Measuring the CP Violating Phase in $B_s$ Mixing Using $B_s^0 \to J/\psi f_0(980)$

Abstract

We show that the decay $B_s^0 \to J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$ can be used to measure the CP violating phase in $B_s$ mixing, $-2\beta_s$, and estimate the sensitivity as $\pm0.050$ rad, for $2 \text{ fb}^{-1}$ of LHCb data. After adding in the related $B_s^0 \to J/\psi \eta'$, $\eta' \to \rho \gamma$ mode, the sensitivity improves to $\pm0.044$ rad. Use of these CP eigenstates obviates the need for a transversity analysis that must be used in the case of $B_s^0 \to J/\psi \phi$ decays.

1 Introduction

While CP violation in $B^0$ decays has been measured unequivocally, attempts at determining the CP violating phase in $B_s$ mixing, $-2\beta_s$ [1] by the CDF and D0 experiments using $B_s^0 \to J/\psi \phi$ decays [2], have given values much larger than Standard Model (SM) predictions, but with large enough errors that the measurements are not statistically significant, even when combined [3]. Since this mode is not a CP eigenstate, but one involving two vector particles an angular analysis is necessary [4]. These analyses, however, did not allow for the possibility of there being an S-wave component in the $\phi$ mass region, thus possibly biasing the result and surely underestimating the error [5].

Since physics beyond the SM can or even should contribute virtual particles that interfere in the $B_s$ mixing loop, it is important to measure the mixing phase as precisely and in an unbiased manner as possible. It has long been known that the modes $B_s^0 \to J/\psi \eta'$ are CP eigenstates, and thus angular analysis is not needed. All of the $\eta$ or $\eta'$ decay modes contain at least one photon, whose reconstruction is much less efficient than charged particles in LHCb. One study has estimated the sensitivity using $\eta' \to \rho \gamma$ [6], but the sensitivity is of the order of a factor of two worse than that expected using $J/\psi \phi$ mode. Other modes have also been considered [7].

In this note we describe the event selection, the backgrounds, and make an estimate of the measurement sensitivity of $-2\beta_s$, using a heretofore not considered mode $B_s^0 \to J/\psi f_0(980)$, where $f_0(980) \to \pi^+\pi^-$. The dominant Feynman diagrams for the $\phi$ and $f_0$ processes are shown in Fig. 1. There also are possible small contributions from penguin diagrams [8] and W-exchange [9].
Figure 1: Decay diagrams for $B_s \rightarrow J/\psi \phi$, and $B_s \rightarrow J/\psi f_0$.

There have been several estimates of the relative widths of these decay modes. Based on studies of hadronic $D_s^+$ decays Stone and Zhang [5] estimate that the relative width is

$$R_{f/\phi} \equiv \frac{\Gamma(B_s^0 \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+ \pi^-)}{\Gamma(B_s^0 \rightarrow J/\psi \phi, \phi \rightarrow K^+ K^-)} \approx 20\% .$$

(1)

There also is a non-$f_0 \pi^+ \pi^-$ S-wave component that is very wide in mass, and contributes an additional 5% of the $J/\psi \phi$ rate using a narrow selection of $\pm 90$ MeV around the $f_0$ mass that was used in the sensitivity estimate [5].

Recently, the CLEO collaboration [10] has reported another estimate of $R_{f/\phi}$ using measurements of the semileptonic widths of $D_s^+ \rightarrow f_0 e^+ \nu$ and $D_s^+ \rightarrow \phi e^+ \nu$ at the endpoint of the four-momentum transfer range where the phase space is maximum, as suggested by Stone and Zhang. These measurements yield

$$R_{f/\phi} \equiv \frac{\frac{d\Gamma}{dq^2}(D_s^+ \rightarrow f_0(980)e^+ \nu, f_0 \rightarrow \pi^+ \pi^-) |_{q^2=0}}{\frac{d\Gamma}{dq^2}(D_s^+ \rightarrow \phi e^+ \nu, \phi \rightarrow K^+ K^-) |_{q^2=0}} = (42 \pm 11)\% .$$

(2)

A note on notation, since it is clumsy to always refer to $-2\beta_s$ we set this equal to $\phi_f$ to indicate that this is the CP violating phase measured in $B_s \rightarrow J/\psi f_0$ decays, which should to an excellent approximation be the same phase as measured in $B_s \rightarrow J/\psi \phi$ decays even in the presence of new physics in the mixing amplitude.

2 Signal Selection and Optimization

The present study is done using a Monte Carlo simulation of the signal and specific backgrounds. For the signal, a $B_s$ is produced in a 14 TeV proton proton collision conforming to the theoretical fragmentation function. It is allowed to decay and the quasi-stable particles then traverse the detector where they are subject to magnetic fields, multiple scattering in material, decays and hadronic interactions [11]. To optimize the selection, we generate a signal sample, and several background samples. We use a generic $pp \rightarrow J/\psi X$ sample to predict the backgrounds when we have a $J/\psi$ present in the event, though these events should be eliminated since the $J/\psi$ is produced at the primary vertex (PV). To study the background from $b$ decays we use a generic
$b$ decay sample that also includes $b \rightarrow J/\psi X$ decays. However, some individual modes present specific problems, so we also generate them separately. Table 1 lists the different decay channels that have been generated, the number of analyzed events passing the geometrical cuts, and the geometrical cut efficiencies.

We first generate the events and pre-select the ones within the geometrical acceptance: for exclusive $b$ decays we insist that the charged $B$ candidate decay tracks are below 400 mrad and larger than 10 mrad with respect to the beam line. In the case of the inclusive $J/\psi$ sample, we insist only that both muon tracks pass the above mentioned criteria. For the inclusive $b\bar{b}$, we only require that the one of the two $B$ mesons be pointed within 400 mrad of the beam line.

Table 1: MC samples used in this study.

| Decay                          | Number of events | Geometrical cut efficiency |
|-------------------------------|------------------|---------------------------|
| $B^0_s \rightarrow J/\psi(\mu\mu)f_0(\pi\pi)$ | 60,565           | 16.4%                     |
| $B^0_d \rightarrow J/\psi(\mu\mu)K^0(K\pi)$   | 2,994,516        | 17.3%                     |
| $B^+_u \rightarrow J/\psi(\mu\mu)K^+$         | 1,928,159        | 17.9%                     |
| $B^0_s \rightarrow J/\psi(\mu\mu)f_0(\rho\gamma)$ | 63,319           | 16.4%                     |
| $B^+_u \rightarrow J/\psi(\mu\mu)X$           | 2,831,431        | 20.4%                     |
| $B^0_d \rightarrow J/\psi(\mu\mu)X$           | 2,924,276        | 20.4%                     |
| inclusive $J/\psi(\mu\mu)$                 | 4,237,046        | 19.7%                     |
| inclusive $b\bar{b}$                    | 20,176,844       | 43.7%                     |

Table 2 lists the production cross sections at 14 TeV predicted by Pythia/EvtGen, used in our Monte Carlo simulation.

Table 2: Production cross sections at 14 TeV predicted by Pythia/EvtGen, used in our Monte Carlo simulation. The double arrow (i.e. $\Rightarrow$) indicates the existence of possible intermediate states, e.g. $\sigma_{pp \Rightarrow J/\psi X}$ includes $\sigma_{pp \rightarrow b \rightarrow J/\psi X}$. The “prompt $J/\psi$” cross section is $\sigma_{\text{prompt } J/\psi} = \sigma_{pp \rightarrow J/\psi X} - \sigma_{pp \rightarrow b \Rightarrow J/\psi X} = 0.266$ mb.

| Cross section | mb    |
|---------------|-------|
| $\sigma_{pp}$ | 102.9 |
| $\sigma_{pp \rightarrow b\bar{b}}$ | 0.698 |
| $\sigma_{pp \rightarrow J/\psi X}$ | 0.286 |
| $\sigma_{pp \rightarrow b \Rightarrow J/\psi X}$ | 0.0204 |

To reconstruct the $J/\psi f_0$ ($J/\psi \rightarrow \mu^+\mu^-$, $f_0 \rightarrow \pi^+\pi^-$) candidates, we first insist that we have two opposite sign muon candidates that form a $J/\psi$ candidate and satisfy the “pre-selection” criteria listed in Table 3. Then we require two additional charged tracks, that satisfy other loose-pre-selection cuts, and are consistent with making a vertex with the two muons. The very loose pre-selection criteria are chosen with the aim to remove as little signal as possible, and reject large parts of the combinational background. This pre-selection is also applied to inclusive $b\bar{b}$ and inclusive $J/\psi$ events.

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1We kept the LHC energy at 14 TeV in order to compare with other simulations involving $\phi_f$. For 10 TeV running, the final signal yields should be scaled by a factor of $\approx 5/7$. 

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Table 3: Cut values for the $B^0_s \rightarrow J/\psi f_0$ pre-selection and selection. Also shown are the selection efficiency of each cut for the signal (absolute) and background (with respect to “pre-selection.”) $\Delta L_{ij}$ is the likelihood ratio of species $i$ relative to species $j$. The product of the $p_T$ values of $J/\psi$ daughters is used to help eliminate any residual minimum bias background.

| Cuts on the muons | Pre-Selection | Selection | signal efficiency(%) | BG efficiency(%) |
|-------------------|---------------|-----------|----------------------|-----------------|
| $\Delta L_{\mu\pi}$ | $> -5$ | $> -5$ | 97.2 | - |
| $\chi^2_{\text{track}/n\text{Dof}}$ | - | < 5 | 98.9 | 85.9 |

| Cuts on the $J/\psi$ |
|---------------------|
| Product $p_T$ of daughters | - | $> 500^2$ MeV$^2$ | 100 | 100 |
| Mass Window | $\pm 42$ MeV | $\pm 42$ MeV | 97.9 | - |

| Cuts on the pions |
|-------------------|
| $\Delta L_{\pi K}$ | $> -10$ | $> -10$ | 99.2 | - |
| $\Delta L_{\pi \mu}$ | $> -10$ | $> -10$ | 99.9 | - |
| $\chi^2_{\text{track}/n\text{Dof}}$ | - | < 4 | 95.3 | 65.2 |
| Min IPS | - | > 3 | 74.8 | 1.5 |

| Cuts on the $f_0(980)$ |
|-----------------------|
| Sum $p_T$ of daughters | - | $> 900$ MeV | 98.6 | 57.6 |
| Mass Window | $\pm 500$ MeV | $\pm 90$ MeV | - | - |

| Cuts on the $B^0_s$ |
|---------------------|
| Max IPS | - | < 5 | 99.7 | 67.5 |
| vertex fit $\chi^2$ | < 50 | < 17 | 88.1 | 51.8 |
| $\cos \theta_p$ | - | > 0.99993 | 80.4 | 4.8 |
| Mass Window | $\pm 300$ MeV | $\pm 50$ MeV | 98.5 | - |

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

Muon candidates are selected by requiring the track has hits in the Muon Chambers and satisfies the identification criterion that requires global $\Delta L_{\mu\pi} > -5$, and has $\chi^2_{\text{track}}$ per # of degrees of freedom (nDOF) of the Kalman fit of the track $< 5$ (Fig. 2 (d)). Specifically, $\Delta L_{p_1,p_2}$ is the difference in the log of the likelihood between the hypothesis that this particle is of type of $p_1$ rather than $p_2$ (equivalent to the likelihood ratio). These cuts were studied in Ref. [12] using minimum bias events and are aimed at rejecting hadrons misidentified as muons due to random combinations of spurious hits in the Muon Chambers. The distributions of transverse momentum ($p_T$) for $\mu^+$ vs. $\mu^-$, the minimum impact parameter significance (IPS) with respect to each primary vertex, $^2\chi^2_{\text{track}/n\text{Dof}}$ and momentum of muon candidates are shown in

$^2$The Impact Parameter Significance is defined as the track impact parameter with respect to a primary vertex divided by its error: $\text{IPS} = (\Delta p_{\text{IP}})/\sigma_{\text{IP}}$. At the luminosity of $2 \times 10^{-32}$ cm$^{-2}$s$^{-1}$ about 35% of the events have
Fig. 2(a-e) from the signal and inclusive $b\bar{b}$ MC after “pre-selection.”

We then combine two opposite sign muon candidates to form a $J/\psi$ candidate. Fig. 3 shows the signal and $b\bar{b}$ distributions for IPS, the flight distance significance (the distance from PV to reconstruction vertex divided by its error), the vertex fit $\chi^2$ and invariant mass of $J/\psi$ candidates from the signal and inclusive $b\bar{b}$ MC after “pre-selection.” We retain those events having $|m_{\mu\mu} - m_{J/\psi}| < 42$ MeV corresponding to about a $\pm 3\sigma$ interval (Fig. 3 (d)). These selections result in a relatively clean $J/\psi$ sample.

2.2 $f_0(980) \rightarrow \pi^+\pi^-$ selection

To select pion candidates we veto tracks identified as kaons with $\Delta L_{K\pi} > 10$ or muons with $\Delta L_{\mu\pi} > 10$. The veto has $> 99\%$ efficiency for signal. Fig. 4 shows the distributions of $p_T$ for $\pi^+$ vs. $\pi^-$, the minimum IPS with respect to each primary vertex, $\chi^2_{\text{track}}/\text{nDOF}$ and momentum of pion candidates from the signal and inclusive $b\bar{b}$ MC after “pre-selection.”

We then combine two opposite sign pion candidates to form a $f_0(980)$ candidate. Fig. 5 shows the minimum IPS, flight significance, and vertex $\chi^2$ distributions for $f_0(980)$ candidates from the signal and inclusive $b\bar{b}$ samples after “pre-selection.”

2.3 $B^0_s$ reconstruction

A $B^0_s$ is reconstructed by combining $J/\psi$ and $f_0(980)$ candidates. We require the four tracks from $J/\psi$ and $f_0(980)$ to be consistent with coming from one vertex as evaluated by examining the vertex fit $\chi^2$, where the nDOF is 5. We also calculate the cosine of the angle between the $B^0_s$ candidates reconstructed momentum and direction from the primary vertex to $B^0_s$ vertex ($\cos \theta_p$), Fig. 6 shows the distributions of $B^0_s$ candidates from the signal and inclusive $b\bar{b}$ MC after “pre-selection.”

2.4 Optimization Criteria

To study how the $\phi_f$ sensitivity depends on the signal statistics ($S$) and the background to signal ratio ($B/S$), we use a fast stimulation or “Toy” Monte Carlo.

We generate and fit 400 “experiments” as a function of the $B/S$ ratio, using $\phi_f$ set to its predicted SM value of -0.0368. For each $B/S$ point we fit the resulting $\phi_f$ distribution to a Gaussian. (This is the same fitter as used in section 6.) The r.m.s. width ($\sigma$) of the Gaussian is taken as the $\phi_f$ sensitivity. For our first point we fix $B/S$ at zero and change only the amount of signal. Fig. 7 shows the error of $\phi_f$ ($\sigma_{\phi_f}$) as a function of signal yield. The curve follows the expected behavior: $\sigma_{\phi_f} \propto 1/\sqrt{S}$. To understand the relation between $\sigma_{\phi_f}$ and $B/S$, we fix $S$ and only change the amount of signal. For our first point we fix $B/S$ at zero and change only the amount of signal. Fig. 7 shows the error of $\phi_f$ ($\sigma_{\phi_f}$) as a function of $B/S$, where the experiment contains signal and a long-lived background, with a lifetime fixed at 0.96 ps, as obtained from $B \rightarrow J/\psi X$ Monte Carlo. We fit the data with a shape $\sigma_{\phi_f} \propto \sqrt{1 + \alpha \times B/S}$. The value of $\alpha$ is $0.63 \pm 0.10$, consistent with the ratio of background lifetime to $B_s$ lifetime, 0.64. For an exponential proper time distribution the lifetime can be quickly estimated using the mean of the distribution. For convenience we take $\alpha$ as the ratio more than one primary vertex, and we choose the smallest IPS.
Figure 2: The distributions of the signal (black solid) and $b\bar{b}$ background (red dashed) for muon candidates from $J/\psi$. The curves in (a) and (b) show the product of $p_T(\mu^+) \cdot p_T(\mu^-) = 500^2$ MeV$^2$, used to eliminate minimum bias events in the preselection. The final cut in (d) is indicated by vertical blue dotted lines.
Figure 3: (a)-(c): The distributions of signal (black solid) and $b\bar{b}$ background (red dashed) for $J/\psi$ candidates. (Numbers of events in the $B$ and $S$ distributions are equal.) (d) The $J/\psi$ mass distribution for signal, fit to a single Gaussian, with the selection cut indicated by vertical lines.
Figure 4: The distributions of signal (black solid) and $b\bar{b}$ background (red dashed) for pion candidates from $f_0$. The final cuts in (a)-(d) are indicated by blue dotted lines. (The number of events in the $B$ and $S$ distributions are equal.)
Figure 5: The distributions of signal (black solid) and $b\bar{b}$ background (red dashed) for $f_0(980)$ candidates. (The number of events in the $B$ and $S$ distributions are equal.)
Figure 6: The distributions of the signal (black solid) and $b\bar{b}$ background (red dashed) for $B_s^0$ candidates. Final cuts on (a)-(c) are indicated by vertical blue dotted lines.
of mean values of the proper-time distributions of background and signal. (We have also found that the $\phi_f$ uncertainty due to the prompt $J/\psi$ background follows this formula.)

![Figure 7](https://example.com/figure7.png)

Figure 7: The error of $\phi_f$ as a function of signal number $S$. ($S$ equal to one corresponds to about 2 fb$^{-1}$ data.) The curve is the result of a fit to $\sigma_{\phi_f} \propto 1/\sqrt{S}$.

### 2.5 Selection Optimization

Our goal is to maximize the $\phi_f$ sensitivity. Specifically, the selection cuts are chosen to maximize $S/\sqrt{S+\alpha B}$ where $S$ ($B$) is the expected signal (background) number within a $\pm 50$ MeV mass window around the $B_s^0$ nominal mass [13], and $\alpha$ is the ratio of the mean values of the proper-time distributions between the background and the signal. The cuts are based on a set of variables that show a marked difference between signal versus background. They include: (1) sum of absolute $p_T$ of $f_0$ daughters (Fig. 4 (a,b)); (2) impact parameter significance of pions (Fig. 4 (c)); (3) track fit $\chi^2_{\text{track}}/\text{nDOF}$ of pions (Fig. 4 (d)); (4) vertex fit $\chi^2$ of $\mu^+\mu^-\pi^+\pi^-$ (Fig. 6 (a)); and (5) the cosine of the angle between the $B_s^0$ candidates reconstructed momentum and its flight direction ($\cos\theta_{\mu}$) (Fig. 6 (b)). (We have not explored optimizing the selection based on a neural network or similar procedure as the tuning of such a method must be based on real data, and here we are trying to understand the sensitivity to first order. If other variables also have some discrimination power between signal and background, we will include them in the future.)

In what follows, we normalize all the yields to 2 fb$^{-1}$ data. We use the expected $b\bar{b}$ production cross-section $\sigma_{b\bar{b}} = 500 \, \mu$b and $\sigma_{\text{prompt } J/\psi} = 265.6 \, \mu$b as predicted by Pythia, and listed in Table 2. Since the Monte Carlo used 698 $\mu$b as the $b\bar{b}$ production cross-section, we scale the number of background events from $b\bar{b}$ to the value corresponding to $\sigma_{b\bar{b}} = 500 \, \mu$b. To have more
Figure 8: The error of $\phi_f$ as a function of background to signal ratio $B/S$ for a fixed $S$. The $S$ corresponds to about 2 fb$^{-1}$ data. The curve shows a fit to $\sigma_{\phi_f} = A \sqrt{1 + \alpha \times B/S}$. Here $\alpha \equiv P2$ and $A \equiv P1$.

statistics in the background estimation, we enlarge the $f_0$ window from the nominal 90 MeV to 500 MeV, and the $B^0$ window from 50 MeV to 300 MeV. If the background is distributed linearly in the larger windows, we can scale the background number in the larger windows down by a factor of 33. The factor $\alpha$ may change among cut variables, so we obtain $\alpha$ from the signal and background proper-time distributions at each set of cut points. (We regard this as a minor point, and first analyses are likely to use a fixed value of $\alpha$.)

We realize that the lower mass region contains a large $B^0 \to J/\psi K^{*0}$ sample when the kaon is misidentified as a pion (see Fig. 11a); there is also a small $B^0_d \to J/\psi \pi^+\pi^-$ background (see Fig. 9), so we remove this background from the calculation of $B$ as we will consider this background separately. The final cuts, called “Selection,” are shown in the third column of Table 3.

A selection cut of 900 MeV on $p_T(\pi^+) + p_T(\pi^-)$ serves to eliminate 42.4% of of the background, costing only 1.4% of the signal efficiency.

3 Signal efficiency and event yields

Table 4 shows the efficiencies computed for $B^0_s \to J/\psi f_0$, where:

- $\epsilon_{geo}$ is the efficiency of the acceptance cut at generator level on the $B^0_s$ daughters between 10 to 400 mrad;
• $\epsilon_{\text{det/geo}}$ is the efficiency of that all $B_s^0$ decay products in the event are reconstructible (has enough MC hits for long track reconstruction);

• $\epsilon_{\text{rec/det}}$ is the efficiency that the reconstructible events are actually reconstructed.

• $\epsilon_{\text{sel/rec}}$ is the efficiency that the reconstructed events are actually selected.

• $\epsilon_{L0}$, $\epsilon_{HLT1}$, and $\epsilon_{HLT2}$ are respective efficiencies for the L0, HLT1 and HLT2 trigger algorithms.

### Table 4: Efficiency for $B_s^0 \rightarrow J/\psi f_0(980)$.

| $\epsilon_{\text{geo}}$ [\%] | $\epsilon_{\text{det/geo}}$ [\%] | $\epsilon_{\text{rec/det}}$ [\%] | $\epsilon_{\text{sel/rec}}$ [\%] | $\epsilon_{L0}$ [\%] | $\epsilon_{HLT1}$ [\%] | $\epsilon_{HLT2}$ [\%] | $\epsilon_{\text{tot}}$ [\%] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 16.4            | 38.7            | 71.4            | 45.4            | 94.0            | 95.0            | 95.0            | 1.75            |

The overall trigger efficiency is 85\%, for signal events with all decay products inside the detector. This is a high efficiency, especially compared with fully hadronic events, which are typically at least a factor of two lower. The total efficiency including HLT2 is the product of the individual efficiencies listed above, which is 1.75\%. The yield for a decay channel is computed as

$$Y = L_{\text{int}} \times \sigma_{b\bar{b}} \times 2 \times f_{B_s} \times B^{\text{vis}} \times \epsilon_{\text{tot}},$$

where $L_{\text{int}} = 2$ fb$^{-1}$ is the assumed integrated luminosity, $\sigma_{b\bar{b}} = 500 \mu$b is the expected $b\bar{b}$ production cross-section, $f_{B_s} = (11.0 \pm 1.2)\%$ is the probability for a $b$-quark to form a $B_s$ meson, and $B^{\text{vis}}$ is the total visible branching fraction, the product of all the individual branching fractions involved in the decay chain. (The factor of 2 arises because we can use either the $b$ or $\bar{b}$ quark.) Assuming that $B(B_s^0 \rightarrow J/\psi f_0) \times B(f_0 \rightarrow \pi^+\pi^-)$ is quarter of $B(B_s^0 \rightarrow J/\psi \phi) \times B(\phi \rightarrow K^+K^-)$, we have $B^{\text{vis}}(B_s^0 \rightarrow J/\psi f_0(\pi\pi)) = 6.8 \times 10^{-6}$. After applying the efficiencies, we expect 26.1k signal events after HLT2. Table 5 shows the branching and $b$-hadron production fractions assumed in the calculation of the yields and background levels discussed below.

### Table 5: Branching and $b$-hadron production fractions assumed in the calculation of the yields and background levels.

| Branching fraction | value | estimated from | Ref. |
|--------------------|-------|----------------|------|
| $B^{\text{vis}}(B_s^0 \rightarrow J/\psi(\mu\mu)f_0(\pi\pi))$ | $6.8 \times 10^{-6}$ | $B_s^0 \rightarrow J/\psi \phi$ | [5] |
| $B^{\text{vis}}(B_s^0 \rightarrow J/\psi(\mu\mu)\eta(\rho\gamma))$ | $10 \times 10^{-6}$ | $B_s^0 \rightarrow J/\psi K^0$ | [14] |
| $B^{\text{vis}}(B_d^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi))$ | $(5.25 \pm 0.24) \times 10^{-3}$ | PDG08 [13] |
| $B^{\text{vis}}(B_u^+ \rightarrow J/\psi(\mu\mu)K^+)$ | $(5.9 \pm 0.2) \times 10^{-3}$ | PDG08 [13] |
| $f_u$ | (39.9 $\pm$ 1.2)\% | PDG08 [13] |
| $f_d$ | (39.9 $\pm$ 1.2)\% | PDG08 [13] |
| $f_s$ | (11.0 $\pm$ 1.2)\% | PDG08 [13] |
4 Background Sources

4.1 Prompt $J/\psi$

We use Monte Carlo corresponding to a 0.00125 fb$^{-1}$ data sample and find 69 candidates passing the selection which are from prompt $J/\psi$ events in the enlarged $f_0$ and $B_s^0$ mass regions, before applying the trigger selections. From prompt $J/\psi$ events we expect $B/S = (11 \pm 1)\%$, where the error reflects only the uncertainty due to Monte Carlo statistics.

4.2 Background from $b\bar{b}$

Our Monte Carlo simulation used $B(b \to J/\psi X) = 1.46\%$ (see Table 2), compared with the PDG value of $(1.16 \pm 0.10)\%$ [13]. Using the Monte Carlo value, we expect $B/S = (26 \pm 2)\%$ from $b\bar{b}$ background, where the error is only the statistical uncertainty from the Monte Carlo. This is reduced to $(20 \pm 2)\%$ using the PDG value. For the purpose of this note we will use the larger value, as that was what was used in previous studies of $J/\psi \phi$. We discuss specific background sources below.

4.2.1 $B_{u,d,s} \to J/\psi X$

Fig. 9 shows the $\mu^+\mu^-\pi^+\pi^-$ invariant mass distribution from $B_{u,d,s} \to J/\psi X$. Fig. 10 shows the $m_{\pi\pi}$ distribution in the $B_s^0$ mass signal region.

4.2.2 $B_s^0 \to J/\psi K^{*0}$

When the kaon is misidentified as a pion, $B_s^0 \to J/\psi K^{*0}$ decay can fake a $B_s \to J/\psi \pi^+\pi^-$ event. Fig. 11 shows the invariant mass distributions for $B_s^0$ and $f_0$ candidates from $B_s^0 \to J/\psi K^{*0}$ decays. If the mass resolution does not deteriorate, we will see almost no events from this source; quantitatively, in 2 fb$^{-1}$ of data, we expect < 10 events at 90% confidence level (C.L.) remaining in the $f_0$ and $B_s^0$ narrow signal regions.

4.2.3 $B_u^+ \to J/\psi K^+$

The $B_u^+ \to J/\psi K^+$ decay can fake a $J/\psi \pi^+\pi^-$ when the $K^+$ is misidentified as pion and a random $\pi^-$ is combined. Fig. 11 shows the invariant mass distributions for $B_s^0$ and $f_0$ from $B_u^+ \to J/\psi K^+$ decays. We expect $(1.29 \pm 0.08) \times 10^3$ events contribute to the background before the trigger in 2 fb$^{-1}$ data.

4.2.4 $B_s^0 \to J/\psi \eta'$

We have studied $\eta' \to \eta \pi^+\pi^-$ and $\eta' \to \rho \gamma$ and found only the latter could contribute as background. It is a dangerous background, because $B_s^0 \to J/\psi \eta'$ has opposite CP to the signal. Fig. 13 shows the invariant mass distributions for $B_s^0$ and $f_0$ from $B_s^0 \to J/\psi \eta'$, $\eta' \to \rho \gamma$ decays. Assuming $B(B_s^0 \to J/\psi \eta') = \frac{2}{3} B(B^0 \to J/\psi K^0)$ [14], we expect $(0.75 \pm 0.07) \times 10^3$ events contribute to the background, before the trigger, in 2 fb$^{-1}$ data. Most of these, however, are not in the narrow signal mass ranges.
Figure 9: $\mu^+\mu^-\pi^+\pi^-$ invariant mass distributions from $B_{u,d,s} \rightarrow J/\psi X$ MC sample in (a) ±90 MeV and (b) ±500 MeV windows around the $f_0(980)$ nominal mass. The expected signal distributions are superimposed. The non-resonant $B^0 \rightarrow J/\psi\pi^+\pi^-$ branching fraction in this MC generation is set to $2 \times 10^{-4}$, about 30% of that of $B^0 \rightarrow J/\psi\phi, \phi \rightarrow K^+K^-$. 

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Figure 10: The $m_{\pi\pi}$ distribution in $B_{s}^{0}$ mass signal region ($|m_{\mu\mu\pi\pi} - m_{B_{s}^{0}}| < 50$ MeV) from the sample including all $B$ decays with $J/\psi$ candidates, except signal.

Figure 11: Distributions from $B_{d}^{0} \rightarrow J/\psi K^{*0}$ decays when the kaon is misidentified as a pion. The vertical lines show the narrow mass windows.

(a) $m_{\mu\mu\pi\pi}$

(b) $m_{\pi\pi}$
Figure 12: Distributions from $B^+_u \to J/\psi K^+$ decays where the $K^+$ is misidentified as pion and a random $\pi^-$ is combined. The vertical lines show the narrow mass windows.

We also intend to reconstruct these events when we can find the photon from the $\eta' \to \rho \gamma$ decay to use in a separate measurement of $\phi_f$ (see Sec. 6.4). We have not vetoed these events in our $J/\psi f_0$ selection, in this study.

Figure 13: Distributions from $B_s^0 \to J/\psi \eta'$, $\eta' \to \rho \gamma$ decays. The vertical lines show the narrow mass windows.

4.3 Background Summary

Table 6 shows the sources of the background and expected yields from 2 fb$^{-1}$ data. The branching fractions and $b$-hadron production fractions used for the calculation are shown in Table 5. The largest background arises from a $J/\psi$ combined with random tracks identified as pions, other than $B_d^0 \to J/\psi K^*$ and $B_s^0 \to J/\psi \eta'$. These backgrounds (mass shape and proper
Table 6: Summary of background sources. The numbers quoted are calculated in the narrow mass windows $|m_{\pi\pi} - m_{f_0(980)}| < 90$ MeV and $|m_{\mu\mu\pi\pi} - m_{B_s^0}| < 50$ MeV. We assume the trigger efficiencies are the same for the signal and backgrounds. The $b\bar{b}$ background does not include the specific $B_s^0$, $B_0^+$, $B_d^0$ channels listed here.

| Sources          | Yield from 2 fb$^{-1}$ before trigger ($\times 10^3$) | $B/S$   |
|------------------|-----------------------------------------------------|---------|
| signal           |                                                     | 29.3    |
| background       |                                                     |         |
| prompt $J/\psi$  | 3.3 ± 0.4                                           | (11 ± 1)$\%$ |
| $b\bar{b}$       | 6.6 ± 0.5                                           | (21 ± 2)$\%$ |
| $B_s^0 \rightarrow J/\psi\eta'$ | 0.75 ± 0.07                                       | (2.4 ± 0.2)$\%$ |
| $B_u^+ \rightarrow J/\psi K^+$    | 1.29 ± 0.08                                        | (4.2 ± 0.3)$\%$ |
| $B_d^0 \rightarrow J/\psi K^*0$   | < 10 @90%C.L.                                      |         |
| Total            | 11.3 ± 0.6                                          | (39 ± 3)$\%$ |

Time distribution can be estimated by reconstructing $J/\psi$ with two same sign-charged pions; we cannot use the $B_s^0$ mass sidebands due to reflections from specific final states. We show in Fig. 14 the $J/\psi\pi\pi$ mass distribution for like sign and opposite sign pion pairs. In the $B_s^0$ signal region, and even above, the distributions are in agreement.

Figure 14: Invariant mass distributions from from $B_s^0 \rightarrow J/\psi\pi\pi$ candidates. The Monte Carlo sample consists of any $B$ decay into a final state containing a $J/\psi$ where the modes $B_s^0 \rightarrow J/\psi f_0$, $B_s^0 \rightarrow J/\psi\eta'$ and $B_d^0 \rightarrow J/\psi\pi^+\pi^-$ have been explicitly removed. The histogram is for $\pi^+\pi^-$ pairs, while the crosses represent $\pi^\pm\pi^\mp$ pairs. The vertical lines define the $B_s^0$ signal window.

Furthermore, as a check, we processed a 5.6 million mini-bias event sample that satisfied the L0 trigger. Only 2 events passed the off-line selection, and they both contain real $J/\psi$ decays.
5 Properties of selected signal events

5.1 $B_s^0$ mass resolution

Fig. 15 shows the reconstructed $B_s^0$ mass distribution for the signal. Performing a double-Gaussian fit gives $\bar{\sigma}(M_{B_s^0}) = 19$ MeV, where the average width $\bar{\sigma} = \sqrt{(1 - f_2)\sigma_1^2 + f_2\sigma_2^2}$, $\sigma_1$ and $\sigma_2$ are the width of the core and second Gaussian, and $f_2$ is the fraction of the second Gaussian [15].

![Figure 15: Reconstructed $B_s^0$ mass for the signal. The HLT1 trigger has been applied.](image)

5.2 Proper time

The $B_s^0$ proper time is defined here as:

$$t^{\text{rec}} = m \cdot \frac{\vec{d} \cdot \vec{p}}{|p|^2}, \quad (4)$$

where $m$ is the reconstructed invariant mass, $\vec{p}$ the momentum and $\vec{d}$ the distance of flight vector of the candidate $B_s^0$ from the primary to the secondary vertices. If more than one primary vertex is found, the one that corresponds to the smallest IP of the $B_s^0$ candidate is chosen.

Fig. 16 shows the distribution of the difference of the reconstructed ($t^{\text{rec}}$) and MC true ($t^{\text{MC}}$) proper time. The average proper time resolution obtained from a double-Gaussian fit is 34 fs.

Fig. 17 shows the proper time error estimate and the proper time pull $\frac{t^{\text{rec}} - t^{\text{MC}}}{\sigma_t}$. The estimate of the error on the reconstructed $B_s^0$ lifetime has a mean value of 27 fs and a most probable value of 25 fs.

The time-dependent selection efficiency is shown in Fig. 18 for events before and after the trigger requirements. It is parameterized by the acceptance function defined as:

$$\epsilon_t(t) = C \times \frac{(at)^n}{1 + (at)^n}, \quad (5)$$
Figure 16: The distribution of the difference between the reconstructed ($t^{\text{rec}}$) and MC true ($t^{\text{MC}}$) proper time. The HLT1 trigger has been applied.

Figure 17: Distributions of (a) the proper time error estimate and (b) the proper time pull.
where $C$ is the selection efficiency at large decay time, and $a$ and $n$ are two parameters which govern the proper time dependence at small decay times.

\[
C = 0.0043 \pm 0.2058, \quad a = 0.06 \pm 1.66, \quad n = 0.072 \pm 1.911
\]

Figure 18: The acceptance function as function of proper time.

6 Sensitivity of $B^0_s \to J/\psi f_0$ Compared With $J/\psi \phi$

In order to perform this task a fast (Toy) Monte Carlo simulation program has been used that is based on RooFit. We simulate 400 LHCb "experiments" with 2 fb$^{-1}$ per sample. For each experiment the program generates events taking into account the results obtained from the full MC simulation and performs a fit according to a likelihood function which includes the $B^0_s - \overline{B}^0_s$ mixing variables. The sensitivity to $\phi_f$ is taken as the root-mean-square width, $\sigma$, resulting from a Gaussian fit to the $\phi_f$ values from each simulation run.

6.1 Likelihood function

The time-dependent decay rates for initially pure $B^0_s$ or $\overline{B}^0_s$ states in $\bar{b} \to \bar{c}c\bar{s}$ or $b \to c\bar{c}s$ quark-level transitions are given by the following expressions for decay into CP eigenstates:

\[
\Gamma(B^0_s \to f_{CP}) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta \Gamma_s t}{2} - \eta_f \cos \phi_f \sinh \frac{\Delta \Gamma_s t}{2} + \eta_f \sin \phi_f \sin(\Delta m_s t) \right\}
\]

\[
\Gamma(\overline{B}^0_s \to f_{CP}) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta \Gamma_s t}{2} - \eta_f \cos \phi_f \sinh \frac{\Delta \Gamma_s t}{2} - \eta_f \sin \phi_f \sin(\Delta m_s t) \right\}
\]

(6)

where $t$ is the proper time, $\eta_f$ is the CP eigenvalue of the state $f_{CP}$, and $\Delta \Gamma_s$ is the lifetime difference between CP+ and CP− eigenstates. Direct CP violation is neglected. Note that for $J/\psi f_0$, $\eta_f = -1$.

The events are used to maximize a likelihood function ($\mathcal{L}$) which is given by

\[
\mathcal{L} = \prod_i^{N_{obs}} P(m_i, t_{i}^{rec}, q_i),
\]

(7)
with
\[ P(m_i, t_i^{\text{rec}}, q_i) = f_{\text{sig}} P_m^{\text{sig}}(m_i) P_t^{\text{sig}}(t_i^{\text{rec}}, q_i) + (1 - f_{\text{sig}}) P_m^{\text{bkg}}(m_i) P_t^{\text{bkg}}(t_i^{\text{rec}}), \] 

where:

- \( P_m^{\text{sig}}(m_i) \) and \( P_m^{\text{bkg}}(m_i) \) are the probability density functions (PDFs) describing the dependence on reconstructed mass \( m_i \) for signal and background events;

- \( P_t^{\text{sig}}(t_i^{\text{rec}}, q_i) \) is the PDF used to describe the signal decay rates for the decay time \( t_i^{\text{rec}} \), which depends on the tagging result at time \( t=0, q_i \) \( (q = +1 \text{ if the signal meson is tagged as } B_s^0, q = -1 \text{ if it is tagged as } \overline{B}_s^0, \text{ or } q = 0 \text{ if no tagging information}) \);

- \( P_t^{\text{bkg}}(t_i^{\text{rec}}) \) is the PDF describing the background decay rates, which do not depend on the tagging performance.

- \( f_{\text{sig}} \) is the fraction of the signal in the fitting region.

The likelihood function includes distinctive contributions from the signal and the background. For both, the PDF is a production of PDFs which model the invariant mass distribution and the time-dependent decay rates. The PDF used for generating the \( B_s^0 \) mass spectrum consists of a double-Gaussian for the signal and a linear function for the background. The PDF for the proper time is modeled by a true decay function smeared by time resolution then multiplied by the decay time acceptance function. From Eq. 6, the true time decay function for the signal can be expressed as:

\[ R(t, q) \propto e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta \Gamma_s t}{2} + \cos \phi_f \sinh \frac{\Delta \Gamma_s t}{2} - q \sin \phi_f \sin(\Delta m_s t) \right\}. \] 

The effect of the wrong-tag probability \( w_{\text{tag}} \) is included in the dilution factor \( D \equiv (1 - 2w_{\text{tag}}). \) We take this value as fixed from studies of other modes such as \( B_s^0 \to D_s^- \pi^+ \), and use \( w_{\text{tag}} = 0.334 \) as our value. We take the wrong tag fractions as the same for \( B_s^0 \) and \( \overline{B}_s^0 \).

### 6.2 Input to the fast Monte Carlo simulation

The PDFs and their input parameters are shown in Table 7. The parameters of the signal are obtained from the distributions shown in Fig. 15, 16 and 18 (b). For the parameters of physics and tagging performance, we use the same as those used in \( B_s^0 \to J/\psi \phi \) study [8], as shown in Table 8. The PDF of the signal proper-time is shown in Fig. 19 for both \( \phi_f = -0.0368 \) (SM value) and \( \phi_f = -0.2 \) rad, where the oscillations are apparent.

The background’s proper time distribution is obtained from \( B_{u,d,s} \to J/\psi X \) shown in Fig. 20. The average proper time is 1.93 ps for the signal and 1.20 ps for the \( b\bar{b} \) background. We use \( B/S = 0.26 \) for background from \( b \) decays and \( B/S = 0.05 \) for that from prompt \( J/\psi \).

\footnote{The tagging efficiency for the prompt \( J/\psi \) background is lower than the signal and \( b\bar{b} \) background [8].}
Figure 19: The proper-time PDF of the signal for $B^0_s$ (solid line) and $\bar{B}^0_s$ (dashed line).

### 6.3 Fit Results

For this baseline study, we fit the Toy Monte Carlo only allowing $\phi_f$ and $\Delta \Gamma$ to float, with the other parameters fixed to their input values. Fig. 21 shows the distributions of mass and the proper time for the events tagged as $B^0_s$ and $\bar{B}^0_s$ from one experiment. The output of $\phi_f$ from the fits is shown in Fig. 22 with signal only and background included. The sensitivity of $\phi_f$ is estimated to be $(0.050 \pm 0.002)$ rad. We also find that allowing the proper time acceptance parameters to float does not increase the uncertainty of $\phi_f$.

### 6.4 Inclusion of $B_s \to J/\psi \eta'$ Events

We have already discussed the contribution of the $J/\psi \eta'$, $\eta' \to \rho^0 \gamma$ events as a source of background in the $J/\psi f_0$ sample. We also intend to reconstruct these events when we can find the photon from the $\eta' \to \rho^0 \gamma$ decay and add them into our final sample (with reversed CP to $f_0$ events). In our simulation we use all photons found in the electromagnetic calorimeter and those that convert in material in front of the magnet, provided that their $p_T$ is larger than 300 MeV/c. The detection efficiency for photons in the solid angle of the detector is about 25%. In 2 fb$^{-1}$ we estimate 5000 of such fully reconstructed events before the trigger. A previous analysis of this mode [6] concluded that an error in the measurement of $\phi_f$ of $\pm 0.8$ rad could be made with a 2 fb$^{-1}$ sample. Adding the two modes together would give an error in $\phi_f$ of $\pm 0.044$ rad.

### 7 Systematic Errors

We have studied several sources of systematic error. Recall the outputs of our fit nominally are $\phi_f$, $\Delta \Gamma$ and the time acceptance parameters ($a$ and $n$). We actually determine, however, the product of the dilution $D$ times $\phi_f$ and use the value of $D$ determined from other measurements. Thus the systematic error on $D$ is fully correlated with the systematic error on $\phi_f$. 

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Table 7: The PDFs for the invariant mass and proper time describing the signal and background.

|            | \(P_m\)                                                                 | \(P_t\)                                                                 |
|------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| **Signal** | Double Gaussian (2G) \(2G(m; m_0, \delta m, \sigma_1, \sigma_2, f_2)\) | \([R(t^{MC}, q) \otimes 2G(t^{rec} - t^{MC}; \mu, \sigma_t^1, \sigma_t^2, f_t^2)] \cdot \varepsilon(t^{rec}; a, n)\) |
|            | \(m_0 = 5368.4\) MeV                                                   | \(\mu = 0.0008\) ps                                                   |
|            | \(\delta m = -22\) MeV                                                 | \(\sigma_t^1 = 0.0236\) ps                                            |
|            | \(\sigma_1 = 16.8\) MeV                                                | \(\sigma_t^2 = 0.047\) ps                                            |
|            | \(\sigma_2 = 33.2\) MeV                                                | \(f_t^2 = 0.36\)                                                     |
|            | \(f_2 = 0.09\)                                                         | \(a = 1.68\)                                                         |
|            |                                                                          | \(n = 1.87\)                                                         |

| **Background** | First-order polynomial \([e^{-\tau_{bkg}} \otimes G(t^{rec} - t^{MC}; \mu, \sigma_t^1)] \cdot \varepsilon(t^{rec}; a, n)\) | \(\mu = 0\) |
| **from b**     |                                                                          | \(\sigma_t^1 = 0.039\) ps |
|                |                                                                          | \(\tau_{bkg} = 0.96\) ps |
|                |                                                                          | \(a = 4.4\) |
|                |                                                                          | \(n = 2.9\) |

| **Background** | First-order polynomial \(2G(t^{rec} - t^{MC}; \mu, \sigma_t^1, \sigma_t^2, f_t^2) \cdot \varepsilon(t^{rec}; a, n)\) | \(\mu = 0\) |
| **from prompt** |                                                                          | \(\sigma_t^1 = 0.11\) ps |
| **J/ψ**        |                                                                          | \(\sigma_t^2 = 2.4\) ps |
|                |                                                                          | \(f_t^2 = 0.17\) |
|                |                                                                          | \(a = 4.4\) |
|                |                                                                          | \(n = 2.9\) |

Now we will estimate the systematic error on \(\omega_{tag}\). This parameter can be measured using a combination of other modes. One simple approach is to measure \(\omega_{tag}\) using \(B^0_s \rightarrow D^{+}_s \pi^-\). We expect differences in the value of \(\omega_{tag}\) here and in the \(J/\psi f_0\) mode because of different triggering in the hadronic and dimuon channels [16]. This difference can be estimated by simulation and checked using other modes. For example, we can use \(B^0 \rightarrow J/\psi K^{*0}\), \(K^{*0} \rightarrow K^+ \pi^-\) to separately measure opposite side tagging. As input to a first estimate we decided to see the difference in Monte Carlo between the \(J/\psi f_0\) and \(D^{+}_s \pi^-\) final states.

Our simulation of \(B^0_s \rightarrow J/\psi f_0\) yields \(\omega_{tag} = (0.326 \pm 0.003)\), where the error is purely statistical. Using exactly the same tagging code on the mode \(B^0 \rightarrow D^{+}_s \pi^-\), which of course we can and will use to measure \(\omega_{tag}\), gives a value of \((0.309 \pm 0.003)\), again the error is statistical. (We believe that we can measure \(\omega_{tag}\) with excellent statistical precision, so we will ignore the statistical error.) The difference is 5.3% in \(\omega_{tag}\), or 10.6% in \(D\). We argue that to first order we can use the Monte Carlo simulation to make the 5.3% correction to account for tagging differences between the two modes. Knowing that Monte Carlo is not perfect, we estimate that we will have \(\approx 25\%\) error or \(\pm 1.3\%\) uncertainty on \(\omega_{tag}\) after subjecting the Monte Carlo to various tests. Thus an systematic error of 2.6% on \(D\) should be achievable without superhuman efforts. We also expect that our belief in the Monte Carlo will change with time, hopefully improving.

Two other sources of error have been investigated thus far using toy Monte Carlo. The
| Parameters | Input values |
|------------|-------------|
| $\Gamma_s$ | 0.680 ps$^{-1}$ |
| $\Delta\Gamma_s$ | 0.049 ps$^{-1}$ |
| $\Delta m_s$ | 17.77 ps$^{-1}$ |
| $\phi_f = -2\beta_s$ | $-0.0368$ rad |
| $\varepsilon_{\text{tag}}$ | 0.564 |
| $\omega_{\text{tag}}$ | 0.334 |

Table 8: The input parameters of physics and tagging performance used for fast Monte Carlo simulation.

general procedure is that we vary a parameter, or a shape parameterization, that has been fixed in the fit by plus and minus the expected error, and then repeat the fit. We record the difference of $\phi_f$ output between this fit and the nominal fit. Then the distribution of the difference is used to set the error by fitting to a single Gaussian. The mean of the Gaussian is taken as the systematic error for each particular source. To check if the systematic errors depends on the central value of $\phi_f$, we use both $\phi_f = -0.2$ and $\phi_f = -0.736$ for generation. We notice that the systematic error does depend on $\phi_f$ and $\sigma_{\phi_f}/\phi_f$ is approximately constant. We plan to measure the time resolution in real data from prompt $J/\psi \rightarrow \mu^+\mu^-$, where we add two other tracks from the primary vertex consistent with the $f_0$ mass. We have seen that the pull distribution of time resolution for the signal and the prompt events, so defined, are identical. Our results are listed in Table 9.

| Source | Value | $\sigma_{\phi_f}/\phi_f$ (%) |
|--------|-------|-----------------------------|
| Time resolution | 34 fs varied by $\pm 5\%$ | 2.5 |
| Misstag rate | $0.334 \pm 0.004$ | 2.6 |
| $B_s$ lifetime | $1.470 \pm 0.027$ fs | 3.0 |
| Total | | 4.7 |

Table 9: Systematic error sources on $\phi_f$

These errors are of comparable sizes. They will improve with increased statistics especially in the control channels. None of the systematic errors changes our estimation of statistics necessary for a significant effect, but merely scales the value of $\phi_f$. We are continuing these preliminary studies.

Other more global sources of systematic errors due to $B_s$ production and $B_s$ decay rates are discussed in the Conclusions.

8 Conclusions

We expect 26,100 $B_s \rightarrow J/\psi f_0$, $f_0 \rightarrow \pi^+\pi^-$ signal events in 2 fb$^{-1}$ of accumulated LHCb data. Based on branching fraction predictions of resonant $B_s^0 \rightarrow J/\psi f_0(980)$, $f_0(980) \rightarrow \pi^+\pi^-$ and non-resonant $B_s^0 \rightarrow J/\psi \pi^+\pi^-$, where the two pions are S-wave [5], we predict an error on the measurement of the CP violating parameter $\phi_f$ of $\pm 0.050$ rad. Adding in the $J/\psi \eta'$, $\eta' \rightarrow \rho\gamma$ final state that we need to measure to estimate backgrounds, reduces the error on $\phi_f$ to $\pm 0.044$ rad.
Figure 20: The background proper time distributions from (a) from $B_{u,d,s} \rightarrow J/\psi X$ and (b) prompt $J/\psi$.

This is larger than the estimate using the $J/\psi \phi$ final state of $\pm 0.03$ rad, however the latter estimate does not consider the effect of a $K^+K^-$ S-wave. Initial indications are that taking the S-wave into account will increase the error by less than 15% [17]. Use of the $J/\psi$ plus scalar or pseudoscalar CP eigenstates removes the need for a complicated angular analysis and should provide, at minimum, a crucial check on the vector-vector result. Both methods have a large $\approx \pm 25\%$ systematic uncertainty on the predicted sensitivity due to uncertainties in the production cross-section and $B_s$ branching ratios. In addition, the estimate based here assumes that relative yield of the $\pi^+\pi^-$ S-wave in the $f_0$ mass region is 25% that of $K^+K^-$ in the $\phi$ mass region. This introduces a considerable uncertainty of about $\pm 40\%$ in the relative rates and $\pm 20\%$ in the sensitivity, giving an overall uncertainty in of $\pm 32\%$ in the error in $\phi_f$. 

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Figure 21: (a) Invariant mass and (b) proper-time distributions for the events tagged as $B_s^0$, and (c) invariant mass and (d) proper-time distributions for those tagged as $\overline{B}_s^0$. The points with error bars are fast simulation data and the solid lines are fit functions. The dashed lines show the background contribution.
9 Acknowledgments

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