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Measuring γ with B meson decays to charmed final states at LHCb

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Progress made by LHCb towards a measurement of γ using B decays to charmed final states is presented. The GLW/ADS analysis of $B^{\pm} \to DK^{\pm}$ using 1.0 fb^{-1} of data taken during 2011 is presented, with a combined 5.8 σ observation of CP violation. Updates on time-dependent studies and further time-integrated analyses are also included.

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1. Introduction

A precise measurement of the unitarity triangle angle γ is a key aim of the LHCb experiment. The angle γ is the least precisely known angle of the unitarity triangle, the experimental world averages are calculated by two different groups: CKMfitter obtain $(66 \pm 12)^\circ$ [1] and UTfit obtain $(75.5 \pm 10.5)^\circ$ [2]. The difference between the central values is under investigation. A summary of constraints to the Standard Model are shown in Fig. 1, it is clear that γ is the least precisely known quantity. Tree level decays provide a method to measure the Standard Model value of γ, as there are no potentially large contributions from new physics effects that enter in loop processes.

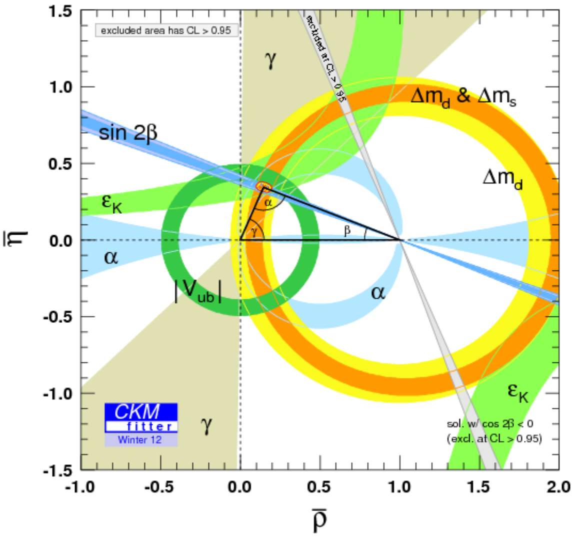

Figure 1: A plot of the $\bar{\rho}$-$\bar{\eta}$ plane, showing the experimental constraints to the Standard Model. Each band represents the best fit to the parameter as labelled. From the CKMfitter group [1].

The LHCb detector [3] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Excellent particle identification is provided by 2 ring imaging Cherenkov detectors to separate kaons, pions and protons. Proper time resolution of the order of 50 fs allows for time-dependent analyses to be performed with high precision. The LHCb software trigger includes topological selections that are designed to trigger very efficiently on B hadron decays to 2 or more charged tracks. The multi-body topological selections are based on multivariate techniques and are described in more detail in Ref. [4]. These are vital when studying the decay modes discussed in this document.

The focus of this report is to present results from two of the three time-integrated methods previously used to measure γ:

- Gronau-London-Wyler (GLW) - for decays of D mesons to CP eigenstates [5, 6].
- Atwood-Dunietz-Soni (ADS) - for decays of D mesons to flavour specific states [7].
- Giri-Grossman-Soffer-Zupan (GGSZ) - for 3 body decays of D mesons [8]. This method will not be discussed further.

There are two observables of interest for the GLW method, a *CP* asymmetry between the partial widths of the B and $\bar{B}$ decays,

$$A_{CP\pm} = \frac{\pm 2r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\gamma)}, \tag{1.1}$$

and a charge averaged rate ratio

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\gamma). \tag{1.2}$$

Here, r_B is the ratio of the suppressed B decay mode to the favoured B decay mode, δ_B is the strong phase difference and γ is the weak phase difference. One problem with the GLW method is that r_B is typically small, this reduces interference between the contributing diagrams.

For the ADS method there are a further two observables of interest, a *CP* asymmetry,

$$A_{ADS} = \frac{2r_B r_D \sin(\delta_D + \delta_B)\sin(\gamma)}{r_D^2 + r_B^2 + 2r_B r_D\cos(\delta_D + \delta_B)\cos(\gamma)}, \tag{1.3}$$

and a rate ratio

$$R_{ADS} = r_D^2 + r_B^2 + 2r_B r_D\cos(\delta_D + \delta_B)\cos(\gamma). \tag{1.4}$$

Here, r_D is the ratio of the suppressed D decay mode to the favoured D decay mode and δ_D is the strong phase difference between the D decay modes and again γ is the weak phase difference. An advantage of the ADS method over the GLW method is that the factor r_D helps to balance out the effect of r_B, increasing interference.

Time-dependent methods are also sensitive to γ [9]. For example, consider the decay $B_s^0 \to D_s^{\mp}K^{\pm}$. The sensitivity to γ derives from *CP* violation in the interference of $B_s^0 - \overline{B}_s^0$ mixing and decay processes. A time-dependent rate asymmetry may be defined:

$$\frac{\Gamma(B_s^0(t) \to D_s^{\mp}K^{\pm}) - \Gamma(\overline{B}_s^0(t) \to D_s^{\mp}K^{\pm})}{\Gamma(B_s^0(t) \to D_s^{\mp}K^{\pm}) + \Gamma(\overline{B}_s^0(t) \to D_s^{\mp}K^{\pm})} = \frac{C\cos(\Delta m_s t) + S\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - A_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}, \tag{1.5}$$

where $\Gamma(X \to YZ)$ is the decay rate of particle X decaying to daughters Y and Z, Δm_s is the mass difference between the B_s mass eigenstates B_s^L (light) and B_s^H (heavy), $\Delta\Gamma_s$ is the difference in width of the B_s mass eigenstates and $A_{\Delta\Gamma}$ is an asymmetry between the rates of the decay and the *CP* conjugate decay. C and S are parameters that are related to the strength of the interference effects between mixing and decay processes, with notation $C_s(S_s)$ for the decay and $\overline{C}_s(\overline{S}_s)$ for the *CP* conjugate decay. In order to measure γ, the four decay rates shown above must be measured; $\Gamma(B_s^0(t) \to D_s^- K^+)$, $\Gamma(B_s^0(t) \to D_s^+ K^-)$, $\Gamma(\overline{B}_s^0(t) \to D_s^- K^+)$ and $\Gamma(\overline{B}_s^0(t) \to D_s^+ K^-)$. Two observables may again be defined to make the dependence on γ clear:

$$s_+ = f(\langle S_s\rangle_+) = \cos(\delta_s)\sin(\phi_s + \gamma) \tag{1.6}$$

and

$$s_- = f(\langle S_s\rangle_-) = -\sin(\delta_s)\cos(\phi_s + \gamma), \tag{1.7}$$

where δ_s is the strong phase difference, ϕ_s is the mixing phase, γ the weak phase difference and

$$\langle S_s\rangle_\pm = \frac{\overline{S}_s \pm S_s}{2}. \tag{1.8}$$

2. GLW at LHCb

The GLW analysis of the decay mode $B^{\pm} \to Dh^{\pm}$, where h is K or π, was performed using the full 2011 data sample of 1.0 fb^{-1}. The decay modes of the D meson used were $\pi^+\pi^-$ and K^+K^-, which are both CP even. For a full description of the analysis see Ref. [10]. The B candidate invariant mass distributions for the $\pi^+\pi^-$ sample are shown in Fig 2 and for K^+K^- in Fig 3. The combined values of A_{CP+} and R_{CP+} were found to be

$$A_{CP+} = 0.145 \pm 0.032 \pm 0.010 \tag{2.1}$$

and

$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012, \tag{2.2}$$

where the first uncertainty is statistical and the second systematic. These measurements represent the most precise determinations of these quantities.

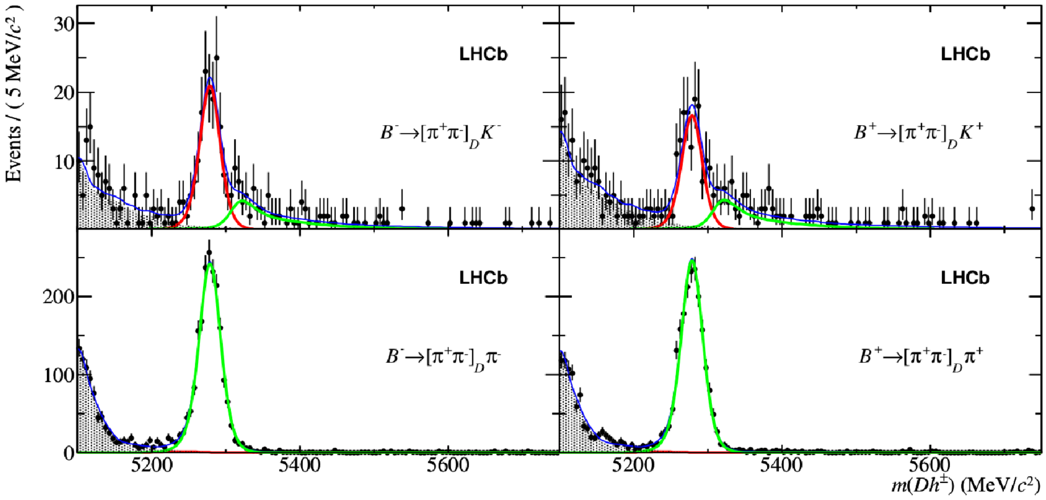

Figure 2: B candidate invariant mass distribution for $B^{\pm} \to Dh^{\pm}$ with $D \to \pi^+\pi^-$ candidates: (Top left) $B^- \to [\pi^+\pi^-]_D K^-$, (top right) $B^+ \to [\pi^+\pi^-]_D K^+$, (bottom left) $B^- \to [\pi^+\pi^-]_D \pi^-$ and (bottom right) $B^+ \to [\pi^+\pi^-]_D \pi^+$. The fitted probability density function (PDF) components are: (Blue) full fit, (red) $B^{\pm} \to DK^{\pm}$, (green) $B^{\pm} \to D\pi^{\pm}$ and (grey shaded) partially reconstructed B decays. Reproduced from Ref. [10].

3. ADS at LHCb

The decay modes $B^{\pm} \to Dh^{\pm}$, where $D \to K^{\mp}\pi^{\pm}$, were used to perform an ADS analysis using 1.0 fb^{-1} of data collected by LHCb in 2011. More details about the analysis can be found in Ref. [10] The B candidate invariant mass distributions for the Cabibbo favoured decay modes are shown in Fig. 4. Clear signal peaks are seen for each mode but no CP violation is visible by eye. The B candidate invariant mass plots are shown for the doubly Cabibbo suppressed modes in Fig 5. Clear hints of CP violation can be seen by eye in both the $B \to DK$ (4.0 σ) and $B \to D\pi$ (2.4 σ) samples. The values of $A_{ADS}(h)$ and $R_{ADS}(h)$ from this analysis are

$$A_{ADS}(K) = -0.52 \pm 0.15 \pm 0.02, \;\; A_{ADS}(\pi) = 0.143 \pm 0.062 \pm 0.011 \tag{3.1}$$

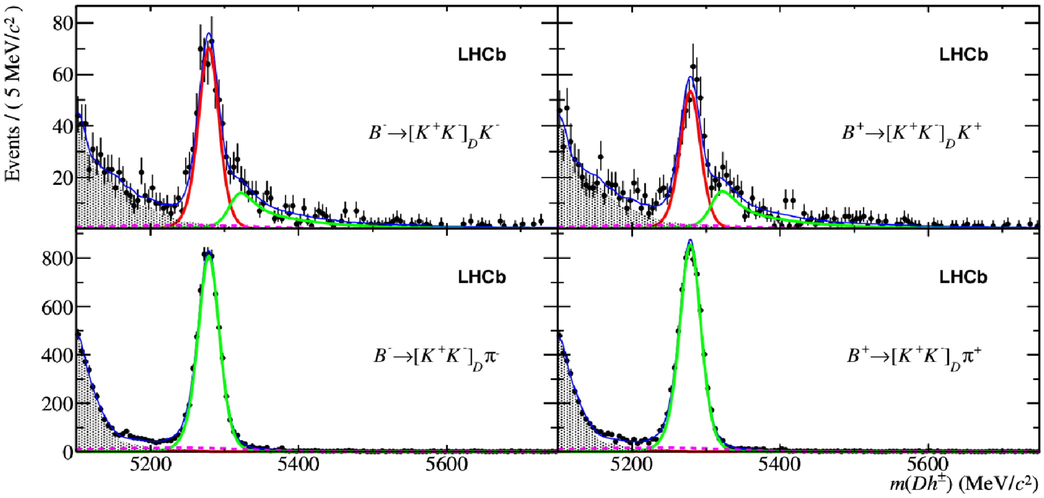

Figure 3: B candidate invariant mass distribution for $B^{\pm} \to Dh^{\pm}$ with $D \to K^+K^-$ candidates: (Top left) $B^- \to [K^+K^-]_D K^-$, (top right) $B^+ \to [K^+K^-]_D K^+$, (bottom left) $B^- \to [K^+K^-]_D \pi^-$ and (bottom right) $B^+ \to [K^+K^-]_D \pi^+$. The fitted PDF components are: (Blue) full fit, (red) $B^{\pm} \to DK^{\pm}$, (green) $B^{\pm} \to D\pi^{\pm}$, (grey shaded) partially reconstructed B decays and (pink dashed) $\Lambda_b \to \Lambda_c h$. Reproduced from Ref. [10].

and

$$R_{ADS}(K) = 0.0152 \pm 0.0020 \pm 0.0004, \;\; R_{ADS}(\pi) = 0.0041 \pm 0.00025 \pm 0.00005 \qquad (3.2)$$

where the first uncertainty is statistical and the second systematic. The notation (h) corresponds to the particle h in $B^{\pm} \to Dh^{\pm}$. The measurements of $A_{ADS}(h)$ and $R_{ADS}(h)$ are the most precise ever made.

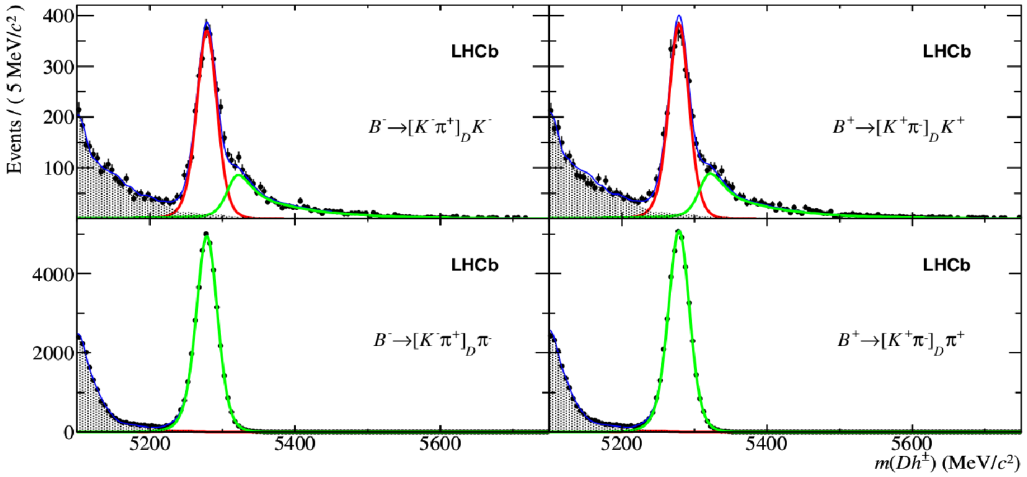

Figure 4: B candidate invariant mass distribution for Cabibbo favoured $B^{\pm} \to Dh^{\pm}$ with $D \to K\pi$ candidates: (Top left) $B^- \to [K^-\pi^+]_D K^-$, (top right) $B^+ \to [K^+\pi^-]_D K^+$, (bottom left) $B^- \to [K^-\pi^+]_D \pi^-$ and (bottom right) $B^+ \to [K^+\pi^-]_D \pi^+$. The fitted PDF components are: (Blue) full fit, (red) $B^{\pm} \to DK^{\pm}$, (green) $B^{\pm} \to D\pi^{\pm}$ and (grey shaded) partially reconstructed B decays. Reproduced from Ref. [10].

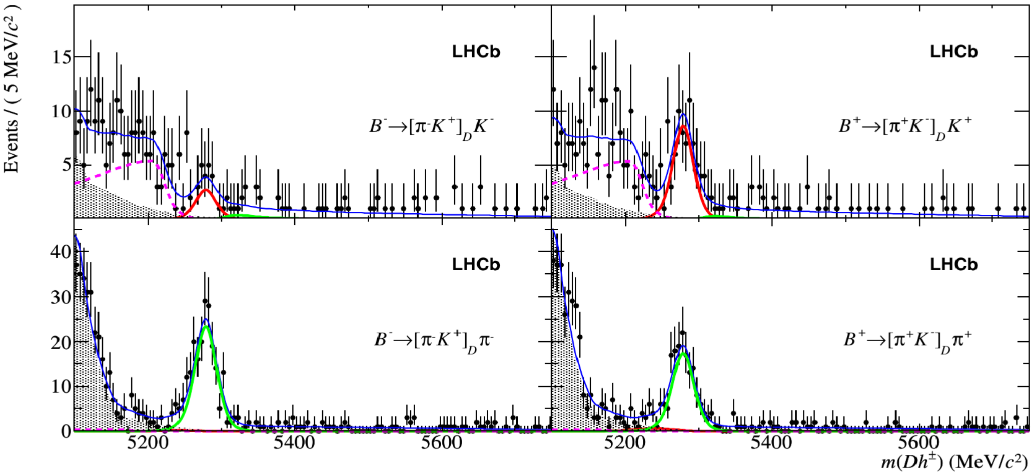

Figure 5: B candidate invariant mass distribution for doubly Cabibbo suppressed $B^\pm \to Dh^\pm$ with $D \to K\pi$ candidates: (Top left) $B^- \to [\pi^- K^+]_D K^-$, (top right) $B^+ \to [\pi^+ K^-]_D K^+$, (bottom left) $B^- \to [\pi^- K^+]_D \pi^-$ and (bottom right) $B^+ \to [\pi^+ K^-]_D \pi^+$. The fitted PDF components are: (Blue) full fit, (red) $B^\pm \to DK^\pm$, (green) $B^\pm \to D\pi^\pm$, (grey shaded) partially reconstructed B decays and (pink dashed) $B_s \to DK\pi$. Reproduced from Ref. [10].

4. Time-dependent methods

Time-dependent methods using decay modes such as $B_s^0 \to D_s^\mp K^\pm$ are sensitive to γ and, for this example, the mixing phase ϕ_s. The amplitudes of both contributing diagrams to this decay mode are of similar order, due to the CKM elements involved. This increases interference and makes this decay mode an exciting opportunity to measure γ. Excellent proper time resolution is required to resolve B_s oscillations and flavour tagging is vital to know the flavour of the B_s meson at production. Progress towards measuring γ using this decay mode at LHCb is promising. The B_s oscillation frequency was measured [11] to be

$$\Delta m_s = 17.63 \pm 0.11 \pm 0.02 \; ps^{-1}, \tag{4.1}$$

where the first uncertainty is statistical and the second systematic. The branching fraction of the decay mode $B_s^0 \to D_s^\mp K^\pm$ has also been measured [12] to be

$$\mathscr{B}(B_s^0 \to D_s^\mp K^\pm) = (1.90 \pm 0.12 \pm 0.13 \,{}^{+0.12}_{-0.14}) \times 10^{-4}, \tag{4.2}$$

where the first uncertainty is statistical, the second systematic and the third from the the value of f_s/f_d [13]. Figure 6 shows the B candidate invariant mass plot of the $B_s^0 \to D_s^\mp K^\pm$ sample.

5. Further studies

LHCb is exploring a vast plethora of decay modes that are sensitive to the angle γ. Some of these modes will be briefly discussed below:

- $B^0 \to DK^{*0}$

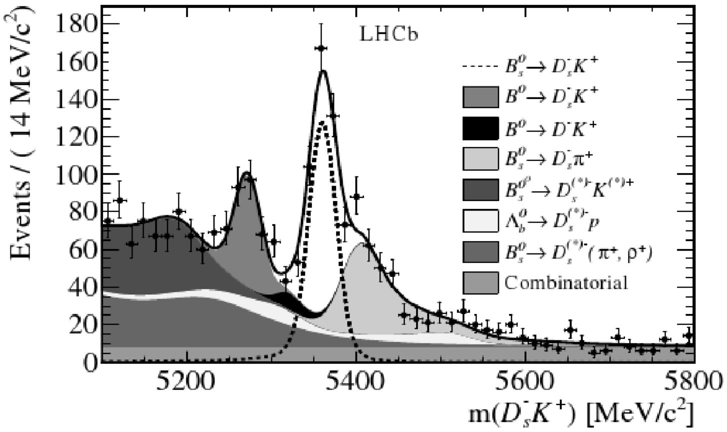

Figure 6: B candidate invariant mass plot of the $B_s^0 \to D_s^{\mp} K^{\pm}$ sample. Reproduced from [12].

- $\Lambda_b \to DpK$
- $B^{\pm} \to DK^{\pm}\pi^{\mp}\pi^{\pm}$

5.1 $B^0 \to DK^{*0}$

The GLW/ADS analysis using the decay mode $B^0 \to DK^{*0}$ is underway at LHCb. The analysis is similar to the GLW/ADS measurements using $B^{\pm} \to Dh^{\pm}$ candidates, as described in Secs. 2 and 3. The current progress is a measurement of the branching fraction of $\bar{B}_s^0 \to D^0 K^{*0}$ to be

$$\mathscr{B}(\bar{B}_s^0 \to D^0 K^{*0}) = (4.72 \pm 1.07 \pm 0.48 \pm 0.37 \pm 0.74) \times 10^{-4}, \tag{5.1}$$

where the uncertainties are statistical, systematic, from f_s/f_d and from $\mathscr{B}(\bar{B}^0 \to D^0 \rho^0)$. This B_s decay is very important because it shares the same final state with the suppressed B^0 decay, with 20 times the expected yield. It is therefore vital to understand this decay mode to be able to fit for the suppressed B^0 decay, which may be obscured by the tails of the B_s^0 mass peak.

5.2 $\Lambda_b \to DpK$

Beauty baryons provide another interesting opportunity to measure γ. One decay mode to consider is $\Lambda_b \to DpK$ because it is well suited to study at LHCb given that all of the final state particles are charged. The first step towards a γ measurement was the first observation [14] of the decay mode $\Lambda_b \to DpK$ at LHCb using approximately a third of the 2011 data sample. The branching ratio was measured with respect to a normalisation channel, $\Lambda_b \to Dp\pi$, to be

$$\frac{\mathscr{B}(\Lambda_b \to D^0 p K^-)}{\mathscr{B}(\Lambda_b \to D^0 p \pi^-)} = 0.112 \pm 0.019\,^{+0.011}_{-0.014}, \tag{5.2}$$

where the first uncertainty is statistical and the second systematic.

5.3 $B^{\pm} \to DK^{\pm}\pi^{\mp}\pi^{\pm}$

Multi-body modes provide additional ways to measure γ. One such mode under study at LHCb is $B^{\pm} \to DK^{\pm}\pi^{\mp}\pi^{\pm}$, which is similar to the decay mode $B^{\pm} \to DK^{\pm}$ with the addition of two charged pions. A first observation of the decay mode $B^{\pm} \to DK^{\pm}\pi^{\mp}\pi^{\pm}$ was performed using 35 pb^{-1} of data collected in 2010. The branching ratio was measured relative to that of $B^{\pm} \to D\pi^{\pm}\pi^{\mp}\pi^{\pm}$ to be

$$\frac{\mathscr{B}(B^- \to D^0K^-\pi^+\pi^-)}{\mathscr{B}(B^- \to D^0\pi^-\pi^+\pi^-)} = (9.4 \pm 1.3 \pm 0.9) \times 10^{-2}, \tag{5.3}$$

where the first uncertainty is statistical and the second systematic.

6. Conclusion

A new era of γ measurements has just started at LHCb. The world's most precise GLW/ADS measurements of the decay mode $B^{\pm} \to DK^{\pm}$ have been made, including a 10 σ observation of the suppressed decay $B^- \to [K^+\pi^-]_D K^-$ and a combined 5.8 σ observation of *CP* violation.

Many other analyses are also in progress, those mentioned in this document only touch the surface of what is to come in the following years. No single method or decay mode dominates the sensitivity to γ [15, 16], so all of the measurements are complimentary.

References

[1] CKMfitter Group, J. Charles et al., *CP violation and the CKM matrix: Assessing the impact of the asymmetric B factories*, *Eur.Phys.J.* **C41** (2005) 1–131, [`arXiv:hep-ph/0406184`].

[2] UTfit Collaboration, M. Ciuchini et al., *2000 CKM triangle analysis: A Critical review with updated experimental inputs and theoretical parameters*, *JHEP* **07** (2001) 013, [`arXiv:hep-ph/0012308`].

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

[4] V. Gligorov, C. Thomas, and M. Williams, *The HLT inclusive B triggers*, Tech. Rep. LHCb-PUB-2011-016, CERN, Geneva, Sep, 2011. LHCb-INT-2011-030.

[5] M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B_d^0 \to DK_S$ and $B_s^0 \to D\phi$*, *Phys. Lett.* **B253** (1991) 483–488.

[6] M. Gronau and D. Wyler, *On determining a weak phase from CP asymmetries in charged B decays*, *Phys. Lett.* **B265** (1991) 172–176.

[7] D. Atwood, I. Dunietz, and A. Soni, *Enhanced CP violation with $B \to KD^0(\bar{D}^0)$ modes and extraction of the CKM angle γ*, *Phys. Rev. Lett.* **78** (1997) 3257–3260, [`arXiv:hep-ph/9612433`].

[8] A. Giri, Y. Grossman, A. Soffer, and J. Zupan, *Determining γ using $B^{\pm} \to DK^{\pm}$ with multibody D decays*, *Phys. Rev.* **D68** (2003) 054018, [`arXiv:hep-ph/0303187`].

[9] R. Fleischer, *New strategies to obtain insights into CP violation through $B_s \to D_s^{\pm}K^{\pm}, D_s^{*\pm}K^{\mp}$ and $B_d \to D^{\pm}\pi^{\mp}, D^{*\pm}\pi^{\mp}$ decays*, *Nucl.Phys.* **B671** (2003) 459–482, [`arXiv:hep-ph/0304027`].

[10] LHCb collaboration, R. Aaij et al., *Observation of CP violation in $B^+ \to DK^+$ decays*, *Phys.Lett.* **B712** (2012) 203–212, [`arXiv:1203.3662`].

[11] LHCb Collaboration, R. Aaij et al., *Measurement of the B_s^0 - $\bar{B}_s^0$ oscillation frequency Δm_s in $B_s^0 \to D_s^-(3)\pi$ decays*, *Phys.Lett.* **B709** (2012) 177–184, [`arXiv:1112.4311`].

[12] LHCb Collaboration, R. Aaij et al., *Measurements of the branching fractions of the decays $B_s^0 \to D_s^{\mp} K^{\pm}$ and $B_s^0 \to D_s^- \pi^+$*, *JHEP* **06** (2012) [arXiv:1204.1237].

[13] LHCb collaboration, R. Aaij et al., *Determination of f_s/f_d for 7 TeV/c^2 pp collisions and a measurement of the branching fraction of the decay $B_d \to D^- K^+$*, *Phys. Rev. Lett.* **107** (2011) 211801, [arXiv:1106.4435].

[14] LHCb Collaboration, R. Aaij et al., *Studies of beauty baryons decaying to $D^0 p\pi^-$ and $D^0 pK^-$*, . LHCb-CONF-2011-031.

[15] J. Zupan, *The case for measuring γ precisely*, arXiv:1101.0134.

[16] A. Poluektov, *Ultimate sensitivity on γ/ϕ_3 from $B \to DK$*, arXiv:1101.4592.