γ/ϕ_3 measurements at LHCb

CKM2014, Vienna

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(on behalf of the LHCb collaboration)

CERN

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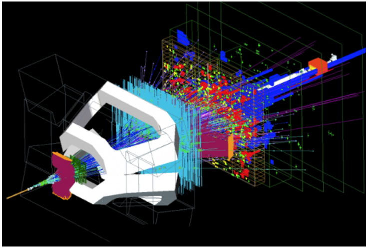
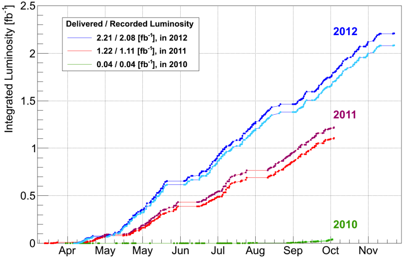
Introduction

- LHCb is a forward spectrometer operated in collider mode.
- precision measurements of b- and c-hadron decays
- rare decays, CP violation, γ
- very good $K^{\pm}/\pi^{\pm}$ separation: two RICH detectors
- very good time resolution (B_s^0 oscillation): VELO
- Dataset:

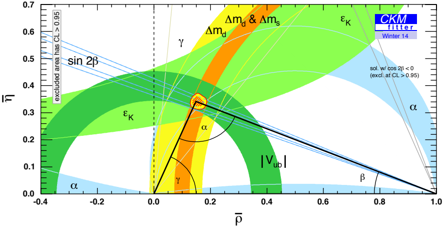
  2011: $1\,\text{fb}^{-1}$
  2012: $2\,\text{fb}^{-1}$
  total: $3\,\text{fb}^{-1}$





Introduction

- γ is the least well known angle of the unitarity triangle
- it can be measured entirely from tree decays
- the residual uncertainty is negligible: $\delta\gamma/\gamma \approx 10^{-7}$
  see Brod on Tuesday!
  Brod, Zupan 2013 [1]



- **however:** the branching ratios are small, typically at the 10^{-7} level
- measure γ in different "methods"

GLW	CP eigenstates, *e.g.* $D \to KK$
ADS	flavored states, *e.g.* $D \to K\pi$
GGSZ	self-conjugate 3-body decays, *e.g.* $D \to K^0_S\pi\pi$
GLS	singly Cabibbo suppressed states, *e.g.* $D \to K^0_S K\pi$
time-dep.	*e.g.* $B^0_s \to D^{\mp}_s K^{\pm}$

Introduction

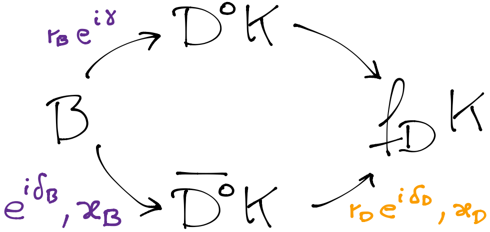


Figure: Example interference diagram. Coherence factors appear with multibody states.

Example observable:

$$R_{+}^{DK,K3\pi} = \frac{\Gamma(B^+ \to [\pi K\pi\pi]_D K^+)}{\Gamma(B^+ \to [K\pi\pi\pi]_D K^+)} ,$$

$$R_{+}^{DK,K3\pi} = \frac{(r_B^{DK})^2 + (r_D^{K3\pi})^2 + 2\kappa_D^{K3\pi} r_B^{DK} r_D^{K3\pi} \cos(\delta_B^{DK} + \delta_D^{K3\pi} + \gamma)}{1 + (r_B^{DK})^2 (r_D^{K3\pi})^2 + 2\kappa_D^{K3\pi} r_B^{DK} r_D^{K3\pi} \cos(\delta_B^{DK} - \delta_D^{K3\pi} + \gamma)}$$

Introduction

Our new results, LHCb-CONF-2014-004, supersede the previous LHCb combinations.

Table: Summary of results for γ from the B factories BaBar and Belle, and from LHCb, and combiners. Errors correspond to 68% confidence or credibility.

experiment	result	date
BaBar [2]	$(69^{+17}_{-16})^\circ$	Jan 2013
Belle [3]	$(68^{+15}_{-14})^\circ$	Jan 2013
LHCb $3\,\text{fb}^{-1}$ preliminary [4]	$(67 \pm 12)^\circ$	Apr 2013 (superseded!)
LHCb $1\,\text{fb}^{-1}$ [5]	$(72.6^{+9.7}_{-17.2})^\circ$	Aug 2013 (superseded!)
UTfit	$(68.3 \pm 7.5)^\circ$	post Moriond 2014
CKMfitter	$(70.0^{+7.7}_{-9.0})^\circ$	Moriond / Jun 2014
CKMfitter	$(73.2^{+6.3}_{-7.0})^\circ$	CKM2014

Inputs

new LHCb results and changes

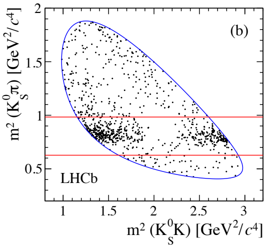
Two combinations:

robust	$\boldsymbol{B \to DK}$**-like**
full	$B \to DK$-like and $B \to D\pi$

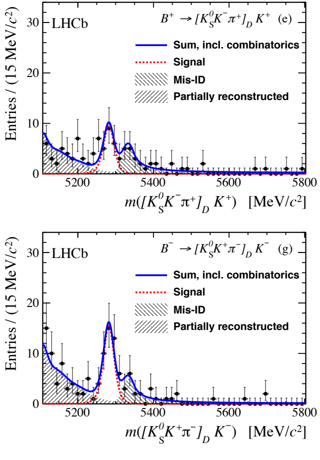
- updated: Update the auxiliary inputs
- $B^+ \to Dh^+$, $D \to hh$, GLW/ADS, $1\,\mathrm{fb}^{-1}$ LHCb [6]
- $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, $1\,\mathrm{fb}^{-1}$ LHCb [7]
- updated: $B^+ \to DK^+$, $D \to K^0_S hh$, model-ind. GGSZ, $3\,\mathrm{fb}^{-1}$ LHCb [8]
- **new:** $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS, $3\,\mathrm{fb}^{-1}$ LHCb [9]
- **new:** $B^0 \to D^0 K^{*0}$, $D \to hh$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ LHCb [10]
- **new:** $B^0_s \to D_s^\mp K^\pm$, $1\,\mathrm{fb}^{-1}$ LHCb [11]

new: $B^+ \to DK^+$, $D \to K^0_{\rm S} K\pi$, GLS, 3 fb^{-1}

- GLS method
  Grossman, Ligeti, Soffer 2002 [12]
- use singly Cabibbo suppressed D decays to non-CP eigenstates
- first GLS measurement! LHCb [9]
- no significant CP violation was observed



we restrict the phase space to the more sensitive $D \to K^{*+}K^-$ region

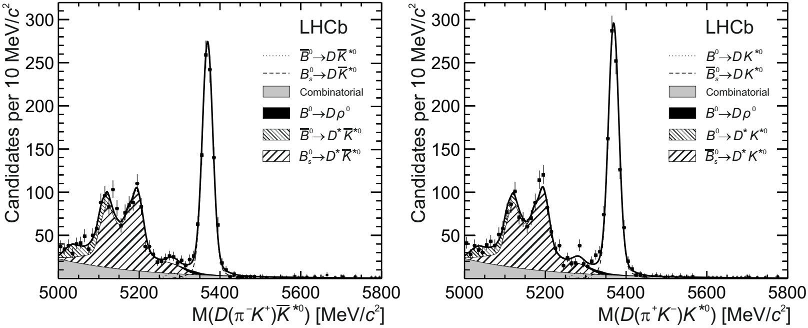


Phys. Lett. B733 (2014) 36 [9]

Figure: "opposite-sign" decays

new: $B^0 \to D^0 K^{*0}$, $D \to hh$, GLW/ADS, 3 fb^{-1}

- this mode has great potential exploiting the full $D^0 K\pi$ phase space Gershon 2009 [13]
- the K^{*0} decay tags the B flavour at decay—no time dependent measurement
- significance for suppressed decay $B^0 \to D^0 K^{*0}$, $D^0 \to \pi^- K^+$: 2.9σ

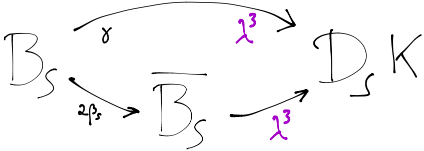


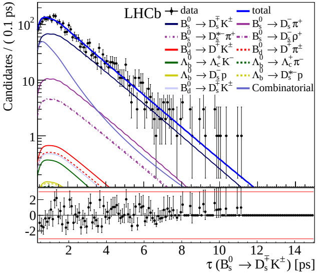
Phys. Lett. B712 (2012) 203 [10]

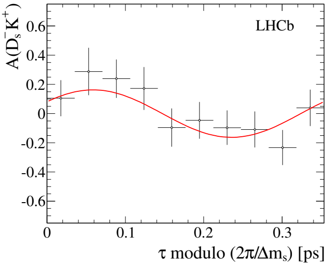
new: $B_s^0 \to D_s^\mp K^\pm$, time-dep., 1 fb^{-1}

LHCb-PAPER-2014-038, 1407.6127, sub. to JHEP

- This new technique gains sensitivity to γ through B_s^0 mixing.







LHCb-PAPER-2014-038 [11]

- first measurement! Different set of systematics, pure "LHCb only"
- B tagging power of $\epsilon_{\text{eff}} = 5.07\%$
- Lots of hadronic backgrounds: use multidemsional fit to identify the signal
- 1770 ± 50 signal events

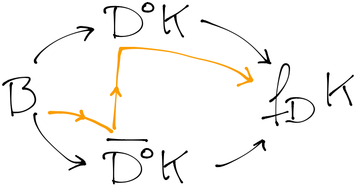
See also talk by Vava Gligorov!

D^0–$\overline{D}^0$ mixing correction

- D^0–$\overline{D}^0$ mixing has an effect on γ
  Meca, Silva, Atwood, Grossman
  [14, 15, 16, 12, 17]
- see also Matteo Rama on Tuesday!
- $\mathcal{O}(1^\circ)$ on γ for $B \to DK$
- The effect can be larger for $B \to D\pi$
  [18, Rama 2013]:

$$\sqrt{x_D^2 + y_D^2}/r_B^{D\pi} \approx \mathcal{O}(1)$$

- The topic was revisited following FPCP2013 Rama; Bondar et al. [19, 18].
- We correct for the effect of D^0–$\overline{D}^0$ mixing
  - in leading order in x_D, y_D
  - taking into account individual D^0 decay time acceptances



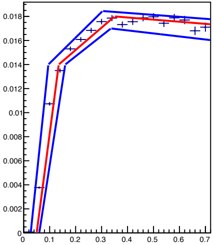
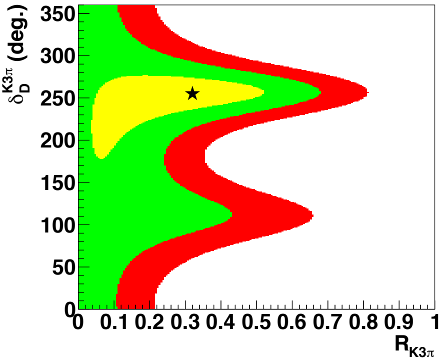


Figure: LHCb D^0 decay time acceptance for $B^+ \to DK^+$, $D \to hh$.

Auxiliary input for $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$

updated:

- The $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$ ADS measurement needs input on the charm system.
- amplitude ratio: $r_D^{K3\pi}$
- eff. strong phase diff.: $\delta_D^{K3\pi}$
- coherence factor: $\kappa_D^{K3\pi}$
- We use the histogrammed likelihood for $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$ from CLEO legacy.
- We use a CLEO [20] and a Belle measurement [21] on $\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)$ and $\Gamma(D^0 \to \pi^-K^+\pi^-\pi^+)$ to constrain $r_D^{K3\pi}$.



Phys. Lett. B731 (2014) 197 [22]

Figure: CLEO legacy likelihood for $\delta_D^{K3\pi}$ and $\kappa_D^{K3\pi}$ (labeled "$R_{K3\pi}$") $D \to K3\pi$. Histogram is used in the combination.

Other auxiliary input

updated: The GLW/ADS measurements need inputs on the charm system:

- for the $D^0 \to K^-\pi^+$ and $D^0 \to \pi^- K^+$ decays: $r_D^{K\pi}$, $\delta_D^{K\pi}$
- for charm mixing: x_D, y_D
- for direct CP violation in $D^0 \to h^+h^-$ decays: $A_{CP}^{\rm dir}(KK)$, $A_{CP}^{\rm dir}(\pi\pi)$
- We use the recent HFAG charm fit (FPCP 2014).

new: Input for $\boldsymbol{D \to K_{\rm S}^0 K\pi}$ **GLS**

- We use a CLEO measurement for $r_D^{K_S K\pi}$, $\delta_D^{K_S K\pi}$, $\kappa_D^{K_S K\pi}$ CLEO [23].

new: Input for $\boldsymbol{B^0 \to D^0 K^{*0}}$ **GLW/ADS**

- We use a MC-based estimate for $\kappa_B^{DK^{*0}} = 0.95 \pm 0.03$ LHCb [10].

new: Input for $\boldsymbol{B_s^0 \to D_s^{\mp} K^{\pm}}$ **time-dep.** to interpret $\gamma - 2\beta_s$

- We use the LHCb measurement of $-2\beta_s \approx \phi_s = 0.01 \pm 0.07 \pm 0.01\,\rm rad$ LHCb [24].

Evolution from the previous preliminary result

1. previous result
   LHCb preliminary [4]
2. Update the auxiliary inputs
3. Add new $B^+ \to DK^+$, $D \to K^0_S hh$ GGSZ measurement
4. Add new $B^+ \to DK^+$, $D \to K^0_S K\pi$ GLS measurement
5. Add new $B^0 \to D^0 K^{*0}$, $D \to hh$ GLW/ADS measurement
6. Add new $B^0_s \to D_s^{\mp} K^{\pm}$ time-dependent measurement
7. robust nominal

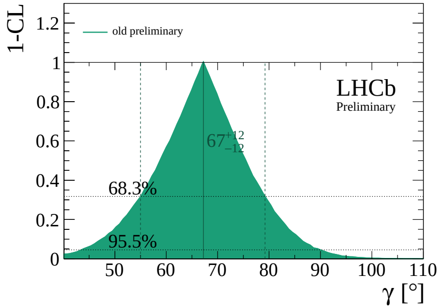


Figure: Making one change at a time. Robust combination.

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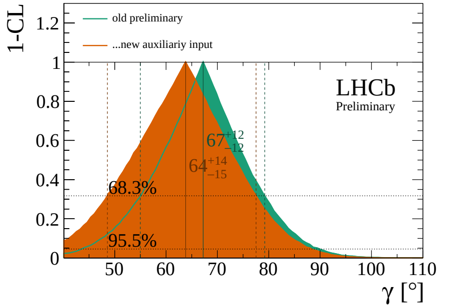

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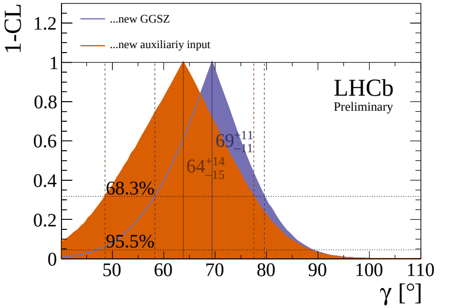

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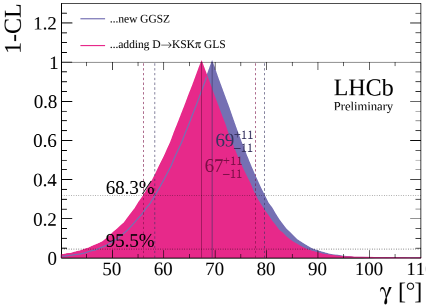

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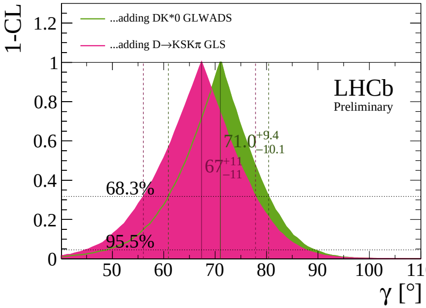

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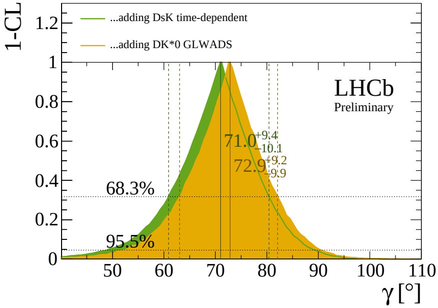

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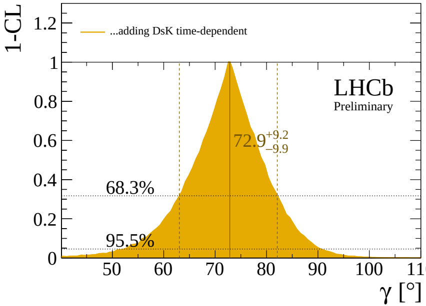

Figure: Making one change at a time. Robust combination.

Statistical procedure

The **method is unchanged** from previous combinations.

- We assume (almost) all observables to be Gaussian distributed.
- We assume Gaussian systematic fluctuations.
- We don't allow non-physical parameter values.
- Use the **plugin method** for nominal results (Feldman-Cousins based frequentist method nuisances at their best-fit values).
- Use the profile likelihood method for 2D illustration.
- Estimate the frequentist coverage.
- Additional **Bayesian interpretation** with uniform priors.

LHCb-CONF-2014-004

Result of the robust combination

Table: Credibility regions and most probable values for the hadronic parameters extracted from the robust combination. The second part of the table repeats the frequentist results for comparison.

Observable	Central value	Intervals	
Frequentist		68%	95%
$\gamma[^\circ]$	72.9	$[63.0, 82.1]$	$[52.0, 90.5]$
$\delta_B^{DK}[^\circ]$	126.8	$[115.3, 136.7]$	$[101.6, 145.2]$
r_B^{DK}	0.0914	$[0.0826, 0.0997]$	$[0.0728, 0.1078]$
Bayesian		68%	95%
$\gamma[^\circ]$	71.9	$[61.9, 81.8]$	$[50.9, 91]$
$\delta_B^{DK}[^\circ]$	127.4	$[115.6, 137.3]$	$[100.3, 147.1]$
r_B^{DK}	0.091	$[0.0826, 0.0984]$	$[0.0740, 0.106]$

The agreement of frequentist and Bayesian results is quite good.

LHCb-CONF-2014-004

Result of the robust combination

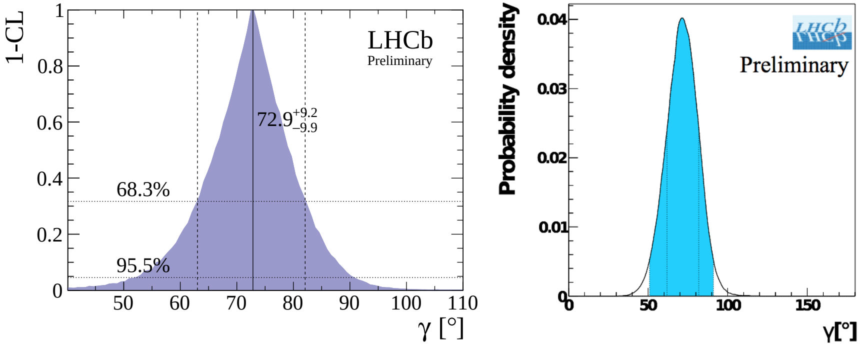

Figure: Graphs for the robust combination (left: frequentist $1 - \mathrm{CL}$ curves, right: Bayesian posterior).

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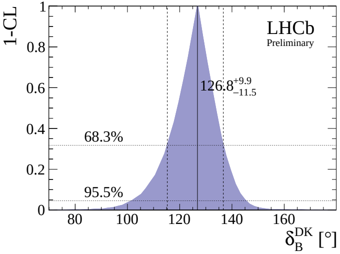
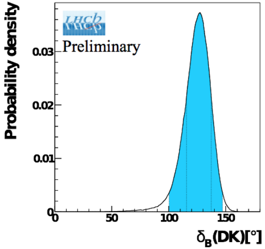
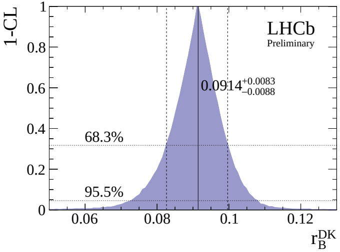
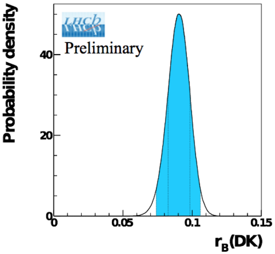
Result of the robust combination









Lets add $B^+ \to D\pi^+$ information

LHCb-CONF-2014-004

Table: Confidence intervals and central values for the full combination.

quantity	full	
γ ($^\circ$)	78.9	72.8
68% CL ($^\circ$)	$[71.5, 84.7]$	
95% CL ($^\circ$)	$[54.6, 91.4]$	
r_B^{DK}	0.0928	
68% CL	$[0.0845, 0.1008]$	
95% CL	$[0.0732, 0.1085]$	
δ_B^{DK} ($^\circ$)	128.9	
68% CL ($^\circ$)	$[118.9, 137.9]$	
95% CL ($^\circ$)	$[102.0, 145.9]$	
$r_B^{D\pi}$	0.027	0.006
68% CL	$[0.016, 0.034]$	$[0.005, 0.007]$
95% CL	$[0.001, 0.040]$	
$\delta_B^{D\pi}$ ($^\circ$)	341.8	215.6
68% CL ($^\circ$)	$[328.7, 351.4]$	$[210.2, 231.5]$
95% CL ($^\circ$)	no constraint	

LHCb-CONF-2014-004

Lets add $B^+ \to D\pi^+$ information

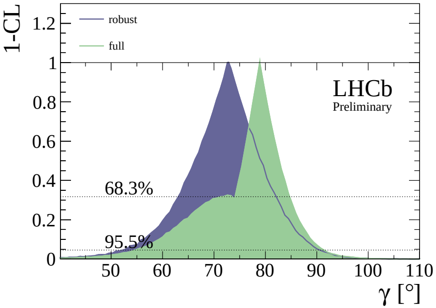
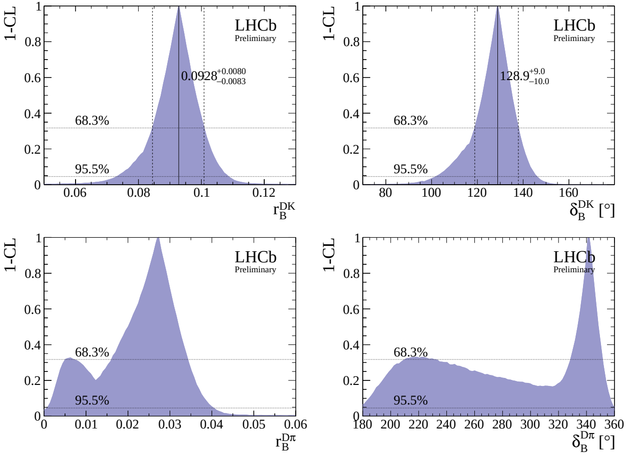


Figure: $1 - \mathrm{CL}$ curve for the robust and full combinations.

- A second minimum appears.
- The 1σ errors are **misleadingly small**: highly non-Gaussian!
- At 2σ, the agreement with the robust combination is very good.

LHCb-CONF-2014-004

Result of the full combination



At 2σ, $r_B^{D\pi}$ is compatible with 0.

LHCb-CONF-2014-004

Result of the full combination

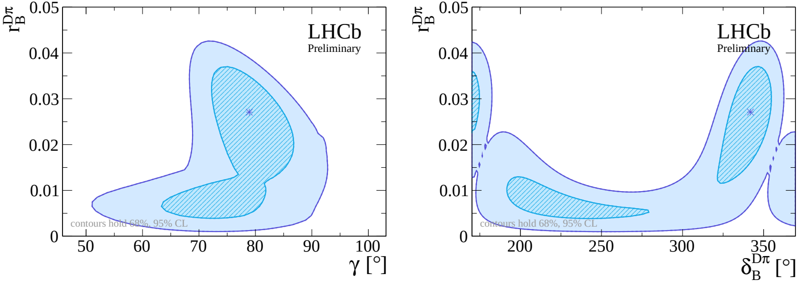


Figure: Profile likelihood contours, full combination. The contours are the two-dimensional 1σ and 2σ contours.

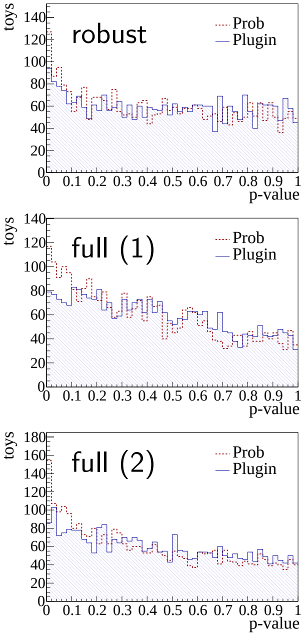
The high observed value of $r_B^{D\pi}$ also pulls up γ.

Coverage test

- We test the frequentist coverage at the minima of the combinations.
- We find that the profile likelihood construction undercovers quite a bit.
- The robust plugin method has good coverage.
- The coverage of the full combination is worse than of the robust. Expected due to the low value of $r_B^{D\pi}$.

$\eta = 0.683$	α (prof. LH.)	α (plugin)
robust	0.6158	0.6494
full (1), $r_B^{D\pi} = 0.027$	0.5593	0.6154
full (2), $r_B^{D\pi} = 0.006$	0.5454	0.6120

LHCb-CONF-2014-004



Conclusion

- We updated the LHCb γ combination of tree-level measurements.
- The effect of D^0–$\overline{D}^0$ mixing is taken into account, the frequentist coverage was tested.
- robust Bayesian results are available and agree.
- We explore $B^+ \to D\pi^+$ channels: they show up early all obstacles on the way to high precision.
- The robust coverage is good.
- Robust frequentist combination:

$$\gamma = (72.9^{+9.2}_{-9.9})^\circ \quad @\,68\%\ \mathrm{CL}\,,$$
$$\gamma \in [63.0, 82.1]^\circ \quad @\,68\%\ \mathrm{CL}\,,$$
$$\gamma \in [52.0, 90.5]^\circ \quad @\,95\%\ \mathrm{CL}\,.$$

- More precise than the B factory legacy.

Backup

Auxiliary input for $D \to K^0_S K\pi$

new:

- Similar input is needed as in the case of $D \to K\pi\pi\pi$.
- rate ratio: $R_D^{K_S K\pi}$
- eff. strong phase diff.: $\delta_D^{K_S K\pi}$
- coherence factor: $\kappa_D^{K_S K\pi}$
- We use a single CLEO measurement [23].

$$R_D^{K_S K\pi} = 0.356 \pm 0.034 \pm 0.007\,,$$
$$\delta_D^{K_S K\pi} = 0.46 \pm 0.28\,,$$
$$\kappa_D^{K_S K\pi} = 1.00 \pm 0.16\,.$$

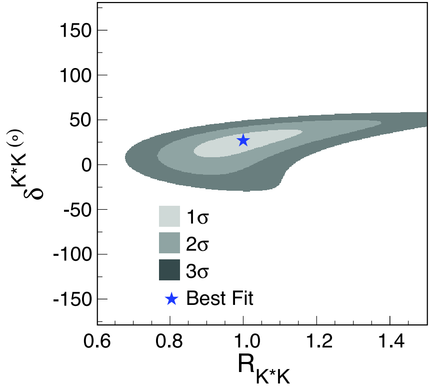


Figure: CLEO likelihood for $\delta_D^{K_S K\pi}$ and $\kappa_D^{K_S K\pi}$ (labeled "R_{K^*K}") [23]. Histogram is not used in the combination.

Auxiliary input from HFAG

taking a step back

Comparing the old auxiliary inputs to the new ones:

old:

- we needed input on the $D \to K\pi\pi\pi$ system from CLEO
- that measurement had some influence on the charm mixing parameters x_D, y_D
- it was obtained using the HFAG status as of 2009 as input
- ...so we took the 2009 CLEO input and added the new LHCb D^0 wrong sign mixing measurement
- we also added "ΔA_{CP}"

Auxiliary input from HFAG

taking a step back

Comparing the old auxiliary inputs to the new ones:

new:

- the input for $D \to K\pi\pi\pi$ was updated using more CLEO-c data
- the new measurement no longer impacts x_D, y_D, as the world average is much stronger now
- it was obtained using the HFAG status as of 2014 as input
- ...so now we can use HFAG directly, including up-to-date charm mixing, and "ΔA_{CP}"

Auxiliary input from HFAG

comparing old and new

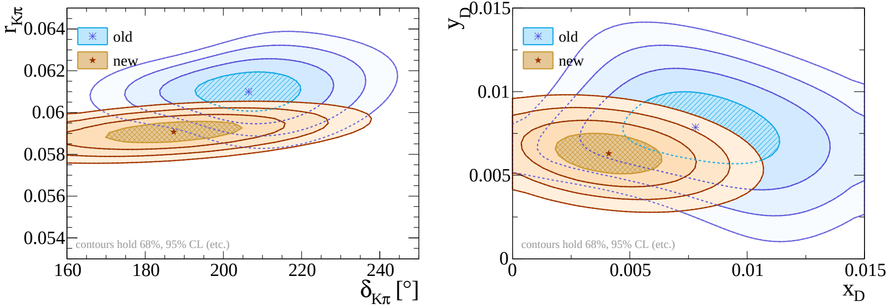


Figure: Profile likelihood contours: The "old" contour corresponds to what was used in the previous (2013) combination (the 2009 CLEO input [25] together with the 2013 LHCb charm mixing measurement [26]). The "new" contour is what is used in this combination (HFAG 2014). The contours are two-dimensional 1–4σ contours.

Auxiliary input from HFAG

The parameter $R_D^{K\pi}$ is the squared ratio of the doubly-Cabibbo-suppressed amplitude $D^0 \to \pi^- K^+$ to the favored one $D^0 \to K^- \pi^+$. It is not the ratio of branching ratios. It gets often measured in time-dependent wrong-sign D^0 mixing measurements:

$$R_{WS} = R_D^{K\pi} + \sqrt{R_D^{K\pi}} \left(x \cos(\delta_D^{K\pi}) \pm y \sin(\delta_D^{K\pi}) \right) \frac{t}{\tau} + \frac{x_D^2 + y_D^2}{4} \left(\frac{t}{\tau} \right)^2$$

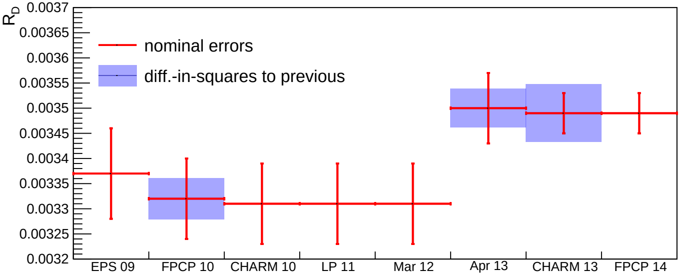


Figure: Evolution of HFAG results on $R_D^{K\pi}$.

Auxiliary input for $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$

updated: We use an updated CLEO-c measurement of $\kappa_D^{K3\pi}$ and $\delta_D^{K3\pi}$ (histogrammed likelihood). For the amplitude ratio

$$r_D^{K3\pi} = \left|A(D^0 \to \pi^- K^+\pi^-\pi^+)/A(D^0 \to K^-\pi^+\pi^-\pi^+)\right| \tag{1}$$

we use

- a CLEO measurement [20] of $\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)$,

$$\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+) = 0.08290 \pm 0.00043 \pm 0.00200\,, \tag{2}$$

- a Belle measurement [21] of $\Gamma(D^0 \to \pi^- K^+\pi^-\pi^+)$,

$$\Gamma(D^0 \to \pi^- K^+\pi^-\pi^+) = 0.00026 \pm 0.00001 \pm 0.00001\,. \tag{3}$$

- These are related to $r_D^{K3\pi}$ through the equation

$$R_{WS}(D \to K\pi\pi\pi) = \tag{4}$$

$$(r_D^{K3\pi})^2 - \kappa_D^{K3\pi} r_D^{K3\pi}(y_D \cos\delta_D^{K3\pi} - x_D \sin\delta_D^{K3\pi}) + \frac{1}{2}(x_D^2 + y_D^2)\,. \tag{5}$$

Goodness of fit

Table: Fit probabilities of the best fit values of the two combinations.

Combination	P (PROB)	P (toy-based)
robust	89.7%	$(89.4 \pm 0.5)\%$
full	97.2%	$(96.8 \pm 0.3)\%$

Result of the robust combination

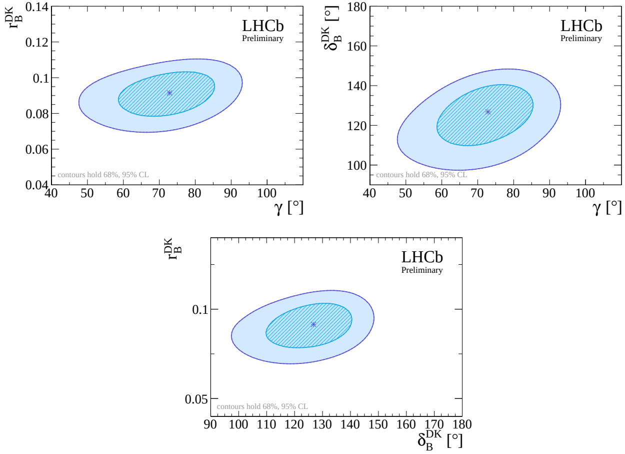


Figure: Profile likelihood contours, robust combination. The contours are the two-dimensional 1σ and 2σ contours.

Result of the full combination

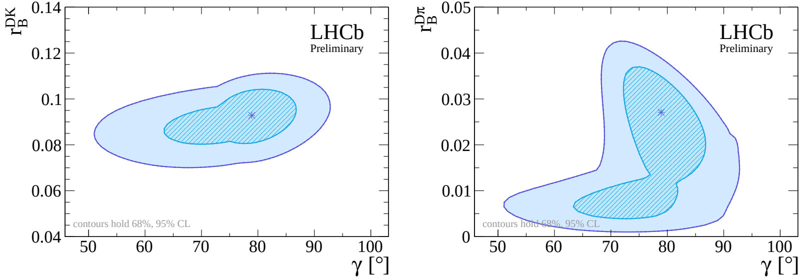


Figure: Profile likelihood contours, full combination. The contours are the two-dimensional 1σ and 2σ contours.

Result of the full combination

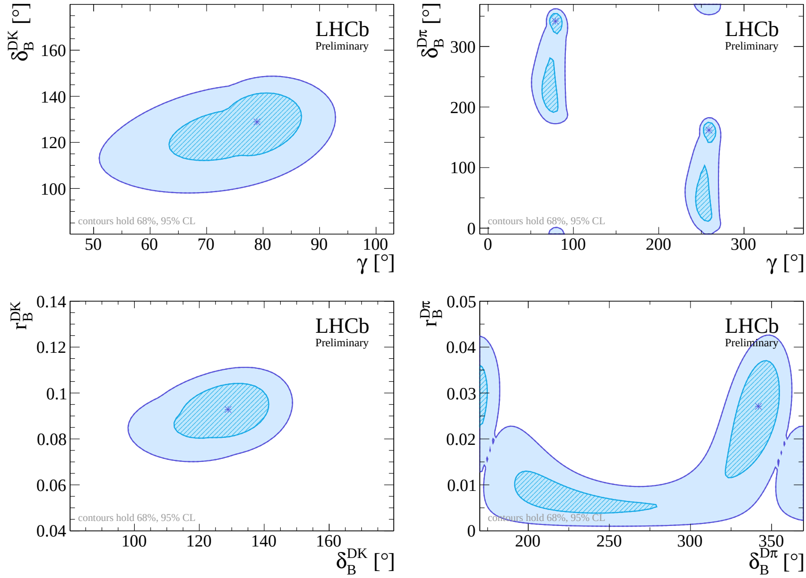


Figure: Profile likelihood contours: full combination. The contours are the

Coverage test

Table: Measured coverage α of the confidence intervals for γ. The expected coverage is denoted as η.

robust	α (profile likelihood)	$(\alpha - \eta)$	α (PLUGIN)	$(\alpha - \eta)$
$\eta = 0.6827$	0.6158 ± 0.0089	-0.0669	0.6494 ± 0.0087	-0.0333
$\eta = 0.9545$	0.9200 ± 0.0050	-0.0345	0.9358 ± 0.0045	-0.0187
$\eta = 0.9973$	0.9923 ± 0.0016	-0.0050	0.9919 ± 0.0016	-0.0054
full, $r_B^{D\pi} = 0.027$	α (profile likelihood)	$(\alpha - \eta)$	α (PLUGIN)	$(\alpha - \eta)$
$\eta = 0.6827$	0.5593 ± 0.0091	-0.1234	0.6154 ± 0.0089	-0.0673
$\eta = 0.9545$	0.9160 ± 0.0051	-0.0385	0.9402 ± 0.0043	-0.0143
$\eta = 0.9973$	0.9929 ± 0.0015	-0.0044	0.9929 ± 0.0015	-0.0044
full, $r_B^{D\pi} = 0.006$	α (profile likelihood)	$(\alpha - \eta)$	α (PLUGIN)	$(\alpha - \eta)$
$\eta = 0.6827$	0.5454 ± 0.0091	-0.1373	0.6120 ± 0.0089	-0.0707
$\eta = 0.9545$	0.9026 ± 0.0054	-0.0519	0.9314 ± 0.0046	-0.0231
$\eta = 0.9973$	0.9906 ± 0.0018	-0.0067	0.9933 ± 0.0015	-0.0040

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