Mixing-induced CP violation in B^0 decays

Marta Calvi[*] [†]
University of Milano Bicocca and INFN
E-mail: marta.calvi@mib.infn.it

Measurements of *CP* violating phases provide valuable tests of the flavour sector in the SM and offer opportunities to search for signs of beyond-SM physics. The LHCb experiment has measured mixing-induced *CP* violation in various B^0 decay modes using proton-proton collision data, corresponding to an integrated luminosity of 3 fb^{-1}, collected at $\sqrt{s} = 7$ and 8 TeV. In this talk latest results on $B^0 \to J/\psi K^0_S$, $B^0 \to D^+D^-$ and $B^0 \to J/\psi\pi^-\pi^+$ decays are reported. The measurements of the *CP* violating phases are presented and the contributions due to tree-level and loop processes are discussed.

9th International Workshop on the CKM Unitarity Triangle
28 November - 3 December 2016
Tataf Institute for Fundamental Research (TIFR), Mumbai, India

---

[*] Speaker.

[†] On behalf of the LHCb Collaboration

PoS(CKM2016)088

Measurement of *CP* violating phases provides valuable tests of the flavour sector in the SM and offers opportunities to search for signs of beyond-SM physics. In the SM the relative phase of the B^0 mixing amplitude and the tree-level decay process is large. It is defined as $\phi_d = 2\beta$, where $\beta \equiv \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$ is an angle of one of the CKM unitary triangles associated to B^0 observables. The combined fit of several existing measurements in the flavour sector (except those on β) provides the estimate $\sin 2\beta^{SM} = 0.740^{+0.020}_{-0.025}$ deg [1]. An effective *CP* phase, $\phi_d^{\rm eff} = \phi_d + \Delta\phi_d$, can be obtained from the measurement of the *CP* asymmetry in decays of B^0 mesons to a *CP* eigenstate f, where $\Delta\phi_d$ is a possible shift induced by higher-order loop processes, described by SM or due to beyond-SM physics. Under the assumption that *CP* violation in the mixing is negligible, the decay-time-dependent *CP* asymmetry can be written in terms of the *CP* observables S and C as

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S\sin(\Delta m t) - C\cos(\Delta m t), \qquad (1)$$

where Δm is the mass difference between the physical B^0 meson eigenstates and it is assumed that their decay with difference $\Delta\Gamma_d = 0$. The observables are related to the phases via $S/\sqrt{1-C^2} = -\eta_{CP}\sin\phi_d^{\rm eff} = -\eta_{CP}\sin(\phi_d + \Delta\phi_d)$, where $\eta_{CP} = \pm 1$ is the *CP* eigenvalue of the final state.

The "golden channel" to measure β is $B^0 \to J/\psi K^0_S$. If its decay amplitude can be described by a dominant tree-level $b \to c\bar{c}s$ transition, $S^{SM}_{B^0\to J/\psi K^0_S} = \sin 2\beta$ and $C^{SM}_{B^0\to J/\psi K^0_S} = 0$. The world average of available measurements of $b \to c\bar{c}s$ decays is $\sin\phi_d^{\rm eff} = 0.691 \pm 0.017$ [2], which is in good agreement with the SM prediction, though still leaves room for contributions of beyond-SM physics.

The latest LHCb measurement in the $B^0 \to J/\psi K^0_S$ decay mode, with $K^0_S \to \pi^+\pi^+$ and $J/\psi \to \mu^+\mu^-$, is from the analysis of Run I data, corresponding to an integrated luminosity of 3 fb^{-1} [3] collected at $\sqrt{s}$ =7 and 8 TeV. In Fig. 1 the distribution of the reconstructed mass of $B^0 \to J/\psi K^0_S$ candidates and the time-dependent signal-yield asymmetry are shown. A total of 41560 ± 270 signal candidates are found. The fit result is $S_{B^0\to J/\psi K^0_S} = 0.731 \pm 0.035(stat) \pm 0.020(syst)$ and

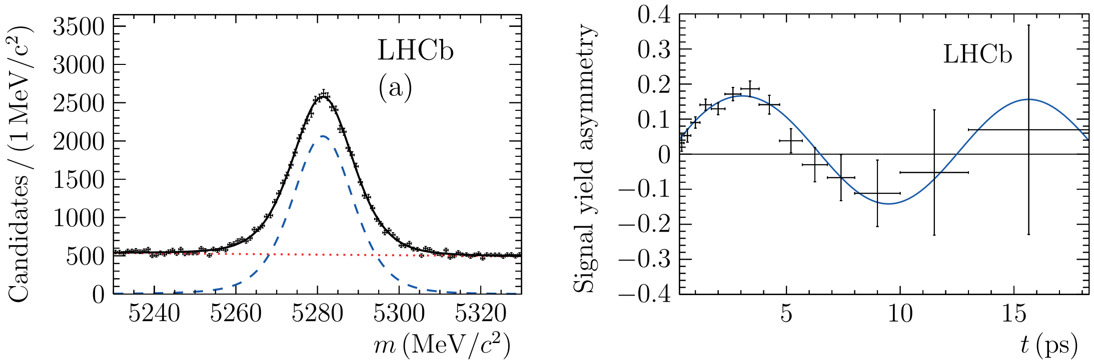

Figure 1: (left) Distribution of the reconstructed mass of tagged $B^0 \to J/\psi K^0_S$ candidates. The solid black line shows the fit projections, while the dashed (dotted) lines show the projections for the signal (combinatoric background) components only. (right) Decay-time-dependent signal yield asymmetry. The data points are obtained with the sPlot technique [4], assigning signal weights to the events based on a fit to the reconstructed mass distribution. The solid curve is the projection of the signal PDF.

$C_{B^0\to J/\psi K^0_S} = -0.038 \pm 0.032(stat) \pm 0.005(syst)$. This result, which is included in the world average quoted above, has a precision comparable to that of single B factory experiments and it is in agreement with them [2].

There are good prospects to further improve this result at LHCb. The precision of the measurement is currently limited by the statistical uncertainty and systematic uncertainties are expected to decrease with the increasing size of the data sample used to determine them. In 2015-2016 LHCb has collected 2 fb^{-1} at $\sqrt{s}$ = 13 TeV, and the full Run II data should amount to about 5 fb^{-1}. Improvements in the analysis, like the use of new flavour tagging algorithms described below, will also increase the statistical power of the data.

In order to translate a precise measurement of ϕ_d^{eff} into an equally precise determination of the CKM angle β, it is essential to take into account possible phase shifts, $\Delta\phi_d$ due to contributions to the decay process of higher-order terms, such as the doubly Cabibbo suppressed contributions from the penguin topologies. By relying on approximate SU(3) flavour symmetry, information on these contributions can be obtained from measurements of *CP* asymmetries in decay modes where the penguin topologies are enhanced. The $B^0_s \to J/\psi K^0_S$ decay mode is the most promising channel for this task. LHCb performed the first tagged time-dependent analysis in this mode with Run I data [5], obtaining, from a signal yield of 908 ± 36 candidates, $S_{B^0_s\to J/\psi K^0_S} = -0.08 \pm 0.40(stat) \pm 0.08(syst)$ and $C_{B^0_s\to J/\psi K^0_S} = -0.28 \pm 0.41(stat) \pm 0.08(syst)$. The precision of this measurement is not yet sufficient to derive a constraint on the phase shift, but the result is a successful proof of principle for future analyses with more data.

Time-dependent *CP* measurements use flavour tagging procedures to determine the B^0 signal flavour at production. At LHCb several algorithms, using information from the rest of the event, are combined to obtain the best tagging decision. Their performance is described by three parameters: the tagging efficiency ε_{tag}, the mistag fraction ω and the tagging power ε_{eff}, defined as

$$\varepsilon_{\text{tag}} = \frac{R+W}{R+W+U}, \quad \omega = \frac{W}{R+W}, \quad \varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1-2\omega)^2, \tag{2}$$

where R, W, and U are the numbers of correctly-tagged, incorrectly-tagged, and untagged B^0 signal candidates. The tagging power determines the sensitivity to the measurement of a decay-time-dependent *CP* asymmetry, as it quantifies the effective reduction in the sample size of flavour-tagged B^0 candidates. One class of algorithms, called opposite-side (OS) taggers [6] attempts to determine the flavour content of the B^0 meson by identifying the other b hadron produced in the same event. Another class, called same-side (SS) taggers, uses particles associated to the B^0 meson production. Two new SS taggers using pions and protons have recently been developed [7]. These algorithms select pions and protons produced at the primary vertex and use a boosted decision tree (BDT) [8] to separate right-tag from wrong-tag candidates. The BDT output is converted into a mistag probability associated to that particle by means of a time-dependent analysis of flavour-specific decay modes. These algorithms were tuned and calibrated on data with $B^0 \to D^-\pi^+$ and $B^0 \to K^+\pi^-$ decays. Calling N^{unmix} (N^{mix}) the number of signal candidates with equal (opposite) flavour at production and decay, as determined by comparing the tagger decision with the flavour of the reconstructed final state, the decay-time-dependent flavour asymmetry is given by

$$A(t) = \frac{N^{\text{unmix}} - N^{\text{mix}}}{N^{\text{unmix}} + N^{\text{mix}}} = (1-2\omega)\cos(\Delta m_d t). \tag{3}$$

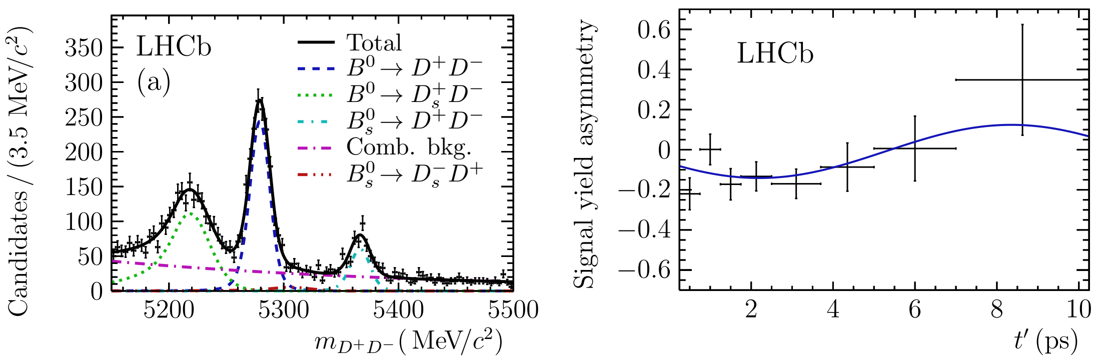

Figure 2: (left) Distribution of the reconstructed mass of all $B^0 \to D^+D^-$ candidates. Besides the data points and the projection of the full PDF (solid black) the projections of the B^0 signal (dashed blue), the $B_s^0 \to D^+D^-$ background (short-dash-dotted turquoise), the $B^0 \to D_s^+D^-$ background (dotted green), the $B_s^0 \to D_s^-D^+$ background (long-dash-three-dotted red) and the combinatorial background (long-dash-dotted purple) are shown. (right) Decay-time-dependent signal yield asymmetry. The solid curve is the projection of the signal PDF.

The pion tagger provides a tagging power 60% larger than the previous algorithm used in the $B^0 \to J/\psi K_S^0$ analysis. The proton tagger adds another 25% of tagging power.

The first LHCb analysis profiting from this improvement is the study of $B^0 \to D^+D^-$ decays in Run I data [9]. This decay mode measures $\sin 2\beta$ from the dominant tree-level $b \to c\bar{c}d$ transition. Higher-order contributions provide sensitivity to additional *CP* phases. Previous measurements of the *CP* observables in the $B^0 \to D^+D^-$ decay by the BaBar and Belle collaborations [10, 11] give world average values of $S_{B^0 \to D^+D^-} = -0.98 \pm 0.17$ and $C_{B^0 \to D^+D^-} = -0.31 \pm 0.14$ [2]. The world average values are at the edge of the physically allowed region of $S^2 + C^2 \leq 1$, which leaves room for a large value of $\Delta\phi_d$.

Candidate $B^0 \to D^+D^-$ decays are reconstructed through the subsequent decays $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^-K^+\pi^+$, with the requirement that the final state contains at most three kaons. Two BDTs are used to suppress combinatorial background. Requirements on the decay time significance of each $D^\pm$ meson reduce the contamination of $B^0 \to D^-K^-K^+\pi^+$ decays. The distribution of the reconstructed mass of all $B^0 \to D^+D^-$ candidates is shown in Fig. 2, the signal yield is 1610 ± 50. The *CP* violation observables S and C are determined from a multidimensional fit to the background-subtracted tag and decay time distributions of the tagged $B^0 \to D^+D^-$ candidates. The decay-time resolution is determined from simulated events while the decay-time acceptance is a free parameter in the fit. The mistag probability is calibrated with a sample of $B^0 \to D_s^+D^-$ decays, with $D_s^+ \to K^+K^-\pi^+$, for which the final state determines the flavour of the B^0 at decay. Since the calibration and signal channels are kinematically very similar, the calibration can be applied to the signal channel without further corrections. The total tagging power in the signal channel is $(8.1 \pm 0.6)\%$, the highest effective tagging efficiency to date in tagged *CP* violation measurements at LHCb thanks to the improved flavour-tagging algorithms and the kinematic properties of the selected $B^0 \to D^+D^-$ decays. The decay-time-dependent signal yield asymmetry $(N_{\bar{B}^0} - N_{B^0})/(N_{\bar{B}^0} + N_{B^0})$, where N_{B^0} is the number of $B^0 \to D^+D^-$ decays with a B^0 flavour tag, and $N_{\bar{B}^0}$ the number with a $\bar{B}^0$ tag, is shown in Fig. 2. The largest systematic uncer-

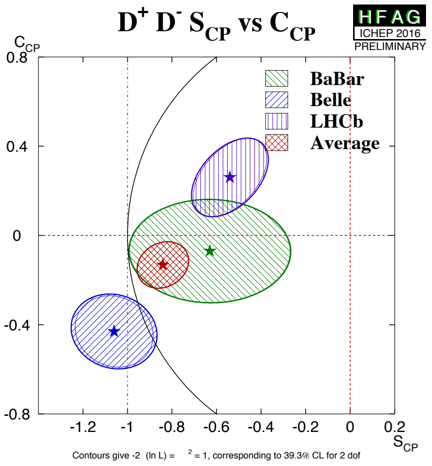

Figure 3: The *CP* parameters S and C as measured in $B^0 \to D^+D^-$ decay from BaBar, Belle and LHCb experiments and their combination.

tainty arises from neglecting backgrounds in which the final state contains only one charm meson, such as $B^0 \to D^-K^-K^+\pi^+$. The yield of these backgrounds is estimated to be about 2% of the signal yield and their impact is assessed by assuming that they maximally violate *CP* symmetry and have the eigenvalue opposite to the signal mode. The *CP* observables are measured to be $S_{B^0\to D^+D^-} = -0.54^{+0.17}_{-0.16}\,(\text{stat}) \pm 0.05\,(\text{syst})$ and $C_{B^0\to D^+D^-} = 0.26^{+0.18}_{-0.17}\,(\text{stat}) \pm 0.02\,(\text{syst})$, with a correlation coefficient of $\rho = 0.48$, larger than at B factories. The comparison with previous results is shown in Fig. 3 [2]. The LHCb result is compatible with the BaBar one, while a comparison with Belle is hampered by non-Gaussian uncertainties. This result constrains the phase shift due to higher-order corrections to $\Delta\phi_d(B^0 \to D^+D^-\ ) = -0.16^{+0.19}_{-0.21}$ rad. SU(3) symmetry relates the phase shift in $B^0 \to D^+D^-$ to the shift in $B^0_s \to D^+_s D^-_s$ therefore this measurement can be used to control the size of penguin contributions to $B^0_s \to D^+_s D^-_s$, as discussed in Refs. [12, 13, 14].

Mixing-induced *CP* violation was recently studied at LHCb also in $B^0 \to J/\psi\,\pi^-\pi^+$ decays [15]. Theoretical models predict that in this mode the ratio of penguin to tree amplitudes is greatly enhanced relative to $B^0 \to J/\psi K^0_S$ [16, 17]. Several final state resonances are considered with an amplitude analysis similar to that of Ref. [18], the main contribution (about 66%) being ascribed to $B^0 \to J/\psi\,\rho^0(770)$. A tagged decay-time-dependent measurement is performed in each resonant final state. To reduce the number of free parameters, in the likelihood fit the three transversity states of the ρ share the same *CP* violation parameter while all other resonances than the ρ share a common *CP* violation parameter. This gives $\phi_d^{\text{eff}}(\rho) = 41.7 \pm 9.6^{+2.8}_{-6.3}$ deg and $\phi_d^{\text{eff}}(other - \rho) = 3.6 \pm 3.6^{+0.9}_{-0.8}$ deg. Comparing this result with the one from Cabbibo favoured B to charmonium result, $B^0 \to J/\psi K^0_S$, the measured difference is $-0.9 \pm 9.7^{+2.8}_{-6.3}$ deg. Approximated SU(3) symmetry can be used to relate the size of the penguin contribution in $B^0 \to J/\psi\,\rho^0(770)$ to that in $B^0_s \to J/\psi\,\phi$ decays [15].

In this talk a selection of measurements on mixing-induced *CP* violation performed by LHCb with Run I data has been presented. The results are compatible with SM predictions, when available. All measurements are statistically limited and improvements can be expected with the analyses of Run II data.

References

[1] CKMfitter Group, J. C. et al. *CP Violation and the CKM Matrix: Assessing the Impact of the Asymmetric B Factories*, Eur. Phys. J. **C41** (2005) 1, updated results and plots available at: http://ckmfitter.in2p3.fr.

[2] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014*, `arXiv:1412.7515`, updated results and plots available at `http://www.slac.stanford.edu/xorg/hfag/`.

[3] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation in $B^0 \to J/\psi K^0_S$ decays*, Phys. Rev. Lett. **115** (2015) 031601, `arXiv:1503.07089`.

[4] M. Pivk and F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, `arXiv:physics/0402083`.

[5] LHCb collaboration, R. Aaij *et al.*, *Measurement of the time-dependent CP asymmetries in $B^0_s \to J/\psi K^0_S$*, JHEP **06** (2015) 131, `arXiv:1503.07055`.

[6] LHCb collaboration, R. Aaij *et al.*, *Opposite-side flavour tagging of B mesons at the LHCb experiment*, Eur. Phys. J. **C72** (2012) 2022, `arXiv:1202.4979`.

[7] LHCb collaboration, R. Aaij *et al.*, *New algorithms to tag the flavour of B^0 mesons using pions and protons*, `arXiv:1610.06019`, submitted to Eur. Phys. J. C.

[8] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.

[9] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation in $B \to D^+D^-$ decays*, Phys. Rev. Lett. **117** (2016) 261801, `arXiv:1608.06620`.

[10] BaBar collaboration, B. Aubert *et al.*, *Measurements of time-dependent CP asymmetries in $B^0 \to D^{(*)+}D^{(*)-}$ decays*, Phys. Rev. **D79** (2009) 032002, `arXiv:0808.1866`.

[11] Belle collaboration, M. Rohrken *et al.*, *Measurements of branching fractions and time-dependent CP violating asymmetries in $B^0 \to D^{(*)\pm}D^{\mp}$ decays*, Phys. Rev. **D85** (2012) 091106, `arXiv:1203.6647`.

[12] R. Fleischer, *Exploring CP violation and penguin effects through $B^0_d \to D^+D^-$ and $B^0_s \to D^+_s D^-_s$*, Eur. Phys. J. **C51** (2007) 849, `arXiv:0705.4421`.

[13] M. Jung and S. Schacht, *Standard model predictions and new physics sensitivity in $B \to DD$ decays*, Phys. Rev. **D91** (2015) 034027, `arXiv:1410.8396`.

[14] L. Bel *et al.*, *Anatomy of $B \to D\bar{D}$ decays*, JHEP **07** (2015) 108, `arXiv:1505.01361`.

[15] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CP-violating phase β in $\bar{B}^0 \to J/\psi\pi^+\pi^-$ decays and limits on penguin effects*, Phys. Lett. **B742** (2015) 38, `arXiv:1411.1634`.

[16] S. Faller, M. Jung, R. Fleischer, T. Mannel, *The golden modes $B^0 \to J/\psi K^0_S$ in the era of precision flavor physics*, Phys. Rev. **D79** (2009) 014030, `arXiv:0809.0842`.

[17] S. Faller, R. Fleischer, T. Mannel, *Precision physics with $B^0_s \to J/\psi\,\phi$ at the LHC: the quest for new physics*, Phys. Rev. **D79** (2009) 014005, `arXiv:0810.4248`.

[18] LHCb collaboration, R. Aaij *et al.*, *Measurement of the resonant and CP components in $\bar{B}^0 \to J/\psi\pi^+\pi^-$ decays*, Phys. Rev. **D90** (2014) 012003, `arXiv:1404.5673`.