Prospects for CP Violation in B_s$^0 \rightarrow$ J/$\psi\Phi$from first LHCb data

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

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Summary. — The determination of the CP-violating phase in $B_s^0 \to J/\psi\phi$ 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 $B_s^0 \to J/\psi\phi$ are reviewed and first studies performed with data collected in 2010 at LHC in pp collisions at 7 TeV center-of-mass energy are presented for the first time. In particular, we report the first LHCb measurements of lifetime in the channels $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_S$, $B_s^0 \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$; the polarization amplitudes in $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$; the width and mass differences of the B_s^0 mass eigenstates, $\Delta\Gamma_s$ and Δm_s. The data sample used corresponds to an integrated luminosity of $36\,\mathrm{pb}^{-1}$.

1. – Introduction

The interference between B_s^0 decays to $J/\psi\phi$ either directly or via B_s^0–$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{J/\psi\phi}$. In the Standard Model, this phase is predicted to be $\simeq -2\beta_s$, where $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$. The indirect determination via global fits to experimental data gives $2\beta_s = (0.0363 \pm 0.0017)$ rad [1], within the Standard Model. The direct measurement of this phase is one of the key goals of the LHCb experiment. Indeed, $\phi_s^{J/\psi\phi}$ 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_s^0–$\overline{B}_s^0$ box diagram. Both CDF and DØ have reported constraints on $\phi_s^{J/\psi\phi}$ with large uncertainties [2, 3].

In this document, we present the steps towards a measurement of $\phi_s^{J/\psi\phi}$ at LHCb and give the first preliminary results obtained with the 2010 data. The CP-violationg phase will be extracted from a tagged time-dependent angular analysis of $B_s^0 \to J/\psi\phi$ decays. Therefore, the following steps are required:

(*) on behalf of the LHCb Collaboration

- in Section **2**, we present the selection and lifetime of $B^0_s \to J/\psi(\mu\mu)\phi(KK)$ channel, together with other $b\to J/\psi(\mu\mu)X$ control channels;
- in Section **3**, we report on the untagged angular analysis of $B^0_s \to J/\psi\phi$, together with the control channel $B^0 \to J/\psi K^{*0}$;
- the tagging of the B^0_s flavour at production is discussed in Section **4**, together with the measurement of Δm_d and Δm_s;
- other channels can be used to measure the mixing-induced CP violation in B^0_s-decays amongst which the $B^0_s \to J/\psi f_0$ channel. The first observation of this decay is reported in Section **5**.

2. – Selections and lifetime measurement

The trigger and selection of $B^0_s \to J/\psi(\mu\mu)\phi(KK)$ and control channels are described in [6]. The measurement of $\phi_s^{J/\psi\phi}$ requires a good understanding of detector effects such as the proper time acceptance and resolution, angular acceptance, mistag fraction and background. The strategy is to trigger and select several $b \to J/\psi X$ decay modes in a similar way and use them as control channels to calibrate the detector and validate the analysis procedures used when studying $B^0_s \to J/\psi\phi$.

The b-hadron lifetimes are extracted from a maximum likelihood fit to the proper time distributions of the fully reconstructed candidates. In order to avoid as much as possible a proper time dependent efficiency both the trigger and the offline selection are chosen to be lifetime unbiased: the selections avoid cutting on variables that are correlated with the b-hadron proper time, such as impact parameters of final state particles with respect to the primary vertex. The only exception is a cut on proper time $t > 0.3$ ps which allows to remove the huge prompt background dominated by combinations of tracks originating from the primary vertex.

The reconstructed mass and proper time projections of $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_S$, $B^0_s \to J/\psi\phi$ and $\Lambda_b \to J/\psi\Lambda$ are shown in Figs. 1 to 5. The extracted lifetimes and the signal yields in the proper time range $t \in [0.3, 14]$ ps are shown in Table I. They are compatible with the PDG values [7]. The proper time resolution measured in $B^0_s \to J/\psi\phi$ event is 50 fs. The systematics uncertainties are given in Table II and detailed in [6].

TABLE I. – *Signal event yields and lifetimes extracted from the likelihood fits to the candidates with proper time* $t \in [0.3, 14]$ ps. *A single exponential is used to fit the proper time distribution.*

Channel	Lifetime (ps)	Yield
$B^+ \to J/\psi K^+$	1.689 ± 0.022 (stat.) ± 0.047 (syst.)	6741 ± 85
$B^0 \to J/\psi K^{*0}$	1.512 ± 0.032 (stat.) ± 0.042 (syst.)	2668 ± 58
$B^0 \to J/\psi K^0_S$	1.558 ± 0.056 (stat.) ± 0.022 (syst.)	838 ± 31
$B^0_s \to J/\psi\phi$	1.447 ± 0.064 (stat.) ± 0.056 (syst.)	570 ± 24
$\Lambda_b \to J/\psi\Lambda$	1.353 ± 0.108 (stat.) ± 0.035 (syst.)	187 ± 16

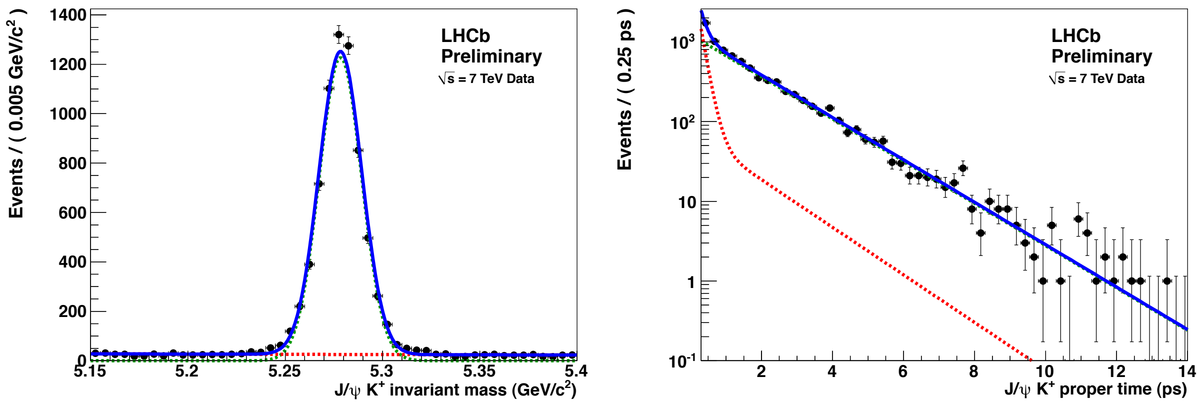

Fig. 1. – B^+ mass (left) and proper time (right) projections of the two-dimensional fit to the $B^+ \to J/\psi K^+$ candidates with $t > 0.3\,\text{ps}$. The total fit is represented by the blue solid line, the signal contribution by the green dashed line and the background contribution by the red dashed line. The mass range for the fit is $m \in [5.15, 5.40]\ \text{GeV}/c^2$.

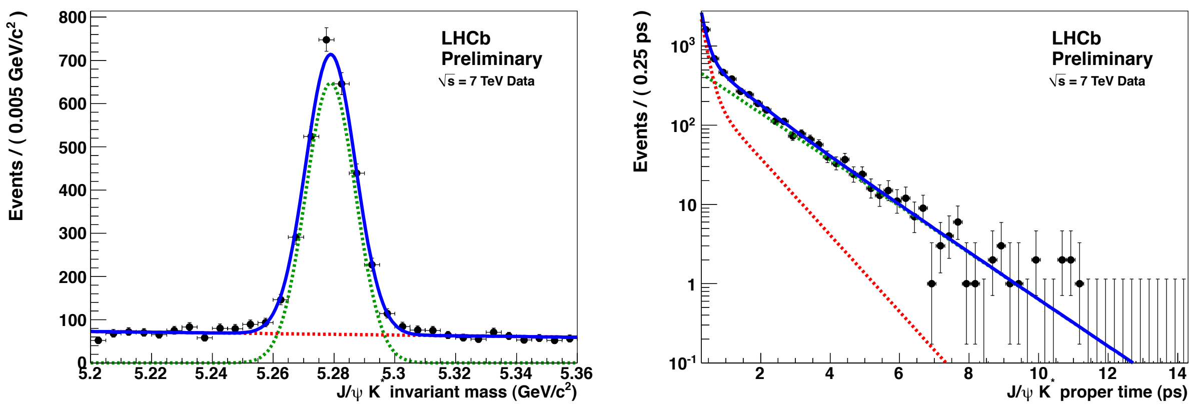

Fig. 2. – B^0 mass (left) and proper time (right) projections of the two-dimensional fit to the $B^0 \to J/\psi K^{*0}$ candidates with $t > 0.3\,\text{ps}$. The total fit is represented by the blue solid line, the signal contribution by the green dashed line and the background contribution by the red dashed line. The mass range for the fit is $m \in [5.20, 5.36]\ \text{GeV}/c^2$.

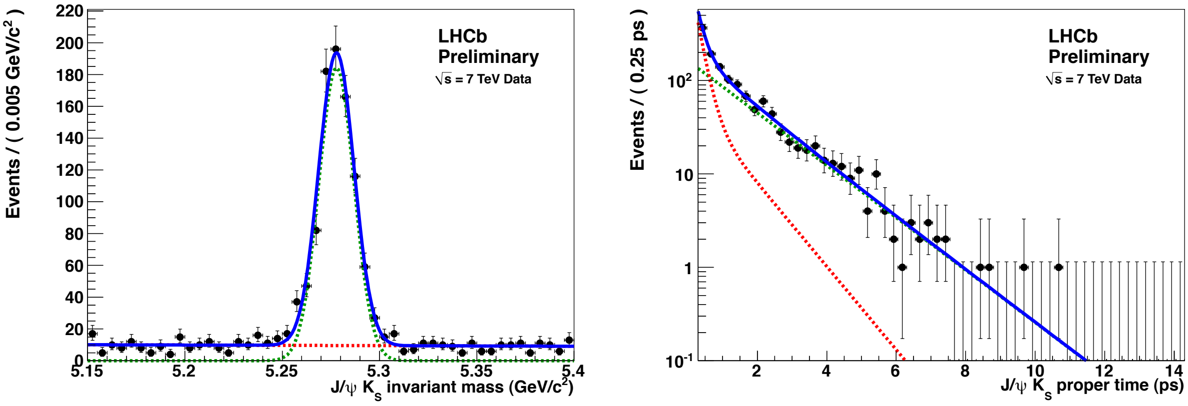

Fig. 3. – B^0 mass (left) and proper time (right) projections of the two-dimensional fit to the $B^0 \to J/\psi K^0_S$ candidates with $t > 0.3$ ps. The total fit is represented by the blue solid line, the signal contribution by the green dashed line and the background contribution by the red dashed line. The mass range for the fit is $m \in [5.15, 5.40]$ GeV/c^2.

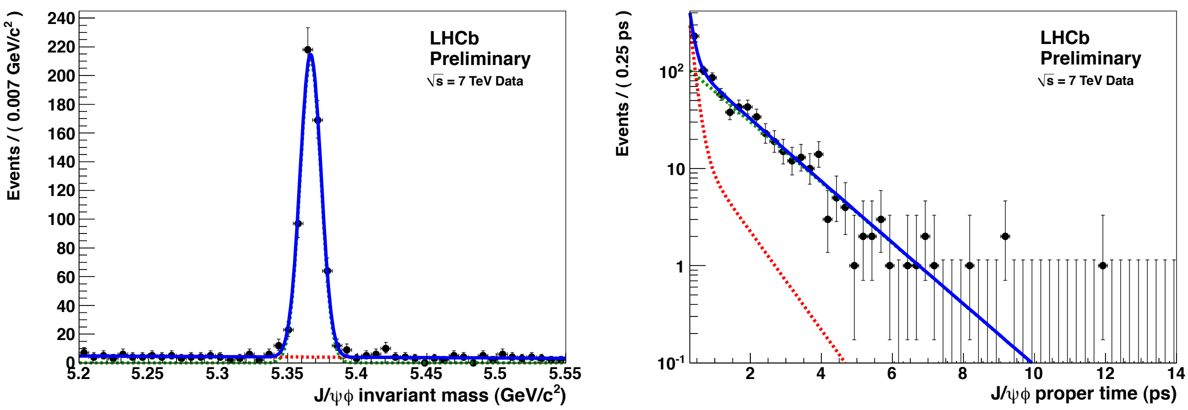

Fig. 4. – B^0_s mass (left) and proper time (right) projections of the two-dimensional fit to the $B^0_s \to J/\psi\phi$ candidates with $t > 0.3$ ps. The total fit is represented by the blue solid line, the signal contribution by the green dashed line and the background contribution by the red dashed line. The mass range for the fit is $m \in [5.20, 5.55]$ GeV/c^2.

TABLE II. – *Systematic uncertainties in the lifetime measurements (ps).*

	$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K^{*0}$	$B_s^0 \to J/\psi\phi$	$B^0 \to J/\psi K_S^0$	$\Lambda_b \to J/\psi\Lambda$
Signal mass model	0.002	0.002	0.010	0.014	0.012
Signal time model	0.043	0.038	0.040	0.015	0.022
Bkg. mass model	0.009	0.020	0.005	0.008	0.023
Bkg. time model	0.003	0.006	0.003	0.006	0.006
Time resol. model	0.005	0.005	0.005	0.005	0.005
Momentum scale	0.001	0.001	0.001	0.001	0.001
Decay length scale	0.001	0.001	0.001	0.001	0.001
Quadratic sum	0.047	0.042	0.056	0.022	0.035

3. – Untagged angular analysis of $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$

The decays $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ are both pseudo-scalar to vector-vector transitions. Both decays are described by three time dependent decay amplitudes corresponding to transitions in which the J/ψ and ϕ (or K^{*0}) have a relative orbital momentum L of 0, 1, or 2. In the transversity formalism [4], the initial amplitudes at time $t = 0$, $A_0(0)$ and $A_\parallel(0)$ describe the decays with $L = 0, 2$ while $A_\perp(0)$ describes the $L = 1$ final states. The arguments of these complex amplitudes are strong phases denoted δ_0, $\delta_\parallel$ and $\delta_\perp$. The measurement of the polarization amplitudes and strong phases using untagged

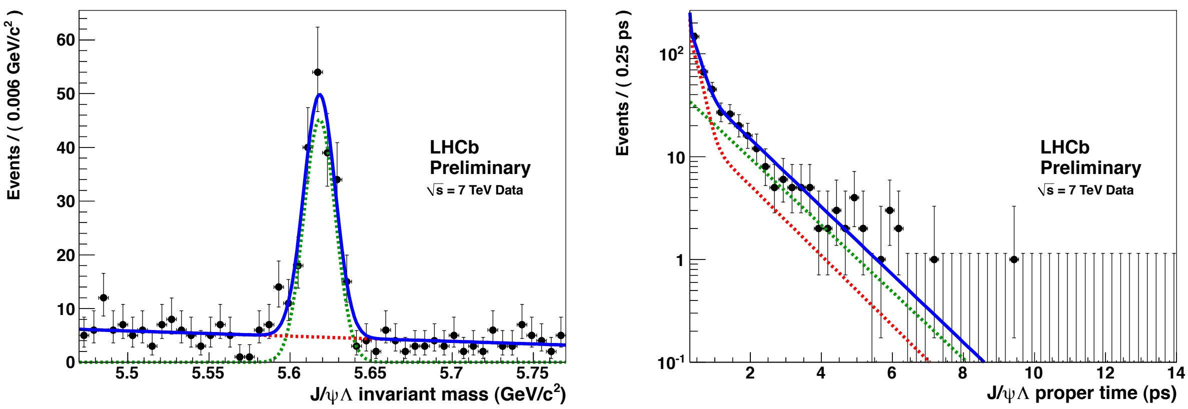

Fig. 5. – Λ_b mass (left) and proper time (right) projections of the two-dimensional fit to the $\Lambda_b \to J/\psi\Lambda$ candidates with $t > 0.3$ ps. The total fit is represented by the blue solid line, the signal contribution by the green dashed line and the background contribution by the red dashed line. The mass range for the fit is $m \in [5.47, 5.77]$ GeV/c^2.

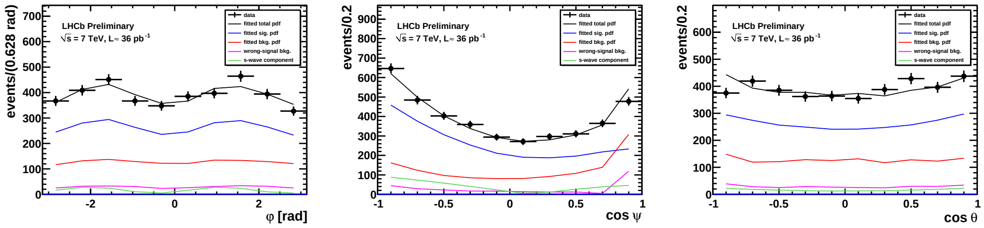

Fig. 6. – Fitted PDF with S-wave included projected on the transversity angles compared to the data distributions for the selected $B^0 \to J/\psi K^{*0}$ candidates. Shown are the total PDF, the PDFs for signal (blue), S-wave (green), total background (red) and wrong-signal(purple).

events is presented in [8]. For the $B^0 \to J/\psi K^{*0}$ channel, we find:

$$
\begin{aligned}
|A_{\parallel}(0)|^2 &= 0.252 \pm 0.020 \pm 0.016\,, \\
|A_{\perp}(0)|^2 &= 0.178 \pm 0.022 \pm 0.017\,, \\
\delta_{\parallel} &= -2.87 \pm 0.11 \pm 0.10\,, \\
\delta_{\perp} &= 3.02 \pm 0.10 \pm 0.07\,.
\end{aligned}
$$

The first error is the statistical uncertainty from the 5-dimensional fit (mass, proper time and 3 angles). The second error is the systematic uncertainty, details of which are given in [8]. The 1-dimensional projections of the 5-dimensional fit function are compared to the measured data in Figure 6.

For the $B_s^0 \to J/\psi\phi$ channel, assuming $\phi_s^{J/\psi\phi}$=0, we measure:

$$
\begin{aligned}
\Gamma_s &= 0.680 \pm 0.034 \pm 0.027\,\mathrm{ps}^{-1}\,, \\
\Delta\Gamma_s &= 0.084 \pm 0.112 \pm 0.021\,\mathrm{ps}^{-1}\,, \\
|A_{\perp}(0)|^2 &= 0.279 \pm 0.057 \pm 0.014\,, \\
|A_0(0)|^2 &= 0.532 \pm 0.040 \pm 0.028\,, \\
\cos\delta_{\parallel} &= -1.24 \pm 0.27 \pm 0.09\,,
\end{aligned}
$$

where the first error is the statistical error from the fit and the second error is the systematic uncertainty detailed in Table **3**. The 1-dimensional projections of the 5-dimensional fit function are compared to the measured data in Figure 7.

4. – Flavour tagging and measurement of Δm_s using $B_s^0 \to D_s^-(3)\pi^+$

The tagging of the initial B-flavour in LHCb is a key step towards the measurement of $\phi_s^{J/\psi\phi}$. It is described in [9]. The algorithm exploits charged tracks originating from the b-hadron opposite to the signal B-meson (kaon, muon, electron and vertex charge) and also tracks close to the signal B-meson (same-side tagging). The algorithm is optimized using $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^+ \to J/\psi K^+$ events and calibrated using $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$ events. In [11], the calibration is cross-checked using $B^0 \to K^+\pi^-$ events and the B^0–$\overline{B}^0$

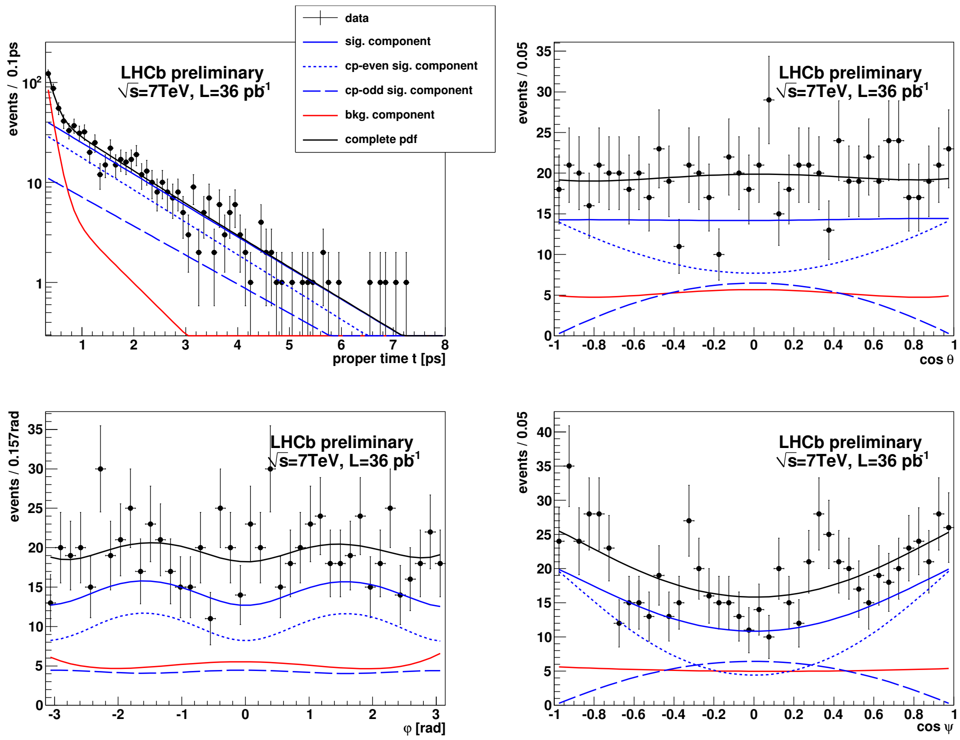

Fig. 7. – Fitted PDF projected on the lifetime and the transversity angles compared to the data distributions for the selected $B_s^0 \to J/\psi\phi$ candidates. Shown are the total PDF, the PDFs for signal, the PDFs for the CP-even and CP-odd signal components and the total background PDF.

TABLE III. – *Systematic uncertainties assigned to the extracted physics parameters of the decay* $B_s^0 \to J/\psi\phi$.

Systematic effect	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp(0)\rvert^2$	$\lvert A_\parallel(0)\rvert^2$	$\cos\delta_\parallel$
Proper time resolution	0.0001	-	-	-	-
Angular acceptance	-	-	-	0.0007	-
Acceptance parametrisation	0.0002	0.001	0.0017	0.0013	-
Proper time acceptance	0.0272	0.001	0.0003	0.0002	-
S-wave treatment	0.003	0.003	0.013	0.028	0.09
Background treatment	0.0002	0.02	0.0016	0.0012	-
Mass model	0.0004	0.004	0.0032	0.0006	-
Total (quadratic sum)	0.0274	0.0206	0.0136	0.0281	0.09

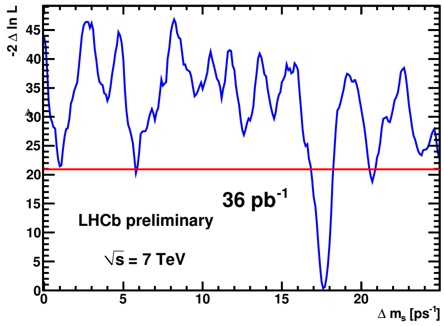

Fig. 8. – Likelihood scan for Δm_s in the range from [0.0,25.0] ps^{-1}. The line at 20.94 indicates the likelihood value evaluated in the limit of infinite mixing frequency.

mixing frequency is measured to be:

$$\Delta m_d = 0.499 \pm 0.032\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \mathrm{ps}^{-1}\,.$$

An additionnal crucial test is performed in [10], by measuring the $\mathrm{B_s^0}$–$\mathrm{\overline{B}_s^0}$ mixing frequency using $\mathrm{B_s^0} \to \mathrm{D_s^-}(3)\pi^+$ events. In that case, only opposite side tagging is used. The effective tagging efficiency is $(3.8 \pm 2.1)\%$. Using the events sample given in Table IV, we measure:

$$\Delta m_s = 17.63 \pm 0.11\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \mathrm{ps}^{-1}\,,$$

which is compatible and competitive with the world best measurement [12]. The details of the systematics uncertainties are given in [10]. The likelihood profile as a function of the mixing frequency Δm_s is shown in Figure 8. The statistical significance of the signal is evaluated by comparing the likelihood value at the measured Δm_s value of $17.63\,\mathrm{ps}^{-1}$ with the likelihood value obtained on the same sample in the limit of infinitely high

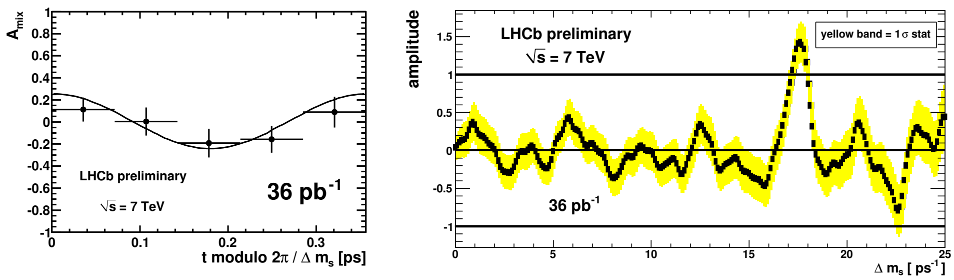

Fig. 9. – Left: Mixing asymmetry for signal B_s^0 candidates as function of proper time modulo $\frac{2\pi}{\Delta m_s}$. The fitted signal asymmetry is superimposed. Right: Fitted amplitude as a function of Δm_s. See the text for further explanation.

TABLE IV. – *Number of B_s^0 signal candidates used in the Δm_smeasurement.*

Decay mode	# signal candidates
$B_s \to D_s^-(\phi\pi^-)\pi^+$	515 ± 25
$B_s \to D_s^-(K^*K)\pi^+$	338 ± 27
$B_s \to D_s^-(K^+K^-\pi^-)\pi^+$	283 ± 27
$B_s \to D_s^-(K^+K^-\pi^-)3\pi$	245 ± 46

mixing frequency. We find a significance of 4.6 σ for the observed mixing signal. The statistical size of the sample is not large enough to illustrate the oscillation pattern of the time dependent asymmetry. However we can more clearly observe the oscillation if we plot the asymmetry as a function of the proper time modulo $\frac{2\pi}{\Delta m_s}$ (Figure 9). Additionally we provide an amplitude scan in Figure 9, with all details given in [10].

5. – First observation of $B_s^0 \to J/\psi f_0$

When LHCb will have accumulated more data, the measurement of ϕ_s will not only be done in $B_s^0 \to J/\psi\phi$, but also in other similar channels. One of them, $B_s^0 \to J/\psi f_0$, has been observed for the first time in LHCb [13]. The $J/\psi\pi^+\pi^-$ and $\pi^+\pi^-$ invariant masses are shown in Figure 10. We measure:

$$R_{f_0/\phi} \equiv \frac{\Gamma(B_s^0 \to J/\psi f_0,\ f_0 \to \pi^+\pi^-)}{\Gamma\ (B_s^0 \to J/\psi\phi,\ \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

Despite a smaller branching ratio, with respect to $B_s^0 \to J/\psi\phi$, the fact that $J/\psi f_0$ is a pure CP-odd final state makes the measurement of ϕ_s simpler, since no angular analysis is required.

6. – Epilogue

While completing these proceedings LHCb has released its first preliminary results on $\phi_s^{J/\psi\phi}$ [14]. The dataset was too small to calibrate the same-side tagger; the opposite side tagger has a measured effective efficiency of $2.2 \pm 0.4\%$. Although it was not possible to give a point estimate contours in ϕ_s–$\Delta\Gamma_s$ space could be calculated.

7. – Conclusions

The $B_s^0 \to J/\psi\phi$ channel will allow LHCb to probe possible New Physics effects in the B_s^0–$\overline{B}_s^0$ box diagram. We have presented, for the first time at this conference, the preliminary results needed for a $\phi_s^{J/\psi\phi}$ measurement, obtained with the data taken in 2010. The data sample used corresponds to an integrated luminosity of $35\,\mathrm{pb}^{-1}$. We have measured the lifetime of $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$, the polarization amplitudes in $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$, the width and mass differences of the B_s^0 mass eigenstates, $\Delta\Gamma_s$ and Δm_s. In particular, we measure: $\Delta m_s = 17.73 \pm 0.11$ (stat.) ± 0.04 (syst.) ps^{-1}. With the data currently being taken in 2011, we expect to obtain this year the world best measurement of $\phi_s^{J/\psi\phi}$.

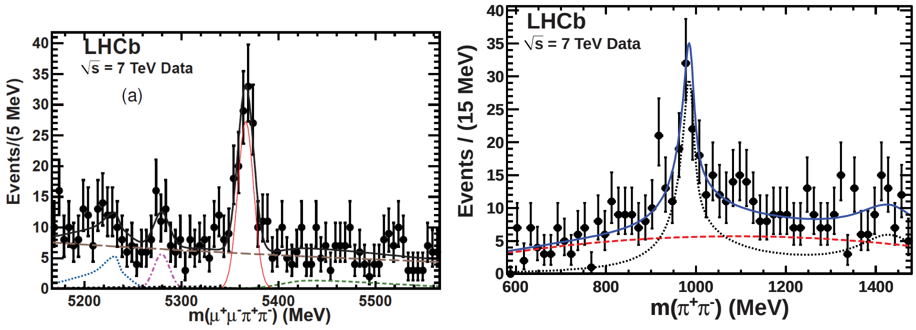

Fig. 10. – Left: The invariant mass of $J/\psi\pi^+\pi^-$ combinations when the $\pi^+\pi^-$ pair is required to be within ± 90 MeV of the $f_0(980)$ mass. The data have been fit with a signal Gaussian and several background functions. The thin (red) solid curve shows the signal, the long-dashed (brown) curve the combinatorial background, the dashed (green) curve the $B^+ \to J/\psi K^+(\pi^+)$ background, the dotted (blue) curve the $B^0 \to J/\psi K^{*0}$ background, the dash-dot curve (purple) the $B^0 \to J/\psi\pi^+\pi^-$ background, the barely visible dotted curve (black) the sum of $B_s^0 \to J/\psi\eta'$ and $J/\psi\phi$ backgrounds, and the thick-solid (black) curve the total. Right: The invariant mass of $\pi^+\pi^-$ combinations when the $J/\psi\pi^+\pi^-$ combination is required to be within ± 30 MeV of the B_s^0 mass. The dashed curve is the like-sign background that is taken from the data both in shape and absolute normalization. The dotted curve is the result of the fit described in [13].

* * *

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