PROCEEDINGS OF SCIENCE

Measurements of the CKM angle γ at LHCb

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These proceedings describe two LHCb measurements of the CKM angle γ: a measurement with $B^0 \to DK^{*0}$ decays where the D meson decays into two- and four-body final states, using proton-proton collision data corresponding to an integrated luminosity of $5\,\mathrm{fb}^{-1}$, and a measurement using $B^{\pm} \to DK^{\pm}$ decays where the D decays into the final states $K^0_S\pi^+\pi^-$ and $K^0_S K^+ K^-$, using data corresponding to an integrated luminosity of $2\,\mathrm{fb}^{-1}$. Furthermore, the combination of all LHCb measurements of γ is described. This combination constitutes the world-leading, single-experiment direct determination of γ and obtains the value $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$.

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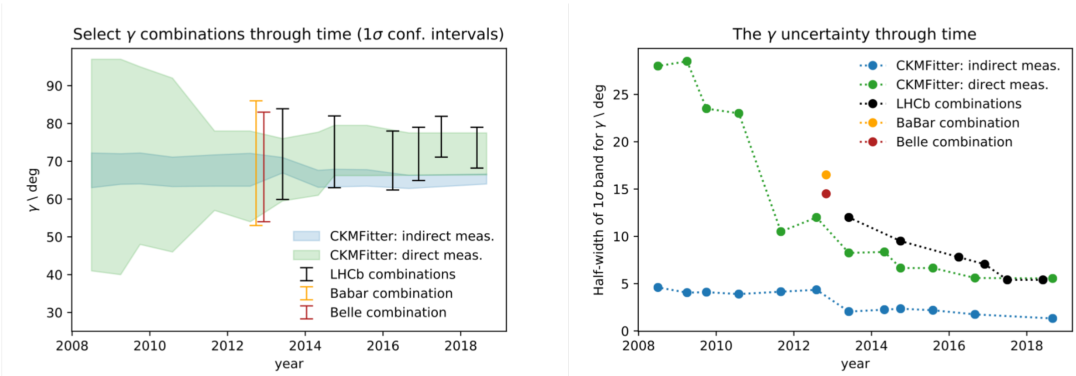

Figure 1: (Left) Combinations of direct γ measurements from Belle [4], BaBar [5], LHCb [6, 7, 8, 9, 10, 11], and the global averages by CKMFitter [12], as well as indirect determinations of γ by CKMFitter [12]. (Right) Comparison of uncertainties on the γ combinations.

1. Introduction

One of the main physics goals of the LHCb experiment is to perform high precision measurements of CKM [1, 2] parameters of the Standard Model (SM). Measurements of the CKM angle $\gamma \equiv \arg\left(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right)$ play a key role, because γ can be measured in tree-level processes, with negligible theoretical uncertainties [3]. Thus, these measurements are simple to interpret within the SM, and less likely to be affected by potential New Physics effects than measurements relying on loop-level processes. A consistency test of the SM can be obtained by comparing direct measurements of γ with indirect determinations, based on observables measured in loop-level processes and related to γ assuming the SM to hold true. Recent averages of both direct measurements and indirect determinations of γ are shown in Fig. 1, where it is clear that this consistency test is currently limited by the precision of existing direct measurements. The LHCb experiment is currently world-leading in improving this precision.

Experimentally, γ is probed via observables sensitive to interference between $b \to uW$ and $b \to cW$ quark-level transitions. The majority of LHCb measurements of γ rely on interference between $B \to D^0K$ and $B \to \bar{D}^0K$ type decays, the classical example being the $B^\pm \to DK^\pm$ channel, where the D meson is reconstructed in a final state common to D^0 and $\bar{D}^0$ mesons.[1] The CP-violating phase between the two B decays is $\pm\gamma$, where the sign depends on the B charge (or flavour), and can be measured along with a CP-conserving phase difference, δ_B, and the ratio of the amplitude magnitudes, r_B. For a D final state f common to both D^0 and $\bar{D}^0$ mesons, as well as its CP conjugate state $\bar{f}$, four decay rates sensitive to γ can be considered:

$$
\begin{aligned}
\Gamma(B^- \to D(\to f)K^-) &\propto 1 + r_D^2 r_B^2 + 2r_B r_D \cos\left[\delta_B + \delta_D - \gamma\right], \\
\Gamma(B^+ \to D(\to f)K^+) &\propto r_D^2 + \ \ r_B^2 + 2r_B r_D \cos\left[\delta_B - \delta_D + \gamma\right], \\
\Gamma(B^- \to D(\to \bar{f})K^-) &\propto r_D^2 + \ \ r_B^2 + 2r_B r_D \cos\left[\delta_B - \delta_D - \gamma\right], \\
\Gamma(B^+ \to D(\to \bar{f})K^+) &\propto 1 + r_D^2 r_B^2 + 2r_B r_D \cos\left[\delta_B + \delta_D + \gamma\right].
\end{aligned}
\tag{1.1}
$$

[1] LHCb has also published measurements based on time-dependent analyses of $B_s^0 \to D_s^\mp K^\pm$ [13] and $B^0 \to D^\mp \pi^\pm$ [14] decays, but they are not treated in these proceedings.

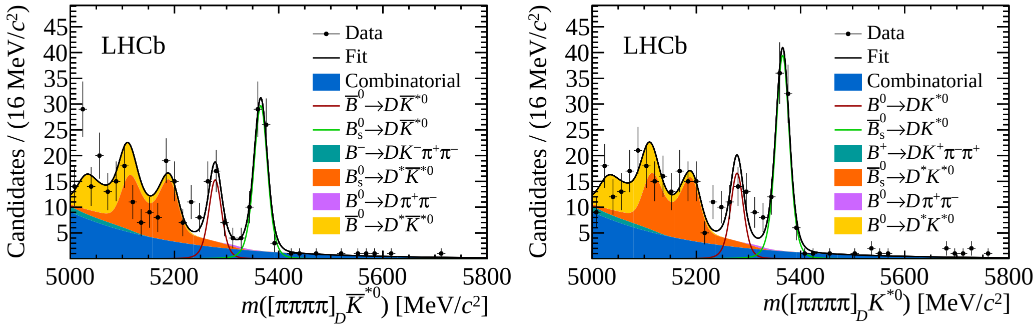

Figure 2: Invariant-mass distributions (data points with error bars) and fit projections (lines and coloured areas) for the four-body GLW modes (left) $\bar{B}^0 \to D(\to \pi^+\pi^-\pi^+\pi^-)\bar{K}^{*0}$ and (right) $B^0 \to D(\to \pi^+\pi^-\pi^+\pi^-)K^{*0}$.

Here, the decay amplitudes for $\bar{D}^0 \to f$ decays and $D^0 \to f$ decays are related via $A(\bar{D}^0 \to f) = r_D e^{i\delta_D} A(D^0 \to f)$, where $r_D < 1$ if f is chosen so the former decay is suppressed. The effect of *CP* violation in the D decay is not included, and is negligible compared to the precision of current measurements. These equations (or equivalent versions for $B^0 \to DK^{*0}$ and other, similar decays) form the basis of a number of related measurement strategies, the exact analysis approach depending on the chosen D final state. Naturally, the best sensitivity to γ is achieved by combining measurements in many different channels. These proceedings cover two such measurements, as well as the combination of all LHCb results.

2. ADS/GLW measurement with $B^0 \to DK^{*0}$ decays

LHCb has recently published a measurement using $B^0 \to DK^{*0}$ decays [15], where the D mesons decay in the so-called GLW [16, 17] modes $D \to \pi^+\pi^-$ and $D \to K^+K^-$, which are *CP* eigenstates, the quasi-GLW [18, 19] mode $D \to \pi^+\pi^-\pi^+\pi^-$, as well as the so-called ADS [20, 21] modes $D \to \pi^\pm K^\mp$ and $D \to \pi^\pm K^\mp \pi^+\pi^-$. Two charge associations of the $K\pi$ pair are considered in the latter cases, denoted the favoured mode, $D^0 \to K^-\pi^+(\pi\pi)$, and suppressed mode, $D^0 \to \pi^- K^+(\pi\pi)$. The measurement uses 3 fb^{-1} of data taken in Run 1, and 2 fb^{-1} of data taken in 2015 and 2016.

In the GLW channels, where the D mesons are reconstructed in *CP* eigenstates, Eqs. (1.1) simplify since $f = \bar{f}$, $r_D = 1$, and $\delta_D = 0$ (for *CP*-even eigenstates). The *CP* asymmetry

$$A_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \to D_{CP}\bar{K}^{*0}) - \Gamma(B^0 \to D_{CP}K^{*0})}{\Gamma(\bar{B}^0 \to D_{CP}\bar{K}^{*0}) + \Gamma(B^0 \to D_{CP}K^{*0})} = \frac{2\kappa r_B^{DK^{*0}} \sin\delta_B^{DK^{*0}} \sin\gamma}{R_{CP}} \tag{2.1}$$

is measured. It can be obtained from the raw yield asymmetry, if it is corrected for any potential production asymmetry between B^0 and $\bar{B}^0$ mesons, and detection asymmetries for the final state products. As shown, it can be related to the physics parameters $(\gamma, r_B^{DK^{*0}}, \delta_B^{DK^{*0}})$ via another observable, the ratio

$$R_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \to D_{CP}\bar{K}^{*0}) + \Gamma(B^0 \to D_{CP}K^{*0})}{\Gamma(\bar{B}^0 \to D^0\bar{K}^{*0}) + \Gamma(B^0 \to \bar{D}^0K^{*0})}. \tag{2.2}$$

The relation can be derived via equations equivalent to those in Eq. (1.1), with the inclusion of a coherence factor, $\kappa = 0.958^{+0.005}_{-0.046}$ [22], in the interference term that accounts for the fact that $B^0 \to DK^{*0}$ is not the only resonance contributing to the full $B \to D\pi K$ amplitude. The ratio R_{CP} can be obtained from the yield ratio between the GLW mode in question and the favoured ADS mode, using known branching fractions of the D^0 meson. The $D \to \pi^+\pi^-\pi^+\pi^-$ mode can be analysed analogously to the pure *CP* eigenstates because the *CP*-even fraction of the decay $F_+^{4\pi} = 0.769 \pm 0.023$ has been measured in quantum-correlated $D^0\bar{D}^0$ decays [23]. For this mode, all interference terms of Eqs. (1.1) obtain an additional factor of $(2F_+^{4\pi} - 1)$. The B mass spectra that have been fit to obtain the yields are shown for this channel in Fig. 2. The obtained results from all GLW-like measurements are

$$\begin{aligned} A_{CP}^{KK} &= -0.05 \pm 0.10 \pm 0.01, \\ A_{CP}^{\pi\pi} &= -0.18 \pm 0.14 \pm 0.01, \\ R_{CP}^{KK} &= 0.92 \pm 0.10 \pm 0.02, \\ R_{CP}^{\pi\pi} &= 1.32 \pm 0.19 \pm 0.03, \\ A_{CP}^{4\pi} &= -0.03 \pm 0.15 \pm 0.01, \\ R_{CP}^{4\pi} &= 1.01 \pm 0.16 \pm 0.04, \end{aligned} \tag{2.3}$$

where the first uncertainty is statistical, and the second arises due to systematic effects. Furthermore this measurement constitutes a first observation of the decay mode $B^0 \to D(\to \pi^+\pi^-\pi^+\pi^-)K^{*0}$ with a significance of 8.4σ.

In the ADS modes, the measured observables are the ratios

$$\begin{aligned} R_+^{\pi K(\pi\pi)} &= \frac{\Gamma(B^0 \to D(\to \pi^+K^-(\pi^+\pi^-))K^{*0})}{\Gamma(B^0 \to D(\to K^+\pi^-(\pi^+\pi^-))K^{*0})}, \\ R_-^{\pi K(\pi\pi)} &= \frac{\Gamma(\bar{B}^0 \to D(\to \pi^+K^-(\pi^+\pi^-))\bar{K}^{*0})}{\Gamma(\bar{B}^0 \to D(\to K^+\pi^-(\pi^+\pi^-))\bar{K}^{*0})}. \end{aligned} \tag{2.4}$$

These ratios can be related to the underlying physics parameters of interest $(\gamma, r_B^{DK^{*0}}, \delta_B^{DK^{*0}})$ via equations equivalent to those in Eq. (1.1), again including the coherence factor κ, and, in the $D \to K^\pm\pi^\mp\pi^+\pi^-$ case, a second coherence factor, $\kappa^{K3\pi} = 0.43^{+0.17}_{-0.13}$ [24] that arises due to interference between the D^0 and $\bar{D}^0$ amplitudes over the phase space of the D decay. The obtained results are

$$\begin{aligned} R_+^{\pi K} &= 0.064 \pm 0.021 \pm 0.002, \\ R_-^{\pi K} &= 0.095 \pm 0.021 \pm 0.003, \\ R_+^{\pi K\pi\pi} &= 0.074 \pm 0.026 \pm 0.002, \\ R_-^{\pi K\pi\pi} &= 0.072 \pm 0.025 \pm 0.003, \end{aligned} \tag{2.5}$$

where the first uncertainty is statistical, and the second arises due to systematic effects. *CP* asymmetries analogous to that in Eq. (2.1) are measured in the favoured ADS channels, where they are expected to be very small. The obtained values are $A_{ADS}^{K\pi} = 0.047 \pm 0.027 \pm 0.010$ and $A_{ADS}^{K\pi\pi\pi} = 0.037 \pm 0.032 \pm 0.010$. Finally, this measurement constitutes a first observation of the suppressed ADS decay mode $B^0 \to D(\to \pi^-K^+)K^{*0}$ with a significance of 5.8σ, and obtains evidence of the suppressed four-body mode with a significance of 4.4σ.

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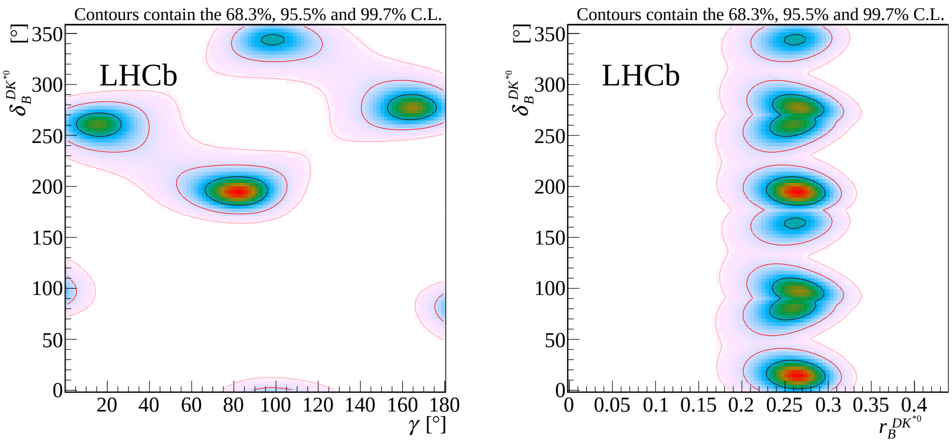

Figure 3: Constraints on (left) $(\gamma, \delta_B^{DK^{*0}})$ and (right) $(r_B^{DK^{*0}}, \delta_B^{DK^{*0}})$ from the LHCb ADS/GLW measurement [15] of $B^0 \to DK^{*0}$ decays, where $D \to h^+h'^-(\pi^+\pi^-)$.

The measured yield asymmetries and ratios can be used to constrain the underlying physics parameters $(\gamma, r_B^{DK^{*0}}, \delta_B^{DK^{*0}})$, resulting in the two-dimensional confidence regions of Fig. 3. The measurement of $r_B^{DK^{*0}} = 0.265 \pm 0.023$ has an uncertainty 50 % lower than that of the current LHCb combination [11], which was performed including only Run 1 results for this set of modes, showcasing the increased precision to come with the inclusion of the Run 2 data set in other decay channels.

3. GGSZ measurement with $B^\pm \to DK^\pm$ decays

LHCb has recently published a measurement using $B^\pm \to DK^\pm$ decays, with the self-conjugate three-body final states $K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$, based on a data set corresponding to an integrated luminosity of 2 fb^{-1} taken in 2015 and 2016 [25]. This is an update of an analysis also performed on Run 1 data [26]. In this case, r_D and δ_D of Eqs. (1.1) vary over the phase-space of the D decay, and the equations simplify again since $f = \bar{f}$. This phase-space variation can be exploited to make a measurement with sensitivity to γ by measuring the decay yields in multiple bins of the phase space [27, 28]. Defining the (real) *CP*-violation observables of interest $(x_\pm, y_\pm)$ via the relation

$$x_\pm + iy_\pm = r_B \exp[i(\delta_B \pm \gamma)], \tag{3.1}$$

the signal yield from $B^\pm$ decays in bin i of the Dalitz plot, $N_i^\pm$, can be expressed [29, 30]

$$\begin{aligned} N_i^+ &= h^+ \left(F_{-i} + r_B^2 F_i + 2r_B\sqrt{F_iF_{-i}}(x_+c_i + y_+s_i) \right), \\ N_i^- &= h^- \left(F_i + r_B^2 F_{-i} + 2r_B\sqrt{F_iF_{-i}}(x_-c_i - y_-s_i) \right) \end{aligned} \tag{3.2}$$

if the bins are chosen to be symmetric around the $m^2(K_S^0\pi^+) = m^2(K_S^0\pi^-)$ diagonal of the Dalitz plot, numbered so that bins above the diagonal have $i > 0$, and for a given bin $+i$, the symmetric bin below the diagonal has number $-i$. The binning schemes used in this measurement are shown in Fig. 4. In Eq. (3.2), the F_i parameters denote the fraction of D^0 decays in bin i, and are measured in

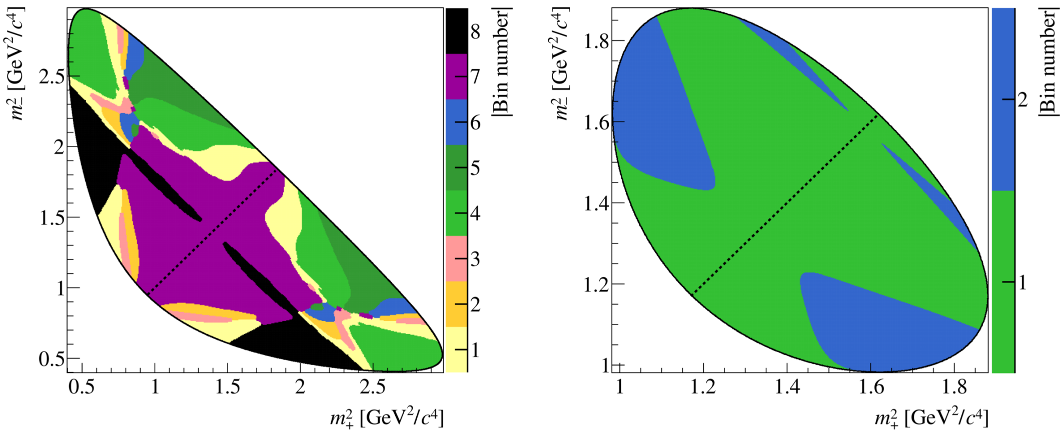

Figure 4: Binning schemes of the (left) $D \to K_S^0\pi^+\pi^-$ and (right) $D \to K_S^0K^+K^-$ Dalitz plots used in the GGSZ measurements.

a control channel of double-flavour tagged D^0 decays: $B \to D^{*+}(\to D^0\pi^+)\mu^-\bar{\nu}_\mu X$. Corrections are applied to take into account that there are unavoidable differences in the reconstruction efficiency profile over the Dalitz plot between signal and control channels. The parameters c_i and s_i are the average cosine and sine of δ_D over bin i. These are external inputs, measured independently by the CLEO collaboration [31] using quantum-correlated D^0-$\bar{D}^0$ pairs produced via decay of the $\psi(3770)$ resonance.

The observables of interest, $x_\pm$ and $y_\pm$, are determined directly in the fit to data, via a simultaneous fit to the B mass spectrum in all bins, where the signal yields are parameterised using Eqs. (3.2). The normalisation constants $h^\pm$ are determined independently of each other in the measurement, which leaves it insensitive to production and detection asymmetries, as well as the leading-order effects of CP-violation and material interaction of the K_S^0 [32]. The obtained values are combined with the results obtained from analysing the Run 1 data set [26], and used to constrain the physics parameters of interest $(\gamma, r_B^{DK^\pm}, \delta_B^{DK^\pm})$. The confidence regions for these parameters are shown in Fig. 5. The Run 1 and 2015+16 results yield a combined measurement of $\gamma = (80^{+10}_{-9})^\circ$, which is the most precise measurement of γ in a single decay channel to date.

4. Combination of LHCb measurements

LHCb has published a combination of many independent measurements, in order to obtain the most sensitive overall determination of γ [11]. The combination includes measurements based on decays of $B^\pm$ and B^0 decays analysed using several different ADS, GLW, and GGSZ-type D final states. Furthermore, time-dependent analyses of $B_s^0 \to D_s^\mp K^\pm$ [13] and $B^0 \to D^\mp\pi^\pm$ [14] decays are included. These rely on interference between mixing and decay, are sensitive to both γ and $\beta_{(s)}$, and allow for unambiguous solutions for γ. The combined value is $\gamma = (74.0^{+5.0}_{-5.8})^\circ$, which dominates the current world averages. The confidence limits for γ obtained in the combination are shown in Fig. 6, for both the overall combination and individually for measurements that use a given B

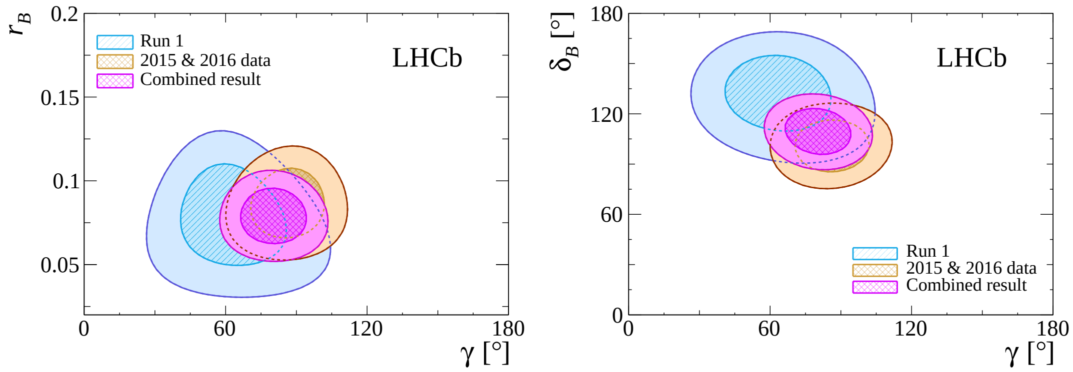

Figure 5: Constraints on (left) $(\gamma, r_B^{DK^\pm})$ and (right) $(\gamma, \delta_B^{DK^\pm})$ from the LHCb GGSZ measurements [25, 26] of $B^\pm \to DK^\pm$ decays, where $D \to K_S^0 h^+ h^-$.

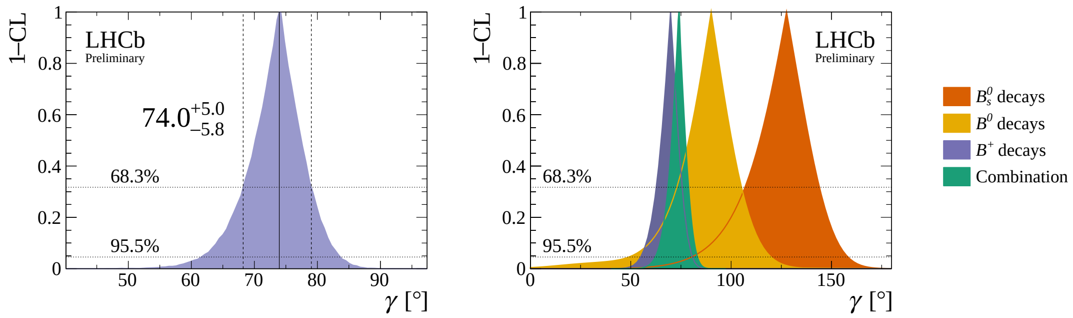

Figure 6: (Left) Overall confidence limit for γ in the LHCb combination, and (right) split by B decay mode (the results of Section 2 have not yet been included in the constraints from B^0 decays).

meson species. The results of Section 2 have been published after the latest LHCb combination, but will be included in the next version.

The overall uncertainty on the LHCb γ combination is driven by the GLW analysis of $B^\pm \to D(\to hh)K^\pm$ decays. All systematic uncertainties in this channel can be studied with the LHCb data set, and therefore continuous improvement can be expected as data sets corresponding to 50 fb^{-1} of integrated luminosity will have been collected after the LHCb Upgrade phase, and 300 fb^{-1} or more after the proposed Upgrade Phase II [33]. Still, GGSZ measurements are crucial, as they provide a single, unambiguous solution for γ, and serve as an important consistency check of the LHCb combination. The obtainable sensitivity on these measurements depend on the precision of external strong-phase inputs, as described in Section 3, which currently contribute a systematic uncertainty of about 4°. Forthcoming, and much anticipated, measurements from BESIII will reduce this number to approximately $1-2°$ in the near future. However, further strong-phase measurements will be necessary to obtain the best possible precision on γ in model-independent GGSZ measurements, both for LHCb and Belle II.

5. Conclusions and outlook

These proceedings have detailed two of the latest γ measurements made by the LHCb collaboration, an ADS/GLW measurement made with $B^0 \to DK^{*0}$ decays and a GGSZ measurement made with $B^{\pm} \to DK^{\pm}$ decays, as well as the LHCb combination of γ measurements, which provides the world-leading, single-experiment determination $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$. Significant updates to the LHCb combination can be expected in the near future, including the inclusion of the $B^0 \to DK^{*0}$ measurement described in Section 2, which was published after the current LHCb combination, and a number of results with the full Run 1 and 2 data set. As the full Run 2 data set is analysed the precision on γ will be reduced to 4°, and may surpass this expectation.

The uncertainty on γ will reach sub-degree levels within the next 5–10 years, reaching a world average of 0.3° by ~ 2035. This will be achieved with data corresponding to an integrated luminosity of $50\,\mathrm{ab}^{-1}$ collected by Belle II, and $300\,\mathrm{fb}^{-1}$ with the LHCb upgrades, and will allow for many interesting, ultra-high precision tests of the Standard Model in the years to come.

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