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B_s oscillations at LHC*b*

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Summary. — The main results obtained by LHC*b* in the study on B_s^0 oscillations and CP violation parameters using the 2010 data sample are presented.

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1. – Introduction

New phenomena beyond the Standard Model (SM) may alter the CP violation in B decays. An example that has received much experimental and theoretical attention is the $B_s^0 \to J/\psi\phi$ decay. The oscillation frequency of B_s^0-$\bar{B}_s^0$ mixing is characterized by the mass difference Δm_s of the"heavy" (B_H) and "light" (B_L) mass eigenstates, and by a CP-violating mixing phase ϕ_s which describes "mixing-induced" CP violation. In the SM this phase is small and precisely predicted: $\phi_s = -0.0363 \pm 0.0017\,\text{rad}$ [1]. New Physics models can induce large ϕ_s whilst satisfying all existing constraints, including the measurement of Δm_s at the Tevatron: $17.77 \pm 0.10 \pm 0.07\,\text{ps}^{-1}$ [2]. The third physical quantity involved in B_s^0-$\bar{B}_s^0$ oscillations is the width difference $\Delta\Gamma_s$ which at the moment is not measured precisely. LHC*b* aims to improve the existing measurements using the large number of B-mesons produced at LHC and the excellent performance of the detector in triggering and reconstructing B-meson decays. In the following the main steps toward the measurement of the B_s^0 mixing properties are presented.

2. – Lifetimes measurement

The measurement of ϕ_s requires a good understanding of the detector effects, such as the proper time acceptance and resolution, and of the tagging performance and the background contamination. For this reason it was decided to trigger and select in a similar way several $b \to J/\psi X$ decay modes and to use them as control channels to calibrate the detector and validate the analysis procedure of $B_s^0 \to J/\psi\phi$ channel. The b-hadron lifetime are extracted from a fit to the proper time distribution of the reconstructed events in different exclusive decays [3]. In the case of B_s decay a single exponential was used (assuming $\Delta\Gamma_s = 0$). In order to limit the corrections due to the detector

Table I. – *Signal event yields and lifetime of different b-hadrons measured in different* $b \to J/\psi X$ *channels.*

Channel	Signal yield	LHC*b* τ [ps]	PDG τ [ps]
$B^+ \to J/\psi K^+$	6741 ± 85	$1.689 \pm 0.022 \pm 0.047$	1.638 ± 0.011
$B^0 \to J/\psi K^{*0}$	2668 ± 58	$1.512 \pm 0.032 \pm 0.042$	1.525 ± 0.009
$B_s^0 \to J/\psi \phi$	570 ± 24	$1.447 \pm 0.064 \pm 0.056$	$1.472^{+0.024}_{-0.026}$
$B_d^0 \to J/\psi K_S^0$	838 ± 31	$1.558 \pm 0.056 \pm 0.022$	1.525 ± 0.009
$\Lambda_b \to J/\psi \Lambda$	187 ± 16	$1.353 \pm 0.108 \pm 0.035$	$1.391^{+0.038}_{-0.037}$

acceptance, both the trigger and the offline selections are chosen to be lifetime unbiased by avoiding any selection based on variables correlated to the proper time. Nevertheless, in order to suppress the large background due to combinations of tracks originating from the primary vertex, only events with reconstructed proper time greater than 0.3 ps are considered. In table I the measured lifetimes for the different *b*-hadrons in the different channels and the corresponding signal yields are summarized. The results are compatible with the PDG values [4]. The systematic errors are dominated by the uncertainties on the time acceptance that is partially statistical in origin.

3. – Measurement of the polarization amplitudes in $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ channels

Both $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ are decays of a pseudo-scalar particle to two vector mesons, which can proceed through three different amplitudes corresponding to different relative angular momentum of the J/ψ and the K^{*0} (or ϕ): $\ell = 0, 1, 2$. A fit to the angular distribution is needed to extract the polarization amplitudes and strong phases. In the case of the $B_s^0 \to J/\psi \phi$ channel the measurement of ϕ_s requires to disentangle CP odd ($\ell = 1$) from CP even ($\ell = 0, 2$) amplitudes. The fit is performed in the transversity frame accounting for the angular acceptance, which is determined from Monte Carlo simulations [5]. In the case of $B^0 \to J/\psi K^{*0}$ channel the fit also includes an S-wave contribution to the $K\pi$ amplitude. Table II summarizes the results obtained, which are in good agreement with the previous results from BaBar [6], even if less precise. The main systematic uncertainties are due to the parametrization of the S-wave contribution, to the acceptance function and to the parametrization of the background contribution.

The results of the angular analysis of the $B^0 \to J/\psi K^{*0}$ channels support the correctness of the analysis procedure, that is applied to the untagged analysis of

Table II. – *Results of the fit to the* $B^0 \to J/\psi K^{*0}$ *events and comparison with BaBar results.*

Results	$\lvert A_\parallel \rvert^2$	$\lvert A_\perp \rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]
LHC*b*	$0.252 \pm 0.020 \pm 0.016$	$0.178 \pm 0.022 \pm 0.017$	$-2.87 \pm 0.11 \pm 0.10$	$3.02 \pm 0.10 \pm 0.07$
BaBar [6]	$0.211 \pm 0.010 \pm 0.006$	$0.233 \pm 0.010 \pm 0.005$	$-2.93 \pm 0.08 \pm 0.04$	$2.91 \pm 0.05 \pm 0.03$

TABLE III. – *Results of the untagged fit to the selected* $B_s^0 \to J/\psi\phi$ *candidates with the assumption* $\phi_s = 0$.

Parameter	Value	Parameter	Value
Γ_s [ps^{-1}]	$0.679 \pm 0.036 \pm 0.027$	$\lvert A_0\rvert^2$	$0.528 \pm 0.040 \pm 0.028$
$\Delta\Gamma_s$ [ps^{-1}]	$0.077 \pm 0.119 \pm 0.021$	$\lvert A_\perp\rvert^2$	$0.263 \pm 0.056 \pm 0.014$
		$\delta_\parallel$ [rad]	$3.14 \pm 0.52 \pm 0.13$

$B_s^0 \to J/\psi\phi$ events. In this case, in addition to the polarization magnitudes and strong phases, the fit depends also on the weak phase ϕ_s, the average B_s^0 decay width Γ_s and the decay width difference $\Delta\Gamma_s$. Nevertheless, since no tagging information is used in this analysis, the data has very little power to constrain ϕ_s. The fit results when fixing $\phi_s = 0$ are given in table III. They are compatible to previous results from CDF [7].

4. – Flavour tagging and measurement of Δm_s and Δm_d

The information on the initial flavour of a B-particle (*flavour tagging*) is crucial for any measurement of CP violation effects in neutral B decays. In particular in the case of the $B_s^0 \to J/\psi\phi$ channel the sensitivity to ϕ_s of the tagged analysis is largely higher than the untagged one. The flavour tagging can be inferred from the charge of the decay products of the b-hadron opposite to the signal B-meson (opposite side tagging: muon, electron, kaon and vertex charge) or from the charge of the highly correlated particles reconstructed close to the signal B-meson (same side tagging: pion, kaon). The performance of the flavour tagging was optimized using data of several control channels: $B^0 \to D^{*-}\mu^+\nu_\mu$, $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ [8]. Moreover the predicted probability of mistag, computed event by event, was calibrated using the $B^+ \to J/\psi K^+$ channel and cross-checked in the $B^0 \to J/\psi K^{*0}$ decay in order to be used in the tagged analysis of the $B_s^0 \to J/\psi\phi$ channel.

In order to confirm the reliability of the tagging we measured the B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ mixing frequencies using the $B_d^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+(\pi^+\pi^-)$ decays, respectively. The B_d^0 mixing frequency is measured to be: $\Delta m_d = 0.499 \pm 0.032 \pm 0.003\,\text{ps}^{-1}$ [9], based on ~ 6000 signal events and a measured tagging power(1) of $(4.3 \pm 1.0)\%$, given by the combination of both same side and opposite side results. The measurement of the B_s^0 mixing frequency is based on ~1 350 signal events obtained by combining different decay modes ($D_s^- \to \phi\pi^-$, $D_s^- \to K^*K$ and $D_s^- \to K^+K^-\pi^-$) [10]. Using only the opposite side tagging information(2) a 4.6σ significant mixing signal is observed corresponding to a mixing frequency of $\Delta m_s = 17.63 \pm 0.11 \pm 0.04\,\text{ps}^{-1}$, which is compatible and competitive with the CDF measurement [2] ($17.77 \pm 0.10 \pm 0.07\,\text{ps}^{-1}$). The likelihood scan and the oscillation plot, obtained folding the data modulo $2\pi/\Delta m_s$, are shown in fig. 1. The achievement of such a good precision is mainly due to the excellent proper time resolution, which was measured on data to be $\langle\sigma_t\rangle$ = 36–44 fs, depending on the

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(1) The tagging power represents the reducing factor of the statistical sample that is introduced in asymmetry measurements and is defined by: $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1-2\omega)^2$, where ε_{tag} is the tagging efficiency and ω is the mistag fraction, *i.e.* the fraction of wrongly tagged events.

(2) Currently the same side kaon tagging is still under development.

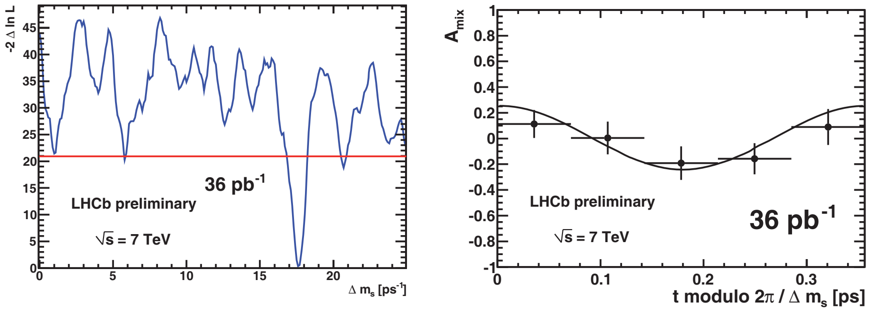

Fig. 1. – Left: likelihood scan for Δm_s values. The horizontal line indicates the likelihood value evaluated in the limit of infinite mixing frequency. Right: Mixing asymmetry for signal B_s^0 candidates as function of proper time modulo $2\pi/\Delta m_s$.

decay channel, and to the limited systematic errors, dominated by the uncertainties on the mistag calibration and to the not yet optimal detector alignment and magnetic field calibration. Therefore there are good prospects for LHC*b* to improve the precision on Δm_s in the near future.

5. – Tagged analysis of $B_s^0 \to J/\psi\phi$ channel

Given the results discussed in the previous sections we can be confident that all the intermediate steps of the complex tagged, angular and time dependent analysis of $B_s^0 \to J/\psi\phi$ channels are under control. For this study [11] the number of signal events selected requiring $t > 0.3$ ps are 737 ± 28, not enough to give an unique solution for the ϕ_s estimate. For this reason the results are presented in fig. 2 as two-dimensional confidence regions in the $(\phi_s,\, \Delta\Gamma_s)$ plane. The results show a 1.2 σ deviation from the Standard Model prediction. Several sources of systematic errors were considered and found to be negligible with respect to the dominant statistical uncertainty.

The tagged analysis benefits from an excellent proper time resolution of ~ 50 fs. So far the analysis only uses the opposite-side event by event information, which has an

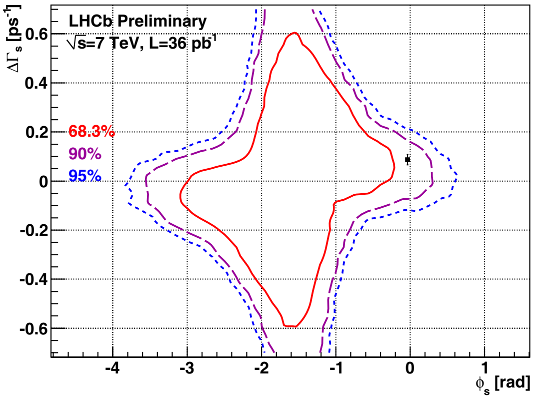

Fig. 2. – Confidence contours in the $(\phi_s,\, \Delta\Gamma_s)$ plane from tagged fit to the $B_s^0 \to J/\psi\phi$ signal candidates.

overall tagging power of $(2.2 \pm 0.5)\%$. The inclusion of the same-side kaon tagger is expected to almost double the tagging power. As a consequence there are very good prospects for LHC*b* to improve the precision on ϕ_s at the level of the CDF results with $200\,\mathrm{pb}^{-1}$ of data and to provide the world's best measurement of ϕ_s with about $1\,\mathrm{fb}^{-1}$ of data, collected in 2011.

Good prospects to improve the measurement of ϕ_s in a longer term come also from the analysis of additional decay channels. In particular LHC*b* made the first observation of a new CP odd decay $B_s^0 \to J/\psi f_0(980)$ with $f_0(980) \to \pi^+\pi^-$ [12].

The ratio to the $J/\psi\phi$ production is measured to be $R_{f_0/\phi} = \frac{\Gamma(B_s \to J/\psi f_0, f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\phi, \phi \to K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$, consistent with the theoretical expectation [13].

6. – Conclusions

The main steps of the analysis for the measurement of B_s^0 mixing properties at LHCb have been presented. Using the $\sim 36\,\mathrm{pb}^{-1}$ of data taken in 2010 it was possible to measure the lifetime of several $b-$hadrons in different $J/\psi X$ final states. The measurements of the polarization amplitudes and strong phases in the $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ channels are compatible within the errors with the previous determinations. Using the flavour tagging information, which was optimized and calibrated using data of several control channels, it was possible to extract the values of the B_d^0 and B_s^0 mixing frequencies, which are in agreement with the previous results. In particular the measurement of $\Delta m_s = 17.63 \pm 0.11 \pm 0.04\,\mathrm{ps}^{-1}$ is competitive with the world average. Finally the tagged, angular and time dependent analysis of the $B_s^0 \to J/\psi\phi$ channel was performed. Due to the small number of events it was only possible to determine a two dimensional confidence contours in the $(\Delta\Gamma_s,\, \phi_s)$ plane and calculate a 1.2σ deviation from the predicted values of the Standard Model. With $1\,\mathrm{fb}^{-1}$ of data taken in 2011 there are very good prospects for LHC*b* to provide the best world measurement of ϕ_s. The analysis of additional decay channels, like the recently observed $B_s^0 \to J/\psi f_0(980)$ decay, will also contribute to improve the results in a longer term.

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