between channels with identical topologies but not same end products. A substantial $\pi$-$K$ ($> 5\sigma$ significance) separation is achieved by the RICH detectors over most of the momentum range of interest ($> 3\text{GeV}/c$) [23]. The average efficiency for kaon identification between 2 and 100$\text{GeV}/c$ is 88\%. The average pion misidentification for that range is 3\%.
The ECAL identifies electrons, photons and $\pi^0$. Electrons are identified by matching tracks and ECAL clusters. An estimator $\chi^2_e$ is constructed as a $\chi^2$ of a global matching procedure, which includes the balance of track momentum and the energy of the charged ECAL cluster as well as the matching between the barycenter position of the cluster and the extrapolated position of the track. Charged clusters are defined as another estimator (see below) for which $\chi^2_\gamma < 49$. In addition, the ECAL cluster must be compatible with an electromagnetic shower, i.e. a significant energy deposit in the preshower and a small deposit along the trajectory in the HCAL have to be present for electron candidates. As an example of performance identifying electrons we can regard the channel $B^0 \rightarrow J/\psi K_s$, for which the average efficiency to identify electrons arising from $J/\psi \rightarrow e^+e^-$ is 95% for a corresponding pion misidentification rate of 0.7% [23].

Photons are reconstructed and identified in the ECAL as neutral clusters. Those clusters are created by an algorithm and are tested to match any tracks. Comparison of the cluster barycenter to the impact point of the tracks together with track’s covariance matrix and 2nd order cluster moments matrix results in a cluster track estimator $\chi^2_\gamma$. Photons are found by searching for clusters that cannot be matched to a reconstructed track. The cluster-track matching procedure requires that $\chi^2_\gamma > 4$. Photons converted ($\gamma \rightarrow e^+e^-$) after the magnet can also be identified as the electron pair often leaves a hit in the SPD. For the channel, $B^0 \rightarrow K^*\gamma$, 70% of the reconstructed photons are selected as non-converted, while the remaining are identified as converted photons, with correct assignment fractions of 90% and 79% respectively.

Muons are identified by extrapolating good reconstructed tracks ($p > 3\text{GeV}/c^2$) into each muon station. Tracks have to be within the M2 and M5 acceptance. Detector hits are searched for within fields of interest (FOI). A track is considered a muon if have left hits in a minimum (which depends on the momentum of the track) number of muon stations.

![Figure 4.6](image)

**Figure 4.6:** Concept of muon track finding and particle ID. The finding procedure starts with hits in M3 and then searches for additional hits in fields of interest in the other stations (highlighted). The muon tracks are assumed to originate from the interaction point. The corresponding kink obtained in the magnet is used to estimate the momentum $p$. A track is considered a muon when a minimum number of stations have hits in their FOI’s.

### 4.4 Flavour Tagging: Flavour at production

Many LHCb studies need the knowledge of the flavour of the $B$ meson at production. This is necessary for instance, when measuring the time-dependent CP asymmetry $A_{CP}$, (see
Section 1.5), or when studying flavour oscillations of neutral mesons. The identification
of the initial flavour of the reconstructed signal B meson (either $B^0_s$ or $B^0$) is called Flavour
Tagging. Different algorithms [63] have been envisaged in order to determine the flavour
of the B mesons, whose outcomes may be combined to come up with a flavour estimate
(tag), that can be either b or $\overline{b}$ or even unknown. The different methods used to estimate
the flavour of the signal B mesons are described in next section.

Before we detail those methods, let us now to introduce some definitions that will help us
to evaluate the performance of the flavour tagging algorithms:

- The **tagging efficiency** $\varepsilon_{\text{tag}}$: as the probability that the tagging procedure gives an
  answer, defined by:

$$\varepsilon_{\text{tag}} = \frac{R + W}{R + W + U} \quad (4.1)$$

where R, W, U are the number of correctly tagged, wrongly tagged, and untagged
events respectively.

- The **wrong-tag fraction** $\omega_{\text{tag}}$: as the probability for the answer to be incorrect when
  a tag is present, given by:

$$\omega_{\text{tag}} = \frac{W}{R + W} \quad (4.2)$$

The mistag fraction given above, $\omega_{\text{tag}}$, has the effect of diminishing the amplitude of the
oscillations of the $B^0_q - \overline{B}^0_q$ system and also diluting any CP or flavour asymmetry by a factor
$D = (1 - 2 \cdot \omega_{\text{tag}})$ called dilution factor. Hence, the observed time-dependent asymmetry
defined for a final state being CP-eigenstate, $A_{\text{obs}}$, can be expressed in terms of the true
asymmetry, $A_{\text{true}}$ (Equation 1.36), by:

$$A_{\text{obs}}(t) = \frac{R[B_s^0(t) \to f_{\text{CP}}] - R[B_s^0(t) \to \overline{f}_{\text{CP}}]}{R[B_s^0(t) \to f_{\text{CP}}] + R[B_s^0(t) \to \overline{f}_{\text{CP}}]} = D \times A_{\text{true}}(t).$$

If we look at the statistical uncertainty of the observed CP asymmetry, $\sigma_{A_{\text{obs}}}$, propagating
the errors quadratically we can show that the error is inversely proportional to the so-
called effective tagging efficiency$^3$ or also tagging power, $\varepsilon_{\text{eff}}$, namely:

$$\sigma_{A_{\text{obs}}}^2 \propto \frac{1}{\varepsilon_{\text{eff}}} \quad (4.3)$$

Where the effective tagging efficiency is defined as:

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot D^2 = \varepsilon_{\text{tag}} \cdot (1 - 2 \cdot \omega_{\text{tag}})^2.$$  

The goal of any tagging algorithm is hence, to maximise the effective tagging efficiency so
that the statistical error on the measured asymmetries is minimised.

$^3$This quantity naturally combines both $\varepsilon_{\text{tag}}$ and $\omega_{\text{tag}}$ in a single entity
4.4.1 Taggers

Different algorithms are available for tagging purposes. Those will be described in detail below. The tagging methods need any information available in an event to come up with a certain tagging hypothesis. Fortunately, b quarks are produced in pairs, so there exists a correlation in flavour between the two mesons. Besides, any mesons newly formed after hadronization, carry some information about the other present in the same event. Some of algorithms use a single tag particle to provide an outcome, others make use of several tagging particles to yield an hypothesis. In any case, particle identification is of key importance for the different algorithms. We recall that this is achieved by the two RICH counters, as well as the calorimeters and the muon chambers.

Depending whether the flavour is extracted from the signal meson or from the hadron accompanying the signal one, the tagging procedures may be classified as Same-side tagging or Opposite-side Tagging respectively.

Hereafter, are presented the algorithms envisaged by the LHCb collaboration [64] to carry out the tagging. Several other approaches are being studied by the tagging working group. The result from each of these methods is a tag hypothesis, saved under a tag category. A Neural Network approach have been designed to combine all the tagging categories into a single probability outcome. Further information about the subject can be found in Chapter 5.

**Opposite-side (OS)** The flavour of the signal $B$ meson is inferred through any signature left by the correlated $B$-hadron produced with the other $b$ quark. This method contains an intrinsic dilution due to the fact that any neutral $B$ meson produced after hadronisation of the non-signal $b$ quark might have oscillated before decaying. Three independent methods are used:

- OS lepton tagger: The charge of the lepton from a semileptonic $b$-hadron decay is used, eg.: $b \rightarrow X \ell^+ \bar{\nu}$
- OS kaon tagger: The charge of the kaon from a $b \rightarrow c \rightarrow s$ decay chain defines the tag.
• Vertex Charge: Defined as the sum of the charges of the particles arising from the inclusively reconstructed decay vertex of the accompanying b-hadron.

**Same-side (SS)** The flavour of the signal B meson is directly determined from flavour correlations in the fragmentation decay chain.

- SS kaon tagger: In the case that a \( B_s^0 \) (b s) meson is produced in the fragmentation of a b quark, an extra s must be available to form either a charged or a neutral kaon with equal probabilities. Furthermore, the kaons comes from the same primary vertex as the signal \( B_s^0 \) meson and are correlated in phase space with those.

- SS pion tagger: A similar procedure is followed when the b-meson formed is a \( B_d \) (b d). Now the available quark is instead a d, that may form a \( \pi^+ \) in the hadronisation process by combining with a u quark from the sea. This method is limited by the large pion combinatorics expected when reconstructed. SS pions taggers are also expected from B resonances as, eg. \( B^{**} \rightarrow B^* \pi^\pm \).

### 4.5 Data Samples: DC04

The Monte Carlo studies being regarded in the next section, used samples that were generated as part of the so-called Data Challenge 04 (DC04) [45]. These samples will be described hereafter as well as some problems in the generation of those. The section might result quite technical and it is not required in order to understand both the selection and the sensitivity chapter. The samples have been generated through EVTGEN. Information about the decay files used to generate all samples can be found in [52], following the numbering scheme for Monte Carlo particles given in [65].

First generated samples (thereafter v1) present a bug in the generation whereas subsequent ones (v2) were free of this bug. The problem found in the generation will be explained to a certain extent in 4.5.1. Now, we will only show the samples and the number of generated events. Those samples have extracted from [66].

- **DC04-v1** 179'500 events of the type: 13144410 (\( B_s^0 \rightarrow J/\psi \eta' \) signal events.)
- **DC04-v1** 18'060'757 stripped \( b\bar{b} \) events (bug present: used only to tune selection cuts for \( B_s^0 \rightarrow J/\psi \eta' \))
- **DC04-v2** 33'926'781 stripped \( b\bar{b} \) events (used in this dissertation to quote background-over-signal levels)

#### 4.5.1 Monte Carlo random seed bug

The generation of a Monte Carlo event needs a seed number. The generation software in DC04 was thought to use a 32 bit number as seed, what implies \( 2^{32} = 4'294'967'296 \) different events. Due to a bug in the software, the first stage of generated events, called afterwards, DC04-v1, only used the 24 least significant bits of such a seed, leaving only \( 2^{24} = 16'777'216 \) different events, if all seeds are used at least once.

The number of independent events \( N_{\text{indep}} \) and its error \( \sigma_{N_{\text{indep}}} \) can be estimated assuming that any subsample of the generated events contains the same fraction of independent
events [67] by the following formulae:

\[
N_{\text{indep}} = M - M \cdot \left(1 - \frac{1}{M}\right)^N \approx M \cdot \left(1 - e^{-\frac{N}{M}}\right),
\]

\[
\sigma^2_{N_{\text{indep}}} = M \cdot (M - 1) \cdot \left(1 - \frac{2}{M}\right)^N + M \cdot \left(1 - \frac{1}{M}\right)^N - M^2 \cdot \left(1 - \frac{1}{M}\right)^{2N}
\approx N_{\text{indep}} \cdot e^{-\frac{N}{M}},
\]

where \(M = 2^{24}\) and \(N\) is the number of events in the original sample. The fraction of independent events for a given sample is hence computed as \(f_{\text{indep}} = N_{\text{indep}}/N\). When computing efficiencies using DC04-v1 data, these are not affected by the bug, only a correction of the error will be demanded for those samples. The bug was amended for the next produced samples, namely, DC04-v2.
This chapter describes the reconstruction of the $B_s^0 \rightarrow J/\psi \eta'$ channel in the LHCb experiment. Firstly, we will introduce how final states are reconstructed. Then, both the preselection and selection will be discussed. The results of physical observables from the selection of events will be then shown. Proper time estimates will be improved following two distinct methods. Finally, the performances of the channel selection will be also discussed.

5.1 Assigning a Particle ID

As we have seen in Chapter 4, the outcomes of the reconstruction stage are either tracks or clusters. A set of particle hypotheses will be assigned to them. Those are potential objects which serve as ingredients from which we correctly identify the events of interest for physics analyses. Hence, after the assignment of particle hypotheses, we will name those reconstruction products as protoparticles.

Information about the probability of being a certain particle is glued to the protoparticles. The decision is then taken at the time of selection. A protoparticle however could keep several hypotheses and make them available for the selection as different particles. This is what we call inclusive identification, so that the same protoparticle could be used twice in the selection of an event with different particle identification (PID) tags. If a single hypothesis is used instead we refer to this as exclusive identification. Inclusive selection of protoparticles is of great help for correct identification of particles as distinct hypotheses are allowed to face extra constraints from which we are able to make an improved choice.

Likelihood information is provided by each subdetector depending on the ability of such a detector to identify specific particles. Hence, each subdetector will tell us the probability of a particle being under a certain hypothesis. For instance, RICH counters help us to decide whether a particle is an hadron or a lepton. That is to say, the likelihood of being a $\pi$, $K$, $p$ or a lepton. ECAL and HCAL on the other hand, can shed light on the probability of being an electron, photon or an hadron. $\pi^0$ identification is exclusively performed with the ECAL information. Muons are finally identified by the muon system which can also add extra information in the identification of other particles by other subdetectors. Therefore, for each protoparticle a likelihood function is constructed from all the available information which tell us the combined probability to lie under a certain hypothesis. This likelihood function is hence the product of the individual subdetector likelihoods. For
CHAPTER 5. SELECTION OF $B_s^0 \to J/\psi \eta'$

instance,

$$\mathcal{L}(e) = \mathcal{L}^{RICH}(e)\mathcal{L}^{CALO}(e)\mathcal{L}^{MUON}(\text{non } \mu),$$
$$\mathcal{L}(\mu) = \mathcal{L}^{RICH}(\mu)\mathcal{L}^{CALO}(\text{non } e)\mathcal{L}^{MUON}(\mu),$$
$$\mathcal{L}(h) = \mathcal{L}^{RICH}(h)\mathcal{L}^{CALO}(\text{non } e)\mathcal{L}^{MUON}(\text{non } \mu),$$

where $h$ stands for hadron, $e$ electron and $\mu$ muon. PID information is hence extracted from the comparison of a given PID hypothesis to the probability of being a pion. From the two hypothesis a Delta Log Likelihood (DLL) function is constructed to ease the Particle identification, i.e.

$$\Delta \ln \mathcal{L}_{AB} = \ln \mathcal{L}(A) - \ln \mathcal{L}(\pi) = \ln \left[ \frac{\mathcal{L}(A)}{\mathcal{L}(\pi)} \right],$$

(5.1)

For correctly identified "A" particles the function tends to give positive results. It is worth noting that any $\Delta \ln \mathcal{L}_{AB}$ can be obtained by simply knowing that:

$$\Delta \ln \mathcal{L}_{AB} = \ln \mathcal{L}(A\pi) - \ln \mathcal{L}(B\pi).$$

The above can only be applied to charged tracks. Neutral clusters are identified by the combined information provided by the ECAL and SPD cells. Let us recall that a photon particle will be defined after the matching procedure of associating a track to a neutral cluster has failed. This ECAL cluster is then considered to be a photon. If the energy associated to the ECAL cluster is compatible with that deposited by two photons, we hence have a candidate for a $\pi^0$.

5.2 Selection strategy

The presence of photons in the channel under study in this dissertation renders the reconstruction of the signal events a difficult task. The poor resolution of the LHCb ECAL limits our knowledge of $\eta$ and consequently of $\eta'$. When one compares our channel decay mode $B^0_s \to J/\psi (\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$ to $B^0_s \to J/\psi (\mu^+ \mu^-) \eta (\gamma \gamma)$ we see that two extra pions help in the precise decay vertex reconstruction of the candidate, however they increase the multiplicity so that the selection efficiency is decreased. A typical $B^0_s \to J/\psi \eta'$ event contains lots of neutral clusters identified as photons, as well as pions and kaons. RICH counters should in principle help us to disentangle pions from kaons. Overall, constraints need to be efficiently identified in order to limit the huge number of combinations coming out at each event. Photons from $B^0_s \to J/\psi \eta$ or $B^0_s \to J/\psi \eta'$ channels are not so energetic and their energies are not accurately determined.

A key-point in the selection strategy is the number or dimuons which enter within the $J/\psi$ category. Those are low, but well identified and reconstructed. So those are the first particles to be reconstructed. Events which fail to reconstruct a $J/\psi$ candidate will be ignored in the subsequent selection stages. Pions from $\eta'$ help us to remove wrong $\eta$ candidates but this is not enough to diminish the huge combinatorics.

When looking at a typical physics analysis we realise that the architecture of selection is repeated several times. Particles are combined to form composite ones which are further mixed to reach high level objects. For each of those particles we shall define some thresholds or cut-offs to retain most likely candidates from which the physics can be extracted.
The use of common methods of analysis is rapidly acknowledged. High Level Trigger designers realised those facts and then started to pave the way for the use of generic selection algorithms [68] as well as implement typical tools that are extensively demanded on every selection. Some other methods to perform physics selections with DaVinci are available, but the use of generic algorithms is now widespread within the LHCb collaboration. For completeness, it should be said that interactive methods like Bender [69] are of great help when prototyping.

When considering the design of a selection we have two possibilities. Either we implement everything in the selection as a single algorithm or as a matter of convenience we separate each individual task as a single algorithm and share their outputs in the so-called Transient Event Store (TES) [68].

We choose the latter aiming to follow the same approach that of the HLT so that the efficiency of trigger selection is increased accordingly. PID tags are assigned to the protoparticles as the very first step of the selection so that the 4-momentum vectors could be computed and successively reconstruct the grand-daughters and daughters resulting in the final selection of $B^0_s$ meson candidates. As it has already been mentioned before the first daughter to be reconstructed is the $J/\psi$ since its selection efficiency is quite high which saves on computation time in the case of failed reconstruction since any further implementation of processing algorithms would disallow further processing of subsequent candidates. Check Figure (5.1) for a scheme of the algorithm sequence.

It has to be stressed that in this way the selection part is completely isolated from any further studies or fittings that could be envisaged since $B^0_s$ meson candidates are stored in the TES which can be accessed by any other selection routine.

Since long tracks provide a better momentum resolution and are easily identified as being a specific particle, those will be the object of study for our selection. It is assumed that adding any other kind of tracks will render the selection far from effective to be of use in physics analyses.

### 5.3 Preliminary studies

At TDR times, data was simulated according to the geometry available (LHCb v254r1). Only small samples of $b \bar{b}$ events were available for analyses. After reoptimisation, further changes were introduced to detector elements so that the radiation length seen by the particles were minimised. To account for a more detailed geometry and recent releases of applications that better describe the reconstruction and simulation of electronics, was launched a Data Challenge (DC) period in which larger $b \bar{b}$ samples were generated as well as new signal samples.

As it has already been said above the number of photons and pions encountered in a signal event is huge so a series of well defined and effective cuts for the TDR data had to be searched for. As an illustrative picture check the $\eta$ mass distributions in Figure 5.2 obtained with TDR data by simply combining two photons after a simple $p_T$ threshold had been applied to them.

A new filter tool has been available from DC 04 that ease the searching of cuts. The filter allows us to keep only the reconstructed particles that have been associated to signal Monte Carlo ones leading to more faithful physics probability distributions from which preliminary cuts may be identified.
Figure 5.1: Scheme of the algorithm sequence.

Figure 5.2: Distribution of the invariant mass of $\eta$ candidates formed by combining two photons after having been applied a preliminary cut of: (a) $P_T > 100$ MeV/c, (b) $P_T > 500$ MeV/c, (c) $P_T > 1300$ MeV/c.

5.3.1 Preselecting final states

Any (pre)selection of events starts with the searching of production vertices, also called primary vertices. Those vertices are of main importance if we want to get estimates of most of the selection variables envisaged. A specific primary vertices searching algorithm has been designed by the collaboration in order to cope with this task. Details of the finding procedure can be found elsewhere within the LHCb publications, see for instance Ref. [23, 70].

If we recall TDR distributions for $\eta$ candidates, we notice that all these distributions are obtained by simply combining any pair of reconstructed photons. Most of them come
5.3. PRELIMINARY STUDIES

Figure 5.3: Distributions for some kinematical variables of the final states particles which are associated to their Monte Carlo particles. No cuts have been applied to those particles. The vertical red lines and the direction of the arrows indicates the final selection cuts that were found subsequently after the optimization stage. (See Section 5.5)

from the event background, photons that might occur simultaneously. Hence, we face the problem of distinguishing neutral photons clusters coming from our channel and the rest of reconstructed ones. Any probability distribution for the variables of interest would be otherwise hidden by a vast amount of noise which would render the distributions not likely for their use in the searching of possible cuts.

In order to display the most-likely distributions of the variables corresponding to our channel decay, we can make use of the tool mentioned earlier which just keep particles associated to the Monte Carlo truth. We proceed in this way in order to define some very preliminary cuts for the final states that facilitates the searching of (pre) cuts. By prese-
lecting those final states in an early stage with very relaxed cuts allow us to run the whole selection sequence and hence we could have a look to certain selection variables that are less discriminant for the signal than for the background. Since our channel involves six particles in the final state, of which two are neutrals, the selection of B’s among the very large quantity of candidates is a very challenging task. I do want again to stress here the importance of defining early very soft cuts which let us to look at the significant variables for the physics analysis without having to fight against unlikely candidates which are product of combinatorics among final states not belonging to the real event.

At this point, it is worth describing in more detail how a $B_s^0$ candidate is selected. Once all the final states of our decay have been saved onto the temporary stores we have available all the main ingredients necessary to start the reconstruction.

The most discriminant particle to be selected is, as already said above, $J/\psi$. It is constructed from two muons with opposite charge. Their tracks are fitted together to form a common decay vertex from which a simple $\chi^2$ computation can be extracted. The invariant mass of the candidates constructed in this way is hence computed. A certain mass window for the $J/\psi$ candidates will be defined subsequently to keep only candidates which are close enough to the nominal $J/\psi$ mass given at the PDG [71] ($M_{J/\psi} = 3096.97$ MeV/c$^2$). The fit of the vertex does not take into account the $J/\psi$ mass, i.e. the computation of the four-momentum vector for each track is not constraint by the meson mass. From now on,
5.3. PRELIMINARY STUDIES

Figure 5.5: Distributions for some kinematical and geometrical variables of the final states particles which are associated to their Monte Carlo particles. No cuts have been applied to those particles. The vertical red lines and the direction of the arrows indicates the final selection cuts that were found subsequently after the optimization stage. (See Section 5.5)

we shall name this fit as unconstrained vertex fit. Once all the $J/\psi$ candidates have been saved onto the TES, we can proceed with the reconstruction of any pair of photons to be the $\eta$ candidates. The number of photons is huge so we need to remove non-signal photons as soon as possible to avoid large combinatorics. Photons were reconstructed as ECAL clusters which have not been linked to any charged track. Position and energy depositions might be estimated for those ECAL clusters. Since photons do not leave information into the tracking system we cannot guess

\footnote{Once we have identified the whole event as $B_0^\pm \rightarrow J/\psi \eta'$ we will redo the vertex fit for the $B_0^\pm$ constraining the mass of $\eta'$. This procedure will improve the $B_0^\pm$ vertex and hence its proper time determination.}
what the decay origin of them may be and yet their direction. In this case the nominal collision point of LHCb is assumed as the common origin for any photon. DaVinci selection tools will allow us to recompute their four-momentum vectors if a decay vertex is defined for them afterwards. Hence at this early stage of selection of $\eta$ candidates a simple invariant mass computation is done to come up with those. The nominal interaction point is used for these computations. Again a mass window, after being defined, will preserve candidates which are close to the $\eta$ nominal mass. The mass window have to keep enlarged since no decay vertex information is attainable for the candidates at this preliminary selection step.
η’ candidates are reconstructed from the combination of any η candidate plus a pair of opposite charged pions. Firstly, an unconstrained vertex fit is carried out with the pions from which an η’ decay vertex could be inferred, and then the energy-momentum vectors of the photons are recomputed taking into account this new decay vertex. It is assumed that the η meson is short lived enough so that its decay vertex overlaps the one of the η’ meson. Hence, a common vertex is defined for both. An η’ candidate births then from the invariant mass of those four particles computed at the π⁺, π⁻ vertex.

Finally any J/ψ candidate and η’ are blended together to form the $B_s^0$ candidates. An unconstrained vertex fit is again applied to those daughter particles to come up with their
origin vertices from which a $\chi^2$ is also computed. Having said all the above, we want now to show the distributions of the physical variables that served us to diminish the huge computation time needed to process very large combinatorics coming from our selection algorithm sequence. The choice of those mimics the ones of the HLT stream that is related to our channel and also adds the channel specific ones.

Before doing so, we shall sort out the most common variables in the selection of the physics events according to certain criteria. An explanation of the motivations for applying such variable cuts will follow each of the points. Any other variable cuts needed for the selection will be exposed and discussed in detailed once they are requested throughout the text.

5.3.2 Identifying potential selection variables

LHCb has been designed to select $B_s^0$ events in the forward direction due to the fact that the $b\bar{b}$ pairs are emitted preferentially either backward or forward parallel to the beam direction. In order to simplify the design and decrease the instantaneous huge amount of data, the solution of a forward geometry was preferred even though half of the statistics were lost. We already know that $B_s^0$ species are long-lived so both the on-line and off-line selection are primordially based of this key-fact. In addition, the large boost in the beam direction contributes to increasing the flight of those $B_s^0$ mesons. A very distinct signature for the selection of $B_s^0$ events is therefore the identification of secondaries vertices which are displaced enough with respect to the primary ones. Moreover, as a consequence of this displacement, any $B_s^0$ daughters and grand-daughters should have large impact parameters.

The difference in masses between the daughters and the mother is an additional bonus in the selection. It makes that those particles have large transverse momentum compared to any other leaving the interaction point. Let us now to introduce the main variables for the selection of $B_s^0$ mesons:

Kinematical variables

- **Energy and momentum cuts.** Following the trigger path, those are the cuts that should be applied from the very beginning. It allows us to removes many soft background final states present in each event that only contribute to the non-controlled presence of numerous fake candidates. To this end, they will be applied after final state particles have been identified.

- **Traverse momentum.** As it has already been explained, daughters and final state particles of $B_s^0$ mesons acquire large transverse momentum when compared to any others present in the events.

- **Invariant mass.** Reconstructed invariant mass for the candidates should lie within a Gaussian distribution centered on the true nominal value and being of a certain sigma. The cut is specifically defined depending of each particle as being situated 3,4,5 sigmas apart from this nominal value.

- **Correlation cuts.** Correlation between the $\eta'$ and $\eta$ invariant masses. Normally the cuts are applied as a mass difference between the nominal masses of both mesons.

Geometrical variables
5.4 EVENTS PRESELECTION

- **Quality of the vertex fit.** Both unconstrained and constrained vertex fits are characterised by a $\chi^2$ function. It is a measurement of the deviation of the track directions with respect to a certain common point in the space.

Even though muons and pions tracks do not come from a common decay vertex, the particles from which they originate are very short-lived enough for us to consider them to form a common vertex.

- **Distance of flight.** $B_s^0$ mesons have to flight enough to be seen as detached from the primary vertex. The main source of error in the measurement is produced by the space resolution of the apparatus. We hence define flight distance (FD) as the modulus of the difference in position between the secondary and primary vertices. It should be normalised by the error computed for that measurement($\sigma_{FD}$). Hence, a flight distance significance (FS) is also considered, being defined as: $FS \equiv FD/\sigma_{FD}$.

- **Impact parameter.** Impact parameter is defined as the distance of closest approach for a given track to a point, in this case, the primary vertices. Its estimation is dominated by position errors once more. Unsigned impact parameter significances are defined for those considering the error estimated for that measurement ($\sigma_{IP}$) as $IPS \equiv IP/\sigma_{IP}$. Daughters or final states should have a significantly large IP while $B_s^0$ candidates should point back to the primary so a small IPS is required for them. Since a bunch of reconstructed primary vertices are available for each event, we cut on the smallest IPS (or IP) since it is the less discriminant cut.

- **Angle between Flight vector and $B_s^0$ momentum direction ($\cos \theta_{LP}$).** The momentum vector of $B_s^0$ candidates should follows the direction given by the Flight vector, so a cut on the angle between those two are applied to them. See Figure (5.8).

5.4 Events preselection

The search of preselection cuts is the first step in the procedure of finding the final parameters which will define the selection of this channel decay. They aim to facilitate manipulation of big samples of background events which cause that many random combinations are present over the signal candidates. Defining a preselection set of cuts let us to reduce significantly the amount of fake combinations both in signal and background events without a drastic lost of signal events.

We can now visualize the physics distributions obtained for the reconstructed particles once the MC filter has been applied to those final states. We recall that only reconstructed candidates which have the whole decay chain associated to the MC event can benefit from being saved onto the TES storage. Allowing no cuts at all, except for the preselection of final states to be either pions, muons or photons, shows us where we could already cut without risking to loose too many events.
Figure 5.9: Distributions for some kinematical and geometrical variables of the final states particles which are associated to their Monte Carlo particles (Red) together with the corresponding distributions for $b\bar{b}$ candidates (Blue) after preselection cuts have been applied to both samples. The vertical green lines and the direction of the arrows indicates the final selection cuts being applied. For a better comparison both distributions were normalised to the unity.

Afterwards, once selection cuts will be released, we could have estimates of the signal lost for each individual cut.

In order to come out with a set of preselection cuts we have to compare the signal distribution to the ones obtained from any potential source of background. The dominant source of background is considered to be the inclusive $b\bar{b}$ events. They exhibit displaced secondary vertices as well as many other features common to our channel decay. On the contrary, light flavor quarks do not show those behaviours. Therefore, $b\bar{b}$ events due
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1) \[ \text{MeV/c} \]

\( T' : \text{Phty} \int_{0}^{s} B \)

0 1000 2000 3000 4000

Entries / (57.50)

0

0.02

0.04

0.06

0.08

0.1

0.12

0.14

0.16

0.18

2) \[ \text{MeV/c} \]

\( T' : \text{Phty} \int_{0}^{s} B \)

0 10 20 30 40 50

Entries / (626.25)

0

0.01

0.02

0.03

0.04

0.05

0.06

2)

\( T' : \text{Phty} \int_{0}^{s} B \)

0 20 40 60 80 100

Entries / (1251.25)

0

0.02

0.04

0.06

0.08

0.1

0.12

Figure 5.10: Distributions for some kinematical and geometrical variables (photon transverse energy and total energy. \( \gamma_1 \) corresponds to the less energetic photon) of the final states particles which are associated to their Monte Carlo particles (Red) together with the corresponding distributions for \( b\bar{b} \) candidates (Blue) after preselection cuts have been applied to both samples. The vertical green lines and the direction of the arrows indicates the final selection cuts being applied. For a better comparison both distributions were normalised to the unity.

to their huge production fraction represent the main source of background to be taken into account due to the fact that they will eclipse any other source. To this end, we will choose the set of variables as preselection cuts which remove the better this source of background in a very safe fashion, i.e. the set of cuts is adjusted with a minimum impact on the signal but at least reaching at rejection factor for the background of 1000. For a better comparison we will normalise both the signal and \( b\bar{b} \) background distributions to the unity. See Figures 5.9 - 5.13 for the normalised signal and background distributions after preselection cuts have been applied to them. Preselection cuts will be obtained using the "buggy" samples, i.e., DC04-v1 for \( b\bar{b} \). The fraction of non-independent events is negligible for the signal but it is not for the \( b\bar{b} \) background sample. When estimating background levels we will use the \( b\bar{b} \) DC04-v2 data sample for which those bugs in the generation phase had already been removed. By using this latter sample we will get an unbiased estimation of the background levels deriving from the final selection cuts.

A large preselection mass window for the \( B^0 \) candidates will be considered since the few millions \( b\bar{b} \) events of MC data represent only a very small fraction of the amount to be saved when real data will be available since those amount to only a few minutes of LHCb running. This enlarged mass window for the \( B^0 \) let us to simulate an increased amount of
Figure 5.11: Distributions for some kinematical and geometrical variables of the final states particles which are associated to their Monte Carlo particles (Red) together with the corresponding distributions for $b\bar{b}$ candidates (Blue) after preselection cuts have been applied to both samples. The vertical green lines and the direction of the arrows indicates the final selection cuts being applied. For a better comparison both distributions were normalised to the unity.

Looking at the $\Delta \ln L_{\mu\tau}$ distribution (Fig. 5.14) for the muons which are associated to MC truth, we see that the value used represents a safe precut for the preselection of muons.

$^{2}$The ratio of preselection to selection $B_s^0$ mass windows give us the number of times more of $b\bar{b}$ data passing our selection cuts. It is assumed a flat regime for the background mass distribution within those limits.
Afterwards it will be tighten to diminish data pollutions. For the pions not any specific cut is requested as they are constructed by default as being the last product of reconstruction after some default $\Delta \ln \mathcal{L}$ cuts are applied to the charged protoparticles. Carbon-copying the HLT trigger cuts, we will apply preliminary cuts on the transverse momentum both for the muons and pions as well as photons which is determined to be greater than 300 MeV/c. It is also safe, to precut on the momentum of photon and pions as they represent the main source of pollution in the selection of events.
Figure 5.13: Distributions for some kinematical and geometrical variables of the final states particles which are associated to their Monte Carlo particles (Red) together with the corresponding distributions for $b\bar{b}$ candidates (Blue) after preselection cuts have been applied to both samples. The vertical green lines and the direction of the arrows indicates the final selection cuts being applied. For a better comparison both distributions were normalised to the unity.

Large mass windows for the $J/\psi$ are fixed as precuts in order to keep as much $J/\psi$ candidates as possible to participate in the final selection cuts as they are very well reconstructed and belong to one of the HLT streams for physics analyses. The $\chi^2$ is also kept open enough for the same reasons. As we do not know very well which $\eta$ candidates should be removed or not we keep a very large mass windows for those. The poor resolution information for the photons makes the momentum estimation being degraded. It is also assumed that the association procedure is not 100% effective with photons clusters.
### 5.5 Events Selection

Let us now have a look at the method that we used to find the final set of selection cuts. We should firstly mimic those cuts present in the HLT that are related to our channel decay. Some were already imposed in the preliminary cuts.

We decided not to follow a typical cut optimisation \[72\] procedure\(^3\) as this would bias

\(^3\)Optimisation methods try to maximise the function \[ \frac{S_{\text{year}}}{\sqrt{S_{\text{year}} + B_{\text{year}}}} \], where \(S_{\text{year}}\) is annual signal yield and

<table>
<thead>
<tr>
<th>Cuts</th>
<th>(B_s^0 \to J/\psi , \eta' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \ln L_{\pi \pi} (\mu^+, \mu^-) ) &gt;</td>
<td>-20</td>
</tr>
<tr>
<td>(P_T (\mu^\pm) ) [MeV/c] &gt;</td>
<td>300</td>
</tr>
<tr>
<td>(P_T (\gamma) ) [MeV/c] &gt;</td>
<td>300</td>
</tr>
<tr>
<td>(P_T (\pi^\pm) ) [MeV/c] &gt;</td>
<td>300</td>
</tr>
<tr>
<td>(P (\pi^\pm), P (\gamma) ) [MeV/c] &gt;</td>
<td>1000</td>
</tr>
<tr>
<td>(\chi^2 (J/\psi) ) &lt;</td>
<td>16</td>
</tr>
<tr>
<td>(\delta (m) (J/\psi) ) [MeV/c^2 ] ±</td>
<td>50</td>
</tr>
<tr>
<td>(\delta (m) (\eta) ) [MeV/c^2 ] ±</td>
<td>200</td>
</tr>
<tr>
<td>(\chi^2 (\eta') ) &lt;</td>
<td>16</td>
</tr>
<tr>
<td>(P_T (\eta') ) [MeV/c] &gt;</td>
<td>1000</td>
</tr>
<tr>
<td>(\delta (m) (\eta') ) [MeV/c^2 ] ±</td>
<td>250</td>
</tr>
<tr>
<td>(\chi^2 (B_s^0) ) &lt;</td>
<td>30</td>
</tr>
<tr>
<td>(\cos \theta_{LP} ) &gt;</td>
<td>0</td>
</tr>
<tr>
<td>(\delta (m) (B_s^0) ) [MeV/c^2 ] ±</td>
<td>1000</td>
</tr>
</tbody>
</table>

**Table 5.1: Pre-selection cuts used for \(B_s^0 \to J/\psi (\mu^+ \mu^-) \, \eta' (\pi^+ \pi^- \eta (\gamma \gamma)) \) decay channel.**

In this manner, decision will be taken after the reconstruction of the \(\eta'\) candidates. Hence, since a large Pt is expected for \(\eta'\) candidates a reasonably large cut is demanded for those and not for \(\eta\) candidates as the uncertainty on the Pt for the latter could put in danger the successful selection of the formers. As already been said, mass windows will be kept large enough for increasing \(b \bar{b}\) statistics purposes. A value of ± 1000 MeV is considered to be enough. A very relaxed preliminary cut for the \(\chi^2\) of the vertex fit between \(J/\psi\) candidates and \(\eta'\) is safe enough to pass to the optimization stage. Finally, the angle between the flight vector of the \(B_s^0\) candidates and the reconstructed \(B_s^0\) momentum is kept sufficiently open as well.
CHAPTER 5. SELECTION OF $B^0_s \rightarrow J/\psi \eta'$

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Figure 5.14: Distributions for the DLL($\mu^- - \pi$) hypotheses corresponding to the $\mu^-$ (Left) and $\mu^+$ (Right) particles both for signal Monte Carlo associated candidates (Red) and $b\bar{b}$ inclusive background (Blue) after having passed the preliminary cuts. The final cut for the DLL($\mu^- - \pi$) is used instead of the preliminary one and is indicated as a vertical green line and the direction of the arrow.

much our selection cuts to both the small $b\bar{b}$ sample available and also the signal sample. It is expected a more detailed description of the LHCb spectrometer and its reconstruction performances in future LHCb software releases as well as major changes in the methods of selection for the new generation of DST tapes (DC06).

Variable cuts will be optimized relative to $b\bar{b}$ events which are considered as being the only predominant source of background noise. However, some of the variable cuts were fixed according to a suitable background over signal ratio based on the normalised distributions and a subset of the rest was chosen to be varied in order to removes any $b\bar{b}$ candidates passing the cuts while keeping the signal candidates as high as possible, bearing in mind that the multiplicity of selection candidates per event have to be kept to a very low level, i.e. the purity$^4$ of the signal sample should be as high as possible, reaching at least the 90% level. We recall that the data sample used for the fine tuning of the cuts was DC04v1 even though a seed bug was present in the generation.

Once a set of cuts fulfill the envisaged levels of S/N ratio and signal purity, we could try to tight other cuts without loosing significantly signal events. We know that many of the cuts are physically correlated so tightening the cuts will avoid any bad surprises when running on real events.

For the pions and muons an IP significance cut was added to each of them as these particles originates from decays and should not point to the primary vertex. Those cuts mimic the ones already applied in the HLT. They were kept as low as possible to ensure availability and decide subsequently on which candidates suit the best by adding extra constraints.

The high cut in $P_T$ for the photons when compared to the ones applied in similar channels [70, 72] is justified by the fact that two photons are present at the lowest level of our channel decay. That leads to an estimation of the invariant mass for the $\eta$ candidates which

$B_{year}$ the background expected for that period of time.

$^4$The ratio between the number of signal candidates associated to the MC truth and the non-associated ones.
will be degraded as the momentum for those is expected to be subject to computational
uncertainty in the case of soft photons. In addition, the association efficiency expected for
soft photons is much lower than that obtained for the most energetic partners. Similar
arguments could be followed for the momentum variables.

In a second step, after a set of cuts was found, some of them could still be further
refined due to their correlations with others. The mass window for the η candidates is
large because the photon momentum estimation is the main source of contamination. It
was determined to be ∼ 3σ of the nominal η mass.

Fake η candidates will be removed afterwards, as the better estimation of the momentum
for the photons candidates will be available once a vertex is provided by the pions,
mainly when imposing a high level in the transverse momentum of the η candidates.

The ∼ 3σ cut was also required for the η′ candidates in their invariant mass computa-
tion. Due to the large amount of η′ fake candidates (due to the uncertainty given by η), we
decide to have a look at the correlation between the two mesons masses. It is clear from
the plot (5.15) that the signal candidates are highly correlated while b̄b candidates remain
as a background cloud all over the mass space. This cut was found to be very effective
to remove fakes candidates. It was implemented as a mass difference cut window with
respect to the nominal mass difference between η′ and η taken from the figures appearing
at the PDG [71].

![Figure 5.15: Correlation between the η′ and η invariant masses. Red dots indicates signal
events whereas blue dots are b̄b background events. The right hand side plot indicates the
remaining area after the selection cut in the correlation of those mesons has been applied.
](image-url)

The main distinct feature of B_s^0 mesons compared to the b̄b events is their relatively
large flight path. Therefore, it is expected from them show a significant flight distance
greater than 4 times the flight distance significance. Furthermore, candidates should point
back to the primary vertex where their production vertex is located. It is demanded then
a relatively small angle between the flight vector and their reconstructed momentum di-
rection. This cut is supposed to be quite powerful in removing both fake combinatorial
candidates as well as background ones. However, we decided not to tighten any further
as that cut is directly correlated to cutting in propertime for those events. Similarly, the smallest impact parameter significance for those should be kept sufficiently low. See Table (5.2) for exact figures.

We draw the attention to the fact that the mass windows for the selection of $B^0_s$ candidates is 150MeV. This is $\sim 3\sigma$ of the nominal $B^0_s$ meson mass (Figure 5.18). The large mass resolution obtained for those $B^0_s$ mesons is due to the fact that two photons are present in our channel. Neutral clusters are characterised for their x,y position and their E estimation at certain point z. The resolution in energy is poor for them. Notice also that any $P_T$ cut was avoided for the $B^0_s$ mesons candidates.

$$
\begin{array}{|c|c|}
\hline
\text{Cuts} & \text{B}^0_s \to J/\psi \eta' \\
\hline
\Delta \ln L_{\mu\pi} (\mu^+, \mu^-) > & -10 \\
\hline
P_T (\mu^\pm) \text{ [MeV/c]} > & 300 \\
\hline
IP/\sigma_{IP}(\mu^\pm) > & 0 \\
\hline
P_T (\pi^\pm) \text{ [MeV/c]} > & 400 \\
\hline
IP/\sigma_{IP}(\pi^\pm) > & 1 \\
\hline
P_T (\gamma) \text{ [MeV/c]} > & 700 \\
\hline
P (\gamma) \text{ [MeV/c]} > & 1000 \\
\hline
P (\pi^\pm) \text{ [MeV/c]} > & 2000 \\
\hline
\chi^2 (J/\psi) < & 16 \\
\hline
P_T (J/\psi) \text{ [MeV/c]} > & 300 \\
\hline
\delta(m) (J/\psi) \text{ [MeV/c}^2] \pm & 50 \\
\hline
P_T (\eta) \text{ [MeV/c]} > & 500 \\
\hline
\delta(m) (\eta) \text{ [MeV/c}^2] \pm & 120 \\
\hline
\chi^2 (\eta') < & 9 \\
\hline
P_T (\eta') \text{ [MeV/c]} > & 2400 \\
\hline
\delta(m) (\eta') \text{ [MeV/c}^2] \pm & 110 \\
\hline
\delta(m) (\eta'-\eta) \text{ [MeV/c}^2] \pm & 50 \\
\hline
\chi^2 (B^0_s) < & 25 \\
\hline
\cos \theta_{LP} > & 0.99995 \\
\hline
\delta(m) (B^0_s) \text{ [MeV/c}^2] \pm & 150 \\
\hline
\text{IPS (B}^0_s) < & 5 \\
\hline
\text{FS (B}^0_s) > & 4 \\
\hline
\end{array}
$$

Table 5.2: Selection cuts used for $B^0_s \to J/\psi(\mu^+ \mu^-) \eta' (\pi^+ \pi^- \eta (\gamma \gamma))$ decay channel.
5.6 Selection results

The ability of the LHCb experiment to resolve the fast $B_s^0 - \bar{B}_s^0$-oscillations directly depends on the proper time resolution. To this end, our proper-time observables need to be measured with a sufficient resolution. In this section we will present the results that we obtain after the tight set of selection cuts have been applied to the events. Trigger efficiencies will be discussed afterwards. For the sake of better estimations of the resolutions, we will only consider those events which have been associated to the MC generated ones, i.e., that they have all their final states associated to their corresponding MC particles.

5.6.1 Mass Resolutions

The intrinsic width of the particles involved in our channel decay are significantly narrow to be neglected when plotting mass distributions. Even so, distributions of the MC generated masses of the $\eta'$ and $J/\psi$ will be shown in order to cross-check that they were properly generated.

The association procedure is far from being perfect. That means that even if we apply very strong cuts to the selection variables we will realise that at times there are a few candidates available per event. Ideally, we should establish a criterion that chooses between those who provide a sole survivor candidate per event. For a more precise estimation of the mass resolutions we will only look at those events which show an unique candidate per event. Otherwise, distortions would be visible in the distributions.

The invariant mass distribution obtained for the $J/\psi$ candidates is shown in Fig. (5.18(a)). The mass resolution is given by fitting a single Gaussian to the distribution. The obtained mean value shows us that the reconstructed mass lies within the intrinsic width of the $J/\psi$ generated value. The sigma value resulting from the fit is $\sigma_{m(J/\psi)} = (11.3 \pm 0.3)\,\text{MeV}/c^2$, which is as expected similar to the ones obtained from similar decays.

Given the fact that the true generated mass $HepMc$ is not constant for $J/\psi$, we might plot the residuals\(^5\) of the $J/\psi$ mass in order to get an estimate of the error in the invariant mass. In Fig. (5.19(c)) we shown the error distribution expected for the $J/\psi$ mass. The mean value is as expected close to zero and the sigma of the residuals distribution gives us a clear estimate of the error for the $J/\psi$ mass.

In the case of $\eta$, the resulting mass distribution width appears to be larger than the $J/\psi$ due to the fact that photons energy is poorly reconstructed. The value resulting from a single Gaussian fit is $\sigma_{m(\eta)} = (26.01 \pm 0.89)\,\text{MeV}/c^2$. The mean value is $\mu_{m(\eta)} = (548.9 \pm 0.9)\,\text{MeV}/c^2$ which exhibits a small shift due to incorrect estimations in energy. This bias will hence be propagated to the computation of the invariant masses of subsequent particles.

The invariant mass of $\eta'$ is shown in Fig. (5.18(c)). Even though we increase the number of particles the sigma of the Gaussian fit remains quite similar to that of the $\eta$ as the mass resolution of the $\eta'$ candidates is dominated by the energy resolution of the photons. The mean value $\mu_{m(\eta')} = (959.28 \pm 0.92)\,\text{MeV}/c^2$ exhibits as predicted above a small displacement.

Finally, in Fig. (5.18(d)) we can see the corresponding mass distribution for the $B_s^0$ candidates which are associated to the MC events. It is of great importance to have a

\(^5\)Residuals are defined as the difference between the reconstructed/measured value and the one used in the MC generation.
good mass resolution for the $B_s^0$ candidate events. The invariant mass is one of the key ingredients when computing the proper time of those.

Likewise, we fit the mass distribution with a single Gaussian resulting in a mean value of $\mu_{m(B)} = (5373.27 \pm 1.73)$ MeV/c$^2$ and its sigma value amounts to $\sigma_{m(B)} = (52.49 \pm 1.50)$ MeV/c$^2$.

### 5.6.2 Momentum Resolutions

For our proper time measurement, another key ingredient is the momentum estimation of the $B_s^0$ candidates. As we have already discussed, $B_s^0$ mesons are ejected in the forward direction with a certain boost. As a result, more accurate momentum resolutions are expected for the transverse axes compared to the beam axis. Hence, $B_s^0$ momentum resolution will be predominantly determined by the resolution in momentum along the z-axis.

In Figures (5.16(a), 5.16(b), 5.17(b)) those features are easily demonstrated. Sigma values for the transverse momenta obtained after a single Gaussian fit are $\sigma_{p_x(B)} = (87.7 \pm 3.2)$ MeV/c and $\sigma_{p_y(B)} = (80.9 \pm 3.2)$ MeV/c. For the beam axis the momentum resolution achieved after selection is $\sigma_{p_z(B)} = (1397.5 \pm 50.9)$ MeV/c.

![Figure 5.16: Momentum residuals for $B_s^0$ candidates being fitted by a Single Gaussian corresponding to the transverse components x (a) and y (b).](image)

### 5.6.3 Vertices Resolutions

Moreover, proper time measurements depend on the scalar product between the momentum vector and the flight vector of the $B_s^0$ candidates. LHCb have been designed to achieve a primary vertex resolution along the beam axis of about 40$\mu$m or better. The computation of the primary vertices is performed before the selection part. It is an iterative procedure which ends up with a set of primary vertices after neglecting tracks that do not fit a common point.

The distributions shown in Figure (5.20) for the primary vertex exhibit the foreseen vertex resolutions on each axis component. Vertex resolution are obtained after fitting.
5.6. SELECTION RESULTS

5.6.4 Proper time measurements

As we saw in Chapter 1, $\bar{b} \rightarrow \bar{c}c\bar{s}$ transitions decaying to CP-even eigenstates lead to an analytical CP-asymmetry which is proper time dependent. In the case of $B^0_s$ mesons the oscillation between meson and antimeson is so fast that in order to disentangle those rapid oscillations we need an excellent proper time resolution for the channel decay under study. We anticipate that if LHCb VELO has been designed to achieve a notorious primary vertex resolution, the proper time resolution will be mainly dominated by our ability to reconstruct precisely both secondary vertex as well as improve our estimate of the momentum of decaying particles. The consequence of a poor proper time determination will be a dilution of the wiggles similar to that caused by the lack of $B^0_s$ mesons tagging information.
Figure 5.18: Invariant mass distributions for the $B_s^0$ meson candidates as well as its daughters. Invariant masses used in the Monte Carlo simulations are $M_{J/\psi} = 3096.87 \pm 0.04$, $M_{\eta} = 547.30 \pm 0.12$, $M_{\eta'} = 957.78 \pm 0.14$ and $M_{B_s^0} = 5369.6 \pm 2.4$ as given in the PDG booklet [71]
5.6. SELECTION RESULTS

(a) True generated (HepMC) mass for $J/\psi$

(b) True generated (HepMC) mass for $\eta'$

(c) Residuals for the $J/\psi$ candidates

(d) Residuals for the $\eta'$ candidates

Figure 5.19:
Figure 5.20: Position residuals for the reconstructed primary vertex (Left) and the $B_s^0$ decay vertex (Right).
Our event-by-event observables are the momentum and flight distance of the $B^0_s$ mesons.

As it is well known, time in the lab frame appears to be dilated compared to that measured for the moving relativistic particle, hence, we have there a relationship between our observable $t$ in the lab frame and the proper time $\tau$ given by $t = \gamma \tau$, where $\gamma$ is the relativistic Lorentz factor\(^6\) for a particle travelling at speed $\beta c$.

The $B^0_s$ meson moving at a speed $\beta c$ will decay at time $t$ after following a flight distance $\overrightarrow{FD} = \overrightarrow{S} - \overrightarrow{P}$ where $\overrightarrow{S}$ and $\overrightarrow{P}$ are the position vectors of the secondary and primary vertices respectively, with respect to the LHCb reference frame.

$$\overrightarrow{FD} = \beta ct = \beta c \gamma \tau$$

If $\vec{p} = m \vec{\beta} c \gamma$ is the momentum of the reconstructed candidate where $m$ is the $B^0_s$ mass, we can hence deduce the candidate proper time using our observables from the above expression taking into account the $B^0_s$ momentum observable:

$$\overrightarrow{FD} = \frac{\vec{p}}{m} \iff \tau = \frac{m \vec{p} \cdot \overrightarrow{FD}}{|p|^2} \quad (5.2)$$

In previous Sections we have shown that the errors in momentum of $B^0_s$ are underestimated so in order to take into account the errors and their correlations we combine them with the observables to get estimates of the proper time constrained by the above kinematical formula (5.2), we make use of a tool called **LifeTimeFitter** that will minimise a Least Squares function $\chi^2(\theta)$, (where $\theta$ are the unknown parameters) which takes into account our observables and their covariance matrices assuming no error in the determination of the $B^0_s$ mass. The outcome of such a fit is an estimation of the proper time for that event candidate and the error in the measurement. A detailed explanation of the method of Least Squares applied to the proper time estimator can be found in Appendix (B).

- **Proper time acceptance**

Before discussing the results obtained from the proper time fits, let us introduce the acceptance function and what is meant by proper time selection efficiency. There are some selection variables which are highly correlated to the proper time exhibited by each of the events. Specifically, our trigger and selection cuts are based on the fact that $B^0_s$ mesons are long lived and hence present displaced decay vertices with respect to the primary ones. Cuts such as **Impact Parameter**, **Flight distance** for the decay products and $B^0_s$ mesons respectively, bias our proper time distributions cutting at low proper times.

Hence, after the tight selection cuts, the probability to detect true signal events will not be uniform anymore\(^7\), instead it will depend on the proper time and will be less favorable for short-lived true events. This probability is hence a time-dependent selection efficiency and may be parametrised by a so-called acceptance function.

In order to display this proper time acceptance distribution we will plot the bin-to-bin ratio of entries for the histogram of the true proper time after all selection cuts to the corresponding histogram before any cuts. Because one is a subset of the other, it is a bin-to-bin true proper time efficiency. After having plotted it, we could try to fit the proper time dependent efficiency with the acceptance function which can be simply defined as:

\(^6\gamma = (1 - \vec{\beta})^{-1/2}\)

\(^7\)neglecting reconstruction efficiencies
\[ \varepsilon(t) = \text{acc}_a \cdot \frac{(\text{acc}_s \cdot t)^3}{1 + (\text{acc}_s \cdot t)^3}, \]  

(5.3)

where \( \text{acc}_a \) is a normalization factor and \( \text{acc}_s \) parametrises the slope of the rise at low proper times. The fit will minimise a \( \chi^2 \) function of the acceptance function with respect to the bin-to-bin data.

In Fig.(5.21(a)) it is shown the proper time acceptance distribution obtained after the tight selection cuts and in Fig.(5.21(b)) the one resulting after been applied the selection cuts and subsequently all the trigger levels, i.e., L0, L1, as well as HLT trigger. In both Figures is visible the cut made on events with short true proper times. They are certainly removed by the cuts on the impact parameter of decay products, and cuts on the flight distance of the \( B_0^s \) candidates. The cut on the angle between the momentum of the \( B_0^s \) mesons and their flight vectors is also correlated to cut in small proper times.

The obtained values are \( \text{acc}_a = (2.14 \pm 0.10) \text{ ps}^{-1} \) before any trigger and \( \text{acc}_s = (1.98 \pm 0.10) \text{ ps}^{-1} \) after the events have passed the L0, L1 and HLT trigger levels.

The trigger as a whole slightly decrease the value of the slope \( \text{acc}_s \) but the difference is within statistical fluctuations indicating that our selection cuts are possibly quite tough.

In the results of next section this cut at low proper times will be visible in the distribution of reconstructed proper time, so the acceptance function given by Equation (5.3) is assumed to define properly this behaviour at small proper times whereas an exponential decay law better suits the distribution at larger proper times.

In real life, the method to determine the proper time dependent acceptance efficiency remains to be defined.

\[ \text{MC}^{t;0}_{h+p+p'} \]

\[ \text{MC}^{t;0}_{h+p+p'} \]

Figure 5.21: Proper time acceptance distributions fitted with the acceptance function. A choice of binning smaller than 1 ps or more statistics will allow us to better fit the acceptance function.

- Proper time fit results

We are now going to analyse the resulting proper time obtained from the lifetime fit. In Figure (5.22(a)) can be seen the distribution of the proper time obtained from the Least
Squares fit, $\tau_{\text{rec}}$. The distribution is fitted with the product of an acceptance function as being defined in Equation (5.3) and an exponential law with decay constant $\tau$. The resulting lifetime is $\sim 3\sigma$ away from the true MC value $\tau = 1.461$ ps.

The per-event error distribution is shown in Figure (5.22(b)) $\tau_{\text{err}}$. This error $\tau_{\text{err}}$ is obtained from the fit and it is given by the second order derivatives of the $\chi^2(\theta)$ Least Squares function with respect to the least-square estimators. See Appendix (B).

Let us now look at the residuals distribution of the proper time, i.e. $\tau_{\text{rec}} - \tau_{\text{MC}}$. In Figure 5.22(c) is displayed the proper time residuals distribution together with a single Gaussian fit. It can be noticed from this plot that the proper time resolution is not good enough to resolve the oscillations, the sigma value is $\sigma_{\text{resol}} = 96.77 \pm 3.25$ fs, also, a small shift of the mean of $\sim 2\sigma$ is visible. In Figure (5.22(e)) the distribution of the proper time residuals is fitted with a double Gaussian which fits the better the distribution. The core Gaussian which represents the $\sim 81\%$ of the curve has a sigma value of $\sigma_{\text{resol}} = 82.12 \pm 4.86$ fs. We will show below that the main contribution to the proper time resolution comes from the $B^0_s$ momentum reconstruction.

The proper time resolution result is what we expect from channels decaying into photons. When compared to $B^0_s \to J/\psi (\mu^+\mu^-)\eta(\gamma\gamma)$ [70], we see that the proper time resolution is better due to the fact that our channel have a better $B^0_s$ decay vertex resolution given by the presence of extra charged tracks. Even so, this proper time resolution is not satisfactory and it should be improved. In Section (5.7) we will discuss some methods searching for such an improvement. In Figure 5.22(d) can be checked the obtained proper time pull of these measurements $\tau_{\text{rec}} - \tau_{\text{MC}}/\tau_{\text{err}}$. An apparently correct estimation of the errors in proper time is seen from the distribution given by the sigma of the single Gaussian fit. The obtained value is $\sigma_\tau = 1.01 \pm 0.03$. The mean of the pull also stays centered at zero.

Just for completeness, the distribution of the $\chi^2$ least-squares from the fit is shown in Figure (5.22(f)) showing a low value in the minimisation process.

- **Contributions to the proper time fit**

We recall here that the pull of a variable indicates us how well the errors are estimated for that physical observable. In the case of the proper time the fit depends on three physical parameters$^8$ (see Equation 5.2) which translates to measure seven physical observables. Hence, the pull of the proper time do only tell us about the average proper time errors resulting from the least-square fit. In Figure (5.22(d)) can be seen those facts. The sigma of the pull of the proper time is close to one but we have already seen above that both the resolution obtained by the LHCb spectrometer both in the decay vertices of the $B^0_s$ candidates and their momentum are not entirely satisfactory. Only the primary vertex gives us an acceptable resolution. The value of the pull hence highlight the fact that the poor estimation of error in momentum is hidden by a similar factor when determining the decay vertex of the $B^0_s$ candidates.

In order to quantify those contributions to the errors, we can smartly substitute each time the true MC value for any of the parameters involved in the proper time fit for every event and check what proper time resolutions are obtained when doing so. The resulting residuals of the cheated lifetime fits are shown in Figure (5.23). It turns out from the single Gaussian fit of Figure (5.23(a)) that the poor momentum estimation of the $B^0_s$ mesons is a chief effect to be take into account. The inefficiency in determining this observable really

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$^8$The mass of the $B^0_s$ is regarded to be a constant of the fit. See Appendix B.
CHAPTER 5. SELECTION OF $B_s^0 \to J/\psi \eta$'

Figure 5.22: Proper time distributions given by the LifeTimeFitter tool for candidates passing all the cuts.
spoils our proper time estimates. A sigma value for the Gauss curve of \( \sigma_{\delta \tau} = 28.6 \pm 0.85 \text{ fs} \) is obtained close to what were expected for a decay with six final charged states [73]. We can pinpoint the cause of such an inaccuracy in the momentum measurement: this is just another confirmation of the poor performance of the ECAL and their energy error estimations.

If we look now at the Figure (5.23(c)), again a single Gaussian fit is performed on the distribution. From that fit we can deduce that the badly estimate of the decay vertex position does not spoils that much the proper time fits as compared to the momentum measurements. The four charged tracks are the only contribution in the determination of the decay vertex. Finally the determination of the proper time is not much affected by the contribution arising from the primary vertex.

5.7 Improving the proper time resolution

The proper time resolution of the \( B_0^s \) obtained from our selection procedure is completely unsatisfactory for the searching of time dependent CP asymmetries. A good proper time resolution is needed if we want to resolve the fast oscillations of the \( B_0^s \) mesons.

We have seen above that our proper time measurements are spoiled by our bad knowledge of the momentum of the \( B_0^s \) mesons. We know as well that this comes from our poor resolution when dealing with photons. Hence, we should find a method that treat photon properly and correct their momentum estimations. Two distinct methods have been envisaged in order to improve the proper time resolution of the \( B_0^s \) mesons. On one hand we will use a mass constrained fit for the \( \eta \) mass and on the other hand we will analyse how proper time is obtained if we use the so-called Kalman filter fit technique.

5.7.1 Mass constrained vertex fit

Our knowledge of the 4-momentum for the \( \eta \) mesons is quite poor. Photons are reconstructed in a previous step as being independent particles coming from the nominal interaction point of the LHCb spectrometer. The covariance matrices are computed in accordance. In this method we request the momentum of the photons decaying from the \( \eta \) meson to exhibit an invariant mass equal to the nominal \( \eta \) mass which is equal to 547.3 MeV/c\(^2\). Therefore, as we constraint the meson mass the fitter will modify the momentum vectors of the photons to match this constrained mass. We recall that the momentum estimation is given with the nominal interaction point as the photon origin. Once this fit is achieved we can add up our photon momentum information to the pions in order to form the new \( \eta' \) candidates and hence the new \( B_0^s \) mesons. The obtained \( B_0^s \) mass distribution after the \( \eta \) mass constrained fit is show in Figure 5.25(b). We see from the distribution that the mass resolution is drastically improved by this method. The obtained figure is a sigma value from the single Gaussian fit of \( \sigma_{B_0^s} = 23.05 \pm 0.88 \text{ MeV/c}\(^2\)\). In Figure 5.24(a) can be seen the proper time distribution issued by the lifetimefitter tool. The combined acceptance and exponential function better fit the distribution compared to the previous one. The obtained lifetime \( \tau = 1.46 \pm 0.06 \text{ ps} \) perfectly matches the true value.

After the mass constrained fit, the proper time resolution given by the residuals is largely improved as well as the mean error for that observable. Check Figure 5.24(b) and 5.24(c) respectively. The obtained value for the proper time resolution is \( \sigma_{\delta \tau} = 35.2 \pm 1.8 \text{ fs} \). The mean error value drops approximately a factor three.
(a) Proper time resolution of $B_s^0$ candidates requiring the TrueMC $B_s^0$ momentum.

(b) Proper time resolution of $B_s^0$ candidates requiring the TrueMC primary vertex.

(c) Proper time resolution of $B_s^0$ candidates requiring the TrueMC $B_s^0$ vertex.

(d) Proper time resolution of $B_s^0$ candidates requiring the TrueMC $B_s^0$ vertex fitted with 2 Gaussians.

Figure 5.23: Proper time distributions given by the LifeTimeFitter tool for signal candidates passing all the cuts after substituting a true MC value.
5.7. **IMPROVING THE PROPER TIME RESOLUTION**

Figure 5.24: Proper time distributions given by the LifeTimeFitter tool for candidates passing all the cuts and refitted after a mass constrained fit have been applied to the $\eta$ mass.
The significantly larger value of the variance of the proper time pull seems to unveil the hidden cancellation effect when determining the proper time. When we constraint the \( \eta' \) mass to its true value the momentum of the \( B_s^0 \) mesons is hence better estimated but the errors are not well computed due to the underestimation of the errors of the photons. There is an under-estimation of errors of \( \sim 16\% \). This kind of fit does not improve any decay vertex resolution as it keeps the vertices as they were.

### 5.7.2 Kalman Filter fit

The second method that we have integrated in our selection code in order to improve the estimation of the proper time is based on the so-called Kalman Filter fit\(^9\).

A DAVINCI tool based on this powerful method has been released by the collaboration in order to properly take into account the information given by neutral particles and the correlation to their decay vertex.

In the case of the mass constrained fit, the decay vertex of \( \eta' \) was obtained in a first step from the charged particles and then the photons from \( \eta \) were treated as ordinary neutral particles, i.e. no information about the decay vertex is available to them, only ECAL information. After the mass constrained fit, momentum information was changed to suit the \( \eta \) mass, but always given at the nominal collision point. Hence, there exists no information in the covariance matrix of the \( \eta' \) about the correlation between the momentum of the photons and the \( \eta' \) decay vertex.

The Kalman filter fit tool [74], instead, takes into account the existing correlation between the momentum of the photons and their decay vertex. This fact is naturally integrated by the Kalman technique as being considered as an additional measurement that weight the actual prediction both for the energy-position estimates and their correlation matrices. An outline of what is exactly done by the tool for our channel decay can be found as an brief Appendix (5.A) of this thesis. For now, we will only recover the most important steps that makes that the correlation information between the photon momentum and its origin vertex position being carried by the covariance matrix of \( \eta' \).

The trajectories of the charged particles (\( \pi^+ , \pi^- , \mu^+ , \mu^- \)) are refitted with the aid of the Kalman filter fit in order to form a decay vertex for the neutral particles (they are assumed to be issued from it). From the measurements of the ECAL clusters we can infer the momentum of the photons given the decay vertex previously computed. Hence, here is where the Kalman filter fit tool takes into account this correlation between decay vertex and momentum information. The measured information will be transformed through a Jacobian to the desirable state vector of the \( \eta' \) particle. The correlation information have a big impact when computing the lifetime of the \( B_s^0 \) meson using the lifetime fitter as the correlation matrix is properly accounted for. Hereafter, the results obtained using this tool will be discussed.

The obtained \( B_s^0 \) mass distribution after the Kalman filter fit is show in Figure (5.25(a)). As it can be seen, mass resolution seems to takes advantage from the KM fit tool. The better resolution in mass is due to a better momentum estimation of the \( B_s^0 \) candidates since photons are properly treated. Moreover, mass constrained fits have been applied both to the \( J/\psi \) and \( \eta' \) as well as \( \eta \) candidates, so, an improvement is also expected from those fits. The obtained figure from the single Gaussian fit is of a sigma value \( \sigma^{B_s^0}_{\eta'} = 18.26 \pm 0.66 \text{ MeV}/c^2 \). In the case of double Gaussian fit, the obtained value is \( \sigma^{B_s^0}_{\eta'} = \)

\(^9\)The filter is named after Rudolf E. Kalman (1960), though Thorvald Nicolai Thiele and Peter Swerling (1958) actually developed a similar algorithm earlier. See Appendix A for a brief explanation of the method.
15.74 ± 1.38 MeV/c² and the core Gaussian represents ∼ 83% of the weight. The core Gaussian represents better the distribution than in the case of the η mass constrained.

As it has been argued above, covariance matrix is better computed by this tool since it takes into account the correlation existing between the momentum of the photons and their decay vertex given by the decay vertex of the η' candidates. It is hence expected that the lifetimefitter tool benefits from that improvement.

In Figure (5.26(a)) can be seen the resulting proper time distribution. The combined acceptance and exponential function properly fit the distribution. The obtained lifetime \( \tau = 1.42 \pm 0.06 \) ps match the true value within statistical uncertainty. The Kalman filter tool appears to improve also the proper time resolution. The obtained figure for a single Gaussian fit is \( \sigma_{\delta\tau} = 32.59 \pm 0.95 \) fs. Now, the core Gaussian for the double fit reflects that a single physical process represents ∼ 92% of the distribution. See Figures (5.26(b)) and (5.26(e)) for a single and a double Gaussian fit of the proper time residuals. The mean error given by the lifetime tool appears also to diminish. Check Figure (5.26(c)) for the distribution. If we now look at the distribution of the proper time pull (5.26(d)) we see that again an under-estimation of the errors appears on the distribution. Now, this effect appears to be larger than in the case of η mass constrained (∼ 37%), what might point to a possible under-estimation of errors at the ECAL level. The effect is not visible after selection cuts maybe because some under-estimation of errors are hidden by over-estimation of other variables.

5.8 Annual Signal Yield: Performance efficiencies

It is time to estimate what would be the annual signal rate expected for this channel decay in LHCb. Firstly, we will introduce some definitions of the efficiencies involved in the computation of the signal yield as well as some required nomenclature. Secondly, we will compute the performance of our final selection cuts on the signal. It is recalled that in the generation of Monte Carlo samples, a random seed bug was introduced which needs to be taken into account for the estimation of performances, even though, the fraction of data that is affected by the bug is negligible for the signal events. (See Section (4.5.1)). It is presupposed that any sub dataset of the original signal sample obtained by selection cuts keep those proportions of repeated events. Finally, the computation of trigger as well as tagging performances will be addressed. The estimation of the background levels for these signal events will be performed separately in Section (5.9).

5.8.1 Total signal efficiency

The first question that we could make ourselves is, “what is the performance of our selection cuts?”, i.e., how well have been selected the signal events?. To quantify that process, we could hence define the so-called efficiency of selection on signal events as the fraction of the generated Monte Carlo events which have been selected, that is to say, which have passed our selection cuts after being reconstructed by the LHCb software.

To cope with the definitions of reconstruction and selection performances we will firstly introduce some useful nomenclature:

- \( N_{\text{gen}} \): the total number of Monte Carlo events that have been generated for the signal and that will be used for the selection analysis.
- \( N_{\text{sel}} \): the subset of \( N_{\text{gen}} \) surviving the off-line selection cuts.
Figure 5.25: Mass distribution of $B_s^0$ candidates which result from the refit performed by the Kalman Filter fit DAVINCI tool (Left). Mass distribution of $B_s^0$ candidates resulting after a mass constrained of the $\eta$ mesons (Right).
Figure 5.26: Proper time distributions given by the LifeTimeFitter tool for candidates passing all the cuts and refitted by means of the Kalman Filter DA\textsc{\textregistered}NC\textsc{\textregistered} tool.
• $N'_{\text{ble}}$: the number of reconstructible events, having only long tracks and neutral particles. See Section (4.2.4).

• $N'_{\text{ed}}$: the number of reconstructed events, that have all their charged final states reconstructed as long tracks and photons. See Section (4.2.4).

• $N'_{\text{ble/ed}}$: the number of generated events that lie simultaneously on the categories of reconstructible and reconstructed.

In table (5.3) are shown the number of events for each of the above definitions that correspond to our channel decay. The large number of reconstructed events compared to the reconstructible ones may be explained by the fact that the reconstruction performance algorithm is not really suitable for photon channels. Similar reconstruction results can be seen in [70].

<table>
<thead>
<tr>
<th>$B_s^0 \to J/\psi \eta'$</th>
<th>$N'_{\text{gen}}$</th>
<th>$N'_{\text{ble}}$</th>
<th>$N'_{\text{ed}}$</th>
<th>$N'_{\text{ble/ed}}$</th>
<th>$N_{\text{sel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \to \pi^+\pi^-\eta(\gamma\gamma)$</td>
<td>179'500</td>
<td>22'966</td>
<td>25'140</td>
<td>18'035</td>
<td>1'151</td>
</tr>
</tbody>
</table>

Table 5.3: Reconstruction and off-line selection numbers for $B_s^0 \to J/\psi \eta'$.

We recall here that the signal sample suffered an acceptance cut of 400 mrad at the generation level. So, taking into account this generator-level cut on the signal $B_s^0$ events, named $\varepsilon_{\text{sig}} B_s^0$, which only keeps $\varepsilon_{\text{sig}} B_s^0 = 34.7 \pm 0.3\%$ of the generated events within the LHCb acceptance, we can define the total selection efficiency before any trigger being applied as:

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{sig}} B_s^0 \times \frac{N_{\text{sel}}}{N_{\text{gen}}}$$  \hspace{1cm} (5.4)

If we wish now to factorize this total efficiency in terms of detection, reconstruction and selection processes, namely, $\varepsilon_{\text{tot}} = \varepsilon_{\text{det}} \times \varepsilon_{\text{rec/det}} \times \varepsilon_{\text{sel/rec}}$, we could hence come out with the following definitions:

* $\varepsilon_{\text{det}} = \varepsilon_{\text{sig}} B_s^0 \times \frac{N_{\text{sel}}}{N_{\text{gen}}} \times \frac{1}{\varepsilon_{\text{rec/det}}} \times \frac{1}{\varepsilon_{\text{sel/rec}}}$ is the detection efficiency which includes the effect of the 400 mrad cut on the polar angle for the b-hadron at the generator level as well as the selection of reconstructible events;

* $\varepsilon_{\text{rec/det}} = \frac{N'_{\text{ble/ed}}}{N'_{\text{ble}}}$ is the reconstruction efficiency on reconstructible (detected) events;

* $\varepsilon_{\text{sel/rec}} = \frac{N_{\text{sel}}}{N'_{\text{ed}}}$ is the off-line selection efficiency on the reconstructed events.

All of the above efficiencies are estimated and given in Table (5.4). The estimated errors for those figures are statistical and assume a fraction of independent events $f$ as computed in section (4.5.1)$^{10}$. The efficiency errors are computed as ordinary Binomial errors, but introducing the fraction of independent events $f$ regarded as a constant and hence neglecting its error. Hence, for a efficiency, say, $\varepsilon = N/M$, the statistical error is given by $\sigma_\varepsilon = \sqrt{(\varepsilon(1-\varepsilon))/fM}$ [73]. Quadratic propagation of errors have been used when necessary in Table 5.4. We used the expression given by the Equation (5.4) to compute the error for the total efficiency, $\varepsilon_{\text{tot}}$.

$^{10}$
5.8. ANNUAL SIGNAL YIELD: PERFORMANCE EFFICIENCIES

<table>
<thead>
<tr>
<th>$B^0_s \rightarrow J/\psi \eta'$</th>
<th>$\varepsilon_{\text{det}}$ [%]</th>
<th>$\varepsilon_{\text{rec/det}}$ [%]</th>
<th>$\varepsilon_{\text{sel/rec}}$ [%]</th>
<th>$\varepsilon_{\text{tot}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow \pi^+ \pi^- \eta(\gamma \gamma)$</td>
<td>6.19 ± 0.04</td>
<td>78.5 ± 0.3</td>
<td>4.58 ± 0.14</td>
<td>0.223 ± 0.007</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of the signal efficiencies for the DC04 $B^0_s \rightarrow J/\psi \eta'$ data.

5.8.2 Trigger performance on signal events

Let us now to focus on how signal events that pass our selection cuts are treated by the distinct trigger levels. We are going to evaluate the performances of those individual triggers when selecting our signal events.

As we already know from Section (2.1.8), three levels of increasing complexity are envisaged by the LHCb collaboration, namely, L0, L1 and the HLT. We can hence define for those levels the corresponding trigger efficiencies as follow, being $N_{L0}, N_{L1}, N_{HLT}$ the number of events that pass successively the triggers L0, L1 and HLT:

* $\varepsilon_{L0/sel} = \frac{N_{L0}}{N_{sel}}$, being the efficiency of the trigger level L0 to successfully keep those off-line selected signal events.

* $\varepsilon_{L1/L0} = \frac{N_{L1}}{N_{L0}}$, being the efficiency of the L1 level to trigger signal events that have already passed L0.

* $\varepsilon_{HLT/L1} = \frac{N_{HLT}}{N_{L1}}$, being the efficiency of the HLT level\(^{11}\) to trigger signal events that have already passed both L0 and L1.

The numbers obtained after selection for each of the trigger contributions are show in Table 5.5. Furthermore, the resulting trigger efficiencies are computed and given in Table 5.6. Statistical errors are computed as before.\(^{10}\)

The numbers obtained after selection for each of the trigger contributions are show in Table 5.5. Furthermore, the resulting trigger efficiencies are computed and given in Table 5.6. Statistical errors are computed as before.\(^{10}\)

\[^{11}\text{Specifically for our channel decay, the HLT following the Muon Highway, will select events which have dimuons whose invariant mass is close to the } J/\psi \text{ mass. See Section (2.1.8.c).}\]

<table>
<thead>
<tr>
<th>$B^0_s \rightarrow J/\psi \eta'$</th>
<th>$N_{sel}$</th>
<th>$N_{L0}$</th>
<th>$N_{L1}$</th>
<th>$N_{HLT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow \pi^+ \pi^- \eta(\gamma \gamma)$</td>
<td>1'151</td>
<td>1'112</td>
<td>1059</td>
<td>982</td>
</tr>
</tbody>
</table>

Table 5.5: Trigger contributions for the studied decay.

<table>
<thead>
<tr>
<th>$B^0_s \rightarrow J/\psi \eta'$</th>
<th>$\varepsilon_{L0/sel}$</th>
<th>$\varepsilon_{L1/L0}$</th>
<th>$\varepsilon_{HLT/L1}$</th>
<th>$\varepsilon_{HLT/sel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow \pi^+ \pi^- \eta(\gamma \gamma)$</td>
<td>96.6 ± 0.5</td>
<td>95.1 ± 0.6</td>
<td>92.7 ± 0.8</td>
<td>85.30 ± 0.10</td>
</tr>
</tbody>
</table>

Table 5.6: Trigger Efficiency breakdown for the studied decay.

In Table 5.7 are shown the different trigger lines for the L1 trigger level. A possible overlapping is allowed as each line act on distinct selection criteria. The different HLT streams contributions are provided in Table 5.8. As it can be remarked from those figures,
the Dimuon level seems to select most of the interesting events. Furthermore, inclusive and exclusive modes of selection of B candidates are of great help as well.

<table>
<thead>
<tr>
<th>L1 line</th>
<th>$B_s^0 \rightarrow J/\psi \eta'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic $(p_T) / \Sigma \ln p_T$</td>
<td>815</td>
</tr>
<tr>
<td>Single-muon</td>
<td>713</td>
</tr>
<tr>
<td>Dimuon general</td>
<td>399</td>
</tr>
<tr>
<td>Dimuon $J/\psi$</td>
<td>914</td>
</tr>
<tr>
<td>Electron</td>
<td>87</td>
</tr>
<tr>
<td>Photon</td>
<td>113</td>
</tr>
<tr>
<td>L1-Decision</td>
<td>1059</td>
</tr>
</tbody>
</table>

Table 5.7: L1 trigger lines selection.

<table>
<thead>
<tr>
<th>HLT Stream</th>
<th>$B_s^0 \rightarrow J/\psi \eta'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT-Generic</td>
<td>982</td>
</tr>
<tr>
<td>Inclusive B</td>
<td>711</td>
</tr>
<tr>
<td>Exclusive B</td>
<td>727</td>
</tr>
<tr>
<td>Dimuon</td>
<td>818</td>
</tr>
<tr>
<td>$D^*$</td>
<td>22</td>
</tr>
<tr>
<td>HLT-Decision</td>
<td>982</td>
</tr>
</tbody>
</table>

Table 5.8: HLT streams selection.

### 5.8.3 Tagging performance

As we have already introduced in Section (4.4), when looking at CP asymmetries arising in different decay channels the knowledge of the initial $B_s^0$ meson flavor is of great importance. For the channel under study the tagging performance is a key issue, since a poor reconstruction of the flavor at production would degrade the observed asymmetry and hence would introduce systematic errors on the expected sensitivities to $\phi_s$. It is worth mentioning here that a lack of the tagging information for some events might still be helpful to determine both $\Delta \Gamma_s$ and $\phi_s$, since it will remain in the CP asymmetry function a term in $\cos(\phi_s)$ that is still sensitive to New Physics.

In Table 5.9 are summarised the figures obtained for the tagging efficiency, $\varepsilon_{tag}$, wrong-tag fraction, $\omega_{tag}$, and the effective tagging efficiency, $\varepsilon_{eff}$, after passing the selection cuts, and subsequently adding the L0, L1 and HLT triggers constraints. See Section (4.4) for the definitions of those efficiencies.

The flavour is given to a certain selected meson by a Neural Network\(^{12}\) procedure

\(^{12}\)A Neural Network algorithm constructs a test statistic which can discriminate between multivariable hypothesis to come up with a likely outcome [75]
5.8. ANNUAL SIGNAL YIELD: PERFORMANCE EFFICIENCIES

developed by the LHCb tagging group [76], that it takes into account the outcomes of the different taggers (See Section 4.4.1) to combine them into a single result. It is recalled that sometimes, no tag is assigned to the mesons by this algorithm.

The cleanness of the selection mainly due to the charged tracks might explain the favorable numbers after HL T.

In the next Chapter we will try to estimate how sensitive our channel decay is to the measurement of $\phi_s$ as well as $\Delta \Gamma_s$. We will hence need a flavour specific control channel decay in order to simultaneously fit both channels and hence been able to extract $\omega_{tag}$ in an unbiased manner. It is required for this method that both the control channel and our channel have similar tagging performances. The control channel is $B_s^0 \rightarrow D_s^+ \pi^-$ and it is foreseen a $\omega_{tag} \sim 31\%$ and $\varepsilon_{tag} \sim 63\%$ for that channel [77, 78]. Those figures agree well with the ones that we have obtained for our channel decay. (Check Table 5.9.)

<table>
<thead>
<tr>
<th>Selection</th>
<th>L0</th>
<th>L1</th>
<th>HL T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{tag}$ [%]</td>
<td>62.9 ± 1.4</td>
<td>63.2 ± 1.4</td>
<td>63.9 ± 1.5</td>
</tr>
<tr>
<td>$\omega_{tag}$ [%]</td>
<td>31.5 ± 1.7</td>
<td>31.4 ± 1.7</td>
<td>31.5 ± 1.8</td>
</tr>
<tr>
<td>$\varepsilon_{eff}$ [%]</td>
<td>8.6 ± 2.0</td>
<td>8.7 ± 2.0</td>
<td>8.7 ± 2.2</td>
</tr>
</tbody>
</table>

Table 5.9: Tagging efficiency, wrong tag fraction and effective combined tagging efficiency obtained after selection cuts, L0, L1, and HL T have been applied subsequently.

5.8.4 Annual signal yield

At this point we can already compute the number of events that is expected to be available for physics studies annually, that is to say, $B_s^0$ events that have been produced in the spectrometer acceptance with the demanded signatures and that have been triggered, reconstructed and selected per year of data taken ($\sim 2fb^{-1}$). If we recall Section (3.1.4), there, we computed the number of signal events produced in one year, say, $N_{B_s^0 \rightarrow J/\psi \eta'}^{2fb^{-1}}$.

If we also take into account the total efficiency, $\varepsilon_{tot}$, which englobes the geometrical detector acceptance, as well as the trigger performance given by:

$$\varepsilon_{HLT/sel} = \varepsilon_{L0/sel} \times \varepsilon_{L1/L0} \times \varepsilon_{HLT/L1},$$

we can hence compute the expected annual signal yield, S, using the following formula:

$$S = N_{B_s^0 \rightarrow J/\psi \eta'}^{2fb^{-1}} \times \varepsilon_{tot} \times \varepsilon_{HLT/sel}.$$ 

Therefore, considering the obtained visible branching fractions given in Table 3.2 for the two expected bounds of the quark-mixing angle, i.e., $-20^\circ, -10^\circ$, we obtain these two signal yields:

$$S \mid_{-20^\circ} = (2.57 \pm 0.08) \times 10^3.$$

$$S \mid_{-10^\circ} = (1.92 \pm 0.07) \times 10^3.$$ 

For comparison, yield of other $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ quark transitions are given in 6.1.
5.9 Background levels

In earlier sections we have considered as the main source of background the one resulting from $b\bar{b}$ events. This is essentially because of the huge number of events produced having a heavy $b$-quark pair present that might hadronise to $B$-hadrons hence mimicking the signature of $B^0_s$ meson events. Other sources of background will succeed to avoid the tight selection cuts but even so they are not considered to be risky samples. This is explained by the very low branching ratio of those sources compared to the huge number of $b\bar{b}$ events expected within the spectrometer. Besides, we could have events like prompt $J/\psi$ which have large production rates. They are though to pass the trigger lines but even so will remain as a negligible source of background because of the impact parameter demanded to charged tracks and mainly because of the flight distance cut that is required to those $B^0_s$ candidates. The estimation of background levels for the latter specific sources requires very large samples of events if we want to obtain good estimates since their very low branching ratios leave us with low statistics to be able to perform safely such a computation.

5.9.1 Inclusive $b\bar{b}$ background level

We can try to estimate the level of background expected for the $b\bar{b}$ events by computing the background over signal ratio given by the formula (5.6) in which is taken into account the available signal and background samples and the efficiency of selection on both samples in terms of the strength of our selection cuts. The expression includes factors of production of events and their visibility within the spectrometer.

$$\left( \frac{B}{S} \right)_{\text{signal}}^{b\bar{b}} = \left( \frac{\epsilon_{b\bar{b}}}{\epsilon_{\text{signal}}} \right) \left( \frac{1}{2 \cdot f_{B^0_s} \cdot BR_{\text{vis}}^{signal}} \right) \left( \frac{N_{b\bar{b}}^{sel}}{N_{b\bar{b}}^{gen}} \right) \left( \frac{N_{\text{signal}}^{sel}}{N_{\text{signal}}^{gen}} \right), \quad (5.6)$$

where:

- $\epsilon_{b\bar{b}} = 43.21\%$ is the 400 mrad acceptance cut for the $b\bar{b}$ events;
- $\epsilon_{\text{signal}} = 34.71\%$ is the 400 mrad acceptance cut for the signal events;
- $f_{B^0_s}$ is the $b\bar{b}$ hadronization factor for $B^0_s$ production (see Tab. (3.1)),
- $BR_{\text{vis}}^{signal}$ is the $B^0_s \rightarrow J/\psi \eta'$ visible branching fraction as given in Tab. (3.2);
- $N_{b\bar{b}}^{gen}$ is the number of generated $b\bar{b}$ background events used for the computation of the background level. See Section 4.5;
- $N_{b\bar{b}}^{sel}$ is the number of background events passing the tight cuts;
- $N_{\text{signal}}^{gen}$ is the number of generated signal events available for the analysis (Check Section 4.5);
- $N_{\text{signal}}^{sel}$ is the number of signal events selected.

In previous sections we have drawn the attention to the fact that the Monte Carlo sample generated by the collaboration in the DC04 effort, barely represents a few minutes of real recorded data when LHCb will start its days. The sample to tune any of
the envisaged cuts is almost a factor two smaller than the one used to get an estimate of the background levels arising from $b\bar{b}$ events (Section 4.5). Since the generation of full simulated Monte Carlo events is a very time consuming task, we will assume that the inclusive $b\bar{b}$ background is a linear function of the reconstructed $B^0_s$ mass and hence relaxing the mass windows for the $b\bar{b}$ events has the effect of simulating an increase of statistics within the mass windows for those events by a factor given by the ratio between the expanded mass window and the tight $B^0_s$ mass window. Let us call this factor $F$, hence, $F = \frac{\delta M(B^0_s)_{Loose}}{\delta M(B^0_s)_{Tight}}$ should multiply $N_{b\bar{b}}^{gen}$ in the above expression. Besides, the $N_{b\bar{b}}^{sel}$ of events considered for the computation of $B/S$ is the one obtained for the loose mass window.

It is assumed in the above formula that all $b\bar{b}$ events may contaminate the signal, but this is not the case due to an overestimation of the inclusive $H_b \rightarrow J/\psi X$ production that was used in the simulation of events for the DC04. We assume that only events as $H_b \rightarrow J/\psi X$ contribute to the computation of $b\bar{b}$ inclusive background [70]. Hence, a correction factor have to multiply the numerator in order to account for this over-estimation of inclusive $H_b \rightarrow J/\psi X$ events. The correction factor, $f_{H_b \rightarrow J/\psi X}^{prod}$, has been computed and is provided in [70]. This factor is $f_{H_b \rightarrow J/\psi X}^{prod} = 0.60 \pm 0.22$.

We use for the computation of the background level the stripped$^{13}$ sample of inclusive $b\bar{b}$ events version DC04v2r3. The total number of generated $b\bar{b}$ events used for the stripping is 33'926'781 events. This figure is to be used as $N_{b\bar{b}}^{gen}$. We expect that our selection cuts will keep a number of $b\bar{b}$ events selected very close to zero, and we know that the $N_{b\bar{b}}^{sel}$ selected should exhibit a Poisson-distributed behaviour with a certain mean close to zero. Because of this fact when constructing confidence levels for the $B/S$ we should avoid the traditional construction and use the unified approach of Feldman and Cousins [79] instead, which gives the unified confidence intervals $[\nu_1, \nu_2]$ for the mean of a Poisson variable given $N_{b\bar{b}}^{sel}$ observed events in the absence of any other source of background, for different confidence level values. We will use the 90% confidence level interval here below. From the obtained Feldman and Cousins interval we can hence compute the 90% confidence level corresponding to the background-over-signal ratio by simply substituting each of the values in the amended formula.

We will only quote figures corresponding to the background-over-signal ratios before any trigger since it is assumed that the trigger affect in the same fashion both to signal and background events, leaving the ratio equal. The computation of the ratio after trigger is avoided because of the lack of statistics that will render its computation a bad estimate due to the large statistical errors. See formula (5.6) above. Our F factor will be $\sim 6$ as we pass from a tight window mass of 150 MeV/c$^2$ to a loose mass window for the $B^0_s$ candidates of 1000 MeV/c$^2$.

After running on the $b\bar{b}$ inclusive sample none of the events were selected, hence, $N_{b\bar{b}}^{sel} = 0$. The 90% confidence level interval obtained for the background level is $B/S = [0, 1.1]$. See table (5.10).

5.9.2 Prompt $J/\psi$ background

The number of prompt $J/\psi$ produced is large, however, those events are characterised by a small flight distance. Hence, as a Flight distance cut is demanded to the $B^0_s$ candidates

$^{13}$The stripped data sample is a reduced DST file that only contains events which have passed some loose cuts, say, in our case, that pre-select the $J/\psi$ meson candidates.
<table>
<thead>
<tr>
<th>Decays</th>
<th>$\theta_p = -15^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No trigger</td>
<td></td>
</tr>
</tbody>
</table>

| $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta (\pi^+ \pi^- \eta (\gamma \gamma))$ | [0.0, 1.14] |

Table 5.10: 90% confidence level interval of the inclusive $b\bar{b}$ background to signal level, before any triggers.

(FDS $> 4$), prompt $J/\psi$ events are expected not to be selected. This was confirmed by a previous selection analysis (based on DAVinci object oriented programming) in which we used DC03 data corresponding to those prompt events and none of them passed the cuts.

We refer to the thesis dissertation of Benjamin Carron who has studied a similar channel as ours ($B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta (\pi^+ \pi^- \pi^0)$) [70].
5.10 Full Monte Carlo Simulation: Results breakdown

In this last section, we summarise the main results obtained after the reconstruction and selection of the $B_s^0 \rightarrow J/\psi \eta'$ decay channel, from which, we could determine the figures that we will use in the next Chapter, where we will take these results as parameters of some Fast Toy Monte Carlo simulations that will serve us to estimate our sensitivity to the main physics parameters involved in the $B_s^0$-mixing. As the better estimates are given when the Kalman Filter tool is used to optimise the results, we will only quote the corresponding figures obtained from that method.

- $B_s^0$ mass resolution: $\sigma_{B_s^0} = 18.26 \pm 0.66$ MeV/c$^2$.
- Proper time resolution: $\sigma_{\delta\tau} = 32.59 \pm 0.95$ fs
- Per-event proper time error and Scale factor: A mean value of 24.1 fs is found for the lifetime error distribution. The Scale Factor given by the standard deviation of the proper time pull distribution and which correct the error estimation is equal to 1.37.
- Acceptance Slope: the value of $acc_s$ resulting from the fit of the acceptance function is equal to $acc_s = (1.98 \pm 0.10)$ ps$^{-1}$, when the events have passed any of the trigger levels.
- Tagging performance: $\varepsilon_{tag} = 64\%$, $\omega_{tag} = 31\%$, $\varepsilon_{eff} = 9.5\%$

Below it is added a summary of the yields and efficiencies that are obtained for our channel decay:

<table>
<thead>
<tr>
<th>$\theta_p$</th>
<th>$\varepsilon_{det}$</th>
<th>$\varepsilon_{rec/det}$</th>
<th>$\varepsilon_{sel/rec}$</th>
<th>$\varepsilon_{tot}$</th>
<th>$\varepsilon_{HLT/sel}$</th>
<th>B.R$_{vis} (10^{-6})$</th>
<th>A.yield</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-20$^\circ$]</td>
<td>6.2 %</td>
<td>78.5 %</td>
<td>4.6 %</td>
<td>0.2 %</td>
<td>85.3 %</td>
<td>6.8</td>
<td>2.57 k</td>
<td>$\leq 1.0$</td>
</tr>
<tr>
<td>[-10$^\circ$]</td>
<td>5.1</td>
<td>19.2 k</td>
<td>$\leq 1.3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.11: **Summary of efficiencies and yields obtained after selection for our channel decay.**
Appendix to Chapter 5

5.A Kalman Filter Fit DaVinci Tool

5.A.1 Outline of the steps followed by the tool for the $B^0_s \to J/\psi \eta'$ case

These are the main steps followed by the Kalman Filter Fit DaVinci tool when analysing the selected $B^0_s \to J/\psi \eta'$ candidate event [80]:

- Construct a combined $\pi^+ \pi^-$ vertex from the available pions of the decay.
- Get calorimeter information for two gammas $\gamma_1 = (x_1, y_1, E_1)$ and $\gamma_2 = (x_2, y_2, E_2)$ at the respective z positions $z_1$, $z_2$.
- Construct a measurement vector including the $(\pi^+, \pi^-)$ vertex measurement and the photon measurements, i.e.: $\mathbf{V}_{\text{meas}}(13 \times 1) = (V_x, V_y, V_z, P_x, P_y, P_z, x_1, y_1, E_1, x_2, y_2, E_2)$ with its respective full covariance matrix, $C_{\text{meas}}(13 \times 13)$.
- Estimate the momentum for each photon using the $(\pi^+, \pi^-)$ vertex.
- Construct a state vector for the $\psi'$ candidate of dimension 8, i.e.: $\mathbf{V}_{\psi'}(8 \times 1) = (v_x, v_y, v_z, p_x, p_y, p_z, E, m_{\psi'})$.
- Construct the Jacobian transformation matrix between the measurements and the state vector, $\mathbf{V}_{\text{meas}} \Rightarrow \mathbf{V}_{\psi'}$ given by $J_1(8 \times 13)$.
- Compute the new covariance matrix for the state vector $\psi'$ given by: $C_{\psi'} = J_1 C_{\text{meas}} J_1^T$.
- Apply a mass constrain fit for the $\eta$ mass, so a shift of the $m_{\eta}$ is expected and hence the covariance matrix of the $\eta$ candidate, $C_{\eta}$, is adjusted accordingly.
- Drop the $m_{\eta}$ mass from the state vector $\mathbf{V}_{\psi'}$ as well as in the corresponding covariance matrix, $C_{\psi'}$. The resulting vector is the state vector to be used for the analysis that define the $\psi'$ particle.
- Make $J/\psi$ vertex using the $\mu^+$ and $\mu^-$ from the decay chain.
- Mass constrains are also applied to the non-resonances particle, namely, both $J/\psi$ and $\psi'$ particles.
- Merge both $J/\psi$ and $\psi'$ vertices to define the one of the $B^0_s$ meson particle. The 4-momentum vector and the corresponding error matrix are computed from the two decay particles.
Chapter 6

Sensitivity to $\phi_s$ in LHCb

This chapter describes the toy Monte Carlo that has been constructed in order to estimate the statistical sensitivity to $\phi_s$ expected in the LHCb for decays through $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ quark transitions. From this Monte Carlo simulation, other mixing parameters will be also extracted. The physics models describing those transitions both to pure and to an admixture of CP are included. Results for the $B_s^0 \rightarrow J/\psi \phi$ decay mode will be given and discussed at the end of the chapter. Other $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ transitions to pure and to admixture of CP eigenstates are also considered.

6.1 Monte Carlo Fast Toys

The events generated previously for selection purposes simulate fully the LHCb spectrometer. They amount only to a few signal and background events and do not have any information about the physics to which we want to be sensitive. Hence in order to extract the physics parameters and the sensitivity that we could reach in measuring them we have made use of the so-called Toy Monte Carlo simulations. Toy Monte Carlo is fast because it takes as inputs the physics parameters obtained from the Full Monte Carlo analyses. The physics is also modelled within the Toys for those generated events: an extended likelihood function is constructed that will model the foreseen signal and background events from which a fit to the likelihood of all the events will extract the physics parameters and their errors.

The generation of fast Monte Carlo events is performed by the toolkit for data modelling RooFit\(^1\) [81], which uses MINUIT\(^2\) [82] for the fitting part. ROOT\(^2\) [83] is integrated together with the RooFit package for the data analysis.

Toy Events will be generated according to the B/S ratio. For each event, a series of random observables will be available. In the case of CP even decays, those are the mass of the $B_s^0$ mesons, their proper time and the error in that measurement. The cosine of the "transversity angle" will be another observable for the Golden-plated channel $B_s^0 \rightarrow J/\psi \phi$ [84]. The probability density function will also take into account both the wrong tag probabilities and any resolution effect for the observables. The acceptance function is also implemented as a selection bias on the proper time of our events.

\(^1\)The version of RooFit used for these studies is v2.03 which have been modified to fulfill the $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ decays requirements.

\(^2\)ROOT v 4.02.
We will generate the expected signal events with the corresponding computed background events. Those events will be generated in a Poisson-like distribution having as a mean the number of events given by the untagged annual yield. Each of these series of events will constitute a "experiment" and about 250 experiment will be produce for the sensitivities studies. Each of the experiments corresponds to a year of data taking that amounts to $2 \text{ fb}^{-1}$.

In order to have a better estimate of the wrong-tag fraction and the $B_s^0$ oscillation parameter $\Delta M_{B_s}$, we will use the control channel $B_s^0 \to D_s \pi$, which shows similar wrong-tag fraction and tagging efficiencies as ours.

### 6.2 Extended Likelihood description

In this section we are going to have a closer look to the general likelihood function that will describe the generation of events and will serve to extract from a fit the physics parameters that are of our interest. This total likelihood function is an extended likelihood [85] that takes into account the proportion of signal and background events distributed in a Poisson-like fashion. It runs over all the events generated both for signal and background and can be written as follows:

$$
L_{tot} = \frac{(N_{\text{sig}} + N_{\text{bkg}})N_{\text{obs}}}{N_{\text{obs}}!} e^{-(N_{\text{sig}} + N_{\text{bkg}})} \prod_{i \in B^0_s \to f} L_i (m_i, t_i, (\theta_{\text{Tri}}), \sigma_{t_i^{\text{rec}}, q_i})
$$

where $N_{\text{obs}}$ is the total number of observed events in the data sample (Poisson distributed). $N_{\text{sig}}$ and $N_{\text{bkg}}$ are the signal and background events expected by the model. The total likelihood function is made up of signal and background events so it can be decomposed in two likelihoods corresponding to the signal and background.

$$
L_i(m_i, t_i, (\theta_{\text{Tri}}), \sigma_{t_i^{\text{rec}}, q_i}) = f_{\text{sig}} L_{m_i}^{\text{sig}} (m_i, t_i^{\text{rec}}, (\theta_{\text{Tri}}), \sigma_{t_i^{\text{rec}}, q_i}) + f_{\text{bkg}} L_{m_i}^{\text{bkg}} (m_i, t_i^{\text{rec}}, (\theta_{\text{Tri}}), \sigma_{t_i^{\text{rec}}, q_i})
$$

(6.1)

It is characterised by three observables, namely, mass ($m_i$) and proper time ($t_i^{\text{rec}}$) of the $B^0_s$ mesons candidates as well as the transversity angle ($\theta_{\text{Tri}}$) in the case of the $B^0_s \to J/\psi \phi$ channel where an angular analysis is required to discern CP-even from CP-odd components. Those observables will be modelled afterwards as individual likelihood functions but now we rather will comment on some concerns for each of them.

The $B_s$ mass observable indicates us if a certain event is signal or rather a background one. We will define three distinct regions within the mass distribution that will serve us to establish the probability of an event to be signal or background:

1. **The total mass region** ($\delta m_{\text{tot}}$) establishes the mass region where any event can be generated. Defined as $M_{B^0_s} \pm \delta m_{\text{tot}}$ where $M_{B^0_s}$ is the nominal $B^0_s$ mass used in the generation and $\delta m_{\text{tot}}$ is the mass window that for our study has been defined to be $200\text{MeV/c}^2$.

2. **The signal mass region** ($m_{\text{sig}}$) where signal events lie and that serves us to compute the B/S ratio and from that region also extract the physics parameters that we search. We define it as $|m_i - M_{B^0_s}| < 60\text{MeV/c}^2$.
3. The sideband mass regions \((m_{\text{side}})\) this region defines background events; it will allow us to characterize the background and it will also let us fit the acceptance function under the hypothesis that our acceptance function is the same for both background and signal events. For our analysis we will use \(|m_i - M_{B^0_s}| > 80\text{MeV}/c^2\).

**Proper time** The signal events are assigned a proper time uncertainty given by the error distribution obtained from the proper time fit in the full Monte Carlo. Both for the signal and control decay. As shown below, the decay rates will also take into account other realistic features as the wrong-tag fraction, the proper time resolution and the proper time acceptance function given in the previous chapter.

**Transversity angle** \(\theta_{Tr}\) This observable is only available for \(B_s^0 \rightarrow J/\psi \phi\). The generated distribution will be a function of \(\cos \theta_{Tr}\)

### 6.2.1 Description of the Mass Model

The pdf describing the \(B_s^0\) signal events for the toy MC will be a Gaussian \((G)\) which takes as parameters the generated mass and the mass resolution obtained in the selection of events after being refitted by the Kalman Filter. It has been checked that an exponential pdf might define properly the background within the total mass region \((\delta m_{\text{tot}})\).

Thereby, the following likelihoods are constructed:

\[
\begin{align*}
\mathcal{L}_{m}^{\text{sig}}(m_i; m_{B^0_s}, \sigma_{B^0_s}) & \propto G(m_i; m_{B^0_s}, \sigma_{B^0_s}), \\
\mathcal{L}_{m}^{\text{bkg}}(m_i; \kappa_{\text{bkg}}) & \propto E(m_i; \kappa_{\text{bkg}}),
\end{align*}
\]  

(6.2)

where:

\[
\begin{align*}
G(m_i; m_{B^0_s}, \sigma_{B^0_s}) & = \exp \left( -\frac{1}{2} \left( \frac{m_i - m_{B^0_s}}{\sigma_{B^0_s}} \right)^2 \right), \\
E(m_i; \kappa_{\text{bkg}}) & = \exp \left( \kappa_{\text{bkg}} m_i \right).
\end{align*}
\]  

(6.3)

The reconstructed mass for the \(i\) experiment being \(m_i\) and the parameters extracted from the full simulation being:

- \(m_{B^0_s}\) 5.3696 GeV/c\(^2\) the nominal mass of the \(B_s^0\) used in the simulation;
- \(\sigma_{B^0_s}\) stands for the \(B\)-mass resolution achieved by the LHCb experiment.

In the case of the background, \(\kappa_{\text{bkg}}\) defines the slope of the exponential. With real data we might need to redefine any other function which better fits the background pdf. But based on the full Monte Carlo samples we will use a constant value, \(\kappa_{\text{bkg}} = 1(\text{MeV}/c^2)^{-1}\). The extended likelihood ensures the correct proportion of B/S ratio within the signal region \((m_{\text{sig}})\):

\[
N_{\text{bkg}} = N_{\text{sig}} \times B/S \quad \text{where} \quad N_{\text{sig}} \quad \text{is given by the signal event yield and} \quad B/S \quad \text{is the ratio computed in the previous chapter.}
\]
Accordingly, the resulting signal and background extended likelihood which defines the pdf for the number of observed events $N_{\text{obs}}$ within the total region is expressed as:

$$
e^{-\left(N_{\text{sig}}+N_{\text{bkg}}\right)} \frac{N_{\text{obs}}!}{N_{\text{obs}}!} \prod_{i=0}^{N_{\text{obs}}} \left[ N_{\text{sig}} L_{\text{sig}}^{m_i} (m_i; m_{B_0}, \sigma_{B_0}) + N_{\text{bkg}} L_{\text{bkg}}^{m_i} (m_i; \kappa_{bkg}) \right]$$

The likelihoods projections onto the $B_s^0$ mass distribution of the $B_s^0 \to J/\psi \eta'$ and control channel $B_s^0 \to D_s \pi$ for a given experiment is shown in Figure (6.1). For comparison, the distributions corresponding to the $B_s^0 \to J/\psi \eta(\gamma \gamma)$ and $B_s^0 \to J/\psi \eta(\pi^+ \pi^- \pi^0)$ channel are also shown. The values used to generate them are given in Table (6.1).

Figure 6.1: Projection of the likelihood onto the mass distribution. Units in [GeV/c$^2$]. Figure (6.1(a)) shows the corresponding projection for the channel under study in this thesis. Figure (6.1(b)) shows the obtained projection for the control channel $B_s^0 \to D_s \pi$ used for the simultaneous likelihood fit. For comparison, at the bottom, the distributions resulting from the fit for the $B_s^0 \to J/\psi \eta(\gamma \gamma)$ and $B_s^0 \to J/\psi \eta(\pi^+ \pi^- \pi^0)$ channels are also shown. (Fig. (6.1(c)) and Fig. (6.1(d)) respectively). For all distribution plot, the dotted red line indicates the CP-even signal contribution whereas the background is given by the dashed black line. The blue solid line hence indicates the projection of both contributions.
6.2.2 Description of the Angular Model

In the case of the Golden channel\textsuperscript{5}, $B^0_s \rightarrow J/\psi \phi$ does not decay to a pure CP eigenstate, on the contrary, it decays to a final state of mixed CP where the angular analysis is needed to come out with the CP-odd and CP-even components.

The spinless $B^0_s$ decays to two pseudo-vectors with $J^{PC} = 1^{--}$. Total spin conservation implies hence that the final states have in the $J/\psi$ rest frame relative orbital angular momentum states of $l = 0, 1, 2$. Therefore, the possible CP-eigenvalues for the final states are given by $\text{CP}(J/\psi) = \text{CP}(J/\psi) \times \text{CP}(\phi) \times (-1)^l = \{+1, -1, +1\}$. Hence, the final state is a admixture of CP-even and CP-odd components as already said above. It is therefore needed for the sensitivity study a separation of those different CP eigenstates. Following [86, 87], we see that the decay amplitude for this channel can be expressed in terms of linear polarization states of the $J/\psi$ and $\phi$ vector mesons. The amplitude is therefore decomposed in three different parts corresponding to the CP-even and CP-odd components. They are, the linear polarization amplitudes $A_0(t), A_{\parallel}(t)$ (CP-even), and $A_{\perp}(t)$ (CP-odd). The final state rate is hence given in terms of these three normalized amplitudes as:

$$\Gamma(t) \propto |A_0(t)|^2 + |A_{\parallel}(t)|^2 + |A_{\perp}(t)|^2$$ \hspace{1cm} (6.4)

The time evolution of these amplitudes, is that resulting from the decay rates for a pure CP eigenstates $b \rightarrow \bar{c}c\bar{s}$ transition, (either CP-even or odd). Assuming a tagging procedure (with a dilution factor $D$) and perfect resolution, we have then:

$$|A_{\{0,\parallel\}}(t)|^2 = |A_{\{0,\parallel\}}|^2 \cdot e^{-\Gamma_{st}t} \times \left\{ \cosh\left(\frac{\Delta \Gamma_{st}}{2}\right) - \cos(\phi_s) \sinh\left(\frac{\Delta \Gamma_{st}}{2}\right) + D \sin(\phi_s) \sin(\Delta m_{st}) \right\},$$

$$|A_{\perp}(t)|^2 = |A_{\perp}|^2 \cdot e^{-\Gamma_{st}t} \times \left\{ \cosh\left(\frac{\Delta \Gamma_{st}}{2}\right) + \cos(\phi_s) \sinh\left(\frac{\Delta \Gamma_{st}}{2}\right) - D \sin(\phi_s) \sin(\Delta m_{st}) \right\}. $$

Analytical rates are obtained from these expressions by simply setting $\omega_{\text{tag}} = 0$ in the dilution factor $D = (1 - 2\omega_{\text{tag}})$. Likewise, decay rates corresponding to the CP transformation of $B^0_s$ are defined.

In order to ease the angular analysis of this channel decay, the transversity basis [73] is defined, that make use of the direction of the momenta of the final states to define three independent physical angles. The three-angle distribution arising from this basis makes it a complicated expression, so that a likelihood fit to the full three-angle distribution turns out to be a very difficult task. The analysis is considerably simplified if we integrate two of the angles and leave intact the so-called transversity angle ($\theta_{\text{Tr}}$). A loss of sensitivity is assumed but the fit is then easily performed. This simplification is only possible if the acceptance over those angles is flat.

This $\theta_{\text{Tr}}$ angle is defined as the angle between the positive charged lepton and the vector which defines the $\phi$ decay plane, in the $J/\psi$ rest frame, as shown on Fig. (6.2).

The angular differential one-angle distribution is then given by [87, 88]:

$$\frac{d\Gamma(t)}{d(\cos(\theta_{\text{Tr}}))} \propto \left[ |A_0(t)|^2 + |A_{\parallel}(t)|^2 \right] \frac{3}{8} (1 + \cos^2 \theta_{\text{Tr}}) + |A_{\perp}(t)|^2 \frac{3}{4} \sin^2 \theta_{\text{Tr}}.$$ \hspace{1cm} (6.5)

\textsuperscript{5}It is denominated Golden channel because of its relatively larger branching ratio compared to the CP-even modes.
Figure 6.2: Definition of the transversity angle $\theta_{\text{tr}}$ in the rest frame of the $J/\psi$, in the $B_s^0 \rightarrow J/\psi(\ell^+\ell^-) \phi(K^+K^-)$ decay. Picture taken from [84].

With the help of this one-angle distribution, the observables $|A_0(t)|^2$, $|A_{\parallel}(t)|^2$ and $|A_{\perp}(t)|^2$, as well as their CP conjugates, can be determined.

Thereby, the likelihoods for each of the signal and background components can be written in terms of the $\cos \theta_{\text{tr}}$ as follows:

$$
L_{\text{sig,even}}^{\text{even}}(\theta_{\text{tr}}) \propto \frac{(1 + \cos \theta_{\text{tr}}^2)}{2},
$$

$$
L_{\text{sig,odd}}^{\text{odd}}(\theta_{\text{tr}}) \propto (1 - \cos \theta_{\text{tr}}^2),
$$

$$
L_{\text{bkg}}^{\text{bkg}}(\theta_{\text{tr}}) \propto (1 + \alpha_{\text{bkg}} \cos \theta_{\text{tr}}^2),
$$

(6.6)

The background is assumed to be flat which leads to a $\alpha_{\text{bkg}}$ nominal value of zero.

The effect of the resolution in $\theta_{\text{tr}}$ will be introduced in the generation of the fast Monte Carlo toys by smearing the $\theta_{\text{tr}}$ distribution with a Normal Gaussian variable times a constant factor of 20mrad. However, the likelihoods used in the fit will neglect that resolution effect as we expect small variations in the $\theta_{\text{tr}}$ distribution compared to the resolution.

The relative amount of CP-even and CP-odd will be controlled by the introduction of the $R_T$ observable, which is just the fraction of CP odd amplitude with respect to the total. Hence we can define $R_T$ as:

$$
R_T \equiv \frac{|A_{\perp}(0)|^2}{\sum_{f=0,\parallel,\perp} |A_f(0)|^2}.
$$

The fraction have been estimated in [89] by CDF collaboration to be $R_T = (0.2 \pm 0.1)$. When introduced in front of the $\sin(\phi_s)$ will also act as a dilution term. The effect of $R_T$

---

6The resolution for $\theta_{\text{tr}}$ is obtained from the rms of the residual of $\theta_{\text{tr}}$ distribution ($\theta_{\text{tr}}^{\text{res}} - \theta_{\text{tr}}^{\text{true}}$) observed in the full Monte Carlo simulation studied in [84]. A similar study have been performed in [73] yielding a rms of about 25mrad at the generator level.
dilution is clearly seen in Figure 6.4(b) where the observed decay rates for the $B^0_s \rightarrow J/\psi \phi$ channel are compared to the expected rates for a $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ pure CP channel. For a realistic case, it has been introduced both an acceptance function and a proper time Gaussian resolution for those decay rates. In order to make visible the oscillation wiggles a five times the SM $\phi_s$ value has been used for the plots. In the case, of the CP admixture channel the odd component has been fixed to $R_T = 0.2$. Ones can see from the comparison of both plots that the $R_T$ has the effect of reducing the amplitude of the wiggles, i.e., introduce a dilution term.

Figure 6.3: Projection of the likelihood onto the mass distribution for the $B^0_s \rightarrow J/\psi \phi$ [Left]. Units in [GeV/c$^2$]. Figure (6.3(a)) shows such a projection for the channel to an admixture of CP. Figure (6.3(b)) [Right], shows on the other hand the projection of the likelihood onto the $\cos \theta_{TR}$ distribution for that $B^0_s \rightarrow J/\psi \phi$ channel. The dotted red line indicates the CP-even signal contribution whereas the dashed-dotted red line indicates the CP-odd one. The flat background is given by the dashed black line. Hence, the blue solid line indicates the projection of all contributions.

Figure 6.4: Signal decay rates for a $\bar{b} \rightarrow \bar{c}\bar{c}\bar{s}$ quark transition to pure CP-even eigenstates (Left) and for a transition to an admixture of CP (Right). Units in [ps]. All disturbing effects of proper time resolution, proper time acceptance as well as wrong-tag inefficiency are included. The mixing phase $\phi_s$ used is a five times larger value than that expected from the SM. The fraction of CP-odd decays $R_T$ used in the case of CP admixture decays is 20%.
6.2.3 Description of the Proper Time Model

In the following we will describe the likelihoods modelling the proper time to be used in the Toy Monte Carlo, both for any signal or background events. Signal likelihood is decomposed in two pdf's, whether the final state is CP-even or CP-odd. If we recall the expressions given in section 1.41 governing the decay rates of a \( \bar{b} \rightarrow \bar{c}c\bar{s} \) transition, we can here introduce the observed decay rates which take into account the effect of flavour tagging. As we have already seen in Section (4.4), the wrong-tag fraction \( \omega_{\text{tag}} \) leads to a dilution of the observed CP asymmetry by a factor \( D = (1 - 2 \cdot \omega_{\text{tag}}) \) through the \( \sin (\phi_s) \) (see Equation 1.42). The observed decay rates are hence defined as:

\[
R (\text{B}_s^0 (t) \rightarrow f) = (1 - \omega_{\text{tag}}) \Gamma (\text{B}_s^0 (t) \rightarrow f) + \omega_{\text{tag}} \Gamma (\bar{\text{B}}_s^0 (t) \rightarrow f),
\]

\[
R (\bar{\text{B}}_s^0 (t) \rightarrow f) = \omega_{\text{tag}} \Gamma (\text{B}_s^0 (t) \rightarrow f) + (1 - \omega_{\text{tag}}) \Gamma (\bar{\text{B}}_s^0 (t) \rightarrow f),
\]

(6.7)

where the \( \Gamma (\text{B}_s^0 (t) \rightarrow f) \) and \( \Gamma (\bar{\text{B}}_s^0 (t) \rightarrow f) \) are the analytical decay rates defined in 1.41. We note that the observed decay rates do not consider the effect of proper time resolution for now.

Developing the above expressions in terms of the physical parameters that rule the \( \text{B}_s^0 \)-system leads to:

\[
R (\text{B}_s^0 (t) \rightarrow f) = |A_f(0)|^2 \cdot e^{-\Gamma_t} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \eta_{\text{fcp}} \cos (\phi_s) \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right. \\
\left. \quad + D \eta_{\text{fcp}} \sin (\phi_s) \sin (\Delta m_s t) \right],
\]

\[
R (\bar{\text{B}}_s^0 (t) \rightarrow f) = |A_f(0)|^2 \cdot e^{-\Gamma_t} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \eta_{\text{fcp}} \cos (\phi_s) \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right. \\
\left. \quad - D \eta_{\text{fcp}} \sin (\phi_s) \sin (\Delta m_s t) \right],
\]

(6.8)

Equation 6.8 allow us to combine the signal decay rates for our model of \( \bar{b} \rightarrow \bar{c}c\bar{s} \) transitions into a single expression, by introducing the tagging categories, \( q_i \). The tagging result can hence easily be integrated as \( q_i = \{+1, -1, 0\} \) whether the signal meson is tagged at production as a \( \text{B}_s^0, \bar{\text{B}}_s^0 \), or untagged respectively. We can hence write the following expression to define the \( b \rightarrow \bar{c}c\bar{s} \) decay rates:

\[
R_f (t^\text{true}_i, q_i; \omega_{\text{tag}}, \alpha) \propto e^{-\Gamma_t t^\text{true}_i} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t^\text{true}_i}{2} \right) - \eta_{\text{fcp}} \cos (\phi_s) \sinh \left( \frac{\Delta \Gamma_s t^\text{true}_i}{2} \right) \right. \\
\left. \quad + q_i D \eta_{\text{fcp}} \sin (\phi_s) \sin (\Delta m_s t^\text{true}_i) \right],
\]

(6.9)

where:

- \( t^\text{true}_i \) is the true proper time used for the generation of the Toy Monte Carlo event.

---

\(^7\)See selection chapter.

\(^8\)See selection chapter.
• \( \overline{\alpha} = (\Delta \Gamma_s, \Gamma_s, \phi_s, \Delta M_s) \) is the vector of physics parameters which rules the \( B_s^0 \rightarrow \overline{B}_s^0 \) mixing.

If we now consider the effect of the selection cuts on the proper time as an acceptance efficiency function as well as the proper time Gaussian resolution which convolutes with the true proper time signal rates, we can define the proper time pdf’s for the CP-even and CP-odd modes as:

\[
\mathcal{L}_{t,\text{even}}^{\text{sig}}(t_i^{\text{rec}}, \sigma_{t_i^{\text{rec}}}, q_i; \overline{\alpha}, \omega_{\text{tag}}, \text{acc}_s, S, \mu_T) \propto A(t_i^{\text{rec}}; \text{acc}_s) \times R_{\text{even}}(t_i^{\text{true}}, q_i; \omega_{\text{tag}}, \overline{\alpha}) \\
\otimes G(t_i^{\text{rec}} - t_i^{\text{true}}; \mu_T, \sigma_{t_i^{\text{rec}}}, S, \sigma_{t_i^{\text{rec}}}),
\]

\[
\mathcal{L}_{t,\text{odd}}^{\text{sig}}(t_i^{\text{rec}}, \sigma_{t_i^{\text{rec}}}, q_i; \overline{\alpha}, \omega_{\text{tag}}, \text{acc}_s, S, \mu_T) \propto A(t_i^{\text{rec}}; \text{acc}_s) \times R_{\text{odd}}(t_i^{\text{true}}, q_i; \omega_{\text{tag}}, \overline{\alpha}) \\
\otimes G(t_i^{\text{rec}} - t_i^{\text{true}}; \mu_T, \sigma_{t_i^{\text{rec}}}, S, \sigma_{t_i^{\text{rec}}}),
\]

(6.10)

where:

• \( A(t_i^{\text{rec}}; \text{acc}_s) \) is the time dependent acceptance function parameterised as a function of the reconstructed proper time \( t_i^{\text{rec}} \) in order to factorise the acceptance out of the true proper time convolution;

• \( G \) is the Gaussian resolution model which depends of the computed proper time error \( \sigma_{t_i^{\text{rec}}} \) that is multiplied by the scale factor \( S \) obtained from the proper time pull distributions described in the selection chapter in order to account for the underestimation of errors. The likelihood also accounts for any bias present in the proper distribution \( \mu_T \) which we assume to be equal to zero.

The pdf defining the background contribution is instead be parameterised by a simple exponential lifetime component to which we may also add the effect of the proper time acceptance as well as be convoluted to a simple delta resolution function to shift the exponential.

\[
\mathcal{L}_{t}^{\text{bkg}}(t_i^{\text{true}}, \tau_{\text{bkg}}, \text{acc}_s) \propto A(t_i^{\text{rec}}; \text{acc}_s) \times E(t_i^{\text{true}}; \tau_{\text{bkg}}) \otimes \delta(t_i^{\text{rec}} - t_i^{\text{true}}),
\]

(6.11)

where:

• \( E \) is the exponential modelling the background proper time where \( \tau_{\text{bkg}} = 1.0 \text{ ps}^{-1} \)

has been defined for simplicity as the decay constant.

To illustrate the behaviour of those observed signal \( \overline{b} \rightarrow \overline{c}c\overline{s} \) decay rates, we can firstly draw the analytical rates \((\Gamma(B_s^0(t) \rightarrow f))\) and \((\Gamma(\overline{B}_s^0(t) \rightarrow f))\) having the nominal SM values as inputs parameters, i.e.: \( \Delta M_s = 17.5 \text{ ps}^{-1}, \tau_s = 1/\Gamma_s = 1.45 \text{ ps}, \Delta \Gamma_s/\Gamma_s = 15\% \). In order to accentuate the oscillation wiggles we may consider a non SM value for \( \phi_s = -0.2 \text{ rad} \) which is five times larger than that expected from the SM. We will also consider the effect of proper time resolution on those rates, as well as the acceptance function. We will use the nominal values obtained from the full MC simulation selection in order to also show the expected truncated rates corresponding to our channel decay, so that they will illustrate those effects in a more realistic fashion. The wrong-tag fraction have been fixed to 31% for all the plots. Figure 6.5(a) shows the analytical rates diluted by the wrong-tag fraction as obtained from Equation 6.8. The red line indicates the rates for a initially
tagged \(B^0\) whereas the blue dashed one correspond to a initially tagged \(B^0_s\) meson. Figure 6.5(b) shows the effect of the proper time resolution. The negative tail will allow us in principle to estimate from it the proper time resolution with real data. Proper time resolution have a dilution-like effect as the proper time measurement is inaccurately determined. Figure 6.5(c) shows the effect of the proper time acceptance function alone, removing short-lived events. Figure 6.5(d) shows the effect on the observed rates of all disturbing processes being combined. We see from that plot that our proper time resolution measurement will be spoiled but the acceptance function as the negative tail is not anymore present, hence making that resolution estimation not possible.

![Graphs showing decay rates](image)

(a) Analytical decay rates for a \(\bar{b} \rightarrow \bar{c}c\bar{s}\) quark transition diluted by a wrong-tag inefficiency
(b) Decay rates showing the effect of a constant proper time Gaussian resolution
(c) Decay rates obtained when we assume a proper time acceptance function
(d) Decay rates obtained when combining the effects of proper time resolution, wrong-tag, as well as, the proper time dependent acceptance function

Figure 6.5: Signal decay rates for a \(\bar{b} \rightarrow \bar{c}c\bar{s}\) quark transition to pure CP-even eigenstates. Units in \([\text{ps}]\). The red solid line indicates the expected rates for an initially tagged \(B^0_s\) meson, whereas for an initially tagged as \(B^0\) the blue dashed line decay channel show its time dependent rate behaviour. The effect of a wrong-tag, constant proper-time resolution as well as the acceptance function are show on these plots. The nominal SM values are used for this simulation, except for the mixing phase which uses a five times larger value than that expected from the SM, as this value allow us to clearly see the oscillation wiggles.

Extracting the physics parameters from a likehood fit to the data is a very challenging task. The effect of background levels, not enough statistics as well as proper time uncertainty will make difficult the fit from which we could extract reliable physics parameters. In order to illustrate the difficulty of extracting the physics from the likelihood fit will be show
in Figure 6.6 the projections of the likelihood function onto the proper time for several channels as well as for our channel decay. We have used the nominal full MC results and the expected SM physics, as previously done, as input values for those plots. We will display on those plots both the signal projections and the background contributions. If we compare the projections obtained for initially tagged as $B^0_s$ mesons in the signal region for the decay channel $B^0_s \rightarrow J/\psi \eta'$ and $B^0 \rightarrow J/\psi \eta$ given in Figures 6.6(a) and 6.6(c), we see that the oscillations are visible for $B^0_s \rightarrow J/\psi \eta'$ but merely visible for $B^0 \rightarrow J/\psi \eta$ given in those plots as a red line. The better proper time resolution achieved from $B^0_s \rightarrow J/\psi \eta'$ is the cause from such a difference in the wiggles. Furthermore, the background (given as black dashed line) tends to flatten the total likelihood projection shown in those plots as a blue line. Specially for the $B^0 \rightarrow J/\psi \eta$ channel as the expected background is bigger than for $B^0_s \rightarrow J/\psi \eta'$. The background effect for $B^0 \rightarrow J/\psi \eta$ is compensated by the large signal yield expected for that channel [70]. On the other hand, the projection for the admixture CP case is shown in Figure 6.6(d). Even though we have to perform an angular analysis to disentangle the CP-even and CP-odd components, the large statistics expected from that decay channel will provided the best accuracy in the $\phi_s$ measurement.

(a) Projection for events initially tagged as $B^0_s$ for the $B^0_s \rightarrow J/\psi \eta'$ channel  
(b) Projection for events initially tagged as $B^0$ for the $B^0 \rightarrow J/\psi \eta'$ channel  
(c) Projection for events initially tagged as $B^0$ for the $B^0 \rightarrow J/\psi \eta$ channel  
(d) Projection for events initially tagged as $B^0_s$ for the $B^0_s \rightarrow J/\psi \phi$ channel

Figure 6.6: Projection of the likelihood onto the proper time distribution. Units in [ps]. The dotted red line is the signal CP-even contribution, and the dashed black line correspond to the background. The solid blue curve hence is the projection of the all contributions, i.e. signal plus background. In the case of the golden channel, $B^0_s \rightarrow J/\psi \phi$, the CP-odd contribution is shown as a dashed-dotted red line.
Flavour specific control channel: decay rates

The use of a control channel similar to the decay under analysis is mandatory. The effect of dilution of the wiggles expected for the proper time distributions needs to accurately be estimated. This attenuation is due to the wrong-tag fraction, $\omega_{\text{tag}}$, that must be determined with the fit using the control channel, as we will concentrate with our channel decay. It is foreseen that a large correlation exists between them. It is therefore necessary to use a flavour specific control channel to come with an estimation of the wrong-tag fraction $\omega_{\text{tag}}$ assumed to be channel-independent\textsuperscript{9}. On top of that, a channel that do not exhibit CP-violation will also allow for the determination of the oscillatory parameter $\Delta M_s$. This is necessary because the sensitivity to $\phi_s$ is larger for the term containing $\sin(\Delta M_s)$. The chosen channel for the sensitivity studies is the flavour specific $B^0_s \rightarrow D_s \pi$ decay for which a single tree diagram is expected to contribute to the decay amplitude. The proper time rates do not contain therefore CP-violating terms, so, following similar considerations as above to account for wrong-tag effects we could deduced the observed rates for the control channel as:

$$ R(B^0_s(t) \rightarrow f) = |A_f(0)|^2 \cdot e^{-\Gamma_s t^\text{true}_i} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t^\text{true}_i}{2} \right) + D \cos \left( \frac{\Delta M_s t^\text{true}_i}{2} \right) \right], $$

$$ R(B^0_s(t) \rightarrow \bar{f}) = |\bar{A}_f(0)|^2 \cdot e^{-\Gamma_s t^\text{true}_i} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t^\text{true}_i}{2} \right) - D \cos \left( \frac{\Delta M_s t^\text{true}_i}{2} \right) \right], $$

that we can again integrate as a sole expression as:

$$ R_f \left( t^\text{true}_i, r_i; \omega_{\text{tag}}, \bar{\beta} \right) \propto e^{-\Gamma_s t^\text{true}_i} \times \left[ \cosh \left( \frac{\Delta \Gamma_s t^\text{true}_i}{2} \right) + r_i D \cos \left( \frac{\Delta M_s t^\text{true}_i}{2} \right) \right], $$

(6.12)

where now:

- $r_i = \{+1, -1, 0\}$ stands for an initially $B^0_s$ candidate tagged as unmixed\textsuperscript{10}, mixed or untagged respectively.

- now the physics vector is given by $\bar{\beta} = (\Delta \Gamma_s, \Gamma_s, \Delta M_s)$.

To illustrate the behaviour of the observed $B^0_s \rightarrow D_s \pi$ decay rates, we will draw the analytical rates having the nominal SM values as inputs parameters and a fixed wrong-tag fraction of 31\% (Equations 6.12), i.e.: $\Delta M_s = 17.5$ ps$^{-1}$, $\tau_s = 1/\Gamma_s = 1.45$ ps, $\Delta \Gamma_s/\Gamma_s = 15\%$. The channel will serve us to extract both the dilution factor $D$ and $\Delta M_s$.

Figure 6.7(a) shows the analytical rates diluted by the wrong-tag fraction as obtained from Equations 6.12. The red line indicates the rates for a initially tagged $B^0_s$ whereas the blue dashed one correspond to a initially tagged $\bar{B}^0_s$ meson. The effect of introducing a proper time resolution is exhibit in Figure 6.7(b). On the other hand, an acceptance function will modify the initial observed rates as shown in Figure 6.7(c). Finally, Figure 6.7(d) shows the effect on the observed rates arising when combining all disturbing processes.

\textsuperscript{9}The selection cuts for each channel will provoke inevitably a systematic effect, since cuts act on each channel separately

\textsuperscript{10}When the candidate does not have changed its flavour compared to the production flavour.
These decay rates will allow us to determine accurately the oscillation frequency, $\Delta M$, the proper time $\tau_{B^0_s}$ and the decay width difference for the $B^0_s$ mesons, so that it can be simultaneously used in the fit helping in the determination of the wrong-tag fraction of our channel decay.

Figure 6.7: Signal decay rates for the $B^0_s \to D_s \pi$ decay channel. Units in [ps]. The red solid line indicates the expected rates for an initially tagged $B^0_s$ meson, whereas for an initially tagged as $B^0_s$ the blue dashed line decay channel show its time dependent rate behaviour. The effect of a wrong-tag, constant proper-time resolution as well as the acceptance function are shown on these plots. The nominal SM values are used for this simulation.

### 6.3 Fit Strategy

If we want that the simultaneous fit converges we need to adopt a strategy which simplifies the global fit. The method used to achieve such a goal is to divide the fit procedure in several independent fits, after each some variables are fixed and hence used to find out the remaining ones. The large number of variables to be fitted within the likelihood as well as the considerable number of events for each simulated experiment let us as a sole possibility the following approach. The likelihood fit is performed in three distinct
steps successively for each of the distributions of the observables, namely, the mass \( m_i \) distribution, the transversity angle, \( \theta_{Tri} \), in the case of the angular analysis sample, and the proper time distribution, \( t_i^{rec} \). We will now enumerate and briefly describe the three steps followed by the Fast Toy Monte Carlo in order to come up with the estimates of the physics vectors for each of the generated experiments.

1. **Mass distributions fit** For each sample (\( \bar{b} \to \bar{c}c\bar{s} \) and control samples) the mass distribution is fitted for the whole mass range, i.e., the total mass window, \( \delta m_{tot} \). From that fit we can extract the signal and background probabilities for each of them. The only parameters let free in the likelihood fit are:
   - \( N_{\text{sig}} \)
   - \( B/S \)
   - \( M_{B_i^0} \)
   - \( \sigma_{B_i^0} \)
   - \( \kappa_{\text{bkg}} \)

   After fitting those parameters, they will be kept constants for the next fitting stage.

2. **Sidebands fit** In this second stage we want to determine the parameters that parameter the background behaviour. We are specifically interested in the low proper time slope that defines our acceptance model (\( \text{acc}_s \)) and also on the decay time constant (\( \tau_{\text{bkg}} \)). The parameter \( \text{acc}_s \) is assumed to be the same for the Fast Toy Monte Carlo since the background model let us to consider that the acceptance function adds in the same fashion for both the signal and background events. To achieve this goal, we will only consider the events present in the sidebands. We expect thus a similar background behaviour within the signal region. The paramater that are let free in this stage are, for all the said above, \( \tau_{\text{bkg}}, \text{acc}_s \). In the case of the Golden Channel, where the angular model is present, we will fit \( \alpha_{\text{bkg}}, \text{acc}_s \) instead. As in the previous step, all these fitted parameters are assumed to be constants for the next fitting stage.

3. **Signal window fit** The last stage, search the extraction of the physics vectors, from the signal region. Hence, any previously determined parameter is fixed for this last step, leaving only as free parameters, \( \Delta \Gamma_s, \tau_s = 1/\Gamma_s, \Delta M_s, \phi_s \). For non-pure eigenstates \( R_T \) is also let it free. Considering all the above, the only parameters to be determined uniquely by the \( \bar{b} \to \bar{c}c\bar{s} \) channels are hence, \( \phi_s, R_T \).

### 6.4 Toy Monte Carlo: Input and Results

We have seen in the previous section the strategy to follow for the likelihood fit. In this section, will be shown the distributions for each of the physics parameters, obtained for our channel decay. The nominal physics parameters taken as Standard Model values are the following:

- \( M_{B_i^0} = 5369.6 \) MeV/c\(^2 \);
- \( \Delta M_s = 17.5 \) ps\(^{-1} \);
6.4. TOY MONTE CARLO: INPUT AND RESULTS

- $\phi_s = -0.04$ rad;
- $\Delta \Gamma_s / \Gamma_s = 0.15$;
- $\tau_s = 1 / \Gamma_s = 1.45$ ps.

The performance for decay channel under study extracted from the full Monte Carlo simulation will be used as input to the Toy Monte Carlo. Recall Section 5.10. Check for the used values in Table 6.1. The results arising from the fit of about 250 generated Toy Monte Carlo experiments are shown in Figures 6.8 and 6.9, and will be hereafter be commented. It is worth noting here that the Toy Monte Carlo algorithm is constructed as to obtain a reliable calibration from which our only knowledge in the real experiment of the error distribution will allow to have the statistical uncertainty of the foreseen measurement. Hence, attention needs to be paid on how well errors of the physics parameters are estimated. Since some of the error distributions do not properly define the uncertainty of the measurement even when they are corrected by a certain scale factor given by the pull of the parameter, we will quote the sensitivity to each of the physics parameters as the rms of the central values, and not as given by the mean of the error distribution as desired in the real experiment.

In each of the columns of those figures are shown successively from the top to the bottom the following outcomes:

- the output from the likelihood fit for that physics parameter,
- the estimated error on that measurement,
- the pull distribution obtained as the error normalised residual,
- and the global correlation coefficient\(^{11}\).

From the obtained distributions for each of the physics parameters we can highlight the following facts:

- Looking at the pull distribution of $\phi_s$, we check that its sigma value is close to one, as expected, but the obtained value seems to indicate an overestimation of the errors in $\phi_s$ by $\sim 11\%$. The mean value for the $\phi_s$ error distribution matches the rms of the fit outputs so a description of the sensitivity given by this parameters seems suitable. No significant bias is present for the fitted values. As both $\phi_s$ and $\omega_{tag}$ modulate the $B_0^0$-system oscillation, some correlation effect is expected for those parameters, but, the global correlation coefficient indicates not significant correlation for that measurement.

- The parameters $\Delta \Gamma_s / \Gamma_s$ and $\tau_s = 1 / \Gamma_s$ are strongly correlated as expected from their definitions. The global correlation coefficients for those indicates such an effect. The mean of the fit output on both distributions shows a large bias. This might be explained by a lack of statistics. This effect should be less predominant when

\(^{11}\)The global correlation coefficient is defined as: $\rho_i = \sqrt{1 - \frac{1}{(V^{-1})_{ii} (V^{-1})_{ii}}}$, $0 \leq \rho_i \leq 1$, where $(V^{-1})_{ii}$ are the diagonal elements of the covariance matrix and its inverse respectively. This $\rho_i$ coefficient is a measure of the largest correlation between the $i$-th variable $x_i$ and every possible linear combination of all the other variables.
increasing significantly the stored data. The bias is clearly visible from the non-centered at zero pull distributions. The errors for $\Delta \Gamma_s/\Gamma_s$ are over-estimated by $\sim 50\%$ as seen from its pull distribution. On the other hand, an under-estimation of $\sim 15\%$ is present for $1/\Gamma_s$. It is also worth noting here that with real data, a simultaneous fit with all pure CP eigenstates channels will be carried out, so the bias issue should not be a major problem.

- The other parameters, namely, $\Delta M_s$ and $\omega_{\text{tag}}$, are completely determined by the control channel. This fact is confirmed by the figures obtained for our channel decay as they are in very close agreement with the ones obtained if only the control channel was used to determine those parameters.

For a certain vector of measurements $\vec{x}$ we may define the correlation matrix as:

$$\rho_{ij} = \frac{(V)_{ij}}{\sigma(x_i)\sigma(x_j)}, -1 \leq \rho_{ij} \leq 1$$  \hspace{1cm} (6.13)

where $(V)_{ij}$ stands for the covariance matrix defined by:

$$(V)_{ij} = E[x_i x_j] - E[x_i]E[x_j]$$  \hspace{1cm} (6.14)

being $E[x_i]$ the expectation value for the measurement $x_i$.

The correlation matrix $(\rho)_{ij}$ obtained for the physics parameters vector given at Equation 6.15 and corresponding to the fit of the $B_s^0 \rightarrow J/\psi \eta'$ channel and the control channel is shown in Equation 6.16. It is obtained at the last step of the minimisation fit for all the generated experiments using the nominal parameters in the simulation.

$$\vec{x} = \left( \frac{\Delta \Gamma_s}{\Gamma_s}, \frac{\Delta M_s}{\Gamma_s}, \phi_s, \tau_s = \frac{1}{\Gamma_s}, \omega_{\text{tag}} \right)$$  \hspace{1cm} (6.15)

$$(\rho)_{ij} = \begin{pmatrix}
1.000 & 0.001 & -0.031 & -0.134 & -0.022 \\
0.001 & 1.000 & -0.006 & -0.002 & -0.005 \\
-0.031 & -0.006 & 1.000 & 0.004 & 0.027 \\
-0.134 & -0.002 & 0.004 & 1.000 & -0.003 \\
-0.022 & -0.005 & 0.027 & -0.003 & 1.000
\end{pmatrix}$$  \hspace{1cm} (6.16)

We can check from this correlation matrix that $\Delta \Gamma_s/\Gamma_s$ and $\tau_s = 1/\Gamma_s$ are the most anti-correlated as expected from their definitions. There exists also a small correlation between the $\phi_s$ and $\omega_{\text{tag}}$ as they contribute in the same fashion as a dilution effect for the observed rates. $\phi_s$ and $\omega_{\text{tag}}$ exhibits also a small anticorrelation to $\Delta \Gamma_s/\Gamma_s$.

### 6.4.1 Combined sensitivity to $\phi_s$

Let us now to combine the sensitivity to $\phi_s$ for our channel mode with the measurements obtained from other different channels\textsuperscript{12}, including the one for the Golden channel $B_s^0 \rightarrow
Figure 6.8: Outputs from the likelihood fit for the $B_s^0 \to J/\psi \, \eta'$ mode. From the left to the right each column shows outputs for the physics parameters $\phi_s$, $\Delta \Gamma_s/\Gamma_s$, and $\tau_s = 1/\Gamma_s$ respectively. From top to bottom rows, the outputs regarded are: the fitted output, the error estimated by the fit, the pull distribution and the global correlation coefficient.
Figure 6.9: Outputs from the likelihood fit for the $B_s^0 \rightarrow J/\psi \eta'$ mode. The left column shows outputs for the physics parameter $\Delta M_s$ whereas the right column shows the outputs for $\omega_{\text{tag}}$. From top to bottom rows, the outputs regarded are: the fitted output, the error estimated by the fit, the pull distribution and the global correlation coefficient.
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Table 6.1: Inputs from the full MC used in the toys MC toys to extract the sensitivity to the physics parameters for the channel under study (last column) together with performances of similar pure CP channels as well as the channel with admixture of CP eigenstates. The control sample performances are also included.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$J/\psi \eta(\gamma\gamma)$</th>
<th>$J/\psi \eta(\pi^+\pi^-\pi^0)$</th>
<th>$D_s D_s$</th>
<th>$\eta_c \phi$</th>
<th>$J/\psi \phi$</th>
<th>$D_s \pi$</th>
<th>$J/\psi \eta'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{sig}$ [k events]</td>
<td>8.5</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>131</td>
<td>120</td>
<td>2.2</td>
</tr>
<tr>
<td>$B/S$</td>
<td>2.0</td>
<td>3.0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.12</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sigma_{B^0_s}$ [MeV/c²]</td>
<td>34</td>
<td>20</td>
<td>6</td>
<td>12</td>
<td>14</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>$acc_s$ [ps⁻¹]</td>
<td>1.86</td>
<td>1.54</td>
<td>1.6</td>
<td>1.25</td>
<td>2.81</td>
<td>1.36</td>
<td>1.98</td>
</tr>
<tr>
<td>$&lt;\sigma_{\text{Frec}}&gt;_{[fs]}$</td>
<td>30.4</td>
<td>25.5</td>
<td>44.4</td>
<td>26.2</td>
<td>29.5</td>
<td>32.9</td>
<td>24.1</td>
</tr>
<tr>
<td>Scale Factor</td>
<td>1.2</td>
<td>1.32</td>
<td>1.26</td>
<td>1.26</td>
<td>1.22</td>
<td>1.21</td>
<td>1.4</td>
</tr>
<tr>
<td>$\omega_{\text{tag}}$ [%]</td>
<td>35</td>
<td>30</td>
<td>34</td>
<td>31</td>
<td>33</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tag}}$ [%]</td>
<td>63</td>
<td>62</td>
<td>57</td>
<td>66</td>
<td>57</td>
<td>63</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 6.2: Combined $\phi_s$ sensitivity for the $\bar{b} \rightarrow c\bar{c}\bar{s}$ decays into CP eigenstates with and without the $B^0_s \rightarrow J/\psi \phi$.

The combined sensitivity for all these decay modes is hence given by:

$$\sigma_{\text{stat}}(\phi_s) = \frac{1}{\sqrt{\sum_i \frac{1}{\sigma_i^2}},} \quad (6.17)$$

where $\sigma_i$ correspond to the sensitivity for the channel $i$. The resulting weight for each channel is indicated by the rightmost column and is computed by $(\sigma/\sigma_i)^2$.

As expected the best sensitivity to $\phi_s$ is obtained for the Golden decay mode, as its statistics is much larger than for the pure CP modes. Among those CP modes, $B^0_s \rightarrow \eta_c \phi$ is
by far the best, because of better proper time and mass resolutions. Although the proper
time resolution for the $B^0_s \to J/\psi \eta (\pi^+ \pi^- \pi^0)$ and $B^0_s \to J/\psi \eta' (\pi^+ \pi^- \eta)$ is within desired
standards in comparison to other channels, their low statistics and their worse proper
time resolutions thus reduce our sensitivity to $\phi_s$. Nevertheless, their relative contribution
amounts to $\sim 2\%$ for each channel.

The combined sensitivity achieved using only pure CP eigenstates modes represents
only $\sim 14\%$ which is significant as they will be of benefit to the measurement as additional
constraints in the determination of the $B^0_s - \bar{B}^0_s$ mixing phase.

If we now scale the sensitivity obtained combining all channels to what is expected after
10$fb^{-1}$ of recorded data, we get this figure: $\sigma(\phi_s) = \pm 0.0094$ rad which is in full agreement
to what obtained in [73]. N years of data taking are assumed to improve our sensitivity by
a factor $\sim 1/\sqrt{N}$. 10$fb^{-1}$ corresponds to 5 years of data taking. The sensitivity achieved
after 5 years of data taking will allow us to measure a SM value of $\phi_s$ ($\sim -0.04$ rad) with
$\sim 4.3\sigma$ precision. Hence, any other New Physics value will be comfortably measured after
few years of data taking. With the sensitivity provided by all channels together will be
able to have a $\sim 2\sigma$ measurement of $\phi_s$ after only one year of data taking, assuming a SM
value. Any non SM $\phi_s$ phase value, will be determined with great precision after one year
of data taking.

### 6.4.2 Likelihood projection

For the sake of completeness we will show here the resulting $-lnL^{b-\bar{c}\bar{c}}$ projections for
each of the physics parameters that we want to determine and that correspond to the
outcomes of our channel decay. Each of those likelihood projections are simultaneously
minimised together with the control sample, and result from leaving the parameter in
which we are interested free and keep the others at their simultaneous fit output values.
The plots are exhibited in Figure 6.10. It is clearly from those plots that the minimum
of the curves match the ones used as SM values. It is also important to mention that the
bias observed for the $\Delta \Gamma_s / \Gamma_s$ and $\tau_s$ distributions is clearly visible on those projections as
many physics parameters share the minimum of the likelihood function. It is worth noting
that the shape obtained from $-lnL^{b-\bar{c}\bar{c}}$ for $\phi_s$ should allow us to distinguish between the
ambiguity from $\phi_s$ and $\pi - \phi_s$ since there exists a $\cos \phi_s$ term in the signal decay rates.

The plot showing the likelihood projection for $\Delta M_s$ is shown in Figure 6.11(a). From
that plot we can only draw one conclusion, the likelihood fit achieved for a $b \to \bar{c}\bar{c}s$
channel does not permit us to obtain a reliable value for $\Delta M_s$. This is due to the fact that
the likelihood fit does not provide us with an unique minimum for $-lnL^{b-\bar{c}\bar{c}}$. Therefore,
the control sample is really needed in order to extract the $\Delta M_s$ parameter.

### 6.4.3 Scanned parameters

In order to have a glimpse of how different scenarios could influence in our sensitivity
measurements, here below we will scan the parameter space of $\Delta \Gamma_s / \Gamma_s$ and $\phi_s$. The
parameter to be varied will successively take the foreseen values while the other physics
parameters remains in their SM positions. We are only worried in this section about the
paramaters to which our channel might provide some sensitivity. The values used for
the $\phi_s$ are: the nominal SM, $-0.04$ rad, and two other possible New Physics values as,$-0.2$ rad, or $-\pi/4$ rad. In the case of $\Delta \Gamma_s / \Gamma_s$ we will be varying those taking the
following values: 0.05, 0.15 which is the nominal one, and 0.5. The results from those
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Figure 6.10: Projection of $-\ln \mathcal{L}^{b\rightarrow c\bar{c}s}$ for $\phi_{s_0}$, $\Delta \Gamma_{s}/\Gamma_{s_0}$, $\tau_{s} = 1/\Gamma_{s}$ and $\omega_{tag}$, (Figures 6.10(a), 6.10(b), 6.10(c) and 6.10(d) respectively), corresponding to a given experiment for the channel $B^{0}_{s} \rightarrow J/\psi \eta'$ with its nominal input parameters simultaneously fitted with the control channel $B^{0}_{s} \rightarrow D_{s} \pi$.

Figure 6.11: Projection of $-\ln \mathcal{L}^{b\rightarrow c\bar{c}s}$ for $\Delta M_{s}$, corresponding to a random experiment for the channel $B^{0}_{s} \rightarrow J/\psi \eta'$ with its nominal input parameters simultaneously fitted with the control channel $B^{0}_{s} \rightarrow D_{s} \pi$. 

parameter scans are shown in Figures 6.12(a) and 6.12(b). Regarding the first plot, we check that the error to measure $\phi_s$ increases as the phase value increase in absolute value. Nevertheless, the achieved sensitivity to $\phi_s$ at the larger $\phi_s$ phase leads to a significance of $\sim 3\sigma$ in the measurement. The second plot does not show a significant degradation of the sensitivity to $\phi_s$ for a $\Delta \Gamma_s/\Gamma_s$ value smaller than SM one.

Similar scans have been carried out for $B^0_s \rightarrow J/\psi \phi$ as is the channel that will obtain by far the best performances. These results are given in [73] and show that the sensitivity to $\phi_s$ is practically unaffected by non-Standard Model values arising in either $\phi_s$ or $\Delta \Gamma_s/\Gamma_s$. It is also worth noting here that in that analysis, it is shown that even in the case that the fraction of the odd CP component amount to 50%, the sensitivity from this channel will be much better than with all the pure CP eigenstates together.

It is also important to note that, no parameter scan was performed for $\Delta M_s$ as the oscillation parameter for the $B^0_s$-mesons has accurately been measured recently [91].

As a final test, we may consider a worse performance both in the proper time resolution and a twice as big background level compared to the signal events. The effect of the proper time on the sensitivity to the physical parameters is introduced through an underestimation of the proper time errors by 10% with respect to the nominal value found from the full MC simulation, while we may also consider an overestimation of the errors by the same amount. The results for the sensitivity to $\phi_s$ are given hereafter:

<table>
<thead>
<tr>
<th>$\sigma(\phi_s)$</th>
<th>nominal</th>
<th>$+10%$ Scale F.</th>
<th>$-10%$ Scale F.</th>
<th>$B/S = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1544</td>
<td>0.1625</td>
<td>0.1533</td>
<td>0.1827</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Different scenarios performances.

From Table 6.3 we can draw the following conclusion. The important parameter to be taken into account is the background level. For the nominal background level, $B/S = 1$, we will obtain a sensitivity to $\phi_s$ for $B^0_s \rightarrow J/\psi \eta'$, after five years of data taking of $\sigma(\phi_s) = 0.069$ rad. To achieve an equivalent sensitivity, for $B/S = 2$, we will need at least 6.5 years provided that the statistics are the only source of uncertainty.

As we know the key parameter to resolve the fast $B^0_s$ meson oscillations is the proper time resolution. An underestimation of the proper time error by 10% implies that the scale factor has to be increased accordingly. The effect on the sensitivity to $\phi_s$ is marginal compared to that introduced if the background level is twice the signal.
Figure 6.12: Sensitivity to $\phi_s$ plots, showing the estimates of sensitivities when a physics parameter is scanned while keeping the others at their nominal values. Figure 6.12(a) shows the mean error on $\phi_s$ [rad] as we vary the value of $\phi_s$ [rad] from the nominal SM to $\pi/4$ rad, extracted from the $B_s^0 \rightarrow J/\psi \eta'$ decay mode. On the other Figure, 6.12(b), the sensitivity to $\phi_s$ is shown as we scan the $\Delta \Gamma_s/\Gamma_s$ value from the nominal value to a larger or smaller width.
CHAPTER 6. SENSITIVITY TO $\phi_S$ IN LHCb
The studies presented in this thesis can be split up into two parts: the selection of $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta'(\pi^+ \pi^- \eta(\gamma \gamma))$ events, and the study of the sensitivity of such a channel decay together with other $b \rightarrow c\bar{c}s$ quark-level transitions to the $B_s^0 - \overline{B_s^0}$ mixing parameters. We outline hereafter the main results obtained in this dissertation.

The selection of $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta'(\pi^+ \pi^- \eta(\gamma \gamma))$ events has been carried out, for the first time at LHCb, using a full Monte Carlo simulation which included both the generation of signal events and a detailed description of the LHCb spectrometer. The selection algorithms used kinematic and topological features of $B_s^0$ meson decays to achieve the goal of selecting the largest number of signal events possible, while keeping the background levels at a very low values. After off-line selection of the signal events and considering trigger effects, we achieved an annual event yield ranging in the $[1.9k-2.6k]$ interval. The range is motivated by the unknown pseudoscalar mixing angle $\theta_P$, governing the $\eta'$ meson production and estimated to be between $\theta_P = -20^\circ$ and $\theta_P = -10^\circ$. Taking into account the pseudoscalar mixing angle, the branching fraction for the $B_s^0 \rightarrow J/\psi \eta'$ has been estimated to be between $[5.7 \cdot 10^{-4}; 4.3 \cdot 10^{-4}]$ for $\theta_P = [-20^\circ; -10^\circ]$ respectively. The annual yield is expected to be improved as new energy correction methods are envisaged by the LHCb collaboration to get better estimates of the photon’s energy which is the main causes of poor momentum estimation of $B_s^0$ candidates. Since the branching fraction for this decay is not well known, space is left for an unexpected larger yield. The dominant source of background expected for our channel decay was found to be the inclusive $b\bar{b}$ events. In order to have an sole estimate of the background over signal levels we used the branching fraction arising from a $\theta_P = -15^\circ$ mixing angle for the computation. This consideration yields a 90% unified confidence interval for the $B/S = [0, 1.1]$.

After applying a Kalman Filter fit the mass resolution of the $B_s^0$ candidates largely improved, obtaining a value of 18 MeV/c$^2$. The different contributions to the $B_s^0$ proper time have been identified. The proper time performance achieved for those candidates is quite satisfactory, with a proper time resolution of $\sim 32$ fs. The pull distributions for the proper time indicates an under-estimation of the errors by $\sim 37\%$. Since for the sensitivities studies the important input is the proper time errors, the obtained distribution for the proper time has been corrected by a scale factor directly taken from the pull.

The tagging power for this channel reaches the level of $9.5 \pm 2.4\%$. Although the annual yield obtained from this channel is low, the results are very encouraging since trigger efficiencies for this channel are expected to be improved. Also better estimation of energy of photons as well as new selection method might improve the yield largely. New vertex and proper time fitting techniques will certainly improve the performances of this decay channel.

The full Monte Carlo simulation of $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta'(\pi^+ \pi^- \eta(\gamma \gamma))$ served us
as inputs of a toy Monte Carlo simulation. The goal of this fast parameterised Monte Carlo simulation is to assess the sensitivity of our channel decay to the $B_s^0 - \bar{B}_s^0$ mixing parameters. A likelihood fitting code was available to extract the observables both for any $b \to c\bar{c}s$ quark-level transition to CP eigenstates, as well as for the ones of the flavour-specific channels. The code takes into account, in a realistic fashion, the resolutions, propertime errors, acceptance functions, event yields, B/S ratios and tagging efficiencies for those channels.

In order to assess the sensitivity of our decay channel to the physics observables, were generated and fitted events equivalent to the statistics of one year of data taking for each of the many experiments considered. The rms of the fitted parameters were used to quote the sensitivity to each of the physics observables. The sensitivity to $\phi_s$ with $2fb^{-1}$ for our decay mode assuming SM values of the physics parameters reaches 0.154 rad. For the determination of the mixing phase, $\phi_s$, were also added equivalent information arising from other pure CP modes as well as the golden-plated $B_s^0 \to J/\psi \phi$ decay channel. The dominant contribution comes from the latter channel achieving a statistical uncertainty of $\sigma(\phi_s) = \pm 0.023$ rad. The combined sensitivity to $\phi_s$ from the pure CP modes touch the level of $\sigma(\phi_s) = \pm 0.056$ what indicates a $\sim 14\%$ of contribution to the sensitivity. Hence, the global sensitivity achieved with $2fb^{-1}$ when combining all decays is $\sigma(\phi_s) = \pm 0.021$ rad if SM physics is present.

The $B_s^0$ system will be completely explored with the LHCb experiment. The most promising measurement is that of the $\phi_s$ mixing phase. If a SM value for that phase exits, LHCb will be able to measure it with great precision only after a few years of data taking. But, any non-SM value will be significantly unveiled soon after the year 2008, opening the door to the New Physics.
Appendix A

Kalman Filter Fit

A.1 Method of Kalman Filter fit

As we saw in Chapter 4, in LHCb a track is a collection of a number of measurements and track states. In the Kalman filter fit procedure the measurements are added one by one into the fit, each time updating the fit in the local node. Mathematically the Kalman fit is equivalent to the least squares fit. The Kalman filter consists of the following sub-algorithms:

- Seeding: determining the initial state and covariance before the fit starts
- Prediction: predicting the trajectory (i.e. a state and covariance) in the plane of a measurement
- Projection: updating the track state with the measurement of given plane
- Smoothing: reversing the fit iteration from the last added measurement to the first measurement in order to obtain the full precision in each node.

Detector material is taken into account by adjusting the state vector and its covariance matrix (multiple scattering and energy losses are easily computed with this method).
APPENDIX A. KALMAN FILTER FIT

The measurement at seed plane (k-1), say, $\tilde{x}_{k-1}$, is propagated until measurement plane (k), say, $\tilde{x}_{k}$. The kick introduced by some material together with the measurement $m_k$ are taken into account to obtain the weighted mean $\tilde{x}_k$. The same process is repeated until the last measurement is added and hence the direction of fit is reversed in order to smooth the trajectory.

Figure A.1: Schematic picture of the Kalman Filter fit method applied to the reconstruction of charged tracks.
Appendix B

Lifetime Fit

B.1 Method of Least Squares used by the LifeTimeFitter tool

The LifeTimeFitter tool will constrain the kinematics of the selected event through the formula B.1 to extract an estimate of the proper time of the event as well as the error of the measurement using a $\chi^2$ fit.

$$\tau = m \vec{p} \cdot \vec{FD} / |\vec{p}|^2$$  \hspace{1cm} (B.1)

After the reconstruction of an event, the outcomes are, the assumed production vertex, $\vec{P}$, given by the primary vertex algorithm, and the reconstructed particle, which is given by its decay vertex and the momentum estimation at that vertex, i.e. $\vec{S}$ and $\vec{p}$.

The least squares fit equation has simple properties if the function to be minimised ($\vec{F}$) with respect to the measurements $\vec{y}$ is linear in the unknown parameters ($\theta$). The unknown parameters in this lifetime fit are (in vector form): $\theta = (S_{\text{fit}}, p_{\text{fit}}, \tau_{\text{fit}})$. and the vector of measurements is hence given by $y = (S, p, P)$ The linear function which we want to use in the Least Square fit is given by $F(\theta) = (S_{\text{fit}}, p_{\text{fit}}, S_{\text{fit}} - \tau_{\text{fit}} p_{\text{fit}} / m)$, where we have used the equation B.1 for the last component of the vector function.

In matrix notation, the Least Squares expression is given by: $\chi^2 = (y - F)^T V^{-1} (y - F) = (y - H \theta)^T V^{-1} (y - H \theta)$ where the linear function is expressed in matrix form and given by $F(\theta) = H \theta$. The estimators $\theta^*$ are extracted by minimising $\chi^2$, hence, setting the derivatives with respect to $\theta_i$ to zero, i.e., $\nabla \chi^2 = -2(H^T V^{-1} y - H^T V^{-1} H \theta) = 0$. Hence, solving those linear equations yields to the get the Least Square estimators, i.e.: $\theta^* = (H^T V^{-1} H)^{-1} H^T V^{-1} y \equiv B y$, which implies that the each of the estimators is a linear function of each of the measurements. Thanks to this linear problem, the computation of the error for the estimator is exact. The covariance matrix of the estimators, i.e., $U_{ij} = \text{cov}[\theta_i, \theta_j]$ is given by $U = BB^T$, which is equivalently to compute:

$$U_{ij}^{-1} = \frac{1}{2} \left[ \frac{\partial^2 \chi^2}{\partial \theta_i \partial \theta_j} \right]_{\theta = \theta^*}$$  \hspace{1cm} ([75]). The error on our parameters are hence given by the second order derivatives of the $\chi^2$ with respect to the least-squares estimators.

In our case, the covariance matrix of the measurements, $V_{ij} = \text{cov}[y_i, y_j]$ is simplified as the estimation of the particle parameters ($B^0_s$ momentum and vertex) are assumed to be independent of the estimation of the primary vertex coordinates. Hence, $V_{ij} = V_{ji} = 0$ for $6 \leq i \leq 9$ and $1 \leq j \leq 6$.

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1This appendix is based on [75, 90, 73]
Appendix C

Inner Tracker support ladders

C.1 Thermal and mechanical studies of carbon fiber supports.

This appendix describes the thermal and mechanical studies performed on a prototype of carbon fiber support structure for the silicon sensors in the LHCb Inner Tracker. The amount of material for those supports needs to be kept as low as possible to minimising photon conversion and multiple scattering [92]. The support needs to mechanically hold the silicon sensors and to provide sufficient heat transfer from the sensors to the cooling plate, to keep the sensors at an operating temperature of \( \lesssim 5^\circ C \). These settings will reduce leakage currents and hence shot noise, even after radiation damage foreseen after several years of LHC running [93]. Finite Element Analyses (FEA)\(^1\) performed in Zürich were used in order to decide between different initial designs of the support [94].

C.1.1 Carbon fibre support

C.1.1.a Materials

Several prepreg \(^2\) carbon fiber composites were considered to fulfill all the performance requirements. Among them, the preferred choice was AMOCO K1100 with Cyanate Ester. As a backup solution K13C2U was also chosen since it was also very competitive. Table [C.1] summarises the main physical properties of the carbon composite AMOCO K1100 together with the alternative material K13C2U.

C.1.1.b Geometry and layouts

To provide the necessary rigidity to the support two geometries consisting of several carbon layers were considered. In a first batch (U-shaped geometry), the prototype supports were made of AMOCO K1100 and assembled from four layers with different orientations. The support is bended at both sides in order to form two 2mm high wings. Figure [C.1] shows the cross-section of this U-shaped carbon fiber support and the relative orientation of the fibres. The second batch of prototype frames was built without reinforcement wings and

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\(^1\)Energy balance equations are evaluated for each element of the grid so that the heat transfer rate to the neighbour elements is obtained. The heat conduction equation for a certain thermal conductivity of the material (Fourier's law) and the natural convection equation in which the external temperature remains constant were used in the FEA.

\(^2\)Prepreg is a composite material made of resin-preimpregnated fibres, most often carbon fibers.
only three carbon sheets. Figure [C.2] shows the cross-section of this alternative geometry together with its reinforcement.

Table C.1: Two of the main prepeg materials together with some of their physical properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Amoco K1100/ (with Cyanate Ester resin)</th>
<th>Mitsubishi K13C2U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus ( [GPa] )</td>
<td>930/(560)</td>
<td>896</td>
</tr>
<tr>
<td>Thermal Conductivity (along fiber direction) ( [W/mK] ) (at 20ºC)</td>
<td>1100/(540)</td>
<td>620</td>
</tr>
<tr>
<td>Thermal Expansion ( [10^{-6}m/K] )</td>
<td>-1.2</td>
<td></td>
</tr>
</tbody>
</table>

Figure C.1: Cross-section of the first batch of carbon fiber supports (U-shaped geometry). Orientation of the fibres is also included.

Figure C.2: Cross-section of the second batch of carbon fiber supports. Reinforcement of the geometry is shown in the 3D figure below.
C.1.1.c Mechanical studies

The mechanical precision concerning the flatness of the support structure is driven by the flatness of the Si-sensors and the desired spatial resolution of the LHCb Inner Tracker. Thereby a maximum deviation of $\pm 200\mu m$ from flatness of the carbon support is desirable.

The flatness of the prototype support frames vertically mounted by means of their fixation holes was measured using a custom-made xyz-positioning machine. The results obtained from those studies are show hereafter. Figure [C.3].

The following definitions of “bending” and “twist” were used to quantify the flatness of the support frames:

- bending = average of three different y-coordinates (y-axis define to be normal to the support) measurements being performed at a certain distance from the cooling plate.

- twist = $y(A)-y(B)$ where A, B are two points at the borders of the support, for a given position from the cooling plate.

In view of these results, we have adopted a new design in which two carbon fibers skins with their fibers oriented at $\pm 10^\circ$ with respect to x direction Figure (C.1) sandwich a 1mm AIREX foam. This design ensures a maximum deviation of $< 200\mu m$ from flatness of the support. See Figure 2.8 for a three dimensional view of the ladders design.

The thermal study described hereafter shows how the fiber thermal conductivity degrades when they are embedded with resins.

C.1.1.d Thermal studies

An experimental set-up simulating the Inner Tracker (IT) ladder and its cooling system was built in order to measure the thermal properties of the carbon support and to compare
its temperature profile with the corresponding FEA simulations. At normal IT running conditions, measurements indicated that Beetle DAQ chips release up to 0.5 Watts. The total power dissipated by those readout chips (1.5 Watts), was simulated by equivalent resistors mounted on a hybrid plate. Pt-100 temperature probes were attached along the ladder support to perform the measurements. Additional probes record extra data as the temperature of the hybrid, cooling plate, cooling fluid and ambient. The experimental setup was placed inside an adiabatic enclosure which allowed internal temperature adjusting.

The first FEA simulations were computed at room temperature. The comparison of the experimental temperature profile (while no dissipated power was considered) to the simulations showed that the thermal conductivity of a full support from the first batch (U-shaped) was close to a value of 200 W/(m·K). To confirm the result, a new set of measurements and simulations using the obtained conductivity value were performed at ambient temperatures of 1.8°C, 0.8°C, 0°C and -1.3°C. The results for this full support together with the simulations are shown in Figure [C.4]. They exhibit the foreseen behaviour.

Temperature measurements were also taken for a support from the second batch of prototypes (made of Mitsubishi K13C2U fibres), giving a thermal conductivity value slightly above 200 W/(m·K). The temperature profile obtained while the resistors simulating dissipation were activated was also recorded for this second batch. Figure [C.5] shows the results for the second batch.

![Figure C.4](image)

Figure C.4: Measured temperatures along the AMOCO K1100 support for different ambient temperatures: 1.8°C, 0.8°C, 0°C and -1.3°C (from top to bottom). The temperature at the readout end was -6°C at any time. For comparison, FEA simulations for 200 W/m·K thermal conductivity with the same running conditions are included (curves).

A full discussion on those experimental results and the conclusions obtained for those prototypes can be found in [30].
Figure C.5: Measured temperatures along the second batch supports while the resistors are switched off (circles) or on (stars) for two ambient temperatures: 1.8°C and 0°C. FEA simulations are also included.


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