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O. Leroy

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Prospects for CP violation in $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ from first LHCb data

Olivier Leroy, on behalf of the LHCb collaboration
CPPM, 163 avenue de Luminy Case 907, 13288 Marseille cedex 9, France
E-mail: `Olivier.Leroy@in2p3.fr`

Abstract.
The determination of the CP-violating phase in $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays is one of the key goals of the LHCb experiment. Its value is predicted to be very small in the Standard Model but can be significantly enhanced in many models of New Physics. The steps towards a precise determination of this phase with a flavour-tagged, time-dependent, angular analysis of the decay $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ will be reviewed and first studies performed with data collected at LHC in pp collisions at 7 TeV center-of-mass energy will be presented. Prospects are also given for the measurement of the flavour specific asymmetry using semileptonic $\mathrm{B^0_{d,s}}$ decays.

1. Introduction

The phenomenology of CP violation in $\mathrm{B_s^0}$ decays is described in many articles [1]. Here we just recall the main aspects. The time evolution of the $\mathrm{B_s^0}(\sim \bar{\mathrm{b}}\mathrm{s})$ and $\overline{\mathrm{B}}{}_\mathrm{s}^0(\sim \mathrm{b}\bar{\mathrm{s}})$ mass eigenstates is described by a Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} |\mathrm{B_s^0}(t)\rangle \\ |\overline{\mathrm{B}}{}_\mathrm{s}^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - i\frac{\mathbf{\Gamma}}{2}\right)\begin{pmatrix} |\mathrm{B_s^0}(t)\rangle \\ |\overline{\mathrm{B}}{}_\mathrm{s}^0(t)\rangle \end{pmatrix},$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are the mass and decay matrices. We can define three parameters describing the phenomenom of $\mathrm{B_s^0}$–$\overline{\mathrm{B}}{}_\mathrm{s}^0$ mixing:

$$\Delta m_\mathrm{s} = M_\mathrm{H} - M_\mathrm{L}, \qquad \Delta\Gamma_\mathrm{s} = \Gamma_\mathrm{L} - \Gamma_\mathrm{H}, \qquad \phi_\mathrm{s} = \arg\left(-\frac{M_{12,\mathrm{s}}}{\Gamma_{12,\mathrm{s}}}\right), \tag{1}$$

where the average $\mathrm{B_s^0}$ mass and width (indices L and H for the two mass eigenstates) are:

$$M_{\mathrm{B_s^0}} = \frac{M_\mathrm{H} + M_\mathrm{L}}{2}, \qquad \Gamma_\mathrm{s} = \frac{\Gamma_\mathrm{L} + \Gamma_\mathrm{H}}{2}. \tag{2}$$

There are several ways of probing New Physics using $\mathrm{B_s^0}$–$\overline{\mathrm{B}}{}_\mathrm{s}^0$-mixing. In this document, we describe the golden method using $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays. We also present an alternative method using semileptonic decays.

Within the Standard Model, the decay $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ is dominated by $\bar{\mathrm{b}} \to \bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}$ quark level transitions, as represented in Figure 1 (left), with a weak phase $\Phi_\mathrm{D} = \arg(V_\mathrm{cb}V_\mathrm{cs}^*)$[1]. The $\mathrm{B_s^0}$

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[1] The possible small penguin contribution (same figure, right) is neglected here and discussed further in [2]

meson can also oscillate to a $\overline{\mathrm{B}}^0_\mathrm{s}$ before decaying to J/$\psi\phi$, with a weak phase $\Phi_\mathrm{M} = 2\arg(V^*_\mathrm{ts}V_\mathrm{tb})$ (Figure 2). The interference between both processes gives rise to a CP violating weak phase $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi} = \Phi_\mathrm{M} - 2\Phi_\mathrm{D} = -2\beta_\mathrm{s}$, where $\beta_\mathrm{s} = \arg\left(-V_\mathrm{ts}V^*_\mathrm{tb}/V_\mathrm{cs}V^*_\mathrm{cb}\right)$ is the smallest angle of the "b−s unitarity triangle". The indirect determination via global fits to experimental data gives $2\beta_\mathrm{s} = (0.0363 \pm 0.0017)\,\mathrm{rad}$ [3]. The direct measurement of this phase is one of the key goals of the LHCb experiment. Indeed, $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ is one of the CP observables with the smallest theoretical uncertainty in the Standard Model, and New Physics could significantly modify this prediction. if new particles contribute with a new phase to the B^0_s–$\overline{\mathrm{B}}^0_\mathrm{s}$ box diagram. Both CDF and DØ have reported constraints on $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ with large uncertainties [4].

An alternative way to search for New Physics is to measure the flavour specific asymmetry, which is linked to the quantity

$$a^\mathrm{s}_\mathrm{fs} = \frac{\Delta\Gamma_\mathrm{s}}{\Delta m_\mathrm{s}} \tan\phi_\mathrm{s}\,, \tag{3}$$

as explained in [5] (see also Eq. 7 in Section 4). Within the Standard Model, $\phi_s^\mathrm{SM} = (3.40^{+1.32}_{-0.77}) \times 10^{-3}\,\mathrm{rad}$ [3]. DØ reported in 2010 a 3.2σ deviation with respect to the Standard Model, measuring the the like-sign dimuon charge asymmetry in semileptonic b-hadron decays [6]. The quantity $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ and ϕ_s are two different observables. However, assuming new physics affects only the mixing box diagram, they would be both shifted by the same New Physics phase, ϕ^Δ_s:

$$\phi_\mathrm{s}^{\mathrm{J}/\psi\phi} = -2\beta_\mathrm{s} + \phi^\Delta_\mathrm{s}\,, \tag{4}$$
$$\phi_\mathrm{s} = \phi_s^\mathrm{SM} + \phi^\Delta_\mathrm{s}\,. \tag{5}$$

where we have used the notation of [7].

In Section 2, we present the method to measure $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ at LHCb and the expected sensitivity, based on Monte Carlo estimates. In Section 3, the first preliminary results obtained with the 2010 real data are given. Eventually in Section 4, we present a way to constraint ϕ_s via semileptonic decays.

2. $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ studies based on Monte Carlo

$\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ is a pseudo-scalar to vector-vector decays. The final state is a superposition of three polarizations amplitudes (A_0, $A_\parallel$ and $A_\perp$), and an angular analysis is required to disentangle statistically the CP-odd and CP-even components. The argument of the polarization amplitudes are strong phases denoted δ_0, $\delta_\parallel$ and $\delta_\perp$. The three decay product angles are shown in Figure 3, in the transversity basis, for $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$.

The differential decay rate of $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ is a function of six observables (the proper time, the J/$\psi\phi$ invariant mass, the initial B^0_s flavour and the three decay angles) and nine physics parameters: the weak phase ($\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$), the mass and width difference between B^0_s mass eigenstates (Δm_s and $\Delta\Gamma_\mathrm{s}$), the mass and width of the B^0_s, two amplitudes and two strong phases [8]. The possibility to account for a KK S-wave in the $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\mathrm{K}^+\mathrm{K}^-$ decay is discussed in [9].

In the rest of this section, we present the trigger and selection, the measurement of proper time and decay angles, the flavour tagging, the fit and sytematics studies, based on Monte Carlo [10].

2.1. Trigger and selections

The $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ channels is triggered and selected in a uniform way together with two control channels ($\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}$ and $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$), in order to extract the mistag rate (defined in Section 2.2) without applying large corrections. The trigger and selections are designed to maximize the sensitivity to $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ while avoiding large proper time and angular acceptance

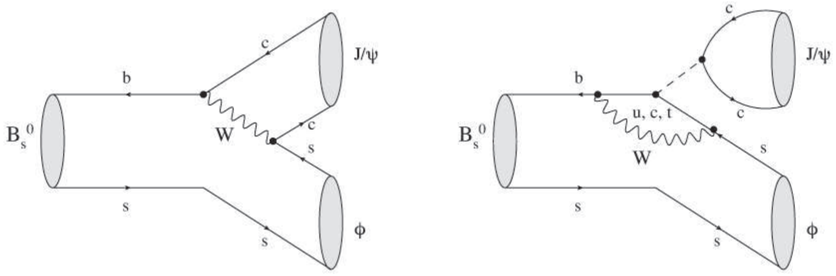

Figure 1. Feynman diagrams contributing to the decay $B_s^0 \to J/\psi\phi$, within the Standard Model. Left: tree; right: penguins.

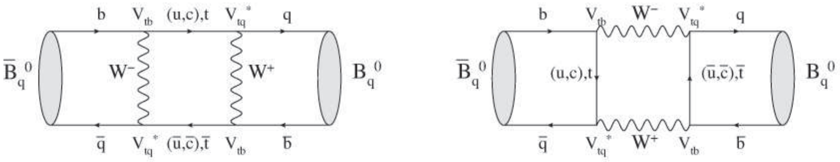

Figure 2. Feynman diagrams responsible for B_q–$\overline{B}_q$ mixing, within the Standard Model (q=s,d).

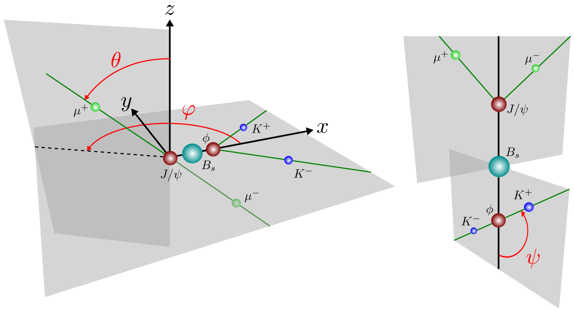

Figure 3. Angle definition: θ is the angle formed by the positive lepton (ℓ^+) and the z axis, in the J/ψ rest frame. The angle φ is the azimuthal angle of ℓ^+ in the same frame. In the ϕ meson rest frame, ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$.

corrections [11]. The J/ψ is reconstructed from its decay to two muons, while the ϕ is reconstructed from two kaons. Based on a Monte Carlo simulation, with a center-of-mass energy of 14 TeV, we expect 117 000 $B_s^0 \to J/\psi\phi$ per 2 fb^{-1}. The total trigger efficiency is $\sim 70\%$. The background is dominated by prompt events, since no cut which can bias the lifetime is used. The angular acceptances for the three transversity angles show distortions below 8%. These are mainly from the LHCb forward geometrical acceptance.

2.2. Flavour tagging

The flavour tagging algorithm and its calibration in LHCb are described in [12, 13]. It is characterized by a mistag rate ($\omega = W/(W+R)$), a tagging efficiency ($\varepsilon_{\rm tag} = (W+R)/(W+R+U)$) and an effective tagging efficiency $\varepsilon_{\rm eff} = \varepsilon_{\rm tag}(1-2\omega)^2$; where W, R and U denotes the number of events wrongly tagged, correctly tagged and untagged. Within each event, all available information is used and combined using a neural network. The combined effective tagging efficiency measured on simulated $\rm B^0_s \to J/\psi\phi$ events is 5.3%.

2.3. Fits and systematics

The fit procedure is described in [10]. The eight physics parameters $\{\phi_s^{J/\psi\phi}, \Gamma_s, \Delta\Gamma_s, R_\perp, R_0, \delta_\perp, \delta_\parallel, \Delta m_s\}$ are determined by an unbinned likelihood fit to six physical observables (mass, proper time, initial flavour and three transversity angles), taking into account 18 detector parameters. The total PDF is the sum of the signal PDF plus two PDFs for modelling the prompt and the long-lived background. The proper time resolution, angular acceptance and mistag fraction are taken into account. The projections of data and fitted probability density function on the transversity angles and on the proper time can be found in Figure 4. The fitted PDFs and Monte Carlo data show very good agreement. Using hundreds of toy Monte Carlo experiments, the statistical uncertainty on $\phi_s^{J/\psi\phi}$ is estimated to be 0.07 rad, with $1\,\mathrm{fb}^{-1}$ of data taken at a LHC centre-of-mass energy of 7 TeV[2]. A summary of the systematic effects is given in Table 1. No irreducible systematic uncertainty has been identified. Figure 5 shows the statistical uncertainty on $\phi_s^{J/\psi\phi}$ versus the integrated luminosity. The latest Tevatron results are also indicated.

Parameter	Variation	$\lvert\phi_s^{\rm wrong} - \phi_s^{\rm true}\rvert/\phi_s^{\rm true}$
Angular distortions	±5%	7%
Proper time resolution	(38 ± 5) fs	6%
Mistag	(34 ± 1)%	7%

Table 1. Relative systematic variation on $\phi_s^{J/\psi\phi}$ (column 3), due to parameter variations (columns 1 and 2).

3. First $\rm B^0_s \to J/\psi\phi$ results based on 2010 real data

In 2010, the LHCb detector recorded $37\,\mathrm{pb}^{-1}$ of data. The detector worked remarkably well, depsite being exposed to a pile-up ~ 5 times higher than the design. The invariant mass of $\rm B^+ \to J/\psi K^+$, $\rm B^0 \to J/\psi K^{*0}$ and $\rm B^0_s \to J/\psi\phi$, $\rm B^0 \to J/\psi K^{*0}$, triggered and selected in $\sim 33\,\mathrm{pb}^{-1}$ are given in Figure 6. 877 ± 32 $\rm B^0_s \to J/\psi\phi$ are reconstructed with a proper time above 0.3 ps. Note that this cut on proper time is just used for illustration purpose, to remove the huge prompt background. It will not be used in the final fit. The proper time resolution of the $\rm B^0_s$ candidates is estimated to be 50 fs, roughly 30% worse than Monte Carlo expectation, but still twice better than the one reported by Tevatron experiments and easily sufficient to resolve the fast $\rm B^0_s$–$\rm \overline{B}{}^0_s$ oscillations, which have a period of 352 fs. First results on opposite side flavour tagging using $\rm B^0 \to D^{*-}\mu^+\nu_\mu$ event gives 60% of the performance expected from Monte Carlo. Since the DISCRETE symposium, much progress in this area has been achieved and new results including same-side tagging will soon be reported.

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[2] Results given in [10] were obtained assuming 14 TeV and $2\,\mathrm{fb}^{-1}$. They have simply been rescaled here to 7 TeV.

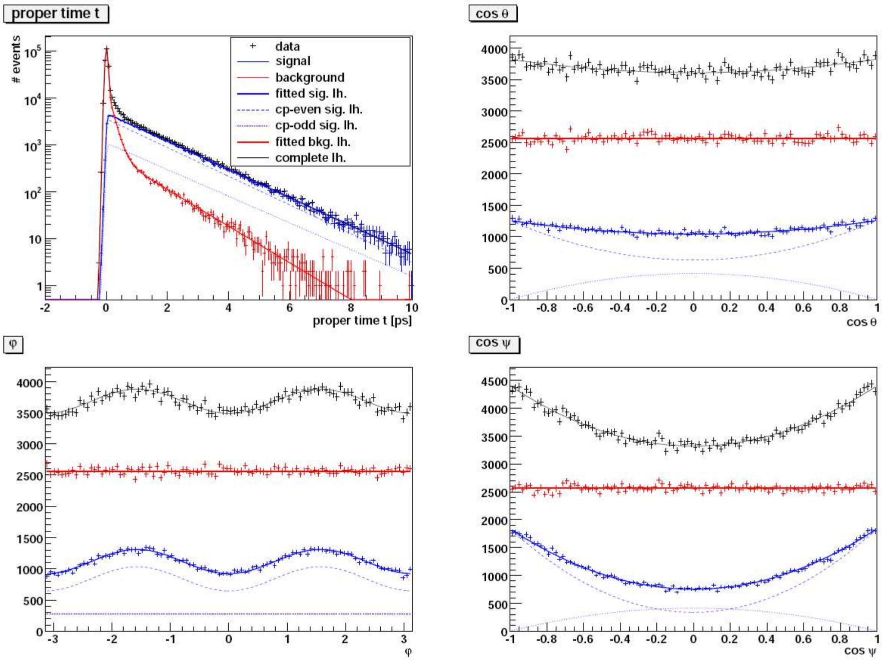

Figure 4. The projections of data and fitted signal PDF including both the angular and proper time acceptance effects, in a sample of toy MC events, including prompt and long-lived background. Also shown are the CP-even (dashed) and the CP-odd (dotted) components.

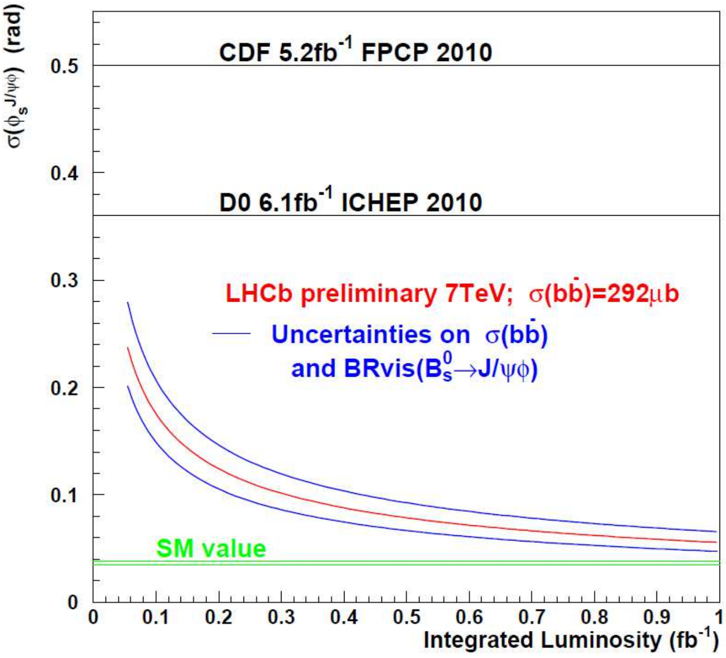

Figure 5. Monte Carlo expected uncertainty on $\phi_{\rm s}^{J/\psi\phi}$ at LHCb versus integrated luminosity, for a LHC centre-of-mass energy of 7 TeV.

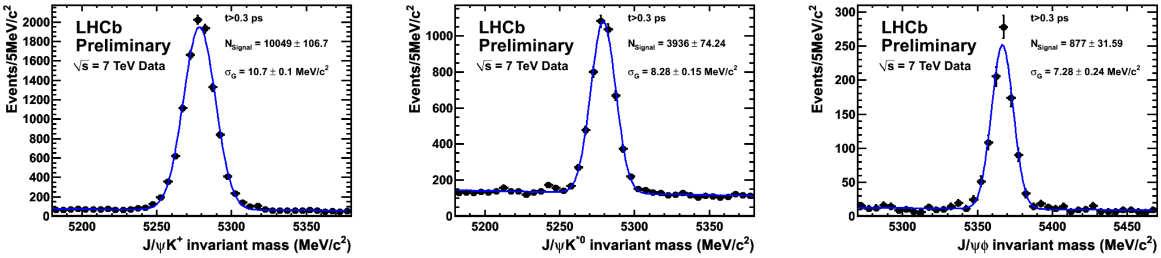

Figure 6. Invariant mass of $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$, $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}$ et $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ candidates reconstructed in the first data ($33\,\mathrm{pb}^{-1}$) collected by the LHCb experiment in 2010.

4. Flavor-specific asymmetry in $\mathrm{B}^0_{\mathrm{d,s}}$ decays

An alternative way to look for New Physics in the mixing box diagram is to measure the flavour specific asymmetry:

$$A^q_{\mathrm{fs}} = \frac{\Gamma(f) - \Gamma(\overline{f})}{\Gamma(f) + \Gamma(\overline{f})} \qquad \mathrm{q} = \mathrm{d}, \mathrm{s}\,. \tag{6}$$

The index $\mathrm{q} = \mathrm{s}, \mathrm{b}$ stands for B^0_s and B^0 mesons. This observable is related to a_{fs} (Eq. 3) via:

$$A^\mathrm{q}_{\mathrm{fs}}(t) = \frac{a^\mathrm{q}_{\mathrm{fs}}}{2} - \frac{\delta^\mathrm{q}_c}{2} - (\frac{a^\mathrm{q}_{\mathrm{fs}}}{2} + \frac{\delta^\mathrm{q}_p}{2})\frac{\cos(\Delta m_\mathrm{q} t)}{\cosh(\Delta\Gamma_\mathrm{q} t/2)} + \frac{\delta^\mathrm{q}_b}{2}\left(\frac{B}{S}\right)^\mathrm{q} \qquad \mathrm{q} = \mathrm{s}, \mathrm{b}\,, \tag{7}$$

where δ_c is the detector asymmetry ($\sim 10^{-2}$), δ_p the production asymmetry ($\sim 10^{-2}$), δ_b the background asymmetry ($\sim 10^{-3}$) and B/S the background over signal ratio. Given the order of magnitude of these polluting contributions, the direct extraction of a_{fs} is extremely challenging at LHCb. The Standard Model predictions are: $a^\mathrm{d}_{\mathrm{fs}}(SM) = (-6.4^{+1.6}_{-1.8}) \times 10^{-4}$, $a^\mathrm{s}_{\mathrm{fs}}(SM) = (3.0^{+1.2}_{-1.3}) \times 10^{-5}$[14]. That is why we propose to use $\mathrm{B}^0_\mathrm{s} \to \mathrm{D}^-_\mathrm{s}\mu^+\nu$ and $\mathrm{B}^0 \to \mathrm{D}^-\mu^+\nu$ with the same final state $\mathrm{K}^+\mathrm{K}^-\pi^-\mu^+$, so that the detector asymmetry cancels in the difference $A^\mathrm{d}_{\mathrm{fs}} - A^\mathrm{d}_{\mathrm{fs}}$. With the huge number of semileptonic decays that will be collected in 2011 at LHCb, we expect a tiny statistical uncertainty on $a^\mathrm{d}_{\mathrm{fs}} - a^\mathrm{s}_{\mathrm{fs}}$. However, the control of the systematic uncertainties will still be a demanding task.

5. Conclusions and Prospects

The $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ channel will allow LHCb to probe possible New Physics effects in the B^0_s–$\overline{\mathrm{B}}^0_\mathrm{s}$ box diagram. We have presented the work-plan to perform the measurement of the CP-violating weak phases in this channel, based on Monte Carlo, together with first results obtained with the real data taken in 2010. 877 $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ candidates have been fully reconstructed with $33\,\mathrm{pb}^{-1}$. With $1\,\mathrm{fb}^{-1}$ of data taken at a center-of-mass energy of $7\,\mathrm{TeV}$, as expected by the end of 2011, we anticipate a statistical uncertainty on $\phi^{\mathrm{J}/\psi\phi}_\mathrm{s}$ of $0.07\,\mathrm{rad}$. We have also presented prospects to measure the semileptonic asymmetry using the $\mathrm{B}^0_\mathrm{s} \to \mathrm{D}^-_\mathrm{s}(\mathrm{K}^+\mathrm{K}^-\pi^-)\mu^+\bar{\nu_\mu}$ and $\mathrm{B}^0 \to \mathrm{D}^-(\mathrm{K}^+\mathrm{K}^-\pi^-)\mu^+\bar{\nu_\mu}$ channels.

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