SENSITIVITY TO THE B_s^0 MIXING PHASE AT LHCb *

P. VANKOV [†]

NIKHEF,

PO Box 41882, 1009 DB Amsterdam, The Netherlands

E-mail: pvankov@nikhef.nl

The sensitivity to the B_s^0 - $\overline{B}_s^0$ mixing phase ϕ_s at the LHCb experiment at CERN is presented. Both the decays to pure and to an admixture of CP-eigenstates, proceed via $\bar{b} \rightarrow \bar{c}c\bar{s}$ transitions and are used to probe the ϕ_s through a time-dependent mixing-induced CP measurement. A detailed Monte-Carlo simulation is performed to study the event selection performance in LHCb for these channels. The results are used in a "toy" MC to estimate the sensitivity for the phase ϕ_s .

1. CP violation and Mixing in the B_s^0 system

The accommodation of Charge-Parity(CP) violation in the Standard Model(SM) is predicated on the theory of Cabibbo-Kobayashi-Maskawa(CKM)^{1,2}. The complex, unitary, 3×3 CKM matrix V_{CKM} , relates the electroweak eigenstates of the down-type quarks with their mass eigenstates. The elements of V_{CKM} are connected through 6 orthogonality conditions, which follows from the unitarity of the quark-mixing matrix. These conditions can be represented graphically as triangles in the complex plane, called *unitarity triangles*. In the SM, all unitarity triangles have the same surface area, which is proportional to the amount of CP violation. The orthogonality relation applicable to the B_s^0 - $\overline{B}_s^0$ system, often called the sb relation is:

$$\underbrace{V_{ub}^* V_{us}}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cb}^* V_{cs}}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{tb}^* V_{ts}}_{\mathcal{O}(\lambda^2)} = 0 \quad . \quad (1)$$

The corresponding unitarity triangle, shown in Fig. 1 is squashed, since its sides are not of comparable magnitude³ - one of the sides is suppressed

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[†]On behalf of the LHCb collaboration.

Figure 1. The sb unitarity triangle.

with respect to the others by a factor $\mathcal{O}(\lambda^4)$, where $\lambda = \sin(\theta_C)$. The measurement of β_s is a complicated task, which requires high experimental precision, since the angle β_s is predicted to be small in the SM (~ 0.02 rad),

$$\beta_s = \arg \left[-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}} \right] \approx \lambda^2 \eta \approx -\arg(V_{ts}) + \pi . \quad (2)$$

The B_s^0 -mixing phase is directly related to the angle β_s :

$$\phi_s \approx 2 \arg[V_{tb}^* V_{ts}] \approx -2\beta_s , \quad (3)$$

and is measured using the interference between a decay with and without mixing, Fig. 2. The time-dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s^0(t) \rightarrow f) - \Gamma(B_s^0(t) \rightarrow f)}{\Gamma(\overline{B}_s^0(t) \rightarrow f) + \Gamma(B_s^0(t) \rightarrow f)} , \quad (4)$$

gives access to ϕ_s . In the case of the modes with $\bar{b} \rightarrow \bar{c}c\bar{s}$ quark transitions, Eq. 4 becomes:

$$A_{CP}(t) = \frac{\eta_f \sin(\phi_s) \sin(\Delta m_s t)}{\cosh(\frac{\Delta \Gamma_s t}{2}) - \eta_f \cos(\phi_s) \sinh(\frac{\Delta \Gamma_s t}{2})} , \quad (5)$$

where $\Delta m_s = 17.5 \text{ ps}^{-1}$ is used for the B_s^0 oscillation frequency, $\Delta \Gamma_s = \Gamma_H - \Gamma_L$ is the difference between the decay widths of the heavy and light

Figure 2. The $B_s^0 \rightarrow J/\psi \phi$ decay can proceed through both ((a) and (b)) diagrams.

mass eigenstates, and $\eta_f = \pm 1$ is a factor that accounts for the CP eigenvalues.

The value of ϕ_s has not been measured yet. Any established deviation from the SM value would be a sign for New Physics (NP) contributions to $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. In other words, the measuring of the B_s^0 mixing phase ϕ_s represents an important test for the consistency of the SM.

2. LHCb Full Monte-Carlo Simulation

The LHCb experiment⁴ at CERN is a dedicated B physics experiment, which will operate at the Large Hadron Collider. Measurement of ϕ_s is one of the main goals of LHCb.

The performance of LHCb in terms of event yield and background suppression is estimated from full GEANT based Monte-Carlo(MC) simulations, in which the detector and trigger inefficiencies, the noise hits and the bunch-bunch overlap effects are considered. The B_s^0 decays, sensitive to ϕ_s at LHCb, used in these studies are listed in Table 1.

The identification of the initial flavor of the reconstructed B_s^0 meson, the so called *Flavour Tagging*(FT) is necessary to study CP asymmetries. In addition to the well known opposite side tagging technique, the LHCb tagging procedure for B_s^0 mesons is also based on the same side kaon tag - the charge of the kaon that emerges from the same primary vertex as the B_s^0 meson could reveal the flavour(B_s^0 or $\overline{B}_s^0$) of the B_s^0 . This is so, since the kaon and the B_s^0 meson are correlated during the fragmentation. The FT process is characterized with *tagging efficiency*, ϵ_{tag} , which is the probability that the tagging procedure gives an answer, and with *wrong tag fraction*, ω_{tag} - the probability for the FT answer to be incorrect. Due to the imperfection of the FT, the observed CP asymmetry is diluted: $A_{CP}^{obs}(t) = D \times A_{CP}^{obs}(t)$, where $D = 1 - 2\omega_{tag}$. The ω_{tag} , ϵ_{tag} , together with Δm_s , are determined by using the control sample $B_s^0 \rightarrow D_s^- \pi^+$.

Table 1. Exploited B_s^0 channels sensitive to ϕ_s .

Channel	Property
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	CP-odd and CP-even eigenstates
$B_s^0 \rightarrow \eta_c(h^+h^-h^+h^-)\phi(K^+K^-)$	CP-even eigenstate
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$	CP-even eigenstate
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	CP-even eigenstate
$B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)D_s^+(K^+K^-\pi^+)$	CP-even eigenstate
$B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)\pi^+$	Control channel, to determine Δm_s and ω_{tag}

Figure 3. Distribution of the proper-time errors, scaled with pull, obtained with the full MC, for the different B_s^0 channels. The B_s^0 proper-time τ_{fit} and its error are extracted on an even-by-event basis by performing a χ^2 fit^{5,6}.

To resolve the fast $B_s^0 - \overline{B}_s^0$ oscillation we need a good proper-time resolution, σ_τ . Most of the explored channels show (Fig. 3) excellent proper-time reconstruction, with $\sigma_\tau \lesssim 40$ fs. The channel $B_s^0 \rightarrow D_s^- D_s^+$ has worse σ_τ (56 fs) due to the displaced $D_s^\pm$ secondary vertices.

The results from the full MC, for the channels of interest, are reported in Table 2. The annual signal yield (for a total integrated luminosity of 2 fb^{-1}), the background to signal ratio, the proper-time and mass resolutions as well as the ω_{tag} and ϵ_{tag} are given. They are used as input parameters for the "toy" MC studies, described in Sec. 3, performed in order to estimate the sensitivity to ϕ_s . Among the investigated channels, the decay $B_s^0 \rightarrow J/\psi \phi$ has the largest signal yield, making it most attractive to use, although it contains an admixture of CP eigenstates and an angular analysis is needed to disentangle the different states.

Table 2. Results from the full MC simulation.

Channel	Yield [$10^3/2\text{fb}^{-1}$]	Bkgr./Sig.	σ_τ [fs]	σ_{mass} [MeV/c ²]	ω_{tag} [%]	ϵ_{tag} [%]
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	131	0.12	36	14		
$B_s^0 \rightarrow \eta_c(h^+h^-h^+h^-)\phi(K^+K^-)$	3.0	0.6	30	12		
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	3.0	3.0	34	20		
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$	8.5	2.0	37	34		
$B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)D_s^+(K^+K^-\pi^+)$	4.0	0.3	56	6		
$B_s^0 \rightarrow D_s^-(K^+K^-\pi^-)\pi^+$	120	0.4	40	14	31	63

3. Sensitivity to ϕ_s studies

To estimate the sensitivity to the mixing parameters, 225 fast parametrized MC programs (Toy MC's) were generated⁶. Each toy experiment corresponded to 2 fb^{-1} (10^7 s at $\mathcal{L} = 2 \times 10^{32} \text{ cm}^2\text{s}^{-1}$). The mixing parameters are extracted through an unbinned maximum likelihood fit to the mass distributions, proper-time distributions and in the case of $B_s^0 \rightarrow J/\psi\phi$ to the transversity angle⁷ θ . The *sensitivity* to a parameter is defined as the RMS of the parameter distribution. The obtained results for the sensitivity to ϕ_s for 2 fb^{-1} (1 nominal year of LHCb operation) are summarized in Table 3. The achieved combined sensitivity to ϕ_s with 10 fb^{-1} (5 years of LHCb operation) is $\sigma(\phi_s) = \pm 0.01 \text{ rad}$.

Table 3. Results on sensitivity to ϕ_s .

Channels (sensitivity for ϕ_s with 2 fb^{-1})	$\sigma(\phi_s)$ [rad]	Weight $\left(\frac{\sigma}{\sigma_i}\right)^2$ [%]
$B_s^0 \rightarrow D_s^- (K^+ K^- \pi^-) D_s^+ (K^+ K^- \pi^+)$	0.133	2.6
$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\pi^+ \pi^- \pi^0(\gamma\gamma))$	0.142	2.8
$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \eta(\gamma\gamma)$	0.109	3.9
$B_s^0 \rightarrow \eta_c(h^+ h^- h^+ h^-) \phi(K^+ K^-)$	0.108	3.9
Combined sensitivity for pure CP eigenstates	0.059	13.2
$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \phi(K^+ K^-)$	0.023	86.8
Combined sensitivity for all CP eigenstates	0.021	100.0

4. Conclusions

The reported results show that LHCb will be able to perform $\sim 2\sigma$ measurement of ϕ_s^{SM} after 1 year of data taking or to detect possible new physics effects. The ϕ_s sensitivity is dominated by the decay mode $B_s^0 \rightarrow J/\psi\phi$.

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