Time-dependent CP asymmetries in $B_s$ decays at LHCb

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Abstract. The LHCb experiment will search for New Physics in $B_s$ mixing. The $B_s$ mixing phase will be extracted from the measurement of the time-dependent CP asymmetry in exclusive $B_s$ decays governed by the $b \to c\bar{c}s$ quark-level transition. Large New Physics effects can be discovered or excluded with the data collected during the very first physics run of LHC. Based on Monte Carlo simulations of the LHCb detector, the expected sensitivity with 2 $fb^{-1}$ on the CP-violation parameter $\phi_s$ is $\sigma(\phi_s) = 0.022$.

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1 Introduction

In the Standard Model (SM), CP-violation in flavour changing currents is caused by one single phase in the mixing matrix. This matrix describes the charged current weak interactions of quarks [1]. This so-called Cabbibo-Kobayashi-Maskawa (CKM) matrix is a complex, unitary, 3x3 matrix which relates the electroweak eigen-states of the down-type quarks with their mass eigen-states. From the unitarity requirement of the CKM matrix 6 orthogonality relations can be derived, which are usually displayed as unitarity triangles in a complex plane.

B-meson decays allow to test some of these relations. An example is the unitarity relation

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0.$$ (1)

which can be studied using $b \to c\bar{c}s$ quark-level transitions of the $B_s$ meson. The elements $V_{xy}$ describe the complex coupling strengths of the up-type quarks ($x = u, c, t$) to the down-type quarks, ($y = d, s, b$). When using the Wolfenstein parameterisation of the CKM matrix [2], it can be shown that the three terms of Eq. (1) relate to each other as $\mathcal{O}(\lambda^4)$ : $\mathcal{O}(\lambda^5)$ : $\mathcal{O}(\lambda^2)$. Here, $\lambda = \sin(\theta_C)$ is the expansion parameter, with $\theta_C$ being the Cabbibo angle. The angle between the two larger sides ($V_{cb}^* V_{cs}$) and ($V_{tb}^* V_{ts}$) is small:

$$\chi_s = \arg \left( \frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}} \right) \approx \lambda^2 \eta \approx -\arg(V_{ts}) + \pi \approx 0.04$$ (2)

The neutral $B_s$ meson undergoes mixing which can be described by an effective Hamiltonian consisting of two 2 x 2 matrices: the mass matrix $M$, and decay matrix $\Gamma$. The mass difference between the mass eigenstates is defined as $\Delta m_s = m_H - m_L$, and the corresponding decay-time difference by $\Delta \Gamma_s = \Gamma_L - \Gamma_H$, where $\{L, H\}$ indicate the heavy and light mass state. Since the mass eigen-states are not equal to the weak eigen-states, these matrices contain off-diagonal elements, $M_{12}$ and $\Gamma_{12}$. The phase difference between $M_{12}$ and $\Gamma_{12}$ leads to an observable CP-violating phase, $\phi_s$. In the SM it is related to $\chi_s$ through $\phi_s \approx 2 \arg(V_{ts} V_{tb}^*)$.

Experimentally, the angle $\phi_s$ is measured by evaluating the time-dependent CP asymmetry of the $B_s \to J/\Psi \phi$ decay,

$$A_{CP}(\phi) = \frac{-\langle \bar{B}_f(\downarrow) \to \uparrow \rangle - \langle \bar{B}_f(\uparrow) \to \downarrow \rangle}{\langle \bar{B}_f(\downarrow) \to \uparrow \rangle + \langle \bar{B}_f(\uparrow) \to \downarrow \rangle}$$ (3)

which is constructed from the time-dependent decay rates $\Gamma$ for initial $B_s$ mesons and $B_s$ mesons to the same final state $f = J/\Psi \phi$. This can then be parameterised as

$$A_{CP}(t) = \frac{-\eta \sin \phi_s \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_1 \frac{t}{2}) - \eta \cos \phi_s \sinh(\Delta \Gamma_1 \frac{t}{2})}$$ (4)

where $\eta_f = +1, -1$ for the CP-even, CP-odd sub sample respectively. The mass-difference between the mass eigen-states of the $B_s^0$ meson determines the oscillation frequency of this asymmetry.

Although the SM predictions of CP-violating observables are consistent with all measurements so far, there is also a clear need for physics beyond the SM because the it is unable to account for the observed baryon asymmetry in the universe [3]. Most Extension of the SM may lead to new CP-violating phases, and therefore to non-SM contributions to CP-observables [1].

2 The LHCb spectrometer

The LHCb spectrometer is a dedicated B-physics experiment for the Large Hadron Collider, at CERN and
is currently under construction. Protons from both beams collide, and subsequently $b\bar{b}$ quark pairs are produced with a cross section of about 500 $\mu$b. Due to the fact the $b\bar{b}$ pairs are produced with a large boost, a forward spectrometer can reconstruct the decay products of the two B-mesons. Figure 2 shows a schematic of the LHCb spectrometer: the VErtex detector (VELO) is located around the interaction point, a second silicon tracker (TT) in front of the 4.2 Tm dipole magnet and together with the Inner Tracker (IT) and Outer Tracker (OT) behind the magnet, comprise the tracking system. Between VELO and TT, a Ring Imaging CHERenkov (RICH) is situated for particle identification. Behind the IT & OT, there is a second RICH detector, followed by an electromagnetic and a hadronic calorimeter. Muons are detected by the Muon System positioned behind the calorimeters. Monte Carlo studies show that a tracking efficiency better than 95% and a momentum resolution between 0.4% and 0.6% is feasible.

3 New Physics from $B_s$ decays

The $B_s \to J/\Psi \phi$ decay can proceed through a tree diagram, where a $b \to c$-quark transition is mediated by a W-boson. The final state, $J/\Psi \phi$, can also be reached through a box diagram where the $B_s$-meson first oscillates into a $B_s$ meson, before it decays. In the $B_s \to \phi\phi$ case, the leading amplitude is a penguin diagram. Similar to the previous case, the $B_s$ meson can oscillate before it decays.

New Physics (NP) can be observed in B-meson decays, through contributions from loop-diagrams. Here, the exchange of new particles in the box-diagram describing $B_s - \bar{B}_s$ mixing of Fig. 2 could lead to new non-SM phases, and therefore observable deviations from SM CP-violation. In a similar way, new particles can contribute to a $b$-quark decay in the loop of a penguin diagram, see Fig. 3. In this article the following parameterisation of NP is used for the off-diagonal elements of the mass-mixing matrix,

$$M'_{12} = M_{12}(1 + h s e^{2i\phi \tau}).$$

The afore mentioned decay, $B_s \to J/\Psi \phi \phi$, is sensitive to the additional contribution to the mixing. The Standard Model predicts the CP-asymmetry $A_{CP} \sim \sin \phi_f$ in this channel to be very small:

$$A_{CP}(B_s \to J/\Psi \phi) \approx -2\chi = -0.035 \text{ rad}.$$  

For the decay $B_s \to \phi\phi$, the Standard Model does not predict any CP-asymmetry and therefore any observation of CP-violation is a clear indication of New Physics.

4 LHCb sensitivity to mixing phase $\phi_s$

The evaluation of the LHCb sensitivity to $\phi_s$ proceeds in two steps. First a detailed Monte Carlo simulation
of physics and LHCb detector response is used to determine signal and background yields, efficiencies, and resolutions. These results have been used in fast MC simulations to determine the sensitivity to $\phi_s$ from different decay channels.

As can be seen from Eq. 4, the observed time-dependent CP-asymmetry is modulated by the oscillations from mixing. The oscillation frequency can be best measured using the $B_s \to D_s \pi$ decay. The observed time-dependent decay rate is given by

$$R(t) \propto e^{-\Gamma_s t} \left\{ \frac{1}{2} \cosh \frac{\Delta \Gamma_s t}{2} + rD \cos(\Delta m_s t) \right\}.$$  

Here, $r = +1$ for $B_s$ mesons and $r = -1$ for $\bar{B}_s$ mesons. The dilution $D$ is given by the probability that a $B_s$ meson was wrongly tagged. In one year of LHCb running (2 $fb^{-1}$), a yield of 140k events is expected, with $B/S < 0.05$ at a tagging efficiency of $\epsilon_{tag} \approx 0.6$ and $D \approx 0.4$. The rate as a function of proper time is shown in Figure 4. From this a statistical accuracy of $\sigma(\Delta m_s) = 0.006$ $ps^{-1}$ is estimated. Systematic uncertainties have not been considered.

The CP-odd and even components are separated from each other on a statistical basis by employing a transversity-angle analysis. The angular dependence of the decay-rate is given by

$$\frac{d\Gamma}{dc} \propto \left| A_0 \right|^2 + \left| A_\parallel \right|^2 \frac{3}{8} (1+c^2) + \left| A_\perp \right|^2 \frac{3}{4} (1-c^2),$$

with $c = \cos \Theta_{tr}$; $A_\parallel$ and $A_0$ are the CP-even components, and $A_\perp$ is the CP-odd component. The transversity angle $\Theta_{tr}$ is defined in the rest-frame of the $J/\Psi$ as the angle between the positive muon and the z-axis, which is perpendicular to the plane spanned by the two decay products of the $\phi$. The transversity angle distribution is shown in Figure 5. It can be described by the sum of the CP-even, CP-odd and background components.

In addition to the parameters which describe detector effects, (see above) the following physics parameters were used as input to the fast simulation: $\phi_s$, $\Delta m_s$, $\Delta \Gamma_s/\Gamma_s$, lifetime of the $B_s (\tau_{B_s})$ and $R_T$, the observable fraction of CP-odd eigenstates, as shown in Table 1, where these values have been taken from literature (e.g. Ref. [5]). In addition to the mixing phase $\phi_s$, the channel $B_s \to J/\Psi \phi$ also allows for the deter-

**Table 1. Input parameters to the fast simulation.**

<table>
<thead>
<tr>
<th>$\phi_s$ [rad]</th>
<th>$\Delta M_s$ [ps$^{-1}$]</th>
<th>$\Delta \Gamma_s/\Gamma_s$</th>
<th>$\tau_{B_s}$ [ps]</th>
<th>$R_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.04</td>
<td>17.5</td>
<td>0.15</td>
<td>1.45</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Fig. 2.** Possible SUSY contribution (gluino exchange) to $B_s - \bar{B}_s$ mixing.

**Fig. 3.** Example of a penguin diagram with SUSY contributions in the form of gluino exchange.

**Fig. 4.** $B_s \to D_s^+ \pi^+$ decay rates vs. proper $B_s$ decay time. The solid line shows the oscillation of an initially produced $B_s$ meson, the dashed line is for an initially $\bar{B}_s$ meson.

**Fig. 5.** Transversity angle distribution of the $B_s \to J/\Psi \phi$ decay. The solid line through the data-points represents the sum of the contributions from the CP-even (dotted line), the CP-odd (dot-dashed) components and from background (dashed).
minimization of the width difference $\Delta \Gamma_s$. The predicted sensitivity for $\Delta \Gamma_s / \Gamma_s$ is $\sigma(\Delta \Gamma_s / \Gamma_s) = 0.008$.

Finally, the predicted uncertainties on the measurement of the weak phase $\phi_s$ are given in Table 2. Here, the sensitivity extracted from the five $b \to ccs$ decays is predicted to be $\sigma(\phi_s) = 0.022$, where the $B_s \to J/\Psi \phi$ is the most sensitive channel.

Table 2. Summary of the estimated LHCb sensitivity for a data set of 2 fb$^{-1}$. The relative weight of the five channels to the determination of $\phi_s$ is given as well.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma(\phi_s)$ [rad]</th>
<th>Weight [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to J/\Psi\eta(3\pi)$</td>
<td>0.14</td>
<td>2.3</td>
</tr>
<tr>
<td>$B_s \to D_s^+ D_s^-$</td>
<td>0.13</td>
<td>2.6</td>
</tr>
<tr>
<td>$B_s \to J/\Psi\eta(\gamma \gamma)$</td>
<td>0.11</td>
<td>3.9</td>
</tr>
<tr>
<td>$B_s \to \eta_s \phi$</td>
<td>0.11</td>
<td>3.9</td>
</tr>
<tr>
<td>Combined sensitivity</td>
<td>0.06</td>
<td>12.7</td>
</tr>
<tr>
<td>$B_s \to J/\Psi \phi$</td>
<td>0.023</td>
<td>87.3</td>
</tr>
<tr>
<td>Total combined sensitivity:</td>
<td>0.022</td>
<td>100.0</td>
</tr>
</tbody>
</table>

These results can then be used to predict limits on NP by using the previously mentioned parameterisation. In an article by Ligeti [6], the reported LHCb sensitivities have been used to estimate limits on $\sigma_s$ and $h_s$. From Ref. [6], two figures have been taken showing exclusion limits on $\sigma_s$ and $h_s$. These limits have been obtained including the first measurements of $\Delta m_s$ [1] (Figure 6). With the predicted LHCb accuracies on $\phi_s$ and $\Delta \Gamma_s / \Gamma_s$ as reported here, the exclusion limits on the amplitude $h_s$ are significantly improved see Figure 7.

5 Conclusions

Despite the success of the Standard Model in predicting and explaining its parameters as measured by experiments, NP leading to additional CP-violation is necessary to explain the baryon asymmetry in the universe. CP-asymmetries of $B$-meson decays are expected to be sensitive probes of New Physics. The SM predicts small asymmetries for the $b \to ccs$ transitions of $B_s$-meson, such as $B_s \to J/\Psi \phi$. Through the contribution of phase from NP, significantly larger CP-violation may occur. The LHCb collaboration is currently constructing a dedicated B-physics spectrometer for the LHC to provide accurate measurements of CP-violation in many rare B decay channels. From Monte Carlo studies of the channels $B_s \to J/\Psi \phi$, $B_s \to D_s^+ D_s^-$, $B_s \to J/\Psi \eta(\gamma \gamma)$, $B_s \to J/\Psi\eta(3\pi)$ and $B_s \to \eta_s \phi$ and $B_s \to D_s^- \pi^+$, a sensitivity for the CP-violating phase $\phi_s$, of $\sigma(\phi_s) = 0.022$ is found.

References