GAMMA MEASUREMENTS AT LHCb

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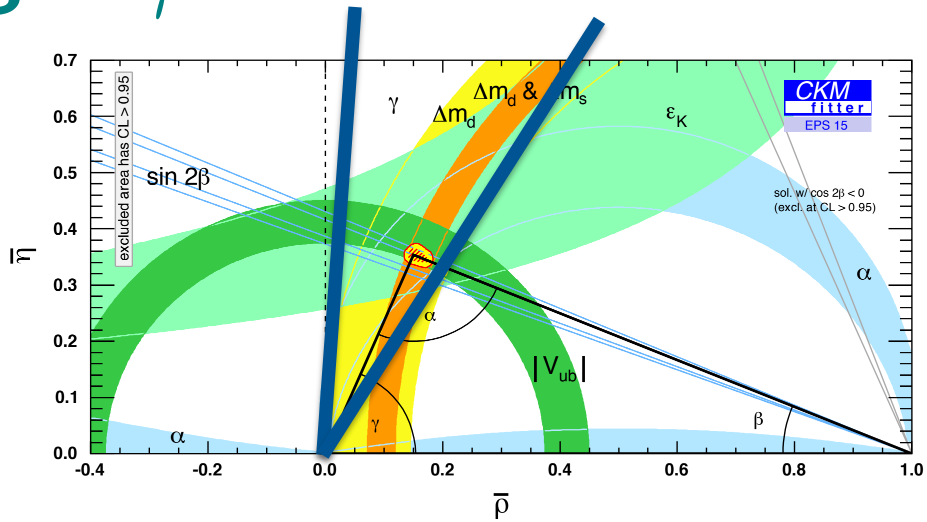
ON BEHALF OF
THE LHCb COLLABORATION

16TH INTERNATIONAL CONFERENCE ON B-PHYSICS AT FRONTIER MACHINES
MARSEILLE, FRANCE
2 – 6 MAY 2016

The CKM angle γ

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



γ can be measured at tree level

no V_{tx} terms: the only angle that can be measured with **no penguin pollution**

(indirect measurement contains loop contributions)

To probe New Physics:

Are direct and indirect measurements of γ consistent?

World average from direct and indirect measurements:

BaBar: $(70 \pm 18)^\circ$

Belle: $(73\,^{+13}_{-15})^\circ$

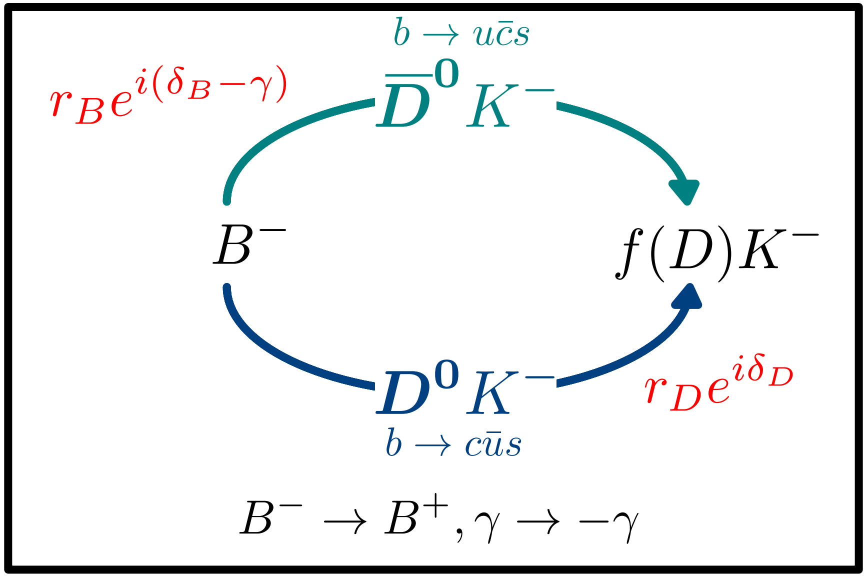
LHCb: $(74.6\,^{+8.4}_{-9.2})^\circ$ CKM2014

$$\gamma = (73.2^{+6.3}_{-7.0})^\circ \qquad \gamma = (66.85^{+0.94}_{-3.44})^\circ$$

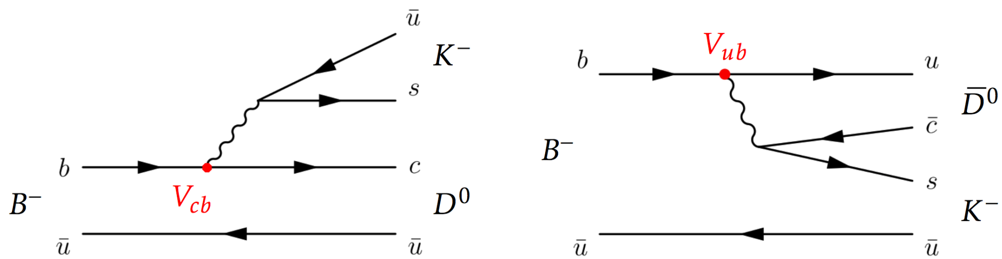
Vital goal of LHCb (and flavour physics!) to measure tree-level γ to **degree-level precision**

Tree-level γ from $B \to DK$

same principles apply for other $B \to DX$ channels



$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



Hadronic parameters can be determined experimentally:

$\delta_B =$ strong-phase difference

$r_B \sim 0.1$ for $B^- \to DK^-$
$=$ size of interference $=$ sensitivity to γ driven by CKM factors and colour suppression factors, determined experimentally

Typical CP violation observables:

Charge asymmetries

$$A = \frac{\Gamma(B^- \to f_D K^-) - \Gamma(B^+ \to \bar{f}_D K^+)}{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to \bar{f}_D K^+)}$$

Partial width ratios

$$R = \frac{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to \bar{f}_D K^+)}{\Gamma(B^- \to f'_D K^-) + \Gamma(B^+ \to \bar{f}'_D K^+)}$$

Many methods using different D decays:

may require external charm inputs for r_D or δ_D or dilution factors for multi-body decays

Today's talk

- Recent LHCb measurements of γ
  - $B^- \to Dh^-, D \to \{h^+h^-, h^+h^-\pi^+\pi^-\}$ [arXiv:1603.08993]
    - ADS/GLW method
  - $B^0 \to DK^{*0}, D \to K^0_S\pi^+\pi^-$ [arXiv:1605.01082]
    - GGSZ model-dependent method
  - $B^0 \to DK^{*0}, D \to \{K^0_S\pi^+\pi^-, K^0_S K^+K^-\}$ [arXiv:1604.05204]
    - GGSZ model-independent method

"B decays to open charm"
S. Haines

$B^0 \to DK^+\pi^-$ ADS/GLW Dalitz method [arXiv:1602.03455]

- Latest combination of LHCb results from $B \to DK$ analyses [LHCb-CONF-2016-001]

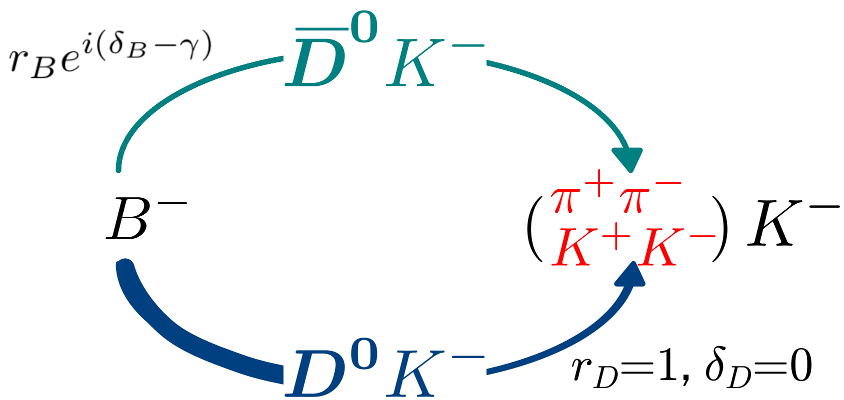
$B^\pm \to Dh^\pm$ GLW/ADS method

Combined analysis of $B \to DK$ and $B \to D\pi$ ($r_B{}^{D\pi} = 0.01$)

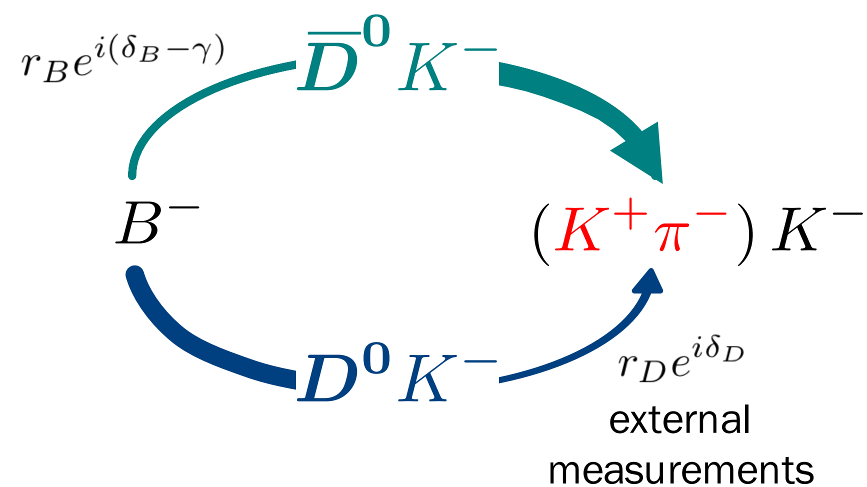
Gronau, London, Wyler
PLB 352 (1991) 483
PLB 265 (1991) 172

Atwood, Dunietz, Soni
PRL 78 (1997) 3257

<u>GLW</u>: CP eigenstates



<u>ADS</u>: large interference (= large asymmetries)
due to fav. and sup. decays in both amplitudes



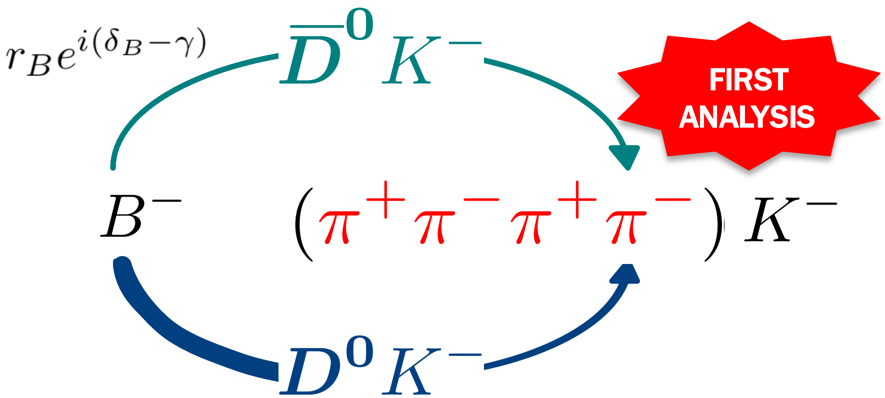
GLW: $\Gamma(B^\mp \to f_D K^\mp) \propto 1 + r_B^2 + 2 r_B \cos(\delta_B \mp \gamma)$

ADS: $\Gamma(B^\mp \to f_D K^\mp) \propto (r_D^f)^2 + r_B^2 + 2 r_B r_D^f \cos(\delta_B + \delta_D^f \mp \gamma)$

$B^\pm \to Dh^\pm$ GLW/ADS

+ four-body analogues:

quasi-GLW:



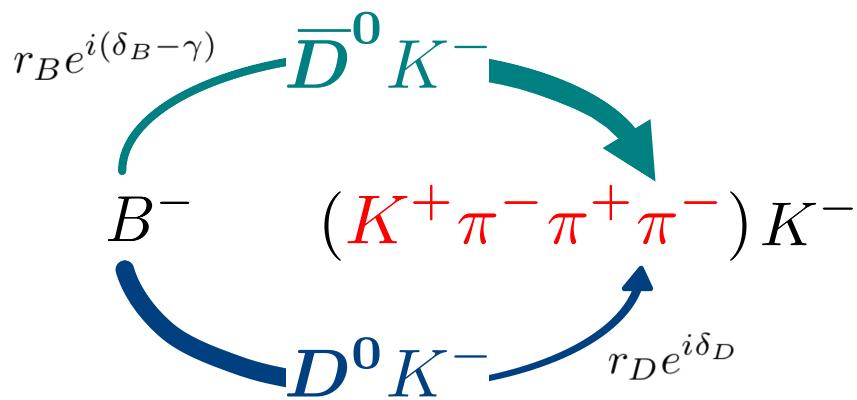
fractional CP-even content

$$F_+ = 0.737 \pm 0.028$$

$$2F_+ - 1 \approx 0.5$$

Malde et al., PLB 747 (2015) 9

quasi-ADS:



coherence factor

$$\kappa_D^{K3\pi} = 0.32 \pm 0.10$$

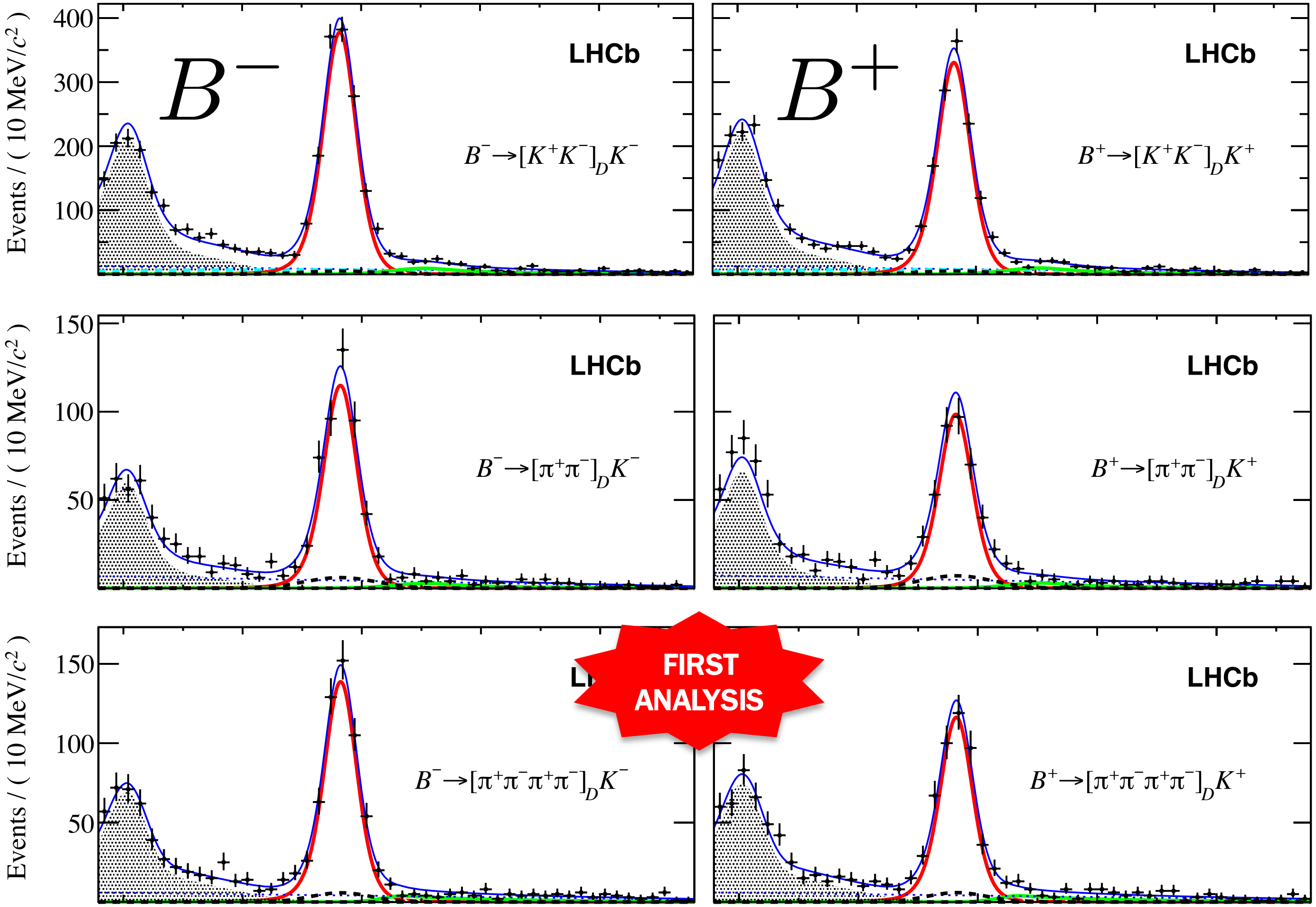
Atwood and Soni, PRD 68 (2003) 033003
LHCb collaboration, arXiv:1602.07430

GLW: $\Gamma(B^\mp \to f_D K^\mp) \propto 1 + r_B^2 + (2F_+ - 1) 2 r_B \cos(\delta_B \mp \gamma)$

ADS: $\Gamma(B^\mp \to f_D K^\mp) \propto r_B^2 + (r_D^f)^2 + 2 r_B r_D^f \kappa_D^f \cos(\delta_B + \delta_D^f \mp \gamma)$

$B^{\pm} \to DK^{\pm}$ GLW

[arXiv:1603.08993]



$N(B^+ + B^-)$

3816 ± 92

1162 ± 48

1497 ± 60

$$\Gamma(B^{\mp} \to f_D K^{\mp}) \propto 1 + r_B^2 + 2 r_B \cos(\delta_B \mp \gamma)$$

$$A = \frac{\Gamma(B^- \to f_D K^-) - \Gamma(B^+ \to \bar{f}_D K^+)}{\Gamma(B^- \to f_D K^-) + \Gamma(B^+ \to \bar{f}_D K^+)}$$

asymmetry diluted by $2F_+ - 1 \approx 0.5$

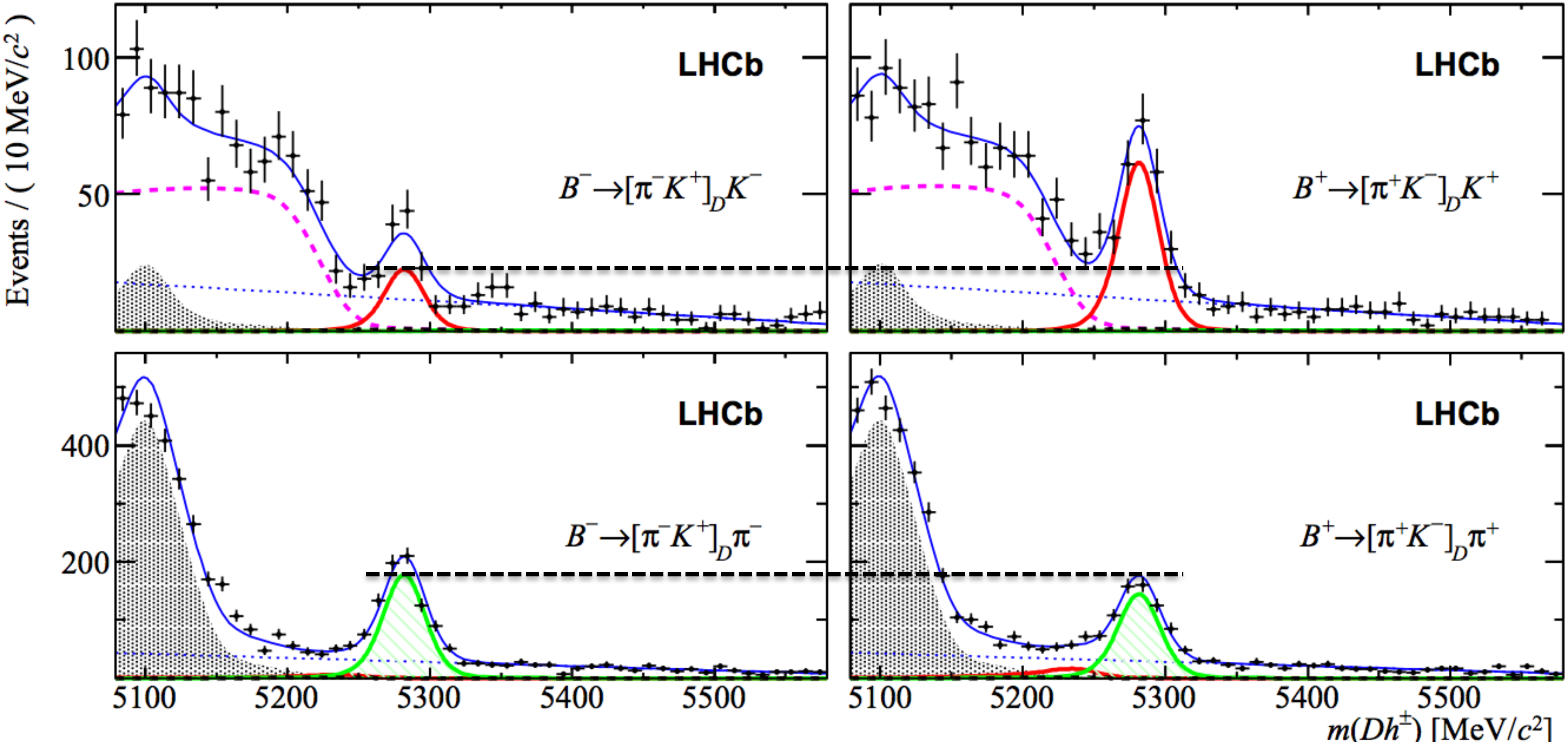
$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008$$

$$A_K^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012$$

$$A_K^{\pi\pi\pi\pi} = 0.100 \pm 0.034 \pm 0.018$$

$B^\pm \to Dh^\pm$ ADS 2-body

[arXiv:1603.08993]



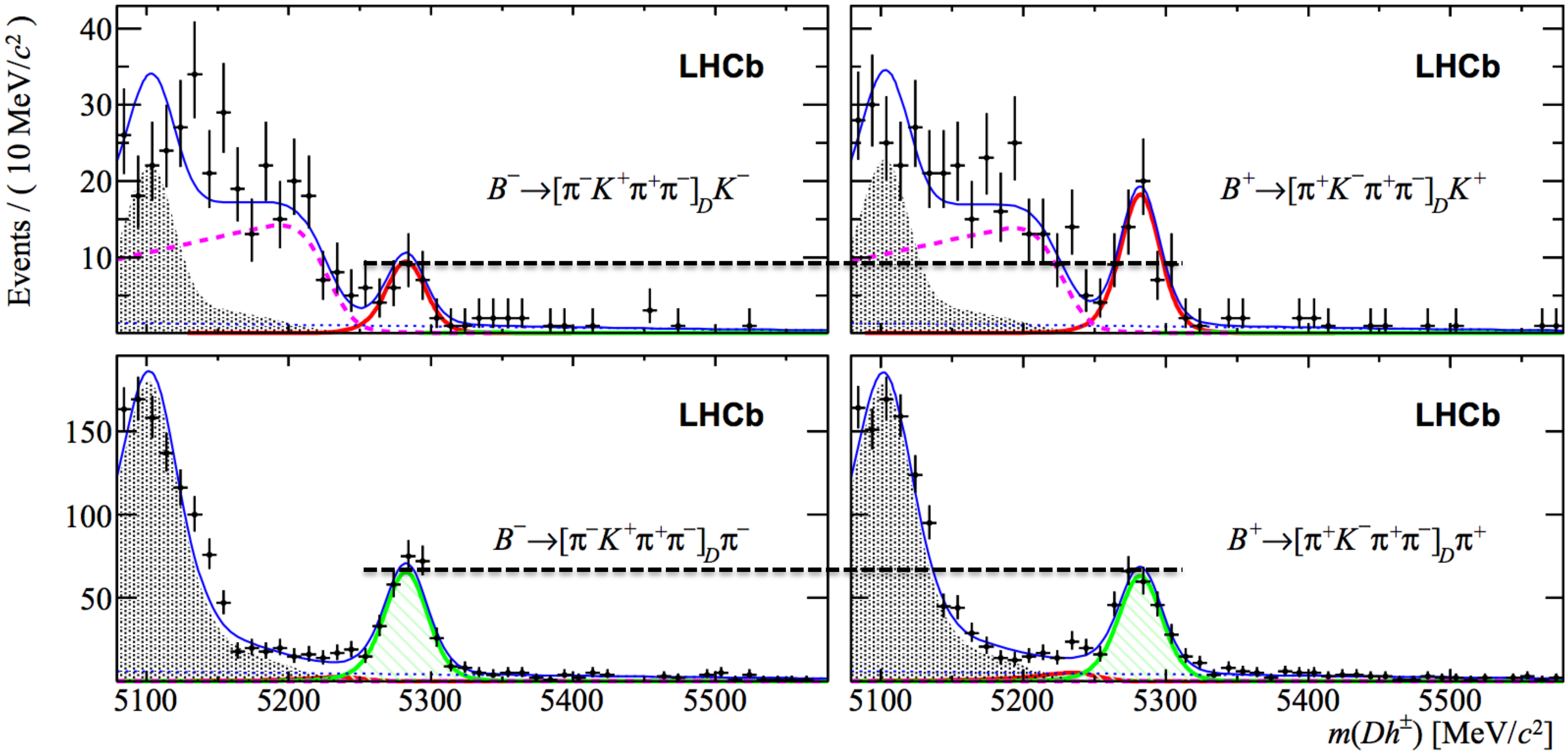
$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \pm 0.056 \pm 0.011$$

8σ First observation of CPV in single $B \to Dh$ decay mode

$$A^{\pi K}_{\mathrm{ADS}(\pi)} = 0.100 \pm 0.031 \pm 0.009$$

$B^{\pm} \to Dh^{\pm}$ ADS 4-body

[arXiv:1603.08993]



$$A^{\pi K \pi\pi}_{\mathrm{ADS}(K)} = -0.313 \pm 0.102 \pm 0.038$$

$$A^{\pi K \pi\pi}_{\mathrm{ADS}(\pi)} = \quad 0.023 \pm 0.048 \pm 0.005$$

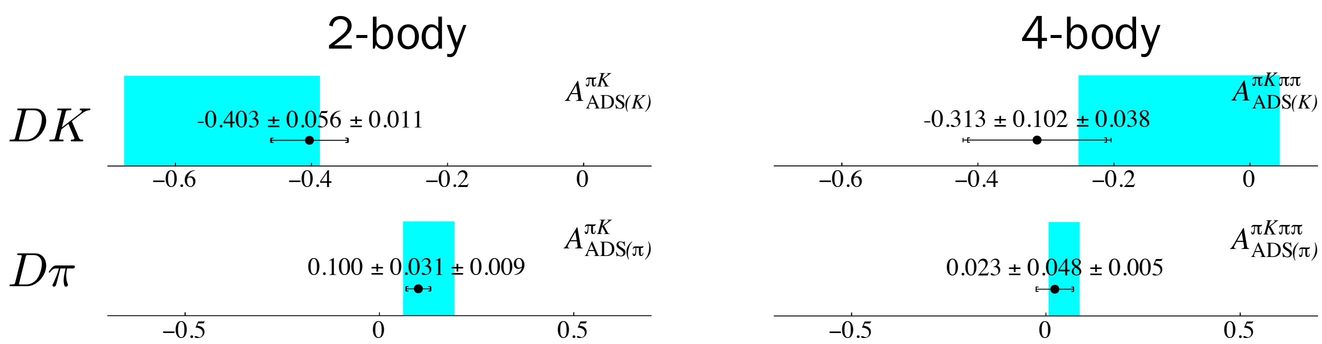
Same sign asymmetry as two-body, as expected from δ_D values

$B^{\pm} \to Dh^{\pm}$ GLW/ADS summary

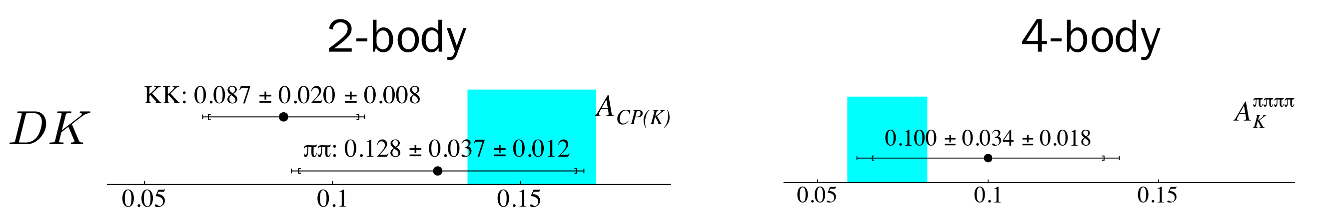
[arXiv:1603.08993]

= 1σ expectation from current knowledge of r_B, δ_B, γ

- **Significant improvement in knowledge of ADS observables:**



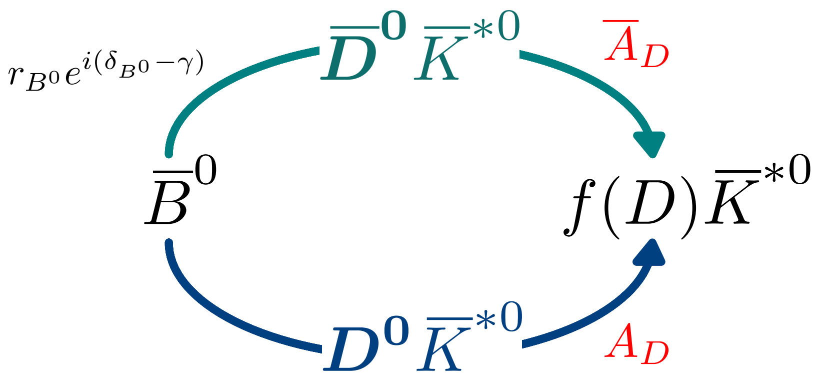
- **DK GLW charge asymmetries:**



- **Results of partial width ratios consistent with expectation**

- **$D\pi$ modes will provide constraints on upcoming DK+$D\pi$ γ combination**

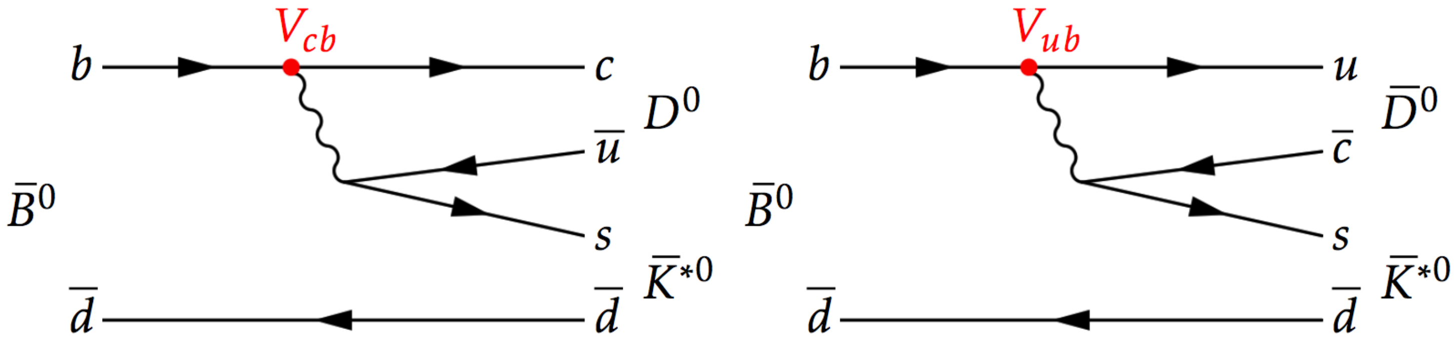
γ from $B^0 \to DK^{*0}$ decays



$\overline{K}^{*0} \to K^- \pi^+$

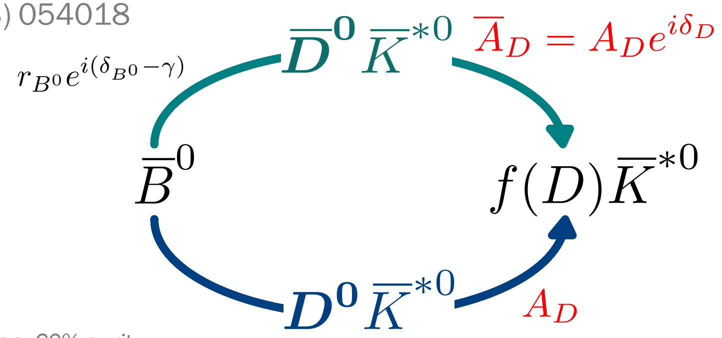
charge of kaon tags flavour of B unambiguously

Factor 20 lower BR than $B^\pm \to DK^\pm$ but larger interference effects $r_{B^0} = 0.3$



$B^0 \to DK^{*0}$ GGSZ

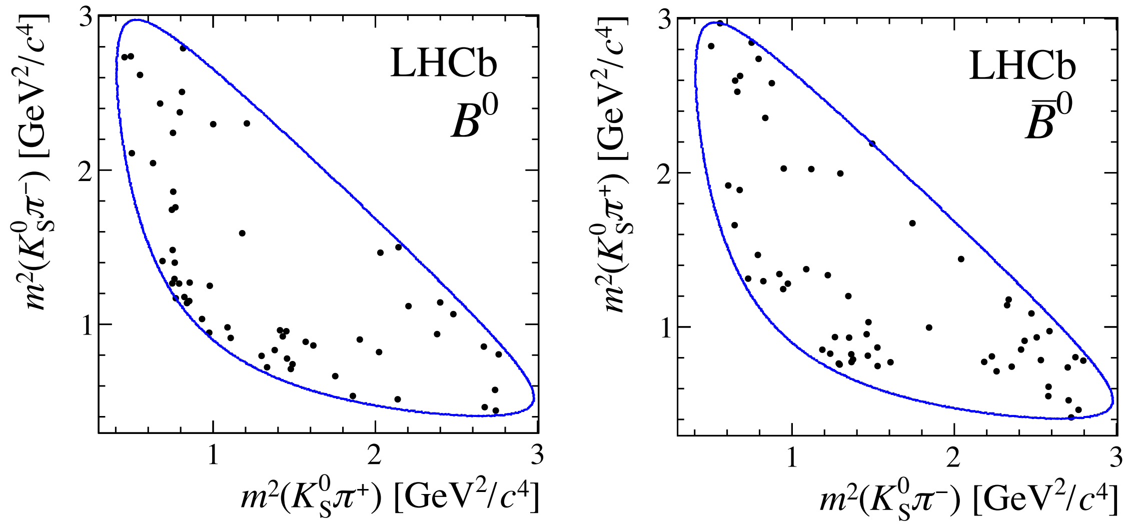
Giri, Grossman, Soffer, Zupan
PRD 68 (2003) 054018



Multi-body *D* decay = δ_D, charge asymmetry varies in $D \to K_S^0 \pi^+ \pi^-$ Dalitz plot

[arXiv:1604.05204]

* Candidates in signal window, no bkg. subtraction, 60% purity



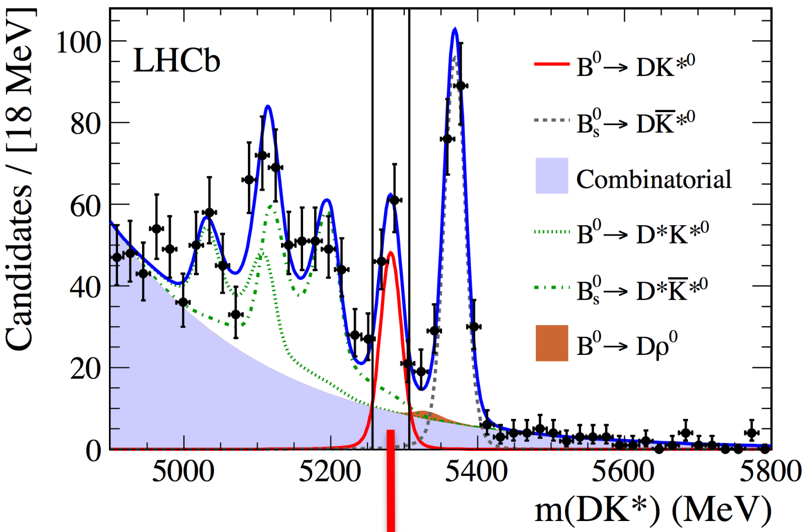
Two methods

Model-dependent method
Use an amplitude model to provide D^0 strong phase
✓ optimal use of statistics

Model-independent method
✓ direct measurements of δ_D in binned Dalitz plot
✓ $K_S^0 K^+ K^-$ included for the first time

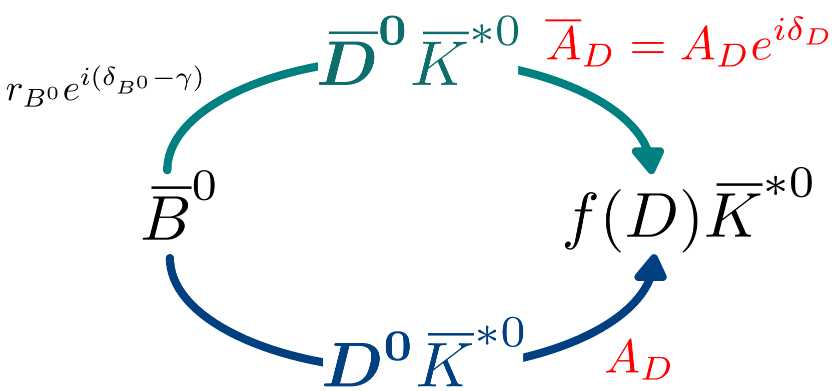
$B^0 \to DK^{*0}$ GGSZ model-dependent

[arXiv:1605.01082]



$$N(B^0 \to (D \to K_S^0\pi^+\pi^-)K^{*0}) = 89 \pm 11$$

x2 of previous B-factory measurements



Decay rate at a point of the Dalitz plot:

$$d\Gamma(B^0 \to DK^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa \mathrm{Re}\left(A_D^*\,\bar{A}_D r_{B^0} e^{i(\delta_{B^0}+\gamma)}\right)$$

$$d\Gamma(\overline{B}^0 \to D\overline{K}^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa \mathrm{Re}\left(A_D^*\,\bar{A}_D r_{B^0} e^{i(\delta_{B^0}-\gamma)}\right)$$

Coherence factor $\kappa = 0.958\,^{+0.005}_{-0.010}\,^{+0.002}_{-0.045}$

$$|m(K^{*0}) - m(K^{*0})_{\mathrm{PDG}}| < 50\,\mathrm{MeV},\ |\cos(\theta^*)| > 0.4$$

Measured in LHCb $B^0 \to DK^+\pi^-$ amplitude analysis

"B decays to open charm"
S. Haines

$B^0 \to DK^{*0}$ GGSZ model-dependent

[arXiv:1605.01082]

Decay rate at a point of the Dalitz plot:

$$d\Gamma(B^0 \to DK^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa\mathrm{Re}\left(\bar{A}_D A_D^* \, r_{B^0} e^{i(\delta_{B^0}+\gamma)}\right)$$

$$d\Gamma(\overline{B}^0 \to D\overline{K}^{*0}) \propto |A_D|^2 + r_{B^0}^2|\bar{A}_D|^2 + 2\kappa\mathrm{Re}\left(\bar{A}_D A_D^* \, r_{B^0} e^{i(\delta_{B^0}-\gamma)}\right)$$

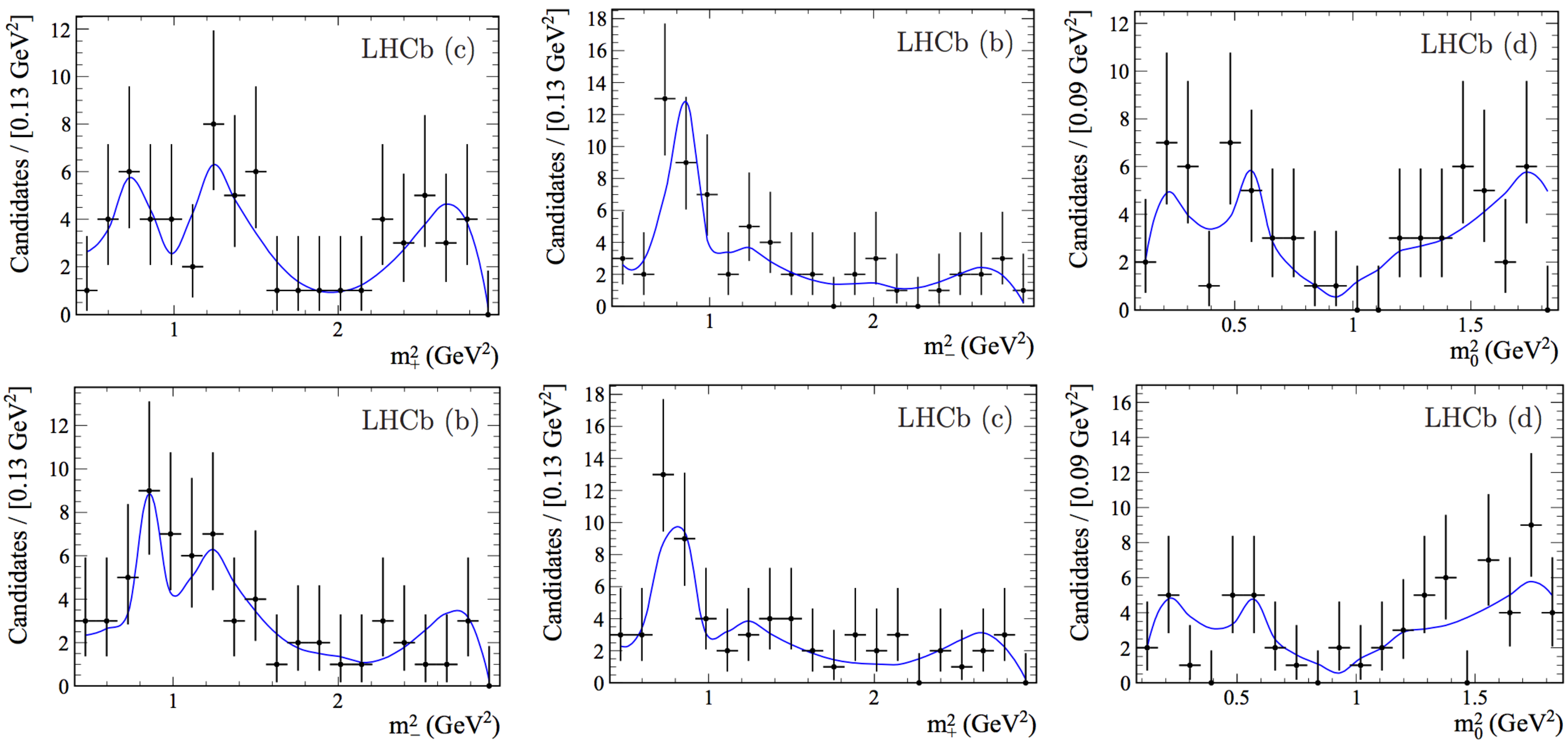
Fit amplitude model to data to extract CP observables:

$$x_\pm = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$

BaBar
PRL 105 (2010) 121801

$\overline{B}^0$

B^0



$B^0 \to DK^{*0}$ GGSZ model-independent

[arXiv:1604.05204]

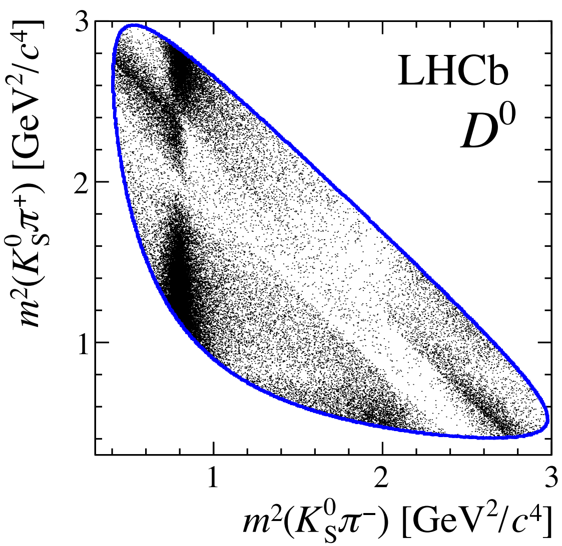
Decay rate ~~at a point~~ in a bin of the Dalitz plot:

$$N_i(B^0) \propto F_{\mp i} + (x_+^2 + y_+^2) F_{\pm i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})$$

$$N_i(\overline{B}^0) \propto F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})$$

yield of flavour-tagged D^0 events in bin

measure with semileptonic B decays



c_i, s_i

CLEO measurements using quantum-correlated $\psi(3770) \to D\overline{D}$ decays

$$c_i = \frac{\int_i |A_D||\bar{A}_D^*| \cos\delta_D}{\sqrt{\int_i |A_D|^2 \int_i |\bar{A}_D^*|^2}}$$

$$s_i = \frac{\int_i |A_D||\bar{A}_D^*| \sin\delta_D}{\sqrt{\int_i |A_D|^2 \int_i |\bar{A}_D^*|^2}}$$

[PRD 82 (2010) 112006]

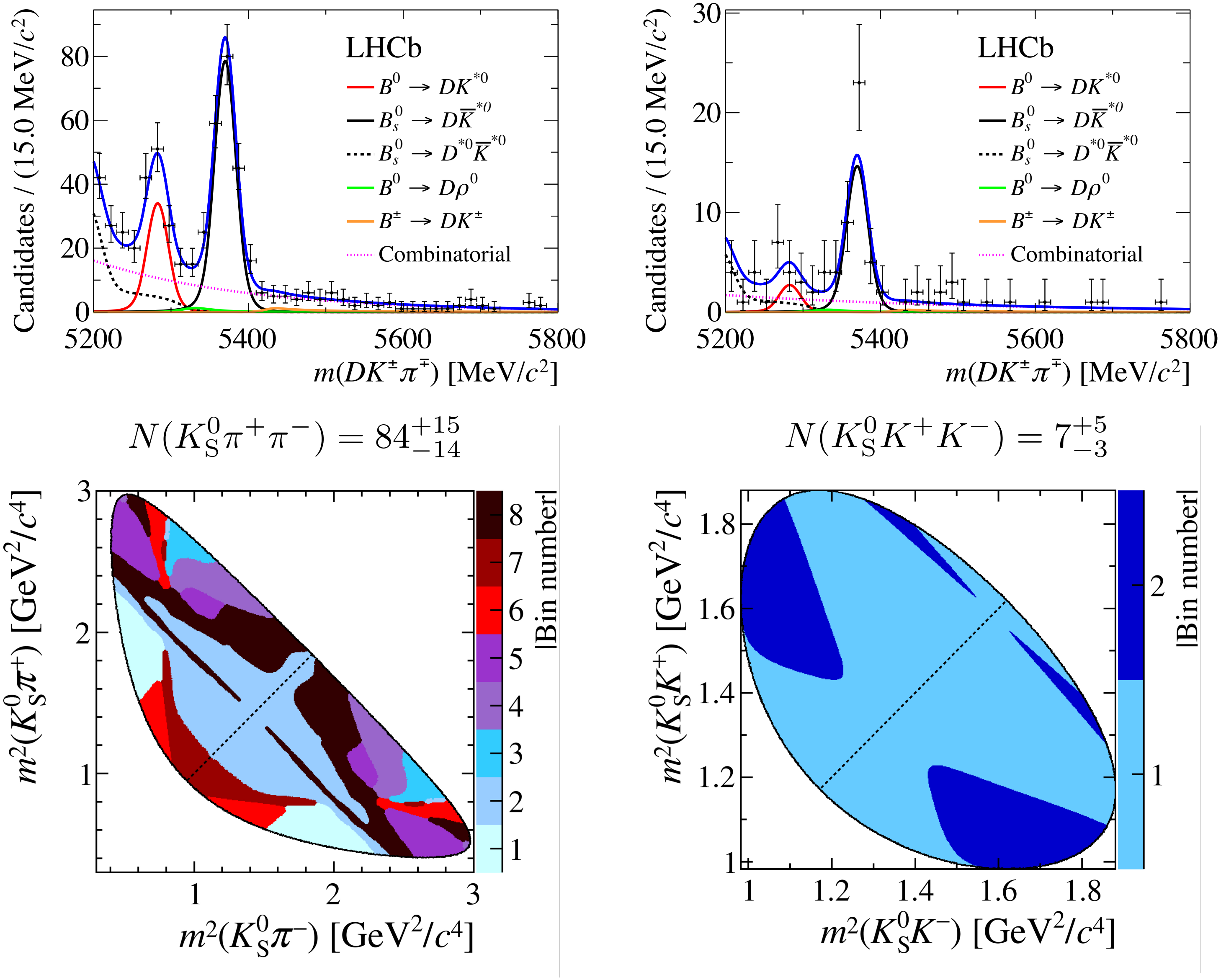
Observables

$$x_\pm = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$

Extract from simultaneous fit of $K_S^0\pi^+\pi^-$ & $K_S^0K^+K^-$ signal yields

$B^0 \to DK^{*0}$ GGSZ model-independent

[arXiv:1604.05204]

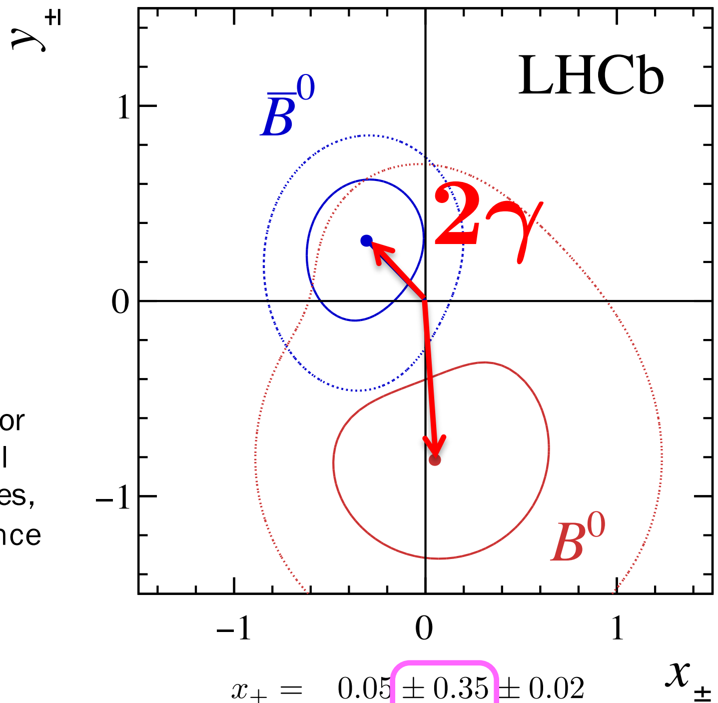


$B^0 \to DK^{*0}$ GGSZ

[arXiv:1604.05204]
[arXiv:1605.01082]

$$x_\pm = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$

model-independent



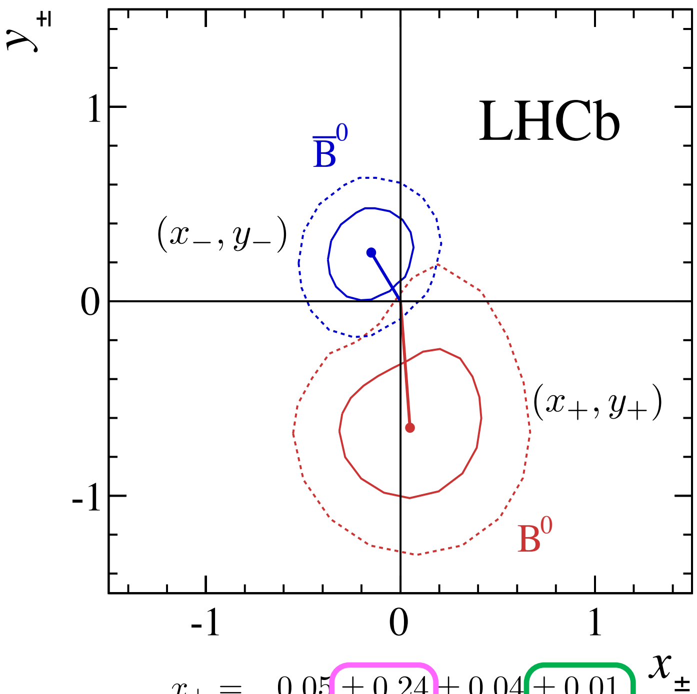
Contours for statistical uncertainties, 2D confidence intervals

$$x_+ = 0.05 \pm 0.35 \pm 0.02$$
$$x_- = -0.31 \pm 0.20 \pm 0.04$$
$$y_+ = -0.81 \pm 0.28 \pm 0.06$$
$$y_- = 0.31 \pm 0.21 \pm 0.05$$

stat. uncertainty for MI includes c_i and s_i errors approx 0.02 for x, 0.05 for y

$$r_{B^0} = 0.56 \pm 0.17$$
$$\delta_{B^0} = (204\,^{+21}_{-20})^\circ$$
$$\gamma = (71 \pm 20)^\circ$$

model-dependent



$$x_+ = 0.05 \pm 0.24 \pm 0.04 \pm 0.01$$
$$x_- = -0.15 \pm 0.14 \pm 0.03 \pm 0.01$$
$$y_+ = -0.65\,^{+0.24}_{-0.33} \pm 0.08 \pm 0.01$$
$$y_- = 0.25 \pm 0.15 \pm 0.06 \pm 0.01$$

model uncertainty

$$r_{B^0} = 0.39 \pm 0.13$$
$$\delta_{B^0} = (197\,^{+24}_{-20})^\circ$$
$$\gamma = (80\,^{+21}_{-22})^\circ$$

LHCb γ combination from $B \to DK$

LHCb measurements

updated/new since CKM'14

$B^+ \to DK^+$	$D \to h^+h^-$	GLW/ADS	✔	[arXiv:1603.08993]
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	quasi-GLW/ADS	✔	
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	quasi-GLW/ADS	✔	[Phys. Rev. D91 (2015) 112014]
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ model-independent		
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	ADS		
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	✔	[arXiv:1602.03455]
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS		
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ model-dependent	✔	[arXiv:1605.01082]
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS		
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^{\mp} \to h^+h^-h^{\mp}$	time-dependent		

"B decays to open charm"
S. Haines

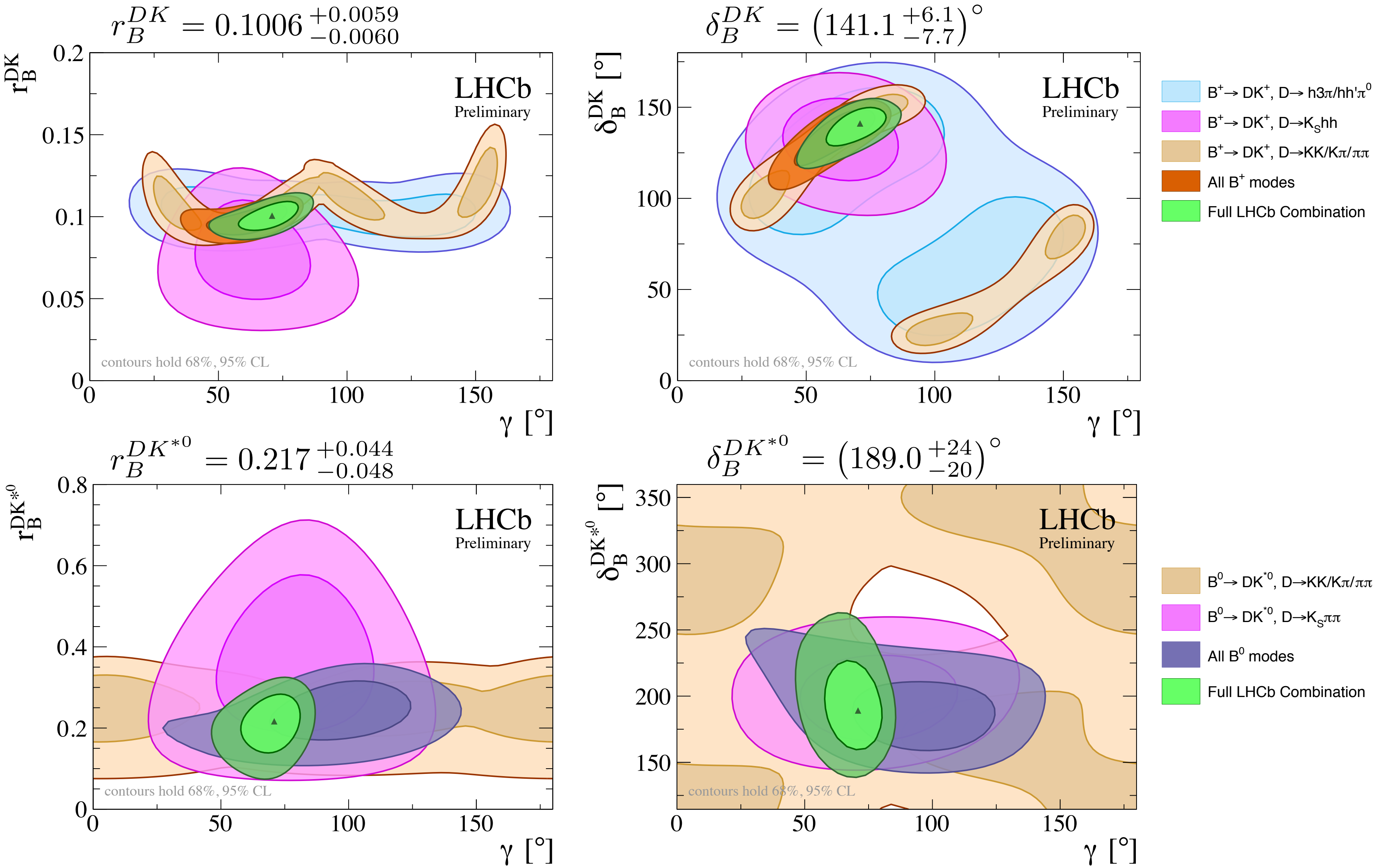
Auxiliary inputs

Charm mixing and CPV:	$x_D, y_D, A_{CP}^{dir}(\pi\pi), A_{CP}^{dir}(KK)$
CP-even fractions:	$F_{\pi\pi\pi^0}, F_{KK\pi^0}, F_{\pi\pi\pi\pi}$
Charm system:	$\delta_D^{K\pi}, R_D^{K\pi}$
	$\kappa_D^{K2\pi}, \delta_D^{K2\pi}, r_D^{K2\pi}$
	$\kappa_D^{K3\pi}, \delta_D^{K3\pi}, r_D^{K3\pi}$
	$\kappa_D^{K^0_S K\pi}, \delta_D^{K^0_S K\pi}, R_D^{K^0_S K\pi}$
$B \to DK\pi$:	$\kappa^{DK^{*0}}, \overline{\Delta}_B^{DK^{*0}}, \overline{R}_B^{DK^{*0}}$
B_s mixing:	ϕ_s

LHCb γ combination

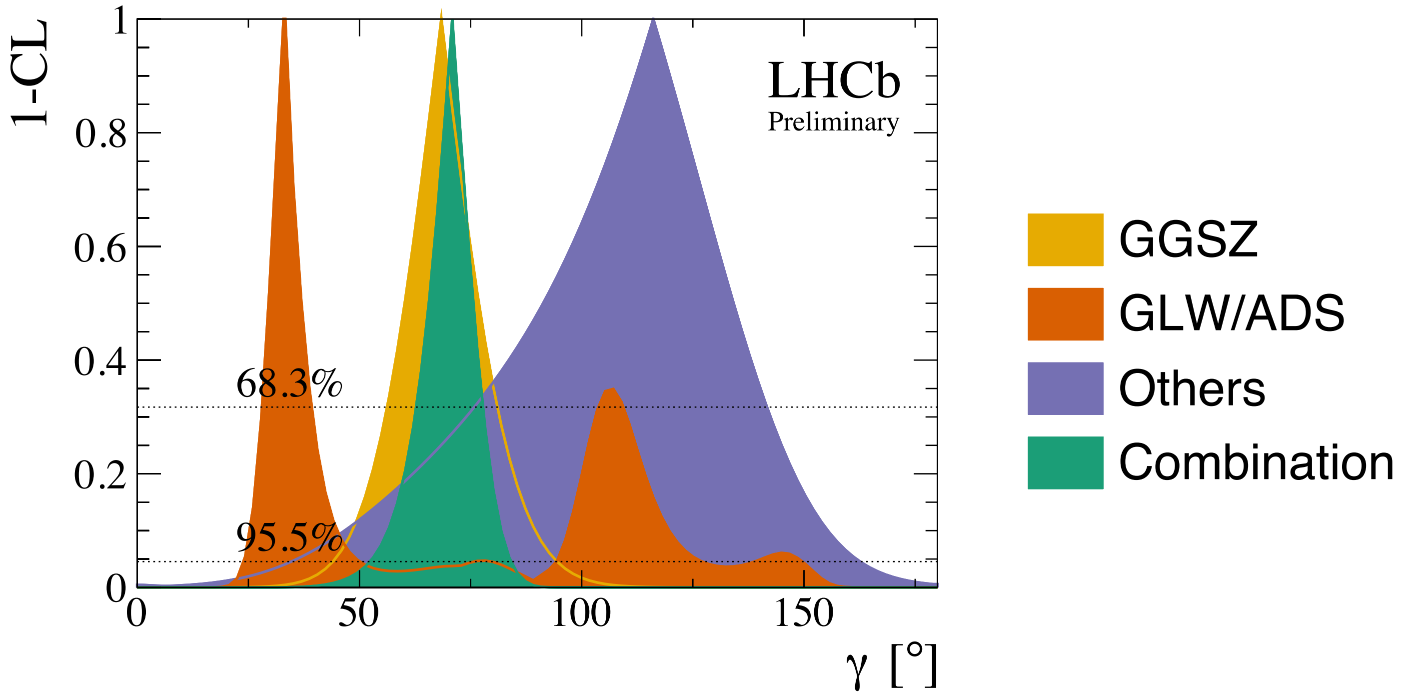
[LHCb-CONF-2016-001]

Complementarity of different methods: ADS/GLW, quasi-ADS/GLW, GGSZ



LHCb γ combination

[LHCb-CONF-2016-001]



- Most precise measurement from a single experiment:

$$\gamma = \left(70.9^{+7.1}_{-8.5}\right)^{\circ}$$

- Consistent with B-factory averages: $\text{BaBar: } (70 \pm 18)^{\circ}$

$$\text{Belle: } (73\,^{+13}_{-15})^{\circ}$$

Summary

- Most precise measurement from a single experiment

$$\gamma = (70.9^{+7.1}_{-8.5})^\circ$$

- Latest LHCb γ analyses presented:

  $B \to DK$ and $B \to D\pi$ with ADS/GLW

  $B^0 \to DK^{*0}$ with GGSZ model-independent

  $B^0 \to DK^{*0}$ with GGSZ model-dependent

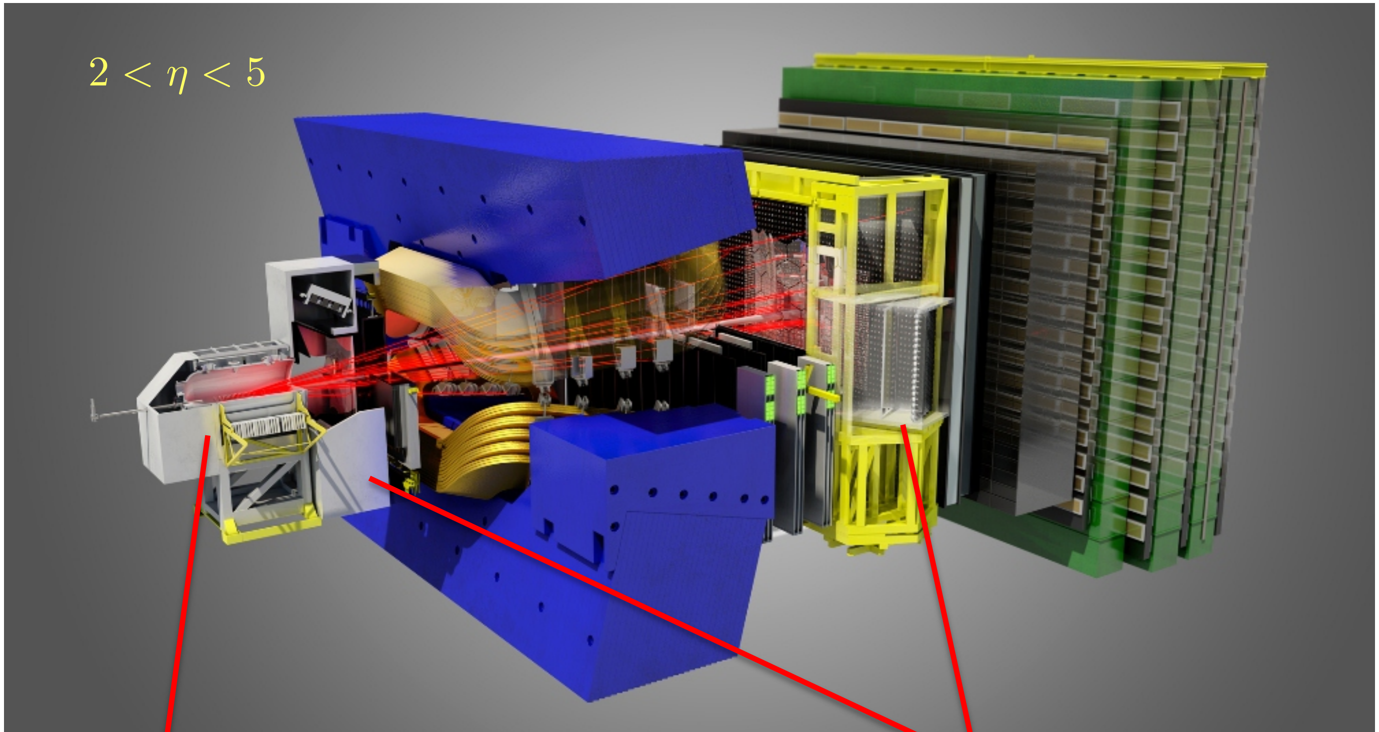
- Stay tuned!
  - LHCb combination including $D\pi$ modes in progress
  - On-going analyses of new B decays; inclusion of Run 2 data
  - $B_s \to D_s K$ Run 1 update

EXTRA SLIDES

LHCb detector

Analyses presented:
1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV

Important features γ for analyses



3
LHCb trigger
45% of Run 1 L0 bandwidth dedicated to hadronic trigger

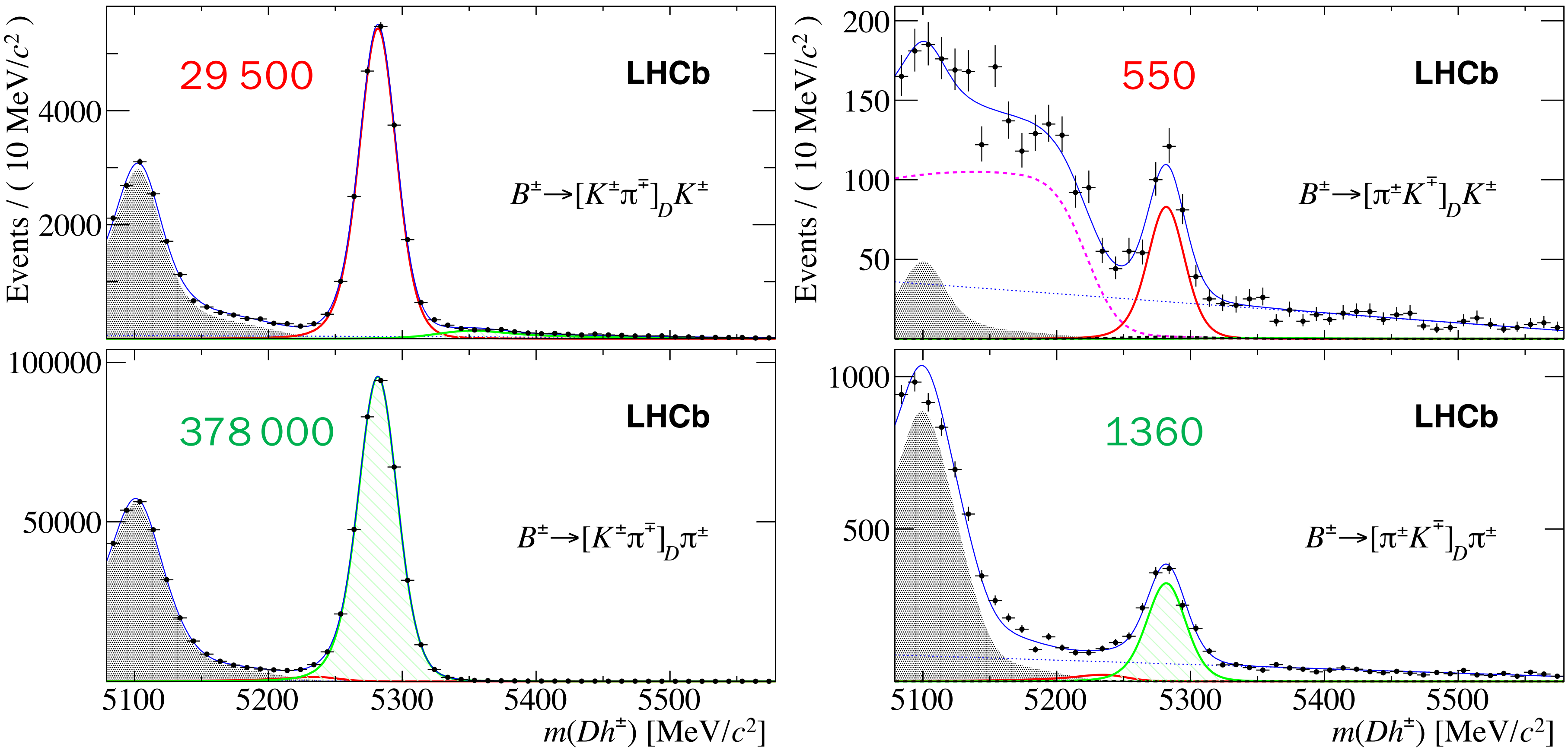
1
VELO
B flight distance ~1 cm,
impact parameter resolution ~20 μm:
powerful discriminator of B mesons and essential for triggers and offline selection

2
RICH I & II
Particle identification: π, K, p
Identify B, D decays + cross-feed suppression
>90% kaon efficiency with 5% pion contamination

$B^{\pm} \to Dh^{\pm}$ GLW/ADS

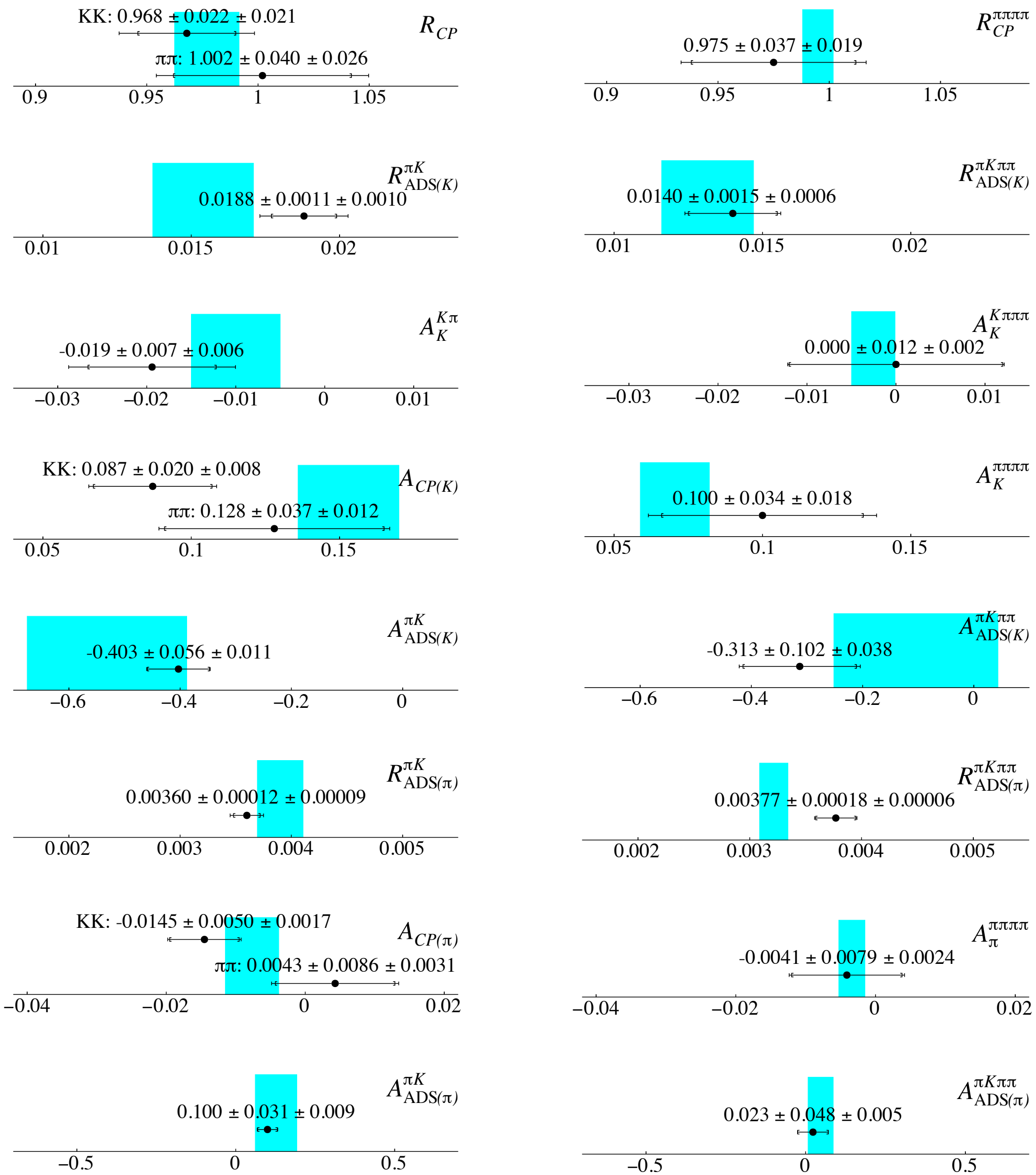
[arXiv:1603.08993]

- Observables: charge asymmetries, partial width ratios
- Normalise to the favoured $D \to K^{-}\pi^{+}(\pi^{-}\pi^{+})$ decay
- Assuming A_{CP}=0, its charge asymmetry is a measure of combined $A_{\text{prod}} \times A_{\text{det}}$



$B^{\pm} \to Dh^{\pm}$ GLW/ADS results

[arXiv:1603.08993]

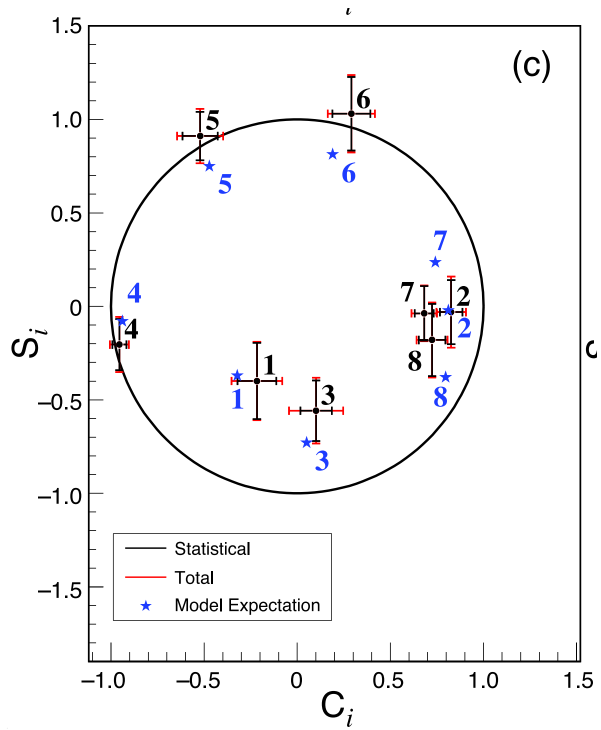


= 1σ expectation from current knowledge of r_B, δ_B, γ

$B^0 \to DK^{*0}$ GGSZ

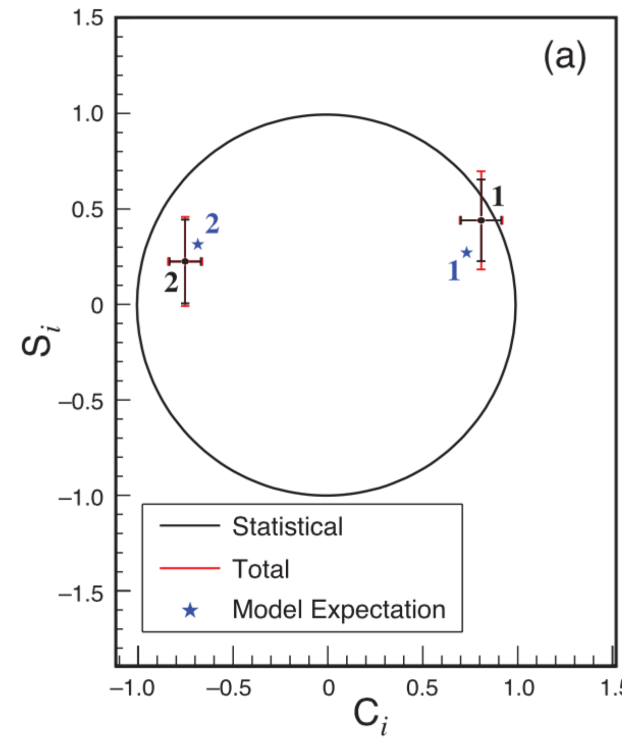
[PRD 82 112006 (2010)]

Comparison of strong-phase difference from CLEO measurements and amplitude model expectation



$K^0_S\pi^+\pi^-$

"Modified optimal" binning



$K^0_S K^+ K^-$

N=2 binning

LHCb γ combination inputs

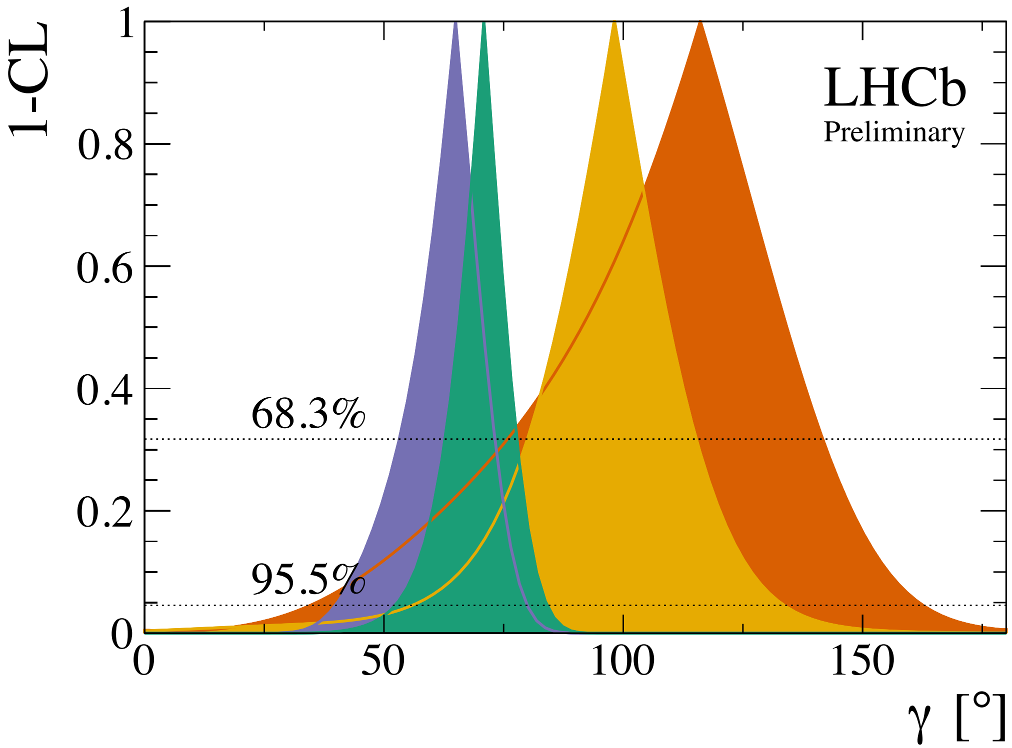
[LHCb-CONF-2016-001]

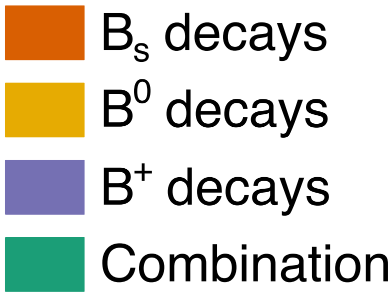
$$x_D = 0.0037 \pm 0.0016\,,$$
$$y_D = 0.0066 \pm 0.0009\,,$$
$$\delta_D^{K\pi} = 3.35 \pm 0.21\,,$$
$$R_D^{K\pi} = 0.00349 \pm 0.00004\,,$$
$$A_{CP}^{\rm dir}(\pi\pi) = 0.0010 \pm 0.0015\,,$$
$$A_{CP}^{\rm dir}(KK) = -0.0015 \pm 0.0014\,.$$
$$F_{\pi\pi\pi^0} = 0.973 \pm 0.017\,,$$
$$F_{KK\pi^0} = 0.732 \pm 0.055\,,$$
$$F_{\pi\pi\pi\pi} = 0.737 \pm 0.032\,.$$
$$\kappa_B^{DK^{*0}} = 0.958 \pm 0.008 \pm 0.024,$$
$$\bar{R}_B^{DK^{*0}} = 1.020 \pm 0.020 \pm 0.060,$$
$$\bar{\Delta}_B^{DK^{*0}} = 0.020 \pm 0.025 \pm 0.110.$$

$$\kappa_D^{K3\pi} = 0.32 \pm 0.10\,,$$
$$\delta_D^{K3\pi} = 2.97 \pm 0.66\,,$$
$$\kappa_D^{K2\pi} = 0.81 \pm 0.07\,,$$
$$\delta_D^{K2\pi} = 3.14 \pm 0.30\,,$$
$$r_D^{K3\pi} = 0.0552 \pm 0.0007\,,$$
$$r_D^{K2\pi} = 0.0440 \pm 0.0012\,.$$
$$\delta_D^{K_S K\pi} = 0.46 \pm 0.28\,,$$
$$\kappa_D^{K_S K\pi} = 1.00 \pm 0.16\,.$$
$$R_D^{K_S K\pi} = 0.370 \pm 0.003 \pm 0.012\,.$$
$$\phi_s = -0.010 \pm 0.039\,\text{rad}\,.$$

LHCb γ combination

[LHCb-CONF-2016-001]





Quantity	Value
γ (°)	70.9
68% CL (°)	[62.4, 78.0]
95% CL (°)	[51.0, 85.0]
r_B^{DK}	0.1006
68% CL	[0.0946, 0.1065]
95% CL	[0.0890, 0.1120]
δ_B^{DK} (°)	141.1
68% CL (°)	[133.4, 147.2]
95% CL (°)	[122.0, 153.0]
$r_B^{DK^{*0}}$	0.217
68% CL	[0.169, 0.261]
95% CL	[0.115, 0.303]
$\delta_B^{DK^{*0}}$ (°)	189.0
68% CL (°)	[169.0, 213.0]
95% CL (°)	[149.0, 243.0]