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LHCb γ results from time-dependent measurements and LHCb γ combination

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The CKM angle γ is the least well measured angle in the CKM triangle today. The LHCb experiment allows to measure a multitude of B decay modes which are sensitive to γ. The latest combined fit of the angle γ based on analyses performed with the LHCb detector in the decay modes $B^{\pm} \to D(K^0_S h^+ h^-)K^{\pm}$, $B^{\pm} \to D(h^+ h^-)h^{\pm}$ or $B^{\pm} \to D(K^{\pm}\pi^{\mp}\pi^+\pi^-)h^{\pm}$ where h stands for either a charged pion or kaon are presented. An outlook on the ongoing work in the γ sensitive, time-dependent channel $B_s \to D_s K$ is also given.

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1. Introduction

The angle $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least well known angle in the unitarity triangle. Current global fits using direct tree-level measurements from the B factories and measurements from LHCb result in a sensitivity between 7.5 and 12 degrees in γ (cf. Fig. 1).

The LHCb experiment can detect many decay modes of B mesons in a relatively clean, high statistics environment, and has thus excellent sensitivity to γ.

In the following, a fit combining all recent LHCb results with sensitivity to γ is described. For the first time, results from the $B^\pm \to D\pi^\pm$ decay mode are also included. An outlook towards the inclusion of time-dependent modes with sensitivity to γ is given near the end.

Unless explicitly indicated otherwise, the charge-conjugate of any given decay mode is implied throughout the text, and the phases γ, δ_B^K, δ_B^π (see below) are expressed modulo 180°.

2. LHCb γ combination

To obtain the ultimate precision of γ, all γ sensitive measurements of LHCb are combined also considering also correlations among measured observables (both of the systematic and, if present, of the statistical uncertainties). The fit is also described in [3] and [4], in greater detail than is possible in these proceedings.

2.1 Input data and fit parameters

The fit to combine γ sensitive observables is performed three times based on analyses using the $1.0\,\mathrm{fb}^{-1}$ of data taken in 2011, once for the $B^\pm \to DK^\pm$ modes, once for the $B^\pm \to D\pi^\pm$ modes and once for both of these modes together. These will be called the "2011 DK", the "2011 $D\pi$" and the "2011 $DK/D\pi$" combinations, respectively.

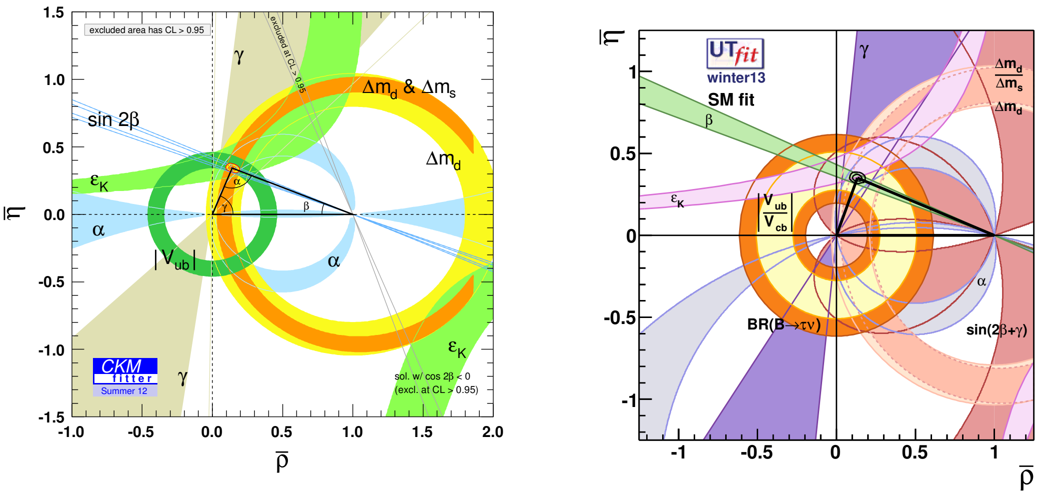

Figure 1: Global fits to γ performed by the CKMFitter (left) and UTFit (right) collaborations. They quote $\gamma = (66 \pm 12)^\circ$ (CKMFitter, [1]) and $\gamma = (71.1 \pm 7.5)^\circ$ (UTFit, [2]) for their direct fit to tree-level quantities with sensitivity to γ.

For these combinations results from the analysis of $1\,\mathrm{fb}^{-1}$ of data taken in 2011 have been used[1]: Results from ADS/GLW [6], [7], [8], [9] modes $B^{\pm} \to D(h^{+}h^{-})h^{\pm}$ [10] and $B^{\pm} \to D(K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})h^{\pm}$ [11], results from the GGSZ [12], [13] decay modes $B^{\pm} \to D(K^{0}_{S}h^{+}h^{-})K^{\pm}$ [14], and results from the variation of the strong phase over the D Dalitz plane from CLEO [15].

A further combination using results for the ADS/GLW $B^{\pm} \to DK^{\pm}$ modes obtained on the 2011 data sample ([10] from above) and a recent GGSZ analysis performed in the $B^{\pm} \to D(K^{0}_{S}h^{+}h^{-})K^{\pm}$ mode on the $3.0\,\mathrm{fb}^{-1}$ of data taken in 2011 and 2012 [16] has also been done. This combination will be referred to as the "2011+2012 DK" combination. Table 1 lists the parameters used in the fit.

After the talk was given, it became apparent that D^0-$\overline{D^0}$ mixing is not negligible in a γ extraction: first because of the description of the decay itself (D^0-$\overline{D^0}$ mixing affects the amplitude, e.g. $B^{+} \to D^{0}K^{+} \to \overline{D^{0}}K^{+} \to fK^{+}$ where f denotes the D^0 final state), second because of the hadronic parameters of the D^0 decay. Since the effect is most pronounced in γ combinations which include $B^{\pm} \to D\pi$ modes (due to the smallness of r_B^{π}), only the "2011 DK", the "2011 $D\pi$" and the "2011 $DK/D\pi$" combinations are corrected for this effect (see [3] for details on the correction procedure), and the tables and figures for these combinations given in these proceedings include the effects of D^0-$\overline{D^0}$ mixing.

However, the shift in the $B^{\pm} \to DK^{\pm}$ ADS mode is about $\Delta\gamma \lesssim 1^{\circ}$, and the GGSZ analysis is affected only to a negligible extent, which is why the (preliminary) "2011+2012 DK" combination neglects the effect of D^0-$\overline{D^0}$ mixing.

2.2 Fit method

The various observables $\vec{A}_i$ of the analyses (labelled by the index i) above are expressed in

Decay	Description	Parameter
$B^{\pm} \to Dh^{\pm}$	CP-violating weak phase	γ
	$\Gamma(B^{-} \to D^{0}K^{-})/\Gamma(B^{-} \to D^{0}\pi^{-})$	R_{cab}
$B^{\pm} \to D\pi^{\pm}$	$A(B^{-} \to \bar{D}^{0}\pi^{-})/A(B^{-} \to D^{0}\pi^{-}) = r_B^{\pi}e^{i(\delta_B^{\pi}-\gamma)}$	r_B^{π}, δ_B^{π}
$B^{\pm} \to DK^{\pm}$	$A(B^{-} \to \bar{D}^{0}K^{-})/A(B^{-} \to D^{0}K^{-}) = r_B^{K}e^{i(\delta_B^{K}-\gamma)}$	r_B^{K}, δ_B^{K}
$D^{0} \to K^{\pm}\pi^{\mp}$	$A(D^{0} \to \pi^{-}K^{+})/A(D^{0} \to K^{-}\pi^{+}) = r_{K\pi}e^{-i\delta_{K\pi}}$	$r_{K\pi}$, $\delta_{K\pi}$
	Cabibbo-favoured rate	$\Gamma(D \to K\pi)$
$D^{0} \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	amplitude ratio and effective strong phase diff.	$r_{K3\pi}$, $\delta_{K3\pi}$
	coherence factor	$\kappa_{K3\pi}$
	Cabibbo-favoured rate	$\Gamma(D \to K\pi\pi\pi)$
$D^{0} \to K^{+}K^{-}$	direct CP asymmetry	$A_{CP}^{\mathrm{dir}}(KK)$
$D^{0} \to \pi^{+}\pi^{-}$	direct CP asymmetry	$A_{CP}^{\mathrm{dir}}(\pi\pi)$
D^{0}–$\bar{D}^{0}$	mixing parameters	x_D, y_D

Table 1: Parameters used in the combined fit. Overall signs of $\delta_{K\pi}$ and $\delta_{K3\pi}$ have been introduced to be in accordance with published measurements. Also, γ gains a sign for the conjugated modes, $A(B^{+} \to D^{0}h^{+})/A(B^{+} \to \bar{D}^{0}h^{+}) = r_B^{h}e^{i(\delta_B^{h}+\gamma)}$, with $h = K, \pi$. (Table from [3].)

[1] Most of the results mentioned below are also discussed in [5].

terms of fit parameters $\vec{\alpha}_i$ (cf. Table 1). For each measurement performed, a χ^2 derived likelihood contribution

$$f_i(\vec{A}_i^{\text{obs}}|\vec{A}_i(\vec{\alpha}_i)) \propto \exp\left(-\chi^2/2\right) \propto \exp\left(-(\vec{A}_i(\vec{\alpha}_i) - \vec{A}_{i,\text{obs}})^T V_i^{-1} (\vec{A}_i(\vec{\alpha}_i) - \vec{A}_{i,\text{obs}})/2\right)$$

is used where V_i is the covariance matrix of the set of observables that make up an analysis. These likelihood contributions are subsequently combined

$$\mathscr{L}(\vec{\alpha}) = \prod_i f_i(\vec{A}_i^{\text{obs}}|\vec{A}_i(\vec{\alpha}_i))$$

and $\mathscr{L}$ is then minimised with respect to the physics parameters $\vec{\alpha}_i$.

2.3 Systematic uncertainties

2.3.1 Coverage

While the method described above clearly identifies the best fit point, more work is needed to obtain confidence intervals (CI). Special attention must be given to the method used to extract CI to ensure that the true value of the physics parameter is really inside the CI at e.g. 68% (claimed) confidence level (CL) in 68% of the cases (the interval is then said to *cover* the true value in 68% of the cases).

In parameter spaces with high dimensionality like the one used here, it is very hard to ensure coverage at reasonable computational cost. Consequently, the so-called "plug-in" method is used which yields CI which cover the true value with almost the indicated CL, but is much cheaper computationally (for details, see [3]).

The amount of undercoverage (the true value is not contained in the interval often enough) is studied in pseudo-experiments where a large number of γ extractions are performed on simulated measurements. The intervals are enlarged by the ratio of the expected CL η over the CL α observed in pseudo-experiments where it is known if the CI covers the true value, accounting for the small remaining undercoverage. Table 2 lists the results of this study.

In the figures throughout the remainder of this text, the output of the plug-in method is shown. To derive the CI from the plots, the given numbers must be scaled by the corresponding factor η/α given in Table 2 to obtain the true CI. In the text and the tables, this scaling is already applied.

α	$1\sigma\,(\eta = 0.6827)$	$2\sigma\,(\eta = 0.9545)$	$3\sigma\,(\eta = 0.9973)$
$DK^\pm$ only	0.6874 ± 0.0050	0.9543 ± 0.0023	0.9952 ± 0.0007
$D\pi^\pm$ only	0.5945 ± 0.0053	0.9391 ± 0.0026	0.9960 ± 0.0007
$DK^\pm$ & $D\pi^\pm$	0.6394 ± 0.0050	0.9374 ± 0.0025	0.9929 ± 0.0009

Table 2: True coverage α observed in a large number of γ extractions based on simulated measurements for claimed confidence levels η corresponding to 1σ, 2σ and 3σ intervals. The coverage properties of the "plug-in" method are very good (i.e. close to the claimed value); the remaining small amount of undercoverage is removed by scaling the width of the extracted CI up by η/α. (Table from [3].)

2.3.2 Correlations

Apart from the discussion above, there is one other major source of systematic uncertainty: No information is available on the correlation of systematic uncertainties between the results of the two and four body ADS/GLW modes. For the nominal combination, they are assumed to be zero. Then, a large number of random correlation matrices is used to study the effect of correlations on the combination (a maximum correlation of 0.75 considered). The DK combinations are unaffected by correlations, whereas the 2011 $D\pi$ needs to have its CI scaled up by 12%. The 2011 $DK/D\pi$ combination is less affected, and effect is only visible in the low side of the interval, so the effect of correlations is treated by adding a 2.5° (5.0°) asymmetric systematic uncertainty in quadrature to the lower 1σ (2σ) errors. Again, these scalings and corrections are applied throughout the text and the tables, but not in the figures.

2.4 Results

2.4.1 Combination using 2011 data only

The results of the three γ combination fits are shown in Table 3. $1-CL$ graphs for the parameters γ, r_B^K, δ_B^K, r_B^π and δ_B^π are shown in Figures 2, 3 and 4.

The sensitivity to γ in the 2011 DK combination is much better than in the 2011 $D\pi$ combination due to the fact that r_B^K is much larger than r_B^π. Moreover, the latter combination seems to favour a smaller best fit value of γ, although the 1σ contours are perfectly compatible. The full 2011 combination including both DK and $D\pi$ modes gives a best fit value of $\gamma = 72.6°$ which is almost exactly what was obtained with the DK only combination, but with smaller CI due to the additional sensitivity in the $D\pi$ channel. The full set of CI for all parameters can be found in [3].

2.4.2 Combination using 2011 and 2012 $B \to DK$ data

The (preliminary) 2011+2012 DK γ combination is described in more detail in [4] and yields a best fit value of $\gamma = 67.2°$. Confidence intervals of $\gamma \in [55.1, 79.1]°$ ($\gamma \in [43.9, 89.5]°$) are set at 68% (95%) CL. Figure 5 shows the $1-\mathrm{CL}$ graphs for δ_B^K, r_B^K and γ, illustrating the nice agreement between the 2011 DK combination and this one.

3. Results in the time-dependent channel $B_s \to D_s^\pm K^\mp$

The excellent decay time resolution of the LHCb experiment and its ability to perform flavour tagging open up a new possibility to improve the measurement of the CKM angle γ in time-

combination	best fit [°]	68% CL [°]	95% CL [°]
2011 DK	72.0	$\gamma \in [56.4, 86.7]$	$\gamma \in [42.6, 99.6]$
2011 $D\pi$	18.9	$\gamma \in [8.9, 80.2] \cup [169.1, 175.7]$	—
2011 $DK/D\pi$	72.6	$\gamma \in [56.7, 81.7]$	$\gamma \in [41.2, 92.3]$

Table 3: Results of the γ combinations performed on the 2011 data sample. Best fit values as well as 68% and 95% CL intervals are given (where applicable). (Values in Table from [3].)

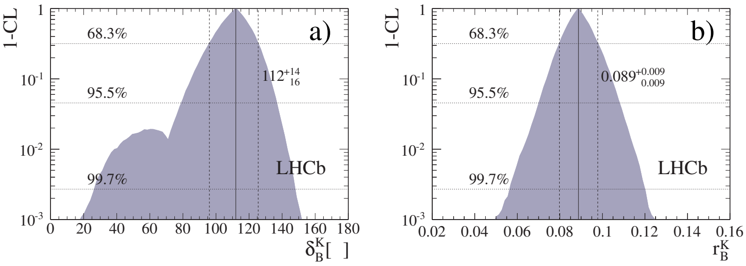

Figure 2: Graphs showing $1-\mathrm{CL}$ for (a) δ_B^K, (b) r_B^K, and (c) γ, for the 2011 DK combination of the two- and four-body GLW/ADS and the $DK^{\pm}$ GGSZ measurements. The reported numbers correspond to the best-fit values and the uncertainties are computed using the respective 68.3% CL confidence interval. (Figures from [3].)

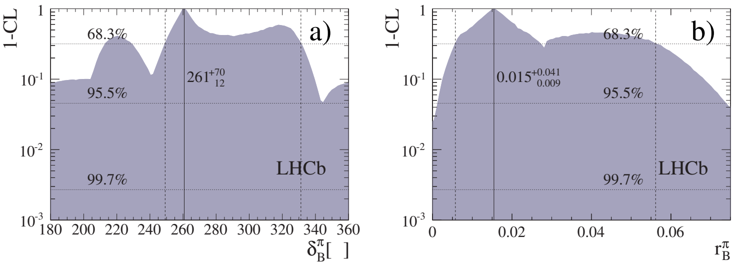

Figure 3: Graphs showing $1-\mathrm{CL}$ for (a) δ_B^{π}, (b) r_B^{π}, and (c) γ, for the 2011 $D\pi$ combination of the two- and four-body GLW/ADS measurements. The reported numbers correspond to the best-fit values and the uncertainties are computed using appropriate 68.3% CL confidence intervals. (Figures from [3].)

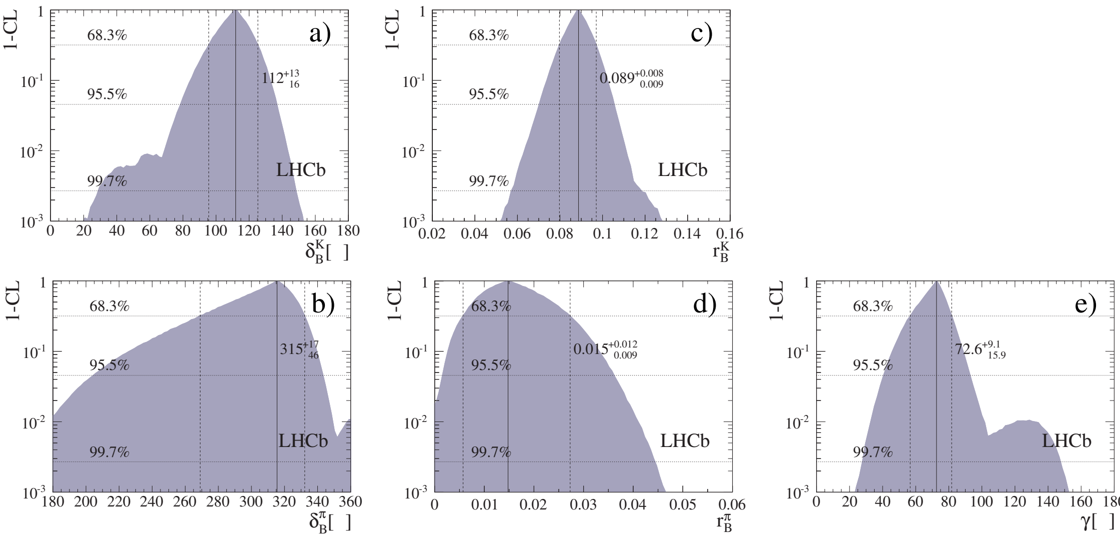

Figure 4: Graphs showing $1-\mathrm{CL}$ for (a) δ_B^K, (b) δ_B^{π}, (c) r_B^K, (d) r_B^{π}, and (e) γ, for the full $DK^{\pm}$ and $D\pi^{\pm}$ combination. The reported numbers correspond to the best-fit values and the uncertainties are computed using appropriate 68.3% CL confidence intervals. (Figures from [3].)

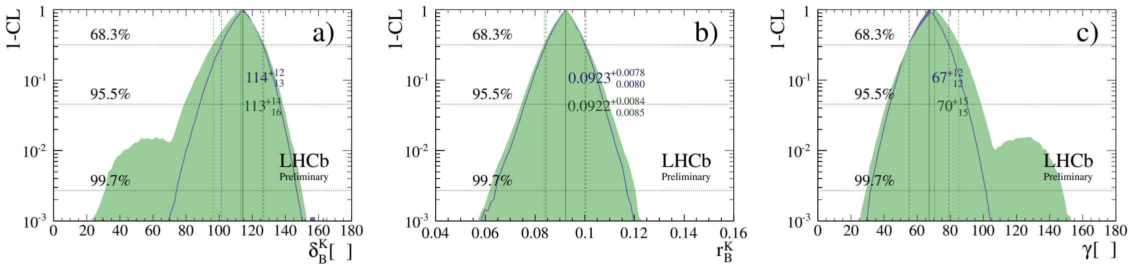

Figure 5: Graphs showing $1-\mathrm{CL}$ for (a) δ_B^K, (b) r_B^K, and (c) γ, for the combination of measurements of the $B^\pm \to DK^\pm$ decay using $1\,\mathrm{fb}^{-1}$ of data (green, filled area, 2011 DK combination). These graphs are compared to the (preliminary) $B^\pm \to DK^\pm$ combination including the new $3\,\mathrm{fb}^{-1}$ GGSZ result (blueish line). The reported numbers correspond to the best fit values and the uncertainties are computed using the respective 68.3% CL confidence intervals. (Figures from [4].)

dependent analyses. The prime example is the decay $B_s \to D_s^\mp K^\pm$. A first preliminary measurement of the CP violating coefficients $C_f = 1.01 \pm 0.50 \pm 0.23$, $S_f = -1.25 \pm 0.56 \pm 0.24$, $S_{\bar{f}} = 0.08 \pm 0.68 \pm 0.28$, $D_f = -1.33 \pm 0.60 \pm 0.26$, $D_{\bar{f}} = -0.81 \pm 0.56 \pm 0.26$ has been performed in this mode in [17] on the 2011 data sample of $1.0\,\mathrm{fb}^{-1}$; the first uncertainty given above is statistical and the second is systematical. While this clearly shows the measurement can be done, the correlations in systematic uncertainties among these five parameters were not known when the γ combination described here was performed, so this result was not included. In the future, improvements in signal extraction and flavour tagging performance, and, of course, the data taken in 2012, promise improvements that will make this channel very interesting indeed to enhance the sensitivity to γ.

4. Summary

LHCb opens up a new era in the determination of the CKM angle γ. The most precise (preliminary) result obtained so far from the combination of $B^\pm \to DK^\pm$ data taken in 2011 and 2012 yields $\gamma = (67 \pm 12)^\circ$ which is in good agreement with the world average from direct measurements, and it is also competitive to similar combinations by the BaBar ($\gamma = (69^{+17}_{-16})^\circ$, [18]) and Belle ($\gamma = (68^{+15}_{-14})^\circ$, [19]) collaborations.

Moreover, a γ combination has been performed for the first time in $B^\pm \to D\pi^\pm$ modes, yielding a best fit value of $\gamma = 18.9^\circ$, and $\gamma \in ([8.9, 80.2] \cup [169.1, 175.7])^\circ$ at 68% CL.

For the future, more data and innovative analyses in new decay modes will further increase the sensitivity of the LHCb experiment to γ.

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