Measurements of the Unitarity Triangle angle γ

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LHCb Implications Workshop

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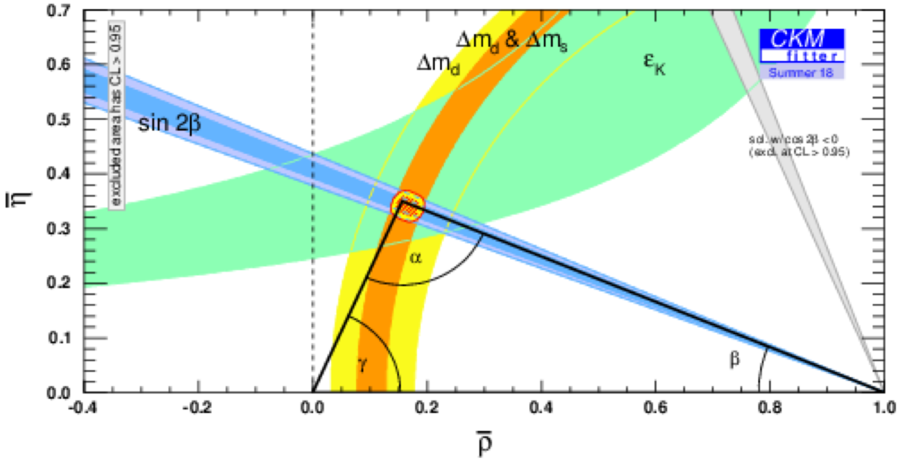
Why measure γ?

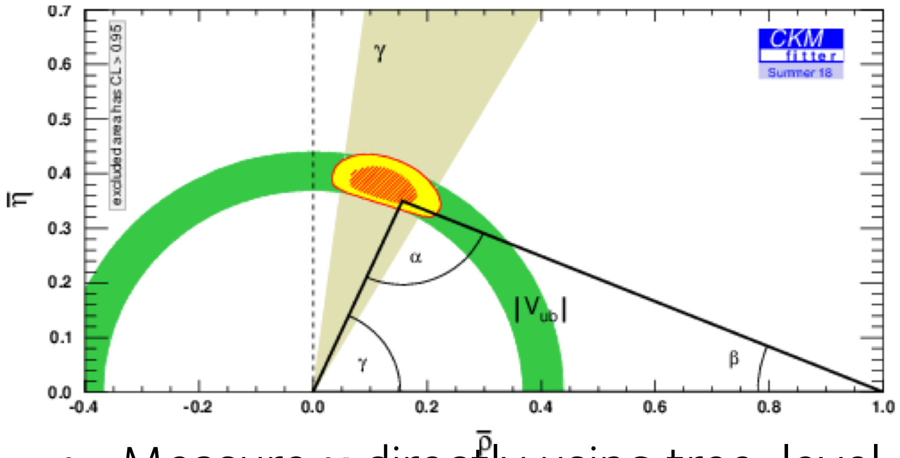
$$V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \longrightarrow V_{ub} = |V_{ub}|e^{-i\gamma}$$

Indirect measurement:



- Extrapolate γ from measurements of α and β
- Measured using loop-level decays: sensitivity to new physics
- CKMFitter result: $\gamma = (65.65^{+0.97}_{-3.42})°$

Direct measurement:

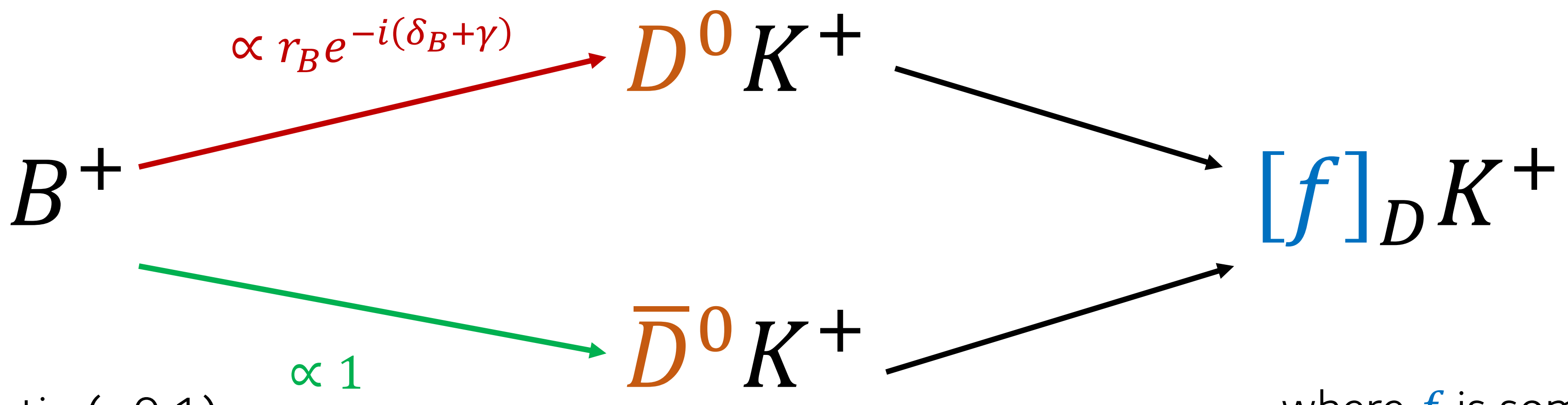


- Measure γ directly using tree-level decays
- Theoretically clean ($\frac{\delta\gamma}{\gamma} < 10^{-7}$)
- LHCb result: $\gamma = (74.0^{+5.0}_{-5.8})°$

Disagreement = NEW PHYSICS!

How to measure γ directly

- We need a $\boldsymbol{b} \rightarrow \boldsymbol{u}$ **quark transition**, so that V_{ub} is in the amplitude
- We need **interference**, so that the squared amplitude is sensitive to the phase of V_{ub}
- Ideal decays: $B^{\pm} \rightarrow DK^{\pm}$ (and similar, e.g. $B^{\pm} \rightarrow D^{*}K^{\pm}, B^{0} \rightarrow DK^{*0}$...)



r_B = magnitude ratio (~0.1)
δ_B = strong-phase difference

where f is some final state accessible to both D^0 and $\overline{D}^0$

Current status of LHCb analyses

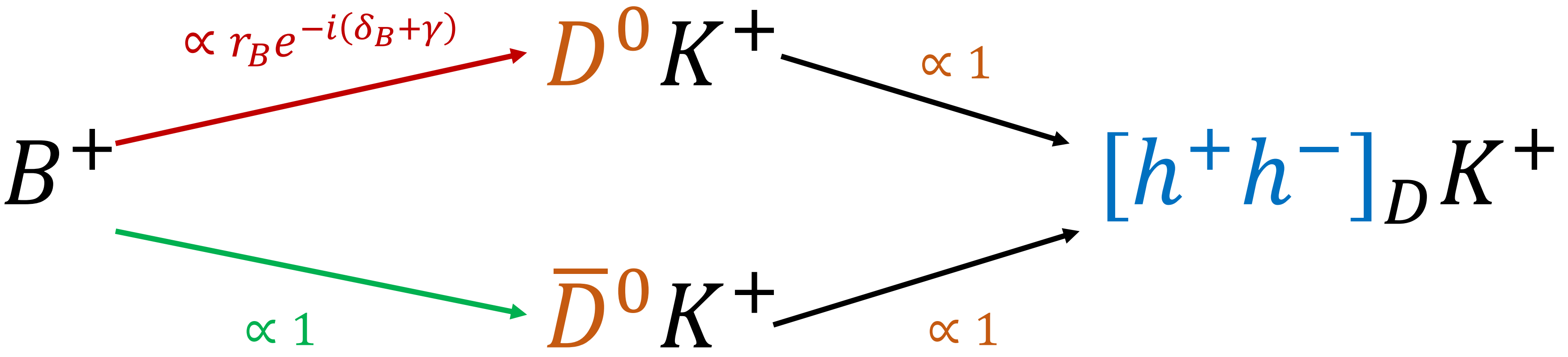
3 fb^{-1} Run 1 data set / Includes 2 fb^{-1} 2015/16 data set

		$B^+ \to DK^+$	$B^+ \to D\pi^+$	$B^0 \to DK^{*0}$	$B^+ \to DK^{*+}$	$B^+ \to DK^+\pi^-\pi^+$	$B^+ \to D^*K^+$
GLW	h^+h^-	PLB.777(18)16		Dalitz method: PRD.93(16)112018 JHEP.08(19)41	JHEP.17(17)156	PRD.92(15)112005	Part. Reco: PLB.777(18)16
	$\pi^+\pi^-\pi^+\pi^-$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156		
	$h^+h^-\pi^0$	PRD.91(25)112014					
ADS	$K^\pm\pi^\mp$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156	PRD.92(15)112005	
	$K^\pm\pi^\mp\pi^+\pi^-$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156		
	$K^\pm\pi^\mp\pi^0$	PRD.91(25)112014					
GGSZ	$K_S^0 h^+h^-$	JHEP.10(14)97 JHEP.08(18)176		MD: JHEP.08(16)137 MI: JHEP.06(16)131			
GLS	$K_S^0 K^+\pi^-$	PLB.733(14)36					
Time dependent		$B_s^0 \to D_s^\mp K^\pm$ [JHEP.03(18)59] and $B^0 \to D^\mp\pi^\pm$ [JHEP.06(18)84]					

Featured in this talk

D final states: GLW modes[1,2]

- First, consider CP-even final states such as $D \to K^+K^-, \pi^+\pi^-$



Changing flavours: sign of γ changes

$$A(B^+ \to [h^+h^-]_D K^+) \propto 1 + r_B e^{-i(\delta_B+\gamma)}$$
$$A(B^- \to [h^+h^-]_D K^-) \propto 1 + r_B e^{-i(\delta_B-\gamma)}$$

[1] M. Gronau and D. Wyler, Phys. Lett. B265 (1991) 172
[2] M. Gronau and D. London, Phys. Lett. B253 (1991) 483

D final states: GLW modes

- Use the yields of B^+ and B^- to construct observables related to γ
- Asymmetry between flavours:

$$A^{hh} = \frac{N(B^- \to [hh]_D K^-) - N(B^+ \to [hh]_D K^+)}{N(B^- \to [hh]_D K^-) + N(B^+ \to [hh]_D K^+)} = \frac{2r_B \sin\delta_B \sin\gamma}{R^{hh}}$$

- Ratio of total yield w.r.t. Cabibbo-favoured decay $D \to K\pi$:

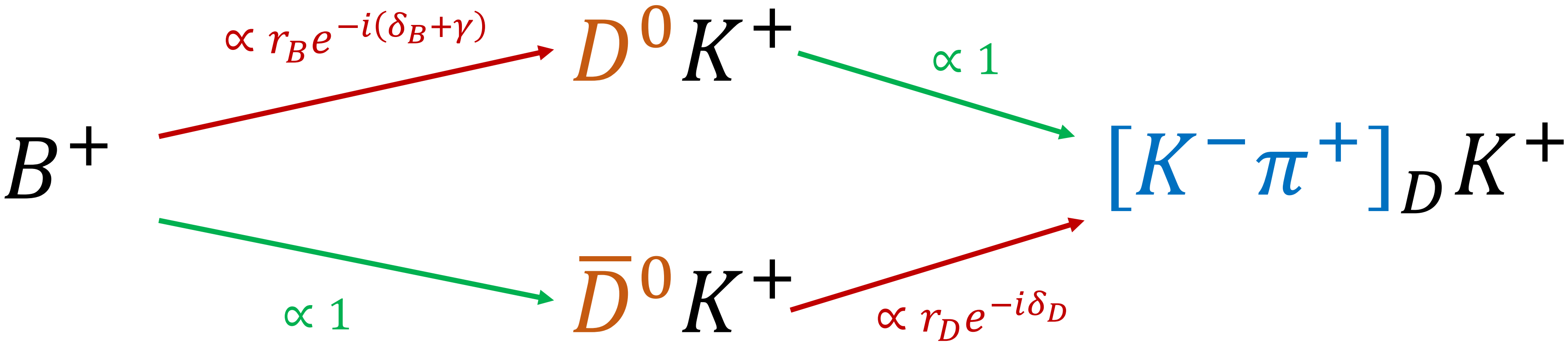
$$R^{hh} = \frac{N(B^- \to [hh]_D K^-) + N(B^+ \to [hh]_D K^+)}{N(B^- \to [K\pi]_D K^-) + N(B^+ \to [K\pi]_D K^+)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$

- Can also use $D \to \pi^+\pi^-\pi^+\pi^-$: insert a factor of $2F_+ - 1$ before interference terms (F_+= CP-even content = 0.769 ± 0.023[1])

[1] JHEP 01 (2018) 144

D final states: ADS modes[1,2]

- Consider the Cabibbo-favoured decay $D^0 \to K^-\pi^+$ and doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$:

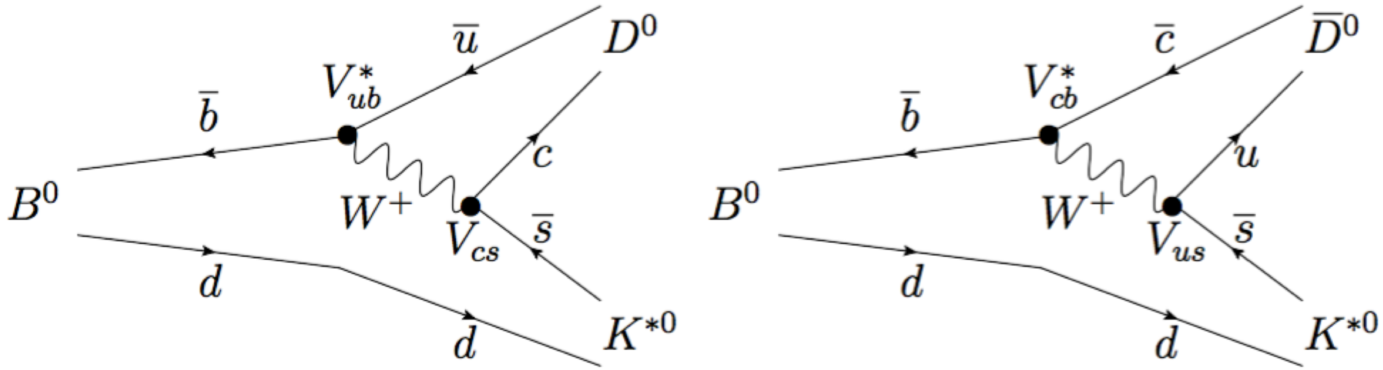


- Treat similarly to GLW, except we also need to input D decay parameters r_D and δ_D
- Can also use $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$, with a coherence factor $R_{K3\pi}$, and $r_D^{K3\pi}$ and $\delta_D^{K3\pi}$ averaged over phase space

[1] D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett. 78 (1997) 3257
[2] D. Atwood, I. Dunietz, and A. Soni , Phys. Rev. D63 (2001) 036005

ADS/GLW analysis of $B^0 \to DK^{*0}$

- New result using 5 fb^{-1} of data (2011 – 2016) [JHEP08(2019)041]
- Reconstruct K^{*0} from $K^+\pi^-$, using sign of kaon to tag B^0 flavour
  - Use coherence factor $\kappa = 0.958^{+0.005}_{-0.046}$ [1] to account for non-resonant $B^0 \to DK^+\pi^-$
- Unlike $B^\pm \to DK^\pm$, both B decays are colour suppressed:



$r_B \approx 0.3$

- This means larger interference terms and more CPV (but lower yields)

[1] Phys. Rev. D93 (2016) 112018

GLW results: D → K^+K^-, $\pi^+\pi^-$

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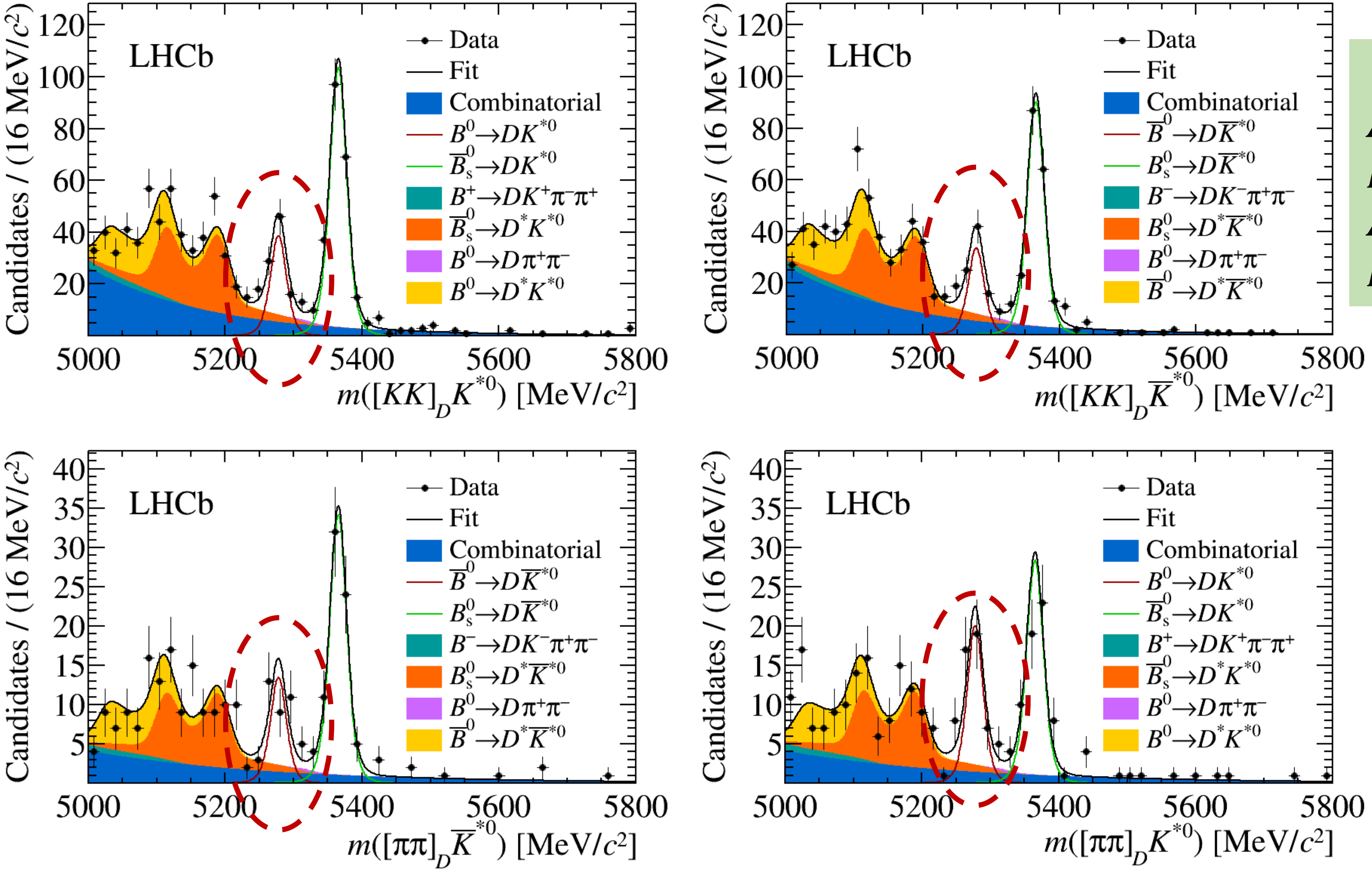
$\bar{B}^0$ decays | B^0 decays

$D \to K^+K^-$

$D \to \pi^+\pi^-$



Results:

$A^{KK} = -0.05 \pm 0.10 \pm 0.01$

$R^{KK} = 0.92 \pm 0.10 \pm 0.02$

$A^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01$

$R^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03$

Corrected for:

- Selection efficiencies
- Detection charge asymmetries
- $B^0 - \bar{B}^0$ production asymmetry

[JHEP08(2019)041]

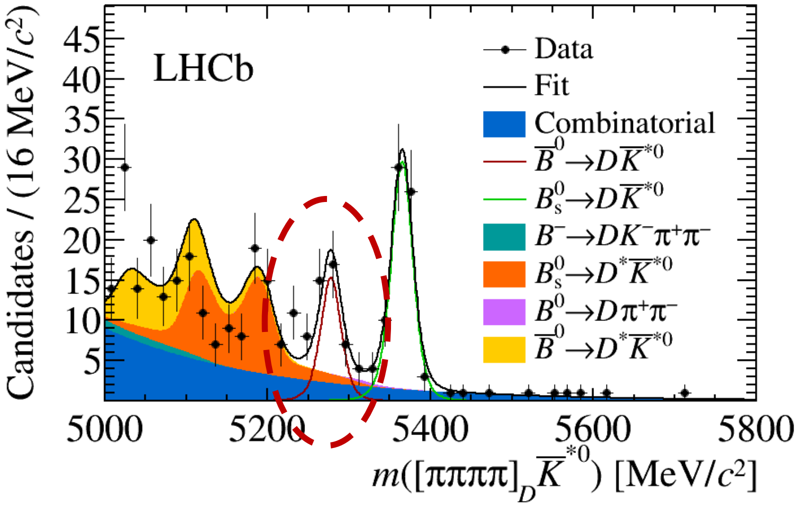
GLW results: D $\rightarrow \pi^+\pi^-\pi^+\pi^-$

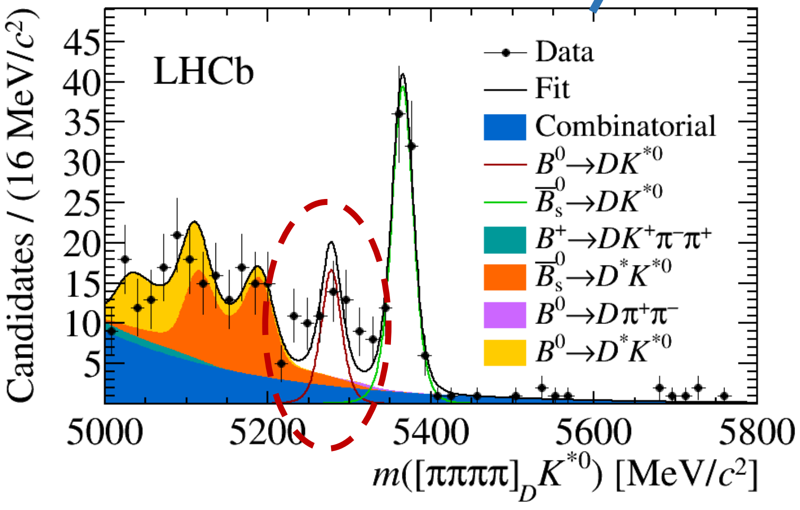
$\bar{B}^0$ decays

B^0 decays

First observation! 8.4σ

$D \rightarrow 4\pi$





Results:

$$A^{4\pi} = -0.03 \pm 0.15 \pm 0.01$$

$$R^{4\pi} = 1.01 \pm 0.16 \pm 0.04$$

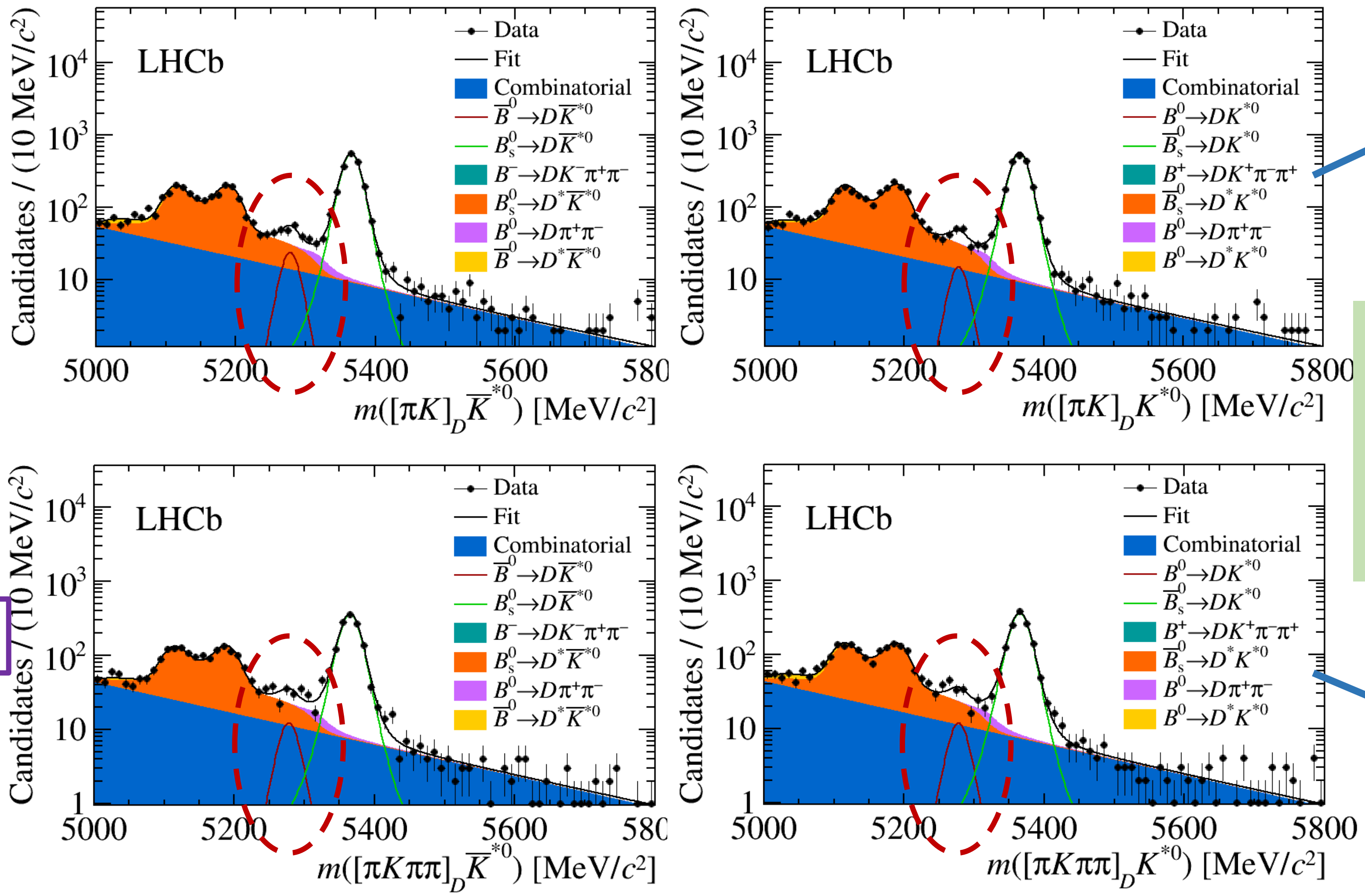
[JHEP08(2019)041]

ADS results: $D \to \pi K(\pi\pi)$

$\bar{B}^0$ decays | B^0 decays

$D \to \pi K$

$D \to \pi K\pi\pi$



First observation! 5.8σ

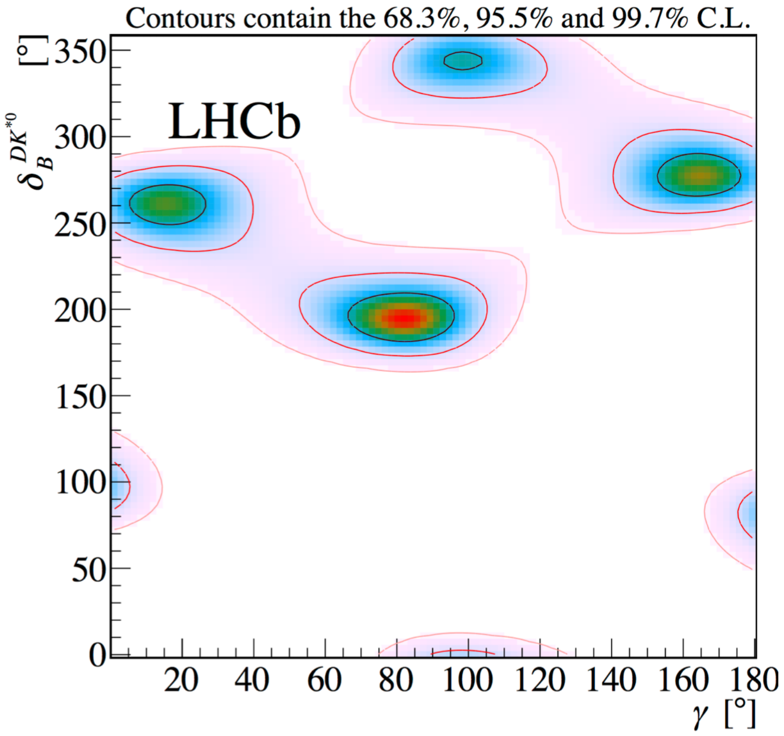
Significance: 4.4σ

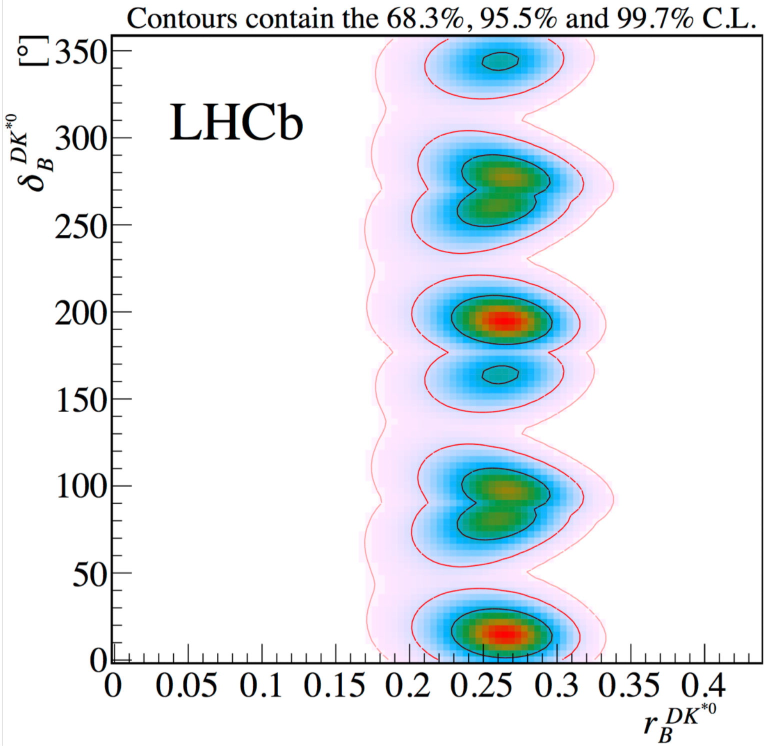
Results:

$$A_{ADS}^{\pi K} = 0.19 \pm 0.19 \pm 0.01$$
$$R_{ADS}^{\pi K} = 0.080 \pm 0.015 \pm 0.002$$
$$A_{ADS}^{\pi K\pi\pi} = -0.01 \pm 0.24 \pm 0.01$$
$$R_{ADS}^{\pi K\pi\pi} = 0.073 \pm 0.018 \pm 0.002$$

[JHEP08(2019)041]

Interpretation of results



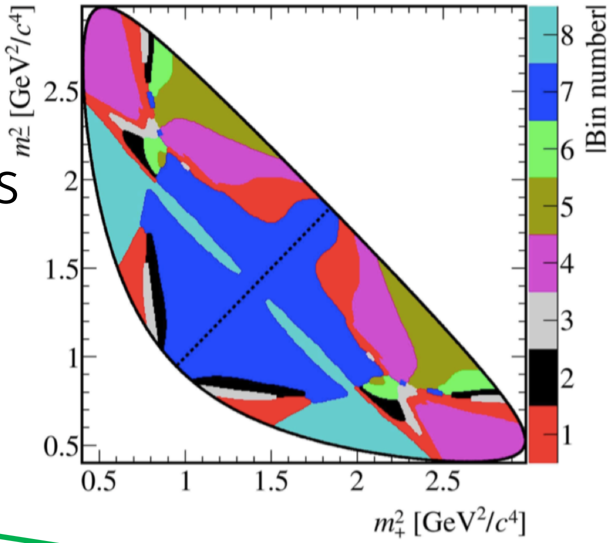


- Multiple solutions for γ and δ_B
- World-best measurement of $r_B = 0.265 \pm 0.023$ (50% increase in precision vs. previous measurement)

D final states: GGSZ modes[1]

- Divide the phase space of $D \to K_S^0 h^+ h^-$ decays into bins and measure the yields of B^+ and B^- in each
  - Sensitivity comes from **phase-space distribution**, not overall asymmetries → not impacted by production/detection asymmetries

Optimal binning scheme:



Measure observables $x_\pm$ and $y_\pm$
$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + i y_\pm$

$$N_{\pm i}^{-} \propto F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}}\,(x_- c_{\pm i} \mp y_- s_{\pm i})$$

F_i : fractional yield of flavor-tagged D^0 decays in bin i
Measured in control channel: $\bar{B}^0 \to D^{*+} \mu^- \nu_\mu X$

c_i / s_i : strong phase difference of $D^0 - \bar{D}^0$ decays in bin i
External input from CLEO measurement

[1] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68 (2003) 054018

Latest GGSZ results

- Analysis of $B^{\pm} \to DK^{\pm}, D \to K_S^0 h^+ h^-$ with 2015 & 2016 data [JHEP.08(18)176]

Observables:

$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4)\times 10^{-2}$
$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1)\times 10^{-2}$
$x_+ = (-7.7 \pm 1.7 \pm 0.7 \pm 0.4)\times 10^{-2}$
$y_- = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9)\times 10^{-2}$

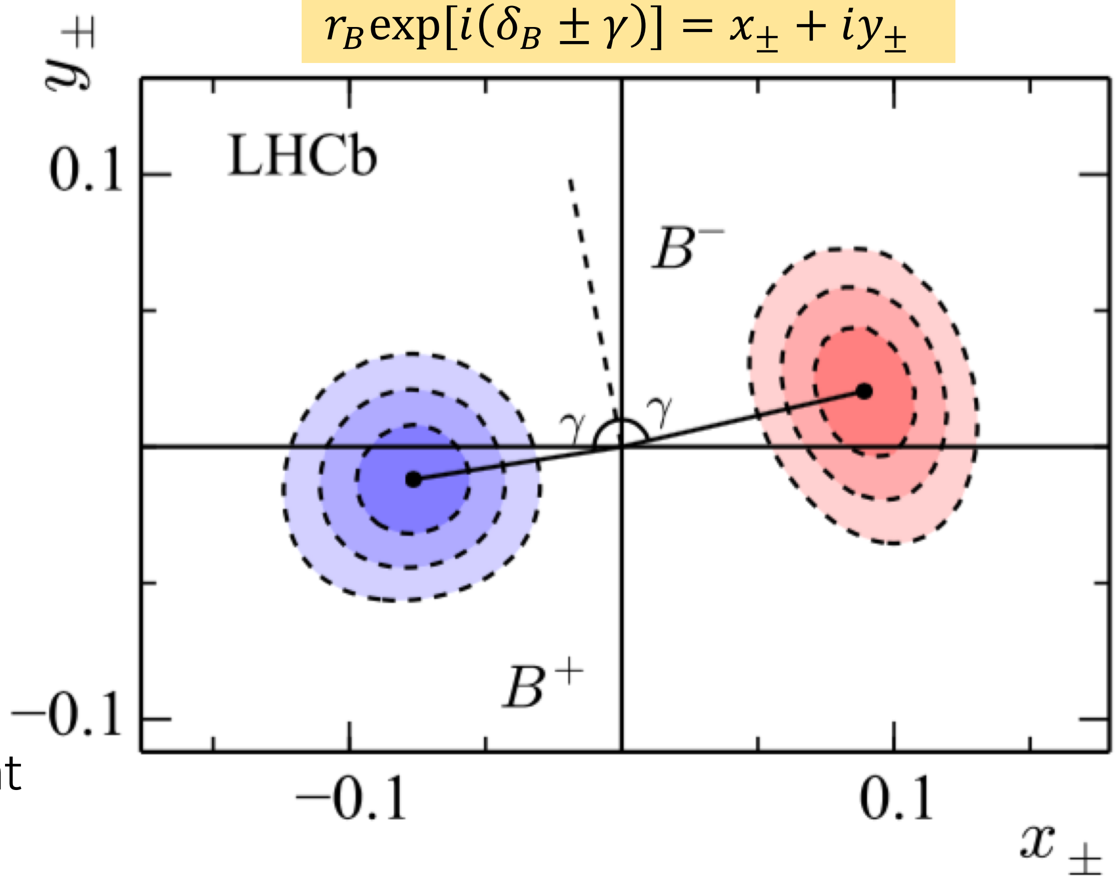
Statistical uncertainty

Analysis-related systematic uncertainty

Uncertainty from CLEO inputs

Currently statistically limited

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



$\gamma = (87^{+11}_{-12})^{\circ}$

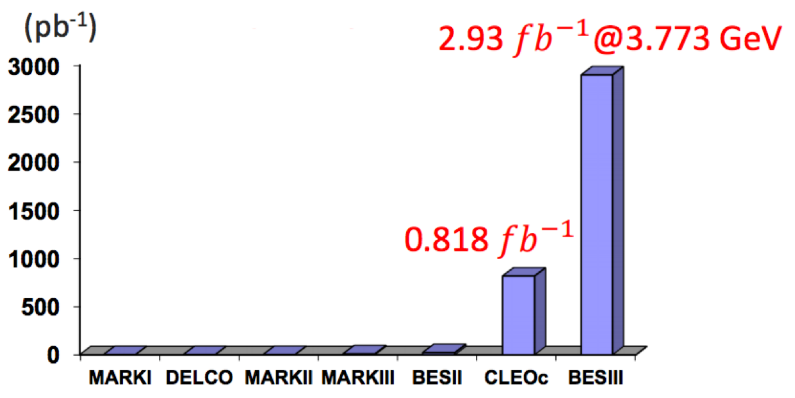
Most precise γ measurement from a single analysis!

New BESIII strong-phase inputs

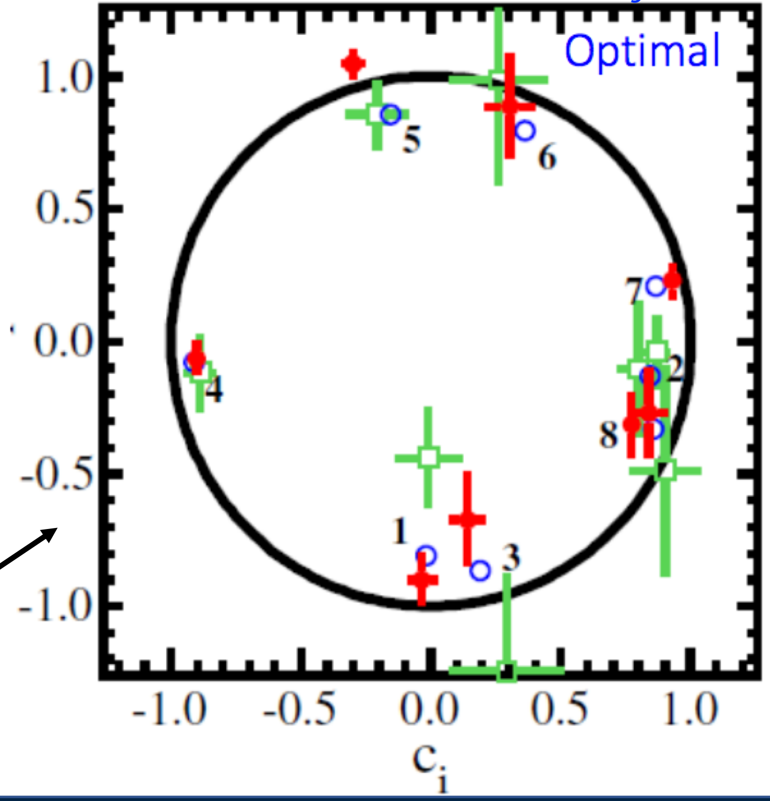
- Measurements of the **strong-phase parameters c_i and s_i** are needed to make the GGSZ analysis **model independent**
- Measured using quantum-correlated $D^0\overline{D}^0$ meson pairs from $\psi(3770)$ decays
- Current CLEO inputs contribute **$\sim 3.9°$ uncertainty to γ**

New BESII results:

- On average, 2.5 (2.0) x more precise for $c_i(s_i)$ than CLEO
- Expect associated uncertainty on γ to decrease by factor of 3

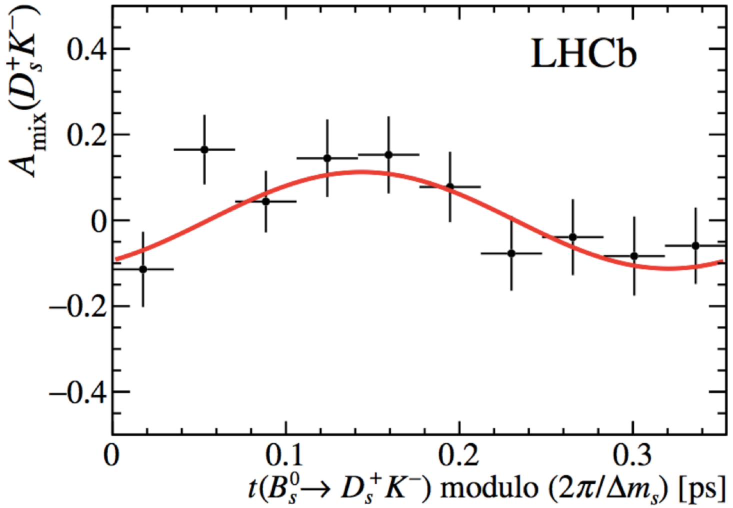


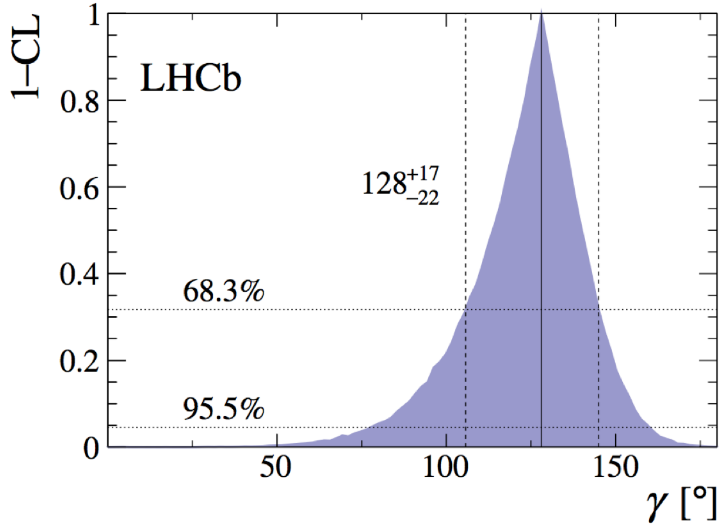
From L. Li's talk at Beauty 2019



Time-dependent analyses of B_s^0 decays

- The only γ measurement involving a B_s^0 is a Run 1 analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$[1]
  - Inteference between mixing and decay amplitudes gives sensitivity to $\gamma - 2\beta_s$
  - Input world-average of $2\beta_s$ from HFLAV
- New analysis of $B_s^0 \to D_s^{\mp} K^{\pm}\pi^{+}\pi^{-}$ using Run 1 + Run 2 data currently under internal review



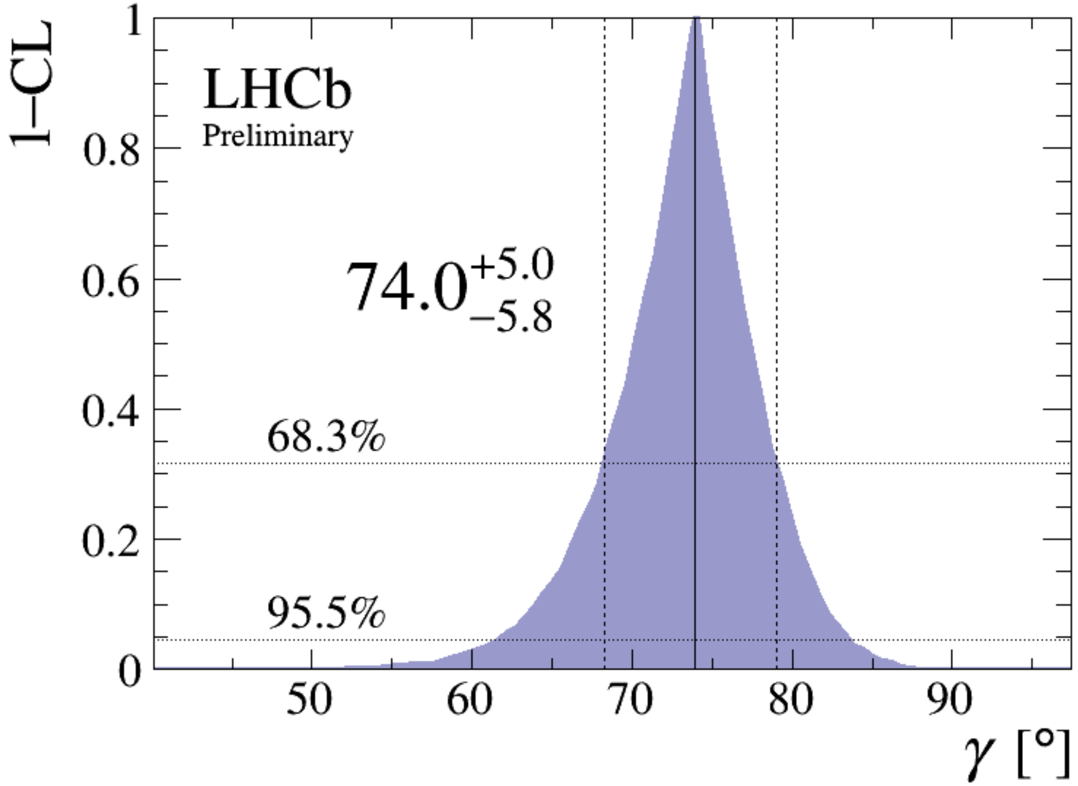


[1] JHEP.03(18)59

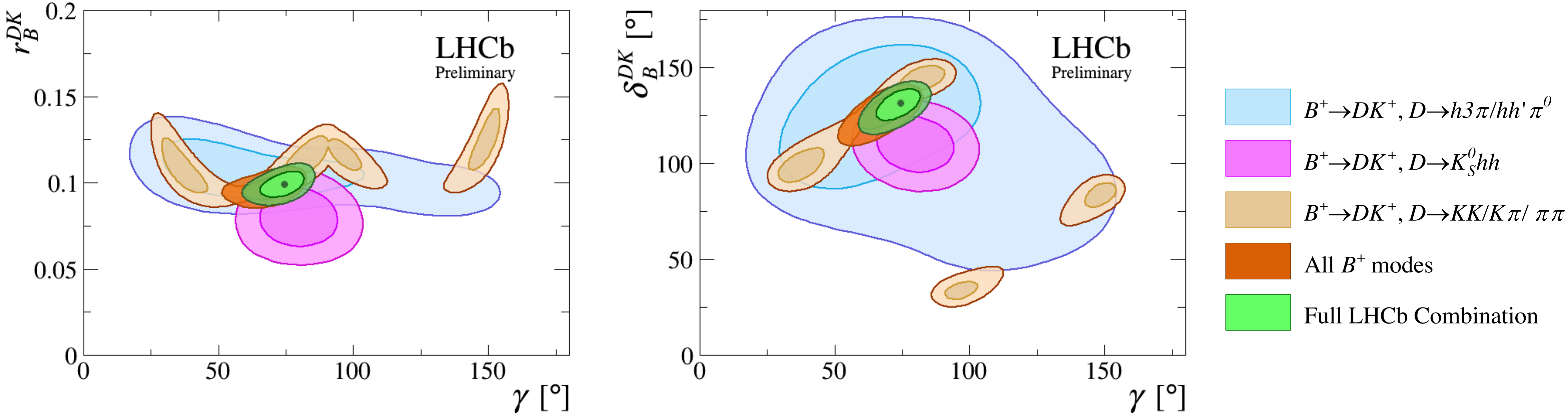
LHCb gamma combination [LHCb-CONF-2018-002]

- Best knowledge of γ comes from combining many measurements
- Maximum likelihood fit
  - 98 observables
  - 40 free parameters
- Most precise determination of γ by a single experiment:

$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$$

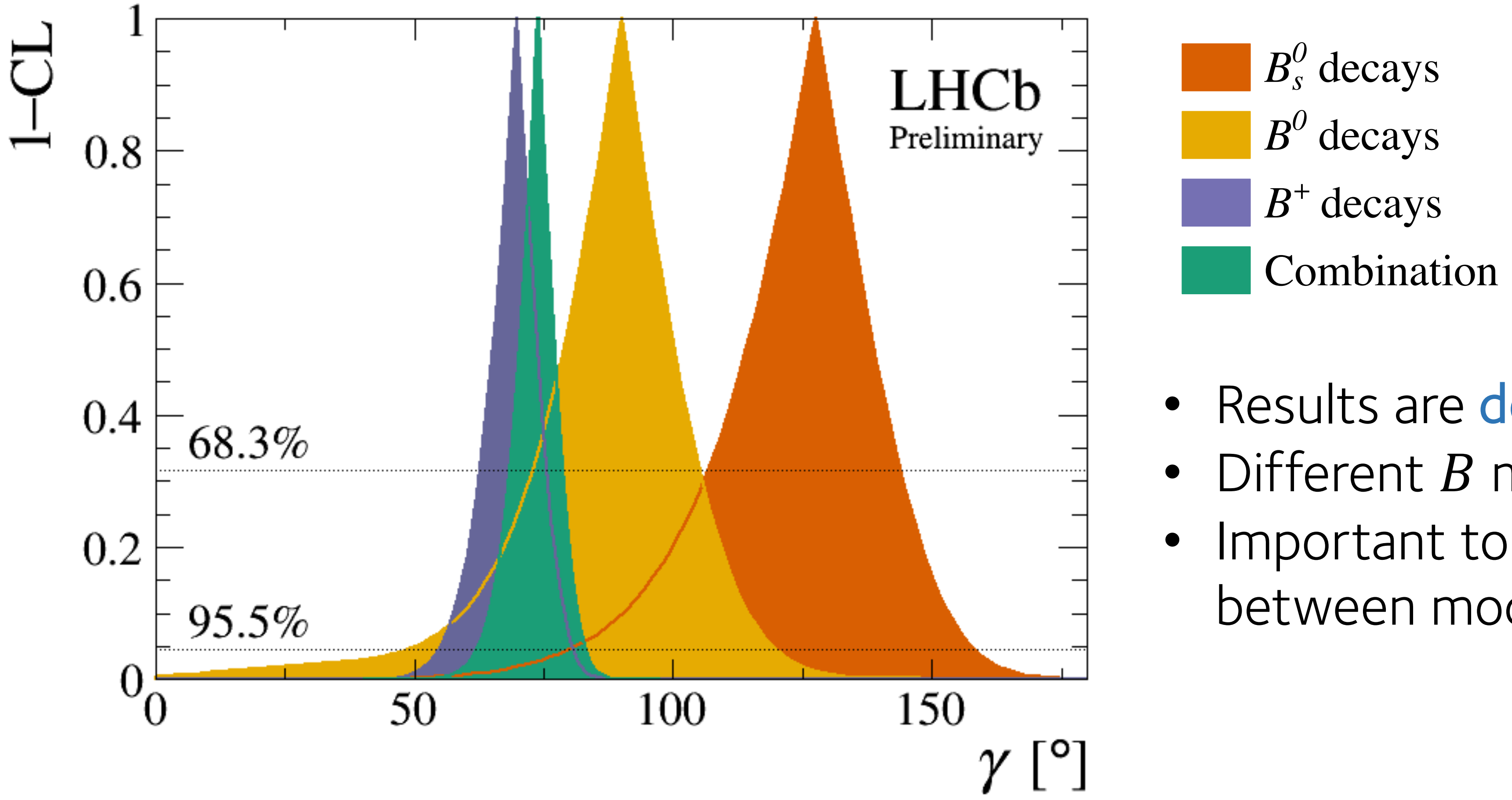


Results across different D decays



- **ADS/GLW**: several narrow solutions
- **GGSZ**: single, wider solution
- Analysing different modes serves as a useful **cross-check**: results have different sources of systematic uncertainty, but should agree

Results across different B decays



- Results are dominated by B^+ decays
- Different B modes agree at 2σ level
- Important to check consistency between modes

Current status of LHCb analyses

3 fb^{-1} Run 1 data set / Includes 2 fb^{-1} 2015/16 data set

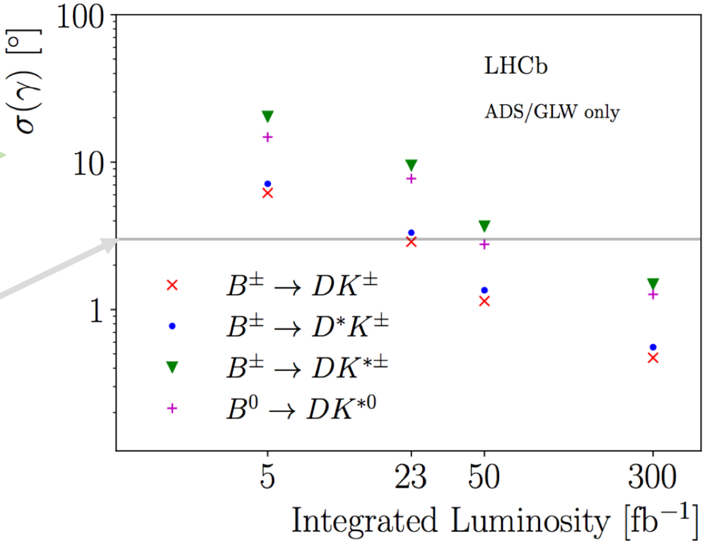
		$B^+ \to DK^+$	$B^+ \to D\pi^+$	$B^0 \to DK^{*0}$	$B^+ \to DK^{*+}$	$B^+ \to DK^+\pi^-\pi^+$	$B^+ \to D^*K^+$
GLW	h^+h^-	PLB.777(18)16		JHEP.08(19)41 Dalitz method: PRD.93(16)112018	JHEP.17(17)156	PRD.92(15)112005	Part. Reco: PLB.777(18)16
	$\pi^+\pi^-\pi^+\pi^-$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156		
	$h^+h^-\pi^0$	PRD.91(25)112014					
ADS	$K^\pm\pi^\mp$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156	PRD.92(15)112005	
	$K^\pm\pi^\mp\pi^+\pi^-$	PLB.760(16)117		JHEP.08(19)41	JHEP.17(17)156		
	$K^\pm\pi^\mp\pi^0$	PRD.91(25)112014					
GGSZ	$K_S^0h^+h^-$	JHEP.10(14)97 JHEP.08(18)176		MD: JHEP.08(16)137 MI: JHEP.06(16)131			
GLS	$K_S^0K^+\pi^-$	PLB.733(14)36					
Time dependent		$B_s^0 \to D_s^\mp K^\pm$ [JHEP.03(18)59] and $B^0 \to D^\mp\pi^\pm$ [JHEP.06(18)84]					

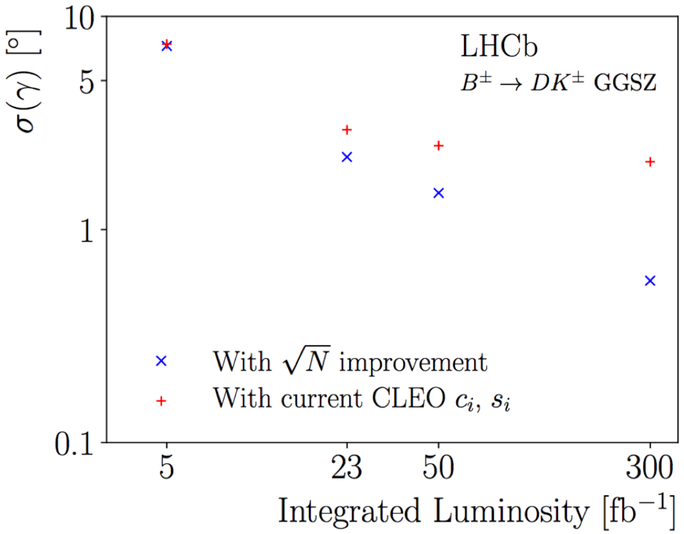
- Many updates using the full Run 2 data set coming soon
- Target precision with all Run 2 data: $\sigma(\gamma) \approx 4°$

Future prospects for γ at LHCb

ADS/GLW

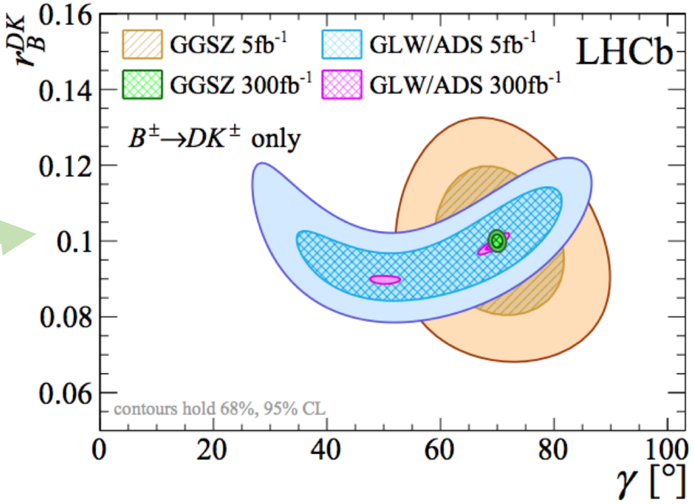
Belle II @ 50 ab^{-1}

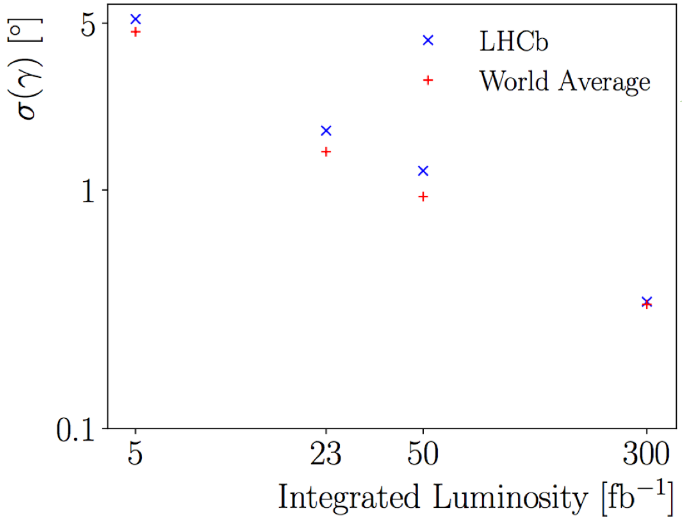




GGSZ

ADS/GLW & GGSZ





Full combination

World average includes Belle II projections

[LHCb-PUB-2018-009]

New approach to $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

- Previous analyses with $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ measure asymmetries integrated across the full $\boldsymbol{D}$ phase space
- Interference terms are multiplied by coherence factor:

$$R_{K3\pi} = 0.43^{+0.17}_{-0.13}$$ [1]

- Due to this low coherence factor, interference effects are diluted $\longrightarrow$ the full power of this mode isn't being harnessed!

[1] Phys. Lett. B757 (2016) 520

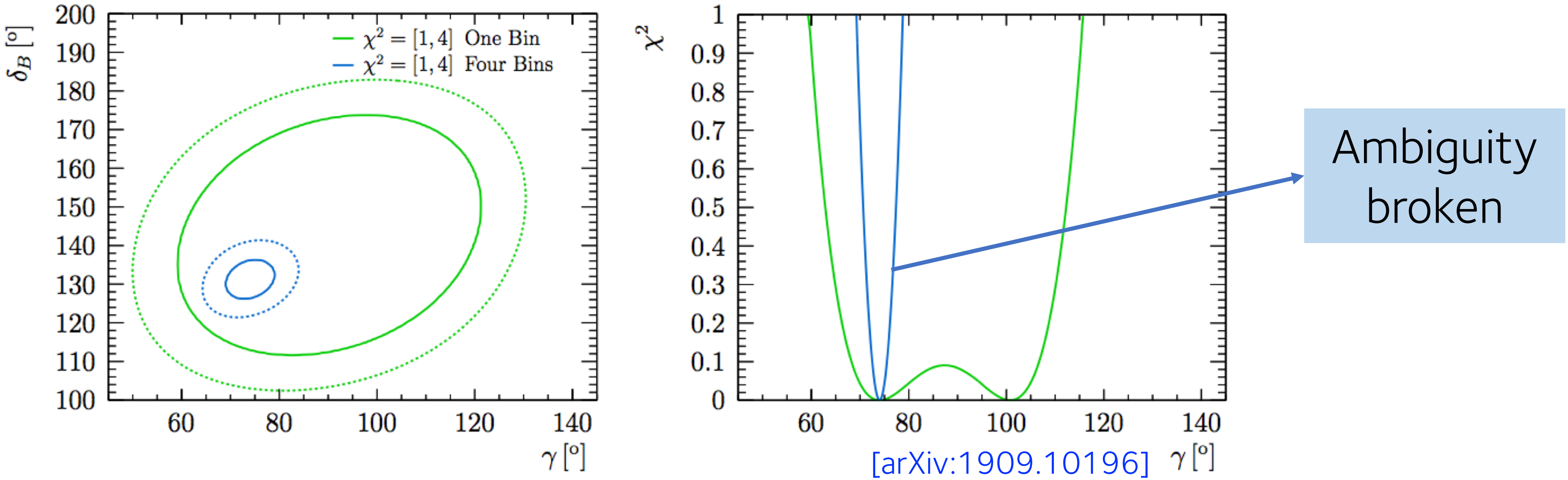
New approach to $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

- A better approach is proposed by T. Evans, J. Libby, S. Malde, G. Wilkinson [arXiv:1909.10196]: bin the data in ***D*** decay phase space and measure asymmetries in each bin (similar to GGSZ technique)

- Proposed binning scheme based on a recent amplitude model of $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ using LHCb data[1]
  - Use CLEO results in each bin, so the analysis is still model independent
  - Amplitude model inaccuracies would only affect sensitivity, not the results themselves

[1] Eur. Phys. J. C 78 (2018) 443

New approach to $D \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$



- With perfect knowledge of the D decay parameters, this approach could give an uncertainty as low as $\sigma(\gamma) = 5°$ with the current LHCb data set (comparable with GGSZ modes!)
- Uncertainty ~ $10°$ with current CLEO measurements (will benefit from BESIII)

Summary

- LHCb has made a world-leading direct measurement of the Unitarity Triangle angle γ:

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

- Many new results utilizing the full Run 1 + 2 data set are still to come, which should yield $\sigma(\gamma) \approx 4^\circ$
- Eventually LHCb should obtain sub-degree precision: expect $\sigma(\gamma) \approx 0.35^\circ$ from 300 fb^{-1} of data in 2034

[LHCb-PUB-2018-009]