PROCEEDINGS OF SCIENCE

CKM angle γ measurement at LHCb

Susan Haines[*] **on behalf of the LHCb collaboration**
University of Cambridge
E-mail: `haines@hep.phy.cam.ac.uk`

Data collected at the LHCb experiment have been used to determine the CKM angle γ with $B^- \to DK^-$, $D \to K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$ decays, leading to the most precise measurement of γ from a single analysis. Decay-time-dependent CP asymmetries in $B^0 \to D^\mp\pi^\pm$ decays have been measured for the first time at a hadron collider and used to place constraints on $|\sin(2\beta+\gamma)|$ and γ that are consistent with world average values. Combining these new results with other LHCb measurements leads to the most precise determination of γ from a single experiment. Decay modes with future sensitivity to γ, such as $B^0_s \to \overline{D}^0 K^+K^-$ and $B^0_s \to \overline{D}^{*0}\phi$, have been observed for the first time, and the most precise determinations of the branching fractions of $B^0 \to \overline{D}^0 K^+K^-$ and $B^0_s \to \overline{D}^0\phi$ decays have been obtained.

Sixth Annual Conference on Large Hadron Collider Physics (LHCP2018)
4-9 June 2018
Bologna, Italy

---

[*] Speaker.

PoS(LHCP2018)173

The angle $\gamma = arg(-(V_{ud}V_{ub}^{*})/(V_{cd}V_{cb}^{*}))$ of the CKM unitarity triangle can be measured directly with tree-level b-hadron decays, using methods that exploit the weak-phase difference of γ between $b \rightarrow u$ and $b \rightarrow c$ quark transitions. The current world average value of γ, determined from direct measurements, is $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$ [1]. Theoretically, within the Standard Model, the value of γ determined in this way is very clean [2] but new physics phenomena, beyond the Standard Model, could affect its value at a level just below current experimental accuracy [3].

The LHCb detector [4] at the Large Hadron Collider is specifically designed for the study of particles containing b or c quarks. Of particular relevance for γ measurements is its high-precision tracking system, which provides a measurement of the momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c, and a decay time resolution of approximately 50 fs [5]. The impact parameter, the minimum distance between a track and a primary proton-proton interaction vertex, is measured with a resolution of $(15 + 29/p_{\mathrm{T}})$ μm, where p_{T} is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons, such as kaons and pions, are distinguished using information from two ring-imaging Cherenkov detectors.

1. GGSZ analysis of $B^{-} \rightarrow DK^{-}$ with $D \rightarrow K^{0}_{S}\pi^{+}\pi^{-}$, $K^{0}_{S}K^{+}K^{-}$ decays

Time-integrated measurements of γ can be made using $B^{-} \rightarrow DK^{-}$ decays[1], where D represents a superposition of D^{0} and $\overline{D}^{0}$ mesons decaying to the same final state. Alongside γ, the related parameters r_B (the magnitude of the ratio of amplitudes of the interfering decays) and δ_B (the strong-phase difference between them) are also measured.

The GGSZ method [6] allows γ to be measured from the difference between the distributions of B^{-} and B^{+} candidate decays across the $D \rightarrow K^{0}_{S}h^{+}h^{-}$ phase space ($h = \pi$ or K). The resonant structure of the multi-body D decay must therefore be taken into account. In particular, knowledge of the strong-phase difference between D^{0} and $\overline{D}^{0}$ decays across the phase space is required. One possible “model-independent” approach uses direct measurements of the strong-phase difference in binned regions of phase space, obtained using quantum-correlated charm threshold data [7].

Using proton-proton collision data corresponding to an integrated luminosity of 2.0 fb^{-1} recorded by LHCb at a centre-of-mass energy of 13 TeV, $B^{-} \rightarrow DK^{-}$ with $D \rightarrow K^{0}_{S}\pi^{+}\pi^{-}$, $K^{0}_{S}K^{+}K^{-}$ decays have been used to measure the CP observables $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$ and $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$ with the model-independent method [8],

$$\begin{aligned}
x_{+} &= (-7.7 \pm 1.9\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.4\ (\text{extl.})) \times 10^{-2},\\
y_{+} &= (-1.0 \pm 1.9\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.9\ (\text{extl.})) \times 10^{-2},\\
x_{-} &= (\ \ 9.0 \pm 1.7\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.4\ (\text{extl.})) \times 10^{-2},\\
y_{-} &= (\ \ 2.1 \pm 2.2\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 1.1\ (\text{extl.})) \times 10^{-2},
\end{aligned}$$

where the third uncertainties arise from external strong-phase difference input measurements. These results constitute the first observation of CP violation in $B^{-} \rightarrow DK^{-}$ with $D \rightarrow K^{0}_{S}\pi^{+}\pi^{-}$, $K^{0}_{S}K^{+}K^{-}$ decays.

---

[1] The inclusion of charge conjugated processes is implied throughout.

Combining them with previous measurements made using LHCb data corresponding to an integrated luminosity of 3.0 fb^{-1} recorded at centre-of-mass energies of 7 and 8 TeV [9] results in the constraints $\gamma = (80^{+10}_{-9})^\circ$, $r_B = 0.080 \pm 0.011$ and $\delta_B = (110 \pm 10)^\circ$. Two-dimensional projections of the corresponding confidence regions are shown in Fig. 1, alongside the constraints obtained using the two separate data sets, demonstrating good agreement between results.

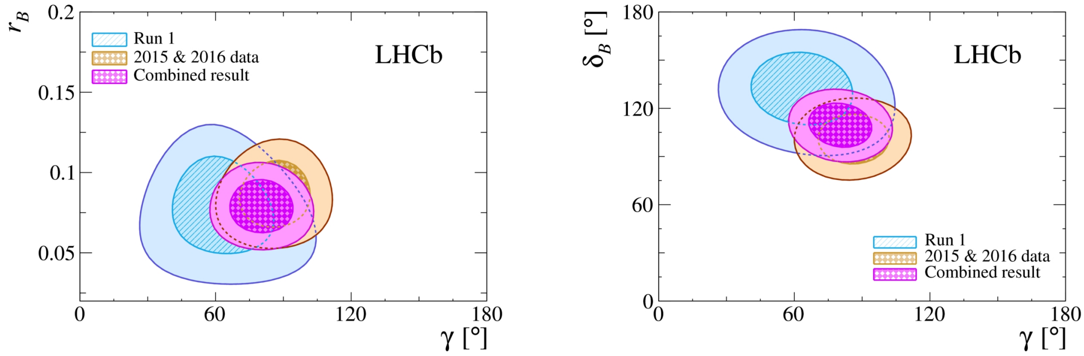

Figure 1: Two-dimensional projections of the 68.3% and 95.5% confidence regions onto the (γ, r_B) and (γ, δ_B) planes [8]. The constraints from measurements using an integrated luminosity of 3.0 fb^{-1} recorded at centre-of-mass energies of 7 and 8 TeV ("Run 1") and 2.0 fb^{-1} at a centre-of-mass energy of 13 TeV ("2015 & 2016 data") are shown, along with their combination.

2. Time-dependent analysis of $B^0 \to D^\mp\pi^\pm$ decays

Measurements of *CP* violation in $B^0 \to D^\mp\pi^\pm$ decays provide information on the angles $\beta = arg(-(V_{cd}V^*_{cb})/(V_{td}V^*_{tb}))$ and γ of the unitarity triangle. A total phase difference of $2\beta + \gamma$ arises between the amplitude of a direct $B^0 \to D^\mp\pi^\pm$ decay and a decay after oscillation to $\overline{B}^0$. It is possible to measure decay-time-dependent *CP* asymmetries in $B^0 \to D^\mp\pi^\pm$ decays using the decay rates of B^0 and $\overline{B}^0$ mesons of known initial flavour, as a function of their decay time t. For an initial B^0 meson, the decay rate to final state $f = D^-\pi^+$ ($\overline{f} = D^+\pi^-$) is $\Gamma_{B^0\to f(\overline{f})}(t) \propto e^{-\Gamma t}[1 + C_{f(\overline{f})}\cos(\Delta m t) - S_{f(\overline{f})}\sin(\Delta m t)]$, where Γ is the average B^0 decay width and Δm is the B^0–$\overline{B}^0$ oscillation frequency. It is assumed that there is no *CP* violation in the decay, that $|q/p| = 1$, where q and p are the coefficients defining the heavy and light mass eigenstates of the B^0 meson system, and that $\Delta\Gamma = 0$, where $\Delta\Gamma$ is the difference in decay width between the two mass eigenstates. Under these assumptions, the *CP* asymmetries $C_{f(\overline{f})}$ and $S_{f(\overline{f})}$ are defined as

$$C_f = -C_{\overline{f}} = \frac{1 - r^2_{D\pi}}{1 + r^2_{D\pi}}, \quad S_f = -\frac{2r_{D\pi}\sin[\delta - (2\beta + \gamma)]}{1 + r^2_{D\pi}}, \quad S_{\overline{f}} = \frac{2r_{D\pi}\sin[\delta + (2\beta + \gamma)]}{1 + r^2_{D\pi}}$$

where $r_{D\pi} = |A(B^0 \to D^+\pi^-)/A(B^0 \to D^-\pi^+)|$ is the ratio of decay amplitudes and δ is the *CP*-conserving phase between them.

A measurement of the *CP* asymmetries S_f and $S_{\overline{f}}$ has been performed using proton-proton collision data collected at LHCb at centre-of-mass energies of 7 and 8 TeV and corresponding to an integrated luminosity of 3.0 fb^{-1} [10]. In this analysis, terms $\mathcal{O}(r^2_{D\pi})$ are neglected, due to the small value of $r_{D\pi}$; this fixes $C_f = -C_{\overline{f}} = 1$. Using external measurement constraints for Δm and Γ, this first measurement of the asymmetries at a hadron collider results in $S_f = 0.058 \pm 0.020\ (\text{stat.}) \pm 0.011\ (\text{syst.})$ and $S_{\overline{f}} = 0.038 \pm 0.020\ (\text{stat.}) \pm 0.007\ (\text{syst.})$, which agree with, and are more precise than, previous measurements [11]. They are used to place constraints on $|\sin(2\beta+\gamma)|$ and γ, shown in Fig. 2, that are consistent with world average values.

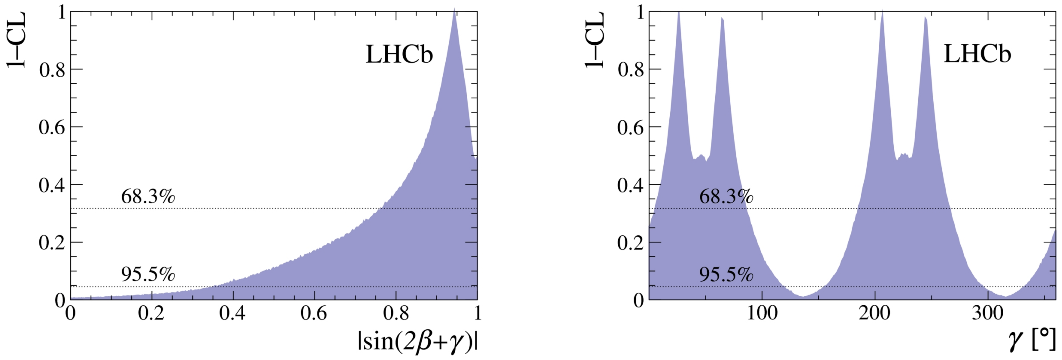

Figure 2: 1-CL (confidence level) as a function of $|\sin(2\beta+\gamma)|$ (left) and γ (right), determined from *CP* asymmetries in $B^0 \to D^{\mp}\pi^{\pm}$ decays [10].

3. Combination of LHCb measurements

Using LHCb data, measurements of γ using time-integrated GLW [12], ADS [13], GGSZ [6] and Dalitz [14] approaches have been performed using b-hadron decays such as $B^- \to D^{(*)}K^{(*)-}$, $B^0 \to DK^{(*)0}$, $B^0 \to DK^+\pi^-$ and $B^- \to DK^-\pi^+\pi^+$ [15]. Time-dependent measurements [16] have also been performed with $B_s^0 \to D_s^{\mp}K^{\pm}$ and $B^0 \to D^{\mp}\pi^{\pm}$ decays. These results, including the new measurements described in Sections 1 and 2, are combined using a frequentist approach to determine γ with the highest precision from a single experiment, $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$ [17].

4. Future γ decay modes: $B^0_{(s)} \to \overline{D}^{(*)0}\phi$ and $B^0_{(s)} \to \overline{D}^0 K^+K^-$

Proton-proton collision data collected at LHCb at centre-of-mass energies of 7 and 8 TeV and corresponding to an integrated luminosity of 3.0 fb^{-1} have been used to measure and set limits on the branching fractions of $B^0_{(s)} \to \overline{D}^0 K^+K^-$, $B^0_{(s)} \to \overline{D}^0\phi$ and $B_s^0 \to \overline{D}^{*0}\phi$ decays [18].

The decays $B_s^0 \to \overline{D}^0 K^+K^-$ and $B_s^0 \to \overline{D}^{*0}\phi$ are observed for the first time with measured branching fractions $\mathcal{B}(B_s^0 \to \overline{D}^0 K^+K^-) = (5.7 \pm 0.5\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.5\ (\text{norm.})) \times 10^{-5}$ and $\mathcal{B}(B_s^0 \to \overline{D}^{*0}\phi) = (3.7 \pm 0.5\ (\text{stat.}) \pm 0.3\ (\text{syst.}) \pm 0.2\ (\text{norm.})) \times 10^{-5}$; the third uncertainties arise from the branching fractions of decay modes used for normalisation. The most precise determinations of $\mathcal{B}(B^0 \to \overline{D}^0 K^+K^-) = (6.1 \pm 0.4\ (\text{stat.}) \pm 0.3\ (\text{syst.}) \pm 0.3\ (\text{norm.})) \times 10^{-5}$ and $\mathcal{B}(B_s^0 \to \overline{D}^0\phi) = (3.0 \pm 0.3\ (\text{stat.}) \pm 0.2\ (\text{syst.}) \pm 0.2\ (\text{norm.})) \times 10^{-5}$ are obtained, and an upper limit on the branching fraction of $B^0 \to \overline{D}^0\phi$ is set, $\mathcal{B}(B^0 \to \overline{D}^0\phi) < 2.0\ (2.2) \times 10^{-6}$ at 90% (95%) confidence level. Figure 3 shows the $B^0_{(s)}$ candidate invariant mass distributions fitted to determine these results.

In future, with larger data samples, $B_s^0 \to D^{(*)}\phi$ will be a promising decay mode to measure γ, and a time-dependent amplitude analysis of $B_s^0 \to DK^+K^-$ decays will allow constraints to be placed on γ and the *CP*-violating phase ϕ_s of the B_s^0 meson system.

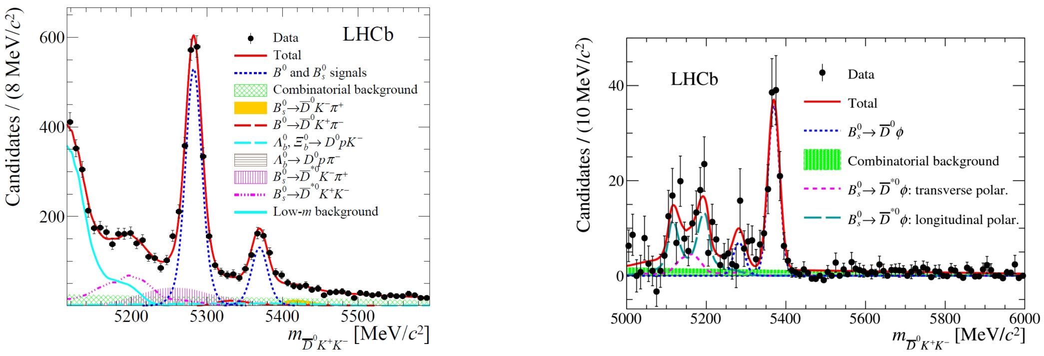

Figure 3: Fitted invariant mass distributions for $B^0_{(s)} \to \overline{D}^0 K^+ K^-$ candidates [18]. The left distribution shows all selected $B^0_{(s)} \to \overline{D}^0 K^+ K^-$ candidates. The right distribution shows the subset of candidates that have been statistically separated as $B^0_{(s)} \to \overline{D}^0 \phi$ using a fit to the K^+K^- invariant mass distribution.

5. Conclusions and prospects

Using LHCb data, the most precise measurement of γ from a single analysis has been determined with $B^- \to DK^-$ with $D \to K^0_S \pi^+ \pi^-$, $K^0_S K^+ K^-$ decays. The first measurement of decay-time-dependent CP asymmetries in $B^0 \to D^{\mp}\pi^{\pm}$ decays at a hadron collider has been used to place constraints on $|\sin(2\beta+\gamma)|$ and γ that are consistent with world average values. A combination of LHCb γ measurements, including these new results, leads to the most precise determination of γ from a single experiment. Decay modes with future sensitivity to γ, such as $B^0_s \to \overline{D}^0 K^+ K^-$ and $B^0_s \to \overline{D}^{*0}\phi$, have been observed for the first time, and the most precise determinations of the branching fractions of $B^0 \to \overline{D}^0 K^+ K^-$ and $B^0_s \to \overline{D}^0 \phi$ decays have been obtained. Studies of other new decay modes and analysis updates to include additional LHCb data will provide further measurements and constraints on γ in the near future.

Acknowledgement

The speaker expresses her gratitude for the generous support of the Leverhulme Trust in funding her participation in the conference.

References

[1] Heavy Flavor Averaging Group, Y. Amhis et al., *Averages of b-hadron, c-hadron, and tau-lepton properties as of summer 2016*, EPJ C77 (2017) 895 [arXiv:1612.07233]; updated Winter 2018 results available at https://hflav.web.cern.ch/

[2] J. Brod and J. Zupan, *The ultimate theoretical error on γ from $B \to DK$ decays*, JHEP 01 (2014) 51 [arXiv:1308.5663]

[3] J. Brod et al., *New physics effects in tree-level decays and the precision in the determination of the quark mixing angle γ*, Phys. Rev. D 92 (2015) 033002 [arXiv:1412.1446]

[4] LHCb collaboration, A. A. Alves Jr et al., *The LHCb Detector at the LHC*, JINST 3 (2008) S08005

[5] LHCb collaboration, R. Aaij et al., *LHCb detector performance*, Int. J. Mod. Phys. A 30 (2015) 1530022 [arXiv:1412.6352]

[6] A. Giri et al., *Determining γ using $B^{\pm} \to DK^{\pm}$ with multibody D decays*, Phys. Rev. D 68 (2003) 054018 [arXiv:hep-ph/0303187]; Belle collaboration, A. Poluektov et al., *Measurement of ϕ_3 with Dalitz plot analysis of $B^{\pm} \to D^{(*)}K^{\pm}$ decay*, Phys. Rev. D 70 (2004) 072003 [arXiv:hep-ex/0406067]

[7] CLEO Collaboration, J. Libby et al., *Model-independent determination of the strong-phase difference between D^0 and $\overline{D}^0 \to K^0_{S,L}h^+h^-$ ($h = \pi$, K) and its impact on the measurement of the CKM angle γ/ϕ_3*, Phys. Rev. D 82 (2010) 112006 [arXiv:hep-ex/1010.2817]

[8] LHCb collaboration, R. Aaij et al., *Measurement of the CKM angle γ using $B^{\pm} \to DK^{\pm}$ with $D \to K^0_S\pi^+\pi^-, K^0_S K^+K^-$ decays*, LHCb-PAPER-2018-017, submitted to JHEP [arXiv:1806.01202]

[9] LHCb collaboration, R. Aaij et al., *Measurement of the CKM angle γ using $B^{\pm} \to DK^{\pm}$ with $D \to K^0_S\pi^+\pi^-, K^0_S K^+K^-$ decays*, JHEP 10 (2014) 097 [arXiv:1408.2748]

[10] LHCb collaboration, R. Aaij et al., *Measurement of CP violation in $B^0 \to D^{\mp}\pi^{\pm}$ decays*, JHEP 06 (2018) 084 [arXiv:1805.03448]

[11] BaBar collaboration, B. Aubert et al., *Measurement of time-dependent CP asymmetries in $B^0 \to D^{(*)\pm}\pi^{\mp}$ and $B^0 \to D^{\pm}\rho^{\mp}$ decays*, Phys. Rev. D 73 (2006) 111101 [arXiv:hep-ex/0602049]; Belle collaboration, F. J. Ronga et al., *Measurements of CP-violation in $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^-\pi^+$ decays*, Phys. Rev. D 73 (2006) 092003 [arXiv:hep-ex/0604013]

[12] M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B^0_d \to DK_S$ and $B^0_s \to D\phi$*, Phys. Lett. B 253 (1991) 483; M. Gronau and D. Wyler, *On determining a weak phase from charged B decay asymmetries*, Phys. Lett. B 265 (1991) 172

[13] D. Atwood, I. Dunietz and A. Soni, *Enhanced CP violation with $B \to KD^0(\overline{D}^0)$ modes and extraction of the Cabibbo-Kobayashi-Maskawa angle γ*, Phys. Rev. Lett. 78 (1997) 3257; D. Atwood, I. Dunietz and A. Soni, *Improved methods for observing CP violation in $B^{\pm} \to KD$ and measuring the CKM phase γ*, Phys. Rev. D 63 (2001) 036005 [arXiv:hep-ph/0008090]

[14] T. Gershon, *On the measurement of the unitarity triangle angle γ from $B^0 \to DK^{*0}$ decays*, Phys. Rev. D 79 (2009) 051301(R) [arXiv:0810.2706]; T. Gershon and M. Williams, *Prospects for the measurement of the unitarity triangle angle γ from $B^0 \to DK^+\pi^-$ decays*, Phys. Rev. D 80 (2009) 092002 [arXiv:0909.1495]

[15] M. Gronau, *Improving bounds on γ in $B^{\pm} \to DK^{\pm}$ and $B^{\pm,0} \to DX_s^{\pm,0}$*, Phys. Lett. B 557 (2003) 198 [arXiv:hep-ph/0211282]

[16] I. Dunietz and R. Sachs, *Asymmetry between inclusive charmed and anticharmed modes in B^0, $\overline{B}^0$ decay as a measure of CP violation*, Phys. Rev. D 37 (1988) 3186; R. Aleksan, I. Dunietz, and B. Kayser, *Determining the CP-violating phase γ*, Z. Phys. C 54 (1992) 653; R. Fleischer, *New strategies to obtain insights into CP violation through $B_s \to D_s^{\pm}K^{\mp}$, $D_s^{*\pm}K^{\mp}$, ... and $B_d \to D^{\pm}\pi^{\mp}$, $D^{*\pm}\pi^{\mp}$, ... decays*, Nucl. Phys. B 671 (2003) 459 [arXiv:hep-ph/0304027]

[17] LHCb collaboration, R. Aaij et al., *Update of the LHCb combination of the CKM angle γ*, LHCb-CONF-2018-002 (2018)

[18] LHCb collaboration, R. Aaij et al., *Observation of the decay $B^0_s \to \overline{D}^0 K^+K^-$*, LHCb-PAPER-2018-014, submitted to Phys. Rev. D [arXiv:1807.01891]; LHCb collaboration, R. Aaij et al., *Observation of $B^0_s \to \overline{D}^{*0}\phi$ and search for $B^0 \to \overline{D}^0\phi$ decays*, LHCb-PAPER-2018-015, submitted to Phys. Rev. Lett. [arXiv:1807.01892]