Combining γ at LHCb

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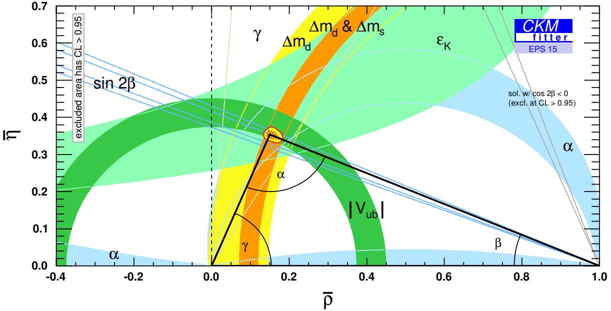
On behalf of the LHCb collaboration

9th International Workshop on the CKM Unitary Triangle
TIFR, Mumbai

The UT is well constrained...



- Global fits to the CKM UT: `UTFit`, `CKMFitter` (shown)
- Using all available measurements, Angles are determined to sub-2 deg precision

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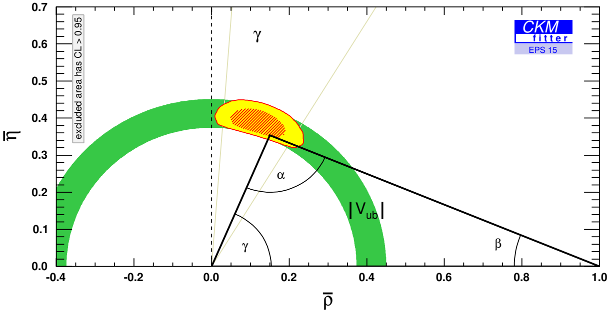
. . . but the SM is not well constrained



- We do not expect NP in tree-level decays
- The only tree-level constraints in the Unitary triangle are from V_{ub} and γ

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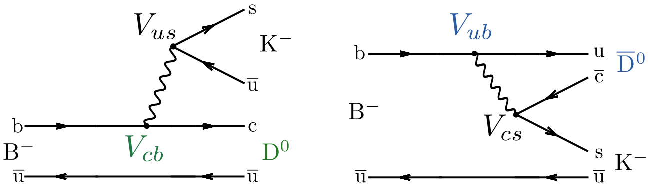
Measuring γ is important...

- γ is unique among the CKM angles
- Can be measured in the interference between $b \to c$ and $b \to u$ transitions, eg:



- theoretically clean measurement: $[\delta\gamma/\gamma] \lesssim \mathcal{O}\left(10^{-7}\right)$ JHEP 1401(2014)051
- Comparing global fit to γ and tree-level measurements:

$$\gamma = (67^{+1}_{-3})^\circ \text{ (constrained)} \qquad \gamma = (73^{+6}_{-7})^\circ \text{ (trees)}$$

- Measuring γ in tree-level decays is crucial: Discrepancies between indirect and direct measurements could signal new physics in loops

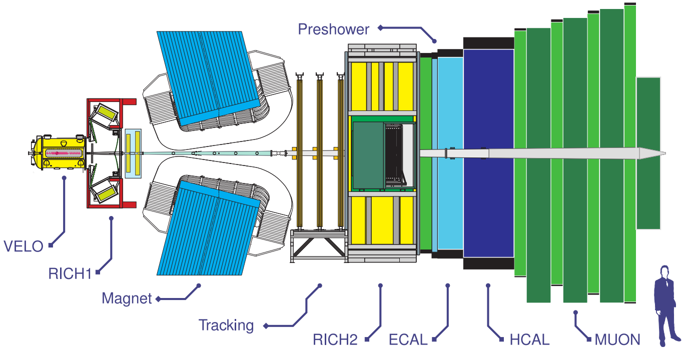
...but measuring γ is hard

- Nothing worth doing is easy:
  - Signal yields are small: BR for $B^- \to DK^-, D \to K\pi \approx 10^{-7}$
  - Interference between favored and suppressed decay modes at the 10% level for DK, 0.5% for $D\pi$
  - Hadronic final states are hard to separate from backgrounds in a hadron collider environment
- No single measurement is sensitive yet:
  Need to make many measurements and combine!
- Even so, LHCb is *the* experiment to measure γ with...

LHCb

Int. J. Mod. Phys. A30, 1530022 (2015)

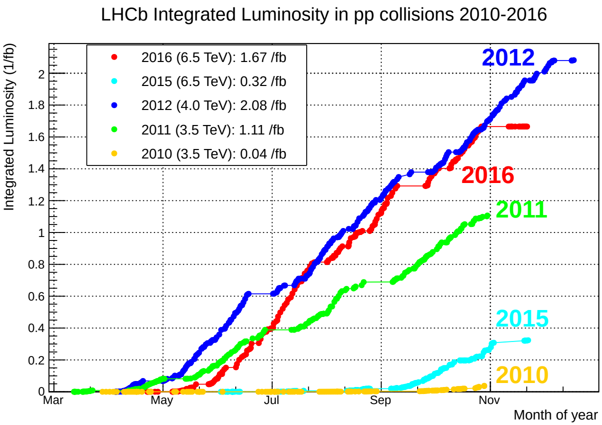
- Beauty (and charm, and strange) physics at a hadron collider:



- Forward spectrometer at the LHC: correlated $b\bar{b}$ on $2 < \eta < 5$
- 10^5 $b\bar{b}$ pairs produced per second
- Decay time resolution $\sim 45 - 55$fs
- Precise π/K identification
- Flexible software trigger

The LHCb dataset

- World's largest beauty and charm dataset:
- Run 1 (2011 + 2012) Dataset corresponds to $\sim 3 \times 10^{11}$ $b\bar{b}$ pairs!



- This talk: $\sqrt{s} = 7, 8$ TeV pp collisions recorded in 2011+2012, $\sim 3\text{fb}^{-1}$
- Run 2: Increased cross-sections + higher trigger efficiencies. Already as many $b\bar{b}$ pairs as Run 1.

Measuring γ

- Four general categories of γ-sensitive measurements:
- "GLW", D decays to $\mathcal{CP}$ eigenstate, $D \to KK$, $D \to \pi\pi$:

$$A_{\mathcal{CP}+} = \frac{2 r_B \sin \delta_B \sin \gamma}{R_{\mathcal{CP}+}}$$
$$R_{\mathcal{CP}+} = 1 + r_B^2 + 2 r_B \cos \delta_B \cos \gamma$$

- "ADS", quasi-flavor-specific final states, eg: $D \to K\pi$, $D \to K3\pi$
  - additional amplitude r_D and phase δ_D enter from D decay:

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

- "GGSZ", Self $\mathcal{CP}$-conjugate 3-body final states, eg: $D \to K_S^0\pi\pi$, $D \to K_S^0 KK$
  - Model independent: binned dalitz plot using CLEO phase variation as input
  - Model dependent: fits to distribution of events in the $D \to K_S^0 hh$ Dalitz plot:

$$x_+ = r_B \cos(\delta_B + \gamma) \qquad y_+ = r_B \sin(\delta_B + \gamma)$$

- Time-dependent: $B_s^0 \to D_s K$ and $B^0 \to D\pi$ measure $\gamma - \phi_s$, $2\beta + \gamma$

While each analysis measures different observables, each contributes *complementary* information

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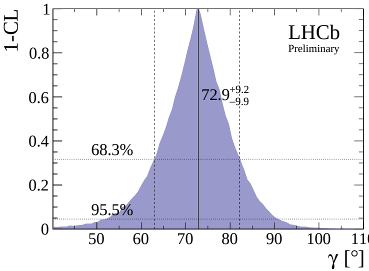
Combining γ at LHCb: DK only

- Last combination in 2014
- Many new/updated results
- See Agnieszka's talk today for Brand-new $B_s^0 \to D_s K$

- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+h^-\pi^0$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K_S^0 h^+h^-$, model-independent GGSZ, $3\,\mathrm{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K_S^0 K^+\pi^-$, GLS, $3\,\mathrm{fb}^{-1}$
- $B^0 \to DK^+\pi^-$, $D \to h^+h^-$, GLW-Dalitz, $3\,\mathrm{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K^+\pi^-$, ADS, $3\,\mathrm{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K_S^0\pi^+\pi^-$, model-dependent GGSZ, $3\,\mathrm{fb}^{-1}$
- $B^+ \to DK^+\pi^+\pi^-$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$
- $B_s^0 \to D_s^{\mp}K^{\pm}$, time-dependent, $1\,\mathrm{fb}^{-1}$,



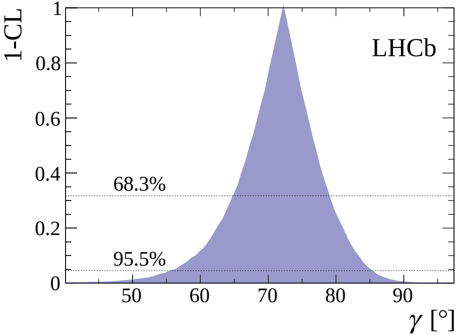
Previous result: $\gamma = (72.9^{+9.2}_{-9.9})^\circ$
LHCb-CONF-2014-004

The 2016 DK combination new!

- New DK combination: Supercedes 2014 result
  - Frequentist and Bayesian interpretations
  - Both show good agreement
  - Coverage is good

arxiv:1611.03076

$$\gamma = (72.2^{+6.8}_{-7.3})^\circ$$



Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
γ (°)	72.2	[64.9, 79.0]	[55.9, 85.2]	[43.7, 90.9]
r_B^{DK}	0.1019	[0.0963, 0.1075]	[0.0907, 0.1128]	[0.0849, 0.1182]
δ_B^{DK} (°)	142.6	[136.0, 148.3]	[127.8, 153.6]	[116.2, 158.7]
$r_B^{DK^{*0}}$	0.218	[0.171, 0.263]	[0.118, 0.305]	[0.000, 0.348]
$\delta_B^{DK^{*0}}$ (°)	189	[169, 212]	[148, 241]	[123, 283]

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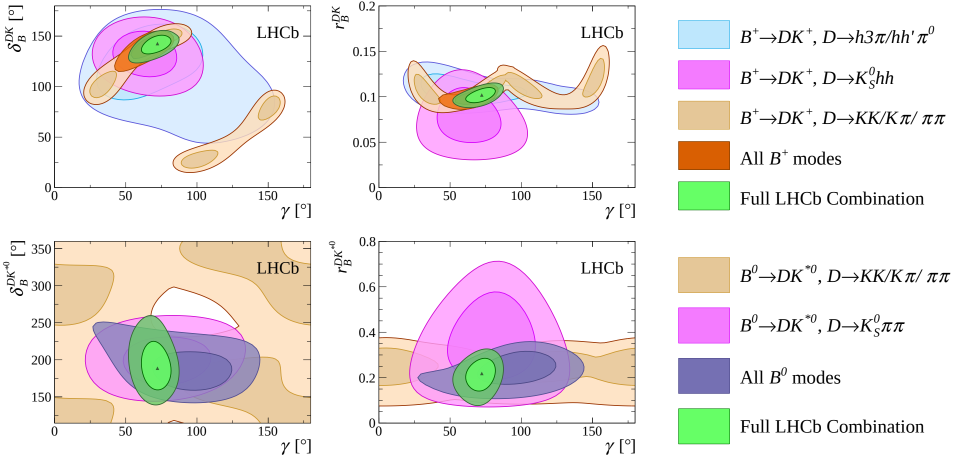
Complementarity of inputs: DK combination

arxiv:1611.03076



DK Combination summary new!

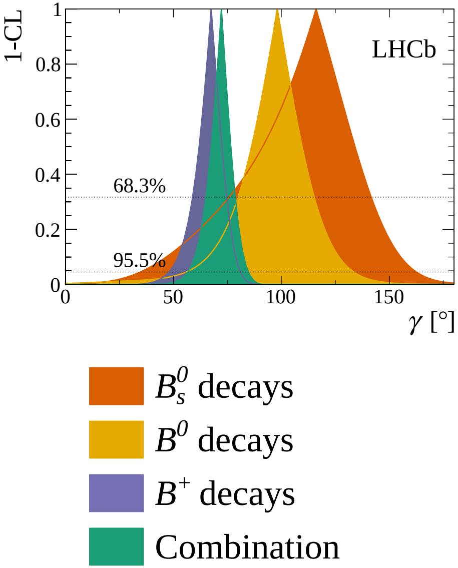
arxiv:1611.03076

- $\sim 2^\circ$ more precise than 2014 result

$$\gamma \in [64.9, 79.0]^\circ \text{ at } 68.3\%\ \mathrm{CL}\,,$$
$$\gamma \in [55.9, 85.2]^\circ \text{ at } 95.5\%\ \mathrm{CL}\,.$$

$$\gamma = (72.2^{+6.8}_{-7.3})^\circ$$

- Several additional analyses in the pipeline on Run 1 data
- Many updates + new analyses with the Run 2 dataset



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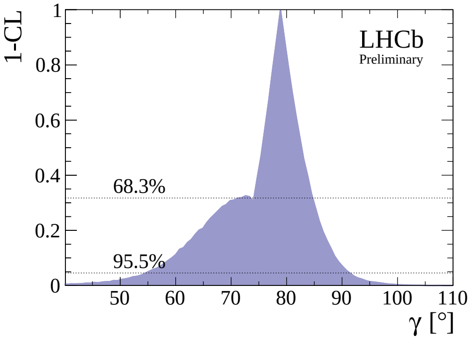
Dh combination

- Dπ final states usually ignored as $r^{D\pi} << r^{DK}$
- but LHCb has collected a lot of them and don't like waste

- Additional inputs:

$$B^+ \to D\pi,\ D \to h^+h^-$$
$$B^+ \to D\pi,\ D \to h^+\pi^-\pi^+\pi^-$$
$$B^+ \to D\pi,\ D \to h^+h^-\pi^0$$
$$B^+ \to D\pi\pi\pi,\ D \to h^+h^-$$

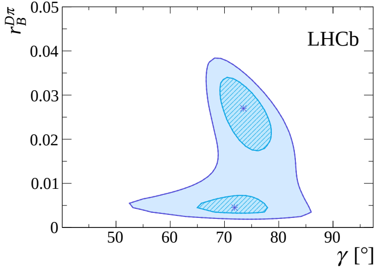


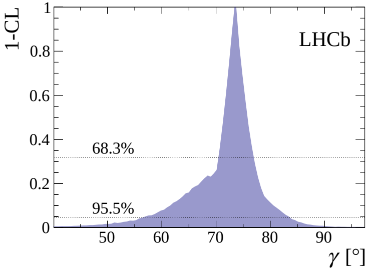
Previous result: LHCb-CONF-2014-004

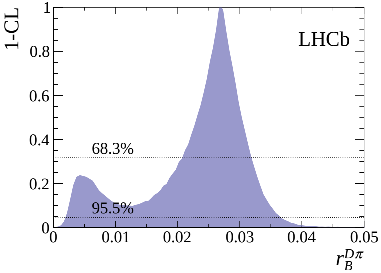
The 2016 Dh combination new!

arxiv:1611.03076

- 2016 Dh combination (Frequentist)
- Two $r^{D\pi}$ solutions:
  - frequentist combination prefers higher solution
  - expectation suppressed at $\sim 1\sigma$







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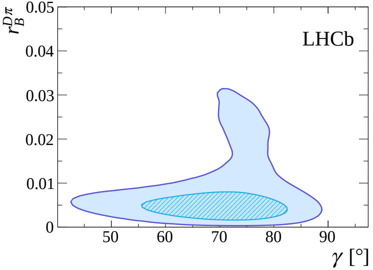
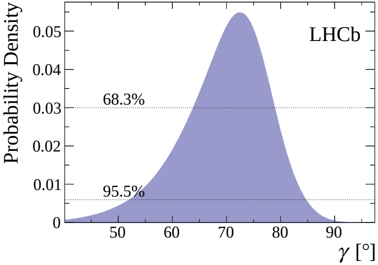
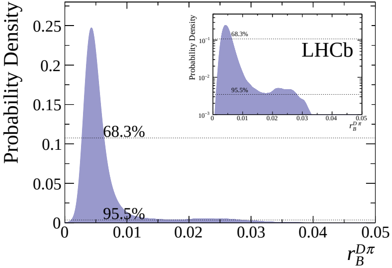
Bayesian Dh combination new!

arxiv:1611.03076

- 2016 Dh combination (Bayesian)
- Two $r^{D\pi}$ solutions:
  - Bayesian favors lower solution
  - solutions compatible at 2σ level







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Dh combination interpretation

- Frequentist result:

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	73.5	$[70.5, 76.8]$	$[56.7, 83.4]$	$[40.1, 90.8]$
r_B^{DK}	0.1017	$[0.0970, 0.1064]$	$[0.0914, 0.1110]$	$[0.0844, 0.1163]$
$\delta_B^{DK}\,(^\circ)$	141.6	$[136.6, 146.3]$	$[127.2, 151.1]$	$[114.6, 155.7]$
$r_B^{DK^{*0}}$	0.220	$[0.173, 0.264]$	$[0.121, 0.307]$	$[0.000, 0.355]$
$\delta_B^{DK^{*0}}\,(^\circ)$	188	$[168, 211]$	$[148, 239]$	$[120, 280]$
$r_B^{D\pi}$	0.027	$[0.0207, 0.0318]$	$[0.0020, 0.0365]$	$[0.0008, 0.0425]$
$\delta_B^{D\pi}\,(^\circ)$	348.3	$[343.2, 352.9]$	$[220.5, 356.4]$	$[192.9, 359.8]$

- Bayesian result:

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	72.4	$[63.9, 79.0]$	$[52.1, 84.6]$	$[40.1, 89.5]$
r_B^{DK}	0.1003	$[0.0948, 0.1057]$	$[0.0893, 0.1109]$	$[0.0838, 0.1159]$
$\delta_B^{DK}\,(^\circ)$	141.0	$[133.3, 147.5]$	$[122.1, 153.1]$	$[108.6, 157.5]$
$r_B^{DK^{*0}}$	0.2072	$[0.1514, 0.2555]$	$[0.0788, 0.3007]$	$[0.0031, 0.3291]$
$\delta_B^{DK^{*0}}\,(^\circ)$	189.8	$[166.3, 216.5]$	$[143.9, 255.2]$	$[120.2, 286.0]$
$r_B^{D\pi}$	0.0043	$[0.0027, 0.0063]$	$[0.0011, 0.0281]$	$[0.0008, 0.0329]$
$\delta_B^{D\pi}\,(^\circ)$	303.7	$[264.7, 332.7]$	$[231.5, 355.2]$	$[202.7, 359.0]$

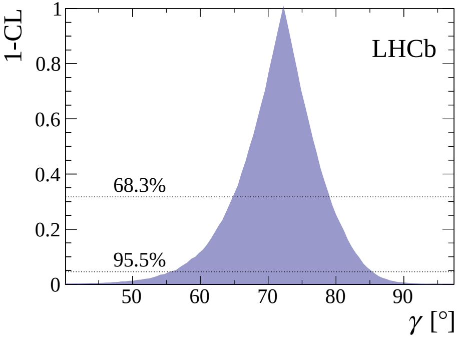
- Both frameworks report the same χ^2 minima
- Differences of this kind not uncommon in presence of a highly non-Gaussian likelihood function

Summary

- LHCb γ combination has been updated
  - Several new measurements + updates to old ones
  - DK and Dh results
  - Bayesian and Frequentist combinations to choose from
- Run 1 sensitivity expected to be $\sigma(\gamma) \to 7^{\circ}$
- We have reached that sensitivity with a few results still to be included

arxiv:1611.03076

$$\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$$



Outlook

- Current indirect precision: $\sigma(\gamma) = (^{+1.0}_{-3.7})^\circ$
- LHCb expects:
- Run 2: (2015-2018)
  - Increased energy $\rightarrow$ factor 2 increase in beauty cross section and more efficient trigger
  - Expect similar sensitivity to Belle II, $\gamma \sim 4^\circ$ with additional 5fb^{-1}
- Upgrade: (2020-2023)
  - Software trigger at full event rate: Doubling of hadronic trigger efficiency
  - Sensitivity to $\gamma \sim 1^\circ$ with $\sim 50\text{fb}^{-1}$
- Expect sensitivity to scale with integrated luminosity. Systematic and ext. input uncertainties should also decrease: See Sam's talk from this morning

Conclusions

- LHCb now dominates the precision on γ with $\sigma(\gamma) \to 7^\circ$ from Run 1
  - More from Run1 still to come:
    - New $B_s^0 \to D_s K$ result from Agnieszka earlier
    - Alex's talk: $B_d^0 \to D\pi$ shows potential
  - Results from Run2 starting to come through: See Frédéric's talk on $B^+ \to D^0 K^{*+}$
- We hope to obtain a combined precision of 1° in the upgrade era
- We look forward to competition (and combination!) from Belle II

Backups

LHCb Inputs

B decay	D decay	Method	Ref.	Status since last combination [28]
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS	[44]	Updated to $3\,\text{fb}^{-1}$
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[44]	Updated to $3\,\text{fb}^{-1}$
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[45]	New
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[46]	As before
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS	[47]	As before
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS	[48]	New
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[49]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[50]	New
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[51]	New
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	[52]	As before

External Inputs

Decay	Parameters	Source
D^0–$\bar{D}^0$-mixing	x_D, y_D	HFAG
$D \to K^+\pi^-$	$r_D^{K\pi}$, $\delta_D^{K\pi}$	HFAG
$D \to h^+h^-$	$A_{KK}^{\rm dir}$, $A_{\pi\pi}^{\rm dir}$	HFAG
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K3\pi}$	CLEO+LHCb
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{\pi\pi\pi\pi}$	CLEO
$D \to K^\pm\pi^\mp\pi^0$	$\delta_D^{K2\pi}$, $\kappa_D^{K2\pi}$, $r_D^{K2\pi}$	CLEO+LHCb
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}$, $F_{KK\pi^0}$	CLEO
$D \to K^0_{\rm S}K^-\pi^+$	$\delta_D^{K_SK\pi}$, $\kappa_D^{K_SK\pi}$, $r_D^{K_SK\pi}$	CLEO
$D \to K^0_{\rm S}K^-\pi^+$	$r_D^{K_SK\pi}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_B^{DK^{*0}}$, $\bar{R}_B^{DK^{*0}}$, $\Delta\bar{\delta}_B^{DK^{*0}}$	LHCb
$B_s^0 \to D_s^\mp K^\pm$	ϕ_s	LHCb

DK combination

- Frequentist result:

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	72.2	$[64.9, 79.0]$	$[55.9, 85.2]$	$[43.7, 90.9]$
r_B^{DK}	0.1019	$[0.0963, 0.1075]$	$[0.0907, 0.1128]$	$[0.0849, 0.1182]$
$\delta_B^{DK}\,(^\circ)$	142.6	$[136.0, 148.3]$	$[127.8, 153.6]$	$[116.2, 158.7]$
$r_B^{DK^{*0}}$	0.218	$[0.171, 0.263]$	$[0.118, 0.305]$	$[0.000, 0.348]$
$\delta_B^{DK^{*0}}\,(^\circ)$	189	$[169, 212]$	$[148, 241]$	$[123, 283]$

- Bayesian result:

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	70.3	$[62.4, 77.4]$	$[52.6, 83.5]$	$[42.1, 88.4]$
r_B^{DK}	0.1012	$[0.0954, 0.1064]$	$[0.0900, 0.1120]$	$[0.0846, 0.1171]$
$\delta_B^{DK}\,(^\circ)$	142.2	$[134.7, 148.1]$	$[125.3, 153.7]$	$[113.2, 157.9]$
$r_B^{DK^{*0}}$	0.204	$[0.149, 0.253]$	$[0.073, 0.299]$	$[0.000, 0.322]$
$\delta_B^{DK^{*0}}\,(^\circ)$	190.3	$[165.8, 218.4]$	$[139.5, 263.4]$	$[117.8, 292.4]$

- Good agreement between the DK combinations