A study for lifetime measurements of B mesons at LHCb

Master Thesis

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Abstract

In this work, we will present a study for the lifetime measurement of the $B^+$ meson using the fully reconstructed decay $B^+ \rightarrow J/\psi K^+$. We use $\mathcal{L} = 16pb^{-1}$ of data collected by the LHCb detector at CERN in 2010. First, we will use Monte-Carlo data in order to analyze the potential bias induce by the stripping decisions, the triggers decision and the offline selections. Then, a study of the lifetime distribution in the sideband region is made and a model is built to fit real data. The measured $B^+$ lifetime finally obtained is:

$$\tau_{B^+} = 1.6391 \pm 0.0201 \pm 0.0055 \text{ ps}$$

The first error is the statistical one and the second error is an estimation of the systematic errors. A Monte-Carlo toy study is performed to validate the fit model.
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1 Introduction

We are now entering a new era of physics. The Large Hadron Collider at CERN is now probing the matter with the highest energy ever used. The LHCb will attempt to answer some of the fundamental questions of science. Which mechanism generated the mass of the particle? What is the composition and the properties of the dark matter? How was the Universe at the beginning of its history? Why are we living in a world of matter and not antimatter? Some of the biggest secrets of the universe will be disclosed in the experiment of ATLAS, CMS, ALICE and LHCb. The LHCb experiment aims to test the standard model (SM) by performing precise studies of CP violation and through indirect searches for new physics. So far CP violation detected in the neutral kaon system and B meson systems is fully compatible with the Standard Model mechanism, where it is generated by a complex phase in the CKM mass mixing matrix. However, this cannot explain the observed matter antimatter asymmetry in the Universe. Therefore, we require new sources of CP violation, which could generate deviations from the Standard Model predictions in CP violation and other rares phenomena in the B meson decays. The LHCb experiment is optimized to make such studies exploiting the large number of B mesons produced at LHC.
1.1 Outline

The aim of this work is to study the propertime distribution of the $B^+$ meson which is define as:

$$
\tau = \frac{\mathbf{P} \cdot \mathbf{d}}{|\mathbf{P}|^2} M_{B^+}
$$

(1)

with $\mathbf{P}$ the momentum of the $B^+$ meson, $\mathbf{d}$ the distance between the primary and decay vertex and $M_{B^+}$ the mass. In the first part of this work, we will introduce some of the theoretical concepts which are necessary for the study of $B$-physics and then go on to describe some of the details of the LHCb detector. We will then perform a study of fully simulated data. This study will give us information about the lifetime distribution and some biases which could be introduced the trigger and the stripping stages of the selection process. After having a good knowledge of the simulation, we will analyze the lifetime distribution of $B^+$ for real data at LHCb. First, we will study the background distribution in the sideband of the $B^+$ meson mass to model it in the signal region. Then, we will model the lifetime distribution of $B^+$ to extract the lifetime $\tau_{B^+}$ and its error. $\tau_{B^+}$ is defined as the time it takes to reduce by a factor $\frac{1}{e}$ the number of $B^+$ of a sample. Finally, we will do a study of the systematic errors and a Monte-Carlo toy simulation to validate the fitting model.

1.2 Standard Model

The Standard Model (SM) is a theory which describes the strong, weak and electromagnetic forces between the elementary particles which compose matter. This quantum field theory is based on the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry group.

![The Standard Model](image)

Figure 1: The Standard Model (SM).
The Standard Model (Figure 1) includes 12 fermions of spin 1/2. Each particles has a corresponding anti-particle. The 6 quarks carry the colour charges and interact with the strong interaction. The 6 leptons do not interact with the strong force but do interact with the weak and the electromagnetic forces. The 3 neutrinos do not carry colour or electromagnetic charge and interact only by the weak interaction. The force carriers are called gauge bosons and are as follows:

- $\gamma$ (photons) mediate the electromagnetic force between the charged particles;
- $W^+, W^-$ and $Z$ mediate the weak interactions between the particles of different flavours;
- 8 gluons mediate the strong force between the colour charged particles.

The Higgs boson is a candidate for explaining the mass generation in the Standard Model and the fact that the gauge bosons $W$ and $Z$ have different properties from the $\gamma$. At the moment, the Higgs boson has not been detected but the LHC will soon be in a position to confirm or not the existence of this gauge boson.

The Standard Model is not a complete theory although the observations are consistent with the model. It does not incorporate gravitation, dark matter particles, and asymmetry between matter and antimatter that require the cosmological observations. Furthermore, it does not explain correctly the neutrino oscillations, explain the hierarchy of the mass between family of particles and the strong $CP$ problem.

The LHC will help answering some of these issues. In particular, the $LHCb$ experiment will probe new Physics beyond the Standard Model and try to understand better the asymmetry between matter and antimatter at the beginning of our Universe.

1.3 $CP$ Violation and B Physics

At the beginning of the Universe, an equal quantity of matter and antimatter was produced. Experimental evidence and observation show that our Universe of today is made of matter. The necessary conditions to explain the domination of matter of the Universe is called the Sakharov criteria [5]:

- the interactions require $C$ and $CP$-violation;
- violation of the number of baryon at high energy;
- the universe passed through a non-thermal equilibrium;
The operation of symmetry \( C \) results to a charge conjugation and the operation of parity \( P \) results of an inversion of space. For example, by applying the operator \( CP \) on an electron of charge \( q = -1 \) and positive helicity \( \tilde{h} = +1 \):

\[
\begin{align*}
C : q &\rightarrow -q \\
P : \tilde{h} &\rightarrow -\tilde{h}
\end{align*}
\]

it results in a positron with negative helicity. The first measure of \( CP \) violation was done by James Cronin and Val Fitch thanks to the neutral kaon oscillation \( K_0 - \bar{K}_0 \) \cite{6}. The Standard Model (SM) predicts \( CP \)-violation but the value of the \( CP \)-violation is too small to explain the asymmetry between matter and anti-matter. It is why a search in higher energy collision is needed to look after other sources of \( CP \)-violation and manifestations of New Physics. Thanks to the \( B \) meson sector, we can explore another region of the quark mixing matrix and potentially discover signs of New Physics. The \( CP \) violation is measured by studying an initial state \( a \) which decaying in a final state \( b \) \cite{1}:

\[
A_{CP} = \frac{\Gamma(a \rightarrow b) - \Gamma(\bar{a} \rightarrow \bar{b})}{\Gamma(a \rightarrow b) + \Gamma(\bar{a} \rightarrow \bar{b})}
\]

with \( \Gamma \) corresponds of the width of the decay amplitude. This equation could be write as :

\[
A_{CP} = -\sin(\Delta m t)\sin(\phi - 2\omega)
\]

with \( \Delta m \) the mass difference of the mass eigenstates, \( \phi \) the mixing phase and \( \omega \) the decay phase.

The phases appeared in the Standard Model with the unitary CKM (Cabibbo-Kobayashi-Maksawa) matrix which describes the change of flavour in the weak interaction.

\[
\begin{pmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle
\end{pmatrix} =
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
|d\rangle \\
|s\rangle \\
|b\rangle
\end{pmatrix}
\]

The state \( |i\rangle \) is the eigenstate of the weak interactions and the \( |i\rangle \) the mass eigenstate of the strong interaction. The CKM matrix gives the probability of transition between two sorts of quarks.
This could be written with the Wolfenstein parametrization [2] :

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

with \( \lambda \) as the sine of the Cabibbo angle, \( \sin(\theta_c) \approx 0.22 \). The four parameters \( \lambda, \eta, \ A \) and \( \rho \) are defined by :

\[
\lambda = s_{12} \\
A\lambda^2 = s_{23} \\
A\lambda^3(\rho - i\eta) = s_{12}e^{-i\delta}
\]

with \( c_{ij} \) and \( s_{ij} \) as the cosines and the sines of the mixing Euler angle of the “Standard” parametrization and \( \delta \) the CP-violating phase. The CP violation arises thanks to the complex phase \( \eta \).

From the unitary condition of the CKM matrix :

\[
V_{CKM}^\dagger V_{CKM} = Id
\]  \hspace{1cm} (2)

From each combinations of quark \( i \) and \( j \) we can obtain three complex numbers which form in the complex plane the sides of a triangle. We get six unitary triangle with a relation of orthogonality, i.e., for the couple \( ds \) :

\[
V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0
\]  \hspace{1cm} (3)

We can define four angles \( \gamma, \beta, \beta_s \) and \( \beta_K \) which are important in the CP violation.

\[
\gamma = \arg\left( -\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*} \right) \quad \beta = \arg\left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) \\
\beta_s = \arg\left( -\frac{V_{us}V_{u\bar{d}}^*}{V_{cs}V_{c\bar{d}}^*} \right) \quad \beta_K = \arg\left( -\frac{V_{ts}V_{ts}^*}{V_{cs}V_{cd}^*} \right)
\]

The main angle in the search of CP violation in the decay of the \( B_s \) meson is \( \beta_s = \arg\left( -\frac{V_{ts}V_{ts}^*}{V_{cs}V_{cb}^*} \right) \).

Figure 2: Unitary triangle in the complex plane for the \( bs \) couple.
The prediction of $\beta_s$ is [2]:

$$2\beta_s = 0.0360^{+0.0020}_{-0.0016} \text{ rad}$$

The previous generation of particle physics experiments (BaBar, Belle) collected large sample of $B^+$ and $B^0$ mesons with which they studied the effects of $CP$-violation. LHCb will be able to provide larger samples of these mesons and also provide access to large samples of $B_s$ mesons. At LHCb, the $B_s$ mixing is a probe of New Physics. Before decaying to $J/\psi\phi$, $B^0_s$ can oscillate into $\bar{B}^0_s$ via a box diagram, Figure 3. The state of the system is a superposition of $|B_s\rangle$ and $|\bar{B}_s\rangle$ which are defined by (by assuming that $CPT$ is conserved):

$$|B_{H,L}\rangle = a|B_s\rangle \mp b|\bar{B}_s\rangle$$

with $H, L$ for heavy and light and $a, b$ the amplitude. The time evolution of those eigenstates is defined as [3]:

$$|B_{H,L}(t)\rangle = e^{-(im_{H,L} + \Gamma_{H,L}/2)t}|B_{H,L}(t = 0)\rangle$$

By measuring the oscillations $\Delta m = m_H - m_L$ and $\Delta \Gamma = \Gamma_H - \Gamma_L$ using a complex time dependent angular analysis technique we can obtain the value of $\beta_s$. Because the final states results of two vector mesons we have to consider three contributions to the decay amplitude. The $CP$ asymmetry tends to disappear when we consider the contribution of each final state together. A time dependent angular analysis is needed to distinguish the two $CP$ even states and the $CP$ odd state (Figure 4).

A deviation of the value of $\beta_s$ predicted by the Standard Model will be an indication of others virtual particles which appears in the box diagram. This new measure could be an indication of New Physics like the discovery of virtual supersymmetric particles or new family of quark. The decay $B^0 \to J/\psi(\mu\mu)K^*(K\pi)$ has the same topology as $B_s \to J/\psi(\mu\mu)\phi(K\bar{K})$ (4 final state particles). In addition, the decay $B^+ \to J/\psi K^+$ will provide a high statistics
sample of \( B \) meson events that are triggered in the same way as \( B_s \rightarrow J/\Psi \phi \), using the two muons in the final state. Together, these two channels are good candidates for control channels for \( B_s \rightarrow J/\psi \phi \). For measuring the length scale of LHCb and mistag rates, both of which are essential for measuring \( B_s \). Therefore the study of the lifetime of \( B^+ \) and \( B^* \) is very important in the ultimate goal to measure the \( CP \)-asymmetry in the \( B_s \) channel.

1.4 LHCb Experiment and Detector

The Large Hadron Collider beauty (LHCb) is one of the four main experiments at the LHC. The LHC is a \( p - p \) collider with high luminosity of \( 10^{34} \text{cm}^{-2}\text{s}^{-1} \). It has been designed to reach an energy of 7 TeV in each beams (\( \sqrt{s} = 14 \text{ TeV} \)). For this study, the energy of each beam is 3.5 TeV. The four main experiments at LHC are CMS, ATLAS, ALICE and LHCb (figure 5). ATLAS and CMS will look for new particles, Higgs boson and will investigate why the matter is dominated by Dark Matter in the Universe. ALICE is designed to study the formation of quark and gluon plasma. This will help us to understand our early Universe after the Big-Bang.
The aim of the LHCb experiment is to measure precisely $CP$ violation processes and search of New Physics in rare decays. LHCb produces $b\bar{b}$ pairs which are boosted along the beam direction with a high momentum but with a relatively small transverse momentum. It is why it has a polar angular coverage of 10 mrad to 400 mrad. On figure 6, the sub-detectors composition of the LHCb is presented. The luminosity at the LHC interaction point is $\mathcal{L} = 2 \cdot 10^{32} cm^{-2}s^{-1}$. This is lower than ATLAS and CMS because the beams are defocusing thanks to the magnets.
The detector is composed of different sub-detectors [7]:

**V**ertex **L**Ocator (VELO) : The $b$ has the property to decay very rapidly and the VELO is made to detect those particles with a very short lifetime. To measure the very short lifetime of particles we need a very high accuracy in the measure of the position of the vertices and the momentum of the particles. The VELO is composed of 25 stations of silicon sensors which measure the radial and azimuthal position of each track coming from the region of the $pp$ collision point. During the injection of the proton beams, the sensors are at the “open” position to avoid any damage. After they are accelerated and produced stable collisions, the sensors are placed to the “closed” position for data taking (Figure 7).

![Figure 7: VERTex LOcator in the “open” and “closed” position.](image)

**Tracking system** : With the VELO and the magnet, the tracking system is composed of the Tracking Turicensis (TT), the inner tracker (IT) and the outer tracker (OT). Each component measures the momentum of charged particles thanks to the curvature of the particles in the magnetic field. The TT and IT consist of silicon microstrips with a high spatial resolution ($50 \mu m$). The Tracker Turicensis is used for the reconstruction of the trajectory of low momentum particles and for long-lived particles which decay outside the VELO. The IT is composed of three stations of four boxes build around the beampipe where we have the highest track density. Approximately 20% of charged particles produced at the collision point hit the IT stations. The IT is designed to provide a optimal spatial resolution for a high charged particles densities and support the radiation damages. The Outer Tracker is a drift-time detector build around the IT to measure charged particles over a large acceptance area. The OT is composed of an
array of gas-straw-tube modules which contain two layers of drift-tubes. On Figure 8, the tracking system is represented. In magenta, the Tracking Turicensis and the Inner Tracker are shown. In blue, we can see the Outer Tracker build around the IT.

![Tracking System](image)

**Figure 8: Tracking System.**

**Ring Imaging Cherenkov Counter** : The RICH detectors measure the velocity ($\beta$) of charged particles by detecting photons of Cherenkov radiation which are emitted when charged particles pass through the medium with a velocity greater than the speed of light in the medium. Combining this with the momentum measured by the tracking system, the mass of the particle can be obtained. The charged particles which have a velocity bigger than the speed of light in the medium of the detectors emit a cone of light with an opening angle $\theta$ (Cherenkov effect). The angle is related to the velocity of the particle as:

$$\cos(\theta) = \frac{1}{\beta n_{med}}$$

from the mass detector identifies protons, charged kaons, and charged pions.

**Calorimeters** : The main purpose of the calorimeters is to measure the energy for electrons, positrons and photons (ECAL) and hadrons (HCAL).

**Muon Chambers** : Detection of the muons is done by the muon system placed at the end of the spectrometer. It consists of five layers of charged particle detectors. The first layer is placed in front of the calorimeter system and the last four are interleaved with Fe absorbers. Since muons interact weakly with material, they can penetrate
through the calorimeter and Fe absorbers, while all the other particles are stopped. The tracking device is composed of Multi Wire Proportional Chambers (MWPC) and Gas Electron Multipliers (GEM). Triple GEM detectors are used instead of MWPC in the inner region of M1 because the expected particle rate is too high for MWPC. With the electromagnetic and hadron calorimeters the information of the muon chambers is essential for the triggering of the $B^+ \rightarrow J/\psi K^+$ and the other channel. The information of the two muons with the highest transverse momentum are selected in the muon chambers and are sent to the L0 trigger.
1.4.1 The LHCb trigger

The role of the trigger is to reduce the number of recorded events which are not interesting for the study of $B$ mesons. It reduces the beam crossing rate of 40 $MHz$ to an acceptable rate for the next trigger decisions ($\approx 1$ $MHz$ for $L0$). Thus, less data are stored and a first selection is made. The main trigger decisions is separated in three level (Figure 9).

![LHCb trigger architecture.](image)

Figure 9: LHCb trigger architecture.

1. Level0
2. HLT1 (High Level Trigger 1)
3. HLT2 (High Level Trigger 2)
Level-0 processes the data using hardware components of the detector. In particular, the L0 looks for:

- the larger $E_T$ of hadrons, electrons and photons in the calorimeters;
- the two highest values of the transverse momentum $p_T$ of muons in the muon chambers;

The $L0$ reduces the visible crossing rate from 10 $MHz$ to 1 $MHz$. The $HLT$ is a software-only application which has access to all information for each events which pass the $L0$ decisions (the alley). The $HLT$ is composed of two sub-levels which reduced the rate to 2 $kHz$. The $HLT$ refines decisions of the $L0$ by adding new information such as the full reconstruction of the particle tracks in LHCb, impact parameters of the reconstructed particles relative to the primary vertices. The ”stripping” is an additional selection which is applied after the initial reconstruction of all events. The stripping aims to centralize and simplify the first stage of the offline physics analysis. Analysts do not have to process the entire dataset but only events in which candidate particles of interest appear.

1.5 Properties of $B^+ \rightarrow J/\psi(1S)K^+$

The quark composition of the $B^+$ is $u \bar{b}$. On the following Table [8], we summarize the main properties of the $B^+$ meson.

<table>
<thead>
<tr>
<th>Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>$(1.638 \pm 0.011) \cdot 10^{-12}$ s</td>
</tr>
<tr>
<td>Mass</td>
<td>$5279.1 \pm 0.29$ MeV/c$^2$</td>
</tr>
<tr>
<td>Quantum numbers</td>
<td>$I(J^P) = \frac{1}{2}(0^-)$</td>
</tr>
</tbody>
</table>

The most likely decay modes of $B^+$ are the semileptonic and leptonic channels. The branching ratio of the decay mode $B^+ \rightarrow J/\psi K^+$ is [8]:

$$BR(B^+ \rightarrow J/\psi K^+) = (1.014 \pm 0.034) \times 10^{-3}$$

The charmonium $J/\psi(1S)$ decays in the most probable case in hadrons ($(87.7 \pm 0.5) \times 10^{-2}$) but the easiest way to reconstruct them is the channel $J/\psi \rightarrow \mu^+\mu^-$ which gives a
very clean signal thanks to the muon chambers. The branching ratio of this channel is:

\[ BR(J/\psi \rightarrow \mu^+\mu^-) = (5.93 \pm 0.06)\% \]

On Figure 10, a possible feynman diagram of the channel \( B^+ \rightarrow J/\psi K^+ \) is presented.

![Feynman Diagram](image)

Figure 10: One of possible feynman diagram of \( B^+ \rightarrow J/\psi K^+ \).

The charged kaon \( K^+ \) is a strange meson with a relatively long mean life \( c\tau = 3.712 \, m \). Because the flight distance of the \( K^+ \) is long and the most probably decay modes are difficult to use \( (K^+ \rightarrow \mu^+\nu_\mu \text{ in } (63.55 \pm 0.11)\% \text{ of cases}) \), the identification is made before the \( K^+ \) decays. Thanks to the information of the RICH, we can separate the kaons of the pions and protons.
2 $B^+ \rightarrow J/\psi(1S)K^+$ Analysis

2.1 Event Selection

In order to extract and study the $B^+$ lifetime, we aim to use event selection which minimizes any bias in the $B^+$ propertime. In this work, we will use the selections which are described in Table 1 for $J/\psi \rightarrow \mu^+\mu^-$ and 2 for $B^+ \rightarrow J/\psi K^+$. The stripping selections are additionally selections made after the initial reconstruction to save data storage. The offline selections are made after the stripping and are chosen to remove enough background and to optimize the study of the $B^+$ lifetime. It is essentially selections on the track and the vertex quality which are unbiased selections ($\Delta\ln L, \chi^2/nDoF$, etc) [9].

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Cut parameter</th>
<th>Stripping value</th>
<th>Offline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \mu\mu$</td>
<td>$DLL_{\mu\mu}$</td>
<td>$&gt; 0$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\chi_{\text{track}}^2/nDoF(\mu)$</td>
<td>$&lt; 5$</td>
<td>$&lt; 4$</td>
</tr>
<tr>
<td></td>
<td>$\chi_{\text{vtx}}^2/nDoF(J/\psi)$</td>
<td>$&lt; 16$</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td></td>
<td>$M(\mu^+\mu^-) - M(J/\psi)$</td>
<td>-</td>
<td>$&lt; 4.2$</td>
</tr>
<tr>
<td></td>
<td>$M(\mu^+\mu^-)$</td>
<td>$-80\text{MeV}/c^2$</td>
<td>$-80\text{MeV}/c^2$</td>
</tr>
<tr>
<td>$J/\psi$ mass constrained to PDG value</td>
<td>$</td>
<td>M(\mu^+\mu^-) - M(J/\psi)</td>
<td>$</td>
</tr>
</tbody>
</table>

Table 1: $J/\psi \rightarrow \mu^+\mu^-$ selections.

We notice that the $J/\psi$ mass is constraint by the PDG value. The DecayTreeFitter is used with the $J/\psi$ mass constraint to get a better resolution on the $B^+$ mass and without the $J/\psi$ mass constraint to measure the $B^+$ propertime. The Difference of Log-Likelihood is the indicator of the particle’s probability to be that the particle we expected. $DLL_{\mu\mu}$ is the likelihood of a muon to be a pion, $DLL_{K\pi}$ is the likelihood of a kaon to be a pion and $DLL_{Kp}$ is the likelihood of a kaon to be a proton. $\chi_{\text{track}}^2/nDoF(X)$ and $\chi_{\text{vtx}}^2/nDoF(X)$ are selections of the quality of the track and the primary vertex divided by the number of degrees of freedom of the system. $\frac{|M(\mu^+\mu^-) - M(J/\psi)|}{\sigma_{M(\mu^+\mu^-)}}$ is an additional selection on the $J/\psi$ mass pull which remove non-$J/\psi$ background. We will discuss this cut further in section 2.3.1. $p(X)$ and $p_T(X)$ are selections on the momentum and the transverse momentum. For the muons, we require that the two muons have a transverse momentum bigger than 0.5 $\text{GeV}/c$. Finally, $IP_{\chi^2}(B_u)$ is a cut on the impact parameter significance with respect to the primary vertex.
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Cut parameter</th>
<th>Stripping value</th>
<th>Offline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>DLL$_{K\pi}$</td>
<td>$&gt; -2$</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td></td>
<td>DLL$_{K\rho}$</td>
<td>$&gt; -2$</td>
<td>$&lt; 4$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{track}/nDoF}(K^+)$</td>
<td>$&lt; 5$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p_T(K^+)$</td>
<td>$&gt; 1\text{GeV}/c$</td>
<td>$&gt; 1\text{GeV}/c$</td>
</tr>
<tr>
<td></td>
<td>$p(K^+)$</td>
<td>$&gt; 10\text{GeV}/c$</td>
<td></td>
</tr>
<tr>
<td>$B_u \rightarrow J/\psi K^+$</td>
<td>$M(B_u)$</td>
<td>$\in (5100, 5550)\text{MeV}/c^2$</td>
<td>$\in (5100, 5450)\text{MeV}/c^2$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{vtx}/nDoF}(B_u)$</td>
<td>$&lt; 10$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{DTF}(B^+pv)/nDoF}(B_u)$</td>
<td>-</td>
<td>$&lt; 25$</td>
</tr>
<tr>
<td></td>
<td>$IP_{\chi^2}(B_u)$</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: $B^+ \rightarrow J/\psi K^+$ selections.

On Table 3, the efficiencies of each individual cut made after the stripping decision are presented. Table 3 was compiled using full reconstructed $B^+ \rightarrow J/\psi K^+$ signal Monte-Carlo data with $\nu = 3$. $\nu$ is the value of the number of $p - p$ interactions per bunch crossing. $\nu = 3$ closely resembles the dataset that was collected in 2010 thanks to the Monte-Carlo data. The Monte-Carlo samples are MC2010 data with production id 7329,7608 and 7649. The efficiency of each cut is defined as:

$$\epsilon_i = \frac{N_{\text{strip sel},i}}{N_{\text{strip tot}}}$$

with $N_{\text{strip sel},i}$ the number of events after the selection $i$ and $N_{\text{strip tot}}$ without any selections. The error on each efficiency $\sigma_{\epsilon}$ is defined as:

$$\sigma_{\epsilon} = \sqrt{\frac{\epsilon(1 - \epsilon)}{N_{\text{strip sel},i}}}$$

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon$</th>
<th>$\sigma_{\epsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2_{\text{track}/nDoF}(\mu^-)$</td>
<td>99.74 %</td>
<td>0.01 %</td>
</tr>
<tr>
<td>$\min(p_T(\mu^-), p_T(\mu^-))$</td>
<td>96.34 %</td>
<td>0.03 %</td>
</tr>
<tr>
<td>$\chi^2_{\text{vtx}/nDoF}(J/\psi)$</td>
<td>99.08 %</td>
<td>0.02 %</td>
</tr>
<tr>
<td>$</td>
<td>M(u^+\mu^-) - M(J/\psi)</td>
<td>$◤ $\sigma_{M(u^+\mu^-)}$</td>
</tr>
<tr>
<td>DLL$_{K\pi}$</td>
<td>97.92 %</td>
<td>0.03 %</td>
</tr>
<tr>
<td>DLL$_{K\rho}$</td>
<td>94.16 %</td>
<td>0.04 %</td>
</tr>
<tr>
<td>$\chi^2_{\text{track}/nDoF}(K^+)$</td>
<td>99.59 %</td>
<td>0.01 %</td>
</tr>
<tr>
<td>$p_T(K^+)$</td>
<td>100 %</td>
<td>-</td>
</tr>
<tr>
<td>$p(K^+)$</td>
<td>87.91 %</td>
<td>0.06 %</td>
</tr>
<tr>
<td>$\chi^2_{\text{DTF}(B^+pv)/nDoF}(B_u)$</td>
<td>95.67 %</td>
<td>0.04 %</td>
</tr>
<tr>
<td>$IP_{\chi^2}(B_u)$</td>
<td>97.65 %</td>
<td>0.03 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>38.16 %</td>
<td>0.14 %</td>
</tr>
</tbody>
</table>

Table 3: Efficiency for each selection relative to the stripping.
2.1.1 Software

All the following studies were made using the library ROOT [21] and RooFit analysis toolkit. The scripts were coded in C++ and Python language. We used the analysis software of LHCb: DaVinci v26r3p2. This software is based on the Gaudi framework. To perform the Monte-Carlo toy study, we used the software Ganga v5.5.8 to run several jobs.

2.2 Selection induced propertime efficiencies

The $B^+ \to J/\psi K^+$ event selection has been designed to minimize the impact on the $B^+$ propertime distribution. In this section we will use fully simulated MC events to study the effect that the trigger and stripping selections have on the $B^+$ propertime efficiency. In particular, we made a special attention in the trigger and stripping efficiencies. Indeed, one must know the potential bias that may be introduced by the trigger and the stripping decision. This potential bias has to be taken into account in the future measure of $\tau_{B^+}$.

2.2.1 Trigger and Stripping efficiencies

In order to study the lifetime of the $B$-meson, the trigger or stripping decisions which are made should ideally not introduce bias. For example, a cut in the momentum or the impact parameter could introduce a final bias in the lifetime measurement. In this work we use the unbiased trigger lines:

\[ (\text{Hlt1SingleMuoNoIPL0 } || \text{Hlt1DiMuonNoIPL0Di}) \&\& \text{Hlt2UnbiasedJPsi} \]

with || the logical operator for “or” and && the logical operator for “and”. The selections of these trigger lines shown in Table 4.

<table>
<thead>
<tr>
<th>Hlt1SingleMuoNoIPL0</th>
<th>Hlt1DiMuonNoIPL0Di</th>
<th>Hlt2UnbiasedJPsi</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0-Muon</td>
<td>L0-DiMuon</td>
<td>-</td>
</tr>
<tr>
<td>PT $&gt;$ 1.8 GeV/c</td>
<td>-</td>
<td>$&gt;$ 500 MeV/c^2</td>
</tr>
<tr>
<td>P $&gt;$ 10 GeV/c</td>
<td>$&gt;$ 10 GeV/c</td>
<td>-</td>
</tr>
<tr>
<td>Track $\chi^2$/ndof</td>
<td>$&lt;$ 10</td>
<td>$&lt;$ 10</td>
</tr>
<tr>
<td>$\chi^2$ of muon hits</td>
<td>$&lt;$ 16</td>
<td>$&lt;$ 16</td>
</tr>
<tr>
<td>Sum PT of dimuon</td>
<td>$&gt;$ 1 GeV/c</td>
<td>-</td>
</tr>
<tr>
<td>Dimuon DOCA</td>
<td>$&lt;$ 0.5mm</td>
<td>-</td>
</tr>
<tr>
<td>Dimuon mass</td>
<td>$&gt;$ 2.5 GeV/c^2</td>
<td>$&gt;$ 2977 MeV/c^2 &amp; $&lt;$ 3217 MeV/c^2</td>
</tr>
</tbody>
</table>

Table 4: Trigger cuts for the Hlt lines of interest in this analysis.

The properties of each trigger lines are:

- **Hlt1SingleMuoNoIPL0**: This line starts from a single L0 muon object and checks if hits in the tracking station can be matched to it. If a match is found in the tracking
stations, the candidate particle is then further matched to reconstructed VELO tracks.

- **Hlt1DiMuonNoIPL0Di**: It uses dimuon candidates from L0 and fits track in the same way as the single muon with additional cut on the momentum and the transverse momentum of the dimuon pair. To check if the dimuon candidate comes from a common point, it uses the information of the distance of closest approach (DOCA).

- **Hlt2DiMuonUnbiasedJPsi**: This trigger line is used for events which pass the Hlt1 decisions. It selects combinations of muon with cut on the invariant mass $\chi^2$ of the vertex formed by the two muon.

Although this trigger lines are “unbiased”, we have to verify that the acceptance after the stripping, the trigger and the offline selection is flat as a function of the propertime and to quantify any bias we introduce. If there is bias induces by the acceptance, we have to introduce an acceptance function in the fitting model. To perform the following study, we generate Monte-Carlo events which give us the information of the generated propertime before and after the step of the stripping and after the step of the trigger decisions and the offline selections with respect to the stripping. On Figure 11 and 12, we present the generated propertime distribution and the acceptance of the stripping and the acceptance of the trigger plus the selections with respect to the stripping. The acceptances are defined as the following, in bins of the $B^+$ generated propertime: :

$$
\epsilon_{\text{strip}} = \frac{N_{\text{strip}}}{N_{\text{tot}}}
$$

$$
\epsilon_{\text{trig+sel}} = \frac{N_{\text{trig+sel}}}{N_{\text{strip}}}
$$

with $N_{\text{tot}}$ the number of events before any decisions or selections, $N_{\text{strip}}$ the number of events which pass the stripping and $N_{\text{trig+sel}}$ the number of single events which pass the trigger and the offline selections with respect to the stripping. On the top of the Figure 11, we present the generated propertime with any decisions (red) and the generated propertime of events which pass the stripping (green). On the bottom, the curve of acceptance $\epsilon_{\text{strip}}$ of events which pass the stripping is shown. On the top of the Figure 12, the generated propertime of events which pass the trigger decision and the offline selections with respect to the stripping is added (blue). On the bottom, we present the curve of acceptance of $\epsilon_{\text{trig+sel}}$ which is the acceptance function of events which pass the trigger and the offline selections with respect to the stripping.
Figure 11: On the top, the generated propertime for events with any selections (red) and for events which pass the stripping (green). On the bottom, the curve of the efficiency $\epsilon_{\text{strip}}$.

We fit the “trigger+selection” efficiency with a constant function and the stripping efficiency with a 1st polynomial function defined as:

$$\epsilon(\tau) = a + b\tau$$

On Table 5, we summarize the parameters of the fit.

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon_{\text{strip}}(\tau)$</th>
<th>$\epsilon_{\text{trig+sel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$0.3281 \pm 0.0006$</td>
<td>$0.3133 \pm 0.0084$</td>
</tr>
<tr>
<td>$b$</td>
<td>$-0.0044 \pm 0.0022$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: Parameters of the 1st polynomial fit of the efficiencies.
Figure 12: On the top, the generated propertime for events which pass the trigger and the offline selections (blue) and for events which pass the stripping (green). On the bottom, the curve of the efficiency $\epsilon_{\text{trig+sel}}$.

We can conclude that the efficiencies of each curve are $\epsilon_{\text{strip}} \approx 33\%$ and $\epsilon_{\text{trig+sel}} \approx 31\%$. As it is expected, the acceptance of the trigger and the selections with respect to the stripping is reasonably flat. However, the acceptance of the stripping clearly shows a linear dependence with $\tau$. This indicates that the function of the total acceptance which is the efficiency after the stripping, the trigger and the offline selections is also not flat. The total acceptance function $\epsilon_{\text{tot}}(\tau)$ is a linear function defined as the product of the two functions:

$$\epsilon_{\text{tot}}(\tau) = \epsilon_{\text{strip}}(\tau) \cdot \epsilon_{\text{trig+sel}}$$

On Table 6, we present the parameters of $\epsilon_{\text{tot}}(\tau)$.

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon_{\text{tot}}(\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$0.1046 \pm 0.0010$</td>
</tr>
<tr>
<td>$b$</td>
<td>$-0.0014 \pm 0.0005$</td>
</tr>
</tbody>
</table>

Table 6: Parameters of $\epsilon_{\text{tot}}(\tau)$. 

21
The slope of the total acceptance function could introduce bias in the final lifetime measurement. In a first approximation, we will study the $B^+$ lifetime without take into account the bias introduce by the curve of the efficiency in the first sections of this work. However, on the last chapter, we will present the results of the measured lifetime $\tau_{B^+}$ with the function of the acceptance incorporate in the fitting model.

2.3 Real Data at $\sqrt{s} = 7$ TeV Analysis

In this section, we study the lifetime of the $B^+$ using a dataset corresponding to $16 \text{pb}^{-1}$ of integrated luminosity collected at LHCb during the 2010 run. The selections presented in the previous section are used for data. First, we will expose the lifetime distribution and additional cut we made to reduce prompt background components. Then, an analysis of the background distribution is needed to model correctly the background under the signal. After this step, we will perform a measurement of the $B^+$ lifetime by using two different fitting methods. The first one is the simultaneous fit and the second one is the 2D fit. The results of these two methods will be consistent and we will extract $\tau_{B^+}$ thanks to the fitting model. Finally, we will perform some studies to determine the systematic errors associated with our selection and fitting model.

2.3.1 Lifetime distribution and additional cut

On the top of the figure 13, the $B^+$ lifetime distribution is presented. We recall that in addition to the standard selections we choose events which passed the “unbiased” trigger lines:

\[ \text{Hlt1SingleMuoNoIPL0 || Hlt1DiMuonNoIPL0Di \&\& Hlt2DiMuonUnbiasedJPsi} \]

It is clear that there are events in the negative side of the propertime distribution. This negative tail comes from a bad primary vertex associations for events with multiple primaries. If we choose the incorrect primary vertex, we can obtain a negative lifetime which will be in the negative side of the histogram. The events in the negative side of the lifetime do not provide physical information of the distribution in the positive side and does not improve the final measurement of the $B^+$ lifetime. For these reasons, we remove the negative tail by considering the lifetime distribution since $\tau > -1 \text{ps}$. We will show later in Section 2.3.5 that this cut does not bias the $B^+$ lifetime measurement. However, it rests a negative components which is not only resolution effect. This negative component induces a third Gaussian for the resolution function of the fitting model. We remark that, by choosing the vertex of the $B^+$ with the best $\chi^2$ for events with multiple vertex, we reduce a little the number of events.
in the negative tail (in blue on figure 13). As of this writing, no selections has been found for removing the negative tail.

Figure 13: $B^+$ lifetime and mass distributions after several cuts. In red, we apply only the trigger and the offline selections without the cut on the $J/\psi$ mass pull. In blue, we add a selection on the best vertex $\chi^2$. In green, the cut on the $J/\psi$ mass pull is added.

If we look at the bottom of the figure 13, we remark that despite the selections we have still a lot of background in the $B^+$ mass distribution. This high level of background is due to the prompt $J/\psi$. By choosing selections that do not bias the lifetime the presence of prompt component is even greater. The dominant process of the prompt component is the combination of a prompt $J/\psi \to \mu^+\mu^-$ with one prompt hadron (prompt $K$ for example)
and results to a peak centered on $\tau = 0 \ \text{ps}$ [9]. However, as we can see in red on figure 14, it remains a lot of background which is non-$J/\psi$ background. The fit of the $J/\psi$ mass is performed with a linear background and a Crystal Ball function for the signal.

The Crystal Ball is defined as:

$$
\frac{\left( \frac{|a|}{a} \right)^n \exp \left( -\frac{1}{2} \frac{M_{J/\psi} - \mu}{\sigma} \right)^2 \left( \frac{n}{|a|} - |a| - M_{J/\psi} \right)^n}{M_{J/\psi} < -|a|} \quad \frac{\exp \left( -\frac{1}{2} \frac{M_{J/\psi} - \mu}{\sigma} \right)^2 \left( \frac{n}{|a|} - |a| - M_{J/\psi} \right)^n}{M_{J/\psi} > -|a|}
$$

with $\mu$ the mean of the $J/\psi$ mass, $\sigma$ the width and $a,n$ are free parameters of the fit.

Figure 14: Fit of the $J/\psi$ mass with a Crystal Ball for the signal (green) and a linear background (red).

By applying a selection in the mass pull of the $J/\psi$ mass, we are able to remove events which are non-$J/\psi$. The mass pull corresponds to:

$$
Pull = \frac{M_{J/\psi} - M_{PDG}}{\sigma_{M_{J/\psi}}} \quad (6)
$$

with $M_{PDG}$ the PDG value of the $J/\psi$ mass and $\sigma_{M_{J/\psi}}$ the error on the $J/\psi$ mass. The distribution of the mass pull fitted with a Crystal Ball and a 1st polynomial function is shown on Figure 16.
Figure 15: Distribution of the $J/\psi$ mass pull fitted with a crystal ball (green dashed) and a first order polynomial function (red) for the flat background.

On Figure 16, we plot the width of the mass pull in bins of the $J/\psi$ momentum. As we see, the width remains constant with the change of the momentum at 1.4. Given that the width is not equal to 1, we introduce a scale factor of $s = 1.4$ when cutting on the $J/\psi$ mass pull.

Finally, by requiring that $\left|\frac{M_{J/\psi} - M_{PDG}}{\sigma_{M_{J/\psi}}}\right| < 3 \cdot s = 4.2$ we remove a lot of non-$J/\psi$ background with a loss of only $\sim 0.003\%$ of $J/\psi$ events which can be see in the green histogram.
on the bottom plot of Figure 13. On Figure 17, we show the pull distribution with the additional cut in red.

\[(M_{J/\psi} - M_{PDG}) / \sigma_{M_{J/\psi}}\]

Figure 17: Distribution of \( \frac{M_{J/\psi} - M_{PDG}}{\sigma_{J/\psi}} \) and the cut at ±4.2.

In table 7, we summarize the number of background, signal events and the ratio \( B/S \) after each cut calculated in the full mass range \( (M \in [5100, 5450] \text{ MeV}/c^2) \). The number of events in the signal region is obtained by fitting the mass with a single Gaussian and the background with a 1st polynomial function. We loose less than 7% of signal events for a gain of more 20% of \( B/S \) thanks to the cut on the \( J/\psi \) mass pull. By removing a lot of non-\( J/\psi \), we also increase the weight of the signal with respect to the background. This is significant for the convergence of the fitting model.

<table>
<thead>
<tr>
<th></th>
<th>( N_{sig} )</th>
<th>( N_{bkg} )</th>
<th>( B/S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>8209 ± 317</td>
<td>364103 ± 675</td>
<td>44.4 ± 1.8</td>
</tr>
<tr>
<td>Trigger + ( \chi^2 )</td>
<td>7946 ± 300</td>
<td>338835 ± 648</td>
<td>42.6 ± 1.7</td>
</tr>
<tr>
<td>Trigger + ( \chi^2 ) + cut on ( J/\psi ) mass</td>
<td>7656 ± 259</td>
<td>255980 ± 561</td>
<td>33.4 ± 1.2</td>
</tr>
</tbody>
</table>

Table 7: Summarize of the effects of the additional cuts (number of events with only the standard selection \( N_0 = 434646 \)).

### 2.3.2 1D fit model for \( B^+ \) lifetime

Because of the large number of events and the complexity of the different component of the background (long-lived,prompt,negative tail, etc), some fitting model does not converge.
A lot of model with different resolution functions were tested. In this section, we present the best model that was obtained. This fitting model will be used during this work to perform a simultaneous one dimensional fit. First, we define the resolution function which convolved with the other components of the model:

\[ R_{\text{res}}(\tau) = f_1 G_1(0, \sigma_1, \tau) + f_2 G_2(0, \sigma_2, \tau) + (1 - f_1 - f_2) G_3(0, \sigma_3, \tau) \]  

(7)

with \( G_i(0, \sigma_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{x^2}{2\sigma_i^2}} \) the Gaussian function and \( f_i \in [0, 1] \) the ratio between the Gaussian. The third Gaussian is needed to taking in account the contribution of the negative tail in the negative side of the lifetime.

Then, we define the background function:

\[ F_{\text{bkg}}(\tau) = g_1 e^{-\frac{\tau}{\tau_{1,3}}} + g_2 e^{-\frac{\tau}{\tau_{2,3}}} + (1 - g_1 - g_2) \delta(0) \]  

(8)

with \( \delta(0) \) the Dirac function centered in zero, \( e^{-\frac{\tau}{\tau_{i,3}}} \) the exponential decay and \( g_i \in [0, 1] \) the ratio between each components. The delta function models the prompt \( J/\psi \) of the background. The two exponential decay model the long-lived components which becomes from a \( J/\psi \) from a \( b\bar{b} \) combined with an other particle \( X \) (\( B_u \rightarrow J/\psi X \)) [9]. We consider both cases where we include the effect of the acceptance in the fit and where it is ignored. In a first approximation, we will not consider the correction of the efficiency.

\[ F_{\text{sig}}^A(\tau) = e^{-\frac{\tau}{\tau_{B^+}}} \]  

\[ F_{\text{sig}}^B(\tau) = e^{-\frac{\tau}{\tau_{B^+}}} \times \epsilon(\tau) \]  

(9) (10)

with \( \tau_{B^+} \) the \( B^+ \) lifetime and \( \epsilon(\tau) = a + b\tau \) the function which take into account the bias made by the trigger and the stripping decisions (the parameters \( a \) and \( b \) are defined in Table 5).

Finally, the total fitting function is:

\[ F_{\text{tot}}^{A,B}(\tau) = N_{\text{bkg}} F_{\text{bkg}}(\tau) \otimes R_{\text{res}}(\tau) + N_{\text{sig}} F_{\text{sig}}^{A,B}(\tau) \otimes R_{\text{res}}(\tau) \]  

(11)

with \( N_{\text{bkg}} \) and \( N_{\text{sig}} \) the yields of the number of events in the background and signal region. The operator \( \otimes \) denotes the operation of convolution defined as:

\[ (f \otimes g)(t) = \int_{-\infty}^{\infty} f(\tau) g(t - \tau) d\tau \]
2.3.3 Background distribution in the mass sideband region

In order to extract the $B^+$ lifetime, we have to fit the lifetime distribution with a model which describes the signal and the background distribution. However, we have to inspect the lifetime distribution in the $B^+$ mass sideband region and see which mass window we can take to model the background distribution. An inhomogeneity of the lifetime distribution along the $B^+$ mass could bias the lifetime measurement. On figure 18, we define the sideband region and the signal region in the $B^+$ mass. The signal region corresponds to a width of $55 \text{ MeV}/c^2 (\approx 5\sigma_M)$ centered on $\mu_M = 5276 \text{ MeV}/c^2$ where $\sigma_M$ and $\mu_M$ are respectively the resolution and the mean of a single Gaussian. Then, the sideband region correspond to a mass range of $M \in [5100, 5251] \cup [5306, 5450] \text{ MeV}/c^2$.

![Figure 18: $B^+$ mass signal and sideband region cut into several windows.](image)

By cutting the sideband region in several sub-regions with the same number of events, we are able to compare the lifetime distribution in each sub-regions. On figure 19, we show the lifetime distribution in each windows (1, 2, 3, 4, 5, 6 denotes the region from left to right). We remark that the distribution is not homogeneous along the sideband as we expected. For example, in the low mass region (1, 2) there is more long-lived components than the high mass region (5, 6). Thus, the inhomogeneity of the background distribution could bias the lifetime measurement. We have to find a balance between having enough events in the sideband region and having a distribution that represents well the background under the signal region. As we see on the figure 19, the distribution of the background near the signal (region 3, 4) is roughly homogeneous.
A way to see if we introduce bias in the lifetime measurement is to perform a simultaneous fit. This method consists to fit simultaneously two independent dataset with two probability density functions (PDFs). In our case, we fit the dataset of the signal region with $PDF_{sig}$ simultaneously with $PDF_{side}$ which are fitted in the dataset in the sideband region. $PDF_{sig}$ and $PDF_{side}$ are respectively the function which model the signal region and the function which model the background. These functions are defined as:

$$PDF_{sig}(\tau) = F_{tot}^A(\tau) \quad M \in [5251, 5306] \text{ MeV/c}^2$$  \hspace{1cm} (12)$$

$$PDF_{side}(\tau) = F_{bkg}(\tau) \otimes R_{res}(\tau) \quad M \in [5100, 5251] \cup [5306, 5450] \text{ MeV/c}^2$$  \hspace{1cm} (13)$$

On Figure 20, we present the simultaneous fit of the two independent dataset. We show $PDF_{sig}(\tau)$ in the signal region and $PDF_{side}(\tau)$ in the sideband region respectively on the top and on the bottom.
Figure 20: Simultaneous fit of the signal and the background dataset. In blue, the total function in each dataset. In red, the background. In green, the signal.

By changing the width of the dataset in the sideband region (Figure 21), we are able to compare the fit parameters along the sideband and see if we introduce any bias in the lifetime measurement by using a too large window in the $B^+$ mass.

Figure 21: Change of the width of the dataset in the $B^+$ mass sideband.
We start to extract $\tau_{B^+}$ with a dataset in the sideband region of a total width of 55 $MeV/c^2$ (22.5 $MeV/c^2$ in the low and high mass region). Then, we increase the width of the sideband step by step for every 30 $MeV/c^2$ (15 $MeV/c^2$ in the low and high mass region) until the total width of the sideband region (295 $MeV/c^2$).

On the top of the figure 22, we show $\tau_{B^+}$ as a function of the width of the sideband region in the simultaneous fit. There is no significant dependence between the lifetime measurement and the width in the sideband region. As it is expected, the error decreases with the increasing of the statistics in the sideband dataset and converges to a value. Despite the inhomogeneity of the background distribution, we introduce any bias in the lifetime measurement by using the whole sideband width. However, in a way to measure a signal of a width of 55 $MeV/c^2$ we do not need to consider the full mass range (295 $MeV/c^2$) to model the background distribution. As we see on the bottom of the Figure 22, we do not improve the error on $\tau_{B^+}$ significantly by taking the whole sideband even we have more statistics on it. It is why we reduce the mass window to $M \in [5150, 5400]$ $MeV/c^2$ which corresponds to a width of 195 $MeV/c^2$ nearest the signal. This allow us to remove a lot of events in the sideband dataset and gain computing time without losing information about the statistics.

In Table 8, the parameters of the simultaneous fit are presented.

![Figure 22: $\tau_{B^+}$ and the error as a function of the width of the $B^+$ mass sideband.](image)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_1$</td>
<td>$3.2166 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>$6.1999 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>$1.9971 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\tau_{B^+}$</td>
<td>1.64022</td>
</tr>
<tr>
<td>$\tau_{ll,1}$</td>
<td>$1.49999 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\tau_{ll,2}$</td>
<td>1.44188</td>
</tr>
<tr>
<td>$f_{ll,1}$</td>
<td>$2.5713 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$f_{ll,2}$</td>
<td>$3.21019 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$f_{res,2}$</td>
<td>$3.2583 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$f_{res,3}$</td>
<td>$8.5849 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 8: Fit parameters of the simultaneous fit performed in mass window of $M \in [5150, 5400]$ MeV/c$^2$.

### 2.3.4 2-dimensional fit to extract $B^+$ lifetime

In this section we will extend the model that was presented in section 2.3.2. Here, we describe a full 2-dimensional fit to the $B$ mass and $B$ propertime which we can use as a cross check of the results in 2.3.3. We use a two dimensional fit of the mass and the propertime which enhances the sensitivity of the results. On Figure 23, we show the two dimensional distribution of the $B^+$ with a colour code. This plot gives a qualitative view of the $B^+$ distribution. As we have previously seen, the majority of the events are prompt background. It is interesting to remark that this component is present all along the mass window. However, the population of prompt background around $\tau \approx 0$ ps is more important in the low mass region. This is essentially due to the fact that we have more events in the low mass region. The long lived component, which are signal and background, are essentially centered in the region of the mean of the $B^+$ mass. As we see in the study of the background distribution, there is also long-lived background in the low and high mass region. However, there is more long-lived background in the low mass region.
Figure 23: Two dimensional distribution: lifetime as a function of the mass.

We use the RooFit data analysis package to build a complete model PDF to describe our dataset. We use a product of two one dimensional PDF to perform the two dimensional fit. The $B^+$ mass distribution is modeled as follow:

$$F_{\text{signal}}, M(\Delta M) = G(\mu_M, \sigma_M, \Delta M)$$

$$F_{\text{bkg}}, M(\Delta M) = k_0 + k_1(\Delta M)$$

$$\Delta M = M - M_{PDG}$$

with $\mu_M$ and $\sigma_M$ the mean and the width of the Gaussian and $k_0, k_1$ the parameters of a first polynomial function. $\Delta M$ represents the mass difference between the measured mass and the PDG value.

The 2D total function is:

$$F_{2D}(\tau, \Delta M) = N_{\text{bkg}}F_{\text{bkg}}, \tau(\tau) \times F_{\text{bkg}}, M(\Delta M) + N_{\text{sig}}F_{\text{signal}}, \tau(\tau) \times F_{\text{signal}}, M(\Delta M) \quad (14)$$

with $N_{\text{sig}}$ and $N_{\text{bkg}}$ the number of events under the signal and the background. On Figure 24 and Figure 25, we present respectively the plot of $\Delta M$ and the lifetime performed with the 2D fit. The total function is drawn in blue, the background in red and the signal in green.
Figure 24: $B^+$ mass performed with the two dimensional fit. In red, the background function of the $B^+$ mass. In green, the signal. In blue the total function.

Figure 25: $B^+$ lifetime performed with the two dimensional fit. In red, the background function of the $B^+$ lifetime. In green, the signal. In blue the total function.

On Table 9, we summarize the parameters of the PDFs. First, we observe that the fit
parameters of the PDF which models the lifetime are consistent with the parameters of the simultaneous fit presented in Table 8. This fit gives a number of events under the signal of $N_{\text{sig}} = 7562 \pm 96$ and a number of events under the background of $N_{\text{bkg}} = 201464 \pm 451$. From those values, we get a ratio $B/S$ of $26.6 \pm 0.4$ which is better than previously thanks to the smaller mass window we used. We note that the first component of the long-lived background has a lifetime relatively short and suggest that this component could be prompt background. However, the model needs two long-lived components to converge well and this suggests that the nature of this component is different than the prompt component. The ratio of the third Gaussian of the resolution model is also very small but this component is necessary to take into account the contribution of the events in the negative tail. From this parameters, we note that the mass resolution is $11.032 \text{ MeV/c}^2$ as we expected.

The value of the $B^+$ lifetime from this model is:

$$\tau_{B^+} = 1.6391 \pm 0.0201 \text{ ps} \quad (15)$$

The average resolution of the propertime is:

$$< \sigma > = \sqrt{(1 - f_{\text{res},2} - f_{\text{res},3})\sigma_1^2 + f_{\text{res},2}\sigma_2^2 + f_{\text{res},3}\sigma_3^2} = 47.8 \pm 0.4 \text{ fs} \quad (16)$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{m_{B^+} - m_{PDG}}$</td>
<td>$-7.22936 \cdot 10^{-1}$</td>
<td>$1.4449 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>$3.2155 \cdot 10^{-2}$</td>
<td>$3.13 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>$6.1950 \cdot 10^{-2}$</td>
<td>$1.027 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>$1.9931 \cdot 10^{-1}$</td>
<td>$9.341 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>$11.032$</td>
<td>$0.122$</td>
</tr>
<tr>
<td>$\tau_{B^+}$</td>
<td>$1.6391$</td>
<td>$0.0201$</td>
</tr>
<tr>
<td>$\tau_{ll,1}$</td>
<td>$1.5021 \cdot 10^{-1}$</td>
<td>$5.85 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$\tau_{ll,2}$</td>
<td>$1.38242$</td>
<td>$0.01169$</td>
</tr>
<tr>
<td>$N_{\text{bkg}}$</td>
<td>$201464$</td>
<td>$451$</td>
</tr>
<tr>
<td>$N_{\text{sig}}$</td>
<td>$7562$</td>
<td>$96$</td>
</tr>
<tr>
<td>$f_{ll,1}$</td>
<td>$2.5795 \cdot 10^{-2}$</td>
<td>$1.066 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$f_{ll,2}$</td>
<td>$2.234 \cdot 10^{-3}$</td>
<td>$2.365 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$f_{\text{res},2}$</td>
<td>$3.2636 \cdot 10^{-1}$</td>
<td>$1.452 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$f_{\text{res},3}$</td>
<td>$8.6751 \cdot 10^{-3}$</td>
<td>$1.127 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 9: Fit parameters.
By using the information of the $\chi^2$ per number of freedom, the projection of the log-likelihood and the Monte-Carlo toy study, we are able to estimate the goodness of our fit. On Table 10, we resume the $\chi^2$ of the fitting model in each dimension of the dataset. For each plot, we get $\chi^2 > 1$ which means that the fit has not completely captured the data. We can observe on Figure 25 that the fit does not fully cover the data in the region of the negative tail ($\tau \in [-1, -0.5]$ ps). It is difficult to improve the quality of the fit in this region because we do not really know the nature of this negative tail. The coverage of the fit in the negative tail also explain why the quality of the fit is a bit better for the mass plot. However, the quality of the fit is acceptable and our model describes well the data.

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime plot</td>
<td>2.352</td>
</tr>
<tr>
<td>Mass plot</td>
<td>1.712</td>
</tr>
</tbody>
</table>

Table 10: $\chi^2$ of the lifetime and the mass plot.

On Figure 26, we show profile of the $-\log L$ of $\tau_{B^+}$ between the lower and the upper limit of this parameter. The value returned by the fit is the minimum as we expected. There are no other local minimum which may indicate that the fit converges to the correct value of the parameter.

Figure 26: Profile of the $-\log L$ of $\tau_{B^+}$.

To finally evaluate the goodness of the fit and to conclude that we modeled correctly the data, we perform a Monte Carlo toy study. This study has several step repeated $N$ times:

- Generate toy Monte-Carlo sample from the fitting model;
• Fit the model on the Monte-Carlo sample;
• Extract the parameters of the fit;

After $N$ iterations, we accumulate the fit statistics of the parameters which are extracted from the Monte-Carlo samples. Thus, we are able to represent the distribution of each fits of the parameter values, the parameter errors and the parameter pull. The pull distribution is defined as the difference between the input parameter from the data $m_i$ and the output parameter $m_f$ from the fit normalized by the quadratic error difference $(\sigma_i, \sigma_f)$:

$$\text{Pull} = \frac{m_i - m_f}{\sqrt{\sigma_i^2 - \sigma_f^2}}$$

If the parameters are well estimated from the fit, the pull distribution should have a $\mu_{\text{pull}} = 0$ and a $\sigma_{\text{pull}} = 1$. On Figure 27, we present the distribution of $\tau_{B^+}$, the distribution of the error on $\tau_{B^+}$ and the pull distribution of $\tau_{B^+}$. We generate 1000 samples of 210000 events each, which is the order of magnitude of the number of events in our 2010 data sample. As we see, the mean value of the parameter $\tau_{B^+}$ and the error on it correspond well to our measured lifetime from the real data. The mean value of the pull is $0.053 \pm 0.032$ and the width is $1.024 \pm 0.023$. In a window of $2\sigma$, the mean and the width have no shift and the parameter is well estimated from the fit.

![Figure 27: Monte-Carlo toy study. Distribution of $\tau_{B^+}$, the error of $\tau_{B^+}$ and the pull.](image)

On Table 11, $\mu_{\text{pull}}$ and $\sigma_{\text{pull}}$ for each parameters are presented. The distribution of the parameter, the error on the parameter and the pull for each parameters are shown in the Appendix B.
From this table, we observe that the majority of the parameter are well estimated in a window of $1 - 2\sigma$. However, $f_{res,3}$ has a pull mean too high. But, this fraction of the third Gaussian has a very small contribution compared to the others Gaussian’s fractions. This Monte-Carlo toy study definitively validates our model.

### 2.3.5 Systematics Study

In this section, we will estimate the systematic errors on the measure of $\tau_{B^+}$. These errors come mainly of the selections and the fitting model we used. First, we have to check if we introduced any errors by removing the negative tail with a cut at $\tau_{B^+} > -1$ ps. On Figure 28, we show on the left the measured lifetime and on the right the error on $\tau_{B^+}^+$ as a function of a cut in the negative tail. The time measured by our model is not dependent on the cut in the negative side of the lifetime distribution.
Figure 28: \( \tau_{B^+} \) and the error on it as a function of the cut in the negative side of the lifetime distribution.

Similarly, we show on Figure 29 how the lifetime and the error change as a function of the upper limit of the lifetime. Until \( \sim 14 \) ps, there is not enough statistics in the signal to measure well \( \tau_{B^+} \). For \( \tau > 14 \) ps, the parameters converge to the measured value. This indicates that the upper limit chosen is good even if a slightly lower limit does not degrade the measurement.

Figure 29: \( \tau_{B^+} \) and the error on it as a function of the upper limit of the lifetime.

To estimate the systematic error induce by the selections, we increase each cut of the Tables 1,2 one by one from 10% and measure the lifetime \( \tau_i \) by leaving others selections unchanged. Then, the spread between \( \tau_{B^+} \) (the measured lifetime with the initial cut) and
the mean value of the measure $\tau_i$ is an estimation of the systematics error $\sigma_{sys}^{sel}$:

$$\sigma_{sys}^{sel} = \frac{1}{N} \left( \sum_{i}^{N} \tau_i \right) - \tau_{B^+}$$

$$\sigma_i^{sel} = \tau_i - \tau_{B^+}$$

with $N = 11$ and $\sigma_i^{sel}$ the individual spread for each modify selections.

On Table 12, 13 and 14 we resume the values $\tau_i$ and the individual spread $\sigma_i^{sel}$ normalized by $\tau_{B^+}$ for each cuts modify by 10%. We remark that lifetime measurement is more sensitive to changes in the selections of $K^+$ transverse momentum and track quality, in the selection on the $J/\psi$ mass pull and in the selections on the $B^+$ impact parameter significance and vertex quality.

<table>
<thead>
<tr>
<th>$\chi^2_{\text{track}}/nDoF(\mu) &lt; 3.6$</th>
<th>$\min(p_T(\mu^+),p_T(\mu^-)) &gt; 0.55$ GeV/c</th>
<th>$\chi^2_{J/\psi}/nDoF(J/\psi) &lt; 9$</th>
<th>$M_{J/\psi}$ Pull &lt; 3.87</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_i$</td>
<td>1.6386</td>
<td>1.6384</td>
<td>1.6386</td>
</tr>
<tr>
<td>$</td>
<td>\sigma_i^{sel}/\tau_{B^+}</td>
<td>$</td>
<td>0.04%</td>
</tr>
</tbody>
</table>

Table 12: $\tau_i$ and $\sigma_i$ normalized by $\tau_{B^+}$ for each selection modify by 10%.

<table>
<thead>
<tr>
<th>$DLL_{K^+} &gt; 0.1$</th>
<th>$DLL_{K^p} &gt; -1.8$</th>
<th>$\chi^2_{\text{track}}/nDoF(K^+ &lt; 3.6$</th>
<th>$p_T(K^+) &gt; 1.43$ GeV/c</th>
<th>$p(K^+) &gt; 11$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_i$</td>
<td>1.6393</td>
<td>1.6408</td>
<td>1.6391</td>
<td>1.6466</td>
</tr>
<tr>
<td>$</td>
<td>\sigma_i^{sel}/\tau_{B^+}</td>
<td>$</td>
<td>0.05%</td>
<td>0.11%</td>
</tr>
</tbody>
</table>

Table 13: $\tau_i$ and $\sigma_i$ normalized by $\tau_{B^+}$ for each selection modify by 10%.

<table>
<thead>
<tr>
<th>$\chi^2_{DTF}/nDoF(B_u) &lt; 4.5$</th>
<th>$IP_{chi^2}(B_u) &lt; 22.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_i$</td>
<td>1.6403</td>
</tr>
<tr>
<td>$</td>
<td>\sigma_i^{sel}/\tau_{B^+}</td>
</tr>
</tbody>
</table>

Table 14: $\tau_i$ and $\sigma_i$ normalized by $\tau_{B^+}$ for each selection modify by 10%.

Thus, the estimation of the systematic error on the selections from these measurements is:

$$\sigma_{sys}^{sel} = 0.0007 \text{ ps}$$

The second source of systematic errors comes from the fitting model. To estimate this error, we modify the model slightly by removing an non-dominant component of the initial model and we extract the $B^+$ lifetime for each modifications. This gives us a few measurements by
which we calculate the gap with $\tau_{B^+}$ measured by the initial model as the estimation of the selections. We modify the model by removing one or two Gaussian of the resolution function and removing one long-lived component. On Table 15, we summarize the measured lifetime of the modified models and the gap between the measure and $\tau_{B^+}$.

<table>
<thead>
<tr>
<th></th>
<th>3 Gaussian / 1 Long-Lived</th>
<th>2 Gaussian / 1 Long-Lived</th>
<th>2 Gaussian / 2 Long-Lived</th>
<th>1 Gaussian / 2 Long-Lived</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_i$</td>
<td>1.6505</td>
<td>1.6497</td>
<td>1.6400</td>
<td>1.6385</td>
</tr>
<tr>
<td>$</td>
<td>\sigma_i^{\text{mod}}/\sigma_i^{\text{sel}}</td>
<td>$</td>
<td>0.7%</td>
<td>0.64%</td>
</tr>
</tbody>
</table>

Table 15: $\tau_i$ and $\sigma_i$ for modified model. We indicate the number of Gaussian of the resolution function and the number of long-lived components.

From this, we get an estimation of the systematic error induced by the model of :

$$\sigma_{\text{sys}^{\text{mod}}} = 0.0055 \text{ ps}$$

The combination of $\sigma_{\text{sys}^{\text{mod}}}$ and $\sigma_{\text{sys}^{\text{sel}}}$ lead us do to an estimation of the total systematic error on the measured lifetime $\tau_{B^+}$. These systematic error are uncorrelated :

$$\sigma_{\text{sys}^{\text{tot}}} = \sqrt{(\sigma_{\text{sys}^{\text{mod}}})^2 + (\sigma_{\text{sys}^{\text{sel}}})^2} = 0.0055$$

Thus, the measured $B^+$ lifetime with the statistical and the systematic error is given by :

$$\tau_{B^+} = 1.6391 \pm 0.0201 \pm 0.0055 \text{ ps} \quad (17)$$

### 2.3.6 $B^+$ lifetime measurement with the acceptance function

We recall that the acceptance function after the stripping, the trigger decisions and the offline selections is not flat. This potentialy introduces a bias in the final lifetime measurement. The parameters of the acceptance function is presented on Table 6. Because this effect is not well understood at the moment, we did not take into account the acceptance function in this work. Indeed, it could be possible that the Monte-Carlo sample that we use does not reproduce the data or that the $B$ production mechanisms are not well understood. However, we will present in this section the results of the fit of the lifetime distribution with a fitting model which incorporates the acceptance function. This PDF has been presented on equation 10 and 11. On table 16, the parameters of the fit is presented. If we compare these parameters with the fit parameters on the Table 9, we remark that there is no difference between the parameters except for $\tau_{B^+}$. The value of $\tau_{B^+}$ is :

$$\tau_{B^+} = 1.67983 \pm 0.02110 \text{ ps}$$

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The acceptance function induces an increase of more than 2.4% of the lifetime measurement without this function in the fitting model. This value is far from the expected measured value. However, the PDG value is still in a region of 2σ of $\tau_{B^+}$. It needs more investigation to understand from where comes the acceptance function and how to quantify it on the final measurement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu m_{B^+} - m_{PDG}$</td>
<td>$-7.22600 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>$3.21526 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>$6.19351 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\sigma_3$</td>
<td>$1.99012 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>$11.0319$</td>
</tr>
<tr>
<td>$\tau_{B^+}$</td>
<td>$1.67983$</td>
</tr>
<tr>
<td>$\tau_{ll,1}$</td>
<td>$1.50208 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\tau_{ll,2}$</td>
<td>$1.38238$</td>
</tr>
<tr>
<td>$N_{bkg}$</td>
<td>$201472$</td>
</tr>
<tr>
<td>$N_{sig}$</td>
<td>$7582$</td>
</tr>
<tr>
<td>$f_{ll,1}$</td>
<td>$2.57981 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$f_{ll,2}$</td>
<td>$2.23336 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$f_{res,2}$</td>
<td>$3.26556 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$f_{res,3}$</td>
<td>$8.67844 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 16: Parameters of the fitting model with the acceptance function.
3 Conclusion

In this work, we were able to reproduce the important stages of the lifetime measurement for the $B$ mesons. In particular, we studied the lifetime of $B^+$ mesons at LHCb. Initially, we analyzed the potential bias of the acceptance function. The Monte-Carlo study showed that the acceptance function after the stripping, the trigger decision and the offline selections is not flat. The curve of the acceptance was fit by a 1st polynomial function given by:

$$\epsilon(\tau) = a + b\tau$$

with $a = 0.1046 \pm 0.0010$ and $b = -0.0014 \pm 0.0005$. By using dataset corresponding to $16 pb^{-1}$ of integrated luminosity collected at LHCb during 2010, we started studied the effect of additional selections on the best $\chi^2$ and on the $J/\psi$ mass pull. This last cut removes a lot of non-$J/\psi$ background and improves the ratio $B_S$ more than 20 %.

Then, the $B^+$ lifetime was fitted in two different ways:

- a simultaneous fit of independent dataset in the sideband and in the signal region;
- a 2-dimensional fit of the $B^+$ lifetime and the $B^+$ mass.

It was shown that these methods gave similar results of the fitting model’s parameters. The first method was used to study the the distribution of the sideband region and showed that the inhomogeneity of the sideband region does not bias the final lifetime measurement. By using the second method, we extracted the value of $\tau_{B^+}$ and we estimated the systematic errors on the selection and the fitting model. The value of the extracted lifetime is:

$$\tau_{B^+} = 1.6391 \pm 0.0201 \pm 0.0055 \, ps$$

with an average propertime resolution of:

$$<\sigma> = 47.8 \pm 0.4 \, fs$$

The fitting model was validated through a Monte-Carlo toy study of 1000 samples. Finally, an effort of fitting the data by adding the acceptance function $\epsilon(\tau)$ was made. This attempt gave us a value of the measured lifetime of $\tau_{B^+} = 1.67983 \pm 0.02110 \, ps$. However, we would need more investigation to understand better the origin of the acceptance function and to figure out how to quantify its effect on the lifetime measurement. This study should be repeated for the control channel $B^* \rightarrow J/\psi K^*$ and for $B^0_s \rightarrow J/\Psi\phi$. 

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A Appendix : Future Work

In a future work, we should replicate the same study for :

- $B^0 \to J/\psi K^*$
- $B^0_s \to J/\psi \phi$

We should investigate where the slope of the acceptance comes from and check if the Monte-Carlo reproduce well the data to finally try to eliminate the effect (Section 2.2.1). We also need to understand how the acceptance function has to be well incorporate in the fitting model of the real data (Section 2.3.6). And we have to know why the generated propertime of the Monte-Carlo study is too small. It would be also interesting to have a better understanding of the provenance of the negative tail in order to improve our model and the quality of the fit.

To have better statistics and thus a smaller error on our measurement, it would be nice to include other trigger lines. On Figure 30, the trigger and the stripping efficiencies for the following unbiased line :

$$(\text{Hlt1SingleMuNoIPLO } || \text{ Hlt1DiMuonNoIPLODi }) \& \& \text{ Hlt2DiMuonUnbiasedJPsi}$$

These lines are more efficient than the previous one but present an important bias. It would be nice to successfully model these curves and add it to the unbiased trigger lines.

Figure 30: Efficiencies for trigger and stripping decisions. In red, the generated propertime. In green, the generated propertime for events which pass unbiased trigger decisions. In blue, the generated propertime for events which pass stripping decisions.
B Appendix: Toy Study Plot

On the following figure, we present the distribution of the parameter, the error on the parameter and the pull for each parameters of the fitting model obtained through the Monte-Carlo toy study and defined in the Section 2.3.4.

Figure 31: $\tau_{B^+}$.

Figure 32: $\sigma_m$. 
Figure 33: $\sigma_1$.

Figure 34: $\sigma_2$.

Figure 35: $\sigma_3$. 
Figure 36: $f_{res,2}$.

Figure 37: $f_{res,3}$.

Figure 38: $f_{ll,1}$. 

iv
C Appendix : Fit of the Monte-Carlo lifetime

For the Monte-Carlo study, the input value of $\tau_{B^+}$ is equal to the PDG value: $\tau_{B^+}^{PDG} = 1.638 \text{ ps}$. Ideally, the $\tau_{B^+}$ lifetime from the generated propertime has to be also equal to the PDG value. On the top of figure 42, we represent the Monte-Carlo generated propertime and the fit of a single exponential (blue).

Figure 42: Generated propertime for LHCb and a $\Omega = 4\pi$ detector.

The extracted value of $\tau_{B^+}$ is:

$$\tau_{B^+}^{LHCb} = 1.625 \pm 0.002 \text{ ps}$$

This value is a bit lower than the PDG value (in a region lower than $2\sigma_{PDG}$). If we look at the Monte-Carlo simulation in a detector which cover the full solid angle (bottom of the figure 42), $\Omega = 4\pi$, the extracted value is

$$\tau_{B^+}^{4\pi} = 1.639 \pm 0.002 \text{ ps}$$

which is exactly the PDG value. By selecting the events of the $4\pi$ detector which are present in the LHCb detector coverage, we find from the generated propertime:

$$\tau_{B^+}^{4\pi\in LHCb} = 1.639 \pm 0.003 \text{ ps}$$

This too low value of $\tau_{B^+}^{LHCb}$ which is not present if we start from a $4\pi$ detector is not well understood. It could be an effect of a bad reconstruction of the events. It requires more investigation to understand from where this difference come from.
References


