Time-independent measurements of the CKM angle γ at LHCb

- Innes Mackay on behalf of the LHCb collaboration
- innes.mackay@physics.ox.ac.uk

- BEACH Conference
- 3-7 June, 2024

UNIVERSITY OF OXFORD

LHCb

Motivation to measure γ

[1] Phys. Rev. D **91**, 073007, ckmfitter.in2p3.fr

- CKM unitarity can be tested by **overconstraining** the Unitarity Triangle (UT)

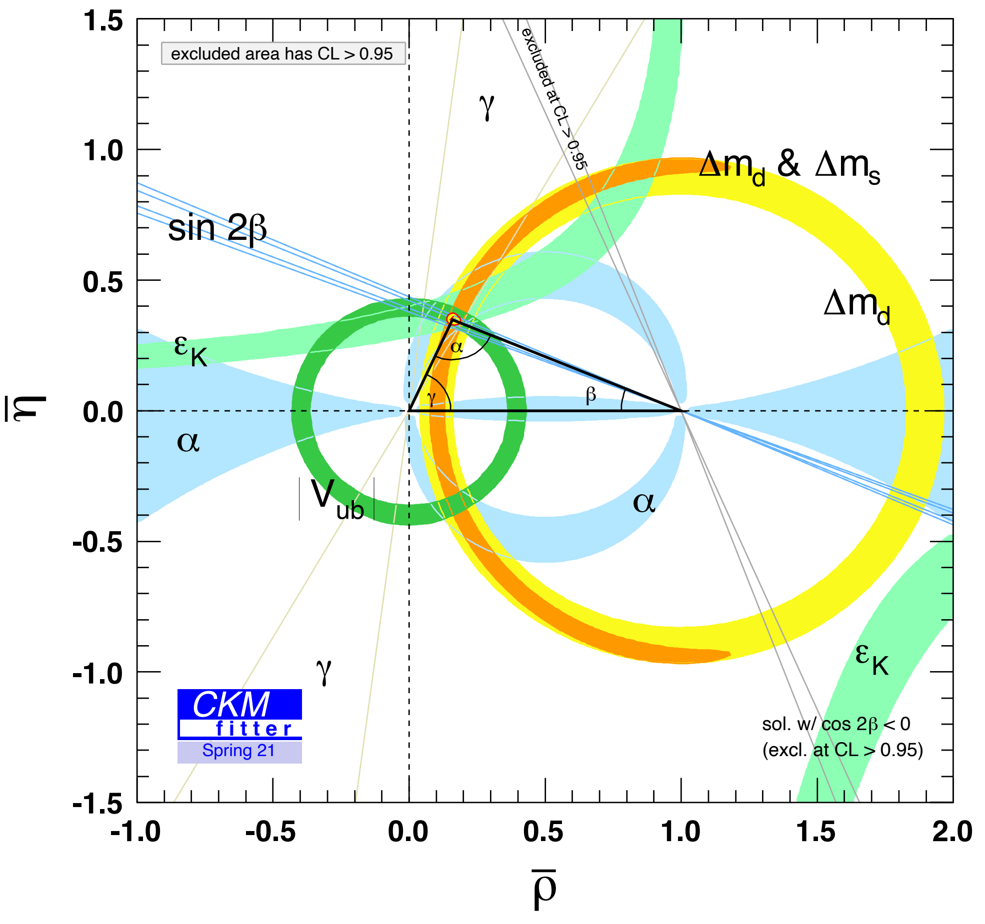
- **Why γ?**
  - Negligible theoretical uncertainty
  - Directly measured at tree level

Measure lengths and angles of the UT ⟶ Fit for γ

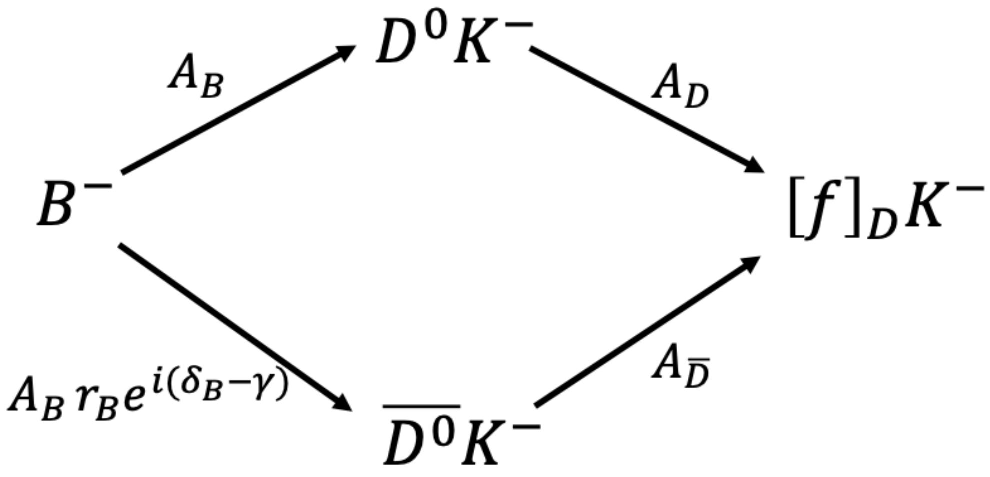
↓

Directly measure γ ⟶ Agree?

$$V_{ud}\,V_{ub}^{*} + V_{cd}\,V_{cb}^{*} + V_{td}\,V_{tb}^{*} = 0$$



Direct measurements of γ through interference



$$|A(B^-)|^2 \propto A_D^2 + r_B^2 A_{\overline{D}}^2 + 2A_D A_{\overline{D}} r_B \cos(\delta_B - \gamma)$$

$$|A(B^+)|^2 \propto A_D^2 + r_B^2 A_{\overline{D}}^2 + 2A_D A_{\overline{D}} r_B \cos(\delta_B + \gamma)$$

Use final states accessible to both D^0 and $\overline{D}^0$ mesons

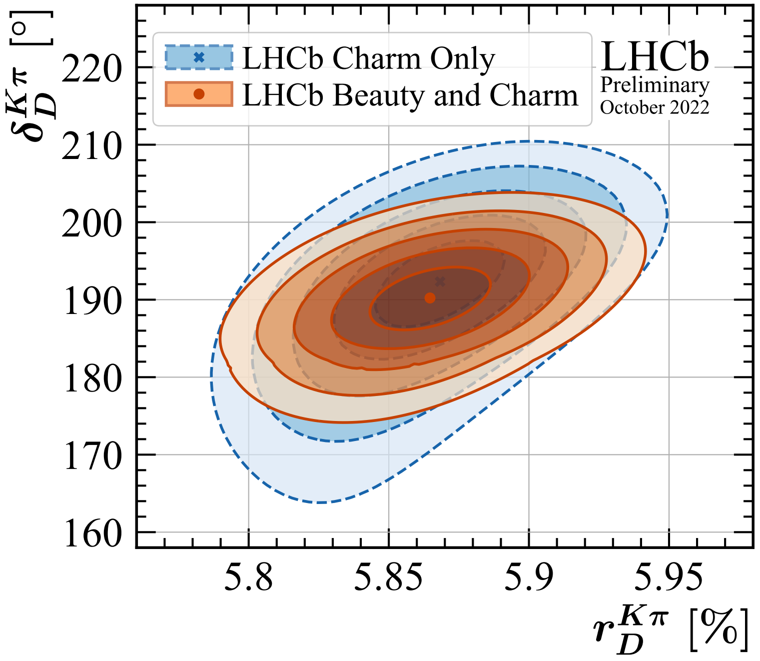
Measurement technique depends on D-decay mode

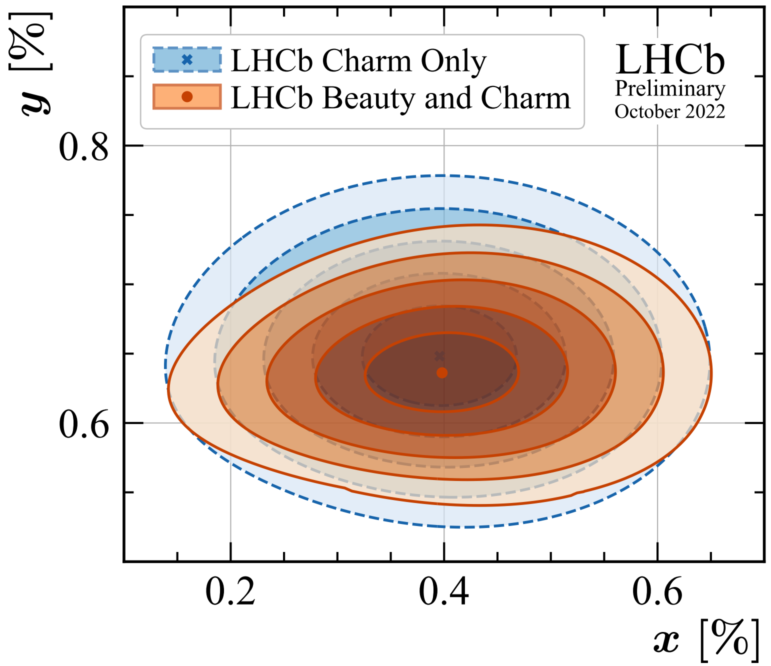
LHCb γ and charm combination

[2] *J. High Energ. Phys.* **2021**, 141 (2021)
[3] LHCb-CONF-2022-003

- First performed by LHCb in 2021 [2] (updated in 2022 [3])
- Input from γ measurements in B–decays can improve knowledge of charm mixing parameters

$$|A(B^- \to [\pi^- K^+]_D K^-)|^2 \propto \cos(\delta_B + \boldsymbol{\delta_D^{K\pi}} - \gamma)$$

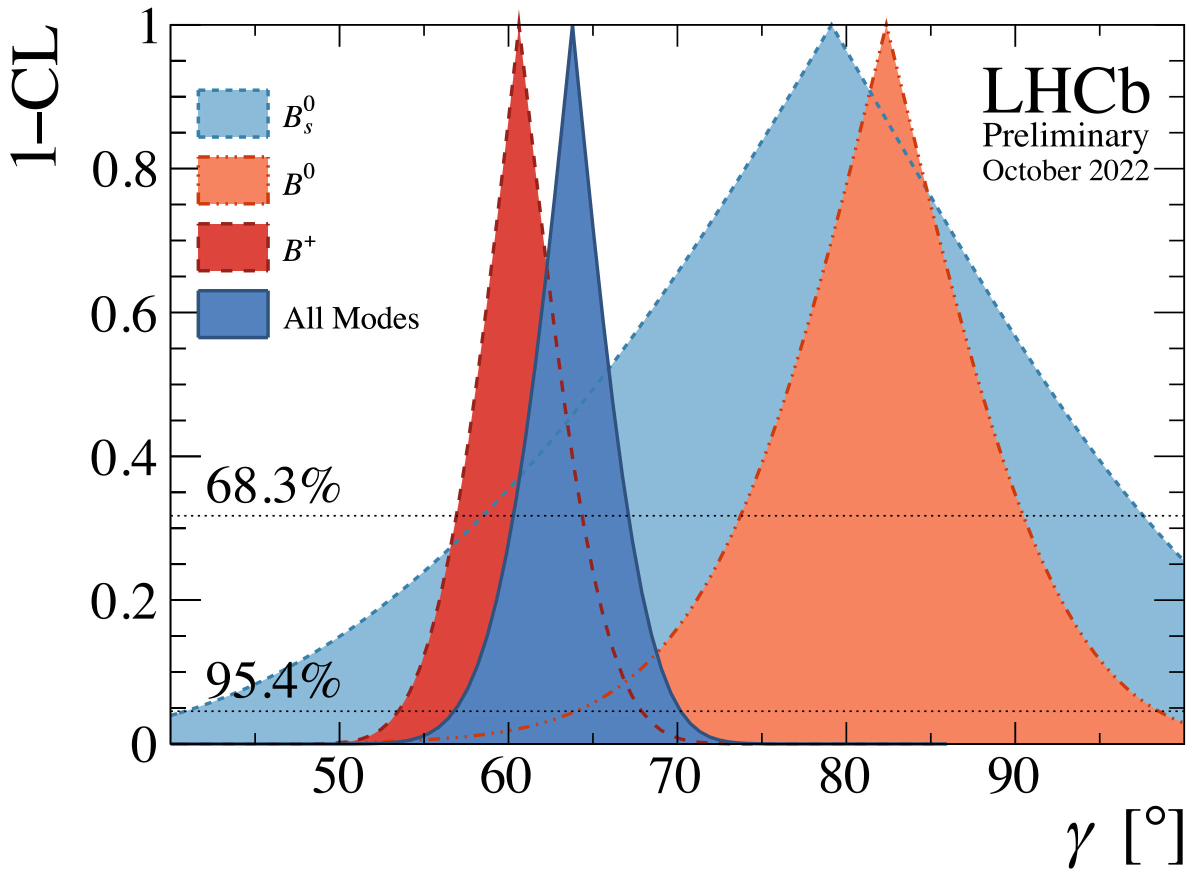




Comparing direct and indirect γ

[4] Phys. Rev. D **107**, 052008, https://hflav.web.cern.ch
[5] *Rend. Fis. Acc. Lincei* **34**, 37–57 (2023)
[6] LHCb-CONF-2023-004

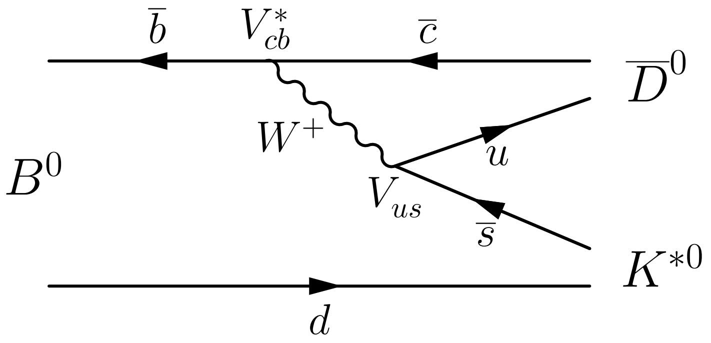
- LHCb combination: $\gamma_{\text{direct}} = (63.8^{+3.5}_{-3.7})\,^{\circ}$ [3]
- HFLAV: $\gamma_{direct} = (66.2^{+3.4}_{-3.6})^{\circ}$ [4]
- Indirect combinations give $\gamma = (65.6^{+0.9}_{-2.7})^{\circ}$ [1] or $\gamma = (65.8 \pm 2.2)\,^{\circ}$ [5]
- New measurements using B_s^0 decays consistent with average [6]
- Tension between B^0 and B^+ is reduced by new measurements in $B^0 \to DK^{*0}$ decays (TODAY)
- To reach LHCb Run 4 goal of $\Delta\gamma = 1^{\circ}$ we will require additional channels e.g. $B^{\pm} \to D^{*}K^{\pm}$ (TODAY)



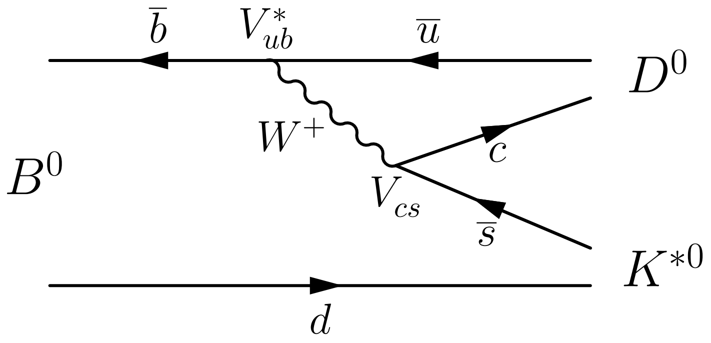
Measurement of γ in $B^0 \to DK^{*0}$ decays

[7] Phys. Rev. D 94, 079902
[8] JHEP 05 (2024) 025
[9] Eur. Phys. J. C 84 (2024) 206

- Charge on the kaon from the $K^{*0}(892) \to K^+\pi^-$ decay indicates B–meson flavour at decay
- Branching fractions lower than in $B^\pm \to DK^\pm$, but interference is larger ($r_{B^0} \sim 3r_{B^\pm}$)
- Interference diluted by coherence factor $\kappa = 0.958^{+0.005}_{-0.046}$ [7]
- Recent results using ADS/GLW [8] and BPGGSZ [9] final states will be presented



Favoured



Suppressed

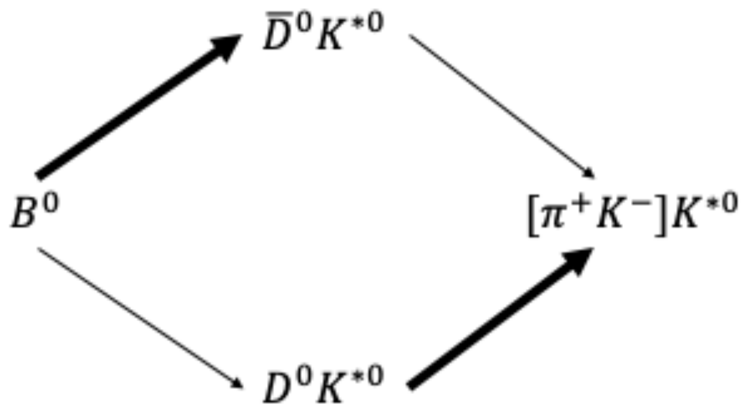
Measurement of γ in $B^0 \rightarrow DK^{*0}$ decays: ADS modes [8]

- Similar amplitudes between the two paths can produce large interference effects when using D-decays with large difference in magnitude between CF/CS D decays e.g. $D \rightarrow K\pi(\pi\pi)$

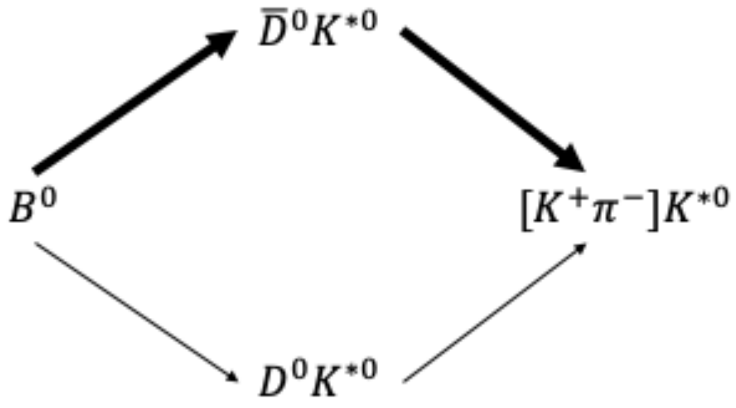
- γ extracted in a fit to ratio observables e.g.

$$r_D e^{-i\delta_D} = \frac{A(D^0 \rightarrow f)}{A(D^0 \rightarrow \bar{f})}$$

$$R_{\pi K}^{-} = \frac{\Gamma(\bar{B}^0 \rightarrow [\pi^+ K^-]_D \bar{K}^{*0})}{\Gamma(\bar{B}^0 \rightarrow [K^+ \pi^-]_D \bar{K}^{*0})} \propto 2\kappa r_{B^0} r_D^{K\pi} \cos(\delta_{B^0} + \delta_D^{K\pi} - \gamma)$$



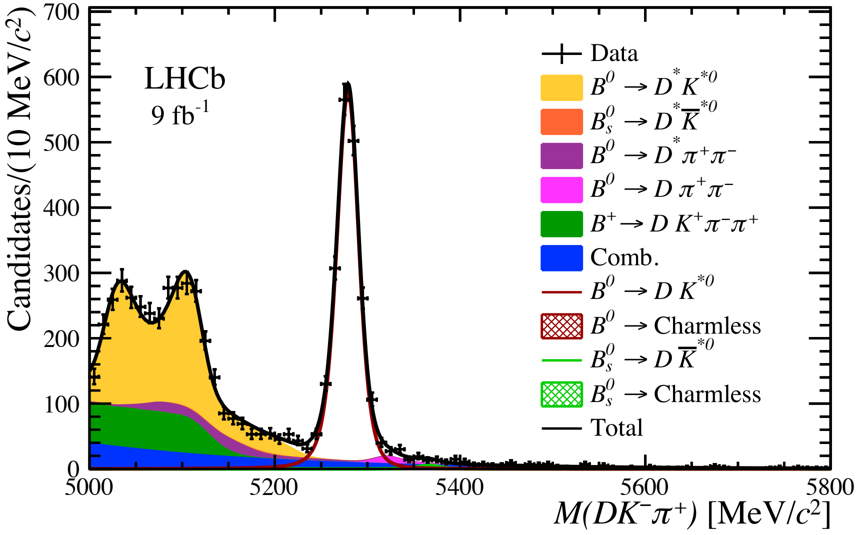
Large interference effects



Small interference effects (control)

Measurement of γ in $B^0 \to DK^{*0}$ decays: ADS modes [8]

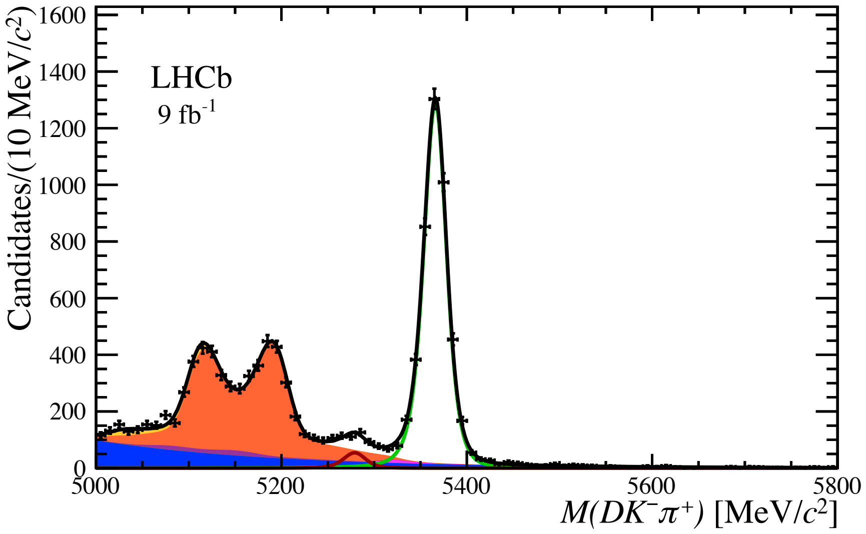
$\bar{B}^0 \to [K^+\pi^-]_D \bar{K}^{*0}$



$R^-_{\pi K} = 0.093 \pm 0.013 \pm 0.005$

$R^-_{\pi K\pi\pi} = 0.038 \pm 0.014 \pm 0.006$

$\bar{B}^0 \to [\pi^+K^-]_D \bar{K}^{*0}$

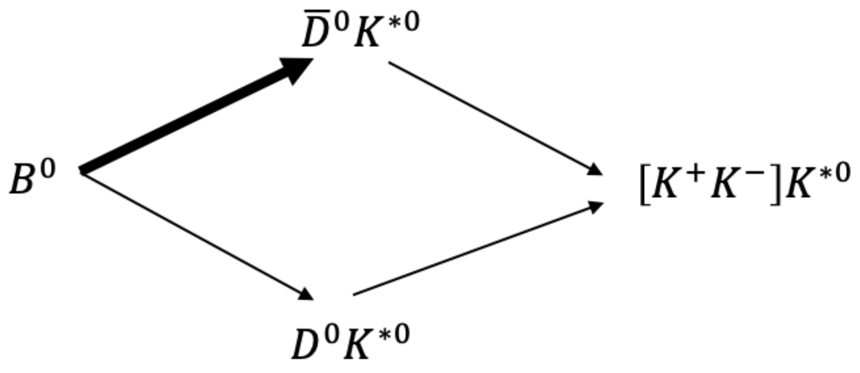


$R^+_{\pi K} = 0.069 \pm 0.013 \pm 0.005$

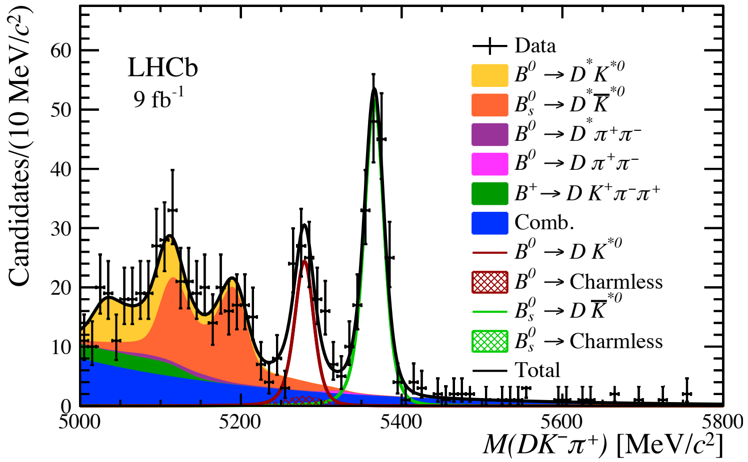
$R^+_{\pi K\pi\pi} = 0.060 \pm 0.014 \pm 0.006$

Measurement of γ in $B^0 \to DK^{*0}$ decays: GLW modes [8]

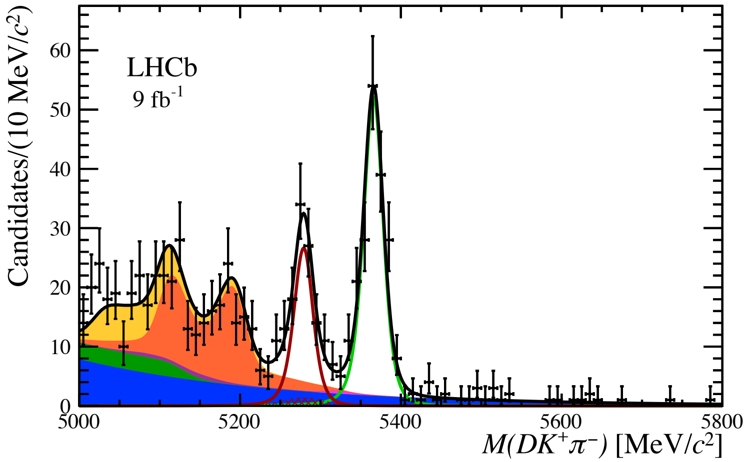
- GLW method uses $D^0 \to CP$ eigenstate decays e.g. $D^0 \to K^+K^-$
- γ extracted from ratio (w.r.t. favoured $B^0 \to [K^+\pi^-]_D K^{*0}$) and asymmetry (comparing rates of B^0 and $\bar{B}^0$ decays) observables
- $D^0 \to 4\pi$ is a quasi-GLW mode with known CP even content



$\bar{B}^0 \to [\pi^+\pi^-]_D \bar{K}^{*0}$



$B^0 \to [\pi^+\pi^-]_D K^{*0}$



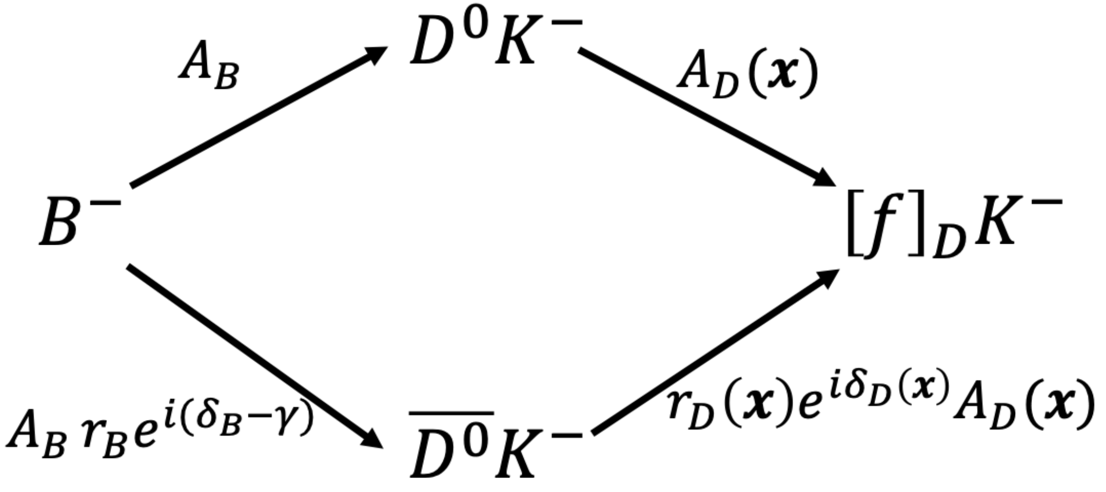
Observable	Value ± stat. ± syst
$R_{CP}^{\pi\pi}$	1.104 ± 0.111 ± 0.026
$A_{CP}^{\pi\pi}$	-0.034 ± 0.094 ± 0.016
R_{CP}^{KK}	0.811 ± 0.057 ± 0.017
A_{CP}^{KK}	-0.047 ± 0.063 ± 0.015
$R_{CP}^{\pi\pi\pi\pi}$	0.882 ± 0.086 ± 0.033
$A_{CP}^{\pi\pi\pi\pi}$	0.021 ± 0.087 ± 0.016

Direct measurements of γ with multibody D–decays

[10] J. High Energ. Phys. 2021, 169 (2021)

- Intermediate resonances introduce phase-space dependence on the D-decay amplitudes
- Self-conjugate $D \to K_S^0 h^+ h^-$ $(h = \pi, K)$ modes described by Dalitz plots
- Measurement requires D-decay strong-phase information as input

$$|A(B^-)|^2(\boldsymbol{x}) \propto 1 + r_B^2 + 2r_B r_D(\boldsymbol{x})\cos(\delta_B - \gamma + \delta_D(\boldsymbol{x}))$$



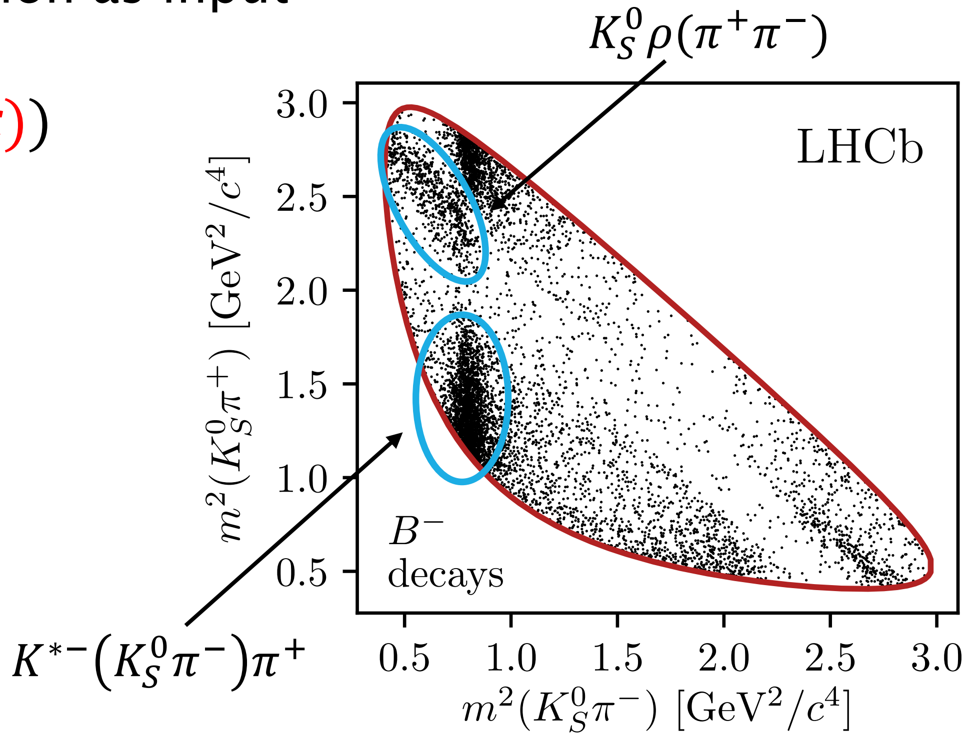


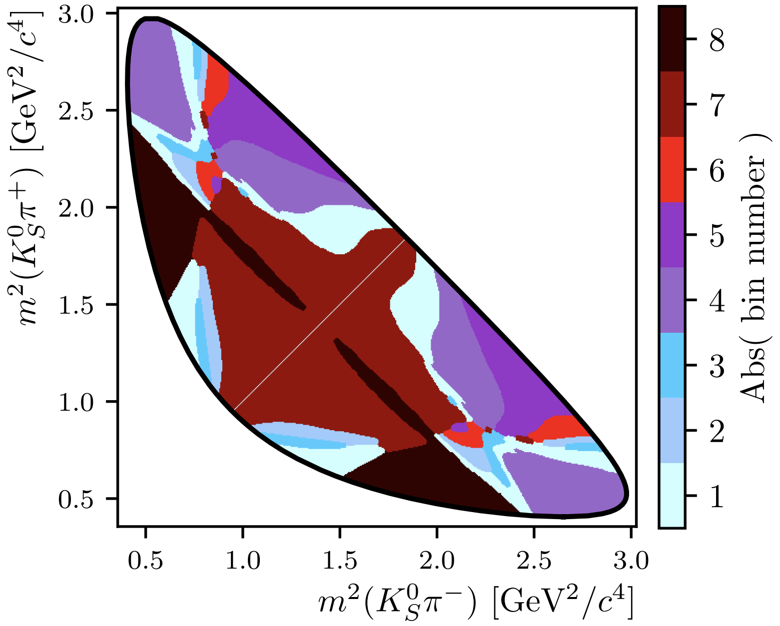
Figure from [10]

Model-independent measurements

[11] Phys. Rev. D 101, 112002
[12] Phys. Rev. D 102, 052008
[13] Phys. Rev. D 82, 112006

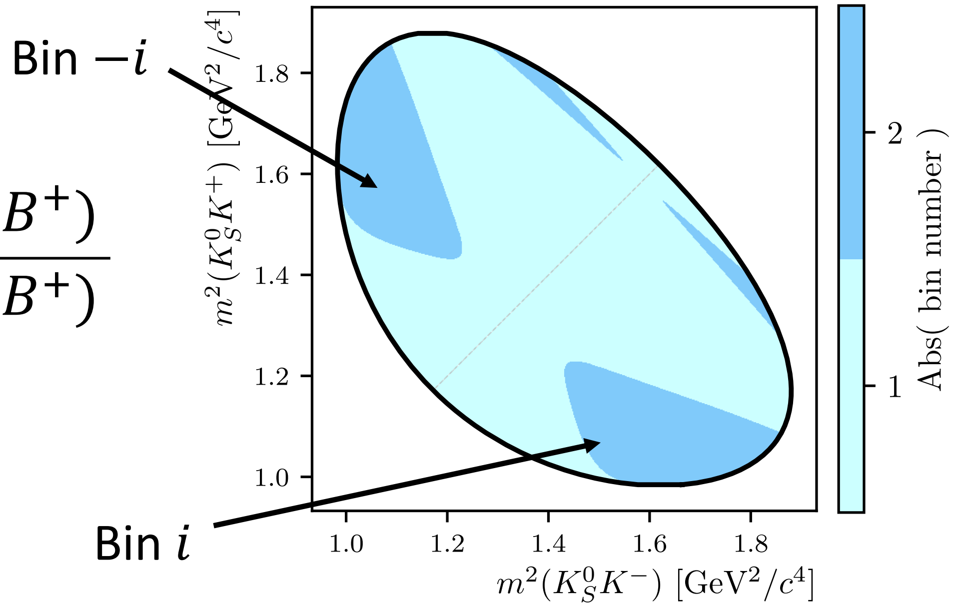
- Systematic uncertainties associated with amplitude models are non-trivial
- Instead strong-phase inputs determined in Dalitz plot bins at charm factories [11,12]
- Binning schemes chosen to optimize sensitivity to γ (isolate regions with similar δ_D) [13]

$D \to K_S^0 \pi^+ \pi^-$



$$\mathcal{A} = \frac{N_{-i}(B^-) - N_i(B^+)}{N_{-i}(B^-) + N_i(B^+)}$$

$D \to K_S^0 K^+ K^-$



Experimental procedure

Normalisation factor

$\kappa_{B^0 \to DK^{*0}} = 0.958^{+0.005}_{-0.046}$ [11]

Amplitude averaged strong-phase difference in $D \to K_S^0 h^+ h^-$ [7,8]

$$N_i(B) = h^B [F_i + (x_-^2 + y_-^2) F_{-i} + 2\kappa \sqrt{F_i F_{-i}} (c_i x_- + s_i y_-)]$$

$$N_i(\bar{B}) = h^{\bar{B}} [F_{-i} + (x_+^2 + y_+^2) F_i + 2\kappa \sqrt{F_i F_{-i}} (c_i x_+ - s_i y_+)]$$

Probability for $D^0 \to K_S^0 h^+ h^-$ decay to be in DP bin, $-i$, given the selection at LHCb

$x_\pm = r_B \cos(\delta_B \pm \gamma)$

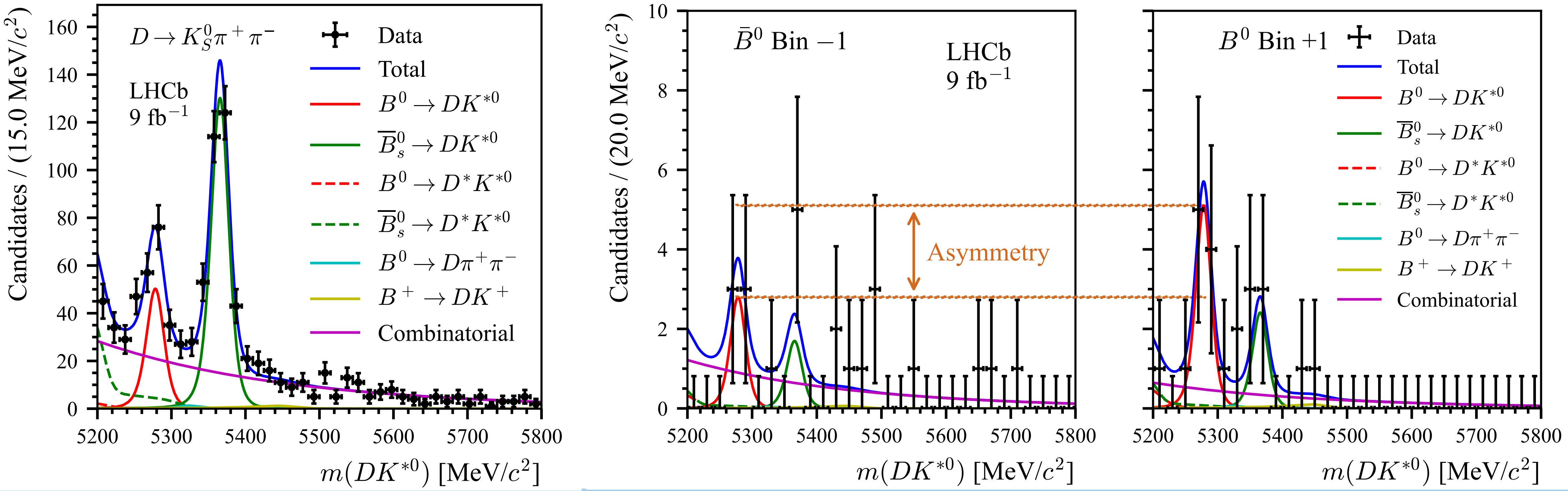
$y_\pm = r_B \sin(\delta_B \pm \gamma)$

"CP violation observables"

Measurement of γ in $B^0 \to DK^{*0}$ decays: BPGGSZ modes [9]

- Integrated fit performed to ensure backgrounds are understood
- Binned fit performed to determine the CP observables
- Each component parameterized according to their expected interference

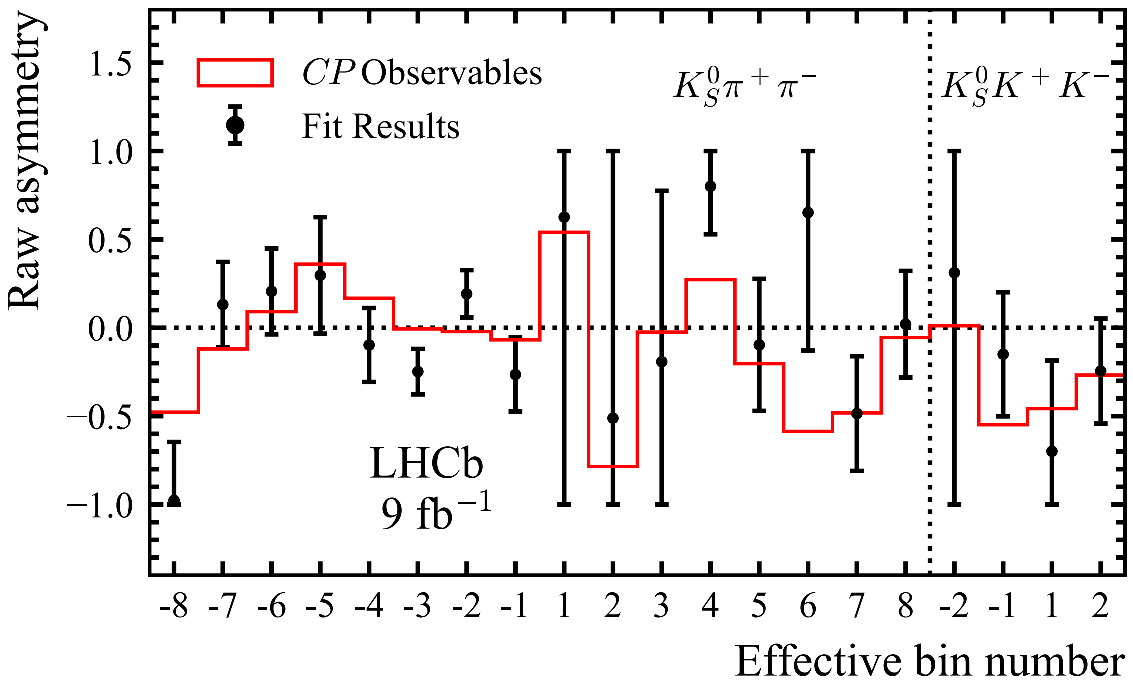
Figures from [10]

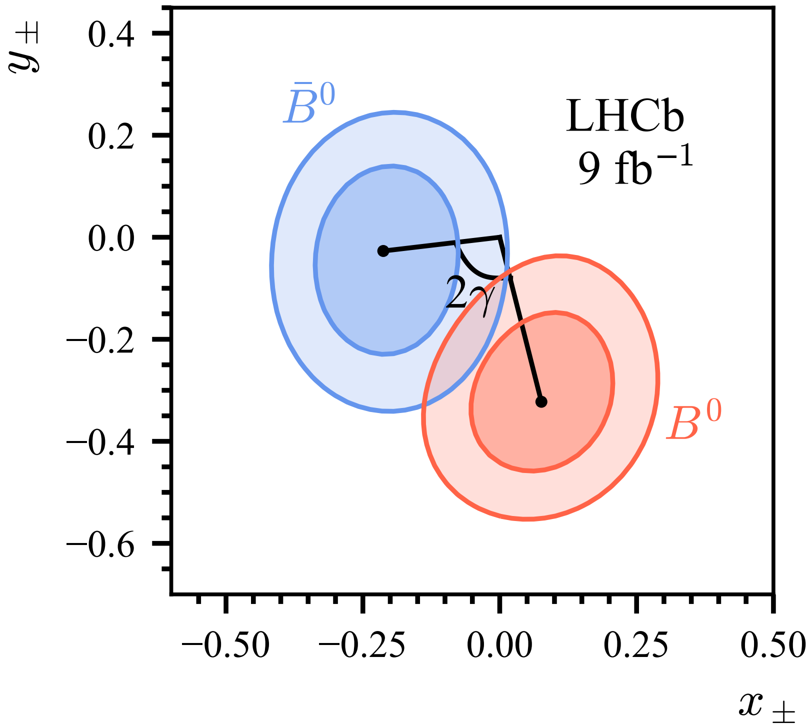


Measurement of γ in $B^0 \to DK^{*0}$ decays: BPGGSZ modes [9]

[14] J. High Energ. Phys. 2016, 131 (2016)1

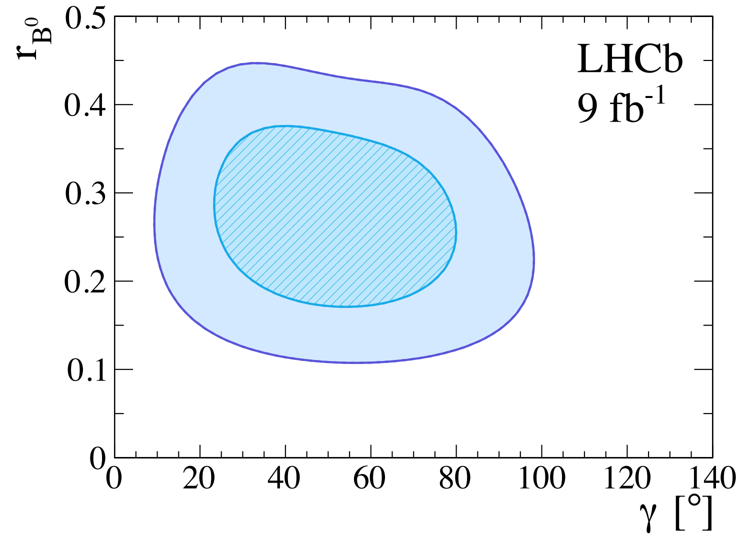
- Bins with large asymmetries enhance the sensitivity to γ
- Measurement supersedes Ref. [14]





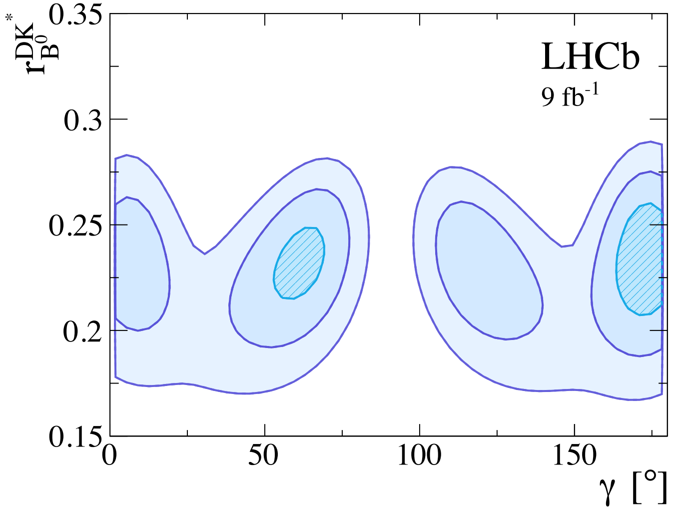
Summary of results using $B^0 \to DK^{*0}$ decays

$D \to K_S^0 h^+ h^-$



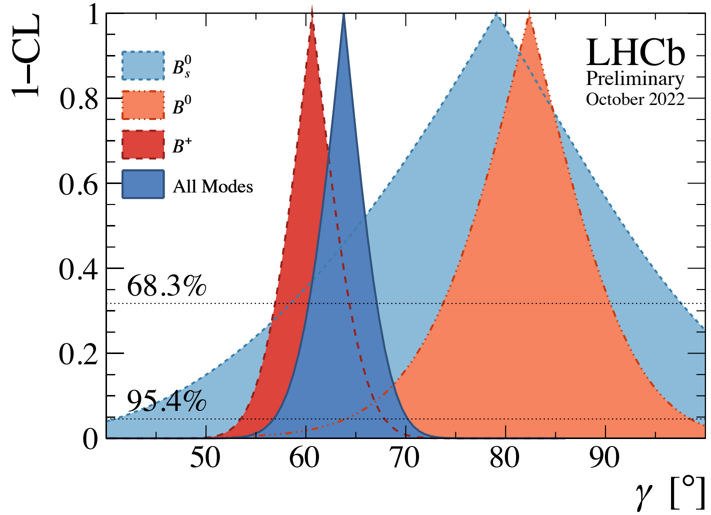
$\gamma = (49^{+23}_{-18})^\circ$

ADS/GLW



Preferred solution at $\gamma = (172 \pm 6)^\circ$
Second solution at $\gamma = (62 \pm 8)^\circ$

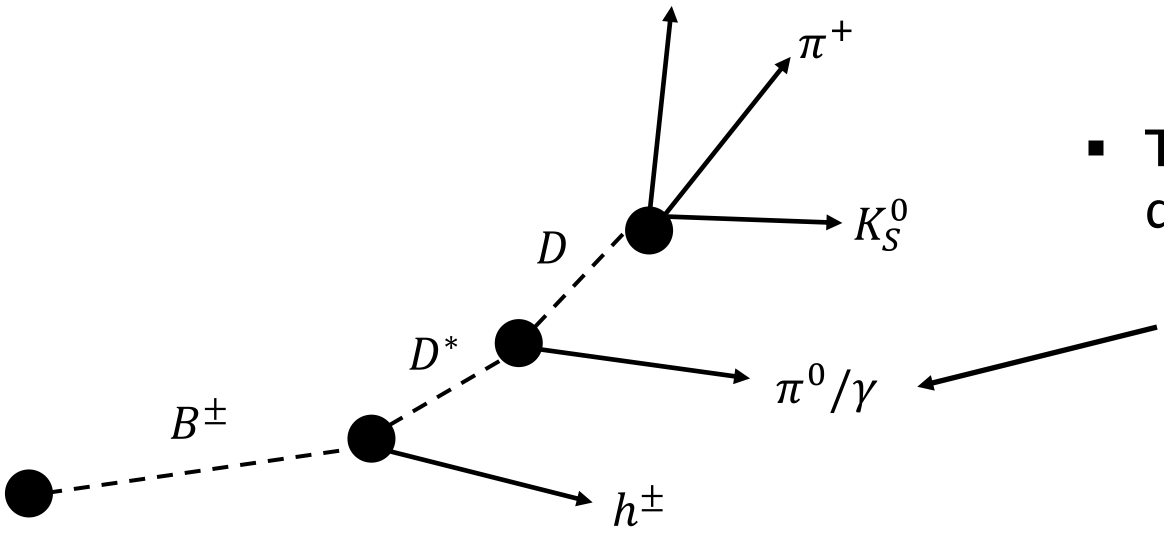
2022 LHCb combination



Combined value $\boldsymbol{\gamma = \left(63.2^{+6.9}_{-8.1}\right)^\circ}$ is more **consistent** with measurements in B^+ decays with **competitive precision**

Measuring γ using $B^{\pm} \to D^{*}K^{\pm}$ decays

[15] JHEP 12 (2023) 013
[16] JHEP 02 (2024) 118



- **Two separate measurements** with the same decay chain but different techniques
  - The neutral particle can be reconstructed [15] or not [16]
  - Negligible overlap between the analyses

$$CP(\pi^0) = -1 \,\&\, CP(\gamma) = 1$$

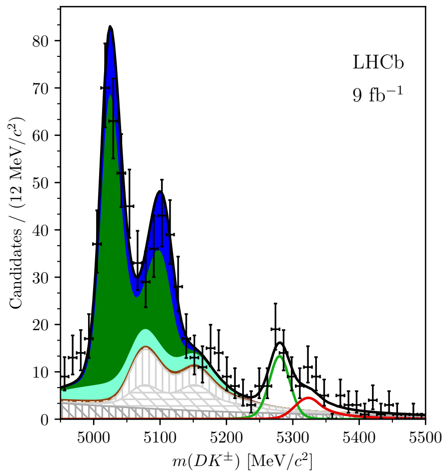
- Introduces phase shift of $\pi \to \mathcal{A}(\pi^0) = -\mathcal{A}(\gamma)$

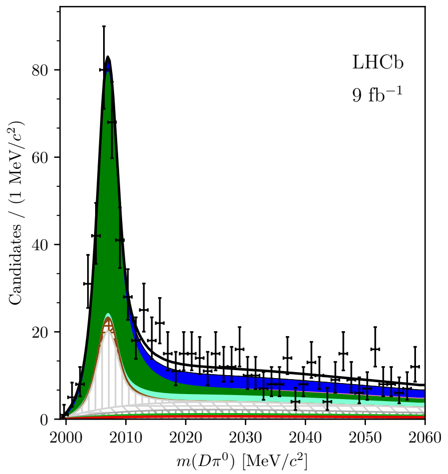
$$N_i(B^-) = h^{B^-}[F_i + (x_-^2 + y_-^2)F_{-i} \pm 2\sqrt{F_i F_{-i}}(c_i x_- + s_i y_-)]$$

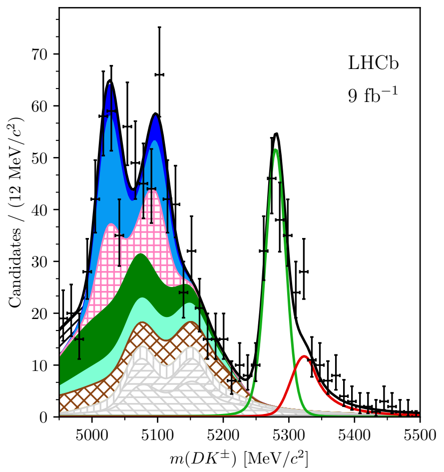
Fully reconstructed $B^{\pm} \to D^* K^{\pm}$ [15]

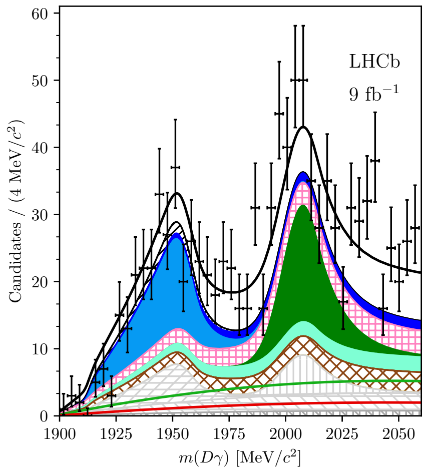
Integrated fit ⟶ Binned fit ⟶ CP observables

- 2D fits to disentangle backgrounds in the signal region
- Signal corresponds to filled shapes
- $B^{\pm} \to D^* \pi^{\pm}$ is additional signal channel – used to determine F_i



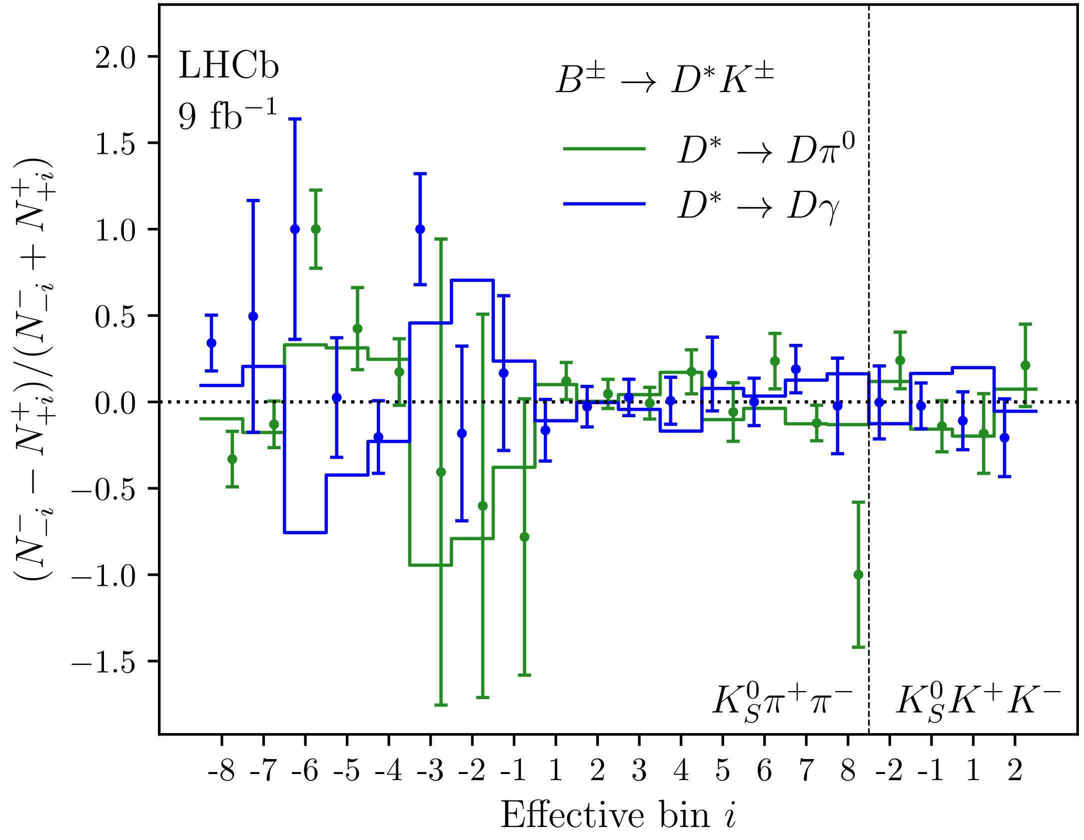






Fully reconstructed $B^{\pm} \to D^{*}K^{\pm}$ [15]

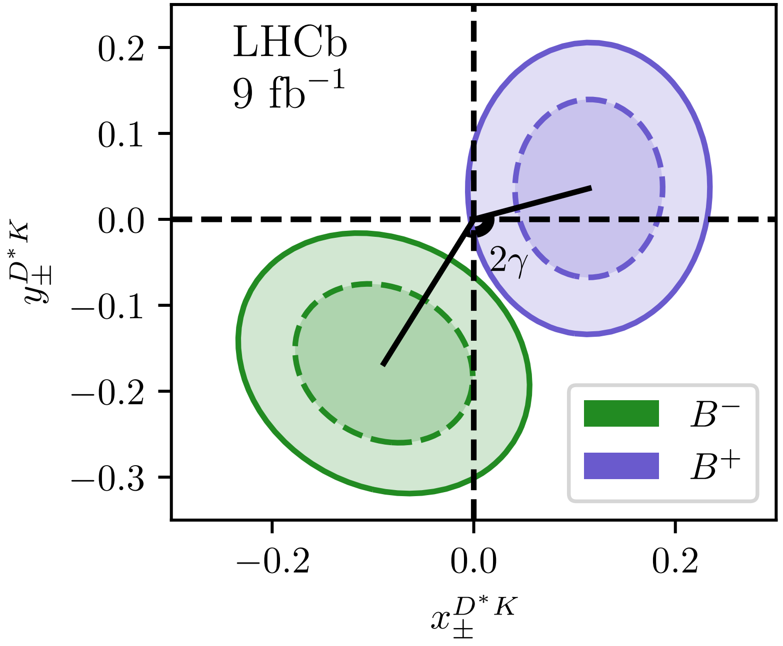
- $\mathcal{A}(\pi^0) = -\mathcal{A}(\gamma)$ observed
- γ consistent with combination



$$\gamma = (69^{+13}_{-14})^{\circ}$$

$$r_B^{D^{*}K} = 0.15 \pm 0.03$$

$$\delta_B^{D^{*}K} = (311 \pm 14)^{\circ}$$



Partially reconstructed $B^{\pm} \to D^{*}K^{\pm}$ [16]

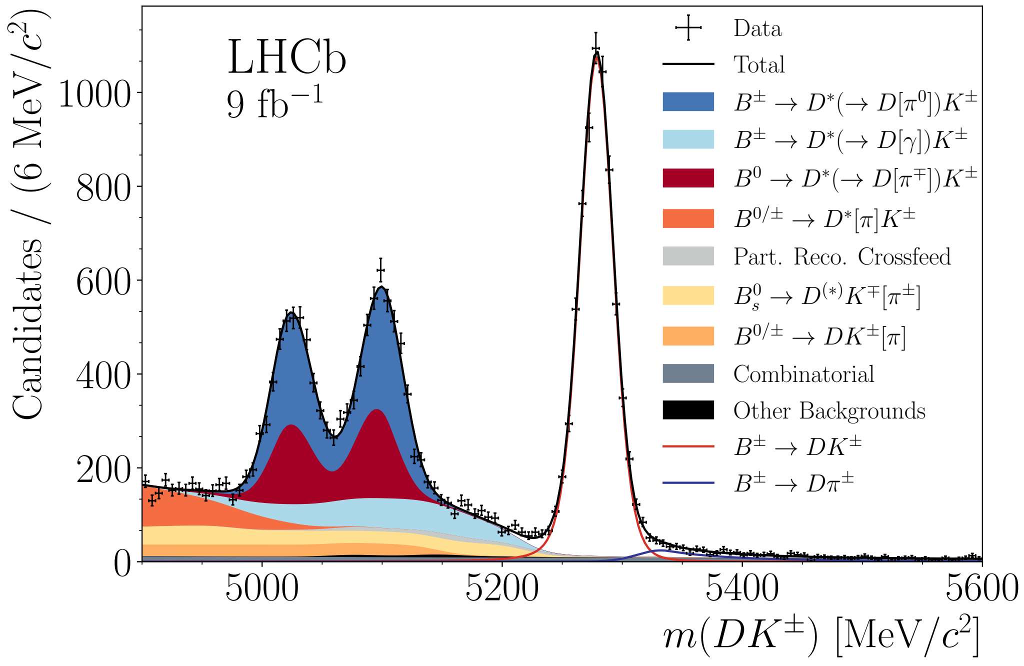
- Blue filled shapes corresponds to signal

Integrated fit → Binned fit → CP observables

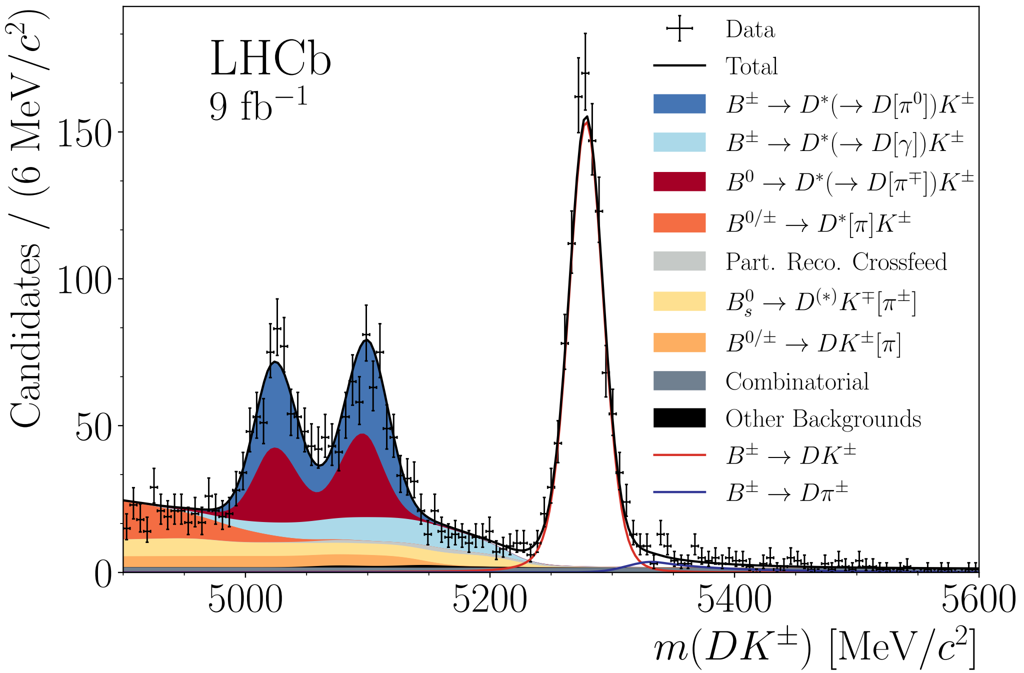
- $B^{\pm} \to D^{*}\pi^{\pm}$ is additional signal channel – used to determine F_i

- Knowledge of the backgrounds is a large systematic uncertainty

$D \to K_S^0\pi^+\pi^-$

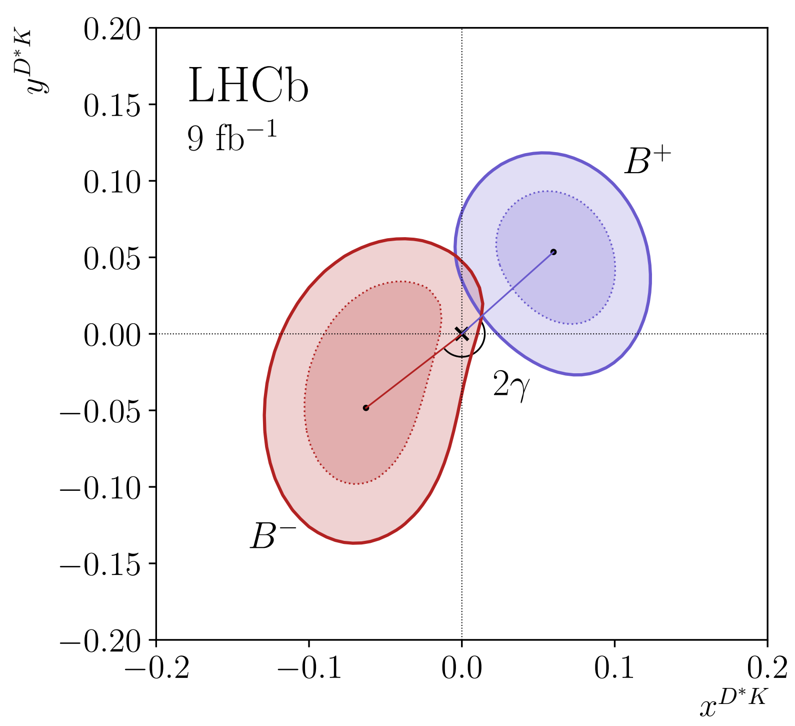


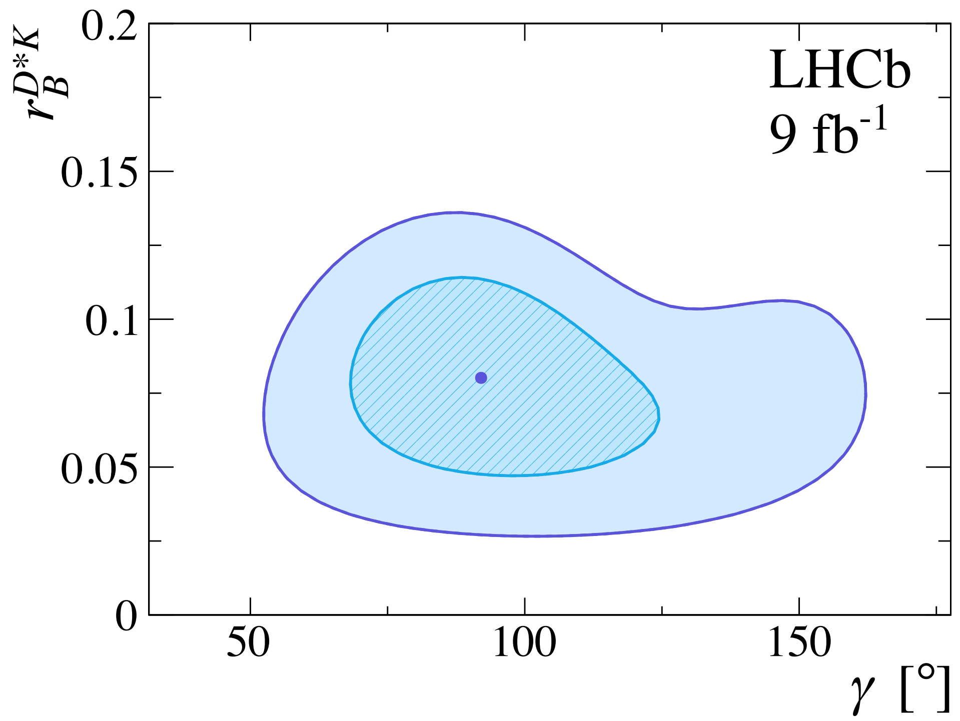
$D \to K_S^0K^+K^-$



Partially reconstructed $B^{\pm} \to D^{*}K^{\pm}$ [16]

- Uncertainty on γ is statistically dominated
- Results consistent with expectations
- $x_{\pm}^{D^*K}, y_{\pm}^{D^*K}$ more precise than in fully reconstructed analysis, but $\Delta\gamma \propto 1/r_B^{D^*K}$





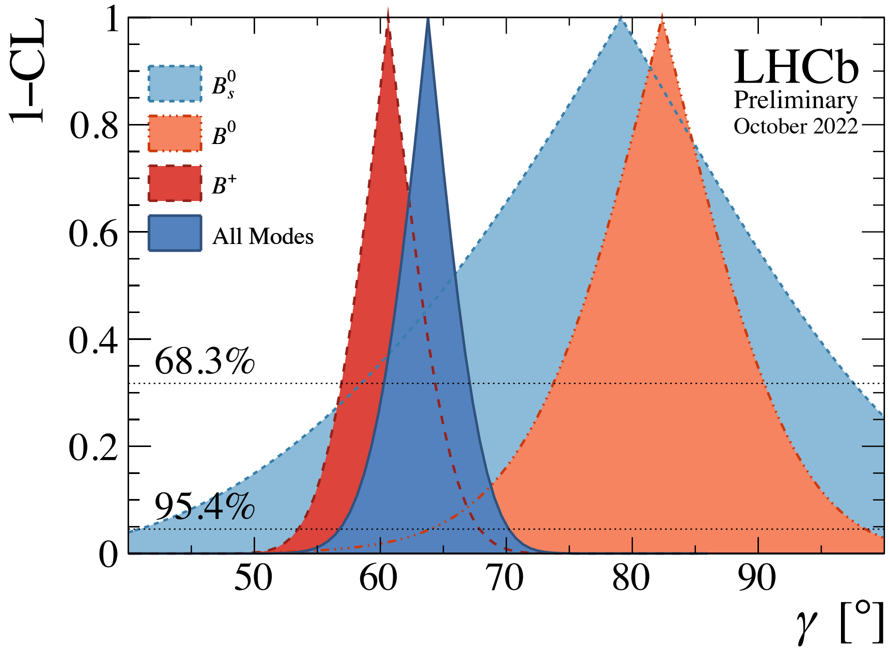
$$\gamma = (92^{+21}_{-17})^{\circ}$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = \left(310^{+15}_{-20}\right)^{\circ}$$

Summary

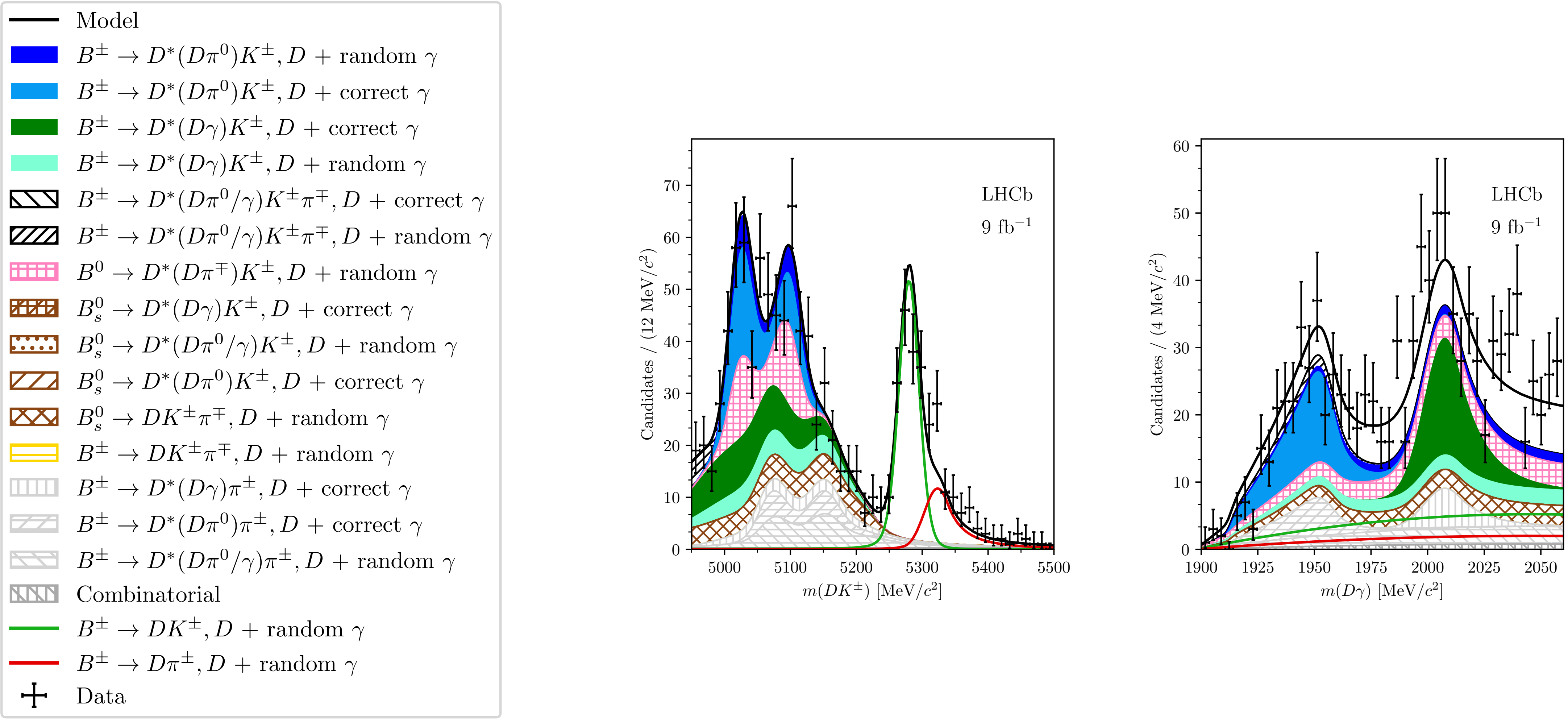
- Presented 4 recent LHCb γ measurements
  - $B^0 \to [h'h(\pi\pi)]_D K^{*0}$ [JHEP 05 (2024) 025]
  - $B^0 \to \left[K_S^0 h^+ h^-\right]_D K^{*0}$ [Eur. Phys. J. C 84 (2024) 206]
  - $B^\pm \to D^* K^\pm$ (full reco.) [JHEP 12 (2023) 013]
  - $B^\pm \to D^* K^\pm$ (partial reco.) [JHEP 02 (2024) 118]



- Tensions resolved in B^0 and B^+ decays
- Two model-independent measurements with $B^\pm \to D^* K^\pm$ decays help improve precision

Questions?

Backup: Fit components in fully reconstructed $B^\pm \to D^*(D\gamma)K^\pm$



Backup: Fit components in fully reconstructed $B^{\pm} \to D^{*}(D\pi^{0})K^{\pm}$