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Recent results on CP violation B^0_s meson decays

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Summary. — Measurements of CP violation in B^0_s mesons decays provide an excellent method to test the prediction of the Standard Model and search for effect of new physics beyond it. With the first $1\,\mathrm{fb}^{-1}$ of data collected in *pp* collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ the LHCb experiment performed the world best precision measurements of the CP-violating phase ϕ_s and on the decay width difference $\Delta\Gamma_s$. The analysis of the $\mathrm{B}^0_\mathrm{s} \to \phi\phi$ decay and the measurement of the B^0_s lifetime in decays to CP eigenstates are also presented.

PACS 12.15.Hh – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.
PACS 13.25.Hw – Decays of bottom mesons.

1. – CP violation in $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ and $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\pi^+\pi^-$ decays

For a final state f equal to its CP conjugate ($f = \bar{f}$), a CP-violating phase arises from the interference between B^0_s decay to f either directly or via B^0_s-$\overline{\mathrm{B}}^0_\mathrm{s}$ oscillation, producing a difference in the proper-time distributions of B^0_s mesons and $\overline{\mathrm{B}}^0_\mathrm{s}$ mesons. The $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi(\mu\mu)\phi(\mathrm{KK})$ decay is considered the golden mode for measuring this type of CP violation. Within the Standard Model (SM) this decay is dominated by $\overline{\mathrm{b}} \to \overline{\mathrm{c}}\mathrm{c}\overline{\mathrm{s}}$ quark level transitions, neglecting QCD penguin contribution the phase is $\phi_\mathrm{s}^\mathrm{SM} = -2\beta_\mathrm{s}$, where $\beta_\mathrm{s} = \arg(-V_\mathrm{ts}V^*_\mathrm{tb}/V_\mathrm{cs}V^*_\mathrm{cb})$. Global fits to experimental data give a small and precise value $2\beta_\mathrm{s} = (-0.036 \pm 0.002)$ rad [1]. New particles could contribute to the mixing box diagram modifying the SM prediction, adding a new phase [2].

The measurement of ϕ_s was first performed at Tevatron in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ by the CDF and D0 experiments, they have recently updated their results on $9.6\,\mathrm{fb}^{-1}$ [3] and $8\,\mathrm{fb}^{-1}$ [4] of data, respectively.

The determination of ϕ_s is improved by the results of LHCb using about $1\,\mathrm{fb}^{-1}$ of data collected in 2011 at LHC in *pp* collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. A total of about 21200 $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ signal events are selected, with a decay time $t > 0.3\,\mathrm{ps}$ [5]. The time resolution is measured on data with a fit to the J/ψ component of the prompt background. The effective decay time resolution is approximately 45 fs.

TABLE I. – *Results for the physics parameters with the statistical and systematic uncertainties, respectively. LHCb preliminary results from* $1\,\mathrm{fb}^{-1}$ [5].

Parameter	Result
Γ_{s} [ps^{-1}]	$0.6580 \pm 0.0054 \pm 0.0066$
$\Delta\Gamma_{\mathrm{s}}$ [ps^{-1}]	$0.116 \pm 0.018 \pm 0.006$
$\lvert A_\perp\rvert^2$	$0.246 \pm 0.010 \pm 0.013$
$\lvert A_0\rvert^2$	$0.523 \pm 0.007 \pm 0.024$
F_S	$0.022 \pm 0.012 \pm 0.007$
ϕ_{s} [rad]	$-0.001 \pm 0.101 \pm 0.027$

The $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decay proceeds via a vector-vector intermediate state with contributions from both CP-even and CP-odd amplitudes. In order to achieve good sensitivity to the two components the distribution of the final state decay angles in the transversity basis is analysed. The decay can be described by three time-dependent amplitudes, at $t = 0$: $A_0(0)$ and $A_\parallel(0)$ are CP-even while $A_\perp(0)$ is CP-odd. The differential decay rate depends on several physics parameters: the $\mathrm{B_s^0}$ decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$, the decay width difference between the light and heavy $\mathrm{B_s^0}$ mass eigenstates $\Delta\Gamma_s = (\Gamma_L - \Gamma_H)$, the mixing frequency $\Delta m_s = m_{B_H} - m_{B_L}$, the CP-violating phase ϕ_{s}, the relative phases and magnitudes of the three angular transversity amplitudes. A contribution from an S-wave component is also considered, with fraction F_S.

The flavour of the B meson at production is determined combining several "opposite side" algorithms, namely high p_T muons, electrons and kaons and the charge of an inclusively reconstructed secondary vertex. The algorithms have been optimized on data for the maximum tagging power ϵD^2, where ϵ is the tagging efficiency, $D = 1 - 2\omega$ is the dilution and ω the mistag. The tagging power is enhanced by using in the fits a per-event mistag probability, which is calibrated on data, using $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$ decays, and validated on $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}$ decays. The tagging power for $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ events is found to be $\epsilon D^2 = (2.29 \pm 0.07 \pm 0.26)\%$

The results of the likelihood fit to the mass, decay time and angular distributions for the main physics parameters are summarized in table I. In addition, the strong phases are determined, they are all consistent with zero or π radians. This analysis provides the most precise measurement of ϕ_{s} so far and constitutes the first observation with more than 5 sigmas of a non-zero lifetime difference. The values of ϕ_{s} and Γ_{s} are in good agreement with the SM prediction. In fig. 1 the projection of the fitted PDF on the decay time and the transversity angle distributions are shown.

It should be noted that the $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decay rates are unchanged under the transformation $(\phi_{\mathrm{s}}, \Delta\Gamma_{\mathrm{s}}, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi - \phi_{\mathrm{s}}, -\Delta\Gamma_{\mathrm{s}}, -\delta_\parallel, \pi - \delta_\perp)$. The values in table I correspond to the solution with $\Delta\Gamma_{\mathrm{s}} > 0$.

This ambiguity is now solved by another LHCb analysis performed on the same data set, but using an extended range in the $\mathrm{K^+K^-}$ invariant mass around the $\phi(1020)$ resonance [6]. As a consequence of the interference between the P- and S-wave components of the final state, a decreasing trend of the strong phase difference is expected, as a function of m_{KK}. The fit is repeated in four bins of m_{KK} and the decreasing trend is observed for the fit solution corresponding to the positive $\Delta\Gamma_{\mathrm{s}}$ value, in agreement with the SM prediction.

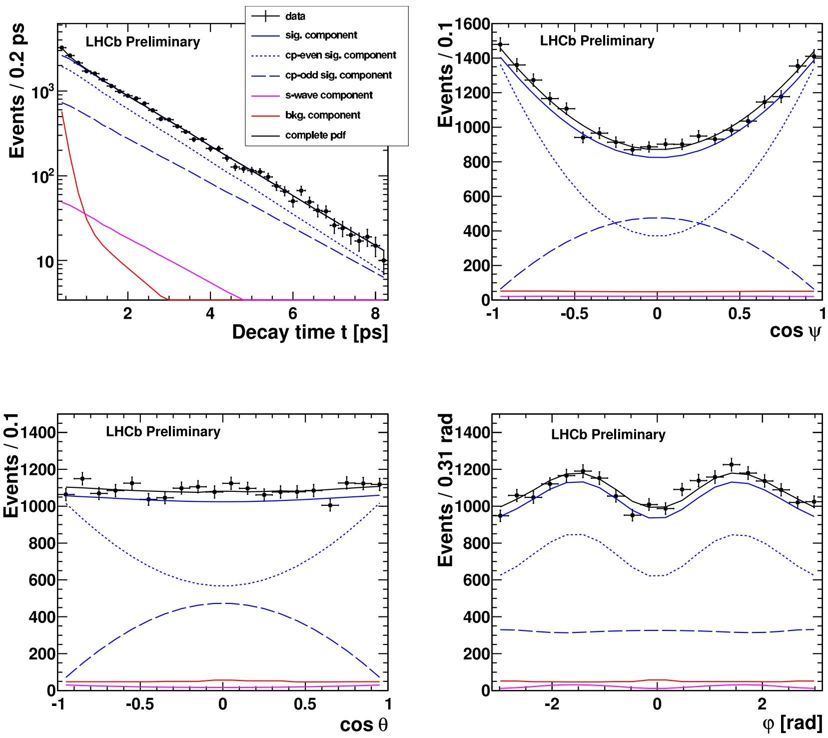

Fig. 1. – Data points overlaid with fit projections for the $B_s^0 \to J/\psi\phi$ decay time and the transversity angle distributions for candidates with an invariant mass within $\pm 20\,\mathrm{MeV}/c^2$ around the nominal B_s^0 mass. The signal component is shown as a solid blue line, the dashed and dotted blue lines represent the CP-even and CP-odd signal components, respectively. The S-wave component and the background component are shown by the solid pink and red line, respectively. LHCb preliminary [5].

An independent measurement of ϕ_s is performed by LHCb in the $B_s^0 \to J/\psi\pi^+\pi^-$ decay channel. A first LHCb measurement of ϕ_s from $B_s^0 \to J/\psi f_0(980)$ events on about $0.4\,\mathrm{fb}^{-1}$ of data was recently published [7]. A new analysis [8] is performed on the full $1\,\mathrm{fb}^{-1}$ data sample collected in 2011, using the final state $J/\psi\pi^+\pi^-$ over a large range of $\pi^+\pi^-$ masses, $(775\text{–}1550)\,\mathrm{MeV}/c^2$. This region has been shown to be 97.7% CP-odd eigenstate, at 95% CL [8]. As a consequence a time-dependent tagged analysis is performed, but no angular study is required. In fig. 2 the invariant-mass distribution of the selected $J/\psi\pi^+\pi^-$ candidates and the mass distribution of the $\pi^+\pi^-$ combinations for events in the B_s^0 signal region are shown. About 7400 B_s^0 signal events are selected. In the likelihood fit the values of Γ_s and $\Delta\Gamma_s$ have been constrained to the result of the previous $B_s^0 \to J/\psi\phi$ analysis. The measured value of the mixing phase is $\phi_s = -0.02 \pm 0.17 \pm 0.004\,\mathrm{rad}$. Combining this result with the preliminary $B_s^0 \to J/\psi\phi$ measurement gives $\phi_s = -0.002 \pm 0.083 \pm 0.027\,\mathrm{rad}$.

2. – CP violation in $B_s^0 \to \phi\phi$ decays

Another interesting channel to search for new physics effects is $B_s^0 \to \phi\phi$ for which the CP-violating observables are predicted with low theoretical uncertainty in the SM.

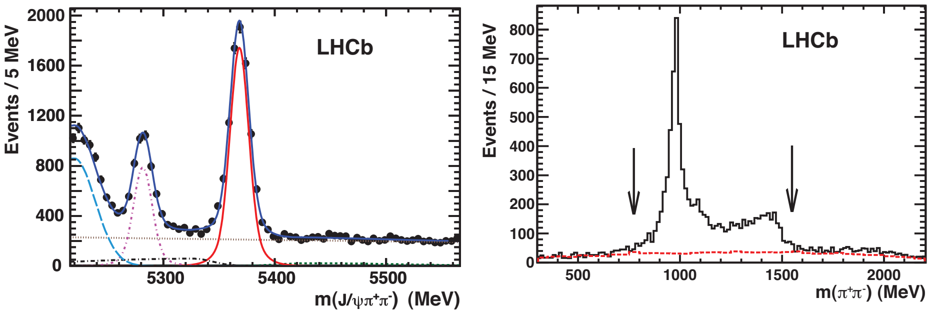

Fig. 2. – Left: mass distribution of the selected $J/\psi\pi^+\pi^-$ combinations with $775 < m_{\pi^+\pi^-} < 1550\,\mathrm{MeV}/c^2$. The blue solid curve shows the result of a fit with a double Gaussian for the signal (red solid curve) and several background components. Right: mass distribution of selected $\pi^+\pi^-$ combinations shown as the (solid black) histogram for events in the B_s^0 signal region. The (dashed red) line shows the background [7].

In $1\,\mathrm{fb}^{-1}$ of data about 800 signal events have been selected, with $\phi \to \mathrm{K}^+\mathrm{K}^-$. The data sample is not yet sufficient to perform a full time-dependent angular analysis of flavour tagged events, as required by a study of the CP-violating phase. However, evidence of possible processes beyond the SM can be searched for in the measurement of triple products asymmetry, that are T-odd quantities. There are two observable triple products denoted $U = \sin(2\Phi)/2$ and $V = \pm\sin(\Phi)$, where the positive sign is taken if the T-even quantity $\cos\theta_1\cos\theta_2 \geq 0$ and the negative sign otherwise. These variables correspond to the T-odd triple products $\sin\Phi = (\hat{n}_1 \times \hat{n}_2)\cdot\hat{p}_1$ and $\sin(2\Phi)/2 = (\hat{n}_1\cdot\hat{n}_2)(\hat{n}_1 \times \hat{n}_2)\cdot\hat{p}_1$ where $\hat{n}_i (i = 1, 2)$ is a unit vector perpendicular to the ϕ_i meson decay plane and $\hat{p}_1$ is a unit vector in the direction of the ϕ_1 meson momentum in the B_s^0 rest frame.

The asymmetry A_U is defined as $A_U = \frac{N_+ - N_-}{N_+ + N_-}$, where $N_+(N_-)$ is the number of events with $U > 0$ $(U < 0)$. Similarly $A_V = \frac{M_+ - M_-}{M_+ + M_-}$, where $M_+(M_-)$ is the number of events with $V > 0$ $(V < 0)$. The measured values are

$$A_U = -0.055 \pm 0.036(\mathrm{stat}) \pm 0.018(\mathrm{syst}), \qquad A_V = 0.010 \pm 0.036(\mathrm{stat}) \pm 0.018(\mathrm{syst}).$$

Both values are in good agreement with those reported by the CDF Collaboration [10] and consistent with the hypothesis of CP conservation.

3. – Lifetime measurements in CP eigenstates

Another route to extract information about $\Delta\Gamma_\mathrm{s}$ and ϕ_s is from a precise determination of the B_s^0 lifetime in decays to final states which are pure CP-even or CP-odd states. If the initial flavour of the B_s^0 meson is unknown, the decay time distribution is proportional to

$$\Gamma(t) \propto (1 - \mathcal{A}_{\Delta\Gamma_s})e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma_s})e^{-\Gamma_H t}. \tag{1}$$

The parameter $\mathcal{A}_{\Delta\Gamma_s}$ is defined as $\mathcal{A}_{\Delta\Gamma_s} = -2\mathrm{Re}(\lambda)/(1 + |\lambda|^2)$, where $\lambda = (q/p)(\bar{A}/A)$, the complex coefficients p and q define the mass eigenstates of the B_s^0 system in terms of the flavour eigenstates and $A(\bar{A})$ is the amplitude for a B_s^0 $(\overline{\mathrm{B}}_s^0)$ meson to decay to

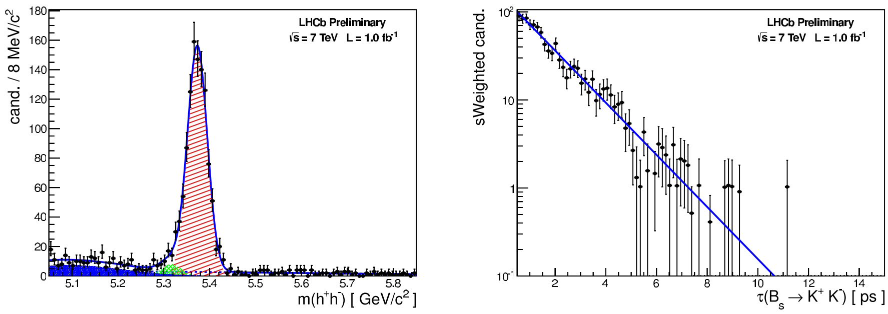

Fig. 3. – Left: invariant-mass distribution for $\mathrm{B^0_{(s)}} \to \mathrm{h^+h^-}$ events. The contribution from $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ is shown in striped (red). The background from $\mathrm{B^0} \to \mathrm{K^+}\pi^-$ and from partially reconstructed B mesons are shown in hatched (green) and shaded (blue), respectively. Right: Corresponding decay time distribution of $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ signal candidates extracted from an unbinned log-likelihood fit to the data.

the same final state. In the absence of CP violation $\mathcal{A}_{\Delta\Gamma_s} = 1(-1)$ for CP-odd (CP-even) eigenstates. Examples are $\mathrm{B_s^0} \to \mathrm{J}/\psi \mathrm{f_0}$ and $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ decay modes which are sensitive to the Γ_H and Γ_L components, respectively. If the decay time distribution given by eq. (1) is fitted with a single exponential function the effective lifetime is given by $\tau_{\mathrm{KK}} = \tau_{\mathrm{B_s}}(1 + \mathcal{A}_{\Delta\Gamma_s} y_s + \mathcal{O}(y_s^2))$, where $\tau_{\mathrm{B_s}} = 1/\Gamma_s$ and $y_s = \Delta\Gamma_s/2\Gamma_s$.

A measurement of $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ lifetime was performed at LHCb on 2010 data [11]. In that analysis $\mathrm{B_s^0}$ meson decay products that are significantly displaced from the $\mathrm{B_s^0}$ meson production vertex were selected. As a consequence, $\mathrm{B_s^0}$ mesons with low decay times are suppressed, introducing a bias to the decay time spectrum which must be corrected. A new analysis has been performed on $1\,\mathrm{fb}^{-1}$ of data with a technique that explicitly avoids a lifetime bias by using a neural network-based trigger and event selection [12].

Figure 3 shows the $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ selected candidates and the corresponding decay time distribution. The preliminary measurement of the effective $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ lifetime is $\tau_{\mathrm{KK}} = 1.468 \pm 0.046(\mathrm{stat}) \pm 0.006(\mathrm{syst})\,\mathrm{ps}$, in agreement with the previous measurement and with SM predictions.

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