PROCEEDINGS OF SCIENCE

LHCb results on *CP* violation in $B^0_{(s)}$ mixing and in the interference with decays

Paul Seyfert[*†]
INFN Milano Biccoca
E-mail: Paul.Seyfert@mib.infn.it

Measurements of *CP* violation in neutral B meson mixing and in the interference with decays are excellent probes to search for physics beyond the Standard Model.
A selection of recent measurements performed by the LHCb experiment using the full Run I dataset is presented. These are a measurement of *CP* violation in the B to double charm decay $B^0 \to D^+D^-$, the first measurement of the *CP* violating phase ϕ_s using $B^0_s \to \psi(2S)\phi$ decays, and a measurement of the *CP*-even B^0_s lifetime in $B^0_s \to J/\psi\eta$ decays. Unprecedented flavour tagging performance is achieved in the $B^0 \to D^+D^-$ decay thanks to new flavour tagging methods.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

*Speaker.
†On behalf of the LHCb collaboration.

The LHCb collaboration performed many *CP* violation measurements using LHC Run I data with great success [1]. While measurements of the "golden modes" need data from Run II to achieve significant improvements, there are still interesting analyses with Run I data to be performed to improve our understanding of *CP* violation.

The LHCb experiment [2] is constructed as a forward spectrometer to detect the decay products of boosted B mesons, close to the beam line. With respect to unboosted B mesons, the boost increases the B flight length and thus improves the decay time resolution for time-dependent measurements.

1. *CP* violation in the B^0 system with $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$

The angle β of the CKM triangle is known to very high precision. The measurements with the highest precision are obtained by studies of $\mathrm{b} \to \mathrm{c\bar{c}s}$ transitions. The *CP* violation in $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ is sensitive to β at tree level in the Standard Model (SM) as well. Higher order diagrams, such as penguin diagrams, can lead to a difference in the *CP* violating phase, $\Delta\phi$, between $\mathrm{b} \to \mathrm{c\bar{c}s}$ transitions and $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$, a measurement of *CP* violation in $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ can thus constrain the contribution of higher order processes to $\mathrm{B} \to \mathrm{DD}$ decays. The time-dependent *CP* asymmetry is for $\Delta\Gamma_\mathrm{d} = 0$ given by

$$A(t) \equiv \frac{\Gamma\left(\overline{\mathrm{B}}^0(t) \to \mathrm{D}^+\mathrm{D}^-\right) - \Gamma\left(\mathrm{B}^0(t) \to \mathrm{D}^+\mathrm{D}^-\right)}{\Gamma\left(\overline{\mathrm{B}}^0(t) \to \mathrm{D}^+\mathrm{D}^-\right) + \Gamma\left(\mathrm{B}^0(t) \to \mathrm{D}^+\mathrm{D}^-\right)} = S_{CP}\sin(\Delta m_\mathrm{d} t) - C_{CP}\cos(\Delta m_\mathrm{d} t)\,,$$

with

$$\frac{S_{CP}}{\sqrt{1-C_{CP}^2}} \equiv -\sin(2\beta^\mathrm{eff}_{\mathrm{B}\to\mathrm{DD}}) = -\sin(2\beta + \Delta\phi)\,.$$

Higher order contributions to $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ are not predicted by theory.

LHCb performed a measurement of the $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ decay rate as a function of the B^0 decay time and separated by B^0 production flavour [3, 4]. The selection requires three-prong decays for both D mesons and that they are compatible with originating[1] in a common vertex. The two final states $\mathrm{D}^+(\mathrm{K}^-\pi^+\pi^+)\mathrm{D}^-(\mathrm{K}^+\pi^-\pi^-)$ and $\mathrm{D}^\pm(\mathrm{K}^\mp\mathrm{K}^\pm\pi^\pm)\mathrm{D}^\mp(\mathrm{K}^\pm\pi^\mp\pi^\mp)$ are selected where the combined $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ candidate must be compatible with originating in a primary vertex. In addition to a cut-based selection including vetoes against misidentified decays[2], two separate multivariate selections for the two final states are applied. A fit to the reconstructed B^0 mass distribution, with components for $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{D}^+\mathrm{D}^-$, as well as misidentified $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{D}^+_\mathrm{s}\mathrm{D}^-$ and combinatorial backgrounds, determines a signal yield of 1610 ± 50.

Whether a reconstructed B^0 candidate was a B^0 or $\overline{\mathrm{B}}^0$ at production is determined with flavour tagging algorithms which exploit either that b quarks are mainly produced in $\mathrm{b\bar{b}}$ pairs at the LHC or the creation of $\mathrm{d\bar{d}}$ pairs in the B^0 hadronisation or strong decays of excited B mesons [5]. The hadronisation of the remaining d quark can result in a charged pion or proton, the charge of which

[1] The boost is sufficient to result in a measurable displacement of the D decay vertices from the B decay vertex.

[2] e.g. $(\mathrm{D}^+_\mathrm{s} \to \mathrm{K}^-\mathrm{K}^+\pi^+) \overset{\text{misid.}}{\rightsquigarrow} (\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+)$

identifies the B^0 production flavour ("same side tagging", SS). The hadronisation of the second b quark will result in a b hadron which eventually decays in the LHCb acceptance ("opposite side tagging", OS). For the first time LHCb uses a SS proton tagging algorithm and an OS charm tagger, which fully reconstructs charm meson decays from $b \to c$ transitions. Furthermore, a new optimisation of the SS pion tagging is applied [6, 7]. The mistag rate (ω) for the flavour tagging is calibrated by measuring the B^0 oscillation amplitude in flavour specific $B^0 \to D_s^+ D^-$ decays. The tagging power in the $B^0 \to D^+D^-$ analysis is $\varepsilon_{\text{eff}} \equiv \varepsilon(1-2\omega)^2 = (8.1 \pm 0.6)\,\%$, where ε is the fraction of events with a tagging decision. This is the highest tagging power achieved at LHCb to date. This is partially due to the application of the new tagging algorithms and optimisations, but also due to the candidate selection, which leads to a comparably hard momentum spectrum and consequently high momenta of the other hadronisation products, which are then easier to identify by the flavour tagging algorithms.

The measured S and C parameters are

$$\begin{aligned} S_{CP} &= -0.54\,^{+0.17}_{-0.16}\,(\text{stat}) \pm 0.05\,(\text{syst})\,, \\ C_{CP} &= 0.26\,^{+0.18}_{-0.17}\,(\text{stat}) \pm 0.02\,(\text{syst})\,. \end{aligned}$$

These two values are more strongly correlated than in the corresponding measurements by the B-factories. A visual comparison is given in Fig. 1. The dominating systematic uncertainty stems from the description of background contributions from residual $B^0 \to Dhhh$ decays, for which the unknown CP parameters are assumed to be maximally biasing.

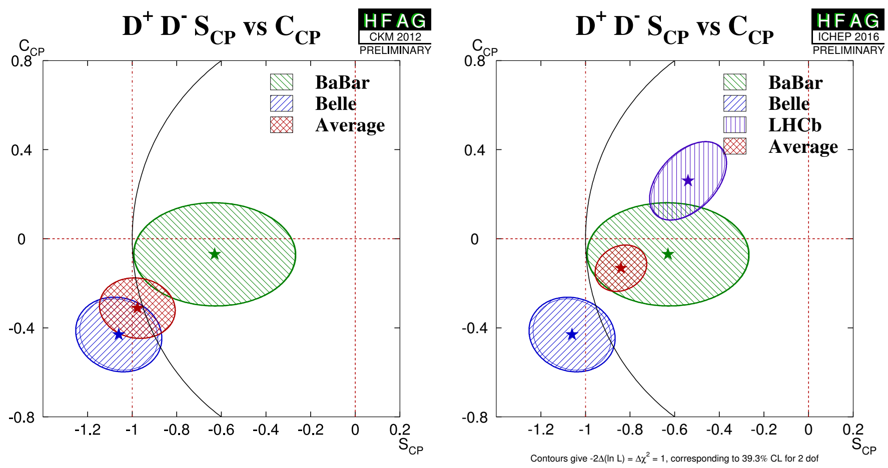

Figure 1: Comparison and combination of CP violation measurement in $B^0 \to D^+D^-$ at the $1\,\sigma$ level [8]. The contours correspond to 39.3 % confidence level. The combination is done before (left) and after (right) the addition of the LHCb result to the measurements in [9, 10]. The figure and combination neglect non-Gaussian behaviour of the individual experiments' likelihoods. The black line indicates the physical boundary.

Implication for ϕ_s

Measuring the CP violation in $B^0 \to D^+D^-$ decays is motivated by more than obtaining an effective $\sin 2\beta^{\text{eff}}_{B\to DD}$ measurement [11, 12, 13]. The measurement of the phase shift $\Delta\phi$ serves as a constraint to the size of penguin amplitudes in B to double charm decays. Assuming U-spin symmetry, the size of the penguin contributions in $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ is the same as in the ϕ_s measurement in $\mathrm{B}^0_\mathrm{s} \to \mathrm{D}^+_\mathrm{s}\mathrm{D}^-_\mathrm{s}$. The phase shift determined from the LHCb measurement is $\Delta\phi = (-0.16^{+0.19}_{-0.21})$ rad, which rules out large penguin contributions.

2. First ϕ_s measurement involving the $\psi(2\mathrm{S})$ resonance

Measurements of ϕ_s in $\mathrm{b} \to \mathrm{c\bar{c}s}$ transitions have all analysed $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi X$ data, with the exception of the measurement with $\mathrm{B}^0_\mathrm{s} \to \mathrm{D}^+_\mathrm{s}\mathrm{D}^-_\mathrm{s}$ decays [14]. The same phenomenological description as for the "golden mode" $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi(\mu\mu)\phi(\mathrm{KK})$ also applies to $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})(\mu\mu)\phi(\mathrm{KK})$, which is analysed for the first time by LHCb [15].

The analysis of 4697 ± 71 signal candidates is performed similarly to previous analyses of $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ decays. An angular analysis of the decay products is necessary to disentangle different *CP* eigenstates which contribute to the decay. A good decay time resolution and its accurate description is crucial due to the fast B^0_s oscillation, it is calibrated with prompt $\mathrm{J}/\psi \to \mu\mu$ decays.

The $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\phi$ analysis also serves as a test environment to establish analysis techniques which have not been applied in previous ϕ_s measurements with $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$. A multivariate selection is used to optimise the statistical sensitivity and the control mode $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\mathrm{K}^*$ is used to calibrate the decay time acceptance.

Same side flavour tagging is done with prompt charged kaons instead of pions and protons. The total tagging power, for SS and OS tagging, is $(3.88 \pm 0.18)\,\%$. The value is lower than that in $\mathrm{B}^0 \to \mathrm{D}^+\mathrm{D}^-$ since the two muons in the final state and the lower number of final state particles allows to reconstruct and select also low momentum B mesons, which have a higher mistag rate than high momentum B mesons.

The results, listed in Table 1, are compatible with previous measurements and the SM prediction. The sensitivity, however, is significantly lower than that of the world average ($\sigma_{\phi_\mathrm{s}} = 0.033$ [8]).

Table 1: Results of the maximum likelihood fit to the selected $\mathrm{B}^0_\mathrm{s} \to \psi(2\mathrm{S})\phi$ candidates including all acceptance and resolution effects [15]. The first uncertainty is statistical and the second is systematic.

Parameter	Value
Γ_s [ps^{-1}]	$0.668 \pm 0.011 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066^{+0.041}_{-0.044} \pm 0.007$
$\lvert A_\perp\rvert^2$	$0.264^{+0.024}_{-0.023} \pm 0.002$
$\lvert A_0\rvert^2$	$0.422 \pm 0.014 \pm 0.003$
$\delta_\parallel$ [rad]	$3.67^{+0.13}_{-0.18} \pm 0.03$
$\delta_\perp$ [rad]	$3.29^{+0.43}_{-0.39} \pm 0.04$
ϕ_s [rad]	$0.23^{+0.29}_{-0.28} \pm 0.02$
$\lvert\lambda\rvert$	$1.045^{+0.069}_{-0.050} \pm 0.007$
F_S	$0.061^{+0.026}_{-0.025} \pm 0.007$
δ_S [rad]	$0.03 \pm 0.14 \pm 0.02$

3. Indirect measurements of *CP* violation in the B^0_s system

The decay channel $B^0_s \to J/\psi\eta$ has been considered a possible mode to measure ϕ_s in the past. An analysis would be simpler since no angular analysis is necessary, but the experimental challenges to reconstruct the $\eta \to \gamma\gamma$ decay make a direct measurement of ϕ_s unfeasible. A measurement of the effective lifetime, however, is feasible and an attractive observable as it should coincide with the lifetime of the light B^0_s eigenstate in the case of *CP* conservation [16, 17].

LHCb performed a measurement with the full Run I dataset [18]. The mass resolution in $B^0_s \to J/\psi\eta$ requires leads to overlapping mass distributions for B^0_s and B^0 decays. This requires to constrain the ratio of B^0_s/B^0 candidates – by means of the $B^0_{(s)}$ production fractions and the corresponding $B^0_{(s)} \to J/\psi\eta$ branching fractions – and to constrain the B^0 lifetime when fitting the $B^0_s \to J/\psi\eta$ candidates. To obtain the best possible sensitivity, a dedicated calorimeter calibration to the $\eta \to \gamma\gamma$ decay is applied.

With the 3021 ± 73 signal candidates, an effective lifetime of $\tau(J/\psi\eta) = (1.479 \pm 0.034\,(\text{stat}) \pm 0.011\,(\text{sys}))$ ps, in agreement with the SM prediction, is found.

4. Conclusion

New measurements of *CP* violation in neutral B meson systems at LHCb complement measurements in the "golden modes". A measurement of the effective mixing phase $2\beta^{\text{eff}}_{B\to DD}$ in $B^0 \to D^+D^-$ with a sensitivity similar or better than existing measurements constrains the effect of higher order contributions to $B \to DD$ decays. A first measurement of ϕ_s with $\psi(2S)$ resonances in the decay chain demonstrates the feasibility of performing a ϕ_s measurement in that decay channel. The lifetime measurement in $B^0_s \to J/\psi\eta$ demonstrates the capabilities of measuring *CP* observables in modes with neutrals in the final state at LHCb. All three measurements are statistically limited and improvements can be expected with Run II data.

References

[1] R. Aaij et al. "Implications of LHCb measurements and future prospects". *Eur. Phys. J.* C73.4 (2013), p. 2373. DOI: 10.1140/epjc/s10052-013-2373-2. arXiv: 1208.3355 [hep-ex].

[2] LHCb collaboration, R. Aaij et al. "LHCb detector performance". *Int. J. Mod. Phys.* A30 (2015), p. 1530022. DOI: 10.1142/S0217751X15300227. arXiv: 1412.6352 [hep-ex].

[3] LHCb collaboration, R. Aaij et al. "Measurement of *CP* violation in $B^0 \to D^+D^-$ decays" (2016). to appear in Phys. Rev. Lett. arXiv: 1608.06620 [hep-ex].

[4] L. Bel. "Time dependent *CPV* measurement in B to open charm decays at LHCb". *Proceedings of the 38th International Conference on High Energy Physics (ICHEP)*. Ed. by Y.-K. Kim et al. 2016.

[5] V. Müller. "Flavour tagging of b-mesons in pp collisions at LHCb". *Proceedings of the 38th International Conference on High Energy Physics (ICHEP)*. Ed. by Y.-K. Kim et al. 2016.

[6] LHCb collaboration, R. Aaij et al. "New algorithms for identifying the flavour of B^0 mesons using pions and protons" (2016). submitted to Eur. Phys. J. C. arXiv: 1610.06019 [hep-ex].

[7] LHCb collaboration, R. Aaij et al. "B flavour tagging using charm decays at the LHCb experiment". *JINST* 10 (2015), P10005. DOI: 10.1088/1748-0221/10/10/P10005. arXiv: 1507.07892 [hep-ex].

[8] Y. Amhis et al. "Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014" (2014). Updated results and plots available at http://www.slac.stanford.edu/xorg/hfag/. arXiv: 1412.7515 [hep-ex].

[9] BaBar collaboration, B. Aubert et al. "Measurements of time-dependent *CP* asymmetries in $B^0 \to D^{(*)+}D^{(*)-}$ decays". *Phys. Rev.* D79 (2009), p. 032002. DOI: 10.1103/PhysRevD.79.032002. arXiv: 0808.1866 [hep-ex].

[10] 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), p. 091106. DOI: 10.1103/PhysRevD.85.091106. arXiv: 1203.6647 [hep-ex].

[11] M. Jung and S. Schacht. "Standard model predictions and new physics sensitivity in $B \to DD$ decays". *Phys. Rev.* D91 (2015), p. 034027. DOI: 10.1103/PhysRevD.91.034027. arXiv: 1410.8396 [hep-ph].

[12] L. Bel et al. "Anatomy of $B \to D\overline{D}$ decays". *JHEP* 07 (2015), p. 108. DOI: 10.1007/JHEP07(2015)108. arXiv: 1505.01361 [hep-ph].

[13] M. Gronau, J. L. Rosner, and D. Pirjol. "Small amplitude effects in $B^0 \to D^+D^-$ and related decays". *Phys. Rev.* D78 (2008), p. 033011. DOI: 10.1103/PhysRevD.78.033011. arXiv: 0805.4601 [hep-ph].

[14] LHCb collaboration, R. Aaij et al. "Measurement of the *CP*-violating phase ϕ_s in $B^0_s \to D^+_s D^-_s$ decays". *Phys. Rev. Lett.* 113 (2014), p. 211801. DOI: 10.1103/PhysRevLett.113.211801. arXiv: 1409.4619 [hep-ex].

[15] LHCb collaboration, R. Aaij et al. "Frist study of the *CP*-violating phase and decay-width difference in $B^0_s \to \psi(2S)\phi$ decays". *Phys. Lett.* B762 (2016), pp. 253–262. DOI: 10.1016/j.physletb.2016.09.028. arXiv: 1608.04855 [hep-ex].

[16] R. Fleischer, R. Knegjens, and G. Ricciardi. "Exploring *CP* Violation and η-η' Mixing with the $B^0_{s,d} \to J/\psi\eta^{(\prime)}$ Systems". *Eur. Phys. J.* C71 (2011), p. 1798. DOI: 10.1140/epjc/s10052-011-1798-8. arXiv: 1110.5490 [hep-ph].

[17] R. Fleischer and R. Knegjens. "Effective Lifetimes of B^0_s Decays and their Constraints on the $B^0_s - \overline{B}^0_s$ Mixing Parameters". *Eur. Phys. J.* C71 (2011), p. 1789. DOI: 10.1140/epjc/s10052-011-1789-9. arXiv: 1109.5115 [hep-ph].

[18] LHCb collaboration, R. Aaij et al. "Measurement of the $B^0_s \to J/\psi\eta$ lifetime". *Phys. Lett.* B762 (2016), pp. 484–492. DOI: 10.1016/j.physletb.2016.10.006. arXiv: 1607.06314 [hep-ex].

PoS(ICHEP2016)555