PROCEEDINGS OF SCIENCE

Measurements of the CKM angle γ at LHCb

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The CKM angle γ is the least well-known angle of the Unitarity Triangle, and the only one easily accessible at tree level. Important constraints on γ are obtained from the analysis of $B^{\pm} \to D^0 K^{\pm}$ decays, where the D^0 meson is reconstructed in the K^+K^- or $\pi^+\pi^-$ final states; the latest world-best results using the Run 1 (2011 and 2012) and Run 2 (2015 and 2016) LHCb datasets are presented here. The measurement of $B^{\pm} \to D^{*0} K^{\pm}$ decays using a partial reconstruction method is also performed at LHCb for the first time, where both $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$ decays are considered. Both sets of results contribute to the ultimate goal of degree level precision on γ, via the exploitation of all possible channels and techniques.

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1. Introduction

Over-constraining the unitarity triangle derived from the CKM matrix is central to the validation of the Standard Model (SM) description of CP violation [1]. Its least well known angle is $\gamma \equiv \arg)(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$, which has been measured with a precision of about 7° from a combination of direct measurements [2]. This can be compared with the 3° and $< 1°$ precision on the other angles α and β [3, 4]. Among the three angles, γ is unique in that it does not depend on any coupling to the top quark, and thus can be studied at tree level with negligible theoretical uncertainty [5, 6]. Disagreement between direct measurements of γ (Fig. 1, top plot) and the value inferred from global CKM fits (Fig. 1, bottom plot), assuming the validity of the SM, would indicate new physics beyond the SM.

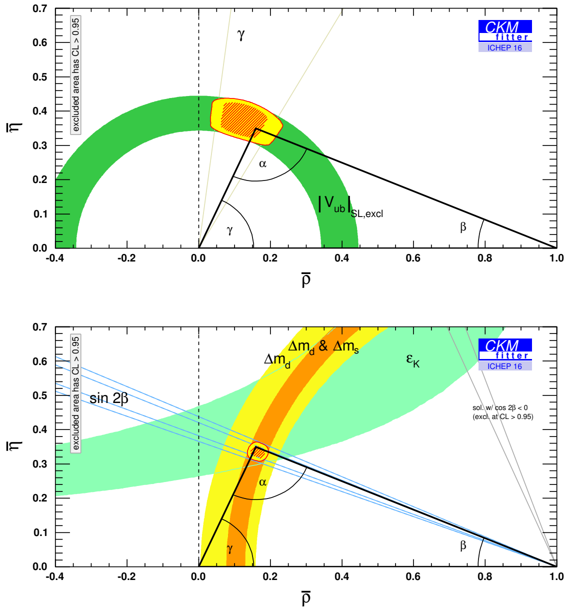

Figure 1: CKMfitter averages in the $(\bar{\rho}, \bar{\eta})$ plane. In the top plot, the current limits using only direct measurements of γ and exclusive measurements of V_{ub} in semileptonic decays are shown. In the bottom plot, the indirect limits are shown. (http://ckmfitter.in2p3.fr)

2. The ADS and GLW methods

The most powerful method for determining γ in tree-level decays is through the measurement of relative partial widths in $B^- \to DK^-$ decays, where D represents a D^0 or $\bar{D}^0$ meson.[1] The amplitude for the $B^- \to D^0K^-$ contribution is proportional to V_{cb} while the amplitude for $B^- \to \bar{D}^0K^-$ is proportional to V_{ub}. By reconstructing hadronic D decays accessible to both D^0 and $\bar{D}^0$ mesons, phase information can be extracted from the interference between the two amplitudes. The size of the resulting direct CP violation is governed by the magnitude of r_B^{DK}, the ratio of the $b \to u\bar{c}s$ amplitude to the $b \to c\bar{u}s$ amplitude. The relatively large value of r_B^{DK} (about 0.1) in $B^- \to DK^-$

[1]The inclusion of charge-conjugate processes is implied except in any discussion of asymmetries.

decays [3] allows the determination of the relative phase of the two interfering amplitudes. This relative phase has a *CP*-violating contribution from the weak interaction, γ, and a *CP*-conserving contribution from the strong interaction, δ_B^{DK}; a measurement of the decay rates for both B^+ and B^- gives sensitivity to γ. Similar interference effects occur in $B^- \to D\pi^-$ decays, albeit with reduced sensitivity to the phases because, due to additional Cabibbo suppression factors, the ratio of amplitudes is about 20 times smaller.

$B^- \to D^*K^-$ decays, in which the vector D^* meson decays to either $D\pi^0$ and $D\gamma$, also exhibit direct *CP* violation effects when hadronic D decays accessible to both D^0 and $\bar{D}^0$ mesons are reconstructed. In this case, the exact strong phase difference of π between $D^* \to D\pi^0$ and $D^* \to D\gamma$ decays can be exploited to measure *CP* observables for states with opposite *CP* eigenvalues [7]. The amount of direct *CP* violation observed in $B^- \to D^*K^-$ decays is determined by the magnitude of the ratio $r_B^{D^*K}$, and a measurement of the phase for both B^+ and B^- allows γ and $\delta_B^{D^*K}$ to be disentangled.

The study of $B^- \to D^{(*)0}K^-$ decays for measurements of γ was first suggested for *CP* eigenstates of the D decay, for example the *CP*-even $D \to K^+K^-$ and $D \to \pi^+\pi^-$ decays, labelled here GLW modes [8, 9]. The argument has also been extended to suppressed $D \to \pi^-K^+$ decays where the interplay between the favoured and suppressed decay paths in both the B^- and the neutral D decays results in a large charge asymmetry. This so-called ADS mode [10] introduces a dependence on the ratio of the suppressed and favoured D decay amplitudes, r_D, and their phase difference, δ_D. The $B^- \to [h^+h^-]_D h^-$ ADS/GLW decays ($h = K, \pi$) have been studied at the B factories [11, 12] and at LHCb [13] using Run 1 data. The $B^- \to (D^{*0} \to [h^+h^-]_D\pi^0)h^-$ and $B^- \to (D^{*0} \to [h^+h^-]_D\gamma)h^-$ decays have also been studied by the B factories [14, 15].

3. Updated $B^- \to Dh^-$ GLW measurements at LHCb

During 2015 and 2016 (Run 2), an additional $2\,\text{fb}^{-1}$ of pp collision data was collected by LHCb at a centre-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$. This resulted in an increase in the sample size of approximately a factor two with respect to the $3\,\text{fb}^{-1}$ Run 1 analysis [13]. The $B^- \to Dh^-$ decays, with $D \to KK$ and $\pi\pi$, have been measured using the combined Run 1 and Run 2 dataset, providing an update of the previous measurements. The results are

$$\begin{aligned}
A_K^{K\pi} &= -0.019 \pm 0.005\ \text{(stat.)} \pm 0.002\ \text{(syst.)}\\
A_\pi^{KK} &= -0.008 \pm 0.003\ \text{(stat.)} \pm 0.002\ \text{(syst.)}\\
A_K^{KK} &= +0.126 \pm 0.014\ \text{(stat.)} \pm 0.001\ \text{(syst.)}\\
A_\pi^{\pi\pi} &= -0.008 \pm 0.006\ \text{(stat.)} \pm 0.002\ \text{(syst.)}\\
A_K^{\pi\pi} &= +0.115 \pm 0.025\ \text{(stat.)} \pm 0.008\ \text{(syst.)}\\
R^{KK} &= 0.988 \pm 0.015\ \text{(stat.)} \pm 0.013\ \text{(syst.)}\\
R^{\pi\pi} &= 0.992 \pm 0.027\ \text{(stat.)} \pm 0.032\ \text{(syst.)}
\end{aligned}$$

where the first uncertainty quoted is statistical and the second is systematic. The results improve upon the precision in Ref. [13], and are world-best measurements of *CP* observables in these decays. Of particular importance is the reduced tension between the *CP* asymmetries measured in $B^- \to$

$[K^+K^-]_D K^-$ and $B^- \to [\pi^+\pi^-]_D K^-$ decays, which are denoted A_K^{KK} and $A_K^{\pi\pi}$, respectively. The tension in the Run 1 measurement has reduced due to a larger value of A_K^{KK} being measured in the Run 2 sample; the values of A_K^{KK} measured in the Run 1 and Run 2 samples are compatible at the level of 2.6 standard deviations. These 2-body GLW updates form part of a suite of measurements employed within a combined LHCb measurement of γ, as described in Sec. 6.

4. Looking beyond $B^- \to DK^-$ decays

Reducing the uncertainty on γ requires the measurement of *CP* observables in many different tree-level decay modes. It is thus important to extend the ADS/GLW formalism beyond $B^- \to DK^-$ decays. This can be achieved through the study of two additional types of *CP*-violating B^- meson decays, namely $B^- \to DK^{*-}$ and $B^- \to D^*K^-$. LHCb has performed a measurement of *CP* observables in $B^- \to DK^{*-}$ decays, where the D meson is reconstructed in the 2-body $K^+\pi^-$, K^+K-, $\pi^+\pi^-$ and $K^-\pi^+$ final states. The 4 fb^{-1} analysis was shown at CKM 2016, and appears in Ref. [16]. It will soon be updated to include the full 5 fb^{-1} dataset.

The $B^- \to D^*K^-$ decay is theoretically similar to $B^- \to DK^-$, with the additional feature that the $D^* \to D\pi^0$ and $D^* \to D\gamma$ sub-decays differ in their strong phase by exactly π [7]. A measurement of *CP* observables in $B^- \to (D^* \to D\pi^0)K^-$ and $B^- \to (D^* \to D\gamma)K^-$ decays enables the determination of γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$, and is thus well motivated to pursue across a variety of D final states. The analysis of such decays is challenging, however, due to the low reconstruction efficiency of π^0 mesons and photons at LHCb. To circumvent this limitation, a partial reconstruction approach has been developed at LHCb, where the π^0 or photon produced in the vector D^* decay is not considered in the total invariant mass calculation. The technique focuses on the invariant mass parameter $m(Dh)$, which in the case of $B^- \to (D^* \to D\pi^0)K^-$ decays exhibits a distinctive double-peaked structure, as shown in Fig. 2 (left plot). The $m(Dh)$ distribution for $B^- \to (D^* \to D\gamma)K^-$ decays by comparison exhibits a gently sloping distribution, as shown in Fig. 2 (right plot). The difference between the distributions is attributable to the different spins and masses of the π^0 and photon produced in the strong D^* decay.

An additional benefit of this procedure is that the partially reconstructed $B^- \to D^*h^-$ candidates are selected in the same reconstructed final state as their $B^- \to Dh^-$ counterparts. This enables the simultaneous measurement of *CP* observables in both $B^- \to Dh^-$ decays (see Sec. 3) and $B^- \to D^*h^-$ decays within the same invariant mass fit.

Binned extended maximum likelihood fits to the data are shown in Figs. 3, 4 and 5 for the $D \to K\pi$, KK and $\pi\pi$ modes, respectively. Candidate B^- mesons are shown in the left plots, while B^+ candidates are shown in the right plots. This split by charge enables *CP* asymmetries to be measured, by correcting raw asymmetries for production and detection asymmetry effects. Candidates reconstructed as $B^- \to D\pi^-$ are shown in the bottom plots, and candidates reconstructed as $B^- \to DK^-$ are shown in the top plots. Each of the components of the invariant mass fit are listed in the Fig. 3 legend. Several sources of background contribute in addition to the $B^- \to Dh^-$ and $B^- \to D^*h^-$ signal contributions.

In Figs. 4 and 5, there is clear evidence of *CP*-violation in $B^- \to DK^-$ decays (red solid line). The $B^- \to (D^* \to D\pi^0)K^-$ (blue filled region) and $B^- \to (D^* \to D\gamma)K^-$ (cyan filled region)

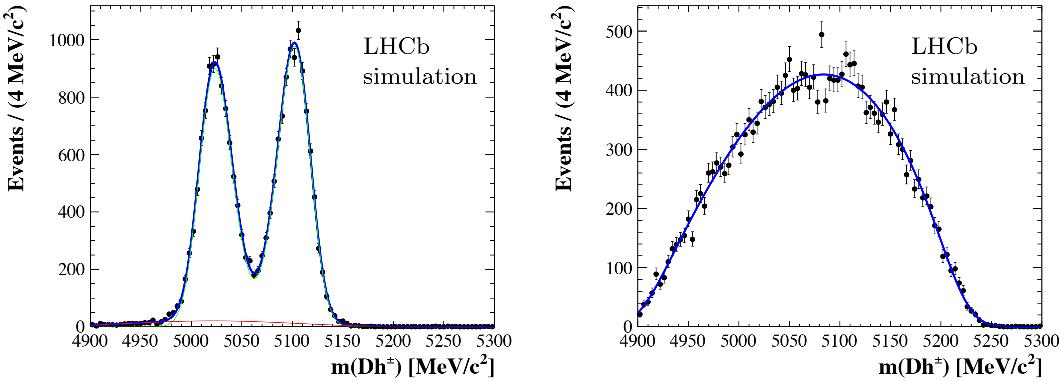

Figure 2: Invariant mass fits to the $m(DK)$ distributions of $B^- \to (D^* \to D\pi^0)K^-$ (left) and $B^- \to (D^* \to D\gamma)K^-$ (right) simulated decays. In the left plot, a small red component is included along with the primary green component in order to model the radiative tail. The visible difference in the $B^- \to (D^* \to D\pi^0)K^-$ (left) and $B^- \to (D^* \to D\gamma)K^-$ distributions enables them to be distinguished in the fit to data.

also have visible *CP* asymmetries, with opposing relative directions relative to each other. This is expected from the strong phase relationship between these modes.

The *CP* observables measured for the partially reconstructed $B^- \to (D^* \to D\pi^0)K^-$ and $B^- \to (D^* \to D\gamma)K^-$ modes are

$$\begin{aligned} A_K^{K\pi,\gamma} &= +0.001 \pm 0.022\ (\text{stat.}) \pm 0.007\ (\text{syst.}) \\ A_K^{K\pi,\pi^0} &= +0.006 \pm 0.012\ (\text{stat.}) \pm 0.004\ (\text{syst.}) \\ A_K^{CP,\gamma} &= +0.273 \pm 0.093\ (\text{stat.}) \pm 0.040\ (\text{syst.}) \\ A_K^{CP,\pi^0} &= -0.151 \pm 0.033\ (\text{stat.}) \pm 0.013\ (\text{syst.}) \\ R^{CP,\gamma} &= 0.909 \pm 0.087\ (\text{stat.}) \pm 0.099\ (\text{syst.}) \\ R^{CP,\pi^0} &= 1.138 \pm 0.029\ (\text{stat.}) \pm 0.082\ (\text{syst.}) \end{aligned}$$

where the first uncertainties quoted are statistical and the second are systematic. This is the first time that $B^- \to D^*K^-$ decays have been measured at LHCb, and also the first time that the partial reconstruction method has been used in order to measure *CP* asymmetries. At present, only the GLW modes are included, but the approach will be extended to include the ADS modes in the near future.

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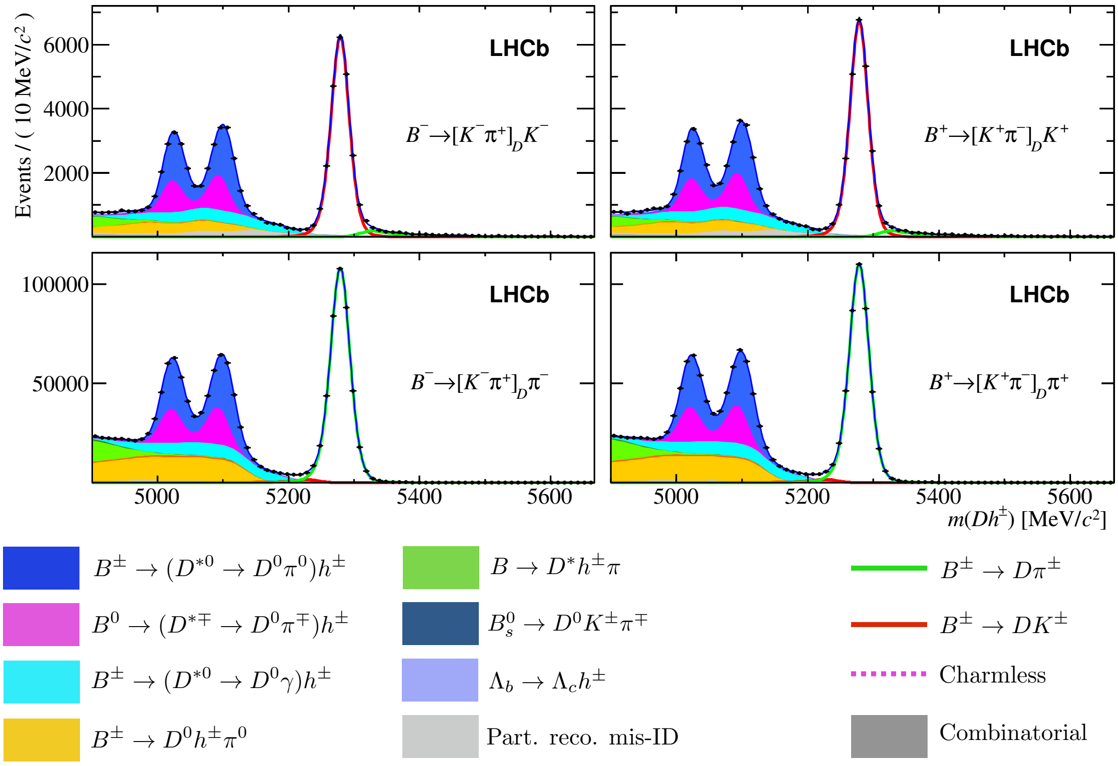

Figure 3: Invariant mass fits to candidates reconstructed in the $[K^-\pi^+]_D h^-$ final state. Each component of the fit is listed in the legend; the total probability density function is shown by the thin blue solid line.

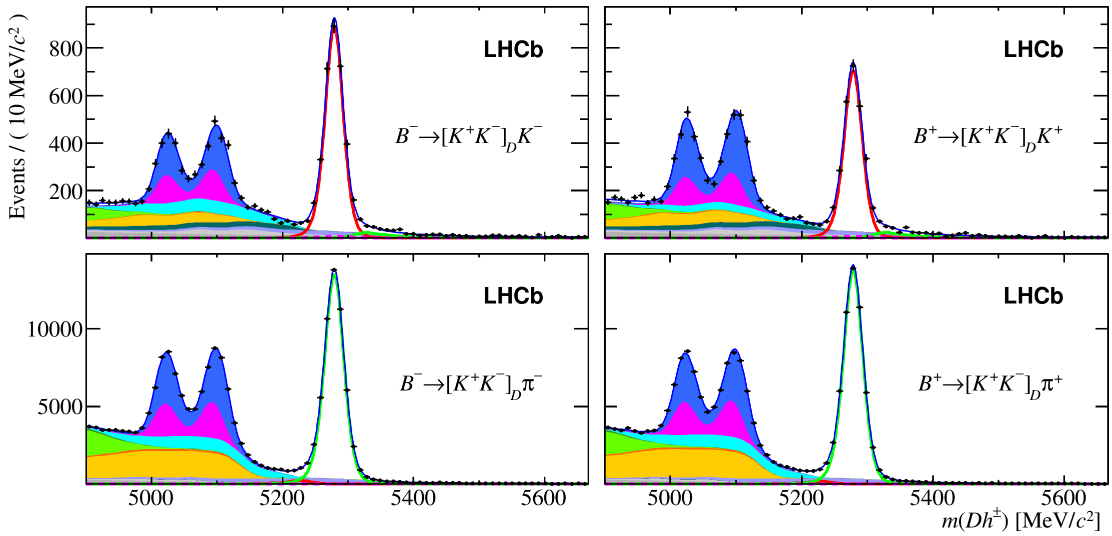

Figure 4: Invariant mass fits to candidates reconstructed in the $[K^-K^+]_D h^-$ final state.

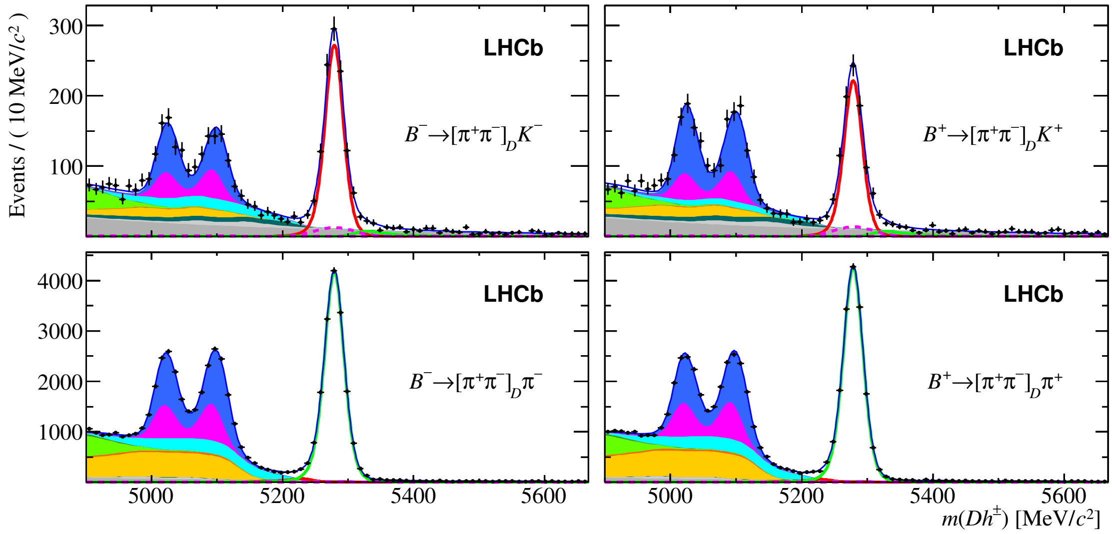

Figure 5: Invariant mass fits to candidates reconstructed in the $[\pi^-\pi^+]_D h^-$ final state.

5. From *CP* observables to γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$

The six *CP* observables measured using partially reconstructed $B^- \to (D^* \to D\pi^0)K^-$ and $B^- \to (D^* \to D\gamma)K^-$ decays can be used to constrain the fundamental parameters γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$. The profile likelihood contours determined using only the measurements listed in Sec. 4 are shown in Fig. 6. Although these measurements alone cannot uniquely determine γ, they do add statistical power when combined with measurements of other B decays such as the fully reconstructed $B^- \to DK^-$ modes. The contours indicate that the value of γ measured agrees within one standard deviation with the LHCb combination average [2]. The preferred values of $r_B^{D^*K}$ and $\delta_B^{D^*K}$ also align well with the current HFLAV world averages for $B^- \to D^*K^-$ decays, which are determined using $D \to K_s^0 h^+ h^-$ decays [17].

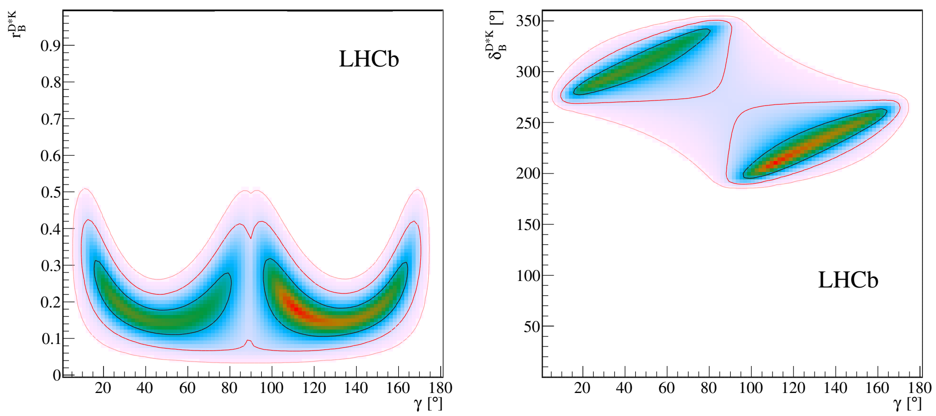

Figure 6: Profile likelihood contours for γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$, constructed using the six *CP* observables measured for partially reconstructed $B^- \to (D^* \to D\pi^0)K^-$ and $B^- \to (D^* \to D\gamma)K^-$ decays.

6. Combination

The *CP* observable results listed in Sec. 3 and Sec. 4 form part of a set of input parameters used in a dedicated measurement of γ at LHCb. This latest combination, which supersedes Ref. [2], contains the following updates and additions:

- $B^- \to D^* K^-$ (to appear in LHCb-PAPER-2017-021)
- $B^- \to DK^-$ GLW update (to appear in LHCb-PAPER-2017-021)
- $B^- \to DK^{*-}$ ADS/GLW [16]
- $B_s^0 \to D_s^- K^+$ time-dependent [18]

The value of γ measured by the full combination (to appear in LHCb-CONF-2017-004) is

$$\gamma = (76.8^{+5.1}_{-5.7})^\circ$$

and the corresponding one-dimensional profile likelihood distribution is shown in Fig. 7. This is the most precise measurement of γ from a single experiment, and improves upon the precision quoted in Ref. [2] by around 2°. The addition of further modes to this combination, as well as updates to existing modes to include Run 2 data, promise to decrease the uncertainty on γ yet further.

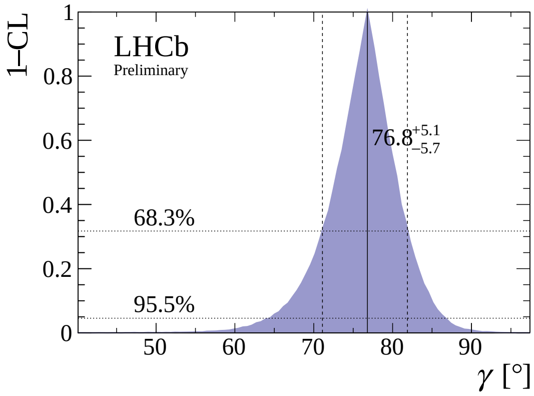

Figure 7: One-dimensional profile likelihood contour for γ, as measured in the latest LHCb combination (to appear in LHCb-CONF-2017-004).

7. Conclusions

Updated measurements of *CP* observables in $B^- \to DK^-$ GLW decays are reported, which improve upon those in Ref. [13] and are world-best measurements. Measurements of *CP* observables in $B^- \to D^* K^-$ decays are also reported for the first time at LHCb, using a novel method of partial reconstruction. Profile likelihood contours for γ, $r_B^{D^*K}$ and $\delta_B^{D^*K}$ are constructed, and are in agreement with the LHCb combination value of γ [2] and the HFLAV averages for $r_B^{D^*K}$ and $\delta_B^{D^*K}$ [17]. An updated combination measurement of γ is also reported, which supersedes Ref. [2] due to the addition of the results presented within, as well as those in Refs. [16] and [18]. The value of γ determined is the most precise measurement by a single experiment, and represents an improvement in precision of around 2° relative to Ref. [2].

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