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 ϕ_s, is $\sigma(\phi_s) = 0.022$.

PACS. 14.40.Nd Bottom mesons – 13.25.Hw Decays of bottom mesons – 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries

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, 3×3 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

$$\mathrm{V}^*_{\mathrm{ub}}\mathrm{V}_{\mathrm{us}} + \mathrm{V}^*_{\mathrm{cb}}\mathrm{V}_{\mathrm{cs}} + \mathrm{V}^*_{\mathrm{tb}}\mathrm{V}_{\mathrm{ts}} = 0. \qquad (1)$$

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 $\mathcal{O}(\lambda^4) : \mathcal{O}(\lambda^2) : \mathcal{O}(\lambda^2)$. Here, $\lambda = sin(\theta_C)$ is the expansion parameter, with θ_C being the Cabbibo angle. The angle between the two larger sides ($\mathrm{V}^*_{\mathrm{cb}}\mathrm{V}_{\mathrm{cs}}$) and ($\mathrm{V}^*_{\mathrm{tb}}\mathrm{V}_{\mathrm{ts}}$) is small:

$$\chi = \arg\left[-\frac{\mathrm{V}^*_{\mathrm{cb}}\mathrm{V}_{\mathrm{cs}}}{\mathrm{V}^*_{\mathrm{tb}}\mathrm{V}_{\mathrm{ts}}}\right] \approx \lambda^2\eta \approx \arg(\mathrm{V}_{\mathrm{ts}}) - \pi \approx 0.02 \qquad (2)$$

The neutral B_s meson undergoes mixing which can be described by an effective Hamiltonian consisting of two 2×2 matrices: the mass matrix M, and decay matrix Γ. The mass difference between the mass eigen states 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 Γ_{12}. The phase difference between M_{12} and Γ_{12} leads to an observable CP-violating phase, ϕ_s. In the SM it is related to χ_s through $\phi_s \approx 2\arg(\mathrm{V}^*_{\mathrm{tb}}\mathrm{V}_{\mathrm{ts}})$.

Experimentally, the angle ϕ_s is measured by evaluating the time-dependent CP asymmetry of the $\mathrm{B}_s \to J/\Psi\phi$ decay,

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{\Gamma(\bar{\mathrm{B}}_s(t) \to f) - \Gamma(\mathrm{B}_s(t) \to f)}{\Gamma(\bar{\mathrm{B}}_s(t) \to f) + \Gamma(\mathrm{B}_s(t) \to f)} \qquad (3)$$

which is constructed from the time-dependent decay rates Γ for initial $\bar{\mathrm{B}}_s$ mesons and B_s mesons to the same finale state $f = J/\Psi\phi$. This can then be parameterised as

$$\mathrm{A}_{\mathrm{CP}}(t) = \frac{-\eta_f \sin\phi_s \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s \frac{t}{2}) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s \frac{t}{2})}, \qquad (4)$$

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^0_s 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 it is unable to account for the observed baryon asymmetry in the universe [3,4]. Most Extension of the SM may lead to new CP-violating phases, and therefore to non-SM contributions to CP-observables [1].

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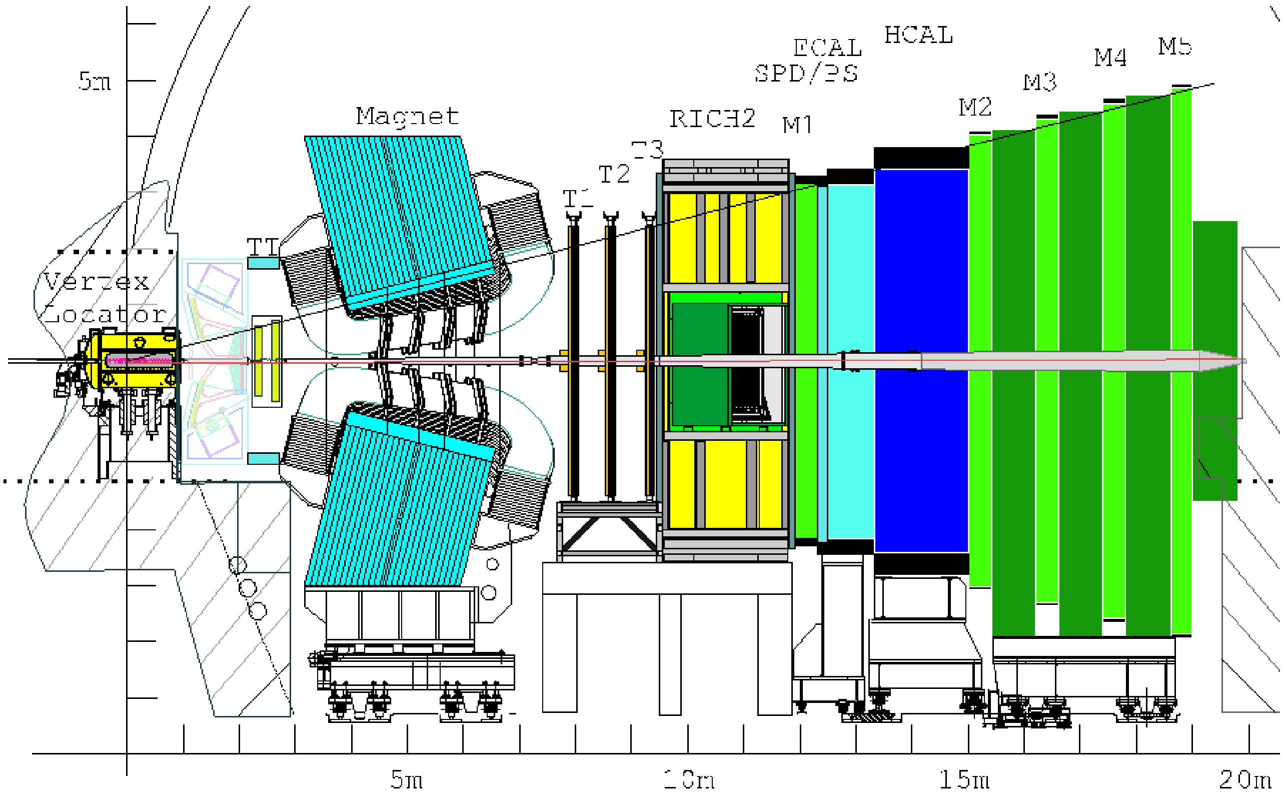

Fig. 1. The LHCb spectrometer, from left to right: the Vertex Locator (VeLo), positioned at the interaction point, the RICH 1 particle identification detector, the TT which is a silicon strip detector, the 4.2 Tm dipole magnet, the Outer Tracker and Inner Tracker, RICH 2, the electromagnetic and hadronic calorimeters and finally the Muon system.

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 μb. 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 $\mathrm{B}_s \rightarrow J/\Psi\phi$ decay can proceed through a tree diagram, where a $b \rightarrow c$-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 $\bar{\mathrm{B}}_s$ meson, before it decays. In the $\mathrm{B}_s \rightarrow \phi\phi$ 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 $\mathrm{B}_s - \bar{\mathrm{B}}_s$ 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,

$$M'_{12} = M_{12}(1 + h_s e^{2i\sigma_s}). \qquad (5)$$

Here, h_s denotes the effective scale of the NP contribution with an effective phase σ_s. The afore mentioned decay, $\mathrm{B}_s \rightarrow J/\Psi\phi$ is sensitive to the additional contribution to the mixing. The Standard Model predicts the CP-asymmetry $\mathcal{A}_{\mathrm{CP}} \sim \sin\phi_s$ in this channel to be very small:

$$\phi_s(\mathrm{B}_s \rightarrow J/\Psi\phi) \approx -2\chi = -0.035 \text{ rad}. \qquad (6)$$

For the decay $\mathrm{B}_s \rightarrow \phi\phi$, the Standard Model does not predict any CP-asymmetry and therefore any observation of CP-violation is a clear indication of New Physics.

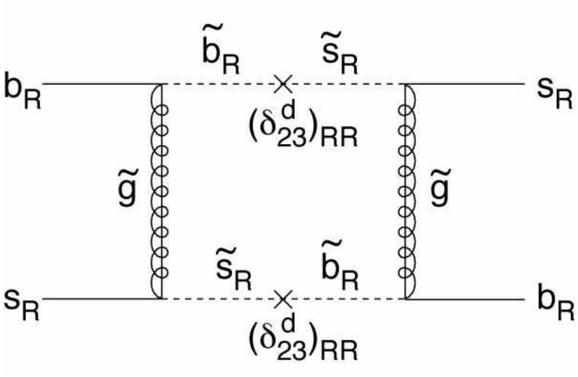

Fig. 2. Possible SUSY contribution (gluino exchange) to $\mathrm{B}_s - \bar{\mathrm{B}_s}$ mixing.

4 LHCb sensitivity to mixing phase ϕ_s

The evaluation of the LHCb sensitivity to ϕ_s proceeds in two steps. First a detailed Monte Carlo simulation of physics and LCHb 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 ϕ_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 $\mathrm{B}_s \to \mathrm{D}_s\pi$ decay. The observed time-dependent decay rate is given by

$$R(t) \propto \frac{e^{-\Gamma_s t}}{2}\left\{\cosh\frac{\Delta\Gamma_s t}{2} + rD\cos(\Delta m_s t)\right\}. \qquad (7)$$

Here, $r = +1$ for B_s mesons and $r = -1$ for $\bar{\mathrm{B}}_s$ 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 a $B/S < 0.05$ at a tagging efficiency of $\epsilon_{\mathrm{tag}} \approx 0.6$ and $D \approx 0.4$. The rate as a function of proper time is shown in Figure 4. From this a statistical accuracy of $\sigma(\Delta m_s) = 0.006\ \mathrm{ps}^{-1}$ is estimated. Systematic uncertainties have not been considered.

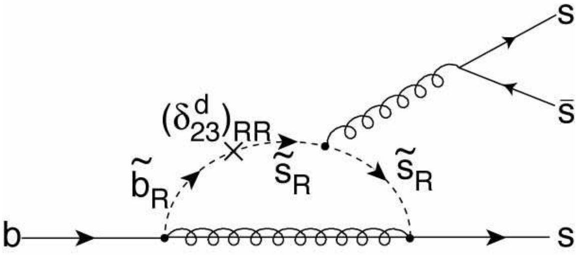

Fig. 3. Example of a penguin diagram with SUSY contributions in the form of gluino exchange.

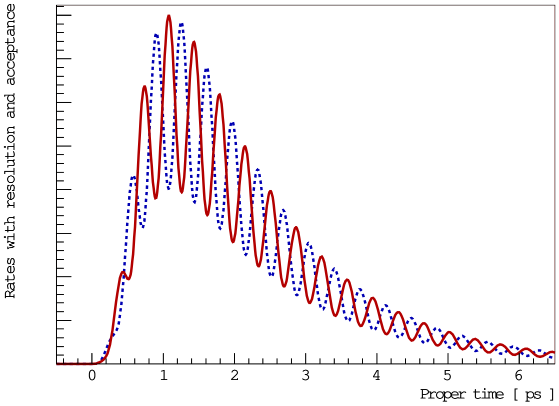

Fig. 4. $\mathrm{B}_s \to \mathrm{D}_s^-\pi^+$ decay rates *vs.* proper B_s decay time. The solid line shows the oscillation of an initially produced B_s meson, the dashed line is for an initially $\bar{\mathrm{B}}_s$ meson.

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

$$\frac{d\Gamma}{dc} \propto \left[\left|\mathrm{A}_0\right|^2 + \left|\mathrm{A}_\parallel\right|^2\right]\frac{3}{8}(1+c^2) + \left|\mathrm{A}_\perp\right|^2\frac{3}{4}(1-c^2), \quad (8)$$

with $c = \cos\Theta_{\mathrm{tr}}$; $\mathrm{A}_\parallel$ and A_0 are the CP-even components, and $\mathrm{A}_\perp$ is the CP-odd component. The transversity angle Θ_{tr} is defined in the rest-frame of the J/Ψ 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 ϕ. 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: ϕ_s, Δm_s, $\Delta\Gamma/\Gamma$, lifetime of the B_s (τ_{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 ϕ_s, the channel $\mathrm{B}_s \to J/\Psi\phi$ also allows for the deter-

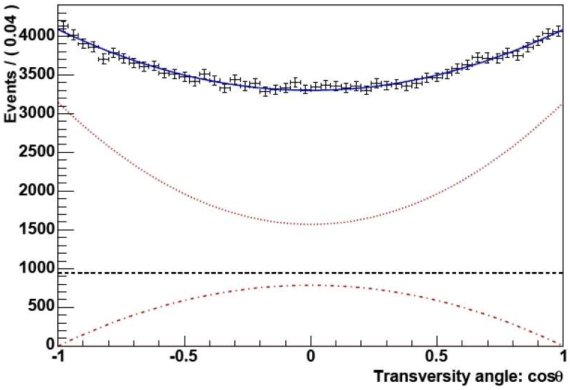

Fig. 5. Transversity angle distribution of the $\mathrm{B}_s \to J/\Psi\phi$ decay. The solid line through the data-points represents the sum of the contributions from the CP-even (dotted line), the CP-odd (dot-dashed) components and from background (dashed).

Table 1. Input parameters to the fast simulation.

ϕ_s[rad]	ΔM$_s$[ps^{-1}]	$\Delta\Gamma_s/\Gamma_s$	$\tau_{B_s^0}$[ps]	R_T
-0.04	17.5	0.15	1.45	0.2

mination 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 ϕ_s are given in Table 2. Here, the sensitivity extracted from the five $b \to c\bar{c}s$ 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 ϕ_s is given as well.

Channel	$\sigma(\phi_s)$[rad]	Weight[%]
B$_s \to J/\Psi\eta(3\pi)$	0.14	2.3
B$_s \to$ D$_s^+$D$_s^-$	0.13	2.6
B$_s \to J/\Psi\eta(\gamma\gamma)$	0.11	3.9
B$_s \to \eta_c\phi$	0.11	3.9
Combined sensitivity :	0.06	12.7
B$_s \to J/\Psi\phi$	0.023	87.3
Total combined sensitivity:	0.022	100.0

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 σ_s and h_s. From Ref. [6], two figures have been taken showing exclusion limits on σ_s and h_s. These limits have been obtained including the first measurements of Δm_s [7] (Figure 6). With the predicted LHCb accuracies on ϕ_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$_s$-meson decays are expected to be sensitive probes of New Physics. The SM predicts small asymmetries for the $b \to c\bar{c}s$ 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$_s \to \eta_c\phi$ and B$_s \to$ D$_s^-\pi^+$, a sensitivity for the CP-violating phase ϕ_s, of $\sigma(\phi_s) = 0.022$ is found.

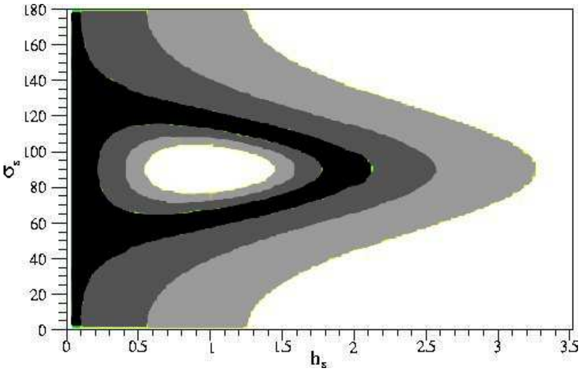

Fig. 6. Limits on the NP parameters σ_s and h_s taken from Ref. [6]. The shaded areas correspond to allowed parameter values with confidence level CL > 0.9 (black), CL > 0.32 (dark grey) and CL > 0.05 (light grey), respectively. The white area around $h_s = 1, \sigma_s = 90$ is caused by cancelling contributions to Δm_s [6].

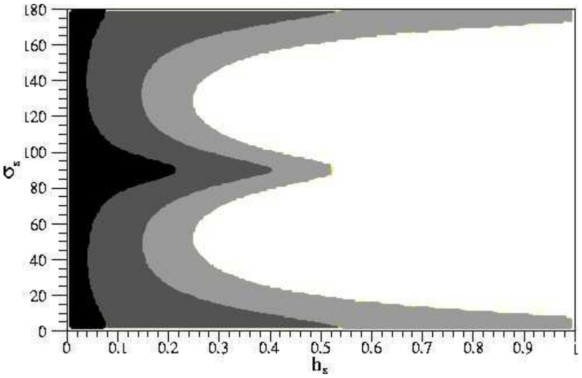

Fig. 7. Limits on σ_s and h_s from Ref. [6] using MC predictions for LHCb measurements of ϕ_s, Δm_s and $\Delta\Gamma_s/\Gamma_s$. The shaded areas show allowed regions for σ_s and h_s for $CL > 0.9$ (black), CL > 0.32 (dark grey) and CL > 0.05 (light grey).

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