Measuring the CKM angle γ with LHCb

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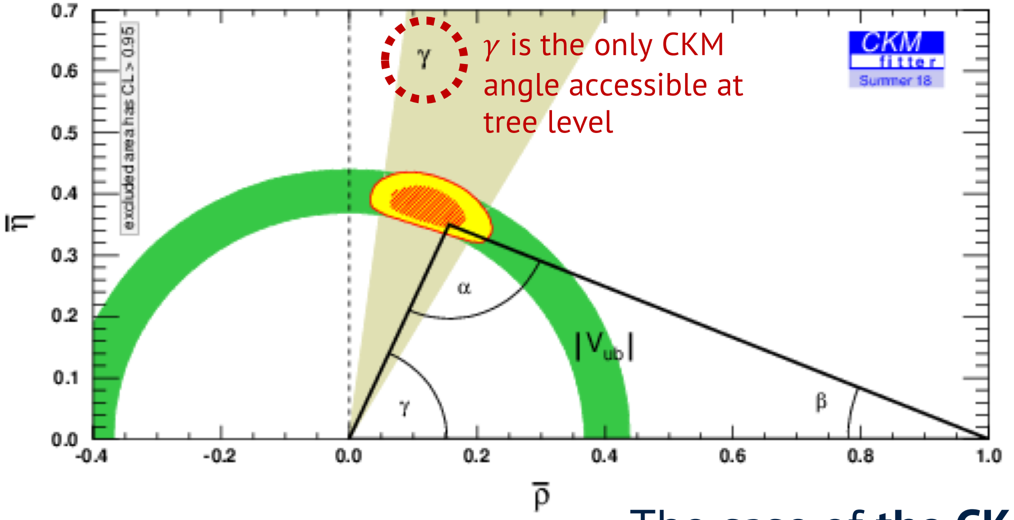
LHCb

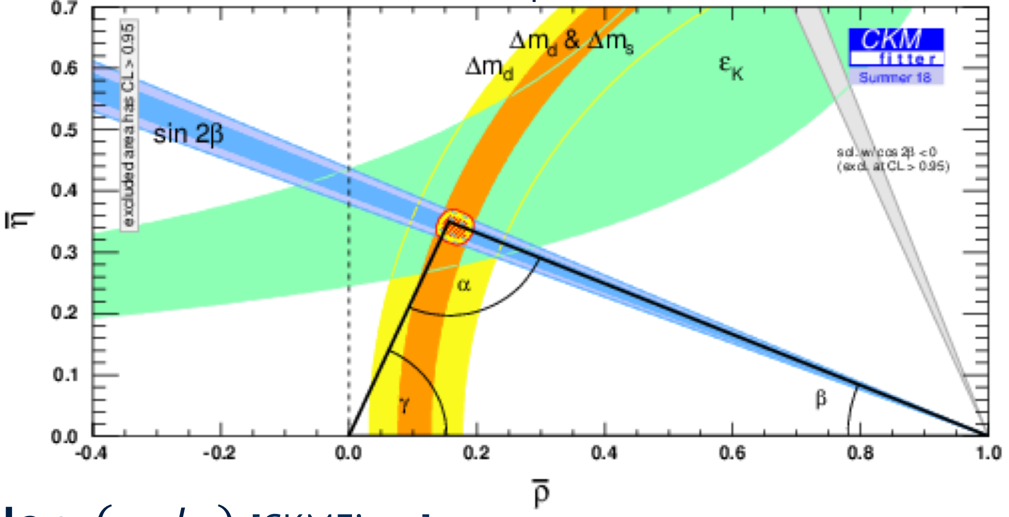
Is the Unitarity Triangle a triangle?

Crucial flavour physics goal: experimentally test consistency of the CKM mechanism by over-constraining parameters

Constraints from "tree-level" observables



Constraints from "loop-level" observables



The case of **the CKM angle** $\boldsymbol{\gamma}$ $(= \phi_3)$ [CKMFitter]

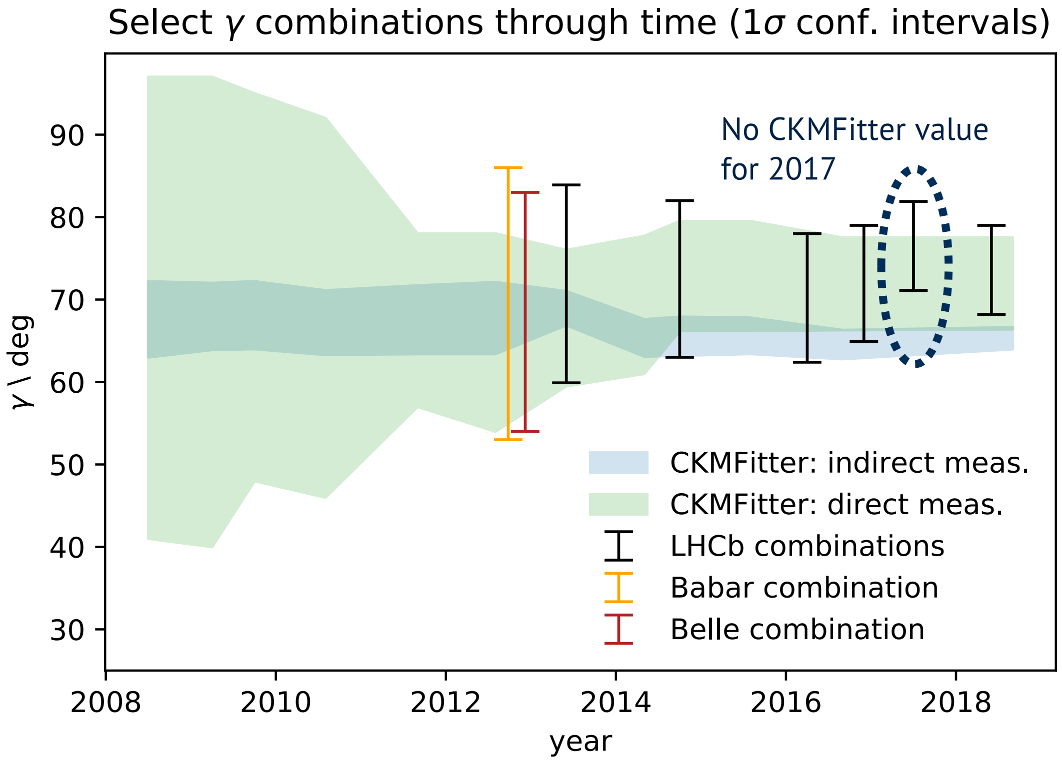
$\gamma_{\text{direct}} = 72.1^{+5.4}_{-5.7}{}^\circ$	**= ?**	$\gamma_{\text{indirect}} = 65.64^{+0.97}_{-3.42}{}^\circ$

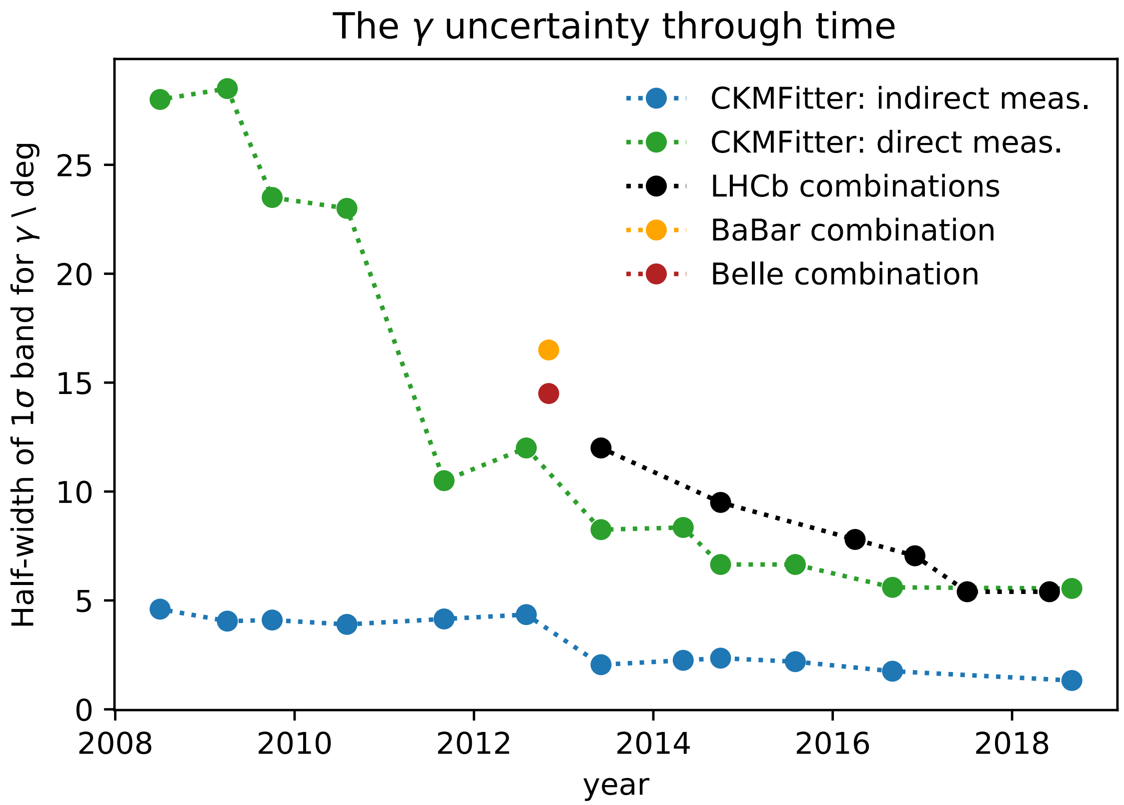
Measured in $B \to DK$ decays and friends

- Theoretically **clean**: $\delta\gamma_{\text{theory}}/\gamma \simeq 10^{-7}$ [JHEP.01(14)51]
- **SM benchmark**: NP contributions to tree level process expected to be small (although not excluded by data: [PRD.92(15)033002])

Indirect determination from other CKM parameters

- $\sin 2\beta$ from $B^0 \to J/\psi K_S^0$
- Δm_d and Δm_s from $B^0_{(s)}$ mixing
- ϵ_k from neutral kaon CPV measurements





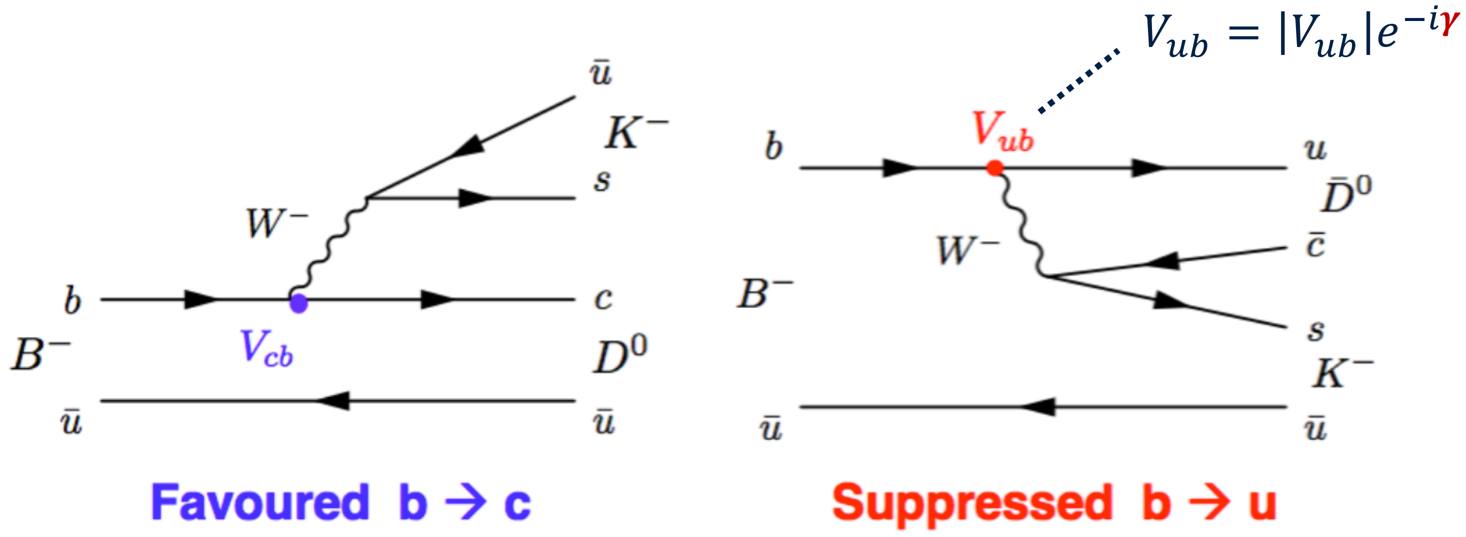
LHCb dominates current world averages of direct γ measurements

The focus of **this talk**:

- LHCb results from $B^0 \to DK^{*0}$ **ADS/GLW** [JHEP.08(19)41] and $B^\pm \to DK^\pm$ **GGSZ** [JHEP.08(18)176] measurements with data from 2015 and 2016
- The **LHCb γ combination** and a look towards the future

BaBar combination: [arXiv:1301.3283], Belle combination: [arXiv:1301.2033]. CKMFitter results: [CKMFitter.in2p3.fr]. Latest LHCb combination: [LHCb-CONF-2018-002]

How to measure γ in $B^{\pm} \to DK^{\pm}$: "the text book example"



Access to γ via **interference between $b \to c$ and $b \to u$** transitions

- γ is the EW (CP-violating) phase between the $B^{\pm} \to D^0 K^{\pm}$ and $B^{\pm} \to \bar{D}^0 K^{\pm}$ amplitudes *(up to relative corrections of $O(\lambda^4) \simeq 2{\times}10^{-3}$)*

$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B \exp[i(\delta_B - \gamma)]$$

$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \bar{D}^0 K^+)} = r_B \exp[i(\delta_B + \gamma)]$$

Exploited using **many D final states** and with other **similar B decays**

The GLW method with $B^0 \to D(\to h^+h^-[\pi^+\pi^-])K^{*0}$ decays

Coherence factor due to other resonances in $B^0 \to DK^+\pi^-$
$\kappa = 0.958^{+0.005}_{-0.046}$ [PRD.93(16)112018]

CP-even fraction of the $D \to 4\pi$ final state

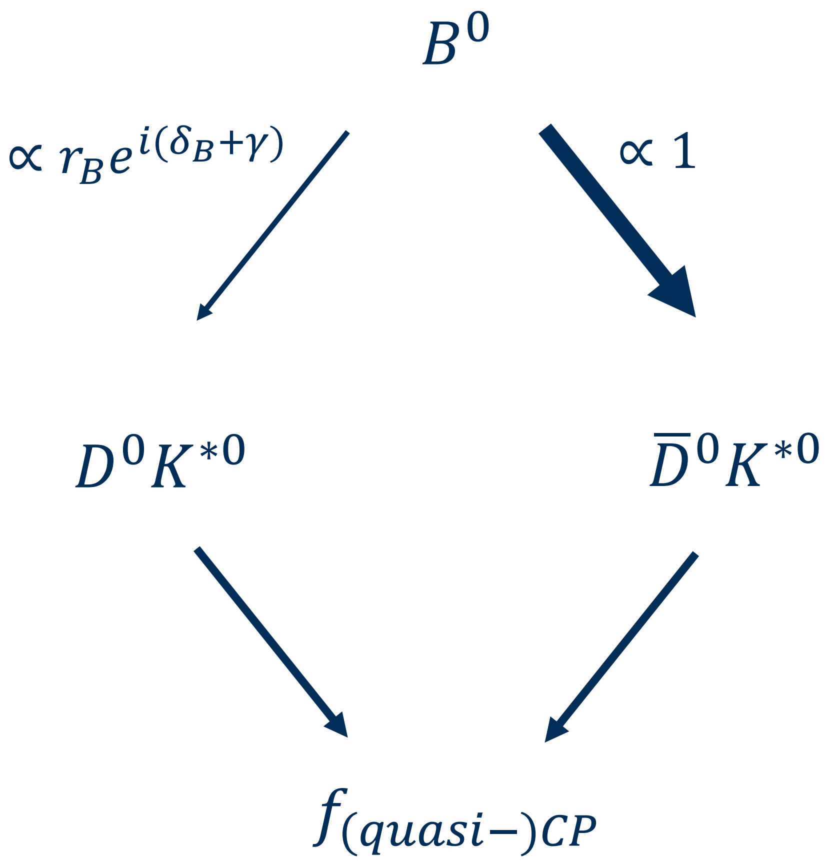
$$d\Gamma \propto 1 + r_B^2 + 2\kappa r_B (2F_+^f - 1)\cos(\delta_B \pm \gamma)$$

Observables of interest: yield asymmetries and ratios

$$A_{CP}^f = \frac{\Gamma(\bar{B}^0 \to f\bar{K}^{*0}) - \Gamma(B^0 \to fK^{*0})}{\Gamma(\bar{B}^0 \to f\bar{K}^{*0}) + \Gamma(B^0 \to fK^{*0})}$$

$$= \frac{2\kappa r_B^X (2F_+^f - 1)\sin\delta_b^X \sin\gamma}{\mathbf{1 + r_B^2 + 2\kappa\left(2F_+^f - 1\right)\cos\delta_B \cos\gamma}}$$

$\equiv R_{CP}^f$: measured independently **in fit** via yield ratio to corresponding $D^0 \to K^-\pi^+$ mode and known BF



$= \pi^+\pi^-, K^+K^-$ $(F_+ = 1)$,
$\pi^+\pi^-\pi^+\pi^-$ $(\boldsymbol{F_+ = 0.769 \pm 0.023})$ [JHEP.01(18)144]

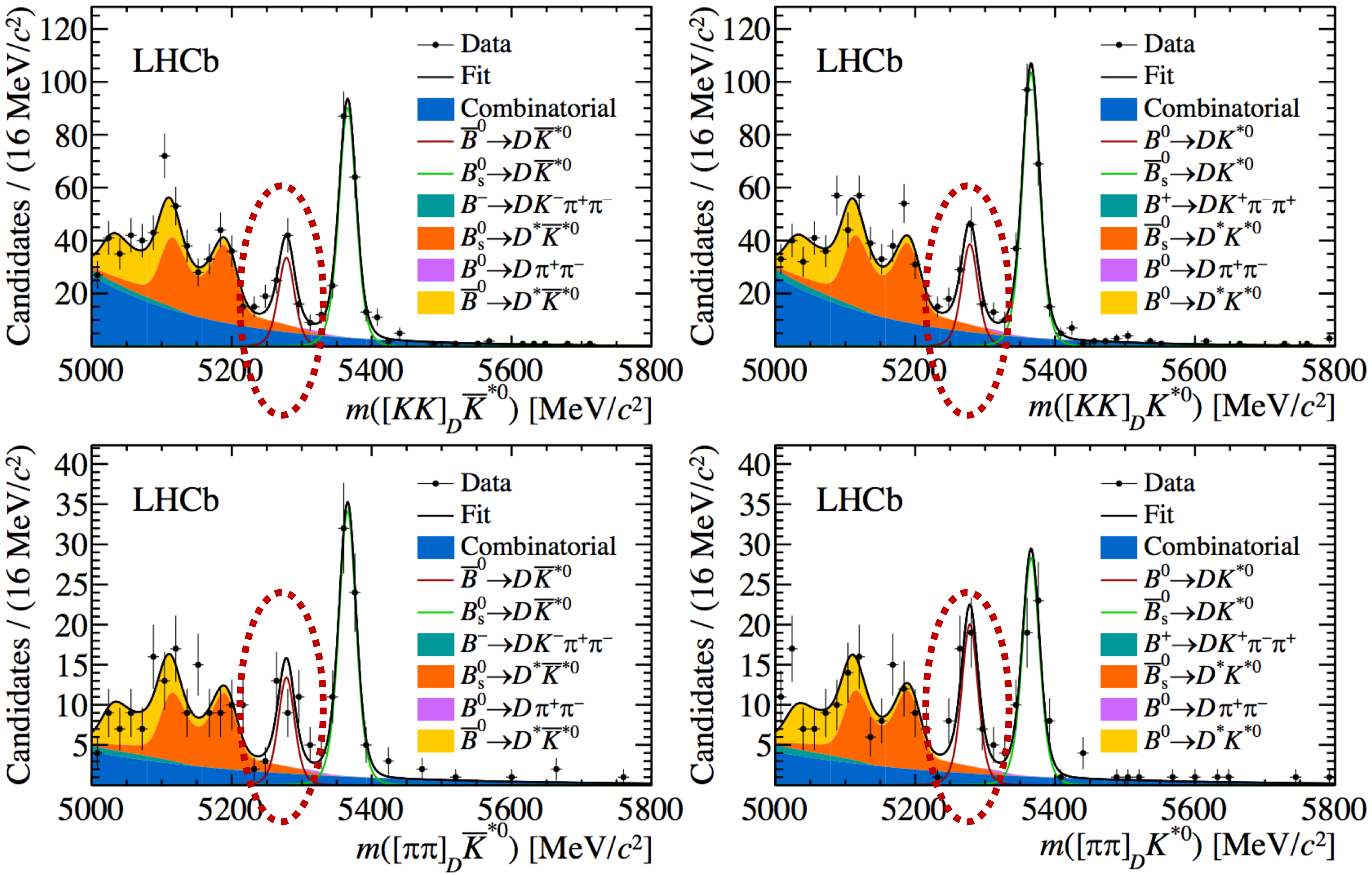
GLW results: $B^0 \to D(\to h^+h^-)K^{*0}$ using Run 1 + 2015 + 16 data (5 fb^{-1}) [JHEP.08(19)41]

Ratio and asymmetry observables are **directly obtained** in fit

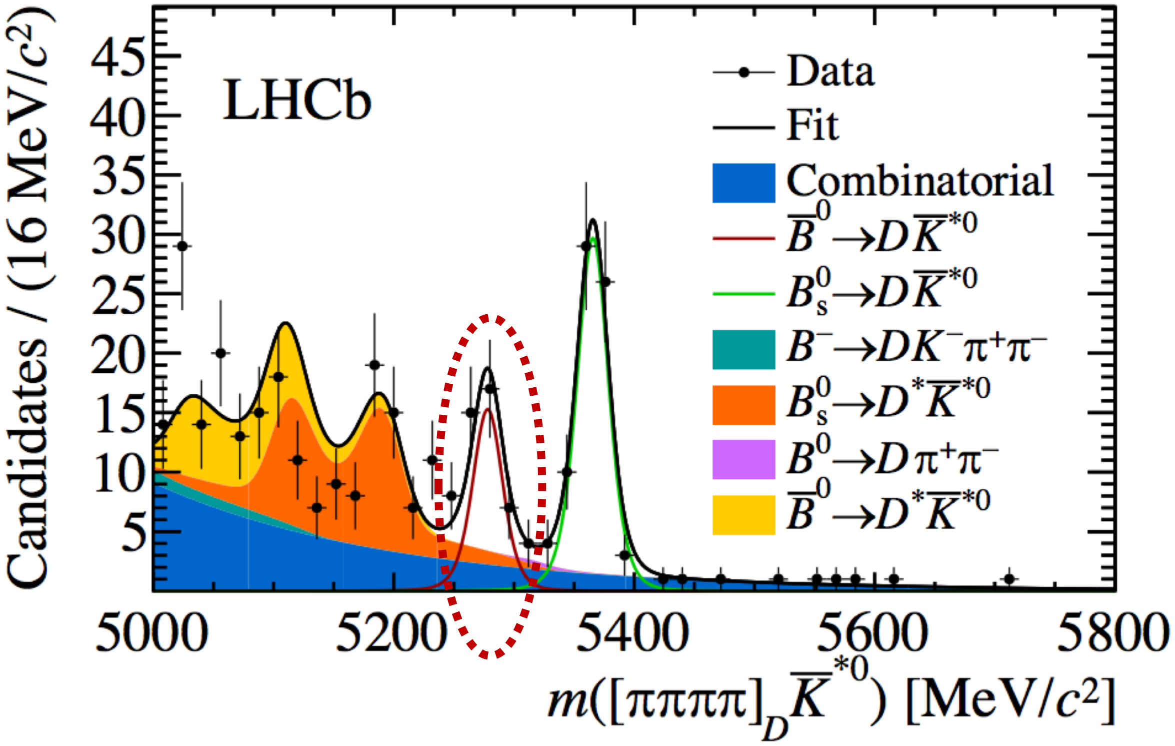
Corrected for
- Different selection efficiencies
- Detection charge-asymmetries
- $B^0 - \bar{B}^0$ production asymmetry

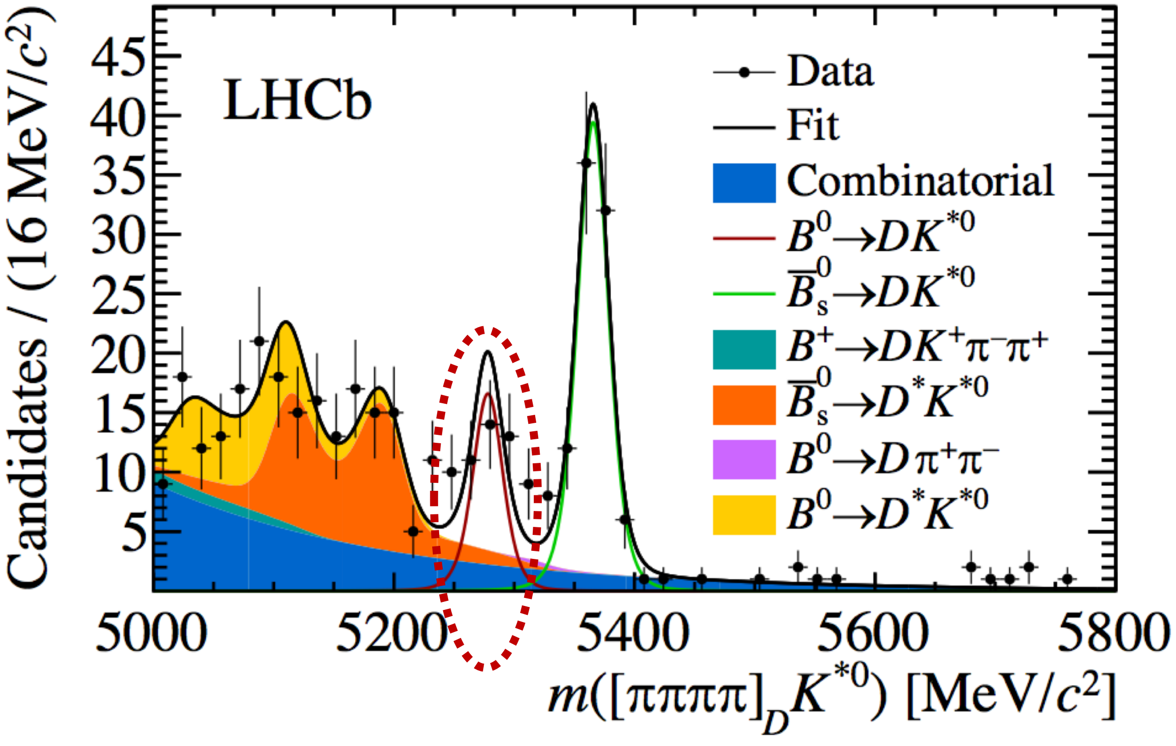
$$A_{CP}^{KK} = -0.05 \pm 0.10 \pm 0.01$$
$$R_{CP}^{KK} = 0.92 \pm 0.10 \pm 0.02$$

$$A_{CP}^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01$$
$$R_{CP}^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03$$



(quasi-)GLW results: $B^0 \to D(\to \pi^+\pi^-\pi^+\pi^-)K^{*0}$ using 2015 + 16 data (2 fb^{-1}) [JHEP.08(19)41]





$$A_{CP}^{4\pi} = -0.03 \pm 0.15 \pm 0.01$$
$$R_{CP}^{4\pi} = 1.01 \pm 0.16 \pm 0.04$$

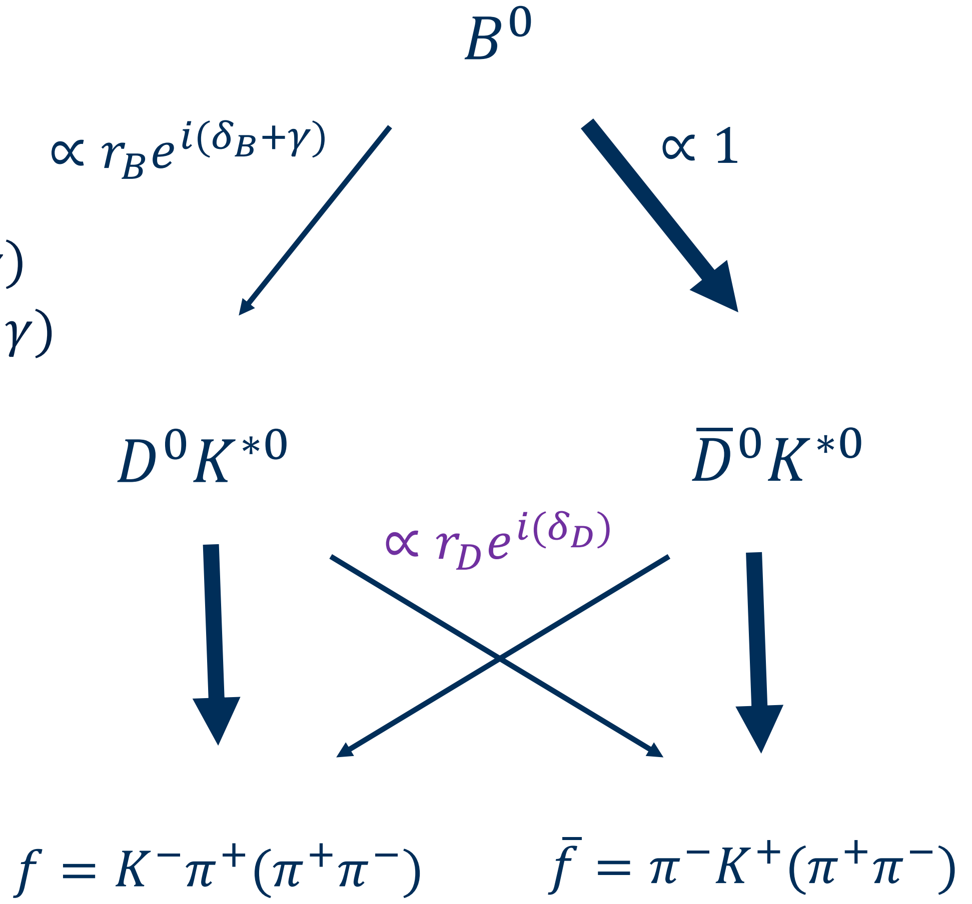
First observation of decay mode: **8.4σ**

The ADS method with $B^0 \to D(\to h'^+h^-[\pi^+\pi^-])K^{*0}$ decays

Coherence factor due to other resonances in $B^0 \to DK^+\pi^-$
$\kappa = 0.958^{+0.005}_{-0.046}$ [PRD.93(16)112018]

Coherence factor due to interference over 4-body D-decay phase space

$$\mathrm{d}\Gamma(\mathrm{B}^0 \to fK^{*0}) \propto r_D^2 + r_B^2 + 2\kappa(\kappa^{K3\pi})r_D r_B \cos(\delta_B + \delta_D + \gamma)$$
$$\mathrm{d}\Gamma(\mathrm{B}^0 \to \bar{f}K^{*0}) \propto 1 + r_D^2 r_B^2 + 2\kappa(\kappa^{K3\pi})r_D r_B \cos(\delta_B + \delta_D + \gamma)$$



Measured observables:

$$R_+^{\pi K(\pi\pi)} = \frac{\Gamma(B^0 \to [K^-\pi^+(\pi^+\pi^-)]_D K^{*0})}{\Gamma(B^0 \to [\pi^-K^+(\pi^+\pi^-)]_D K^{*0})}$$

CPV $\to$ $\neq$

$$R_-^{\pi K(\pi\pi)} = \frac{\Gamma(\bar{B}^0 \to [\pi^-K^+(\pi^+\pi^-)]_D \bar{K}^{*0})}{\Gamma(\bar{B}^0 \to [K^-\pi^+(\pi^+\pi^-)]_D \bar{K}^{*0})}$$

Can be transformed to CP-asymmetries and charge-summed mode ratios similar to GLW observables

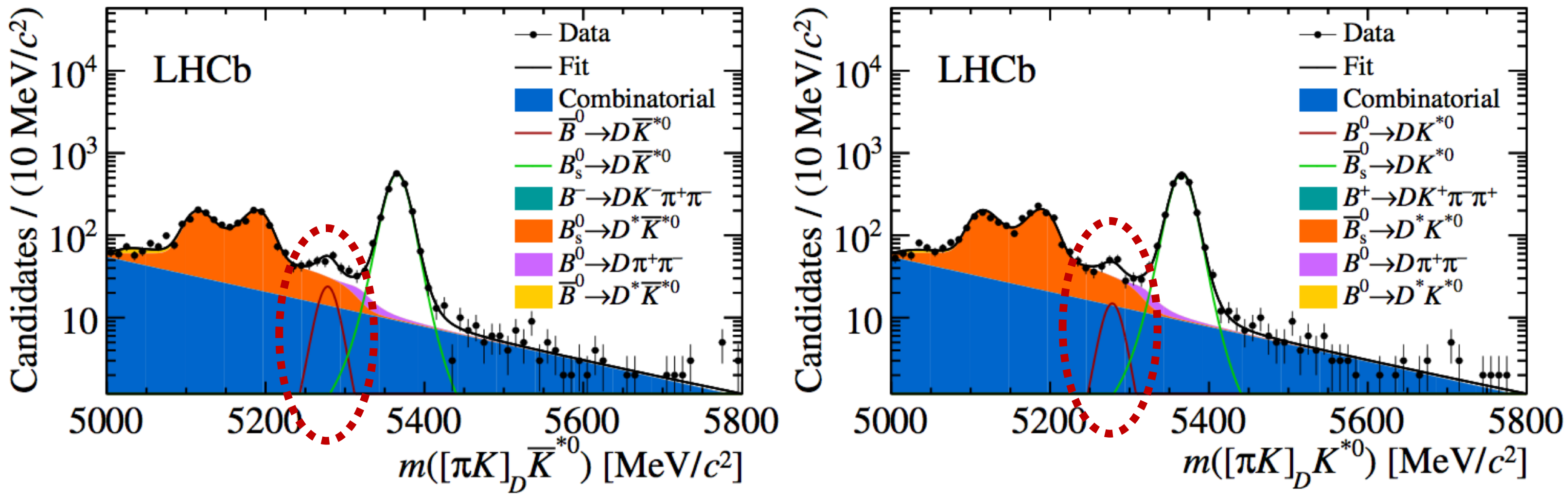
$(\kappa^{K3\pi} = 0.43^{+0.17}_{-0.13})$ [PLB.757(16)520]

ADS results: $B^0 \to D(\to \pi^+K^-(\pi^+\pi^-))K^{*0}$ using Run 1 + 2015 + 16 data (5 fb^{-1}) [JHEP.08(19)41]

In the two-body mode

$$R_+^{\pi K} = 0.064 \pm 0.021 \pm 0.002$$
$$R_-^{\pi K} = 0.095 \pm 0.021 \pm 0.003$$

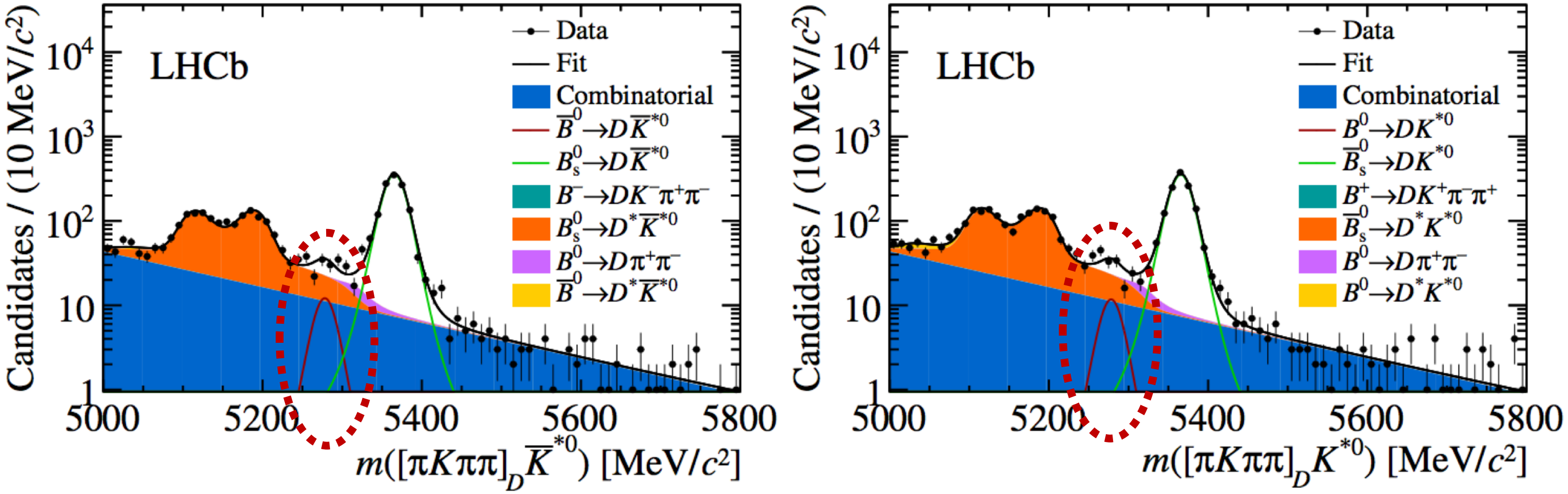
First observation of
suppressed mode: **5.8σ**



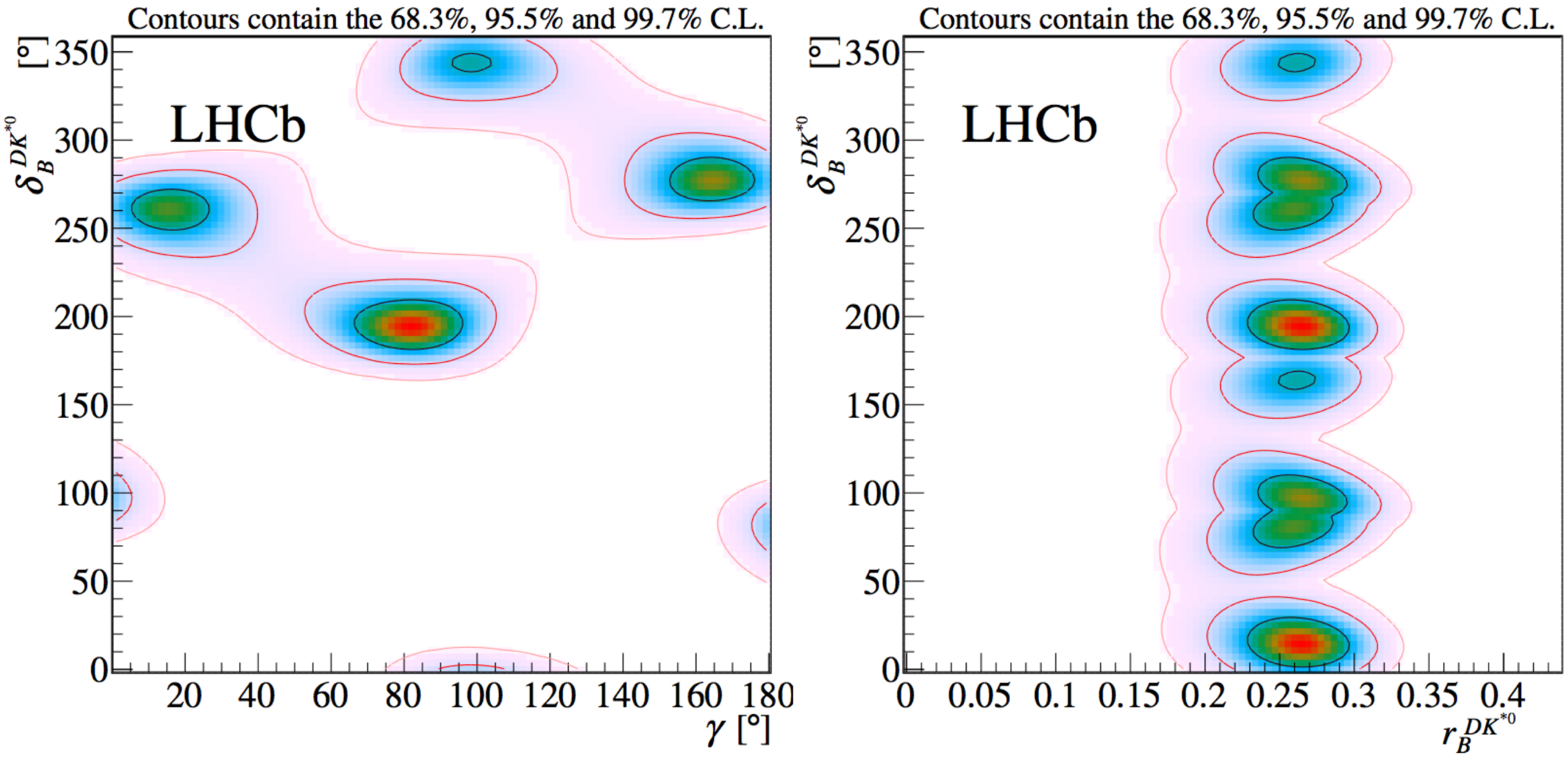
In the 4-body ADS mode:

$$R_+^{\pi K\pi\pi} = 0.074 \pm 0.026 \pm 0.002$$
$$R_-^{\pi K\pi\pi} = 0.072 \pm 0.025 \pm 0.003$$

Suppressed mode
significance: **4.4σ**



Physics parameters in $B^0 \to DK^{*0}$ decays



CP-violating observables put constraints on $(\gamma, r_B^{DK^{*0}}, \delta_B^{DK^{*0}})$

- $r_B^{DK^{*0}} = 0.265 \pm 0.023 \rightarrow$ **50 % decrease in uncertainty** compared to current LHCb combination
  $\rightarrow$ showcase improvements to come from Run 2 dataset

The model-independent GGSZ method: $B^\pm \to D(\to K_S^0 h^+ h^-)K^\pm$ [JHEP.08(18)176]

Divide phase space of $D \to K_S^0 h^+ h^-$ decay into bins and measure yields in each

- Analysis is **independent of modelling** of D decay
- Sensitivity from **phase-space distribution**, not overall asymmetries
  → overall production/detection/K_S^0-CPV asymmetries have no impact

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

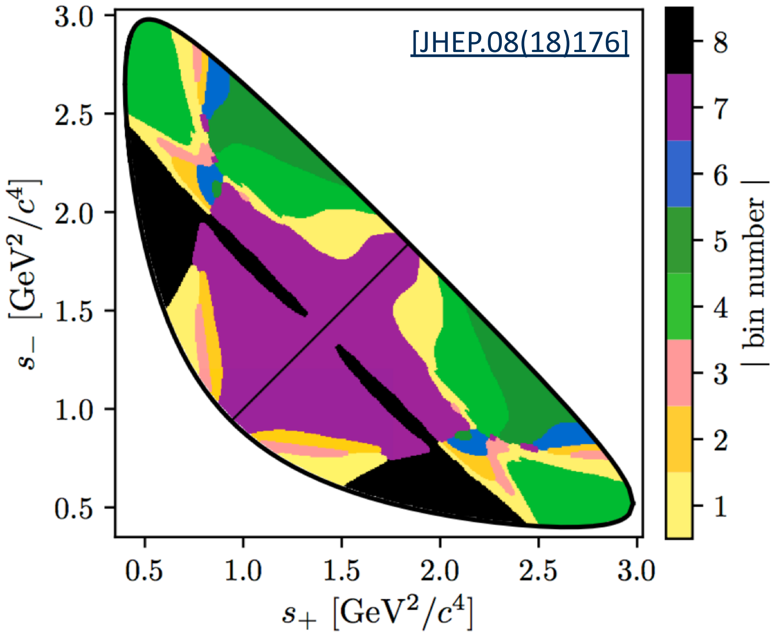
$$N^{-}_{\pm i} \propto F_{\pm i} + (x_\pm^2 + y_\pm^2) F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

F_i : Fractional yield of flavour tagged D^0 into bin i

Measured in control channel: $\bar{B}^0 \to D^{*+}\mu^-\nu_\mu X$

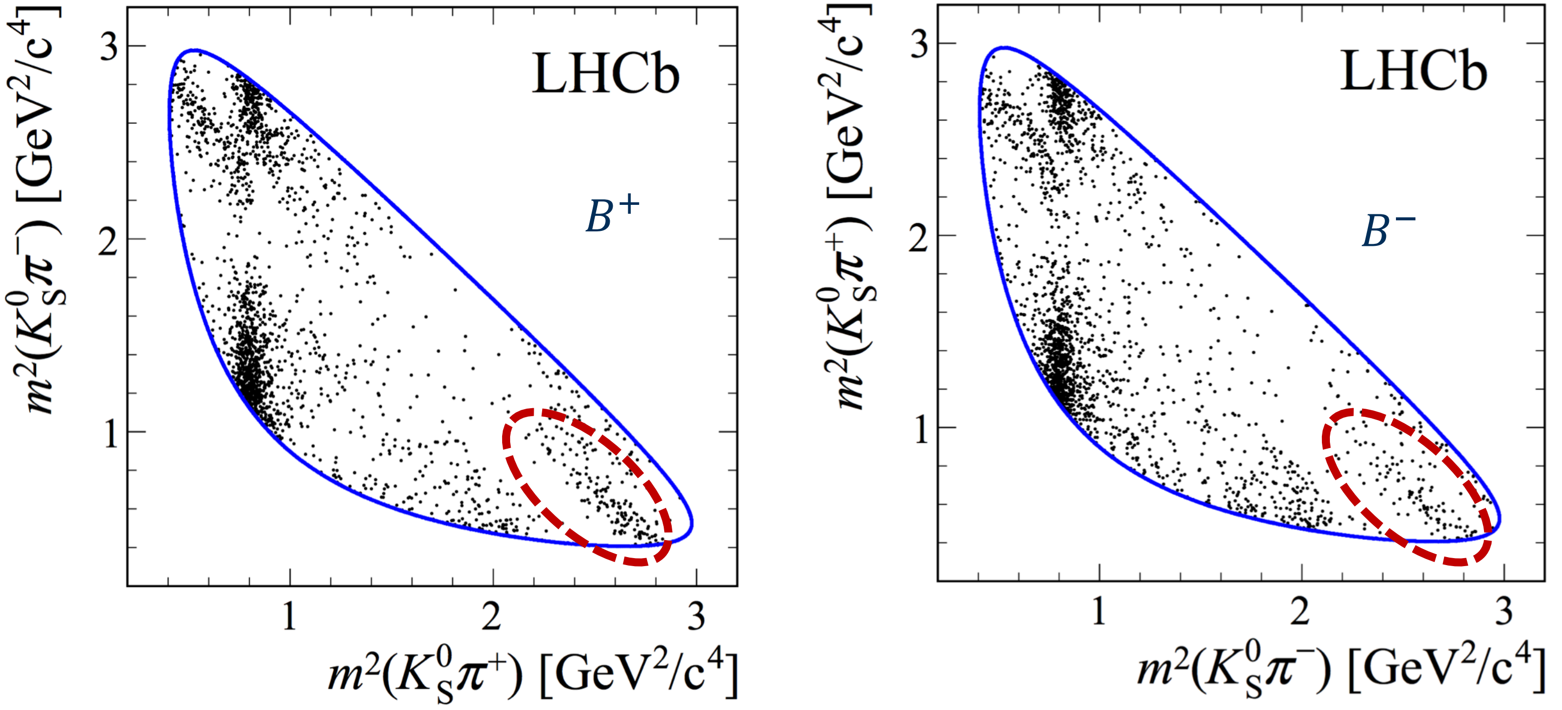
c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

External input from CLEO-c measurement [1010.2817]



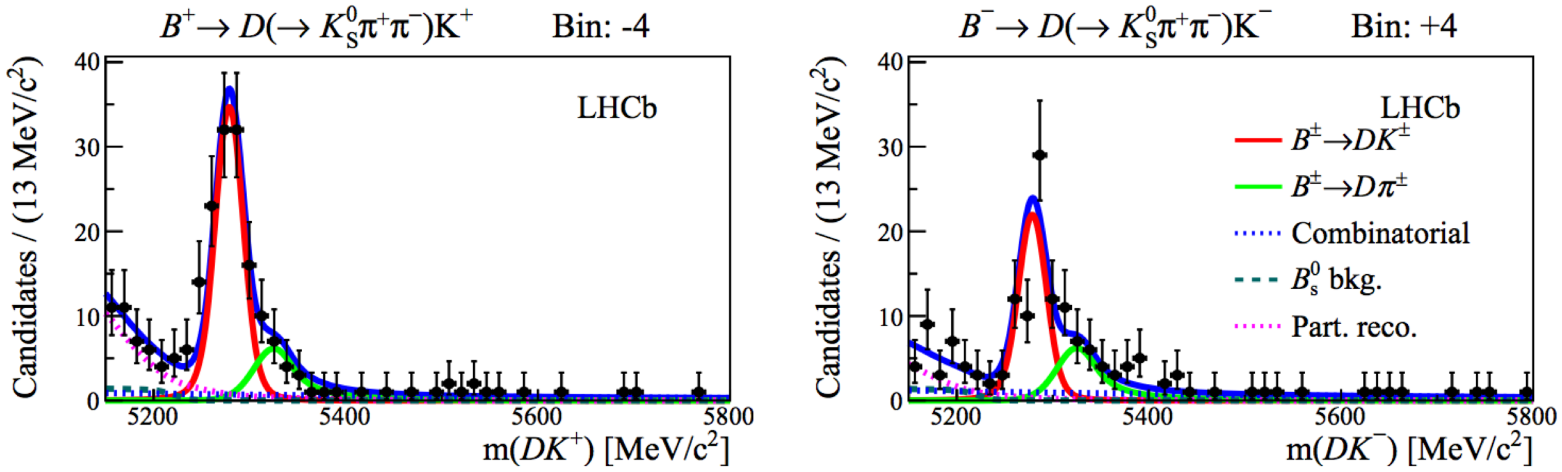
[JHEP.08(18)176]

CP asymmetries



Overall CP asymmetry
small $\simeq 1\%$

But large in certain regions of phase-space



[JHEP.08(18)176]

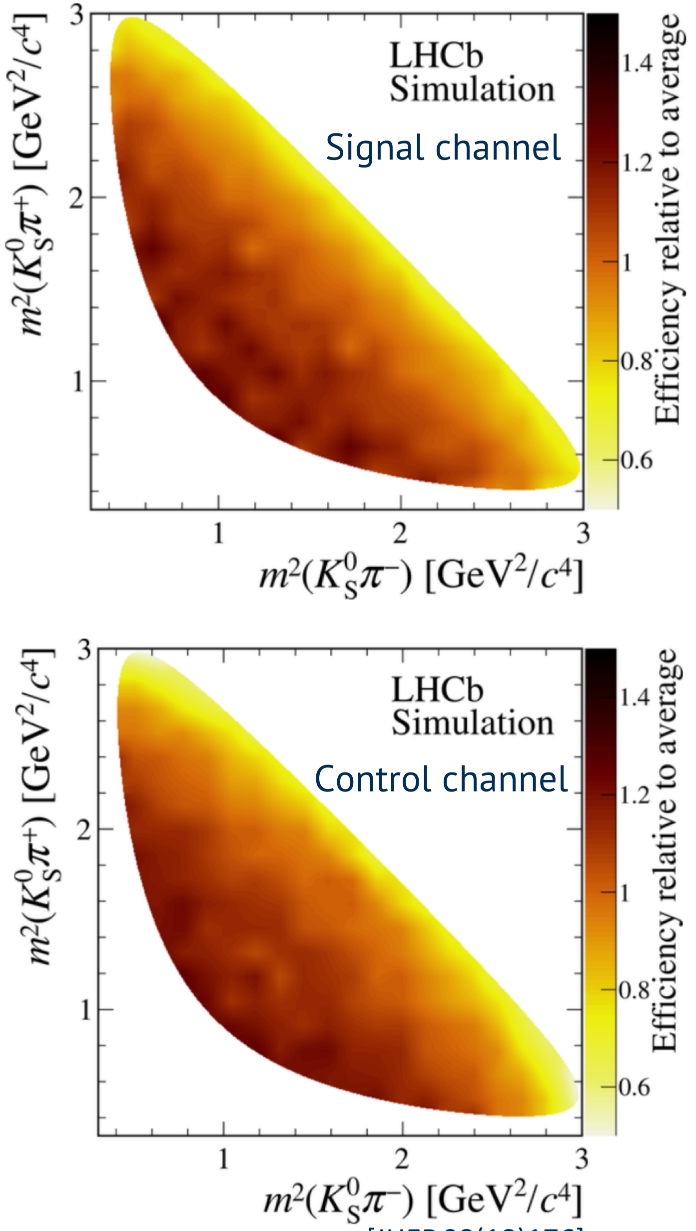
Phase-space dependent efficiency

Significant variation in reconstruction efficiency over phase-space

Handled in data-driven manner: Measure F_i in control channel: $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\mu^-\nu_\mu X$

- Flavour tagged D^0 from B decay: similar efficiency profile → still correct for signal-control efficiency difference
- Signal-control channel efficiency **ratio** from simulation → effects of simulation imperfections cancel to first order
- Naturally incorporates effects of bin migration and D-mixing [PRD.82(10)034033]

Efficiency in simulation



[JHEP.08(18)176]

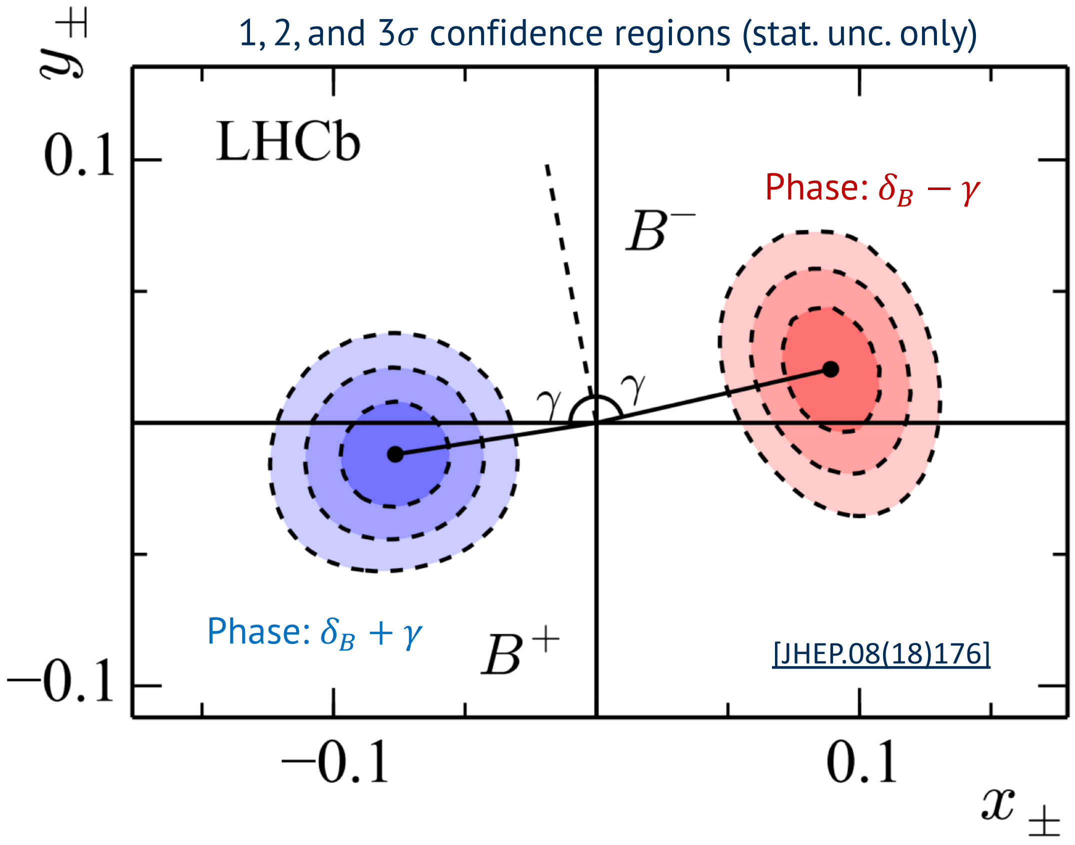
Statistical uncertainty dominates ($\simeq 8°$ on γ)

Leading systematic uncertainties

- **Strong-phase** measurements from CLEO ($\simeq 4°$ on γ)
- **Efficiency correction** between signal and semi-leptonic control channels ($\simeq 1.5°$ on γ)

Secondary effects from D-mixing [PRD.82(10)034033] and K_S^0 CPV [JHEP.07(19)106] well under control

- Important for a future $B^\pm \to D\pi^\pm$ GGSZ measurement

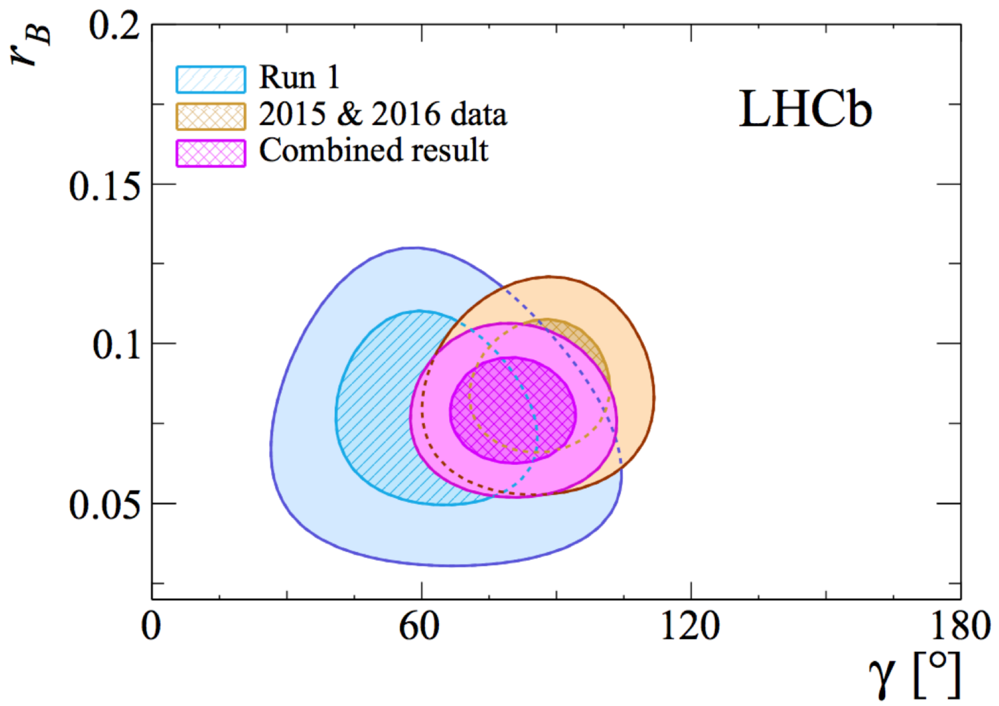


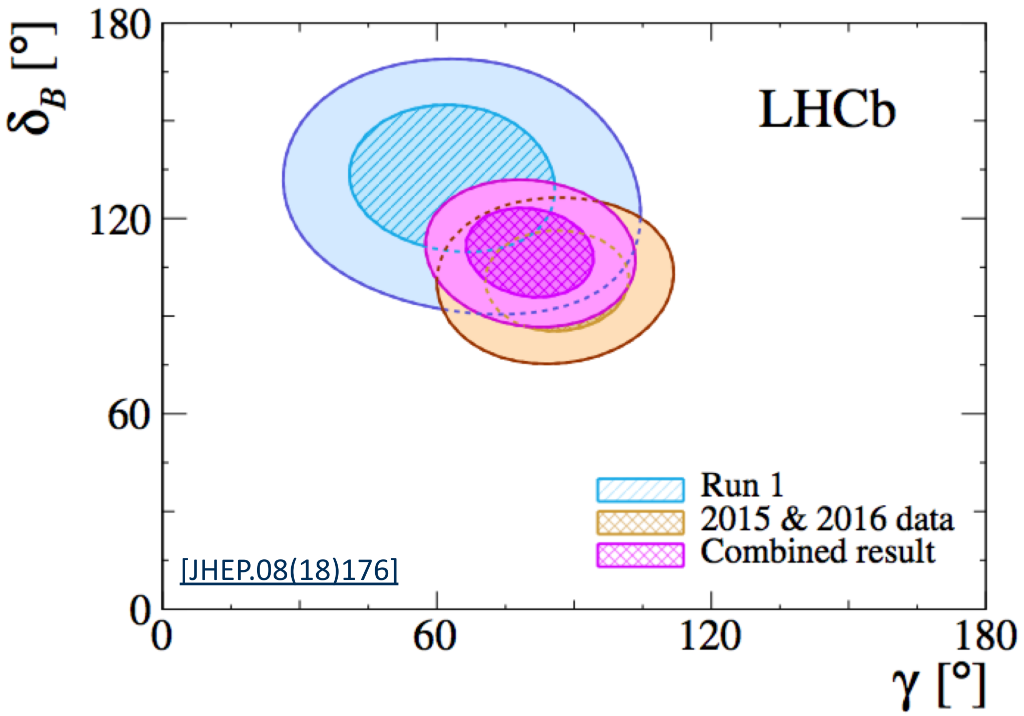
Interpreted and combined with Run 1 GGSZ measurement [JHEP.10(14)97] using gammacombo [JHEP.12(16)87]

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

Combined Run 1 and 15/16: $\gamma = 80^{\circ}{}^{+10^{\circ}}_{-9^{\circ}}$

Most precise stand-alone determinations of γ to date (at 2σ level)





Time dependent γ measurements

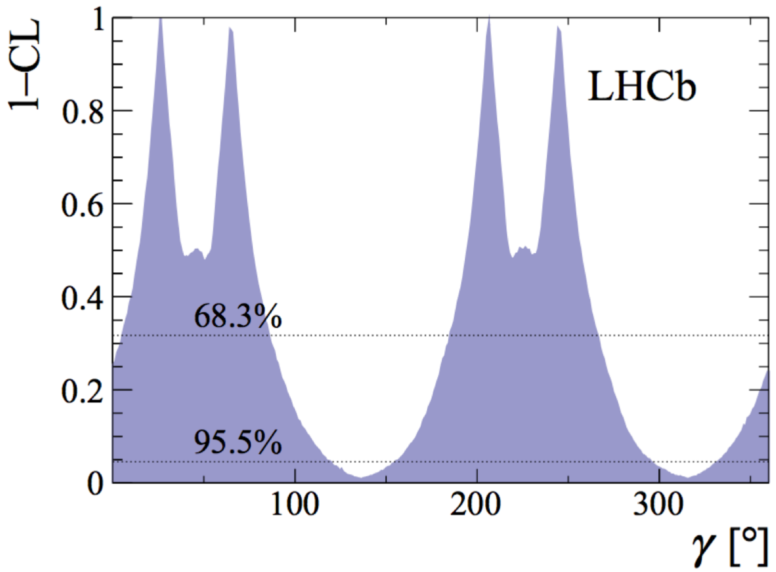
LHCb has also published **time-dependent** γ measurements using

- $B_s^0 \to D_s^{\mp} K^{\pm}$ [JHEP.03(18)59]
- $B^0 \to D^{\mp}\pi^{\pm}$ [JHEP.06(18)84]

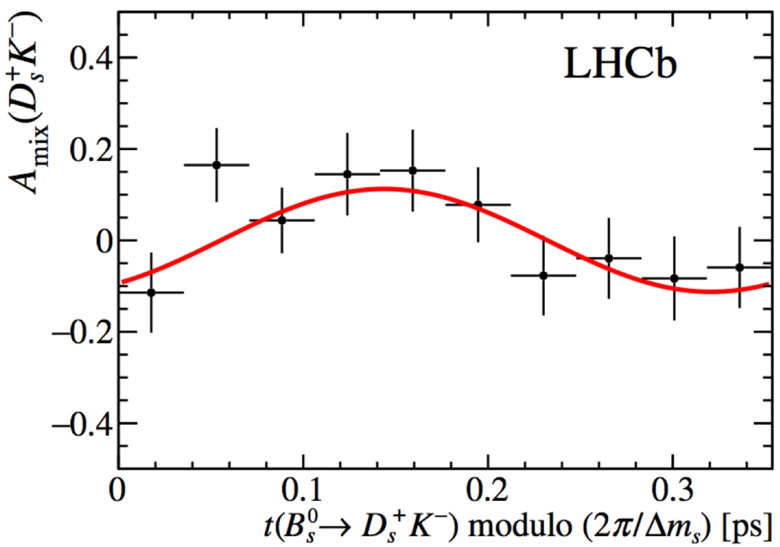
Measurements are based on

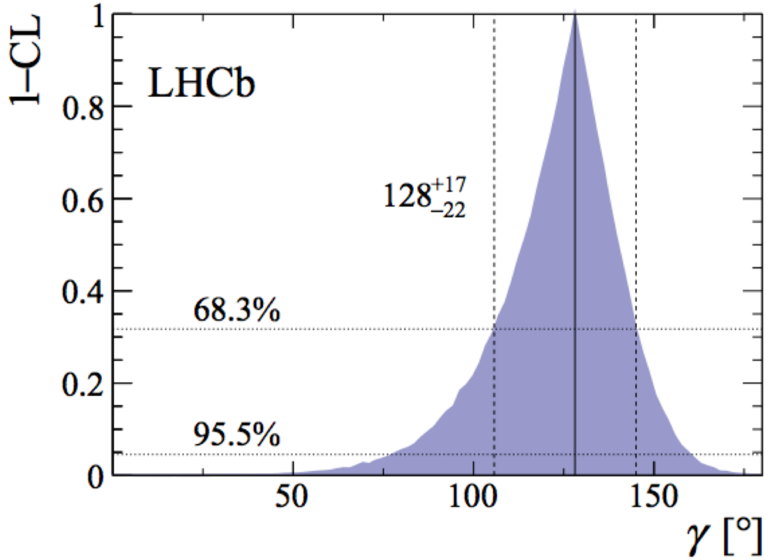
- Interference between **mixing** and decay amplitude sensitive to **CP-violating phase** $\boldsymbol{\gamma + (-)2\beta_{(s)}}$
- Use the **3** $\mathbf{fb^{-1}}$ **Run 1** dataset

$B^0 \to D^{\mp}\pi^{\pm}$



$B_s^0 \to D_s^{\mp} K^{\pm}$





Extraction of γ depends on

- $\beta_s \simeq \phi_s$ from [HFLAV]
- β from [HFLAV]

The LHCb combination of γ measurements [LHCb-CONF-2018-002]

Best knowledge of γ comes from **combining many measurements**

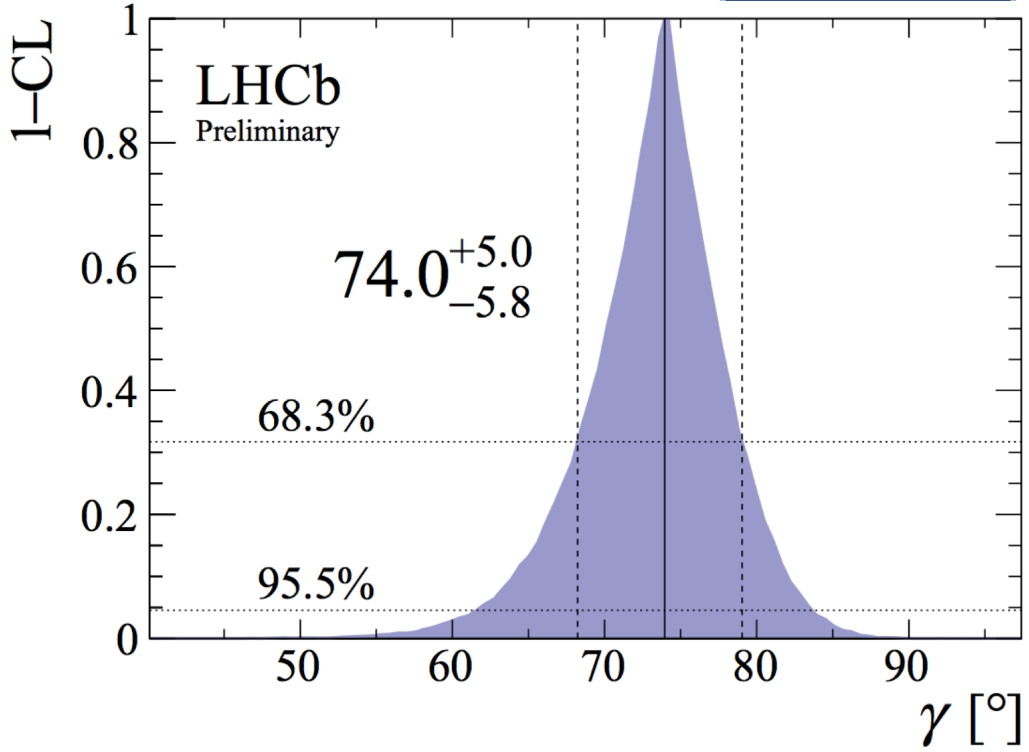
LHCb γ measurements from $B^+ \to D^{(*)}K^{(*)+}$, $B^0 \to DK^{*0}, B^0 \to D^{\mp}\pi^{\pm}$, and $B_s^0 \to D_s^{\mp}K^{\mp}$ decays are combined in a maximum likelihood fit

- 98 observables & 40 free parameters
- Good overall fit quality: $\boldsymbol{p = 69.6 \pm 0.5}$ %

Most precise determination of γ by a single experiment:

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

[LHCb-CONF-2018-002]



Measurements in latest LHCb γ combination [LHCb-CONF-2018-002]

$3\ \mathrm{fb}^{-1}$ Run 1 dataset ● Includes $2\ \mathrm{fb}^{-1}$ 15+16 data ● Not in combination yet

	B-decay mode	$B^+ \to DK^+$	$B^+ \to D^*K^+$		$B^+ \to DK_S^0\pi^+$	$B^0 \to DK^+\pi^-$		$B^+ \to DK^+\pi^+\pi^-$
	D-decay mode		**Part. reco.**	**Full reco.**	DK^{*+}**-res.**	DK^{*0}**-res.**	**Dalitz-method**	
GLW	h^+h^-	PLB.777(18)16	PLB.777(18)16		JHEP.17(17)156	JHEP.08(19)41	PRD.93(16)112018	PRD.92(15)112005
	$\pi^+\pi^-\pi^+\pi^-$	PLB.760(16)117			JHEP.17(17)156	JHEP.08(19)41		
	$h^+h^-\pi^0$	PRD.91(25)112014						
ADS	$K^\pm\pi^\mp$	PLB.760(16)117			JHEP.17(17)156	PRD.90(14)112002 JHEP.08(19)41		PRD.92(15)112005
	$K^\pm\pi^\mp\pi^+\pi^-$	PLB.760(16)117			JHEP.17(17)156	JHEP.08(19)41		
	$K^\pm\pi^\mp\pi^0$	PRD.91(25)112014						
GGSZ	$K_S^0h^+h^-$	JHEP.10(14)97 JHEP.08(18)176				MD: JHEP.08(16)137		
GLS	$K_S^0K^+\pi^-$	PLB.733(14)36						
Time-dependent	Time dependent measurements with $B_s^0 \to D_s^\mp K^\pm$ [JHEP.03(18)59] and $B^0 \to D^\mp\pi^\pm$ [JHEP.06(18)84] decays							

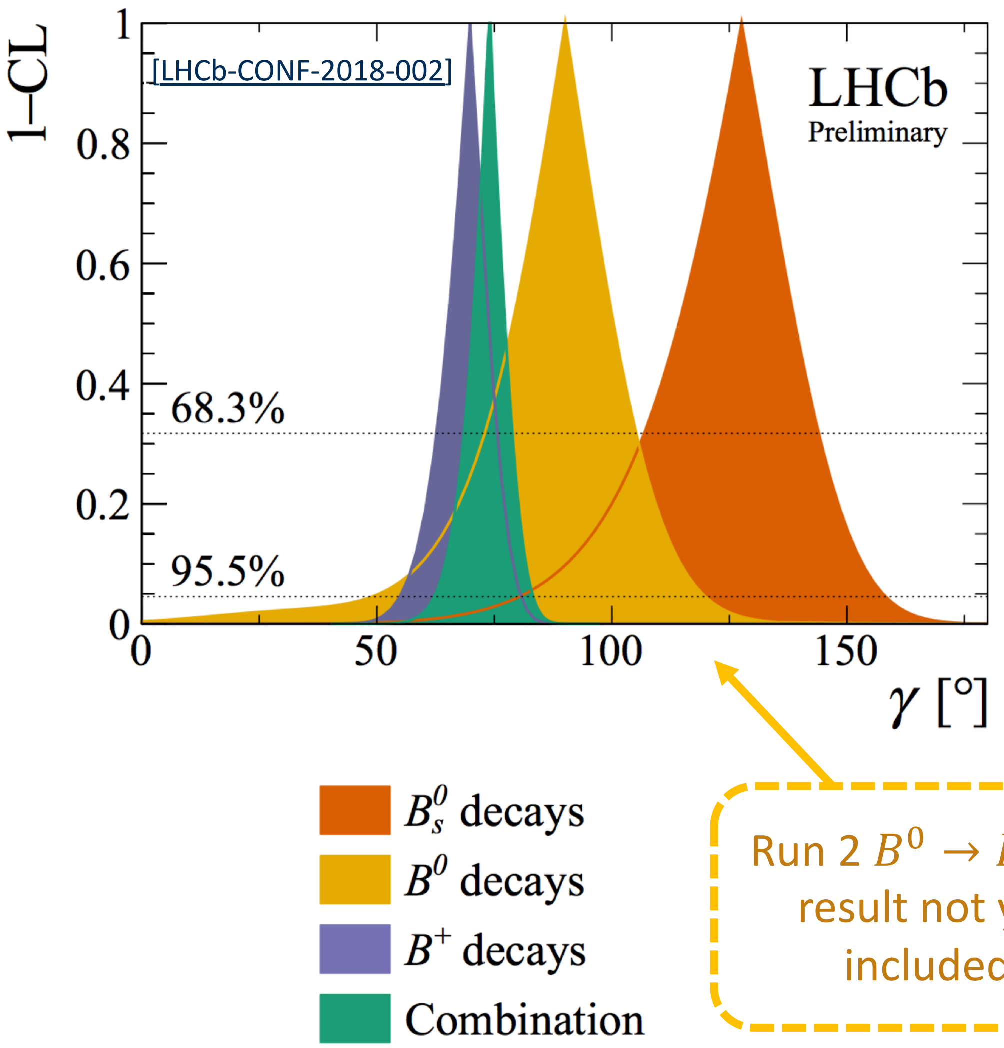
New physics could lead to different results in different B decays

Different B modes agree at 2σ level

Different modes have different challenges and systematics:

- Consistency check important part of LHCb programme

LHCb will reach **few degree precision or better** for each of $B^{\pm}, B^0$, and B_s^0 with 23 fb^{-1} collected after the LHC Run 3 [LHCB-PUB-2018-009]



Run 2 $B^0 \to DK^{*0}$ result not yet included

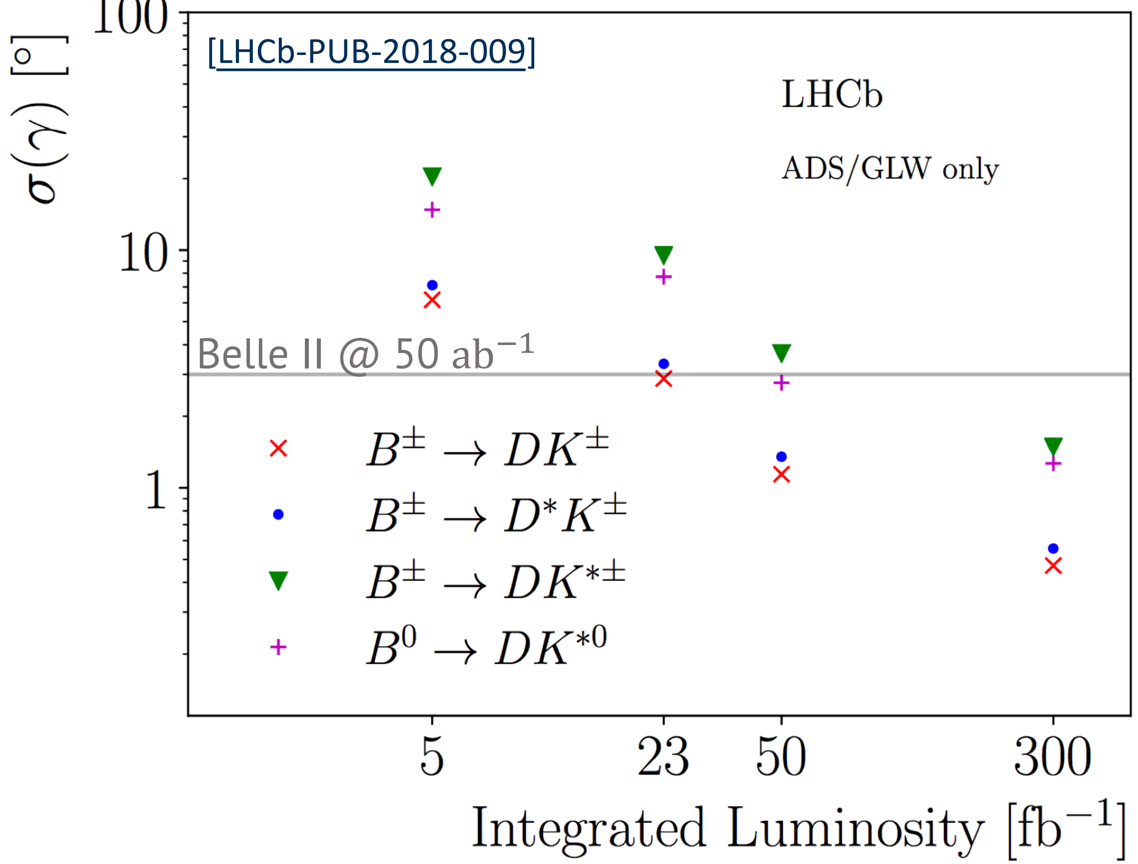
A look towards the future: ADS/GLW

All ADS/GLW analyses are statistically limited

Dominant systematic uncertainties expected to **reduce with $\sqrt{N}$**

- Detection asymmetries determined with calibration samples
- Physics backgrounds subject to dedicated studies with larger sample

Precision when disfavoured solutions are ignored



A look towards the future: GGSZ

Currently **statistically limited**

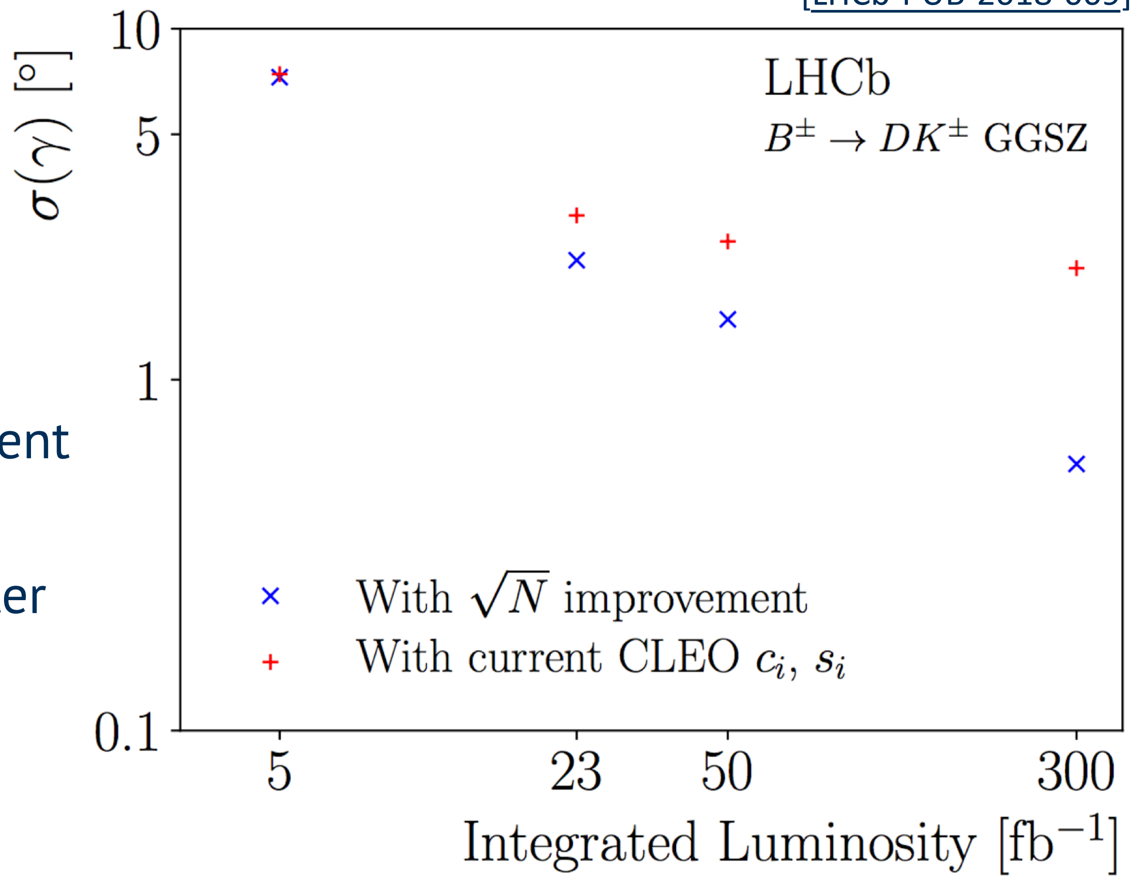
Dominant systematic uncertainty:
charm inputs from CLEO-c ($\simeq 4°$)

- Significant impact by end of Run 2
  → BES III results **crucial** for LHCb measurement

Strong-phase inputs will be limiting systematic after Run 3 or Run 4 even with expected BESIII result

- Future strong-phase measurements necessary to achieve best possible sensitivity to γ

[LHCb-PUB-2018-009]



Summary

LHCb has made the World's best single-experiment determination of γ

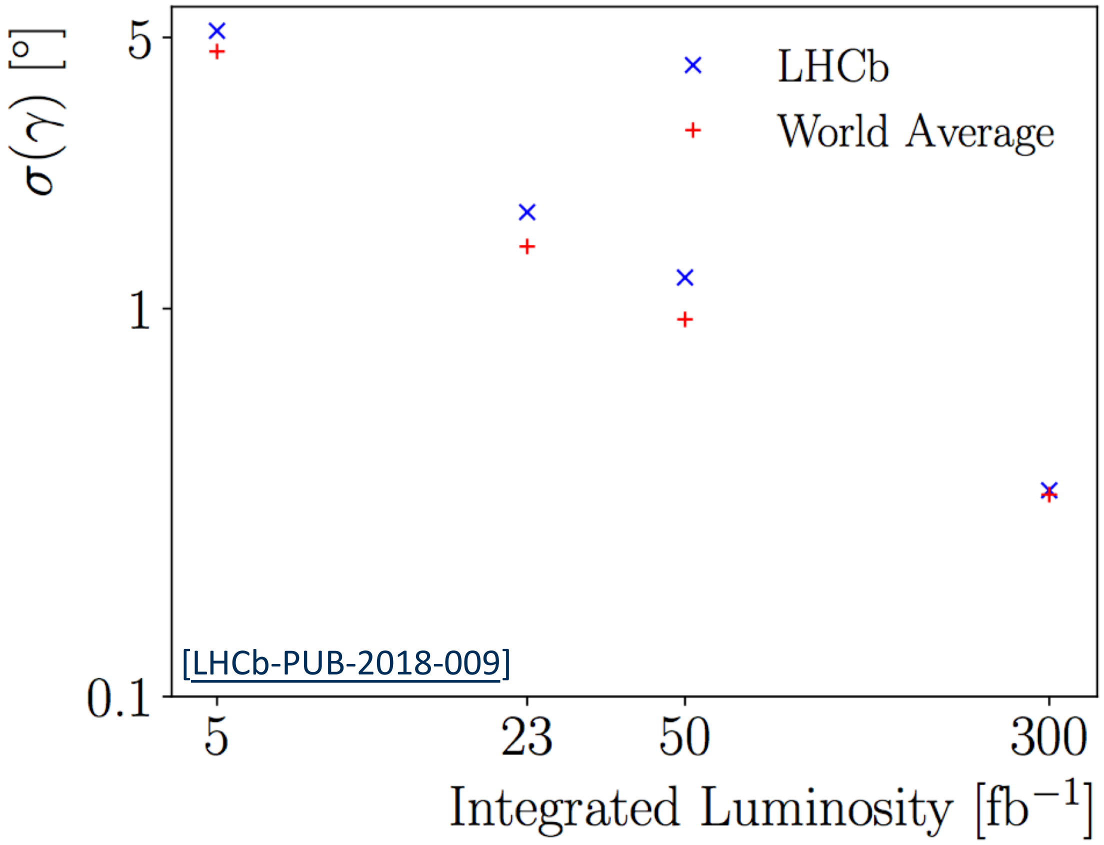
$$\gamma = 74.0^{+5.0}_{-5.8}{}^{\circ}$$

LHCb will continue to play crucial role in determining γ for the foreseeable future [LHCb-TDR-12]

- $\sigma(\gamma) \simeq 4^{\circ}$ with 8 fb^{-1} data (collected by 2018)
- $\sigma(\gamma) \simeq 1.5^{\circ}$ with 23 fb^{-1} data (collected by 2023)
- $\sigma(\gamma) \simeq 0.9$ with 50 fb^{-1} data (collected by 2029)
- $\sigma(\gamma) \simeq 0.35^{\circ}$ with 300 fb^{-1} data (collected with proposed Upgrade II) [LHCb-PUB-2018-009]

Thank you!

Expected LHCb precision using *current decay modes*
Expected world average assuming Belle II predictions



Backup Slides

How to measure γ in $B^{\pm} \to DK^{\pm}$ and related decays

GLW [PLB.243(91)483] / [PLB.265(91)172]

D^0 decay to (quasi-)CP eigenstates:
$\pi^+\pi^-/K^+K^-/\pi^+\pi^-\pi^0/K^+K^-\pi^0$,
$\pi^+\pi^-\pi^+\pi^-/K_S^0\pi^0/K_S^0\phi/K_S^0\omega$

- Modes with neutrals **hard** for LHCb, but used by BaBar & Belle (II)

GGSZ [PRD.68(03)054018]

- D^0 decay to multibody, self-conjugate states:
  $K_S^0\pi^+\pi^-/K_S^0K^+K^-/K_S^0\pi^+\pi^-\pi^0$

ADS [PRD.63(01)036005] / [PRL.78(97)3257]

- D^0 decays to CF & DCS final states:
  $K^{\pm}\pi^{\mp}/K^{\pm}\pi^{\mp}\pi^0/K^{\pm}\pi^{\mp}\pi^+\pi^-$

GLS [PRD.67(03)071301]

- D^0 decays to SCS non CP eigenstate:
  $K_S^0K^{\pm}\pi^{\mp}$

Time dependent

- CPV from interference between mixing and decay
- LHCb has made measurements using
  $B_s^0 \to D_s^{\mp}K^{\pm}$ [JHEP.03(18)59] and
  $B^0 \to D^{\mp}\pi^{\pm}$ [JHEP.06(18)84]
  using 3 fb^{-1} Run 1 data

LHCb measurements of γ

3 fb^{-1} Run 1 dataset ● Includes 2 fb^{-1} 15+16 data

	B-decay mode	$B^+ \to DK^+$	$B^+ \to D^*K^+$		$B^+ \to DK_s^0\pi^+$	$B^0 \to DK^+\pi^-$		$B^+ \to DK^+\pi^+\pi^-$	$B^+ \to D\pi^+$
	D-decay mode		**Part. reco.**	**Full reco.**	DK^{*+}**-res.**	DK^{*0}**-res.**	**Dalitz-method**		
GLW	h^+h^-	PLB.777(18)16	PLB.777(18)16		JHEP.17(17)156	PRD.90(14)112002 JHEP.08(19)41	PRD.93(16)112018	PRD.92(15)112005	PLB.777(18)16
	$\pi^+\pi^-\pi^+\pi^-$	PLB.760(16)117			JHEP.17(17)156	JHEP.08(19)41			PLB.760(16)117
	$h^+h^-\pi^0$	PRD.91(25)112014							PRD.91(25)112014
ADS	$K^\pm\pi^\mp$	PLB.760(16)117			JHEP.17(17)156	PRD.90(14)112002 JHEP.08(19)41		PRD.92(15)112005	PLB.760(16)117
	$K^\pm\pi^\mp\pi^+\pi^-$	PLB.760(16)117			JHEP.17(17)156	JHEP.08(19)41			PLB.760(16)117
	$K^\pm\pi^\mp\pi^0$	PRD.91(25)112014							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							PLB.733(14)36

Time-dependent	Time dependent measurements with $B_s^0 \to D_s^\mp K^\pm$ [JHEP.03(18)59] and $B^0 \to D^\mp\pi^\pm$ [JHEP.06(18)84] decays

* not all measurements are included in the LHCb combination. Only measurements that use the full Run 1 dataset, or Run 2 data are shown in the table.

Contributions from different D decays

Constraints from different **D decay modes**

- **GLW+ADS:** several narrow solutions
- **GGSZ:** single, broader solution

Serves as a **cross-check:** different methods expected to agree