Search for $B_s^0 \to \phi\phi\gamma$ at LHCb

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1 Introduction

The goal of this work is to search for the rare $B$ decay $B^0_s \rightarrow \phi \phi \gamma$ in the data taken by the LHCb experiment in 2011 and 2012, which correspond to an integrated luminosity of 1 $fb^{-1}$ at $\sqrt{s} = 7$ TeV and 2 $fb^{-1}$ at $\sqrt{s} = 8$ TeV respectively. A preliminary study has already been done in TP4 with a selection based on the optimization of a figure of merit with a simplified background model. The present work concentrates on the systematic study of backgrounds in order to obtain a more accurate background model.

To perform this analysis, a selection is carried out first in order to concentrate our study of background on the decays that are very similar to the signal. After the determination of the signal and background shapes, the data collected at the LHC is used to determine the yields and put an upper limit on the branching fraction for $B^0_s \rightarrow \phi \phi \gamma$.

1.1 Theoretical context

The Standard Model is a set of theories that describe our current knowledge of particle physics. Though it has lead to important discoveries — the existence of the Higgs boson [1][2] being one of the most recent — it still has to be investigated. In this respect, the study of the radiative $B$ meson decays is a very interesting tool to probe for New Physics (NP). These flavor changing neutral current decays are forbidden at tree level in the Standard Model (SM), but they are allowed through electroweak loop processes such as the penguin diagram [3] shown in Fig. 1. These loops can be mediated by heavy SM particles (like the top quark) or non-SM particles such as charged Higgs or SUSY particles [4]. As these contributions can affect the branching ratio or other observables (as the photon polarization or CP asymmetry), the radiative $B$ meson decays are studied extensively in the searches for NP.

Figure 1: Feynman diagram of the process $b \rightarrow s \gamma$, also known as penguin diagram.

1.2 Current status of studies on radiative $B$ decays

In the LHCb collaboration, the group in charge of radiative decays concentrates its activities on the study of two body decays like $B \rightarrow K^* \gamma$, $B^0_s \rightarrow \phi \gamma$ and $B \rightarrow K_{res} \gamma$ with $K_{res} \rightarrow K \pi \pi$. On these decays, high precision measurement of branching ratios and CP asymmetry have been performed [5], and photon polarization has been observed [6]. The decay $B^0_s \rightarrow \phi \phi \gamma$ is the first three body radiative $B$ decay to be studied at LHCb and it is particularly challenging because it involves a large
number of tracks (each of the two $\phi$ mesons decays into two kaons of opposite charge, resulting in four tracks in the detector) and a neutral object (the $\gamma$ candidate) that can easily be misidentified with $\pi^0$.

Even though $B_s^0 \to \phi\phi\gamma$ has never been observed and no predictions are available, its branching ratio can be extrapolated as a first approximation from the branching ratio of $B^0 \to \phi K^0\gamma$ which has been measured by the Belle Collaboration [7] to be $(2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$. The Feynman diagrams of these two decays (Fig. 2) differ only by the spectator quark (a quark $d$ for $B^0 \to \phi K^0\gamma$ and a quark $s$ for $B_s^0 \to \phi\phi\gamma$), in the same way as the two well measured decays $B^0 \to K^{\ast 0}\gamma$ and $B_s^0 \to \phi\gamma$. Using the ratio of branching ratios of these two decays which has been measured by LHCb [5] to be $1.23 \pm 0.06 \pm 0.04 \pm 0.10 (f_s/f_d)$ and neglecting the interference effects coming from the vector or pseudo-scalar nature of the mesons involved, the branching ratio can be estimated as:

$$\mathcal{B}(B_s^0 \to \phi\phi\gamma) = \frac{\mathcal{B}(B^0 \to \phi K^0\gamma) \times \mathcal{B}(B_s^0 \to \phi\gamma)}{\mathcal{B}(B^0 \to K^{\ast 0}\gamma)} = (2.2 \pm 0.6) \times 10^{-6}. \quad (1)$$

Figure 2: Feynman diagrams of $B_s^0 \to \phi\phi\gamma$ and $B^0 \to \phi K^0\gamma$ decays.

In addition to completing the knowledge of $b \to s\gamma$ transitions, the study of the three body radiative decay $B_s^0 \to \phi\phi\gamma$ can enable to look for resonances in the hadronic part and to study the particular kinematics of three body decays involving one light body. The Belle Collaboration has reported that in the decay $B^+ \to \phi K^+\gamma$, the mass of the $\phi K$ system was not distributed as it would have been expected from a phase-space three body decay. As shown on Fig. 3a, the $B^+ \to \phi K^+\gamma$ events are concentrated at low masses ($1.5 < M_{\phi K} < 2.0 \text{ GeV}/c^2$). This peculiar distribution has been studied theoretically [8] for the decays of the form $B \to VVP$ (where $V$ stands for vector and $P$ stands for pseudo-scalar mesons) where one of the vector particles is very light. The theoretical distribution for $M_{\phi K}$ (or $M_{VP}$) on Fig. 3b reproduces the shape of the experimental data, but no prediction has yet been made for the invariant mass of $VV$ hadronic systems. Therefore, the invariant mass of $\phi\phi$ systems will also be studied in this project.
2 The LHC and the LHCb experiment

The $B$ mesons studied here are produced through proton-proton collision at the LHC \[9\] (Large Hadron Collider), a two-ring superconducting hadron accelerator and collider installed in a 26.7 km tunnel near Geneva, Switzerland. The four main experiments (ALICE \[10\], ATLAS \[11\], CMS \[12\] and LHCb \[13\]) are situated at different interaction points around the ring and their aim is the investigation of so-far unexplored domains of high-energy physics.

The LHCb experiment is dedicated to the study of $CP$ violation and rare decays of beauty and charm hadrons. Therefore, the detector is designed to trigger, reconstruct and identify the $b$ hadrons coming from the $b\bar{b}$ pairs massively produced through proton-proton collisions at the LHC.

As $b\bar{b}$ pairs generated by $pp$ interactions are boosted along the direction of the beam, they produce $b$-hadrons mainly in the same direction, either backwards or forwards, as can be seen on Fig. 4. To take advantage of this, LHCb has been designed as a one-arm spectrometer with an angle coverage from 10 mrad to 300 mrad along the beam direction \[13\] as shown on Fig. 5.

LHCb is composed of several sub-detectors which can be grouped in three systems:

- The Tracking System, dedicated to the reconstruction of charged particles, consists in:

  - The VErtex LOcator (VELO), a highly precise tracker made of silicon microstrips which is dedicated to the measurement of primary vertices (points where the $pp$ interactions occur) and secondary vertices (decay points of $b$-hadrons).
The Tracker Turisensis (TT), a silicon microstrip detector which is situated in front of the magnet.

Three tracking stations - T1, T2 and T3 - which are composed of a central Inner Tracker station (IT) made of silicon strips and surrounded by an Outer Tracker Station (OT), a drift-time detector using a mixture of Argon and CO$_2$ as a counting gas.

The LHCb magnet, which is used to bend the trajectory of charged particles (with a bending power of 4 Tm) in order to measure their ratio of charge over momentum.

The Particle Identification System consists in:

- Two Ring and Imaging CHERENKOV detectors (RICH1 and RICH2), two Cherenkov counters which are used to perform $\pi$-$K$ separation in the momentum range from 2 to 100 GeV/$c$.

- The Calorimeters (which will be described in details in section 3) which are used to trigger and identify particles.

- Five muon stations (M1, M2, M3, M4 and M5) which compose the muon detector.

The trigger system is composed of some of the already mentioned subdetectors (especially calorimeter and muon systems) plus the pile-up detector which is dedicated exclusively to triggering. This constitutes the first stage of the trigger [14], called L0. This hardware stage is followed by a software stage, in which almost full event reconstruction can be performed. For triggers that require neutral particles, energy deposits in the electromagnetic calorimeter are analysed to reconstruct $\pi^0$ and $\gamma$ candidates.
3 The LHCb calorimeter

The calorimeter fulfills two main goals. The first one is to provide fast information about particles to the hardware stage of the trigger system. The second one is to measure the energy of neutral particles and to provide particle identification used in the analyses.

To reach these goals, the calorimeter is made out of subdetectors based on the same detection principle: Scintillation light is transmitted by wavelength-shifting fibres to photomultiplier tubes. These four subdetectors are:

- The Scintillating Pad Detector (SPD), the subdetector that is closest to the interaction point (it is situated at 12.3 m of the interaction point) which provides an estimate of the number of charged tracks.
- The PreShower detector (PS), which is separated from the SPD by a wall of lead and that aims at identifying the electromagnetic and hadronic showers. It is also used to separate the neutral pions from photons.
- The Electromagnetic CALorimeter (ECAL) which measures the energy and provides trigger information for photons and electrons.
- The Hadronic CALorimeter (HCAL) which mainly provides trigger information for hadrons.

To optimize the energy resolution, the showers from high energy photons must be contained entirely in the ECAL. Thus, the latter has a thickness of 25 radiation lengths [15]. The PS is 10 % as thick as the ECAL.

As the hit occupancy varies by two orders of magnitude over the calorimeter surface, the SPD, PS, ECAL and HCAL have been designed with a variable lateral segmentation into square cells the sizes of which are shown on Table 1. For the
ECAL, three sizes of cells are used. The PS and SPD cells have corresponding sizes such that the cells cover the same angle as those of the ECAL viewed from the interaction point. The HCAL is divided in two regions with larger cells due to the extension of hadronic showers.

Table 1: Cell sizes for the subdetectors of the calorimeter, in mm.

<table>
<thead>
<tr>
<th></th>
<th>SPD</th>
<th>PS</th>
<th>ECAL</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>39.66</td>
<td>39.84</td>
<td>40.40</td>
<td>131.3</td>
</tr>
<tr>
<td>Middle</td>
<td>59.50</td>
<td>59.76</td>
<td>60.60</td>
<td></td>
</tr>
<tr>
<td>Outer</td>
<td>119.0</td>
<td>119.5</td>
<td>121.2</td>
<td>262.6</td>
</tr>
</tbody>
</table>

The energy resolution of the ECAL modules is parametrized as $\sigma_E/E = a/\sqrt{E} + b + c/E$ where $E$ is in GeV and $a$, $b$, $c$ are the stochastic, constant and noise terms respectively. Those parameters depend on the cell size and the beam conditions and they have been measured to be $8.5\% < a < 9.5\%$ and $b \sim 0.8\%$ [15] while $c$ has been found to be negligible.

4 Data samples

This analysis is performed on the merged data from two LHCb running periods. The first one, from March to November 2011, corresponds to a luminosity of 1 fb$^{-1}$ taken at $\sqrt{s} = 7$ TeV. The second one, from March to December 2012, corresponds to a luminosity of 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The Monte-Carlo (MC) sample for $B_s^0 \rightarrow \phi\phi\gamma$ includes 6M events and has been generated with the sim08 2012 configuration. In the simulation, $pp$ collisions are generated using PYTHIA [16, 17] with a specific LHCb configuration [18]. Decays of hadronic particles are described by EVTGEN [19], in which final-state radiation is generated using PHOTOS [20]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [21, 22] as described in Ref. [23].

5 Event selection

This analysis is a blinded analysis, which means that the region of signal around the mass of the $B_s$ meson (i.e. between 5186 and 5546 MeV/$c^2$) in data is not looked at until the selection and modelisation have been decided.

The selection of events collected by LHCb is performed in 3 steps:

1. The trigger (detailed in section 5.1) filters events on site at data-taking time so only the events which pass the trigger are recorded. The others are definitively lost.

2. Raw data are then reconstructed and selected to produce the data samples which are used for physics, in a process called Stripping (the selection applied at this level is discussed in section 5.2).
3. The background level is still high after Stripping, so an offline selection (detailed in section 5.3) has been applied. First, a soft selection has been used to select reasonably well reconstructed $B$ meson. On top of this, a tight cut has been applied on charged tracks identification to reduce significantly the contamination coming from backgrounds with at least one pion in the final state.

5.1 Trigger

First, the events are filtered by the trigger to reduce their rate from 40 MHz down to 5 kHz. The first level of trigger (L0) is meant to lower the event rate to 1 MHz at which the detector can be read out. It is made out of custom electronics and uses only the information of the Pile-Up system, the calorimeters and the muon systems to make a fast decision on whether to keep the events or not, at a rate of 40 MHz. The second level is a software level (High Level Trigger or HLT) made with commercially available equipment to lower the rate of events in such a way to reach a storable rate of 5 kHz. As the events can not be fully reconstructed before the decision-making process because of limitations of the computing power, the HLT is divided into two stages. In the first stage (HLT1), only a part of the event is reconstructed and the rate of events is lowered to 70 kHz. The events are then fully reconstructed and selected by the second stage (HLT2). The requirements to select our events are the following [24]:

- In L0: As the decay products of $B$ mesons are expected to have large transverse energy or high transverse momentum, the events are selected if they include an object with high transverse energy ($E_T$) in the ECAL (photon or electron) or the HCAL (hadron). The events must pass one of the following lines: L0Photon, L0Electron (which correspond to an energy deposition in the ECAL with $E_T$ higher than 2.5 GeV in 2011 and 2.7 GeV in 2012) or L0Hadron (which correspond to $E_T$ in the HCAL higher than 3.5 GeV in 2011 and 3.6 GeV in 2012). The efficiency of L0 on reconstructed signal $B^0_s \rightarrow \phi\phi\gamma$ MC is 64.7%.

- In HLT1: A single detached high momentum track is searched, which is filtered by different lines according to the L0 lines that have been triggered (either Hlt1TrackAllL0 or Hlt1TrackPhoton detailed on Table 2). In short, the track is required to have a minimum number of hits in the VELO, a minimum momentum $p$ and transverse momentum $p_T$, a good detachment of the track measured by its IP $\chi^2$ and a good quality of the track measured by its $\chi^2$. The respective efficiencies of these two lines on signal MC are shown on Table 3, achieving an efficiency of 80.8% for the two lines together on reconstructed signal $B^0_s \rightarrow \phi\phi\gamma$ MC.
Table 2: Requirements for Hlt1TrackAllL0 and Hlt1TrackPhoton. The bold characters indicate specifications that have been changed (between parentheses) or added in 2012 with respect to 2011.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Hlt1TrackAll</th>
<th>Hlt1TrackPhoton</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 requirement</td>
<td>L0_DECISION_PHYSICS</td>
<td>L0PhotonHi or L0ElectronHi(^1)</td>
</tr>
<tr>
<td>Velo Hits</td>
<td>&gt; 9</td>
<td>&gt; 9</td>
</tr>
<tr>
<td>Velo Missing Hits</td>
<td>&lt; 3</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Track Upgrade Tight</td>
<td>Tight</td>
<td>Loose</td>
</tr>
<tr>
<td>Hits</td>
<td>&gt; 16</td>
<td>&gt; 15</td>
</tr>
<tr>
<td>(\chi^2/\text{ndf})</td>
<td>&lt; 2 (1.5)</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>(p) (GeV/c)</td>
<td>&gt; 10</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>(p_T) (GeV/c)</td>
<td>&gt; 1.7 (1.6)</td>
<td>&gt; 1.2</td>
</tr>
<tr>
<td>\text{IP} (\chi^2)</td>
<td>&gt; 16</td>
<td>&gt; 16</td>
</tr>
<tr>
<td>\text{IP} (mm)</td>
<td>&gt; 0.1</td>
<td>&gt; 0.1</td>
</tr>
</tbody>
</table>

Table 3: Efficiencies of the lines of Hlt1 on reconstructed signal MC.

<table>
<thead>
<tr>
<th>Line(s)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hlt1TrackAllL0</td>
<td>74.6</td>
</tr>
<tr>
<td>Hlt1TrackPhoton</td>
<td>42.5</td>
</tr>
<tr>
<td>Hlt1TrackAllL0 or Hlt1TrackPhoton</td>
<td>80.8</td>
</tr>
</tbody>
</table>

– In HLT2: The events are selected through one of the two following types of trigger lines:

  – The inclusive \(\phi\) line (Hlt2IncPhi) which searches for detached \(\phi\) mesons built from pairs of oppositely charged tracks identified as kaons by making use of the RICH detectors. The requirements are presented in Table 4.

  – The radiative topological lines (Hlt2RadiativeTopoTrack and Hlt2RadiativeTopoPhoton in 2012, Hlt2RadiativeTopoTrackTOS and Hlt2RadiativeTopoPhoton in 2011) which trigger inclusively on any \(B\) decay with at least two tracks and one high-\(E_T\) photon \([24]\). The two tracks and photon are reconstructed to build a 3-body object, the \(B\) candidate, which is required to have a minimum \(p_T\) and vertex separation (VS). The content of these lines is detailed on Table 5.

The respective efficiencies of the topological lines all together and the inclusive \(\phi\) line on reconstructed signal MC are shown on Table 6. The total efficiency of the Hlt2 level is 98.1%.

Finally, the events are required to be triggered on signal (TOS) at all levels, which means that the signal part of the event must be sufficient get a positive answer from

\(^1\)Those lines are the same as L0Photon and L0Electron but with a cut on the transverse energy of the calorimeter object \(E_T > 4.2\) GeV
the trigger. This ensures that we get signal events for which the trigger efficiency can be derived from data using the TISTOS method [25].

Table 4: Requirements for Hlt2IncPhi. The bold characters indicate specifications that have been changed (between parentheses) in 2012 with respect to 2011.

<table>
<thead>
<tr>
<th>GEC</th>
<th>Forward Tracks</th>
<th>$&lt; 120$ (180)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>$\chi^2$/ndf</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>IP</td>
<td>$\chi^2$</td>
<td>$&gt; 6$</td>
</tr>
<tr>
<td>$p_T$ (MeV/c)</td>
<td>$&gt; 800$</td>
<td></td>
</tr>
<tr>
<td>PID $K$</td>
<td>$&gt; 0$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>Vertex $\chi^2$/ndf</th>
<th>$&lt; 20$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DOCA $(\text{mm})$</td>
<td>$&lt; 0.20$</td>
</tr>
<tr>
<td></td>
<td>$p_T$ (MeV/c)</td>
<td>$&gt; 1800$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>M - m_\phi(\text{PDG})</td>
</tr>
</tbody>
</table>

Table 5: Requirements for Hlt2RadiativeTopoTrack and Hlt2RadiativeTopoPhoton. The bold characters indicate specifications that have been changed (between parentheses) or added in 2012 with respect to 2011.

<table>
<thead>
<tr>
<th>GEC</th>
<th>Forward Tracks</th>
<th>Hlt2Radiative TopoPhoton</th>
<th>Hlt2Radiative TopoTrack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks</td>
<td>Track $\chi^2$/ndf</td>
<td>$&lt; 5$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td></td>
<td>IP $\chi^2$</td>
<td>$&gt; 10$</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td></td>
<td>$p$ (MeV/c)</td>
<td>$&gt; 5000$</td>
<td>$&gt; 5000$</td>
</tr>
<tr>
<td></td>
<td>$p_T$ (MeV/c)</td>
<td>$&gt; 700$ $(500)$</td>
<td>$&gt; 700$ $(500)$</td>
</tr>
<tr>
<td>2-track object</td>
<td>Vertex $\chi^2$</td>
<td>$&lt; 10$</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td></td>
<td>DOCA $(\text{mm})$</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.15$</td>
</tr>
<tr>
<td></td>
<td>Smallest track $\chi^2$/ndf</td>
<td>$&lt; 3$</td>
<td>$&lt; 3$</td>
</tr>
<tr>
<td></td>
<td>Smallest track IP $\chi^2$/ndf</td>
<td>$&gt; 16$</td>
<td>$&gt; 16$</td>
</tr>
<tr>
<td></td>
<td>DIRA</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td></td>
<td>$p_T$ (MeV/c)</td>
<td>$&gt; 1500$</td>
<td>$&gt; 1500$</td>
</tr>
<tr>
<td></td>
<td>$\text{Largest Track } p_T$ (MeV/c)</td>
<td>$&gt; 1200$</td>
<td>$&gt; 3000$</td>
</tr>
<tr>
<td></td>
<td>$M$ (MeV/c^2)</td>
<td>$&lt; 2000$</td>
<td>$&lt; 2000$</td>
</tr>
<tr>
<td>Photon</td>
<td>$E_T$ (MeV)</td>
<td>$&gt; 2500$</td>
<td>$&gt; 2500$ $(2000)$</td>
</tr>
<tr>
<td></td>
<td>$p_T, K1 + p_T, K2 + E_T, \gamma/c$ (MeV/c)</td>
<td>$&gt; 5000$</td>
<td>$&gt; 5000$</td>
</tr>
<tr>
<td></td>
<td>Vertex separation</td>
<td>$&gt; 0$</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td></td>
<td>Vertex separation $\chi^2$</td>
<td>$&gt; 64$</td>
<td>$&gt; 64$</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{corrected}}$ (MeV/c^2)</td>
<td>[4000,7000]</td>
<td>[4000,7000]</td>
</tr>
</tbody>
</table>

2Global Event Cuts: Set of cuts based on global event properties like the hit multiplicities.
3Distance Of Closest Approach defined as the distance between the two tracks.
5.2 Stripping

The raw data is then processed by the Radiative Stripping S20r0, which builds $B_s^0 \rightarrow \phi \phi \gamma$ candidates with very soft requirements with respect to the trigger except for the cut on $\phi$ vertex separation $\chi^2$. As can be seen on Table 7, the transverse momentum requirements ($E_T$ above 3 GeV for the photon, $p_T$ above 1.5 GeV/c for the $\phi$ candidate, $p_T$ above 5 GeV/c for the $B_s$ candidate) are the same or slightly tighter than those of the trigger. The main difference lies in the requirement on the reconstructed $\phi$ vertex separation $\chi^2$, which is required to be above 81. As can be seen on Fig. 6, this results in the requirement of a reconstructed $B$ meson with a vertex separation $\chi^2$ above 162, which is a tight selection. The $\phi$ meson is also characterized by a narrow natural width of $4.266 \pm 0.031 \text{ MeV}/c^2$ [26]. A window of three natural widths around the $\phi$ mass is selected to reduce the random combinations.

### Table 6: Efficiencies of the lines of Hlt2 on reconstructed signal MC.

<table>
<thead>
<tr>
<th>Line(s)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>radiative topological lines</td>
<td>79.7</td>
</tr>
<tr>
<td>inclusive $\phi$ line</td>
<td>94.9</td>
</tr>
<tr>
<td>radiative topological lines or inclusive $\phi$ line</td>
<td>98.1</td>
</tr>
</tbody>
</table>

### Table 7: Set of cuts applied at the stripping level.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of long tracks</td>
<td>$&lt; 500$</td>
</tr>
<tr>
<td>Track $\chi^2$/ndf</td>
<td>$&lt; 3$</td>
</tr>
<tr>
<td>Track $p_T$ (MeV/c)</td>
<td>$&gt; 500$</td>
</tr>
<tr>
<td>Track $p$ (MeV/c)</td>
<td>$&gt; 3000$</td>
</tr>
<tr>
<td>Track IP $\chi^2$/ndf</td>
<td>$&gt; 16$</td>
</tr>
<tr>
<td>Track ghost probability</td>
<td>$&lt; 0.5$</td>
</tr>
<tr>
<td>Largest track $p$ (MeV/c)</td>
<td>$&gt; 5000$</td>
</tr>
<tr>
<td>Photon $E_T$ (MeV)</td>
<td>$&gt; 2500$</td>
</tr>
<tr>
<td>Neutral vs Charged identification</td>
<td>$&gt; 0.25$</td>
</tr>
<tr>
<td>$\phi$ $p_T$ (MeV/c)</td>
<td>$&gt; 1500$</td>
</tr>
<tr>
<td>$\phi$ vertex $\chi^2$</td>
<td>$&lt; 9$</td>
</tr>
<tr>
<td>$\phi$ vertex separation $\chi^2$</td>
<td>$&gt; 81$</td>
</tr>
<tr>
<td>$B$ meson $p_T$ (MeV/c)</td>
<td>$&gt; 5000$</td>
</tr>
<tr>
<td>$B$ meson vertex $\chi^2$/ndf</td>
<td>$&lt; 16$</td>
</tr>
<tr>
<td>One track $p$ (MeV/c)</td>
<td>$&gt; 5000$</td>
</tr>
<tr>
<td>Same track $p_T$ (MeV/c)</td>
<td>$&gt; 500$</td>
</tr>
<tr>
<td>Same track $\chi^2$/ndf</td>
<td>$&lt; 2.5$</td>
</tr>
<tr>
<td>Same track IP (mm)</td>
<td>$&gt; 0.1$</td>
</tr>
<tr>
<td>$</td>
<td>M_\phi - m_\phi(\text{PDG})</td>
</tr>
</tbody>
</table>
5 EVENT SELECTION

Figure 6: Distributions of the vertex separation $\chi^2$ of the $B$ candidate normalized to unit area after trigger and stripping. The distribution of signal events (filled blue) is extracted from the Monte-Carlo simulation while the background events (depicted in red) are the events of the $B$ mass sidebands (for which the reconstructed invariant mass is above 5546 MeV/$c^2$ or below 5186 MeV/$c^2$) in data.

5.3 Offline Selection

The present work starts from stripped data and therefore the cuts previously presented can not be changed. However, some more cuts have been applied to better select the events which come from $B_s$ meson decays and to reject the backgrounds with a particular emphasis on those coming from decays with at least one pion in the final state (e.g. $B^0 \rightarrow \phi K^*\gamma$ and $B^0 \rightarrow \phi K^{*0}$). To do so, the following offline selection has been applied:

○ $\gamma/\pi^0$ separation variable: Discriminator built from the ECAL and PS information [27]. The background coming from $\pi^0$ is reduced by requiring the $\gamma/\pi^0$ identification to be above 0.6 (following the recommendations of the Calorimeter Objects Group [28]). The $\pi^0$’s decay into two $\gamma$’s which, if they are boosted enough, can form a single cluster in the calorimeter and therefore be identified as a $\gamma$ candidate (in this case, they are called merged $\pi^0$’s). At $p_T$ above
4 GeV/c, merged π^0’s dominate (as can be seen on Fig. 7). It is still possible to make a distinction between the clusters coming from a γ and a π^0 because the latter are more elliptical and their energy is spread around two main points instead of being concentrated in only one point as for a single photon. Thus, the discriminator is built out of the ECAL and PS variables that quantify this ellipticity and the energy spread. This variables takes values around 1 for γ’s and lower values for π^0’s as can be seen on Fig. 8a. As this variable is not perfectly modelled in MC, the samples have been reweighted using the data. The MC which includes a γ is reweighted using calibration tables extracted from a B → K^∗γ sample while for the MC including a π^0, a data sample of D^0 → Kππ^0 is used. For those two data samples, the efficiency of several cuts on the γ/π^0 separation variable with respect to the p_T of the ECAL object is given on Fig. 9.

Figure 8: Distributions of the γ/π^0 separation variable and the E_T of the γ candidate normalized to unit area. The distribution of signal events (filled blue) is extracted from the Monte-Carlo simulation while the background events (depicted in red) are the events of the B mass sidebands (for which the reconstructed invariant mass is above 5546 MeV/c^2 or below 5186 MeV/c^2) in data.

Figure 9: Efficiencies of different cuts on the γ/π^0 variable as a function of the γ candidate p_T for the two reference data samples.

- E_T of the γ candidate: Transverse energy of the reconstructed photon computed from the energy deposits in the PS and the ECAL. To try to remove the backgrounds with a random γ (for which the photon is expected to be softer),
and to align L0 requirements, the events are required to have $E_T$ above 3 GeV (cf. Fig. 8b).

○ Kaon identification (ProbNNk) of each of the decay products: This variable combines the RICH information with track information in order to provide a probability of a given particle to be a kaon. Therefore, its value can be used to discriminate kaons from pions. Since this variable is known to be poorly modelled in simulation, a reweighted distribution (obtained using calibration samples) has been used to get the distribution shown in Fig. 10. As the two kaons originating from the same $\phi$ are supposed to have identical properties if we assume charge symmetry as a first approximation, the same cut will be applied on kaon identification for the four of them. The four tracks are then required to have a kaon identification above 0.2. This selection enables to get rid of most of the backgrounds containing at least one $\pi$ as the background rejection is of 96% (obtained on $B$ mass sidebands in data) while the efficiency is of 80%.

![Figure 10](image-url)  
**Figure 10:** Distributions of the minimum of the four tracks kaon identification normalized to unit area. The description of the plot is detailed in the caption of Fig. 8.

![Figure 11](image-url)  
**Figure 11:** Distributions of the vertex $\chi^2$ and the DIRA normalized to unit area. The description of the plot is detailed in the caption of Fig. 8.

○ Vertex $\chi^2$ of the $B$ meson: $\chi^2$ of the fit of the decay vertex of the $B$ meson. A low vertex $\chi^2$ corresponds to well reconstructed $B$ meson candidate. Therefore, choosing the vertex $\chi^2$ to be below 16 allows to remove some random combinatorics, as can be seen on Fig. 11a.
DIRA of the \( B \) meson: Cosine of the angle between the reconstructed momentum of the \( B \) meson candidate and the direction defined by the vector between the primary vertex and the decay vertex of the \( B \). If the \( B \) meson comes from the primary vertex, this angle is expected to be equal to 0 so DIRA is equal to unity. But if the \( B \) candidate actually originates from partially reconstructed events (i.e. events where some daughter particles are missing in the reconstruction), the reconstructed momentum is not parallel to the direction of flight of the \( B \) candidate since daughters are missing in its reconstruction and the angle takes a non-zero value. In the case of the combinatorial background, tracks are wrongly associated to the \( B \) candidate and the effect is also to modify the reconstructed momentum such that it is no more parallel to the flight direction. The distribution of the variable is shown on Fig. 11b and it can be seen that even in the case of signal, the DIRA is different from 1 because of the resolution. In our case, the DIRA of the \( B \) meson is required to be above 0.9999.

Figure 12: Distributions of the impact parameter \( \chi^2 \) and the vertex separation \( \chi^2 \) normalized to unit area. The description of the plot is detailed in the caption of Fig. 8.

Impact parameter \( \chi^2 \) of the \( B \) meson: This variable measures the compatibility of the \( B \) candidate with the primary vertex by adding it to the vertex and calculating the difference of \( \chi^2 \). A small IP \( \chi^2 \) ensures that the \( B \) is well compatible with the hypothesis that it is coming from the primary vertex, which is in agreement with the distribution shown on Fig. 12a. Therefore, events with IP \( \chi^2 < 9 \) have been selected.

Vertex separation \( \chi^2 \) of the \( B \) meson: \( \chi^2 \) of the common fit of the \( B \) vertex and the primary vertex into one common vertex. The vertex separation \( \chi^2 \) is imposed to be above 200. This cut is motivated by the stripping selection because as discussed in section 5.2, the vertex separation \( \chi^2 \) of the two reconstructed \( \phi \)'s is required to be above 81, and this cut has already a large impact on the selection of the \( B \) meson as the error on the \( \phi \) vertex is important. This cut can be seen on Fig. 12b.

The set of cuts finally applied is shown on Table 8. The reduction effect of these cuts on data sidebands is shown on Fig. 13 where the background rejection induced by the cut on kaon identification appears clearly. After the offline selection, only
two events are left in the high mass sidebands (as can be seen on Fig. 14), which indicates that the combinatorial background has been almost fully removed.

Another type of contamination that has been removed is the so-called self cross-feed, which is a wrong reconstruction that occurs when the four kaons in the final state are not associated properly: a kaon of a given charge is associated with the kaon of opposite charge coming from the other $\phi$. In our case, the narrow windows around the $\phi$ masses suppress most of those wrong combinations. After our selection, the self cross-feed is of $0.22 \pm 0.04 \%$, which will be neglected in the following.

The total efficiency of the entire selection (trigger, stripping and offline selection) on signal MC is:

$$\varepsilon_{\text{sel}} = \varepsilon_{\text{trigger}} \times \varepsilon_{\text{strip}} \times \varepsilon_{\text{offline}}$$

$$= (51.28 \pm 0.27)\% \times (0.570 \pm 0.003)\% \times (61.8 \pm 0.4)\%$$

$$= (0.181 \pm 0.002)\%$$.

The PID and $\gamma/\pi^0$ efficiencies that are incorporated in the computation of $\varepsilon_{\text{offline}}$ have been evaluated by reweighting the MC sample according to the procedures recommended by the PID group [29] and the Calorimeter Objects Group [28]. This reweighting is made in such a way that the efficiency on MC matches the efficiency on data for specific control channels.

Table 8: Set of Selection cuts.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon $E_T$ (MeV)</td>
<td>$&gt;$ 3000</td>
</tr>
<tr>
<td>$\gamma/\pi^0$ separation</td>
<td>$&gt;$ 0.6</td>
</tr>
<tr>
<td>ProbNNk</td>
<td>$&gt;$ 0.2</td>
</tr>
<tr>
<td>$B$ meson DIRA</td>
<td>$&gt;$ 0.9999</td>
</tr>
<tr>
<td>$B$ meson IP $\chi^2$</td>
<td>$&lt;$ 9</td>
</tr>
<tr>
<td>$B$ meson vertex separation $\chi^2$</td>
<td>$&gt;$ 200</td>
</tr>
<tr>
<td>$B$ meson vertex $\chi^2$</td>
<td>$&lt;$ 16</td>
</tr>
</tbody>
</table>

(a) Cuts on the kinematic variables. (b) Cuts on particle identification variables.

Figure 13: Effect of the different cuts of the offline selection on data sidebands.
6 Background study

In order to identify and study the backgrounds that contaminate the signal, a low $B$ mass sideband of approximately 600 MeV/$c^2$ between 4600 and 5186 MeV/$c^2$ has been selected to concentrate on potentially dangerous background (therefore rather close to the signal range). After the selection, this low $B$ mass sideband contains 38 events. In this section, some properties of the background are inferred from the study of the $B$ mass sideband in data. With these elements, background sources are identified and MC samples are generated in order to estimate for each of those sources the number of events that are present in the $B$ mass sideband.

6.1 Study of $K^+K^-$ invariant mass and background candidates

With the events of the low $B$ mass sideband, a simultaneous fit of the invariant masses of the two kaon pairs has been performed with the result shown in Fig. 15: background with two true $\phi$’s dominates. We will hence focus on the estimation of the contribution of $B$ modes containing two true $\phi$’s in the final state and a $\gamma$ candidate and see if they can explain the number of events seen in the $B$ mass sideband.

To make a $\gamma$ candidate in the ECAL, the particle must be neutral (not to be detected by the trackers nor the SPD) and decay into one or more $\gamma$’s (to interact with the ECAL). Both $\pi^0$ and $\eta$ (which both decay into two $\gamma$’s) are good candidates, as well as $K^0_s$ decaying into two $\pi^0$’s. As discussed in section 5.3, the $\pi^0$’s with $p_T$ above 4 GeV/$c$ are so boosted that they are merged in the ECAL, which means that the two daughter $\gamma$’s form two clusters that are superimposed and hence reconstructed as one single cluster. As this cluster is more elliptical than the one originated by a single $\gamma$, the $\pi^0$’s can be differentiated from true $\gamma$’s by making use of the $\gamma/\pi^0$ separation variable. However, the two $\gamma$’s coming from the $\eta$ are separated enough, so the $\eta$ is resolved. Indeed, the angle between the two $\gamma$’s coming from a particle is given by:

$$1 - \cos(\theta) = M_{\text{mother}}^2 / 2E_1E_2 \simeq \theta^2 / 2.$$  (for small angles)  \hfill (3)

As $m_\eta = 548$ MeV/$c^2$ while $m_{\pi^0} = 135$ MeV/$c^2$, the two clusters coming from an $\eta$
Figure 15: Simultaneous fit of the invariant mass of the two kaon pairs in the $B$ mass sideband $4600 - 5186$ MeV/$c^2$. The left and right plots show respectively the invariant mass of the kaon pair with lowest and highest $p_T$. Four components are used to build the total distribution (red solid line). The first component (blue solid line) corresponds to the mass distributions of two phis modelled by Breit-Wigner functions. The magenta (resp. green) dashed line models a phi resonance for the kaon pair of lowest (resp. highest) $p_T$ and a flat distribution for the other kaon pair. Finally, the brown spotted line represents the kaonic background without structure.

are expected to be 4 times more separated than those coming from a $\pi^0$. In the transverse energy range allowed by the ECAL (up to 10 GeV) the $\eta$’s are always resolved so they can form a $\gamma$ candidate if the other $\gamma$ goes out of the acceptance.

Finally, the background modes are $B$ decays with two $\phi$’s and either a merged $\pi^0$ (alone or coming from a $K^0_S$), or a $\gamma$ (for example coming from an $\eta$). Some possibilities are listed below and will be developed in the following:

- $B^0 \to \phi\phi K_S^0$ and $B^0 \to \eta_c K_S^0$ (where $\eta_c \to \phi\phi$)
- $B^0 \to \phi\phi K^{*0}$ (where $K^{*0} \to K_S^0\pi^0$ and $K_S^0 \to \pi^0\pi^0$)
- $B^0 \to \phi\phi K^{*+}$ (where $K^{*+} \to K_S^0\pi^0$ and $K_S^0 \to \pi^+\pi^-$)
- $B^+ \to \phi\phi K^{*+}$ (where $K^{*+} \to K^+\pi^0$) and $B^+ \to \eta_c K^{*+}$ (where $\eta_c \to \phi\phi$ and $K^{*+} \to K^+\pi^0$)
- $B^0_s \to \phi\phi\eta$ and $B^0_s \to \eta_c \eta$ (where $\eta_c \to \phi\phi$)

Using MC simulated samples, the invariant $B$ mass distributions of these decays reconstructed as $B^0_s \to \phi\phi\gamma$ are shown in Fig. 18, 19, 20 and 21.

Some other decays with a $\gamma$ candidate, one $\phi$ and two charged tracks in the final state have also been considered (and have been found negligible thanks to the requirements on kaon identification). In particular, $B^0 \to \phi K^{*0}\gamma$, $B^0_s \to D_s^+ K^{*-} (D_s^+ \to \phi\pi^-) (K^{*-} \to K^-\pi^0)$ and $B^0_s \to D_s^+ K^- (D_s^+ \to \phi\rho^+)$ are studied in Section 6.3.
6.2 Study of the neutrals $\pi^0$ and $\gamma$

In order to estimate the ratio between the true $\pi^0$'s and true $\gamma$'s which are reconstructed as $\gamma$ candidates in the background, the behaviour of the $\gamma/\pi^0$ separation variable can be used. As shown in Fig. 16, the behaviour of the data sideband under cuts on the $\gamma/\pi^0$ separation variable indicates that the gamma candidate in this sideband looks more like a $\pi^0$ than a $\gamma$. It can also be noticed that the ratios of efficiencies for the data, MC $B_s^0 \to \phi\phi\eta$ and MC $B^0 \to \phi\phi K^0_S$ stay roughly constant. As MC for $B_s^0 \to \phi\phi\eta$ gives mainly true gamma candidates in the ECAL (which is equivalent to state that $\eta$'s are resolved) while MC for $B^0 \to \phi\phi K^0_S$ gives $\pi^0$, and assuming also that the gamma candidates in the data sidebands are only $\gamma$ and $\pi^0$, we can estimate that to recover the efficiency curve for the data, the latter must be composed of $(27 \pm 14)$% of $\gamma$ and $(73 \pm 14)$% of $\pi^0$ (using the average of ratios between $\varepsilon_{\text{cut}}(B_s^0 \to \phi\phi\eta) - \varepsilon_{\text{cut}}(\text{data})$ and $\varepsilon_{\text{cut}}(\text{data}) - \varepsilon_{\text{cut}}(B_s^0 \to \phi\phi K^0_S)$). Therefore, our background sideband can not contain more than $10.2 \pm 5.3$ events that include a true $\gamma$.

![Figure 16: Efficiency curves for cuts on the $\gamma/\pi^0$ separation variable for MC $B_s^0 \to \phi\phi\eta$, MC $B^0 \to \phi\phi K^0_S$, MC $B_s^0 \to \phi\phi\gamma$ and data in the $B$ mass sideband 4600 – 5186 MeV/c$^2$. Here, the efficiency is computed with respect to the number of events after trigger, stripping and off-line selection except the cut on $\gamma/\pi^0$ separation variable.]

6.3 Computation of expected yields

The number of expected events for a given $B$ decay is given by:

$$N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \to b\bar{b}X) \cdot f_q \cdot B(B_q \to \text{daughters}) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}. \quad (4)$$

Where:

- $\mathcal{L}$ is the integrated luminosity in fb$^{-1}$. In 2011, at $\sqrt{s} = 7$ TeV of center-of-mass energy, the integrated luminosity is $1.00 \pm 0.04$ fb$^{-1}$ [30]. In 2012, at $\sqrt{s} = 8$ TeV, the integrated luminosity is $2.01 \pm 0.02$ fb$^{-1}$. Considering the whole data set, the total luminosity is of $3.01 \pm 0.04$ fb$^{-1}$. 

σ(pp → b̄bX) is the cross-section of production of b̄b out of the proton proton collision. As this cross-section has only been measured at \( \sqrt{s} = 7 \) TeV by the LHCb Collaboration [31], an average cross-section will be used for the whole data set. As a first approximation, the cross-section at 8 TeV can be set at \( 8/7 \cdot \sigma(7 \text{TeV}) \). Then the total cross-section is the weighted average of the cross-sections at 7 and 8 TeV:

\[
\sigma_{\text{tot}} = \frac{\sigma(7 \text{TeV}) + 2 \cdot 8/7 \cdot \sigma(7 \text{TeV})}{3}.
\]

So the average cross-section is:

\[
\sigma(pp \to b\overline{b}X) = (311 \pm 22 \pm 54) \mu b.
\]

\( f_q \) is the fragmentation fraction, i.e. the probability that the b quark produced in the proton collision hadronizes with a quark q. Here, \( f_u = 0.401 \pm 0.007 \) [32], \( f_d \sim f_u \) and \( f_s/f_d = 0.259 \pm 0.015 \) [33].

\( \mathcal{B}(B_q \to \text{daughters}) \) is the branching ratio of the whole processus \( B_q \to ... \to \text{visible particles} \). The values given by the Particle Data Group [26] are reported in Table 9.

### Table 9: Branching Ratios [26].

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \to J/\psi K^0 )</td>
<td>( (8.73 \pm 0.32) \times 10^{-4} )</td>
</tr>
<tr>
<td>( B^0 \to J/\psi K^{*0} )</td>
<td>( (1.32 \pm 0.06) \times 10^{-3} )</td>
</tr>
<tr>
<td>( B^0 \to \eta_c K^0 )</td>
<td>( (7.9 \pm 1.2) \times 10^{-4} )</td>
</tr>
<tr>
<td>( B^0 \to \eta_c K^{*0} )</td>
<td>( (6.3 \pm 0.9) \times 10^{-4} )</td>
</tr>
<tr>
<td>( B^0 \to \phi\phi K^0 \ (M_{\phi\phi} &lt; 2850 \text{MeV}/c^2) )</td>
<td>( (4.5 \pm 0.9) \times 10^{-6} )</td>
</tr>
<tr>
<td>( B^+ \to \eta_c K^+ )</td>
<td>( (9.6 \pm 1.1) \times 10^{-4} )</td>
</tr>
<tr>
<td>( B^+ \to \eta_c K^{*+} )</td>
<td>( (1.0^{+0.5}_{-0.4}) \times 10^{-3} )</td>
</tr>
<tr>
<td>( B^+ \to \phi\phi K^+ \ (M_{\phi\phi} &lt; 2850 \text{MeV}/c^2) )</td>
<td>( (5.0 \pm 1.2) \times 10^{-6} )</td>
</tr>
<tr>
<td>( B^0_s \to J/\psi \eta )</td>
<td>( (4.0 \pm 0.7) \times 10^{-4} )</td>
</tr>
<tr>
<td>( B^0_s \to D_s^+ K^- )</td>
<td>( (2.03 \pm 0.28) \times 10^{-4} )</td>
</tr>
<tr>
<td>( \eta_c \to \phi\phi )</td>
<td>( (1.76 \pm 0.20) \times 10^{-3} )</td>
</tr>
<tr>
<td>( K^{*+} \to K^+ \pi^0 )</td>
<td>( (33.3003 \pm 0.0030) \times 10^{-2} )</td>
</tr>
<tr>
<td>( K^{*+} \to K^0 \pi^+ )</td>
<td>( (66.601 \pm 0.006) \times 10^{-2} )</td>
</tr>
<tr>
<td>( K^{*0} \to K^\pm \pi^\mp )</td>
<td>( (66.503 \pm 0.014) \times 10^{-2} )</td>
</tr>
<tr>
<td>( K^{*0} \to K^0 \pi^0 )</td>
<td>( (33.251 \pm 0.007) \times 10^{-2} )</td>
</tr>
<tr>
<td>( K^0_s \to \pi^+ \pi^- )</td>
<td>( (69.20 \pm 0.05) \times 10^{-2} )</td>
</tr>
<tr>
<td>( K^0_s \to \pi^0 \pi^0 )</td>
<td>( (30.69 \pm 0.05) \times 10^{-2} )</td>
</tr>
<tr>
<td>( D^+_s \to \phi \pi^+ \ (\phi \to K^+ K^-) )</td>
<td>( (2.24 \pm 0.10) \times 10^{-2} )</td>
</tr>
<tr>
<td>( D^+_s \to \phi p^+ )</td>
<td>( (8.4^{+1.9}_{-2.3}) \times 10^{-2} )</td>
</tr>
<tr>
<td>( \phi \to K^+ K^- )</td>
<td>( (48.9 \pm 0.5) \times 10^{-2} )</td>
</tr>
<tr>
<td>( \rho \to \pi\pi )</td>
<td>( \sim 100% )</td>
</tr>
<tr>
<td>( \eta \to \gamma\gamma )</td>
<td>( (39.41 \pm 0.20) \times 10^{-2} )</td>
</tr>
</tbody>
</table>
6 BACKGROUND STUDY

- $\varepsilon_{\text{acc}}$ is the acceptance of the detector, i.e. the rate of reactions for which all the decay products are in the geometrical area covered by the detector. The acceptance values computed from simulation are reported on Table 10. Those acceptances have to be used carefully because they are calculated differently depending on the daughter particles. In particular, the daughters of a $K_S^0$ are allowed to go out of the geometrical area of the detector, which implies that an event including a $K_S^0$ and charged tracks will be considered 'in the acceptance' if the charged tracks are in the geometrical area of the detector. On the other hand, for an event involving an $\eta$ and charged tracks, the $\gamma$ daughters of the $\eta$ must be in the geometrical area, otherwise the event is rejected. Therefore, some of the efficiencies are underestimated.

Table 10: Detector acceptances for the possible sources of background for the $B_s^0 \to \phi\phi\gamma$ decay [34].

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\varepsilon_{\text{acc}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to \eta_0,\eta$</td>
<td>16.33 ± 0.04</td>
</tr>
<tr>
<td>$B_s^0 \to \phi\phi\eta$</td>
<td>16.19 ± 0.03</td>
</tr>
<tr>
<td>$B^0 \to \eta_0 K^0_S$</td>
<td>15.5 ± 0.1</td>
</tr>
<tr>
<td>$B^0 \to \phi\phi K^0_S$</td>
<td>15.0 ± 0.1</td>
</tr>
<tr>
<td>$B^0 \to \phi\phi K^{*0} (K^0_S \to \pi^0\pi^0)$</td>
<td>13.22 ± 0.04</td>
</tr>
<tr>
<td>$B^0 \to \phi\phi K^{*0} (K^0_S \to \pi^+\pi^-)$</td>
<td>16.72 ± 0.05</td>
</tr>
<tr>
<td>$B^+ \to \eta_0 K^{*+}$</td>
<td>15.9 ± 0.1</td>
</tr>
<tr>
<td>$B^+ \to \phi\phi K^{*+}$</td>
<td>16.0 ± 0.1</td>
</tr>
<tr>
<td>$B^0_s \to D_+^* K^{-}$</td>
<td>16.04 ± 0.04</td>
</tr>
<tr>
<td>$B^0_s \to D_+^* K^{-}$ (D$^+_s \to \phi\pi^+$)</td>
<td>16.03 ± 0.06</td>
</tr>
<tr>
<td>$B_s^0 \to \phi\phi\gamma$</td>
<td>21.43 ± 0.05</td>
</tr>
</tbody>
</table>

- $\varepsilon_{\text{sel}}$ is the efficiency of the cuts applied on data. This efficiency is derived from MC simulation by computing the number of events that pass the cuts over the total number of generated events (the MC samples used in this analysis contain between 500 000 and 6 millions events). The efficiency ratio for particle identification (which is not well modelled in MC) is measured from data by means of a calibration procedure using pure samples of kaons and pions from $D^{\pm} \to D^0 (K^+\pi^-)\pi^{\pm}$ decays selected utilizing only kinematic criteria [29]. The efficiencies of the preselection on the $B$ mass sideband 4600 – 5186 MeV/$c^2$ are shown in Table 11.

In the following subsections, the possible background channels outlined above are studied in detail.

6.3.1 $B^0 \to \phi\phi K_S^0$

The branching ratio of the $B^0 \to \phi\phi K_S^0$ decay (non-resonant) has been measured by the $B$-factories only for $M_{\phi\phi} < 2850$ MeV/$c^2$ to avoid the mass region of the $\eta_c$. 

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Table 11: Table of efficiencies (as the number of events in the $B$ mass sideband [4600-5186 MeV/$c^2$] for the preselection. The central values and errors are calculated using the Wilson score [35]. All the upper limits on efficiency are given at 90% confidence level.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Generated events</th>
<th>Selected events</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \eta_c \eta_c$</td>
<td>220 999</td>
<td>89</td>
<td>$(4.0 \pm 0.4) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0 \to \phi \phi \eta$</td>
<td>406 497</td>
<td>136</td>
<td>$(3.36 \pm 0.29) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0 \to \eta_c K_S^0$</td>
<td>1 413 190</td>
<td>215</td>
<td>$(1.52 \pm 0.10) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0 \to \phi \phi K_S^0$</td>
<td>1 396 780</td>
<td>197</td>
<td>$(1.41 \pm 0.10) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^0 \to \phi \phi K_s^0$</td>
<td>399 499</td>
<td>18</td>
<td>$(4.7 \pm 1.1) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \to \phi \phi K_s^+ (K_s^0 \to \pi^0 \pi^0)$</td>
<td>391 499</td>
<td>2</td>
<td>$(5.0 \pm 3.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^+ \to \eta_c K^{++}$</td>
<td>1 456 643</td>
<td>3</td>
<td>$(2.7 \pm 1.3) \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^+ \to \phi \phi K^{++}$</td>
<td>1 504 565</td>
<td>7</td>
<td>$(5.1 \pm 1.8) \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^0 \to D_s^+ K^*$ $- (D_s^+ \to \phi \pi^+)$</td>
<td>1 143 211</td>
<td>0</td>
<td>$&lt; 2.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^0 \to D_s^+ K^* (D_s^+ \to \phi \pi^+)$</td>
<td>518 500</td>
<td>0</td>
<td>$&lt; 4.4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

$(m = 2983.6 \pm 0.7 \text{MeV}/c^2$, $\Gamma = 32.2 \pm 0.9 \text{MeV}/c^2$) as well as all the resonances present at higher masses (such as $\chi_{c0}$ and $\chi_{c2}$).

To extrapolate this branching ratio to the whole $M_{\phi \phi}$ range, the result of the BaBar collaboration [36] for the $B^+ \to \phi \phi K^+$ decay is used. Figure 17 shows the corresponding $M_{\phi \phi}$ distribution for a nearly constant efficiency of about 28% over the whole range. At first order, $i.e.$ ignoring possible interferences, the total number of $B^+ \to \phi \phi K^+$ events can be estimated as $1.7 \pm 0.3$ times the number of events with $M_{\phi \phi} < 2850 \text{MeV}/c^2$. This extrapolation can be used for $B^0 \to \phi \phi K_S^0$ if we assume that the shape of the $M_{\phi \phi}$ distribution is the same for $B^0 \to \phi \phi K_S^0$ and $B^+ \to \phi \phi K^+$.

Then, the expected number of $B^0 \to \phi \phi K_S^0$ events in the low $B$ mass sideband is:

\[
N_{\text{obs}} = L \cdot 2 \cdot \sigma(pp \to b \bar{b}X) \cdot f_d \cdot B(B^0 \to \phi \phi K_S^0) \cdot B(\phi \to KK)^2 \cdot B(K_S^0 \to \pi^0 \pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}
\]

\[
= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 1.7 \times 4.5/2 \times 10^{-6}.
\]

\[
= 0.489^2 \cdot 0.307 \cdot 0.150 \cdot 1.41 \times 10^{-4}
\]

\[
= 4.5 \pm 1.6.
\]

The contribution from the $B^0 \to \phi \phi K_S^0$ decay can hence explain partially the presence of $\pi^0$s in the low $B$ mass sideband.

Furthermore, the efficiency of the selection for the $B^0 \to \phi \phi K_S^0$ decay can be used to give a rough estimation of the contamination by $B^0 \to J/\psi K_S^0$, $J/\psi \to \phi \phi \gamma$ where the gamma is soft. The branching ratio for $J/\psi \to \phi \phi \gamma$ has been measured to be $(4.4 \pm 0.9) \times 10^{-4}$ [37] so using the branching ratio for $B^0 \to J/\psi K_S^0$ of $(4.38 \pm 0.16) \times 10^{-4}$ given by the PDG [26] the total branching ratio is $(1.9 \pm 0.4) \times 10^{-7}$. Assuming that the efficiency is identical to the $B^0 \to \phi \phi K_S^0$ one provided in Eq. 7, the computation gives 0.2 events, which is negligible. As the $J/\psi$ is expected to give the main contribution for the charmonia, all the decays of the type $B^0 \to \phi \phi K_S^0$ ($c \bar{c} \to \phi \phi \gamma$) give negligible contributions.
6 BACKGROUND STUDY

Figure 17: Fitted \(B^{+} \rightarrow \phi \phi K^{+}\) yield as a function of \(M_{\phi \phi}\) from the BaBar Collaboration \([36]\). Each point shows the results of a maximum likelihood fit of the events in that bin. The inset is the same data with an expanded vertical range to show the shape of the non-resonant component more clearly. The yield has been divided by the bin width and scaled by 0.027 GeV/c^2, which is the bin width of the three bins in the \(\eta_c\) resonance region ([2.94,3.02] GeV/c^2 and dashed vertical lines in the inset). The two narrow bins above the \(\eta_c\) are centered on the \(\chi_{c0}\) (bin range [3.400,3.430] GeV/c^2) and the \(\chi_{c2}\) (bin range [3.552,3.560] GeV/c^2).

6.3.2 \(B^{0} \rightarrow \eta_c K_{S}^{0}\)

The expected yields for \(B^{0} \rightarrow \eta_c K_{S}^{0}\) can be evaluated in two ways:

- The first possibility is to use directly Eq. 4 and the branching ratios given on Table 9. Then the number of events expected in the low \(B\) mass sideband (shown on Fig.18a) is:

\[
N_{\text{obs}} = \mathcal{L} \cdot \sigma(pp \rightarrow b \bar{b}X) \cdot f_d \cdot B(B^{0} \rightarrow \eta_c K_{S}^{0}) \cdot B(\eta_c \rightarrow \phi \phi) \\
B(\phi \rightarrow KK)^2 \cdot B(K_{S}^{0} \rightarrow \pi^0 \pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}} \\
= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 7.9/2 \times 10^{-4} \cdot 1.76 \times 10^{-3} \\
= 0.489^2 \cdot 0.307 \cdot 0.156 \cdot 1.52 \times 10^{-4} \\
= 0.90 \pm 0.29. \tag{8}
\]

- The other possibility is to use the results from the BaBar Collaboration \([36]\). It has been reported that the \(B^{+} \rightarrow \eta_c K^{+}\) yields were 33±8\% of the \(B^{+} \rightarrow \phi \phi K^{+}\) yields. Once more, the reported efficiency is the same for \(B^{+} \rightarrow \eta_c K^{+}\) and \(B^{+} \rightarrow \phi \phi K^{+}\). Assuming that the ratio \(r_{\eta_c/\phi \phi} = N_{B^{0} \rightarrow \eta_c K^{0}}/N_{B^{0} \rightarrow \phi \phi K^{0}}\) is the same for the neutral decay under study\(^4\), this gives an expected number of \(B^{0} \rightarrow \eta_c K_{S}^{0}\) decays of \(N_{\text{obs}} = 1.5 \pm 0.6\).

\(^4\)In fact, this ratio will later be assumed to be the same for all the K resonances, which will give a constraint on the inclusive number of contaminating \(B \rightarrow \phi \phi K\) (whatever the K resonance)
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Figure 18: Mass distributions for the candidates from MC simulations reconstructed as \( \phi \phi \gamma \) after preselection. The two black vertical lines show the range 4600 – 5186 MeV/c\(^2\) and the text indicates the number of candidates in the delimited range.

6.3.3 \( B^0 \rightarrow \phi \phi K^{*0} (K^0_s \rightarrow \pi^0 \pi^0) \)

To compute the expected \( B^0 \rightarrow \phi \phi K^{*0} \) yields (using the MC sample the \( B \) mass of which is shown on Fig.19a), the following assumptions are used:

- \( \mathcal{B}(B^0 \rightarrow \phi \phi K^{*0}) \) for \( M_{\phi \phi} < 2850 \) MeV/c\(^2\) is equal to \( \mathcal{B}(B^0 \rightarrow \phi \phi K^0_s) \) (\( M_{\phi \phi} < 2850 \) MeV/c\(^2\)). This assumption is based on the fact that the branching ratios for the \( B^0 \rightarrow J/\psi K^0 \) and \( B^0 \rightarrow J/\psi K^{*0} \) decays are of the same order (cf. Table 9).

- The efficiency of the preselection is constant over the whole \( M_{\phi \phi} \) range so we can assume the branching ratio for the whole \( M_{\phi \phi} \) range is 1.7 \( \pm \) 0.3 times the branching ratio for \( M_{\phi \phi} < 2850 \) MeV/c\(^2\).

\[
\begin{align*}
N_{\text{obs}} &= \mathcal{L} \cdot 2 \cdot \sigma(pp \rightarrow b \bar{b}X) \cdot f_d \cdot \mathcal{B}(B^0 \rightarrow \phi \phi K^{*0}) \cdot \mathcal{B}(\phi \rightarrow K K)^2 \cdot \mathcal{B}(K^{*0} \rightarrow K^0_s \pi^0) \cdot \mathcal{B}(K^0_s \rightarrow \pi^0 \pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}} \\
&= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 1.7 \times 4.5 \times 10^{-6} \cdot 0.489^2 \cdot 0.33251 \times 1/2 \cdot 0.307 \cdot 0.1322 \cdot 4.7 \times 10^{-5} \\
&= 0.44 \pm 0.19.
\end{align*}
\]

6.3.4 \( B^0 \rightarrow \phi \phi K^{*0} (K^0_s \rightarrow \pi^+ \pi^-) \)

The assumptions to compute the \( B^0 \rightarrow \phi \phi K^{*0} (K^0_s \rightarrow \pi^+ \pi^-) \) yields (using the MC sample shown on Fig.19b) are the same as the ones used in the previous background. Then:

\[
\begin{align*}
N_{\text{obs}} &= \mathcal{L} \cdot 2 \cdot \sigma(pp \rightarrow b \bar{b}X) \cdot f_d \cdot \mathcal{B}(B^0 \rightarrow \phi \phi K^{*0}) \cdot \mathcal{B}(\phi \rightarrow K K)^2 \cdot \mathcal{B}(K^{*0} \rightarrow K^0_s \pi^0) \cdot \mathcal{B}(K^0_s \rightarrow \pi^+ \pi^-) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}} \\
&= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 1.7 \times 4.5 \times 10^{-6} \cdot 0.489^2 \cdot 0.33251 \times 1/2 \cdot 0.6920 \cdot 0.1672 \cdot 5.0 \times 10^{-6} \\
N_{\text{obs}} &= 0.13 \pm 0.10.
\end{align*}
\]
6 BACKGROUND STUDY

(a) $B^0 \rightarrow \phi \phi K^0$ ($K_S^0 \rightarrow \pi^0 \pi^0$)

(b) $B^0 \rightarrow \phi \phi K^+0$ ($K_S^0 \rightarrow \pi^+ \pi^-$)

Figure 19: Mass distributions for the candidates from MC simulations reconstructed as $\phi \phi \gamma$ after preselection. The two black vertical lines show the range $4600 - 5186$ MeV/c$^2$ and the text indicates the number of candidates in the delimited range.

6.3.5 $B^+ \rightarrow \phi \phi K^{*+}$

To compute the expected $B^+ \rightarrow \phi \phi K^{*+}$ yields in the low $B$ mass sideband shown on Fig. 20b, the following assumptions are used:

- $\mathcal{B}(B^+ \rightarrow \phi \phi K^{*+})$ for $M_{\phi \phi} < 2850$ MeV/c$^2$ is equal to $\mathcal{B}(B^+ \rightarrow \phi \phi K^+)$ ($M_{\phi \phi} < 2850$ MeV/c$^2$).

- The efficiency of the preselection cuts is the same on all the $M_{\phi \phi}$ range.

$$N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \rightarrow b \bar{b}X) \cdot f_u \cdot \mathcal{B}(B^+ \rightarrow \phi \phi K^{*+}) \cdot \mathcal{B}(\phi \rightarrow KK)^2 \cdot \mathcal{B}(K^{*+} \rightarrow K^+ \pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}$$

$$= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 1.7 \times 5.0 \times 10^{-6} \cdot 0.489^2 \cdot 0.333 \cdot 0.160 \cdot 5.1 \times 10^{-6}$$

$$= 0.41 \pm 0.22.$$

(a) $B^+ \rightarrow \eta_c K^{*+}$

(b) $B^+ \rightarrow \phi \phi K^{*+}$

Figure 20: Mass distributions for the candidates from MC simulations reconstructed as $\phi \phi \gamma$ after preselection. The two black vertical lines show the range $4600 - 5186$ MeV/c$^2$ and the text indicates the number of candidates in the delimited range.
6 BACKGROUND STUDY

6.3.6 $B^+ \to \eta_c K^{*+}$

Once more, there are two possibilities for the computation of $B^+ \to \eta_c K^{*+}$ yields:

- The first one does not take into account the interferences and assumes that the efficiency of the preselection cuts is the same on all the $M_{\phi\phi}$ range. Using the number of MC events in the low $B$ mass sideband (Fig.20a), this gives:

$$N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \to b\bar{b}X) \cdot f_s \cdot \mathcal{B}(B^+ \to \eta_c K^{*+}) \cdot \mathcal{B}(\eta_c \to \phi\phi) \cdot \mathcal{B}(\phi \to KK)^2 \cdot \mathcal{B}(K^{*+} \to K^+\pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}$$

$$= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \cdot 1.0 \times 10^{-3} \cdot 1.76 \times 10^{-3}.$$  \(12\)

$$= 0.489^2 \cdot 0.333003 \cdot 0.159 \cdot 2.7 \times 10^{-6} = 0.045 \pm 0.034.$$

- The other possibility is based on the assumption that the ratio $N_{B^+ \to \eta_c K}/N_{B^+ \to \phi\phi K}$ for $M_{\phi\phi} < 2850$ MeV/$c^2$ is $33 \pm 8\%$, which leads to $0.14 \pm 0.08$ expected $B^+ \to \phi\phi K^{*+}$ decays.

6.3.7 $B^0 \to \phi K^{*0}\gamma$

Even though the main contamination sources are expected to include two $\phi$'s, the cross-feed contamination from $B^0 \to \phi K^{*0}\gamma$ is considered, using a MC sample of 6M events. Despite the tight cut in kaon identification, the pion coming from the decay $K^{*0} \to \pi K$ can still be misidentified as a kaon. With this wrong mass hypothesis, the invariant mass of the two track system can enter the window $1005 - 1035$ MeV/$c^2$ and the pair can be considered as a $\phi$ candidate.

The efficiency of our set of cuts in the signal region (between 5186 and 5546 MeV/$c^2$) is $(5.0 \pm 2.8) \times 10^{-7}$. So assuming that the branching ratio is the same for $B^0 \to \phi\phi\gamma$, and $B^0 \to \phi K^{*0}\gamma$, the expected yields are three orders of magnitude below the expected yields for $B^0 \to \phi\phi\gamma$ and will be neglected.

6.3.8 $B^0_s \to D_s^+ K^{*-} \quad (D_s^+ \to \phi\pi^+)(K^{*-} \to K^-\pi^0)$

Here, only a limit can be set due to limited MC statistics, assuming $\mathcal{B}(B^0_s \to D^+_s K^{*-})$ equals $\mathcal{B}(B^0_s \to D^+_s K^- \pi^+)$. As no event pass the selection, the upper limit of the mean of the Poisson distribution at 90\% confidence level is 2.3. Therefore:

$$N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \to b\bar{b}X) \cdot f_s \cdot \mathcal{B}(B^0_s \to D^+_s K^{*-}) \cdot \mathcal{B}(D^+_s \to \phi\pi^+) \cdot \mathcal{B}(\phi \to KK) \cdot \mathcal{B}(K^{*-} \to K^-\pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}$$

$$N_{\text{obs}} < 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \times 0.259 \cdot 2.03 \times 10^{-4}.$$  \(13\)

$$= 2.24 \times 10^{-2} \cdot 0.489 \cdot 0.333003 \cdot 0.1604 \cdot 2.0 \times 10^{-6}$$

$$N_{\text{obs}} < 0.046 \pm 0.013.$$

Therefore, no $B^0_s \to D_s^+ K^{*-}$ decay is expected to be seen in the $B$ mass sideband.
6.3.9 \( B^0_s \rightarrow D^+_s K^- (D^+_s \rightarrow \phi \rho^-) \)

Here, only a limit can be set:

\[
N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \rightarrow b\bar{b}X) \cdot f_s \cdot B(B^0_s \rightarrow D^+_s K^-) \cdot B(D^+_s \rightarrow \phi \rho^-) \cdot B(\phi \rightarrow KK) \cdot B(\rho^- \rightarrow \pi^- \pi^0) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}
\]

\[
N_{\text{obs}} < 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \times 0.259 \cdot 2.03 \times 10^{-4}. \quad (14)
\]

\[
8.4 \times 10^{-2} \cdot 0.489 \cdot 1 \cdot 0.1603 \cdot 4.4 \times 10^{-6}
\]

\[
N_{\text{obs}} < 1.1.
\]

Therefore, less than 1.1 \( B^0_s \rightarrow D^+_s K^- \) decay is expected to be seen in the \( B \) mass sideband.

6.3.10 \( B^0_s \rightarrow \eta_c \eta \)

To estimate the branching ratio of \( B^0_s \rightarrow \eta_c \eta \), which has never been measured, it is useful to notice that the Feynman diagrams for \( B(\eta_c \eta \rightarrow D^+_s K^-) \) and \( B(\eta_c K^0 \rightarrow D^+_s K^-) \) differ only by the spectator quark, which is a strange quark in the first case and a down in the second case. Similarly, the two decays \( B(\eta_c \eta \rightarrow J/\psi \eta) \) and \( B(\eta_c K^0 \rightarrow J/\psi K^0) \) differ only by the same spectator quarks. Therefore, the branching ratio for \( B(\eta_c \eta \rightarrow D^+_s K^-) \) can be estimated as:

\[
B(\eta_c \eta \rightarrow D^+_s K^-) = B(\eta_c K^0) \times \frac{B(\eta_c \eta \rightarrow J/\psi \eta)}{B(\eta_c K^0 \rightarrow J/\psi K^0)}
\]

\[
= (3.6 \pm 0.8) \times 10^{-4}. \quad (15)
\]

which gives:

\[
N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \rightarrow b\bar{b}X) \cdot f_s \cdot B(B^0_s \rightarrow \eta_c \eta) \cdot B(\eta_c \rightarrow \phi \phi) \cdot B(\phi \rightarrow KK)^2 \cdot B(\eta \rightarrow \gamma \gamma) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}
\]

\[
= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \times 0.259 \cdot 3.6 \times 10^{-4} \cdot 1.76 \times 10^{-3}.
\]

\[
0.489^2 \cdot 0.3941 \cdot 0.1633 \cdot 4.0 \times 10^{-4}
\]

\[
= 0.76 \pm 0.28. \quad (16)
\]

\[\text{Figure 21:} \] Mass distributions for the candidates reconstructed as \( \phi \phi \gamma \) (MC simulations) after preselection. The two black vertical lines show the range \( 4600 - 5186 \text{ MeV}/c^2 \) and the text indicates the number of candidates in the delimited range.
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6.3.11 $B_s^0 \to \phi \phi \eta$

Contrary to the other $\phi \phi X$ modes investigated so far, the ratio $N_{B_s^0 \to \eta_c K}/N_{B_s^0 \to \phi \phi K}$ is not expected to be the same as $N_{B^+ \to \eta_c K^+}/N_{B^+ \to \phi \phi K^+}$. In the $B^+ \to \phi \phi K^+$ decay, the $K^+$ can only come from the spectator quark, as in $B^+ \to \eta_c K^+$. On the contrary, in the $B_s^0 \to \eta_c \eta$ decay, the $\eta$ also comes from the spectator quark whereas in $B_s^0 \to \phi \phi \eta$, each of the three $s \bar{s}$ pairs in the final state can give an $\eta$.

Therefore, as a naive approximation, the branching ratio for $B_s^0 \to \phi \phi \eta$ can be estimated as:

$$B(B_s^0 \to \phi \phi \eta) = 3 \times B(B^0 \to \phi \phi K^0) \times \frac{B(B_s^0 \to J/\psi \eta)}{B(B^0 \to J/\psi K^0)}$$

$$= (1.05 \pm 0.35) \times 10^{-5}.$$  \hfill (17)

Then:

$$N_{\text{obs}} = \mathcal{L} \cdot 2 \cdot \sigma(pp \to b \bar{b} X) \cdot f_s \cdot B(B_s^0 \to \phi \phi \eta) \cdot B(\phi \to KK)^2 \cdot B(\eta \to \gamma \gamma) \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{sel}}$$

$$= 3.01 \cdot 2 \cdot 3.11 \times 10^{11} \cdot 0.401 \times 0.259 \cdot 1.05 \times 10^{-5}.$$

$$= 3.01 \pm 0.7 \times 10^{11} \cdot 0.489 \cdot 0.3941 \cdot 0.1619 \cdot 3.36 \times 10^{-4}$$

$$= 10.5 \pm 4.5.$$  \hfill (18)

Therefore, the contribution coming from the $B_s^0 \to \phi \phi \eta$ decay can explain the $10.2 \pm 5.3$ events with a true $\gamma$ candidate that are observed in the low $B$ mass sideband (cf. Section 6.2).

Using the efficiency for the $B_s^0 \to \phi \phi \eta$ decay reconstruction, the contamination by $B_s^0 \to J/\psi \eta$, $J/\psi \to \phi \phi \gamma$ where the gamma is soft can be estimated to less than 0.3 events (the computation is similar to the one described in Section 6.3.1), which will be neglected.

6.4 Constraints from data

As it has been discussed in Section 6.3.2, the ratio $N_{B \to \eta_c K}/N_{B \to \phi \phi K}$ is expected to be the same for all the $K$ resonances (even for those whose corresponding branching ratio has not been measured yet). Therefore, the number of $\eta_c$ observed in data gives a constraint on the number of $B \to \phi \phi K$. As shown on Fig. 22, $2.8^{+3.0}_{-2.1}$ $\eta_c$ can be observed in the background, amongst which 0.76$\pm$0.28 should come from $B_s^0 \to \phi \phi \eta$.

Thus, $2.0^{+3.0}_{-2.1}$ events at most could be a signature of $B \to \eta_c K$ decays. Assuming that there are $1/r_{\eta_c/\phi \phi} = 3.0 \pm 0.7$ times more events coming from $B \to \phi \phi K$ processes, up to $6.1^{+9.2}_{-6.5}$ $B \to \phi \phi K$ events can be expected in the $B$ mass sideband.
Figure 22: Distribution of the φφ invariant mass for data in the B mass sideband 4600–5186 MeV/c² after preselection. The green line models the expected flat background whereas the ηc resonance is fitted with a Breit-Wigner distribution (in blue).

6.5 Summary of background study

Table 12: Summary of the results of the study of the B mass sideband between 4600 and 5186 MeV/c².

| γ/π⁰ separation variable | ηc fit and Computation using Total Branching Ratios |
|--------------------------|-----------------------------------------------|-----------------------------------------------|
| true γ candidate: 10     |                                               |                                               |
| B⁰ → ηcγ                  |                                                |                                               |
| B⁰s → ηcφ                 |                                                |                                               |
| B → ηcX_s: < 5            | B⁰ → ηcK⁰⁺: 0.90 ± 0.29                        | 11.3 ± 4.5                                    |
|                          | B⁺ → ηcK⁺⁺: 0.045 ± 0.034                     |                                               |
| B → φφX_s: < 15          | B⁰ → φφK⁰⁺: 4.5 ± 1.6                        |                                               |
|                          | B⁰ → φφK⁺⁺ (K⁰⁺ → π⁺π⁻): 0.44 ± 0.19          |                                               |
|                          |                                               |                                               |
| merged π⁰ candidate: 28   |                                               |                                               |
| B⁰ → D⁺sK_res            |                                               |                                               |
|                          |                                               |                                               |
|                          |                                               |                                               |

The study of backgrounds in the B mass sideband between 4600 and 5186 MeV/c² has shown that the main contributions include two φ’s and a γ candidate. All the results of this section are summarized in Table 12 and can be summarized as follows:

- From the behaviour of the γ/π⁰ separation variable, among the 38 candidates present in this sideband, about 10 contain a true γ while the others contain a
merged $\pi^0$.

- The direct computation of expected yields of different background modes using branching ratios from the Particle Data Group [26] has lead to $11.3 \pm 4.5$ events for $B$ decays involving an $\eta$ in the final state (which exhaust the part of the background containing a true $\gamma$).

- The estimation of the backgrounds containing one $\pi^0$ gives a total number of events of $6.4 \pm 1.7$. This does not explain all the 28 events containing a $\pi^0$ seen in the data $B$ mass sideband. Some additional contributions can come from $B_s^0 \rightarrow \phi\phi \eta'$ ($\eta' \rightarrow \pi^0\pi^0\gamma$) and $B_s^0 \rightarrow \phi\phi \eta$ ($\eta \rightarrow \pi^0\pi^0\pi^0$) but no simulation was available so the expected yields have not been estimated. However, those modes involve more missing mass than $B_s^0 \rightarrow \phi\phi \eta$ ($\eta \rightarrow \gamma\gamma$) so they are not expected to contaminate the signal region.

- The most dangerous contamination remains the contribution from $B_s^0 \rightarrow \phi\phi \eta$ which, as it involves the decay of a $B_s$ meson (as the signal under study), enters the most the signal region (between 5186 and 5546 MeV/$c^2$) where $7.3 \pm 3.2$ events are expected for this decay (the estimation is similar to the one presented in Section 6.3.11). In the signal region, another non negligible contribution comes from $B^0 \rightarrow \phi\phi K_s^0$ for which $2.0 \pm 0.7$ events are expected.

## 7 Signal determination procedure

To extract the signal from data, a fit of the $B$ mass in the range between 4600 and 7000 MeV/$c^2$ has to be performed. In this fit, the shape of the signal is obtained from the MC sample for the $B_s^0 \rightarrow \phi\phi\gamma$ decay. As the $B_s^0 \rightarrow \phi\phi\eta$ decay is the background that contaminates the most the signal region, the MC sample for this channel is used to determine some parameters of the background shape. The quality of the whole model is then probed by generating pseudoexperiments to get information about the possible bias of the fit and the expected significance of the signal. The data remain blinded through this section.

### 7.1 Shape of the signal

The shape of the signal peak is studied in simulation. Two tails are present on each side of the $B$ mass peak: the tail in the low mass region is possibly due to losses of photon energy in the calorimeter, while in the high mass region the tail is mainly composed of events with large errors on the determination of the $B$ mass. The presence of tails can be taken into account by making use of a two-tail Crystal Ball (CB) probability distribution function (PDF), the analytical expression of which is given by:

$$f(x; \alpha_L, n_L, \alpha_R, n_R, \mu_B, \sigma) = N \cdot \begin{cases} A_L \cdot (B_L - \frac{x - \mu_B}{\sigma})^{-n_L}, & \text{for } \frac{x - \mu_B}{\sigma} \leq -|\alpha_L| \\ A_R \cdot (B_R - \frac{x - \mu_B}{\sigma})^{-n_R}, & \text{for } \frac{x - \mu_B}{\sigma} \geq |\alpha_R| \\ \exp(-\frac{(x - \mu_B)^2}{2\sigma^2}), & \text{for } -|\alpha_L| < \frac{x - \mu_B}{\sigma} < |\alpha_R|. \end{cases}$$

(19)
where:

\[
A_L = \left( \frac{n_L}{|\alpha_L|} \right)^{n_L} \cdot \exp \left( -\frac{|\alpha_L|^2}{2} \right)
\]

\[
B_L = \frac{n_L}{|\alpha_L|} - |\alpha_L|
\]

\[
A_R = \left( -\frac{n_R}{|\alpha_R|} \right)^{n_R} \cdot \exp \left( -\frac{|\alpha_R|^2}{2} \right)
\]

\[
B_R = -\frac{n_R}{|\alpha_R|} + |\alpha_R|
\]

and \( N \) is the normalization factor.

Figure 23: Total reconstructed mass for the \( B^0_s \to \phi \phi \gamma \) MC sample, fitted with a Crystal Ball PDF (solid blue line).

The fit performed on off-line selected MC is shown on Fig. 23. From it, we extract the parameters which will be used in the fit to the data (the subscripts \( L \) and \( R \) refer to the left and right tail respectively).

In the case of \( B^0_s \to \phi \phi \gamma \), the determination of the width of the signal peak is difficult due to its dependence on the particular \( M_{\phi \phi} \) distribution and our lack of knowledge of it. This is not the case for most 2-body radiative decays with an intermediate (narrow) resonance. The dependency of the width of the \( B \) mass peak as a function of the relative mass of the hadronic system has been studied on MC for several radiative decays and can be seen on Fig. 24. For low masses of the hadronic system, the resolution of the calorimeter for the photon energy dominates so the width of the \( B \) mass peak is large (reaching 90 MeV/c^2). At higher masses of the hadronic system, the resolution of the detector for the hadronic mass (which is much better than the resolution of the calorimeter) dominates so the width decreases to reach 30 MeV/c^2 when the mass of the hadronic system is 85% of the reconstructed mass of the \( B \) meson. This dependency can naively be modelled with a second order polynomial, the parameters of which are given on Table 13. Assuming that the \( M_{\phi \phi} \) distribution is phase-space as a first approximation, the width of the peak that is used to fit the data can be directly taken from MC.
In order to properly take into account differences between the photon calibration of data and MC, which affects the position of the mass peaks, the $B^0 \rightarrow K^{*0}\gamma$ decay has been used. In Ref. [38] it has been observed a shift of +3.5 MeV/c\(^2\) when going from the MC signal mass peak to the fit on real data. Therefore, this shift is applied on the position of the mass peak. The fitted value from MC will be used to assess the systematic uncertainty related to this correction.

Summarizing, the PDF for signal is chosen as a Crystal-Ball whith all its parameters ($\sigma, \alpha_R, n_R, \alpha_L$ and $n_L$) fixed from MC and the mean value shifted by +3.5 MeV/c\(^2\) from the simulated one. The values of the parameters obtained by fitting the MC sample are given in Table 14.

### Table 13: Parameters of the dependency of the width of the signal peak as a function of the relative mass of the hadronic part, modelled as a second order polynomial ($f(x) = p_0 + p_1 x + p_2 x^2$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>90.6 ± 0.7</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.95 ± 0.43</td>
</tr>
<tr>
<td>$p_2$</td>
<td>-86.2 ± 4.9</td>
</tr>
</tbody>
</table>

![Figure 24: Dependency of the width of the signal peak with the mass of the hadronic part in the radiative decays.](image)
7 SIGNAL DETERMINATION PROCEDURE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_B$</td>
<td>5370.49 ± 0.73</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>53.83 ± 0.73</td>
</tr>
<tr>
<td>$\alpha_L$</td>
<td>2.226 ± 0.085</td>
</tr>
<tr>
<td>$\alpha_R$</td>
<td>1.342 ± 0.060</td>
</tr>
<tr>
<td>$n_L$</td>
<td>1.71 ± 0.21</td>
</tr>
<tr>
<td>$n_R$</td>
<td>8.3 ± 1.5</td>
</tr>
</tbody>
</table>

7.2 Background Model

As discussed previously, $B_s^0 \to \phi \phi \eta$ is the background with less missing mass and thus the one that is more likely to enter the signal region. As shown on Fig. 25, the total reconstructed mass for this decay is peaking on the left on the signal region, with a steep slope on the right, up to the end point. This end point corresponds to the mass of the $B_s^0$ meson ($5366.77 \pm 0.24$ MeV/$c^2$ according to the Particle Data Group [26]) displaced because of the energy loss from the missing $\gamma$. This shape can be modelled by an Argus PDF, the analytical expression of which is:

$$f(x) = \frac{2^{-p} \chi^{2(p+1)} \Gamma(p+1) - \Gamma(p+1, \frac{1}{2} \chi^2)}{\Gamma(p+1) - \Gamma(p+1, \frac{1}{2} \chi^2)} \cdot \frac{x}{c^2} \left(1 - \frac{x^2}{c^2}\right)^p \exp\left\{-\frac{1}{2}\chi^2\left(1 - \frac{x^2}{c^2}\right)\right\}, 0 \leq x \leq c,$$

(20)

where $\Gamma(.)$ is the gamma function, and $\Gamma(.,.)$ is the upper incomplete gamma function. Here parameters $c$, $\chi$ and $p$ represent the cutoff, curvature, and power respectively. The resolution of the detector (which is dominated by the resolution on photon energy given by the calorimeter) has to be taken into account by convolving this Argus PDF with a Gaussian PDF.

The shape describing the partially reconstructed background in data is chosen as an Argus convolved with Gaussian where the cutoff (or end point) and the right slope ($p$) are fixed from $B_s^0 \to \phi \phi \eta$ MC (the values of the parameters are given in Table 15) with the end point used to fit data shifted by $+3.5$ MeV/$c^2$ with respect to the simulation as discussed in the previous section. To take into account the other partially reconstructed backgrounds in the same shape, the left slope (encoded in the curvature $\chi$) is left free.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$</td>
<td>$-3.3 \pm 6.7$</td>
</tr>
<tr>
<td>$p$</td>
<td>$-0.65^{+0.48}_{-0.34}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$5239^{+45}_{-34}$</td>
</tr>
<tr>
<td>Width</td>
<td>$115^{+13}_{-14}$</td>
</tr>
<tr>
<td>$n_{bkg}$</td>
<td>$369^{+20}_{-19}$</td>
</tr>
</tbody>
</table>
7 SIGNAL DETERMINATION PROCEDURE

Figure 25: Total reconstructed mass for the $B^0_s \rightarrow \phi \eta$ MC sample, fitted with an Argus convolved with Gaussian PDF (solid blue line).

The combinatorial background is fitted with a constant PDF and thus the whole background will simply be the sum of this constant PDF and the Argus convolved with Gaussian PDF. The signal is modelled with a Crystal-Ball PDF detailed previously. The shape of the total PDF is shown on Fig. 26.

Figure 26: Simulated events between 4600 and 6300 MeV/c$^2$. The total PDF (solid blue line) includes the signal component (solid red line), the partially reconstructed background (solid green line) and the combinatorics (solid pink line).
7 SIGNAL DETERMINATION PROCEDURE

7.3 Quality of the fit

The quality of the model is evaluated by generating and fitting 1000 samples of 69 events between 4600 and 6300 MeV/c\(^2\) with the PDF described previously. The procedure is the following:

1. For the generation, the total number of events is chosen according to a Poisson distribution around 69. The events themselves are generated using the PDF described previously with a left slope (or curvature) fitted from data sideband, 45 partially reconstructed background events (estimated by extrapolation of the 38 events in the low B mass sideband), 20 signal events (corresponding to a branching ratio of \(1 \times 10^{-6}\)) and 2 combinatorial background events (naively extrapolated from the two events visible in the high B mass sideband).

2. Then, the fit is performed for each sample letting free the yields and the left slope of the PDF which describes the partially reconstructed background.

For each fit, the pull is computed following CDF conventions [39]:

\[
\text{if } ((\text{fit result}) \leq (\text{true value})) : g = \frac{(\text{true value}) - (\text{fit result})}{(\text{positive MINOS error})}, \\
\text{else : } g = \frac{(\text{fit result}) - (\text{true value})}{(\text{negative MINOS error})}.
\]

Then, the pull distribution (shown on Fig. 27a for the 1000 generated samples) is expected to be gaussian centered on zero (otherwise the fit is biased) and with unitary width (to check that the errors are estimated correctly). The background and signal model used in this analysis are therefore validated as the mean of the pull distribution is 0.066 ± 0.032 and the width is 0.98 ± 0.02.

To evaluate the significance of the signal, two fits are performed on each sample. In the first one, we assume the hypothesis that signal and background are present, so \(N_{\text{sig}}\) is left as a free parameter. In the second one, we assume that only background is present so the number of signal events is set to 0 to force the fit to adjust to the data without signal. As the fitting method is based on the maximisation of likelihood, it is possible to extract from each fit the logarithm of maximum likelihood: \(\ln(L_{\text{bkg}})\) and \(\ln(L_{\text{bkg+sig}})\). Using the Wilk’s theorem, the significance \(s\) is given by:

\[
s = \sqrt{2 \left| \ln(L_{\text{bkg}}) - \ln(L_{\text{bkg+sig}}) \right|}.
\]

From the distribution that is obtained with the generated samples (Fig. 27b), an average statistical significance of 4.6\(\sigma\) can be expected for the final fit, given a signal of 20 events.
8 **RESULTS**

After having set the selection of events and built the model to describe signal and background, the data is unblinded and fitted to determine the number of signal events and to study the events present in the signal region.

### 8.1 *B* mass fit and upper limit on the branching ratio for $B^+_s \rightarrow \phi \phi \gamma$

As shown on Fig. 28, the number of signal events is $0.85 \pm 0.08$ (compatible with 0), which means that an upper limit has to be set on the branching ratio for $B^+_s \rightarrow \phi \phi \gamma$.

![Figure 27: Pulls and significances for a sample of 1000 simulations of the 69 events of data.](image)

**Figure 27:** Pulls and significances for a sample of 1000 simulations of the 69 events of data.

**Figure 28:** Invariant mass distribution of $B^+_s \rightarrow \phi \phi \gamma$ candidates between 4600 and 6300 MeV/$c^2$. The total PDF (solid blue line) includes the signal component (solid red line), the partially reconstructed background (solid green line) and the combinatorics (solid pink line).

The stability of this fit can be checked by studying the variations of the likelihood $\mathcal{L}$ when the fit is performed imposing different signal yields. As can be seen on Fig. 29, the likelihood is continuous with a single extremum and slightly asymmetric
around the optimal value (which is due to low statistics). In particular, the absence of other local minimum ensures that the convergence does not depend on the initial value given in the fit.

![Likelihood Profile in N_{sig}](image)

**Figure 29:** Likelihood profile for variations of the signal yields parameter. The two black lines show the values of the signal yields parameter at $-1\sigma$ and $+1\sigma$ (which correspond to $-\ln \mathcal{L} = 0.5$).

### 8.1.1 Systematic uncertainties

The sources of systematic uncertainties on the branching ratio estimation can be divided into the uncertainties related to the signal yields extraction (summarized in Table 17) and the ones related to the reconstruction efficiency and other externally provided parameters (summarized in Table 18). Some of the systematic uncertainties are still unknown but the dominant sources have been evaluated in the following way:

- The systematic uncertainty arising from the limited statistics used to simulate the partially reconstructed background has been studied by repeating the fit on data randomly varying the partially reconstructed shape parameters fixed from $B_s^0 \rightarrow \phi \phi \eta$. Since these parameters are highly correlated, as shown in the covariance matrix in Table 16, they cannot be varied independently. Therefore, they are randomized all together according to a multivariate gaussian with means at the parameters nominal values and width and correlation given by the covariance matrix. The fit has been repeated 100000 times, obtaining the signal yield distribution shown in Fig. 30. The asymmetric error at confidence $\alpha = 0.6827$ has been obtained by finding, at either side of the distribution, the points in the distribution which delimit a region with area $(1 - \alpha)/2$. This error, computed to be of $\pm 0.7$ events, is assigned as a systematic error.
Due to the calibration of the photon, the $B$ mass peak is shifted in data with respect to simulation. To evaluate the error induced by this shift, an alternative fit is performed on data using the mean and endpoint values obtained from simulation, obtaining a signal yield of $N = 1.0^{+3.0}_{-2.3}$. From this, a systematic from the data/simulation discrepancies of $+0.13^{-0.00}$ is assigned.

The systematic related to the assumption that the signal has a $\phi\phi$ mass distribution consistent with EvtGen phase-space (contrary to what was suggested by the $B^+ \to \phi K^+\gamma$ measurements done by Belle [7]) is evaluated by fitting the data using the mass peak width obtained with a $M_{\phi\phi}$ distribution consistent with that shown in Fig. 3a, $\sigma = 72\text{MeV}/c^2$. The yield obtained is $N = 0.3^{+3.3}_{-2.6}$, so a systematic of $+0.6^{-0.5}$ is assigned. Additionally, the change of $M_{\phi\phi}$ distribution assumption also changes the selection efficiency, as can be inferred from Fig. 31, which in the alternative case is $\varepsilon_{sel} = 0.208 \pm 0.004\%$; a systematic of $+17\%^{-0\%}$ on the efficiency is assigned as a consequence of this fact.
Since a data-driven evaluation of the trigger efficiency is not possible, simulation has been used to extract this quantity. The lack of data-driven methods makes it very difficult to estimate the systematic uncertainty related to this choice, which mainly comes from the imprecise L0 simulation. A difference of 10% between the overall trigger efficiency in data and MC for radiative decays has been obtained on 2011 for $B^0 \rightarrow K^{*0}\gamma$ [5] and will be assigned as a systematic uncertainty in this case.

A procedure for reweighting the simulated track efficiencies to match those in data has been established by the Tracking group [40]. Applying the reweighting tables on the $B^0 \rightarrow \phi\phi\gamma$ MC gives an overall correction factor of $1.0066 \pm 0.0020$ on the efficiency. On top of this, an extra systematic uncertainty of 0.4% per track needs to be added, following the recommendations of the Tracking Group.

Systematic uncertainties from the PID efficiency are computed combining the statistical error from the calibration samples with an extra uncertainty arising from the use of the sPlot method, following the guidelines from the PID group [29]. Additionally, one needs to take into account the binning of the calibration samples. Following the calculations of the $B^0_s \rightarrow \phi\phi$ branching fraction measurement [41], a systematic of 0.15% per track is assigned.

As shown in Section 6.3, the estimation of the branching ratio makes use of the luminosity, the fragmentation fraction, the cross-section of production of $b$ quarks. Uncertainties in all these quantities are propagated as systematic uncertainties in the branching ratio calculation and give a total uncertainty of 20%.

The procedure for obtaining the efficiency of the $\gamma/\pi^0$ separation variable from data is analogous to that applied for the charged PID, except that the size of the calibration samples is smaller. This is still ongoing work and no systematic uncertainty evaluation procedure is in place yet, so it will be neglected.
No estimation for the data/simulation correction factor of high transverse momentum photons in LHCb exists, and therefore it will be neglected in this study.

Adding all sources in quadrature, the total systematic errors are estimated to be ±0.7 events for the uncertainties coming from the yields extraction, and +28% −23% for the uncertainties coming from efficiency determination and other external parameters.

Table 17: Systematic uncertainties on signal yields.

<table>
<thead>
<tr>
<th>Source</th>
<th>Positive error</th>
<th>Negative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Statistics for background model</td>
<td>+0.7</td>
<td>−0.5</td>
</tr>
<tr>
<td>Data/Simulation $B$ mass shift</td>
<td>+0.13</td>
<td>−0.0</td>
</tr>
<tr>
<td>Determination of the width for signal</td>
<td>+0.0</td>
<td>−0.5</td>
</tr>
<tr>
<td>Total</td>
<td>+0.7</td>
<td>−0.7</td>
</tr>
</tbody>
</table>

Table 18: Systematic uncertainties on other parameters than signal yields extraction.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency dependency with $M_{\phi\phi}$</td>
<td>+17%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>−0%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>PID $K$ efficiency</td>
<td>0.6%</td>
</tr>
<tr>
<td>Luminosity, cross-section and fragmentation fraction</td>
<td>20%</td>
</tr>
<tr>
<td>$\gamma/\pi^0$ separation efficiency</td>
<td>N/A</td>
</tr>
<tr>
<td>$\gamma$ reconstruction efficiency</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td>+28% −23%</td>
</tr>
</tbody>
</table>

8.1.2 Estimation of the branching ratio

An ensemble of pseudexperiments has been used to determine the upper limit of the branching fraction by scanning 50 possible values of the signal yield. For each point in the scan, 10000 pseudexperiments have been generated with the corresponding signal yield and then fitted according to the model used in data. For each of these points, the confidence level (CL) is defined as the fraction of pseudexperiments that give a fitted yield larger than that of data. The systematic error is accounted for by smearing each fit yield by the total systematic error from Tables 17 and 18, taking care of properly combining relative and absolute errors. In the case of asymmetric errors, the worst case scenario has been used to symmetrize them. The upper limit on the branching ratio at a given CL is then given by

$$B(B_s^0 \rightarrow \phi\phi\gamma) < \frac{N_{CL}}{L \cdot 2 \cdot \sigma(pp \rightarrow b\bar{b}X) \cdot f_s \cdot \mathcal{B}(\phi \rightarrow KK)^2 \cdot \varepsilon_{acc} \cdot \varepsilon_{sel}},$$

(23)

where $N_{CL}$ is the signal yield for the corresponding CL.
From the curves shown in Fig. 32, the black being statistical only and the blue incorporating systematic uncertainties, the upper limit at 90% CL is obtained as the branching ratio that corresponds to a CL of 90%:

\[ \mathcal{B}(B_s^0 \to \phi\phi\gamma) < 3.14 \times 10^{-7} \quad \text{at 90\% CL.} \quad (24) \]

![Figure 32](image)

**Figure 32:** Curves of the limits at 90% confidence level derived from 50 points with 10000 pseudoexperiments. The black curve is statistical only and the blue curve incorporates systematic uncertainties.

### 8.1.3 Cross-check using \( B_s^0 \to \phi\gamma \)

Given that the found upper limit is lower than the naive expectation for the branching ratio, a sanity check has been performed by using the \( B_s^0 \to \phi\gamma \) decay, and doing a branching fraction measurement with the same method as in this study:

1. The selection efficiency of one of the official selections [38] has been evaluated on a MC sample, using data-driven methods for PID efficiencies.
2. The signal yield on 3 fb\(^{-1}\) of data has been extracted from the same reference.
3. The branching fraction has been evaluated using Eq. 23, with the same factors except the square for \( \mathcal{B}(\phi \to K^+K^-) \).

The result is \( \mathcal{B}(B_s^0 \to \phi\gamma) = (2.6 \pm 0.5) \times 10^{-5} \), which is at 2\(\sigma\) of the PDG value only considering statistical uncertainties. This check proves that this method of determining the branching fraction may lead to a bias which would be at most of a factor of 2.
8.2 Behaviour of events in the signal region

Though no significant $B^0_s \rightarrow \phi \phi \gamma$ signal was found in the signal region, it is interesting to study the behaviour of the relevant observables for the background to check the main assumptions made in this analysis, for example the hypothesis that the contamination is dominated by $B^0_s \rightarrow \phi \phi \eta$ decays. The number of background events observed in the signal region (shown in Fig. 28) is $15.2 \pm 2.2$. In this region, the main contamination is expected to come from $B^0_s \rightarrow \phi \phi \eta$ and $B^0 \rightarrow \phi \phi K^0_S$ decays, for which the expected yields in the signal region are $7.3 \pm 3.2$ and $2.0 \pm 0.7$ respectively, so a total of $9.3 \pm 3.3$ which explains most of the observed events. Also, the events in the signal region have very compatible features with the $B^0_s \rightarrow \phi \phi \eta$ decay and with the $B^0 \rightarrow \phi \phi K^0_S$ decay, to a lesser extent:

- The hadronic part is mainly composed of two $\phi$'s, as it is verified by the 2D fit of the $M_{\phi \phi}$ mass shown in Fig. 33.

- The mass of the $\phi \phi$ system is concentrated at low values, as can be seen on Fig. 34a. This behaviour is very close to the shape of the $M_{\phi \phi}$ in $B^+ \rightarrow \phi \phi K^+$ (shown on Fig. 17).

- The distribution of the $\gamma/\pi^0$ separation variable shown on Fig. 34b is similar to the distribution obtained for true $\gamma$'s. This makes this contamination very compatible with the $B^0_s \rightarrow \phi \phi \eta$ channel which is the only contribution containing a true $\gamma$ candidate among the background channels considered in this study.

Figure 33: Simultaneous fit of the invariant mass of the two kaon pairs in the signal region $5186 - 5546$ MeV/$c^2$. The left and right plots show respectively the invariant mass of the kaon pair with lowest and highest $p_T$. Four components are used to build the total distribution (red solid line). The first component (blue solid line) corresponds to the mass distributions of two phis modelled by Breit-Wigner functions. The magenta (resp. green) dashed line models a phi resonance for the kaon pair of lowest (resp. highest) $p_T$ and a flat distribution for the other kaon pair. Finally, the brown spotted line represents the kaonic background without structure.
(a) Invariant mass of the hadronic system (b) $\gamma/\pi^0$ separation variable in the signal region for the data in three $B$ mass regions.

**Figure 34:** Distributions of the hadronic invariant mass and $\gamma/\pi^0$ separation variable for the data events.

It can be noticed that the variables described above do not enable to discriminate $B_s^0 \rightarrow \phi\phi\eta$ decays from $B_s^0 \rightarrow \phi\phi\gamma$ decays and only the distribution of the reconstructed $B$ mass is different between those two channels. The $\eta$ vetoing tool (that rejects the events when the invariant mass of the $\gamma$ candidate and another object in the calorimeter is found to be within 50 MeV/$c^2$ from the $\eta$ mass) is not efficient enough to be used in our analysis as the background rejection is only 60% for an efficiency loss of 50%.
9 Conclusion and further developments

Using a data sample of $3\text{ fb}^{-1}$ taken by the LHCb detector, the $B_s^0 \to \phi\phi\gamma$ decay has been searched for. We obtain yields of $0.85^{+2.98}_{-2.36}$ events so an upper limit of $B(B_s^0 \to \phi\phi\gamma) < 3.14 \times 10^{-7}$ at 90% CL has been determined.

The study of the backgrounds in the signal region has shown that the dominant contribution containing two $\phi$'s and a true $\gamma$ is mostly explained by the $B_s^0 \to \phi\phi\eta$ ($\eta \to \gamma\gamma$) decay. No experimental information is currently available for this mode and a dedicated analysis in the proper detection modes ($\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$) would allow an observation of this decay. This would help constrain further the background contamination to $B_s^0 \to \phi\phi\gamma$.

Improved selection efficiency can be achieved in further studies by using new stripping lines which are currently processed, which will allow significant increase of the efficiency ($\sim 20\%$) by releasing the cut on the $\phi$ vertex separation $\chi^2$. Besides, the use of a more fine-grained non-binary $\eta$ veto could help in separating the $B_s^0 \to \phi\phi\eta$ background.

All these improvements, along with the higher luminosity expected by 2018 with the Run II data ($\sim 5\text{ fb}^{-1}$ on top of Run I data) will increase our sensitivity.

Finally, this analysis highlights the need for careful treatment of the contaminations coming from $B \to \phi K_{\text{res}}$ and $B \to \phi K\eta$ modes in the upcoming study of $B^{\pm} \to \phi K^{\pm}\gamma$. 


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