Update to the LHCb sensitivity to sin(2β) from the CP-asymmetry in $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ decays

S. Amato$^1$, M. Gandelman$^1$, C. Göbel$^2$ and L. de Paula$^1$

$^1$ LAPE - Instituto de Física - Universidade Federal do Rio de Janeiro
$^2$ Depto. de Física, Pontifícia Universidade Católica do Rio de Janeiro

Abstract

This note presents an update of the $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ analysis in order to obtain the LHCb sensitivity to sin(2β). An update of the analysis of $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$, the control channel for tagging, is also shown here. We estimate an annual yield of 236k for $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ channel, with a background to signal ratio (B/S) of 8.4. A yield of 228k with B/S of about 0.9 is obtained by applying a cut to reduce prompt $J/\psi$ decays. We estimate an annual yield of 932k with B/S= 0.155 for $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$. We measure the mistag rate to be $38.7 \pm 0.1\%$ from $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$ and find that this value can be used without corrections for the $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ channel. The statistical sensitivity on sin(2β) is found to be 0.020 for 2 fb$^{-1}$ of data.
1 Introduction

The decay $B^0 \rightarrow J/\psi K_S^0$ is well known as the gold-plated mode for the study of CP violation in the B-meson system. Here, the $B^0$ meson decays to a CP eigenstate – the final state being common to both $B^0$ and $\overline{B}^0$ – allowing for interference through oscillation. Tree and penguin diagrams for this $B^0$ decay are shown in Fig. 1.

Safely neglecting the contribution coming from the penguin topology with internal $u$ quark, we see that no direct CP violation is expected for this decay mode in the Standard Model, $A_{dir}^{CP} = 0$. Consequently the time-dependent CP asymmetry is due entirely to mixing-induced CP-violation contributions, $A_{mix}^{CP}$. Considering also that $\delta = 0$ for $B^0$, this asymmetry is predicted to be described by a simple expression [1, 2]:

$$A_{J/\psi K_S^0}^{CP} = \frac{\Gamma(B_d(t) \rightarrow J/\psi K_S^0) - \Gamma(B_d(t) \rightarrow J/\psi K^0_S)}{\Gamma(B_d(t) \rightarrow J/\psi K_S^0) + \Gamma(B_d(t) \rightarrow J/\psi K^0_S)} = \sin|\Delta M_{B_d}|A_{mix}^{CP} = \sin(|\Delta M_{B_d}|t)\sin(2\beta), \quad (1)$$

where $\Delta M_{B_d} = M_{B^0_d} - M_{\overline{B}^0_d}$ is the mass difference of the two $B^0$ mass eigenstates. This decay mode is also experimentally clean, with relatively low background. Currently, the sensitivity reached by the B-factories are at the level of 4% (see the latest results from Babar [3] and Belle [4]). The current world-averaged result [5] is

$$\sin(2\beta) = 0.678 \pm 0.025 \quad (2)$$

A very precise measurement of $\sin(2\beta)$ is useful not only by itself, but also because the uncertainty on its determination affects the sensitivity to other CP parameters that depend on $\beta$.

A mandatory step in extracting $\sin(2\beta)$ is to tag the initial $B^0$ flavour. A careful study of the tagging efficiency, $\varepsilon_{tag}$, and the wrong tag fraction (mistag), $\omega$, is necessary since the measurement of the assymetry is diluted due to the mistag. The extraction of $\omega$ is better obtained through a control channel – a decay to a self-tagged flavour-specific final state. The natural control channel for $B^0 \rightarrow J/\psi K^0_S$ is $B^0 \rightarrow J/\psi K^{*0}$, with $K^{*0} \rightarrow K^+\pi^-$. The charge of the kaon indicates the flavour of the $B^0$ at the decay time.

In this note, we present an update of the study of the $B^0 \rightarrow J/\psi (\mu\mu)K_S^0$ decay mode aiming to determine the LHCb sensitivity to $\sin(2\beta)$ as well as the update of the study of the $B^0 \rightarrow J/\psi (\mu\mu)K^{*0}$ channel for tagging purposes. We describe reconstruction and selection of the two decay modes in Sect. 2. In Sect. 3 we present event yields and background estimations. Sect. 4 is dedicated to the study of the tagging efficiency and mistag. We present the result for the LHCb sensitivity to $\sin(2\beta)$ in one year of data taking in Sect. 5. Finally, summary and conclusions are presented in Sect. 6.
2 Reconstruction and Selection

All the sensitivities studies in LHCb are performed by analyzing a large sample of simulated minimum-bias proton-proton interactions at $\sqrt{s} = 14$ TeV, including pile-up, generated using PYTHIA[6]. The generated particles are tracked through the detector material and surrounding environment using GEANT 4 [7] where the geometry and material of the LHCb detector is described in great detail, using the Gauss $^1$ LHCb package. The present study uses the internally called Data Challenge 2004 (DC04) data, and the LHCb standard digitization, reconstruction and analysis software, respectively Boole, Brunel and DaVinci $^2$.

The specific channels are obtained by filtering the minimum bias data-set requiring that the b-meson lies within a 400 mrad cone of the LHCb acceptance. The samples used in this analysis are the $B^0 \rightarrow J/\psi (\mu \mu) K_S^0$, which is the signal channel used to infer the sensitivity to $\sin(2\beta)$, the $B^0 \rightarrow J/\psi (\mu \mu) K^{*0}$ used as a control channel to obtain the mistag rate ($\omega$), the inclusive $b\bar{b}$ and prompt $J/\psi (\mu \mu)$ to study the background contamination. The generated sample of inclusive $b\bar{b}$ corresponds to 13 minutes of running at the nominal luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

For the $J/\psi$ and $K^{*0}$ reconstruction only “long tracks” are used, i.e. tracks that crosses the full tracking system, whereas for the $K_S^0$ selection, other types of LHCb tracks are also considered. For details on the LHCb tracking reconstruction and performance see [8].

The particle identification in LHCb is also described in detail in [8]. Basically 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 selection criteria have been chosen in order to maximize the signal and minimize the inclusive $b\bar{b}$ retention. The cuts that would bias the lifetime distribution, such as the distance between primary and the secondary vertices and impact parameters of secondary particles with respect to the primary vertex, have been avoided.

2.1 $J/\psi \rightarrow \mu^+\mu^-$ Selection

The LHCb standard $J/\psi \rightarrow \mu^+\mu^-$ selection [9] has been used for both signal and control channels selection. Pairs of muons of opposite charges are required to come from a common vertex with $\chi^2 < 16$ and to have an invariant mass within $\pm 120$ MeV/c$^2$ of the true $J/\psi$ mass, with $J/\psi$ momentum being above 10 GeV/c. The muons are selected by requiring that the $\Delta \ln L_{\mu\mu}$ is greater than -6, their transverse momentum exceeds 250 MeV/c, and momentum is above 3 GeV/c. A mass-constrained vertex fit is applied to the muon pairs and the combination is kept if its $\chi^2$ is less than 50.

2.2 $K_S^0 \rightarrow \pi^+\pi^-$ Selection

The $K_S^0 \rightarrow \pi^+\pi^-$ decays are reconstructed according to three categories, depending on the types of tracks: LL category, with two “long” tracks; LU category, with one “long”


$^2$The versions used are:
Boole v5 (http://lhcb-release-area.web.cern.ch/LHCb-release-area/DOC/boole),
Brunel v23 (http://lhcb-release-area.web.cern.ch/LHCb-release-area/DOC/brunel),
and one “upstream” track \(^3\); and DD category, with two “downstream” tracks \(^4\), to take into account the long lived \(K^0_S\) which is about 2/3 of the selected sample. Each pair of oppositely-charged pions is fitted to a common vertex, requiring a \(\chi^2 < 20\) (4.0 for LL and 10.0 for LU). The pair is considered as a \(K^0_S\) candidate if its invariant mass is within \(\pm 110\) MeV/c\(^2\) of the true \(K^0_S\) mass and its combined \(p_T\) is above 600 MeV/c (500 MeV/c for LL and 250 MeV/c for LU). For the LU category a mass-constrained vertex fit is further applied requiring a \(\chi^2 < 50\) as discussed in [10].

2.3 \(K^{*0} \rightarrow K^+\pi^-\) Selection

A pair of opposite charged pions and kaons with \(p_T\) above 200 MeV/c, and momentum greater than \(1.0\) GeV/c is combined to form a \(K^{*0}\). The pions and kaons should not point to any primary vertex, so an impact parameter significance above \(1.5\) is required. The vertex fit is accepted if its \(\chi^2 < 10\). The \(K^{*0}\) is taken as a candidate if it has a \(p_T > 200\) MeV/c, \(p > 1.0\) GeV/c, its flight distance significance with respect to all primary vertices is above \(1.0\) and its invariant mass is within \(\pm 200\) MeV/c\(^2\) of the nominal \(K^{*0}\) mass.

2.4 \(B^0 \rightarrow J/\psi(\mu\mu)K^0_S\) Selection

In order to select the \(B^0 \rightarrow J/\psi(\mu\mu)K^0_S\) the same discriminant variables are used for the three \(K^0_S\) categories, but the values of the cuts differ among them and are shown in Table 1, and discussed below. The \(J/\psi\) and \(K^0_S\) are combined in a common vertex fit, and to further ensure that they come from the same vertex, a cut is applied on the impact parameter significance of the \(K^0_S\) with respect to the \(J/\psi\) vertex. To reduce the contamination of \(B^0 \rightarrow J/\psi(\mu\mu)K^{*0}\) and \(B^0 \rightarrow J/\psi\phi\) it is required that the significance on the distance in \(z\) direction between the \(J/\psi\) and \(K^0_S\) vertexes exceeds some value. A cut on the transverse momentum of \(B^0\) and on its impact parameter with respect to the primary vertex minimizes the combinatorial background. If there is more than one primary vertex in the event, the one which gives the smallest impact parameter to the \(B^0\) is chosen. Finally the \(J/\psi K^0_S\) mass must be within \(\pm 60\) MeV/c\(^2\) of the true \(B^0\) mass, and if more than one \(B^0\) candidate is selected in the same event, the one with the smallest \(\chi^2\) of its vertex fit is chosen. The distributions of two of these variables for the signal and inclusive \(b\bar{b}\) events are shown in Figure 2.

Table 1: Cuts applied to select \(B^0 \rightarrow J/\psi(\mu\mu)K^0_S\) candidates for the three \(K^0_S\) categories.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DD</th>
<th>LL</th>
<th>LU</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\chi^2) (B^0) vertex</td>
<td>&lt; 40</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>(l p_{K^0}/\sigma) wrt (J/\psi)</td>
<td>&lt; 6.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>((z_{K^0} - z_{J/\psi})/\sigma)</td>
<td>&gt; 6</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>(p_T) (B^0) [MeV/c]</td>
<td>&gt; 200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>(l p_{B}/\sigma) wrt PV</td>
<td>&lt; 4.5</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>(</td>
<td>\Delta M_{J/\psi K^0_S}</td>
<td>[MeV/c^2])</td>
<td>&lt; 60</td>
</tr>
</tbody>
</table>

\(^3\)“Upstream” tracks leave hits in the VELO and TT stations only.

\(^4\)“Downstream” tracks leave hits in the TT and T stations only.
Figure 2: Distribution of variables used in the selection of $B^0 \to J/\psi(\mu\mu)K_0^*$ events for the DD category. Solid line refers to signal events, dashed are inclusive $b\bar{b}$ events.

Figure 3: Invariant mass distribution for $B^0 \to J/\psi(\mu\mu)K_0^*$ for DD (left), LL (center) and LU (right) categories, after the cuts described in the text.

The $B^0$ mass distribution obtained after this selection has a resolution of 13.1 MeV/$c^2$, 7.7 MeV/$c^2$ and 11.8 MeV/$c^2$ for the DD, LL and LU categories respectively, and is shown in Figure 3. The relative contributions of the various $K_0^*$ categories in the final $B^0$ sample are 63.7% (DD), 27.6% (LL) and 8.7% (LU).

A double Gaussian fit to the proper time ($\tau$) resolution gives a core of $41\pm2$ fs, $35\pm2$ fs, $46\pm2$ fs and a tail of $\approx105$ fs in the three cases. The lifetime resolution used in Section 5 comes from a fit to the sum of all the categories which gives $37.6\pm1.4$ fs for the core (with a mean of $-4\pm1$ fs) and $91\pm6$ fs for the tail (with a mean of $-5\pm4$ fs), with 73% of the events falling into the core. This is shown in Fig. 4.

2.5 $B^0 \to J/\psi(\mu\mu)K^{*0}$ Selection

The $B^0$ selection and the cuts used for the $B^0 \to J/\psi(\mu\mu)K^{*0}$ channel are the same as presented in Ref. [11]. The $B^0$ candidates invariant mass distribution, shown in Fig. 5, has a resolution of 7.6 MeV/$c^2$. 
Figure 4: Lifetime resolution of $B^0$ meson. The core resolution is $37.6 \pm 1.4$ fs and the tail is $91 \pm 6$ fs.

Figure 5: Invariant mass distribution for $B^0 \to J/\psi(\mu\mu)K^{*0}$ candidates.

3 Event Yield and Background Estimation

The results of this section are obtained on a different set of samples from the ones on which the cuts have been tuned. For the tuning, a set of 18M $b\bar{b}$ events, internally called DC04v1 was used, and for the final yield/background estimation we run on 34M DC04v2r3 inclusive $b\bar{b}$. Out of the 1.3M $B^0 \to J/\psi(\mu\mu)K^{*0}$ generated, 75k events passed the final cuts described in the previous section and 54k events survive the L0, L1 and HLT trigger simulation. For the control channel $B^0 \to J/\psi(\mu\mu)K^{*0}$ from 2.5M generated events, 144k passed the selection and HLT simulation. Table 2 shows the number of accepted events for both channels.

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$^{32}$ cm$^{-2}$s$^{-1}$)
Table 2: Results of $B^0 \to J/\psi(\mu\mu)K^0_S$ and $B^0 \to J/\psi(\mu\mu)K^{*0}$ selections. # Generated is the number of generated events used. # Selected is the number of selected events. L0, L1 and HLT are the number of events that pass the Level 0, Level 1 and HLT trigger, respectively.

<table>
<thead>
<tr>
<th>channel</th>
<th>$B^0 \to J/\psi(\mu\mu)K^0_S$</th>
<th>$B^0 \to J/\psi(\mu\mu)K^{*0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>1298500</td>
<td>2568831</td>
</tr>
<tr>
<td>LL</td>
<td>20751</td>
<td>178065</td>
</tr>
<tr>
<td>LU</td>
<td>6474</td>
<td>47788</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Signal and control channel efficiencies.

<table>
<thead>
<tr>
<th>channel</th>
<th>$\varepsilon_{\text{rec}}$</th>
<th>$\varepsilon_{\text{sel}/\text{rec}}$</th>
<th>$\varepsilon_{\text{trg}/\text{sel}}$</th>
<th>$\varepsilon_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to J/\psi(\mu\mu)K^0_S$</td>
<td>3.40±0.13%</td>
<td>59.4±0.3%</td>
<td>72.08±0.16%</td>
<td>1.445±0.006%</td>
</tr>
<tr>
<td>$B^0 \to J/\psi(\mu\mu)K^{*0}$</td>
<td>6.022±0.011%</td>
<td>39.95±0.11%</td>
<td>80.38±0.09%</td>
<td>1.941±0.005%</td>
</tr>
</tbody>
</table>

and a $b\overline{b}$ production cross section of $\sigma_\overline{b} = 500 \mu b$. The probability for a $b$-quark to hadronize into a hadron is assumed to be $f_B = 39.8 \pm 1.0\%$ [12] for $B^0$ and the factor 2 takes into account the production of both $b$- and $\overline{b}$-hadrons. The visible branching ratio $BR_{\text{vis}}$ is the product of all branching ratios involved in the b-hadron of interest. In the case of $B^0 \to J/\psi(\mu\mu)K^0_S$, the visible branching ratio $BR_{\text{vis}}$ is $(20.5 \pm 0.9) \times 10^{-6}$ and for $B^0 \to J/\psi(\mu\mu)K^{*0}$ is $(59.0 \pm 0.3) \times 10^{-6}$, where the individual branching ratios have been taken from [12].

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 that 34.85% of the b-hadron are required to be produced inside the 400 mrad cone around the beam axis, the total signal efficiency is 1.44% and 1.94% for $B^0 \to J/\psi(\mu\mu)K^0_S$ and $B^0 \to J/\psi(\mu\mu)K^{*0}$ channels respectively. This gives an annual yield estimation of 236k events for the signal and 932k events for the control channel.

A possible way to break it down is

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

where $\varepsilon_{\text{rec}}$ is the reconstruction efficiency including the geometrical acceptance, $\varepsilon_{\text{sel}/\text{rec}}$ is the efficiency of offline selection cuts on the reconstructed events and $\varepsilon_{\text{trg}/\text{sel}}$ is the combined L0 × L1 × HLT trigger efficiency on selected events. They are presented in Table 3.

In order to estimate the B/S ratio, calculated after the trigger, two samples have been used, the inclusive $b\overline{b}$ and prompt $J/\psi \rightarrow \mu^+\mu^-$. For the inclusive $b\overline{b}$, we consider the events falling in an enlarged mass window of $\pm 600 \text{MeV}/c^2$ around the nominal $B^0$ mass. Out of the 34M $b\overline{b}$ events, 336 background events pass the $B^0 \to J/\psi(\mu\mu)K^0_S$ selection and 117 are left after HLT. In the narrow
Table 4: Composition of background events passing the $B^0 \to J/\psi(\mu\mu)K_S^0$ selection and HLT in the tight mass window.

<table>
<thead>
<tr>
<th>event</th>
<th>category</th>
<th>associations</th>
<th>B channel generated</th>
</tr>
</thead>
</table>
| 1     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^+ \to J/\psi K^+_s(1270)$ |
| 2     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
$K_S^0$ is a $\Lambda \to p\pi$ from PV | $B^0_{(s)} \to J/\psi K^+K^-\pi^0\pi^0$ |
| 3     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^+ \to J/\psi K^{*0}\pi^+$ |
| 4     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
pions are $e^\pm$ from $\gamma$ from $\pi^0$ | $B^0 \to J/\psi K^{*0}\pi^0$ |
| 5     | DD       | $\mu^-$ is a $\pi$ from PV, true $\mu^+$ from $B^+$
pions are $e^\pm$ from $\gamma$ from $\pi^0$ | $B^+ \to D^{*0}\mu^+\nu_\mu$ |
| 6     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^+ \to D^{*0}\mu^+\nu_\mu$ |
| 7     | DD       | $\mu^-$ is a $\pi$ from PV, true $\mu^+$ from $B^+$
true $K_S^0$ from PV | $B^+ \to D^{*0}\mu^+\nu_\mu$ |
| 8     | DD       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^- \to J/\psi K^{*-}$ |
| 9     | LL       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^+ \to J/\psi K^{*+}\phi$ |
| 10    | LL       | true $\mu^-$ from $B^-$, $\mu^+$ is $\pi^+$ from PV
true $K_S^0$ from PV | $B^- \to D^{*0}\mu^-\nu_\mu$ |
| 11    | LU       | $\mu^\pm$ are $\pi^\pm$ from PV
true $K_S^0$ from PV | $B^+ \to D^0\pi^+\pi^-\pi^0\pi^+$ |
| 12    | LU       | one true $\mu$ from $D_s$ from $B^{*0}$
one true $\mu$ from $B^0$
true $K_S^0$ from PV | $B^0 \to D^-\pi^0\mu^+\nu_\mu$
$B^0 \to D_sD^{*0}\pi^0\pi^0$ |
| 13    | LU       | true $J/\psi \to \mu^+\mu^-$ from B
true $K_S^0$ from PV | $B^0_{(s)} \to J/\psi \pi^+\pi^-\phi$ |

window of $\pm60\,\text{MeV}/c^2$ 13 events survive the HLT simulation, giving a B/S of 0.63$\pm$0.06 considering only this contribution. A closer look to the 13 events that survive the selection and all trigger levels in the tight mass window, show that most of them are a combination of a true $J/\psi \to \mu^+\mu^-$ originating from a B meson, and a true $K_S^0$ coming from the primary vertex. Table 4 shows the details of these events.

For the control channel 142 events are accepted in the wider window, 15 in the narrow and 12 after the trigger. A detailed number of signal and background events passing each level is shown in Table 5.

Another important source of background is the the prompt $J/\psi \to \mu^+\mu^-$. Applying the $B^0 \to J/\psi(\mu\mu)K^{*0}$ selection to a sample of 2M generated events 23 survived, 5 after the trigger. Together with the $b\bar{b}$ inclusive sample this leads to a B/S ratio of 0.155$\pm$0.013 with an expected annual yield of 932k events.
Table 5: Number of events passing the selection in a \( \approx 34 \)M inclusive \( b\bar{b} \) sample; “bck” stands for background.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 )</th>
<th>( B^0 \rightarrow J/\psi(\mu\mu)K^*0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\Delta M_{J/\psi K_s}</td>
<td>[\text{Mev}/c^2] )</td>
</tr>
<tr>
<td># Selected</td>
<td>signal</td>
<td>bck</td>
</tr>
<tr>
<td>L0</td>
<td>33</td>
<td>336</td>
</tr>
<tr>
<td>L0&amp; L1</td>
<td>20</td>
<td>141</td>
</tr>
<tr>
<td>L0&amp; L1&amp; HLT</td>
<td>17</td>
<td>117</td>
</tr>
</tbody>
</table>

Since we have avoided, in the \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) selection criteria, cuts that would bias the proper time distribution, a large number of prompt \( J/\psi \rightarrow \mu^+\mu^- \) is expected to contaminate the selected sample. Applying the selection on \( 1.4 \)M prompt \( J/\psi \rightarrow \mu^+\mu^- \) events, 163 have been selected after the HLT, which gives a B/S of 7.7\( \pm 0.6 \). Despite the fact that it is a large factor, this kind of events are concentrated in the very short lifetime as can be seen in the left plot on Fig. 6. The advantage of not applying “lifetime” cuts is that no acceptance function will be needed when assessing the sensitivity on \( \sin 2\beta \), making easier the estimation of systematic effects. The flatness of the acceptance can be seen in the second plot of Fig. 6.

![Figure 6](image-url)

Figure 6: The plot on the left is the proper time distribution of events passing the selection criteria. Solid line is for \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) and dashed for prompt \( J/\psi \rightarrow \mu^+\mu^- \) events. The signal events are normalized to the number of events in the prompt \( J/\psi \rightarrow \mu^+\mu^- \) sample. On the right plot is shown the acceptance of selected events as a function of proper time.

If a cleaner sample of \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) is needed, a powerful discriminating variable is the significance on the \( z \) distance of the \( B^0 \) vertex with respect to the primary vertex as can be seen in Fig. 7. Requiring that this quantity exceeds 1.8, the signal is reduced from 75013 to 71937 before trigger simulation and to 52194 after HLT, giving an annual yield of 228k. The inclusive \( b\bar{b} \) goes down from 336 to 192 in the enlarged mass window before trigger, and from 13 to 6 in the narrow window after HLT, giving a B/S of 0.45.
if we consider only this contribution. 19 prompt $J/\psi \rightarrow \mu^+\mu^-$ are left before the trigger simulation and 8 after HLT. Since the number of events is less than 10, we calculate the limits of B/S with 90% confidence level as being $[0.19,0.69]$. The total B/S would be within $[0.64,1.16]$ limits. It has been checked though, that the sensitivity to $\sin 2\beta$ does not change significantly after the application of this cut, so it will not be used here. In the second plot of Fig. 7 it is seen the acceptance function needed to correct for this selection. A fit to $A(\tau) = b (\frac{\text{ar}}{\text{ar}+\text{br}})^\tau$ gives $a = (11, 7 \pm 1)\text{ps}^{-1}$ and $b = 0.058 \pm 0.002$.

![Figure 7: Significance on the $z$ distance between $B^0$ and primary vertices distribution of events passing the selection criteria. Solid line is for $B^0 \rightarrow J/\psi(\mu\mu)K_S^0$ and dashed for prompt $J/\psi \rightarrow \mu^+\mu^-$ events (left). Acceptance function after applying $(z_{B^0} - z_{PV})/\sigma > 1.8$ (right).](image)

4 Tagging

Flavour tagging is an important ingredient for measuring $CP$ violation parameters in neutral $B$ meson systems. It is vital to obtain accurate values for the tagging efficiency $\varepsilon_{tag}$ and wrong tag fraction $\omega$. These quantities are defined as

$$\varepsilon_{tag} = \frac{N_{tag}}{N_{tot}}$$

$$\omega = \frac{N_{wronntag}}{N_{tag}}$$

where $N_{tag}$ is the total number of tagged $B$ mesons, $N_{wronntag}$ is the number of wrong tagged events, and $N_{tot}$ is the total number of reconstructed $B^0$’s. The dilution $D$ is related to wrong tag fraction as $D = 1 - 2\omega$.

An adequate approach is to evaluate these quantities from data, instead of simulation, through the use of self-tagged channels – so called control channels. The $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}$ is a good control channel since it has one of the largest $B^0$ inclusive branching ratios, has no CP violation and the charge of final $K$ tags the $B^0$ flavour at the decay time.
In principle, $\varepsilon_{\text{tag}}$ and $\omega$ should be the same independently of the decay products of the $B^0$ meson. Nevertheless, for two different decays - for instance the signal and control channels - the decay products of the $B^0$ can have different distributions in phase space. By applying the trigger selection on these channels the phase space of the decay can be affected differently. Consequently tagging performances for control and signal channels can be different.

A clear difference in the trigger selection between channels appears when the signal products are responsible for the trigger. For each trigger level, an event can be labeled according to three categories:

- Triggered on Signal (TOS): events triggered only by applying cuts on the studied products of the signal $B^0$.
- Triggered Independent of Signal (TIS): events triggered even if the signal products are removed.
- Triggered on Both (TOB): events which need both signal products and the rest of the event to be triggered.

A particular event can be simultaneously TIS and TOS — in this case, it is included in the TIS sample but not in TOS, since it would be triggered independently of the signal channel in any case. Here, we study the tagging performance for L0 and L1 triggers, under TIS and TOS categories, in order to look for any difference between signal, $B^0 \to J/\psi(\mu\mu)K^0_S$, and the control channel, $B^0 \to J/\psi(\mu\mu)K^{*0}$, which would imply eventual corrections. Table 6 shows the composition of the studied samples according to this categories. TOB events are excluded from this study since it is not possible to make a clear comparison between signal and control channels in this case. In addition, they are not statistically relevant.

We have thus considered four classes of events when analyzing tagging performances for signal and the control channel: L0TOS & L1TOS, L0TIS & L1TOS, L0TOS & L1TIS and L0TIS & L1TIS.

Since the sensitivity to measure $\sin(2\beta)$ depends directly on $\omega$ due to the dilution factor $(1 - 2\omega)$, we need to check whether this quantity depends on particular variables that are affected by phase space. Indeed, $B^0 \to J/\psi(\mu\mu)K^0_S$ and $B^0 \to J/\psi(\mu\mu)K^{*0}$ have different $p_T$ distributions for the $B^0$ meson due to phase space, as can be seen in Fig. 8. On the other hand, they both are $J/\psi(\mu\mu)$ channels and, as we can see from Table 6, the trigger acts very similar on them.

Fig. 9 shows the tagging efficiency as a function of $p_T$. The distributions match for signal and control channels, although there is a clear dependence of $\varepsilon_{\text{tag}}$ on $p_T$.

The overall tagging efficiency for $B^0 \to J/\psi(\mu\mu)K^0_S$ is:

<table>
<thead>
<tr>
<th>Channel</th>
<th>L0TOS</th>
<th>L1TOS</th>
<th>L0TIS</th>
<th>L1TIS</th>
<th>L0TOB or L1TOB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to J/\psi(\mu\mu)K^0_S$</td>
<td>67%</td>
<td>6%</td>
<td>19%</td>
<td>6%</td>
<td>2%</td>
</tr>
<tr>
<td>$B^0 \to J/\psi(\mu\mu)K^{*0}$</td>
<td>65%</td>
<td>7%</td>
<td>21%</td>
<td>7%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Figure 8: Distribution of $p_T$ for the $B^0$ meson for $B^0 \to J/\psi(\mu\mu)K^0_S$ (blue circles) and $B^0 \to J/\psi(\mu\mu)K^{*0}$ (red triangles). The small plot on the top is the ratio of the two distributions.

$$\varepsilon_{\text{tag}} = (61.69 \pm 0.17)\%.$$  \hspace{1cm} (7)

For $B^0 \to J/\psi(\mu\mu)K^{*0}$ we obtain $\varepsilon_{\text{tag}} = (64.99 \pm 0.12)\%$. The tagging efficiency for inclusive $b\bar{b}$ is about the same as for $B^0 \to J/\psi(\mu\mu)K^0$, but for prompt $J/\psi(\mu\mu)$ a lower value is obtained, $\varepsilon_{\text{tag}} = (36 \pm 1)\%$.

Fig. 10 presents the true mistag (from MC) as a function of $B^0 p_T$ for these classes, for both $B^0 \to J/\psi(\mu\mu)K^0_S$ and $B^0 \to J/\psi(\mu\mu)K^{*0}$. One can see that there is no apparent dependence of $\omega$ on $p_T$ for all classes and for both channels. Moreover, the distributions match for signal and control channels. This implies that no correction on $\omega$ is necessary – we can use $\omega$ extracted from $B^0 \to J/\psi(\mu\mu)K^0$ in the $B^0 \to J/\psi(\mu\mu)K^{*0}$ analysis.

To extract the $\omega$ value we use the $B^0B^0$ oscillation observed in the control channel. The asymmetry

$$A_{\text{osc}}(t) = \frac{\Gamma(\text{non oscillating}) - \Gamma(\text{oscillating})}{\Gamma(\text{non oscillating}) + \Gamma(\text{oscillating})}$$ \hspace{1cm} (8)

is fitted with the function\textsuperscript{5}

$$A_{\text{osc}}(t) = (1 - 2\omega) \cos(\Delta M_{B_d} t),$$ \hspace{1cm} (9)

where $\Delta M_{B_d}$ is fixed to 0.5 ps$^{-1}$ in the fit.

The $B^0$ flavour at production time is obtained using the LHCb tagging system (Ref. [13]) while at decay time it is determined by the $K$ charge. In Fig. 11 we show the asymmetry

\textsuperscript{5}We use here a simplified function to fit the asymmetry, since there is no background in the control-channel sample and we did not include proper time resolution. In the future, when fitting data and with enough information on background, a more rigorous treatment would be necessary, following the approach presented in Sect. 5, where background and proper time resolution are included.
Figure 9: Tagging efficiency ($\varepsilon_{\text{tag}}$) as a function of $p_T$ for $B^0 \rightarrow J/\psi(\mu\mu)K^0_S$ (blue circle) and $B^0 \rightarrow J/\psi(\mu\mu)K^*(0)$ (red triangle) for the four classes of triggered events.

Figure 10: Wrong tag fraction ($\omega$) as a function of $p_T$ for $B^0 \rightarrow J/\psi(\mu\mu)K^0_S$ (blue circle) and $B^0 \rightarrow J/\psi(\mu\mu)K^*(0)$ (red triangle) for the four classes of triggered events.
curve with the resulting fitting function. By rescaling the error obtained (0.2%) to the expected yield for 2fb\(^{-1}\), the value obtained for \(\omega\) is:

\[
\omega = (38.7 \pm 0.1\%) \tag{10}
\]

From truth MC information, we obtain mistag fractions of 38.54\(\pm\)0.15\% and 38.84\(\pm\)0.22\% for \(B^0 \to J/\psi(\mu\mu)K^{*0}\) and \(B^0 \to J/\psi(\mu\mu)K_S^0\), respectively, in agreement with the value above. In the future, it will be possible to have \(\omega\) event by event, from the different tagging categories, thus allowing us to incorporate a p.d.f for \(\omega\) in the \(\sin(2\beta)\) sensitivity study.

![Figure 11: Asymmetry of \(B^0 \to J/\psi(\mu\mu)K^{*0}\) oscillation measured as a function of the B meson proper time.](image)

### 5 Sensitivity to \(\sin(2\beta)\)

For \(B^0 \to J/\psi K_S^0\), the Standard Model expectations are \(A_{CP}^{\text{dir}} = 0\) and \(A_{CP}^{\text{mix}} = \sin(2\beta)\). The statistical sensitivity on these parameters with one year of data is assessed from toy Monte Carlo events generated and fitted using the RooFit toolkit for data modeling [14]. The parameters used as input to the toy Monte Carlo program are obtained from fully simulated and reconstructed events, as described in the previous sections.

The input parameters used are summarized below for our standard \(B^0 \to J/\psi K_S^0\) cuts (no “lifetime cuts”, see Sect. 3):

- Number of tagged signal events: 145814
- Number of tagged background events
  - bb-inclusive: 92346
  - prompt \(J/\psi\): 659152
- Proper time resolution
  - signal events: 0.04 ps
- **Lifetime**
  - signal events: $(1.46 \pm 0.03)$ ps
  - bb inclusive events: $(0.23 \pm 0.02)$ ps
  - prompt $J/\psi$ events: $(0.037 \pm 0.003)$ ps

- **Mistag probability:** $(38.7 \pm 0.1)$%

Figure 12 shows a plot of the lifetime distributions for signal, bb inclusive and prompt $J/\psi$ events. The lifetime values listed above for the background events come from a fit to these distributions while the signal resolution was presented in Section 3.

![Lifetime distributions for signal (left), bb inclusive (middle) and prompt J/\psi events (right).](image)

For the signal, the proper time is given by the following distribution:

$$f(t; \text{tag}) \propto e^{-t/\tau} (1 + (1 - 2\omega) \times \text{tag} \times \mathcal{A}^\text{mix} \times \sin(\Delta m_d t)),$$

where $\text{tag}$ is +1(-1) for events tagged as $B(\bar{B})$ at the production time and $\omega$ accounts for mistag. The value of $\Delta m_d$ is set to 0.5 ps$^{-1}$ and $\tau$ to 1.46 ps. The parameter $\sin(2\beta)$ is set to 0.73 and left free to vary between -1 and +1.

The physical model above is then convoluted with a proper time Gaussian resolution model.

For the background events, the same procedure is applied using a proper time distribution like:

$$f(t, \text{tag}) \propto e^{-t/\tau}$$

where $\tau$ is now the background lifetime.

Although, for this study, we have obtained an average value for the mistag rate (Eq. (10)), eventually the value of the mistag would be known, event by event, from the LHCb tagging system. Under this circumstance, a p.d.f. for $\omega$ can be incorporated. Here, we assume the mistag p.d.f. to be a Gaussian, with a corresponding width 10 times larger than the error on the central value, that is, we take $\omega = 0.387$ with $\sigma_\omega = 0.01$.\(^6\)

We then have:

$$f(t, \text{tag}, \omega) = F(t, \text{tag}|\omega) \times P(\omega),$$

\(^6\)This value was arbitrarily chosen; the sensitivity result does not change by making reasonable variations on $\sigma_\omega$, since the p.d.f. is included for generation and fit accordingly.
where \( P(\omega) \) is the Gaussian \( \omega \) p.d.f. and \( F(t, \text{tag}|\omega) \) is the proper time distribution (which also depends on \( \text{tag} \)) for a given \( \omega \).

The signal and background Monte Carlo events are generated according to these p.d.f. and then added together to make the full data sample which is then fitted using the sum of the background and signal p.d.f. The only parameter fitted here is \( \sin(2\beta) \).

A plot of the data generated, including signal and background events with the total p.d.f. superimposed is shown in Figure 13.

The error obtained with the fit is

\[
\sigma(\sin 2\beta) = 0.020
\]

for the statistics equivalent to 2fb\(^{-1}\) of data. This value does not change if we choose to use “lifetime” cuts for removing prompt \( J/\psi \) decays, but requires correction due to the acceptance function described in Sect. 3. This value is reproduced by taking the width of the gaussian distribution obtained from simulation of 100 independent toy MC samples with the same statistics.

For comparison, the current world-averaged value for \( \sin(2\beta) \) [5], as shown in Eq. (2), has an uncertainty of 0.025.

It is worth to stress that the critical parts in extracting \( \sin(2\beta) \) are the proper-time resolutions and the mistag rate. Systematic studies were not included here since CP violation was not incorporated for the DC04 \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) samples. This study will be possible using DC06 samples.

6 Summary and Conclusions

In this note, we have presented an update of the \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) and \( B^0 \rightarrow J/\psi(\mu\mu)K^{*0} \) analyses. The channel \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) is the gold-plated mode for the extraction of \( \sin(2\beta) \) and the \( B^0 \rightarrow J/\psi(\mu\mu)K^{*0} \), with no CP violation, serves as the control channel for tagging.

Using DC04 samples, we have estimated an annual yield of 236k \( B^0 \rightarrow J/\psi(\mu\mu)K_S^0 \) events, with a background to signal ratio \( B/S = 0.63 \) for \( bb \) inclusive events, and \( B/S = 7.7 \) for prompt \( J/\psi \). These two kinds of background can be significantly reduced by
applying a cut on the significance of the $z$ separation between primary and secondary vertices: for this quantity greater than 1.8, $B/S$ goes to 0.45 and [0.19,0.69] for inclusive $b\bar{b}$ and prompt J/ψ, respectively. This cut, however, does not affect the $\sin(2\beta)$ sensitivity, so it has not been applied here. For $B^0 \to J/\psi(\mu\mu)K^{*0}$ the annual yield obtained is 932k, with $B/S = 0.155$.

Tagging is a very important issue for measurements of CP violation parameters in $B^0$ decays. We have studied the tagging efficiency and mistag rate $\omega$ for signal and control channels under TIS and TOS categories for both L0 and L1 triggers. We found that $\omega$ does not depend on the $p_T$ of the $B^0$ for all categories, and the distributions match for signal and control channels. This allows $\omega$, measured from $B^0 \to J/\psi(\mu\mu)K^*$, to be used directly in the extraction of the $\sin(2\beta)$ sensitivity from $B^0 \to J/\psi(\mu\mu)K^0_S$ decays.

To assess the sensitivity on $\sin(2\beta)$ we have generated toy Monte Carlo events using the expected yields for signal and background, lifetime information, and mistag rate as inputs. We estimate that after 2 fb$^{-1}$ of data taking, the LHCb sensitivity to $\sin(2\beta)$ is 0.020.

This work has been partially supported by ALFA-EC funds in the framework of HELEN Project, and by the Brazilian funding agencies CNPq, FAPERJ and FINEP.

References