The LHCb sensitivity to $\sin 2\beta$ from $B^0 \to J/\psi(\mu\mu)K_S^0$ asymmetry

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Abstract

The analysis of $B^0 \to J/\psi(\mu\mu)K_S^0$ is presented, with an estimation of 216k annual yield and a background to signal ratio of 0.67 both after trigger simulation. The sensitivity of the experiment to $Im(\eta)$ (which corresponds to $\sin 2\beta$ in the Standard Model) and to $|\eta|$ (1 in the SM) are 0.022 and 0.023, respectively.

Supporting note for the LHCb TDR.
1 Introduction

CP violation was predicted in the decay of B mesons and recently was measured in the B-factories[1, 2]. The LHC collider will start operating in 2007 at CERN. The LHCb detector is specialised in finding these B events and measuring their decay products with very high precision. From these measurements the theory can be very well tested and, because of the high statistics that will be achieved, small effects due to new physics can also be searched for.

It is very important that $\sin 2\beta$ is measured with high precision. Besides being an interesting measurement itself, other parameters depend on $\beta$, so the uncertainty in its determination will affect the sensitivity of LHCb to the other angles.

It will be shown in this note that after one year of data taking LHCb alone will obtain around half ($\approx 0.02$) of the present sensitivity to $\sin 2\beta$, which is the expected combined world results by then.

2 Theoretical Aspects

In this section we follow reference [3] and [4].

The $B^0 \rightarrow J/\psi(\mu\mu)K_s^0$ decay is a CP -1 eigenstate transition and it originates from the quark level $\bar{B} \rightarrow c\tau\bar{\nu}$ decay.

The contributions to the $B^0 \rightarrow J/\psi(\mu\mu)K_s^0$ decay are dominated by the tree diagram with $V_{cb}^*V_{cs}$. Although there exists some contribution from other penguin diagrams, the dominant penguin diagram contribution has the same weak phase as the tree diagram (Figure 1). It can be assumed that there is no CP violation in the decay amplitude.

The general expressions for the time dependent decay rates for the initial $B (R_f(t))$ and initial $\bar{B} (\bar{R}_f(t))$ that decay into a final state $f$ in time $t$ can be written as follows:

$$R_f(t) \propto \frac{|A_f|^2}{2} \exp(-\Gamma t)[I_+(t) + I_-(t)]$$

(1)

$$\bar{R}_f(t) \propto \frac{|A_f|^2}{2} \left| \frac{p}{q} \right|^2 \exp(-\Gamma t)[I_+(t) - I_-(t)]$$

(2)

$A_f$ is the instantaneous decay amplitude for $B \rightarrow f$ and $\Gamma$ is the average decay width for the two mass eigenstates, which are given by:

![Feynman diagrams](image)

Figure 1: Tree (left) and penguin (right) Feynman diagrams contributing to the $B^0 \rightarrow J/\psi(\mu\mu)K_s^0$ decay. The dotted lines in the penguin diagram represent a colour–singlet exchange.
\[
| B_{1(h)} \rangle = \frac{1}{\sqrt{p^2 + q^2}} [ p | B \rangle + (-)q | \bar{B} \rangle ]
\]

The time dependent functions \( I_+(t) \) and \( I_-(t) \) are expressed as:

\[
I_+(t) = (1 + | \eta |^2) \cosh\left(\frac{\Delta \Gamma}{2} t\right) - 2 \text{Re}(\eta) \sinh\left(\frac{\Delta \Gamma}{2} t\right)
\]

\[
I_-(t) = (1 - | \eta |^2) \cos(\Delta m t) - 2 \text{Im}(\eta) \sin(\Delta m t)
\]

and:

\[
\Gamma = \frac{\Gamma_l + \Gamma_h}{2}
\]

\[
\Delta m = m_h - m_l
\]

\[
\Delta \Gamma = \Gamma_l - \Gamma_h
\]

\[
\eta = \frac{q A_f}{p A_f}
\]

Even in the presence of physics beyond the Standard Model, the following hypothesis can be made for the \( B^0 \to J/\psi(\mu\mu)K_S^0 \) decay:

\[
\Delta \Gamma = 0
\]

\[
\frac{A_f}{A_f} = -1
\]

Besides, under the same conditions, the approximation \(| q/p | \approx 1 \) is valid up to a few times \( 10^{-3} \).

The time dependent decay rate asymmetry is defined by:

\[
A(t) = \frac{\bar{R}_f(t) - R_f(t)}{\bar{R}_f(t) + R_f(t)}
\]

and can be written in a general way as:

\[
\mathcal{A}_{\text{CP}} = \mathcal{A}_{\text{dir}} \cos \Delta m t + \mathcal{A}_{\text{mix}} \sin \Delta m t
\]

where \( \mathcal{A}_{\text{dir}} \) is related to the direct CP violation and \( \mathcal{A}_{\text{mix}} \) is related to the mixed CP violation. In the Standard Model, they are equal to zero and \( \sin 2\beta \), respectively. Beyond the Standard Model, however, the first term is very small and the second one is an effective \( \sin 2\beta \).

Taking all those hypothesis into account, the CP asymmetry formula for the \( B^0 \to J/\psi(\mu\mu)K_S^0 \) decay in the presence of new physics can be written as:

\[
A(t) = \frac{1 - | \eta |^2}{(1 + | \eta |^2)} \cos(\Delta m t) + \frac{2 \text{Im}(\eta)}{(1 + | \eta |^2)} \sin(\Delta m t)
\]

The sensitivity to \( \text{Im}(\eta) \) (\( = \sin 2\beta \) in the SM) and to \( | \eta | \) (\( = 1 \) in the SM and consequently \( \mathcal{A}_{\text{dir}} = 0 \)) is obtained by a fit of the CP asymmetry for the \( B^0 \to J/\psi(\mu\mu)K_S^0 \) decay.
3 Simulation

Minimum bias proton-proton interactions at $\sqrt{s} = 14$ TeV are generated using the PYTHIA 6.2 program [5] with the predefined option MSEL=2: this includes hard QCD processes, single diffraction, double diffraction, and elastic scattering. Other samples of events are obtained by filtering a large minimum bias data-set. For example, $b\bar{b}$ events are obtained by selecting events with at least one $b$- or $\bar{b}$-hadron. The total inelastic and $b\bar{b}$ production cross-sections obtained in this mode are 79.2 mb and 633 $\mu$b respectively.

The decay of all unstable particles is performed with the QQ program [6], originally developed by the CLEO collaboration, using a decay table from CDF which includes also $B_s^0$ and $b$-baryon decays. The $B^0$ and $B_s^0$ oscillation parameters are set to $x_d = 0.755$ and $x_s = 20$ respectively.

Generated particles are tracked through the detector material and surrounding environment using the GEANT 3 package [7]. The geometry and material of the LHCb detector are described in detail. The description includes not only the active detection components and their front-end electronics, but also passive material such as the beam-pipe, frames, supports and shielding elements. Low-energy particles, mainly produced in secondary interactions, are also traced, up to an energy cut-off of 10 MeV for hadrons and 1 MeV for electrons and photons. The reconstruction was performed by the LHCb Brunel package version v17r4 with the detector description as in dbase v254r1 and XmlDDDB v15r2.

Several samples of Monte Carlo events have been generated and simulated to assess the performance of the reconstruction, trigger and offline selection with the reoptimised LHCb detector. The ones with interest to this analysis are:

- 50k events of $B^0 \rightarrow J/\psi(\mu\mu)K^0_s$ signal decays;
- a sample of approximately $10^7$ inclusive $b\bar{b}$ events, used for the estimation of the combinatorial background in the offline selections;
- approximately 380k events with a prompt $J/\psi$ produced at the primary vertex and decaying to $\mu^+\mu^-$;
- 50k events of $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$;
- 50k events of $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$;

No cut is imposed at generator level for the minimum bias sample. In all other cases, the particle of interest (i.e. the signal $b$-hadron, or one of the $b$-hadron in inclusive $b\bar{b}$ events, or the prompt $J/\psi$) is required to have a true polar angle smaller than $400$ mrad. This avoids tracking and reconstructing many events where not all interesting decay products are in the detector acceptance. The sample sizes mentioned above are given after this requirement, which has an efficiency of 34.7% for signal $B$ events and 43.2% for inclusive $b\bar{b}$ events. All these samples are produced using a nominal set of simulation parameters, corresponding to the expectations and assumptions from today’s knowledge.

4 Event Reconstruction

The selection program is based on the LHCb Analysis package DaVinci v8r3. The reconstruction of $B^0 \rightarrow J/\psi(\mu\mu)K^0_s$ is performed in three steps. It starts by searching for $J/\psi \rightarrow \mu^+\mu^-$
candidates, and in case a good one is found, it proceeds with the $K^0_S$ reconstruction. The $J/\psi$ and $K^0_S$ are then combined to form $B^0$ mesons. The analysis is done for single and multiple interaction events, and the primary vertex (PV) reconstruction is performed using the algorithm of [8]. In case more than one primary vertex is found, the one which gives the smallest significance on the impact parameter to the $B^0$ is chosen.

The reconstruction program defines 5 types of tracks, related to their trajectories inside the spectrometer, as illustrated in Fig. 2:

- **Long** tracks which traverse the full tracking detector set-up, generating hits in the VELO as well as in T1-T3 stations. They are used in all physics analysis;
- **upstream** tracks leaving hits in the VELO and TT station only. These are in general lower momentum tracks which do not traverse the magnet;
- **downstream** tracks leaving hits in the TT and T stations only;
- **VELO** tracks leaving hits in the VELO only;
- **T** tracks only leaving hits in the T1-T3 stations.

The $J/\psi \rightarrow \mu^+\mu^-$ are reconstructed using only long tracks, while for the $K^0_S \rightarrow \pi^+\pi^-$ the upstream and downstream tracks are also used, since most of the $K^0_S$ decays after the Velo detector. A more detailed information about the different types of tracks can be found in [9].

Particle Identification within LHCb [10] is provided by the two RICH detectors, the Calorimeter system and the Muon Detector. For the common charged particle types ($e, \mu, \pi, K, p$), electrons are primarily identified using the Calorimeter system, muons with the Muon Detector, and the hadrons with the RICH system. However, the RICH detectors can also help improve the lepton identification, so the information from the various detectors is combined. Each detector provides a likelihood for a particle hypothesis and, for each track, the difference in log-likelihood between two hypothesis $a$ and $b$ ($\Delta \ln L_{ab}$) is determined. The particles are identified exclusively in the following order:

- muons, requiring MUON detector information available and $\Delta \ln L_{\mu\pi} > -8$;
- electrons, requiring CALO detectors information available and $\Delta \ln L_{en} > 1$;
Figure 3: Dimuon mass distribution for the $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ signal after the final cuts.

- kaons, requiring RICH detectors information available and $\Delta \ln L_{K\pi} > 0$ and $\Delta \ln L_{Kp} > -2$;
- protons, requiring RICH detectors information available and $\Delta \ln L_{p\pi} > 0$;
- pions as all the remaining particles.

In the case the tracks are of downstream type, they are all assumed to be pions.

The cuts are tuned such that no events are selected from either the inclusive $b\bar{b}$ or prompt $J/\psi \rightarrow \mu^+\mu^-$ samples.

4.1 $J/\psi \rightarrow \mu^+\mu^-$ Selection

Pairs of muons with opposite charges are required to come from a common vertex with $\chi^2 < 20$ and to have an invariant mass within $\pm 50$ MeV/$c^2$ of the true $J/\psi$ mass. A mass-constrained vertex fit is applied to the muon pairs and if its $\chi^2$ is less than 50 the combination is kept. A double Gaussian fit to the $z$ resolution gives a core of 165 $\mu m$.

Figure 3 shows the dimuon mass distribution for the signal after the final cuts. Its mass resolution is found to be 10 MeV/$c^2$. Out of the 50k $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ events generated, 20.1k $J/\psi$ have been reconstructed using long tracks, and 17.1k are selected after the above cuts giving a selection efficiency of 82% (including particle identification).

4.2 $K_S^0 \rightarrow \pi^+\pi^-$ Selection

The $K_S^0 \rightarrow \pi^+\pi^-$ decays are reconstructed with different types of tracks: two long tracks (LL category), one long and one upstream track (LU category), and two downstream tracks (DD category). Each pair of oppositely-charged pions is fitted to a common vertex, requiring a $\chi^2 < 50$ and that its absolute $z$ position lies in the interval $[-0.3, 3]$ m ($[0, 3]$ m for DD). The
Figure 4: Invariant mass distribution of $\pi^+\pi^-$ for $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ signal events where the $K_S^0$ is reconstructed as two downstream (left), two long tracks (center) and one long and one upstream track (right) after the final cuts.

A pair is considered as a $K_S^0$ candidate if its invariant mass is within $\pm 60$ MeV/c$^2$ ($\pm 100$ MeV/c$^2$ for DD) of the true $K_S^0$ mass and its combined $p_T$ above 400 MeV/c (820 MeV/c for DD). The mass distributions after the final cuts are shown in Fig. 4 and their resolutions are 11 MeV/c$^2$, 3.6 MeV/c$^2$ and 11 MeV/c$^2$ for DD, LL and LU respectively.

4.3 $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ Selection

The $J/\psi$ and $K_S^0$ are now combined to make the $B^0$. The values of the cuts are detailed in Table 1 for each $K_S^0$ category. To ensure that the $K_S^0$ comes from the same vertex as the $J/\psi$ a cut on the impact parameter significance of the $K_S^0$ with respect to the $J/\psi$ vertex is applied. A vertex fit is performed for the $B^0 \rightarrow J/\psi K_S^0$ pairs, and it is accepted when its $\chi^2$ is less than 16. At this point the primary vertex is chosen as the one which gives the smallest impact parameter to the $B^0$. To reduce drastically the number of $K_S^0$ candidates formed from pions originating from the PV, it is required that the smallest impact parameter significance between the two pions with respect to the PV exceeds some value. A similar cut is applied to the muons forcing them not to come from the PV.

The $J/\psi$ candidates originating from the PV are rejected by requiring a significant displacement in $z$ between the primary and the $J/\psi$ vertex. To further reduce the contamination of prompt $K_S^0$, it has to be produced away from the PV and a cut on the impact parameter of $K_S^0$ with respect to the PV is applied.

The contribution of ghosts (i.e. tracks not associated to a MC particle) in the DD category is reduced by rejecting any downstream tracks whose seed is due to a particle which comes from beam pipe and is traverses the beam pipe hole of the TT detection layers.

A cut on the transverse momentum of $B^0$ and on its impact parameter with respect to the primary vertex minimises the combinatorial background.

If more than one $B^0$ candidate is selected in the same event, the one with the smallest $\chi^2$ of $B^0$ vertex fit is chosen.

The distributions of some of the most discriminating variables for the signal, inclusive $b\bar{b}$ and prompt $J/\psi \rightarrow \mu^+\mu^-$ events are shown in Figure 4.3.
Figure 5: Distribution of variables used in the selection of \( B^0 \to J/\psi (\ell\ell) K_S^0 \) events for the DD category. None of the final cuts is applied. Solid line refers to signal events, dotted line are for the background which the variable is more discriminating. In the first four plots this background is the inclusive \( b\bar{b} \) events and in the last two are prompt \( J/\psi \to \mu^+\mu^- \).
Table 1: Cuts applied to select $B^0 \to J/\psi(\mu\mu)K^0_S$ candidates for the three $K^0_S$ categories.

<table>
<thead>
<tr>
<th>Cut</th>
<th>DD</th>
<th>LL</th>
<th>LU</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{p_{K^0}} \sigma$ wrt $J/\psi$</td>
<td>&lt; 8.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$\chi^2$ $B^0$ vertex</td>
<td>&lt; 16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$\min(i_{p_\pi^+}/\sigma, i_{p_\pi^-}/\sigma)$</td>
<td>&gt; 2.0</td>
<td>3.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$\min(i_{p_\mu^+}/\sigma, i_{p_\mu^-}/\sigma)$</td>
<td>&gt; 1.2</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>$(z_{J/\psi}/z_{PV})/\sigma$</td>
<td>&gt; 1.2</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>$(z_{K^0}/z_{PV})/\sigma$</td>
<td>&gt; -</td>
<td>5.7</td>
<td>-</td>
</tr>
<tr>
<td>$I_{p_{K^0}} \sigma$ wrt PV</td>
<td>&gt; 0.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>$I_{p_{B}} \sigma$ wrt PV</td>
<td>&lt; 5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>$p_T$ $B^0$ [MeV/c]</td>
<td>&gt; 0.0</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>TT hole [mm]</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>\Delta M_{J/\psi K^0_S}[\text{MeV/c}^2]$</td>
<td>&lt; 60</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 2: Fractions, mass resolutions and vertex resolutions of reconstructed $B^0 \to J/\psi(\mu\mu)K^0_S$ for the three $K^0_S$ categories.

<table>
<thead>
<tr>
<th>$K^0_S$ category</th>
<th>(fraction)</th>
<th>$B^0$ mass resolution [MeV/c^2]</th>
<th>$B^0$ vertex resolution in $z$ [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>(65%)</td>
<td>12 ± 1</td>
<td>146 ± 12</td>
</tr>
<tr>
<td>LL</td>
<td>(26%)</td>
<td>8.9 ± 0.2</td>
<td>122 ± 13</td>
</tr>
<tr>
<td>LU</td>
<td>(9%)</td>
<td>45 ± 4</td>
<td>182 ± 10</td>
</tr>
<tr>
<td>LU, $K^0_S$ mass constraint</td>
<td></td>
<td>12 ± 1</td>
<td>134 ± 11</td>
</tr>
</tbody>
</table>

The $J/\psi K^0_S$ mass must be within $\pm 60$ MeV/c^2 of the true $B^0$ mass, but for the LU category this window was in the beginning relaxed to $\pm 120$ MeV/c^2 because of the deterioration of the momentum resolution of the pions.

The $B^0$ mass distribution obtained after this selection has a core resolution of 12 MeV/c^2, 9 MeV/c^2 and 45 MeV/c^2 for the DD, LL and LU categories respectively, and is shown in Fig. 6. The $B^0$ vertex resolution in $z$ is 147 \mu m, 122 \mu m and 180 \mu m, again for the three categories.

The worse $B^0$ resolutions for the LU category can be recovered by applying a mass-constrained fit to the $K^0_S$, which allow to tighten the $J/\psi K^0_S$ mass window to $\pm 60$ MeV/c^2 like the other two, and increases the number of selected events in this category by 23% keeping the background at the same level. The $B^0$ mass resolution becomes the same as the DD case (also shown in Fig. 6), and the $z$ resolution is improved to 130 \mu m. The mass-constrained fit has also been tried in the LL and DD sets, but since no significant improvement was achieved, the unconstrained vertex fit has been kept. Table 2 contains the $B^0$ mass and $z$ resolutions and the relative contributions of the various $K^0_S$ categories which are, in the final $B^0$ sample, 65% (DD), 26% (LL) and 9% (LU).

The proper time resolution of the $B^0$ meson is very important for the measurement of $\sin(2\beta)$. The proper time ($\tau$) is given by

$$\tau = \frac{t}{\gamma_c}$$

(15)
Figure 6: Invariant mass distribution for $B^0 \rightarrow J/\psi(\mu \mu)K_S^0$ for DD (left), LL (center) and LU (right), after the cuts described in the text. In the LU plot the dashed histogram is obtained without applying a mass constrained fit to the $\pi^+\pi^-$. 

Figure 7: Lifetime resolution of $B^0$ meson for DD (left), LL (center) and LU (right)

where $t$ is the $B^0$ time of flight in the lab frame, $\gamma$ is the Lorentz factor and $c$ is the speed of light. Since $t = \frac{L}{\gamma c}$ (where $L$ is the distance between the $B^0$ decay vertex and the PV, $p$ and $E$ are the $B^0$ momentum and energy) and $\gamma = E/m_{B^0}$, we have $\tau = Lm_{B^0}/pc$.

A double Gaussian fit to the $\tau$ resolution gives a core of 41.0 fs, 46.0 fs, 51.0 fs and a tail of 103 fs, 158 fs and 250 fs for the three categories. The plots are shown in Fig. 7. The lifetime resolution used in section 6 comes from a fit to the sum of the three categories which gives 43.0 fs. The error propagated to $\tau$ involves the errors on the momentum and vertex fit, and if the resolution of the pull distribution ($((\tau_{rec} - \tau_{true})/\sigma)$ is 1, it is an indication that they are properly taken into account, which is the case. The pull distribution for all signal events can be seen in Fig. 8.
Figure 8: Lifetime pull distribution for all signal events selected. The resolution is $1.03 \pm 0.01$.

Table 3: Results of $B^0 \to J/\psi(\mu\mu)K^0_S$ selection on 50k events. Reconstructible is the number of events that could have been reconstructed in each category. Reconstructed is the number of events actually reconstructed. Reconstructible & Reconstructed follows the obvious notation.

<table>
<thead>
<tr>
<th></th>
<th>DD</th>
<th>LL</th>
<th>LU</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructible</td>
<td>5715</td>
<td>2088</td>
<td>905</td>
<td>8708</td>
</tr>
<tr>
<td>Reconstructed</td>
<td>3863</td>
<td>1666</td>
<td>669</td>
<td>6198</td>
</tr>
<tr>
<td>Reconstructible &amp; Reconstructed</td>
<td>3641</td>
<td>1603</td>
<td>551</td>
<td>5795</td>
</tr>
<tr>
<td>Selected Events</td>
<td>2158</td>
<td>863</td>
<td>296</td>
<td>3317</td>
</tr>
<tr>
<td>True Selected Events</td>
<td>2077</td>
<td>850</td>
<td>279</td>
<td>3206</td>
</tr>
<tr>
<td>Accepted by L0</td>
<td>1920</td>
<td>777</td>
<td>266</td>
<td>2963</td>
</tr>
<tr>
<td>Accepted by L0&amp;L1</td>
<td>1252</td>
<td>562</td>
<td>192</td>
<td>2006</td>
</tr>
</tbody>
</table>

5 Event Yield

The $B^0 \to J/\psi(\mu\mu)K^0_S$ selection was applied in 50k signal events and 3317 $B^0$ passed the cuts listed in Table 1 and 2006 events survive the trigger simulation. Table 3 shows the number of events after each step of the reconstruction for each of the three track categories together with the overall results for the combined sample.

The annual signal event yield is computed as

$$S = L_{\text{int}} \times \sigma_{b\bar{b}} \times 2 \times f_B \times \text{BR}_{\text{vis}} \times \varepsilon_{\text{tot}},$$

for a nominal annual integrated luminosity of $L_{\text{int}} = 2 \, \text{fb}^{-1}$ ($10^7$ s at $2 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1}$) and a $b\bar{b}$ production cross section of $\sigma_{b\bar{b}} = 500 \, \mu\text{b}$. The probability for a $b$-quark to hadronize into a hadron is assumed to be $f_B = 39.1\%$ for $B^0$ and $10.0\%$ for $B^0_s$ [11], and the factor 2 takes into account the production of both $b$- and $\bar{b}$-hadrons. The visible branching ratio $\text{BR}_{\text{vis}}$
Table 4: Branching Ratios used to compute $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ BR$_{\text{vis}}$ which is the product of the first four lines. $N_{\text{year}} = L_{\text{int}} \times \sigma_{b\bar{b}} \times 2 \times f_B \times \text{BR}_{\text{vis}}$.

| BR($B^0 \rightarrow J/\psi(\mu\mu)K_S^0$) | $(8.5 \pm 0.5) \times 10^{-4}$ |
| BR($J/\psi(\mu\mu)\gamma$) | $(6.76 \pm 0.17) \times 10^{-2}$ |
| BR($K^0 \rightarrow K_S^0$) | $1/2$ |
| BR($K_S^0 \rightarrow \pi^+\pi^-$) | $(68.95 \pm 0.14) \times 10^{-2}$ |
| BR$_{\text{vis}}$ | $(19.8 \pm 1.3) \times 10^{-6}$ |
| $N_{\text{year}}$ | $(15.5 \pm 1.1) \times 10^6$ |

Table 5: Signal Efficiencies for $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$.

<table>
<thead>
<tr>
<th>$\varepsilon_{\text{det}}$</th>
<th>$\varepsilon_{\text{rec/det}}$</th>
<th>$\varepsilon_{\text{sel/rec}}$</th>
<th>$\varepsilon_{\text{trg/sel}}$</th>
<th>$\varepsilon_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5%</td>
<td>66.5%</td>
<td>53.5%</td>
<td>60.5%</td>
<td>1.39%</td>
</tr>
</tbody>
</table>

is the product of all branching ratios involved in the b-hadron decay of interest. In the case of $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$, the visible branching ratio BR$_{\text{vis}}$ is $(19.8 \pm 1.3) \times 10^{-6}$. The individual branching ratios considered are shown in Table 4.

The total signal efficiency is obtained as the fraction of MC events containing a signal B decay that are triggered, reconstructed, and selected with offline cuts for physics analysis. Taking into account the factor 34.7% due to the fact that the signal b-hadron is required to be produced with an angle smaller than 400mrad (see Section 3), the total signal efficiency is:

$$\varepsilon_{\text{tot}} = 2006 \times 0.347/50000 = 1.39\%$$

(17)

giving an annual yield estimation of 216k events for the $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ channel. In order to understand the effect of the various steps of the reconstruction and selection, the total signal efficiency can be broken down as

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{det}} \times \varepsilon_{\text{rec/det}} \times \varepsilon_{\text{sel/rec}} \times \varepsilon_{\text{trg/sel}} \times \varepsilon_{\text{tot}}$$

(18)

where $\varepsilon_{\text{rec/det}} = \text{Rec’ble} \& \text{Rec’ted} / \text{Rec’ble}$, is the reconstruction efficiency on detected events (track finding efficiency and neutral cluster reconstruction), $\varepsilon_{\text{sel/rec}} = \text{Sel} / \text{Rec’ted}$, is the efficiency of the offline selection cuts on the reconstructed events (designed to discriminate against background), and $\varepsilon_{\text{trg/sel}} = \text{L0\&L1} / \text{Sel}$, is the product of the L0 trigger efficiency on the offline-selected events and the L1 trigger efficiency on offline-selected events passing L0 and $\varepsilon_{\text{det}} = \varepsilon_{\text{tot}} / (\varepsilon_{\text{rec/det}} \times \varepsilon_{\text{sel/rec}} \times \varepsilon_{\text{trg/sel}})$ is the detection efficiency (including the geometrical acceptance in 4$\pi$ and all material effects in the detector, like secondary interactions). It is assumed that the high-level trigger (HLT) will be fully efficient on these events. Flavour tagging efficiency is not included here. Table 5 shows the broken down efficiencies.

No inclusive $b\bar{b}$ event passes the selection out of 10M generated events. If the $B^0$ mass window is enlarged to $\pm 600$ MeV/$c^2$, 37 candidates are accepted, which are mainly formed with a true $J/\psi$ originated away from the primary vertex. The decay modes $B^0 \rightarrow J/\psi(\mu\mu)K^*$, $B^0 \rightarrow J/\psi(\mu\mu)\phi$ and prompt $J/\psi \rightarrow \mu^+\mu^-$ have been studied as a source of background,
Table 6: Number of background events passing the selection. The number between parenthesis represents true signal events in the inclusive $b\bar{b}$ sample.

| $|\Delta M_{J/\psi K^0_s}|$ [MeV/c^2] | Inc bb | J/ψ → $\mu^+\mu^-$ prompt | B^0 → J/ψK^{*0} | B^0_s → J/ψφ |
|--------------------------------------|---------|---------------------------|----------------|----------------|
| N. of Gen.                           | 10.4M   | 360k                      | 50k            | 50k            |
| DD                                   |         |                           |                |                |
| N. Sel                               | 52(3)   | 7(3)                      | 0              | 10             | 10             |
| L0&L1                                | 26      | 1                         | 0              | 5              | 5              |
| LL                                   |         |                           |                |                |
| N. Sel                               | 17(0)   | 1(0)                      | 0              | 3              | 5              |
| L0&L1                                | 9       | 0                         | 0              | 2              | 4              |
| LU                                   |         |                           |                |                |
| N. Sel                               | 4(1)    | 1(1)                      | 0              | 5              | 2              |
| L0&L1                                | 2       | 0                         | 0              | 5              | 2              |
| Total                                |         |                           |                |                |
| N. Sel                               | 73(4)   | 9(4)                      | 0              | 18             | 17             |
| L0&L1                                | 37      | 1                         | 0              | 12             | 11             |

and were found to give a negligible contribution. Table 6 shows the selection result on the background samples for each of the three track categories together with the overall results for the combined sample.

The estimates of the inclusive $b\bar{b}$ background levels, quoted in Table 7, correspond to the most significant contribution to the combinatorial background. They are based on a sample of $\approx 10^7$ inclusive $b\bar{b}$ events where at least one $b$-hadron is emitted forward within 400 mrad of the beam line. This sample of fully-simulated events corresponds to only 4 minutes of data-taking under nominal conditions. To cope with this very limited MC statistics, the $B$ mass cut is relaxed when analysing these events, and the background under the $B$ mass peak is estimated assuming a linear dependence on the reconstructed $B$ mass, after removal of events with a true signal decay. The B/S estimated considering only the inclusive $b\bar{b}$ sample is 0.80 before the trigger simulation and it’s composition is: in 63% of the events, at least one track comes from fragmentation, in 25% the tracks comes from the same $b$-hadron, in 9% the tracks comes from two $b$-hadrons and in 3% at least one track is a ghost. In the cases where all the tracks come from the same $b$-hadron there is a large (50%) contribution of $\Lambda_b \rightarrow J/\psi \Lambda^0$ in the DD category, where one of the pions is wrongly associated to the proton from the $\Lambda^0$ decay.

The prompt $J/\psi$, is also a very important source of background with approximately the same luminosity as the inclusive $b\bar{b}$ sample and its contribution is also estimated.

The B/S ratio before and after trigger are calculated. They are obtained by the background yield divided by the signal yield. The estimation of the total B/S ratio after the trigger simulation is 0.69. The result is shown in Table 7.
Table 7: Signal Efficiency, untagged signal yield and background-over-signal (B/S) ratio. The first set is before the trigger and the second set is after L0&L1 trigger. Quoted errors on B/S are from MC statistics; estimates based on less than 10 background events are quoted between brackets.

<table>
<thead>
<tr>
<th></th>
<th>DD</th>
<th>LL</th>
<th>LU</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{tot}}$ (%)</td>
<td>0.87±0.024</td>
<td>0.390±0.016</td>
<td>0.133±0.010</td>
<td>1.39±0.03</td>
</tr>
<tr>
<td>Annual Yield ($10^3$)</td>
<td>135±4</td>
<td>60±3</td>
<td>20.6±1.5</td>
<td>216±5</td>
</tr>
</tbody>
</table>

**Before Trigger**

| B/S (inc $b\bar{b}$)         | 0.87±0.13 | 0.76±0.19 | [0.14, 0.96] | 0.80±0.10 |
| B/S (prompt $J/\psi \rightarrow \mu^+\mu^-$) | [0.0, 0.43] | [0.0, 1.07] | [0.0, 3.13] | [0.0, 0.28] |
| B/S (others)                 | [0.01, 0.02] | [0.01, 0.03] | [0.02, 0.11] | 0.018±0.004 |
| B/S (Total)                  | [0.81, 1.40] | [0.69, 1.93] | [0.56, 3.80] | [0.75, 1.17] |

**After L0& L1 Trigger**

| B/S (inc $b\bar{b}$)         | 0.77±0.16 | [0.30, 1.05] | [0.11, 1.18] | 0.67±0.11 |
| B/S (prompt $J/\psi \rightarrow \mu^+\mu^-$) | [0.0, 0.43] | [0.0, 1.07] | [0.0, 3.13] | [0.0, 0.28] |
| B/S (others)                 | [0.01, 0.03] | [0.01, 0.04] | [0.04, 0.16] | 0.020±0.05 |
| B/S (Total)                  | [0.53, 1.04] | [0.32, 1.07] | [0.20, 1.29] | 0.69±0.11 |

6 Sensitivity to $Im(\eta)$ and to $|\eta|$ of the LHCb experiment

The LHCb sensitivity to the quantities $Im(\eta)$ (which is equal to $\sin 2\beta$ in the Standard Model) and $|\eta|$ (which is equal to unity in the SM) in $B^0 \rightarrow J/\psi (\mu\mu) K^0_S$ channel is simulated.

The number of signal events used in the simulation is given by $N_{\text{sig}} = 90.6k$ events/year, which comes from the number of signal events (216k events/year) from Table 7 times the tagging efficiency. The tagging efficiency is estimated from an average of [13]. The ratio $B/S = 0.67$ comes from Table 7 and represents the $b\bar{b}$ sample contribution to the background after the trigger. It can be seen from the same table that it is the dominant contribution for the background. It is supposed that the background is tagged with the same efficiency as the signal.

The signal lifetime is $\tau_B = 1.54$ ps and the difference between the CP eigenstate masses is taken as $\Delta m_B = 0.50$ ps$^{-1}$. Unless otherwise mentioned, we use as our default simulation values $Im(\eta) = 0.73$ and $|\eta| = 1.0$.

Each proper time is generated with an uncertainty given by a double Gaussian with width of 43 fs (74%) and 114 fs (26%).

The decay time distribution is generated initially as an exponential, but each decay time is kept according to a probability which is given by function 19.

\[ A(\tau) = b \frac{(a\tau)^3}{1+(a\tau)^3} \]  

with $a = (77 \pm 4) \times 10^2$ ns$^{-1}$ and $b = 0.140 \pm 0.003$.

The decay time distribution is generated initially as an exponential, but each decay time is kept according to a probability which is given by function 19.
The signal is generated with number of events drawn from a Gaussian distribution with mean value given by $N_{\text{sig}}$ and the width given by $\sqrt{N_{\text{sig}}}$. The number of background events is generated in a similar way. Two histograms are then filled: one, containing the events tagged as $B^0$ (signal and background) and the other containing the events tagged as $\bar{B}^0$ (signal and background). Equation 14 was used to set the probability of a given decay time be due to a $B^0$ or a $\bar{B}^0$. The background is subtracted from both histograms using a parameterisation of the distribution expected for the background distribution with the estimated lifetime (see Fig. 10). A fit to the distribution shown in this figure gives $\tau_{\text{back}} = 0.78 \pm 0.05$ ps.

In order to estimate the error ($\sigma_w$) in the mistag ($w$, the fraction of events that are tagged incorrectly), the signal of $B^0 \rightarrow J/\psi K^*0$ is used. $B^0 \rightarrow J/\psi K^*0$ is a self-tagging mode. Under the hypothesis that the tagging efficiency and mistag should be the same to $B^0 \rightarrow J/\psi (\mu \mu) K_S^0$ and to $B^0 \rightarrow J/\psi K^*0$, it is possible to measure from data the tagging efficiency, mistag and mistag error.

For the $B^0 \rightarrow J/\psi K^*0$ mode, we have for tagged events [12]:

- $N_{\text{sig}} = 277k$ events/year
- $N_{\text{back}}/N_{\text{sig}} = [0.16, 0.37]$
- $\tau_{\text{back}} = 0.91 \pm 0.04$ ps
- $w = 0.343$

Assuming that the efficiency of the B selection as a function of the proper time of the $B^0 \rightarrow J/\psi K^*0$ meson is equal to the one for $B^0 \rightarrow J/\psi (\mu \mu) K_S^0$ and also considering that the
uncertainty in the proper time determination $\sigma_t$ is the same for both decay modes, the tagged distribution of $B^0$ generated in a fast MC with the above numbers is fitted and the value $\sigma_w = 0.0011$ is obtained. This value for $\sigma_w$ comes from the average of many fits. A typical fit is shown in Fig. 11.

The limits shown before for $N_{\text{back}}/N_{\text{sig}}$ for the $B^0 \rightarrow J/\psi K^*0$ decay were used and the results for $\sigma_w$ were the same for lower and upper limit values.

The value of $\sigma_w$ obtained is then used in the fit for the $B^0 \rightarrow J/\psi (\mu \mu)K^0_S$ asymmetry. In order to extract the sensitivity numbers, 200 experiments are performed with the mistag error folded in. The expression used for the fit, taking new physics into account, is given by:

$$fitval = - (1 - 2w) \left[ \frac{(1 - |\eta|^2)}{(1 + |\eta|^2)} \cos(\Delta mt) - \frac{2Im(\eta)}{(1 + |\eta|^2)} \sin(\Delta mt) \right]$$

where $w = 0.343$ is the mistag fraction for $B^0 \rightarrow J/\psi (\mu \mu)K^0_S$ and $B^0 \rightarrow J/\psi (\mu \mu)K^*0$. In the Standard Model, $|\eta|$ is equal 1 and $Im(\eta)$ is $\sin 2\beta$. In the presence of physics beyond the standard model, $|\eta|$ is very close to 1.

A distribution of the fitted values for $Im(\eta)$ and $|\eta|$ is shown in Fig. 12 and a typical fit is shown in Fig. 13. The input values for the $B^0 \rightarrow J/\psi (\mu \mu)K^0_S$ decay given before were used to make the typical fit plot and the distribution of the fitted values. From Fig. 12, the sensitivity of the experiment to $Im(\eta)$ is estimated as 0.022 and to $|\eta|$ is 0.023. The correlation coefficient between the two parameters is $r = 0.42$.

A correlation study among the fitted values ($Im(\eta)$ and $|\eta|$) and its errors was made. The results obtained are shown in Fig. 14 for $|\eta|$ fixed to 1 and $Im(\eta)$ changing from 0.63 to 0.83 and in Fig. 15 for $Im(\eta)$ fixed to 0.73 and $|\eta|$ changing from 0.90 to 1.10. The intervals were chosen to have about four times (for each side) the present uncertainty from the world average.
Figure 11: The mixing distribution $A(t)$ for $B^0 \to J/\psi K^*$ with $w = 0.343$. The result of a typical fit to $w$ is shown in the plot.

![Figure 11](image)

Figure 12: The parameters $\text{Im}(\eta)$ and $|\eta|$ from 200 simulations. The input values are shown as a square in the center of the distribution.

![Figure 12](image)
for the $\text{Im}(\eta)$ and $| \eta |$ values (which is about 0.05) around our default simulation values.

In the plot of Fig. 14 it can be observed that there is a correlation between the values of $\text{Im}(\eta)$ and its errors. When the value of $\text{Im}(\eta)$ increases, its error increases too, but the error on $| \eta |$ does not change.

In the plot of Fig. 15 there are correlations between the values of $|\eta|$, its errors and $\text{Im}(\eta)$ errors. When the value of $| \eta |$ increases, its error increases and the error of $\text{Im}(\eta)$ also increases.

7 Acknowledgements

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Figure 14: $|\eta| = 1$ fixed and $\text{Im}(\eta)$ changes from 0.63 to 0.83.

Figure 15: $\text{Im}(\eta) = 0.73$ and $|\eta|$ varies from 0.90 to 1.10.
References


