Measurements of CKM angle gamma and parameters related to mixing and CP violation in the charm at LHCb

- Innes Mackay on behalf of the LHCb collaboration

- CKM Conference
- 18-22 September, 2023

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?

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

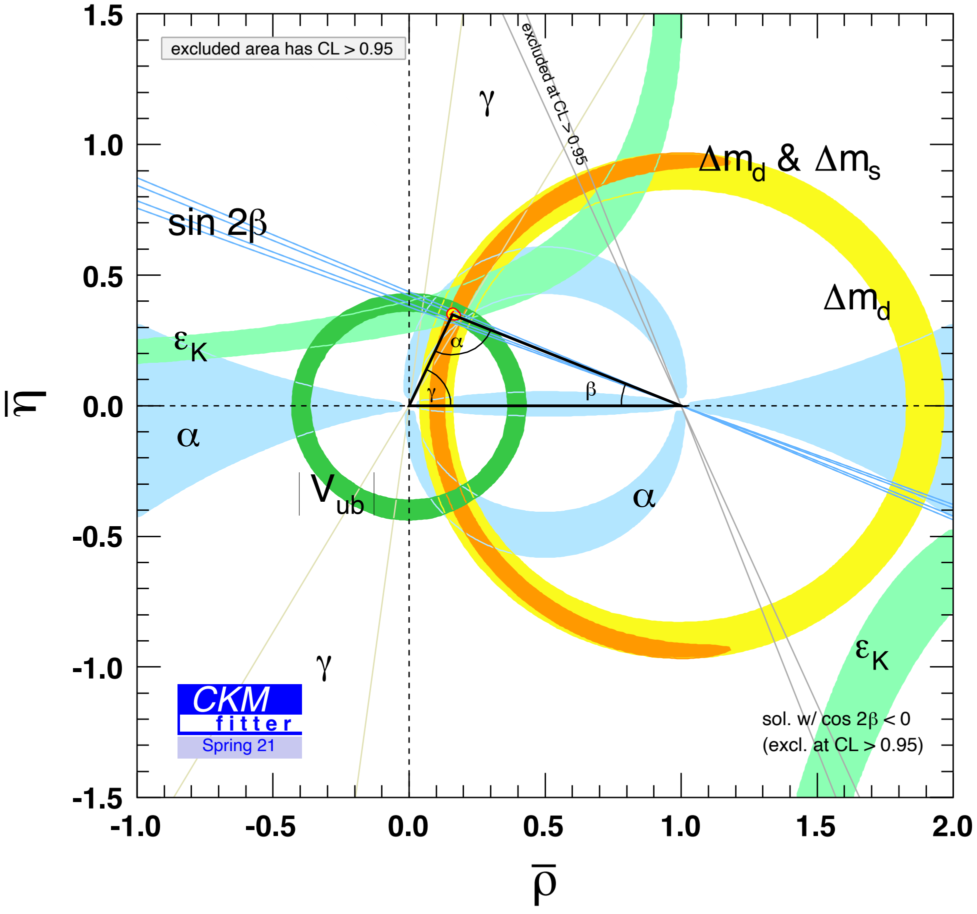


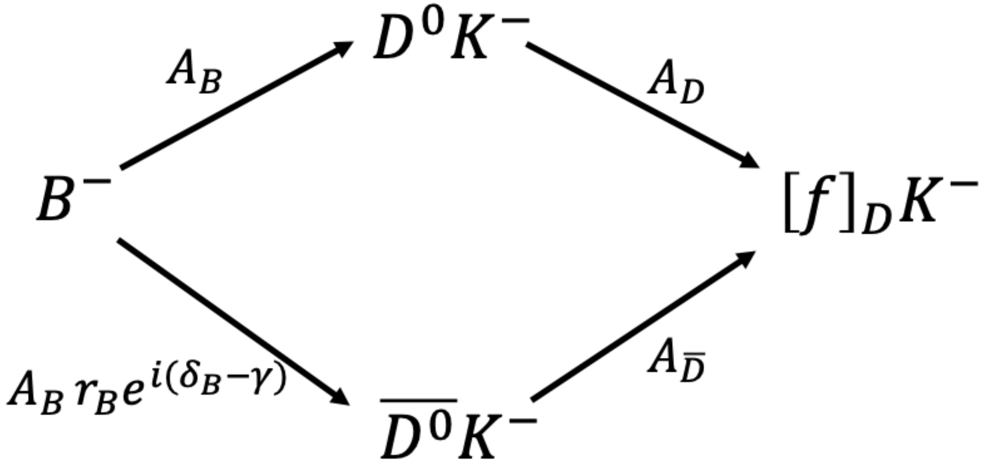
Figure from [1]

Direct measurements of γ

- Use final states accessible to both D^0 and $\overline{D}^0$ to examine interference between $b \to c$ and $b \to u$ quark transitions

- $B^{\pm} \to DK^{\pm}$ is the most precise channel, but additional sensitivity is achieved with others

- Measurement technique depends on D-decay mode



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

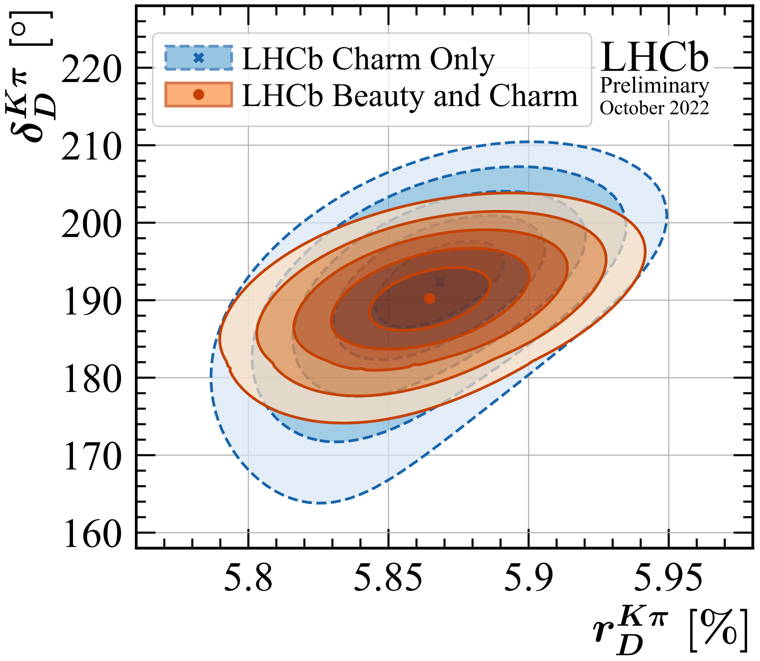
$$|A(B^+)|^2 \propto A_D^2 + \boldsymbol{r_B^2} A_{\overline{D}}^2 + 2A_D A_{\overline{D}} \boldsymbol{r_B} \cos(\boldsymbol{\delta_B} + \gamma)$$

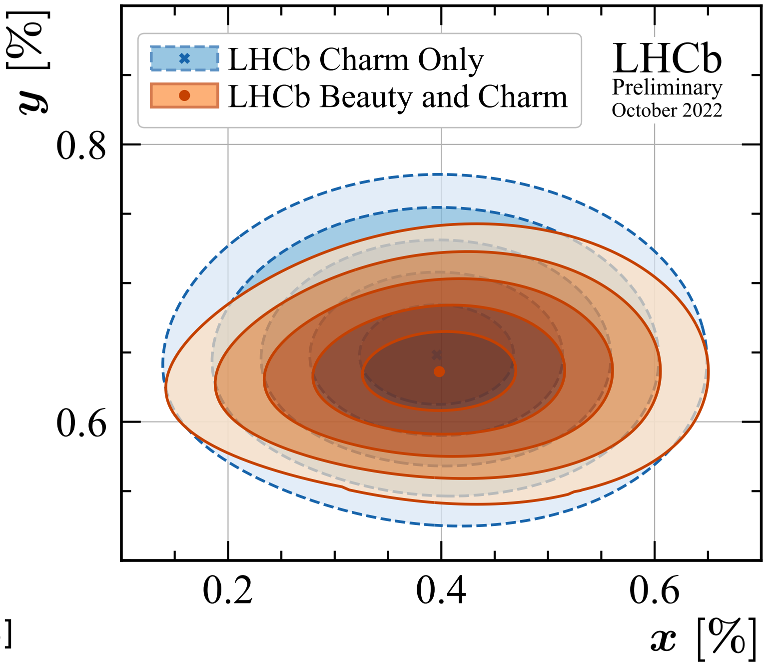
LHCb γ and charm combination

[2] *J. High Energ. Phys.* **2021**, 141 (2021). https://doi.org/10.1007/JHEP12(2021)141
[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
- Dedicated LHCb charm talks are available from Federico and Jolanta

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





Figures from [3]

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), https://doi.org/10.1007/s12210-023-01137-5

- 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 in B_s^0 decays consistent with average [see Quentin's talk]
- Tension between B^0 and B^+ is reduced by new measurements in $B^0 \to DK^{*0}$ decays (not included in 2022 combination)
- LHCb Run 4 aim: $\Delta\gamma = 1^\circ$

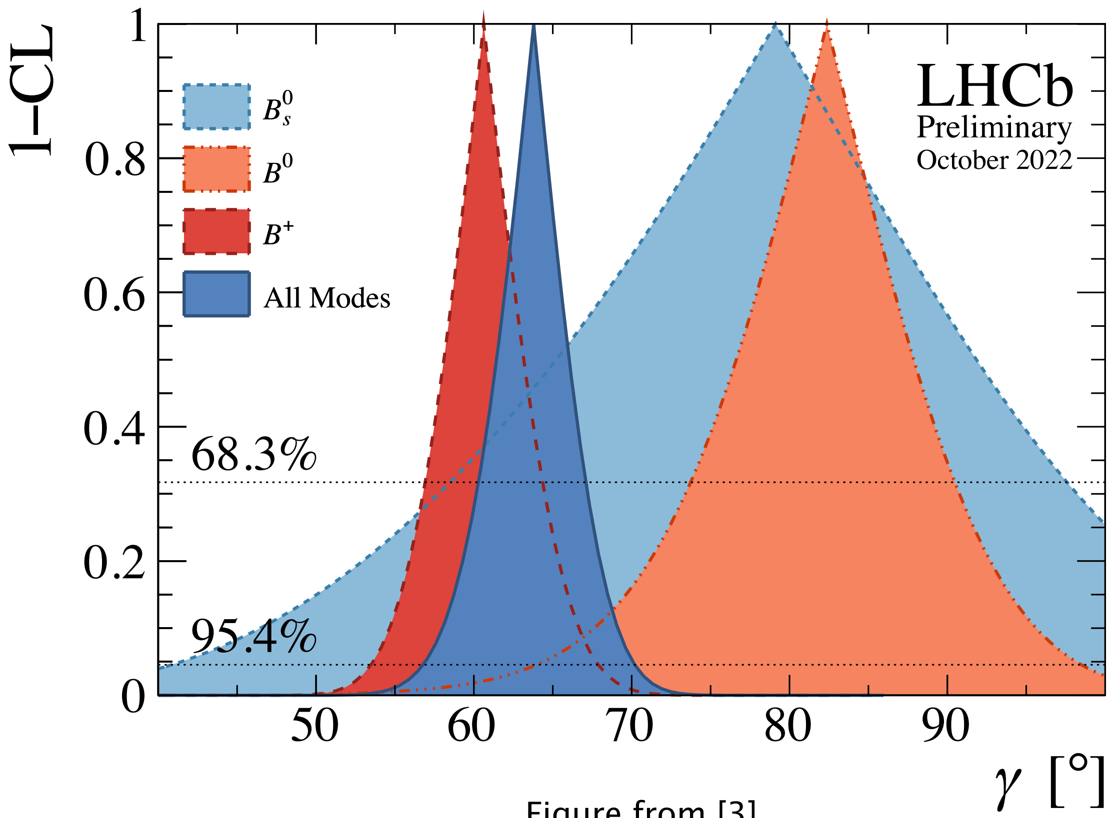


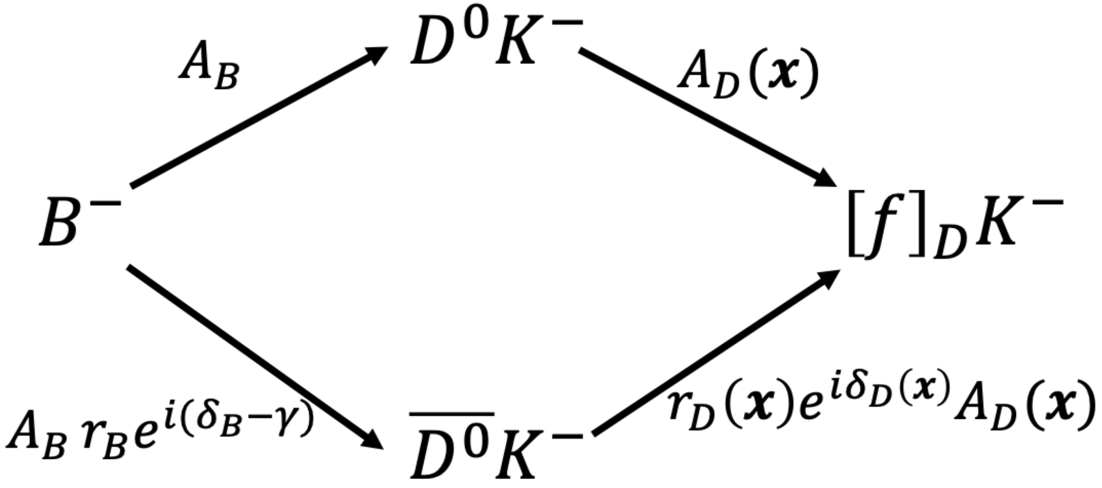
Figure from [3]

Direct measurements of γ with multibody D-decays

[6] *J. High Energ. Phys.* **2021**, 169 (2021). https://doi.org/10.1007/JHEP02(2021)169

- 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

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



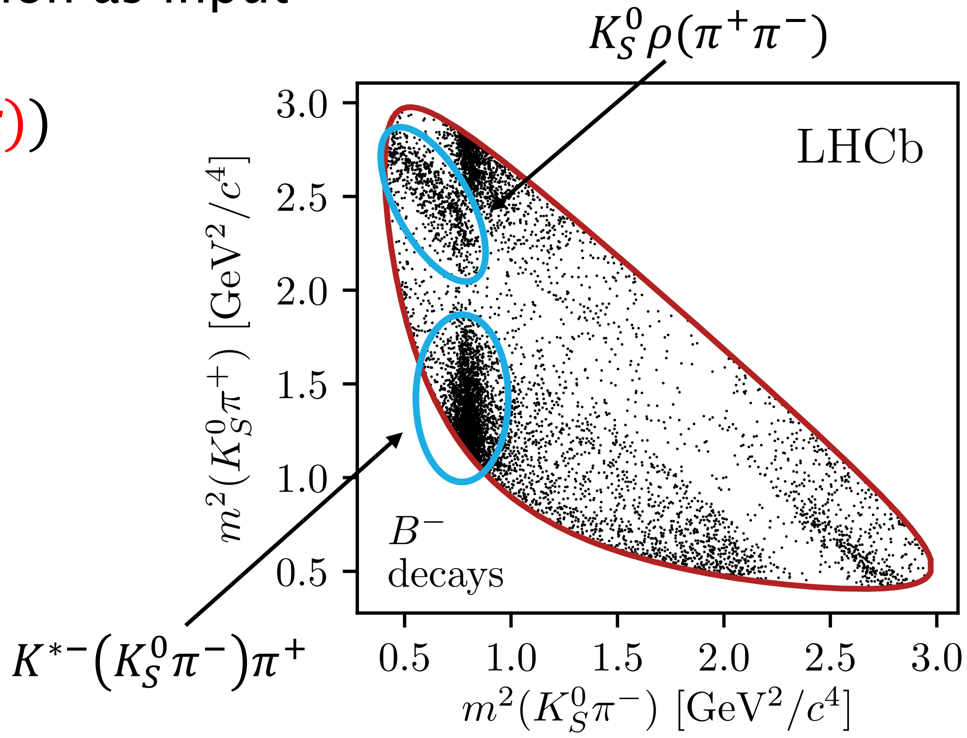


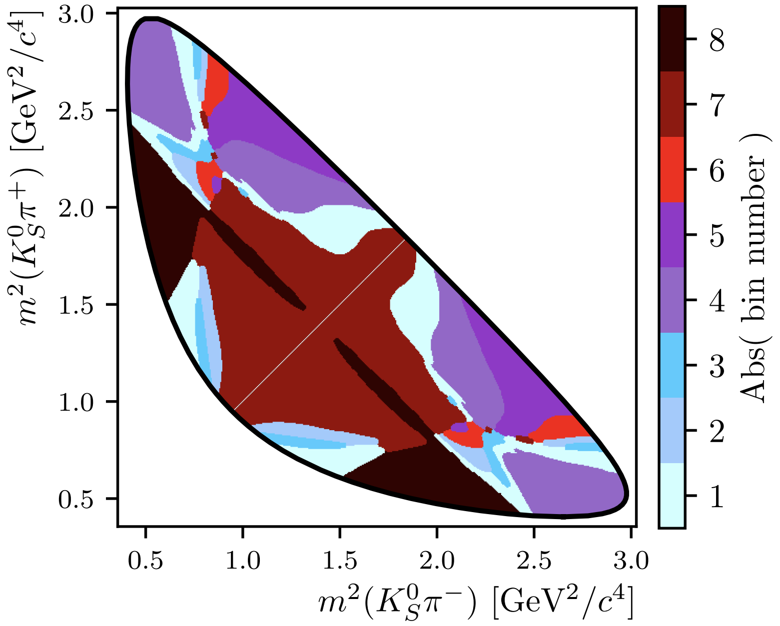
Figure from [6]

Model-independent measurements

[7] Phys. Rev. D 101, 112002
[8] Phys. Rev. D 102, 052008
[9] Phys. Rev. D 82, 112006
[10] https://doi.org/10.48550/arXiv.2309.05514

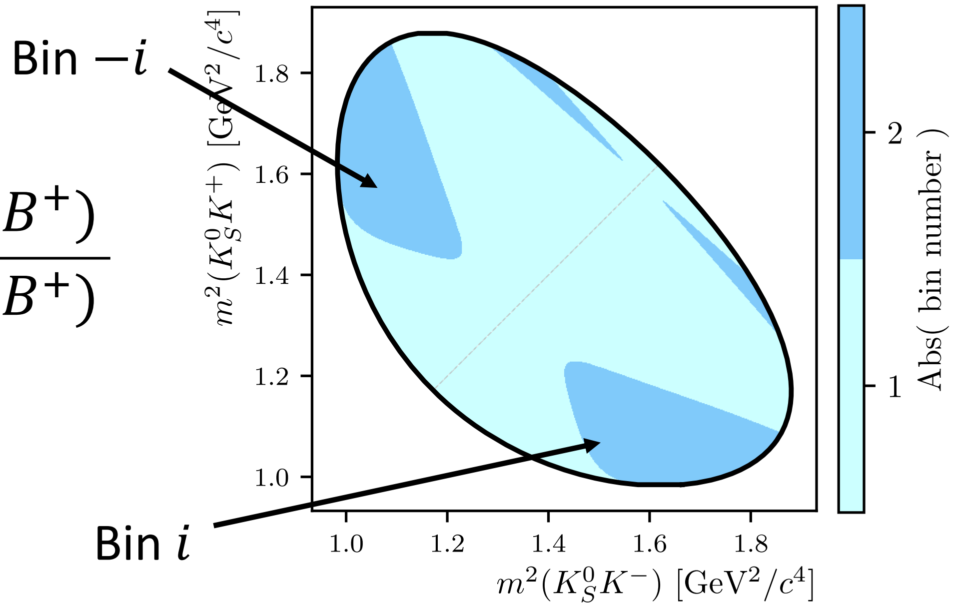
- Systematic uncertainties associated with amplitude models are non-trivial
- Instead strong-phase inputs determined in Dalitz plot bins at charm factories [7,8]
- Binning schemes chosen to optimize sensitivity to γ (isolate regions with similar δ_D) [9]

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



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

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



Figures from [10]

Experimental procedure

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

Normalisation factor

$$N_i(B^-) = \boldsymbol{h}^{\boldsymbol{B}^-}\left[F_i + (\boldsymbol{x}_-^2 + \boldsymbol{y}_-^2)F_{-i} + 2\sqrt{F_i F_{-i}}(c_i \boldsymbol{x}_- + s_i \boldsymbol{y}_-)\right]$$

$$N_i(B^+) = \boldsymbol{h}^{\boldsymbol{B}^+}\left[F_{-i} + (\boldsymbol{x}_+^2 + \boldsymbol{y}_+^2)F_i + 2\sqrt{F_i F_{-i}}(c_i \boldsymbol{x}_+ - s_i \boldsymbol{y}_+)\right]$$

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

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

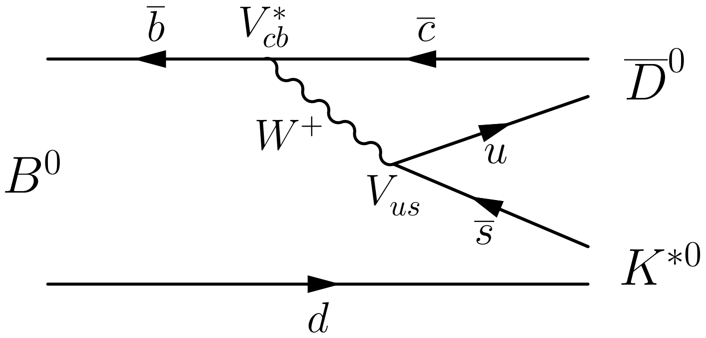
"CP violation observables"

[10]Measuring γ using $B^0 \to [K_S^0 h^+ h^-]_D K^{*0}$ decays

Link to paper on arXiv

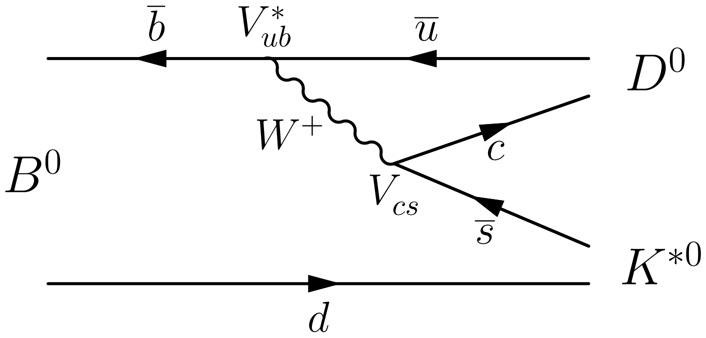
[11] Phys. Rev. D **94**, 079902, https://doi.org/10.1103/PhysRevD.94.079902

- 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 ($r_{B^0} \sim 3r_{B^\pm}$)



Favoured

Figures from [10]



Suppressed

$$N_i(\bar{B}^0) = h^{\bar{B}^0}[F_i + (x_-^2 + y_-^2)F_{-i} + 2\boldsymbol{\kappa}\sqrt{F_i F_{-i}}(c_i x_- + s_i y_-)]$$

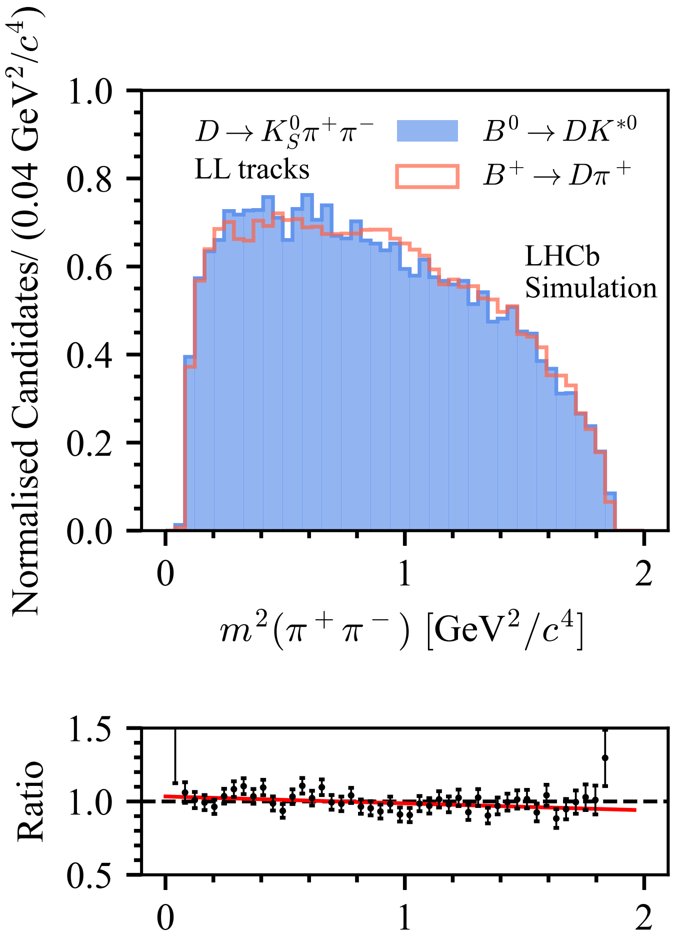
The F_i from $B^\pm \to D\pi^\pm$ decays [6] are used

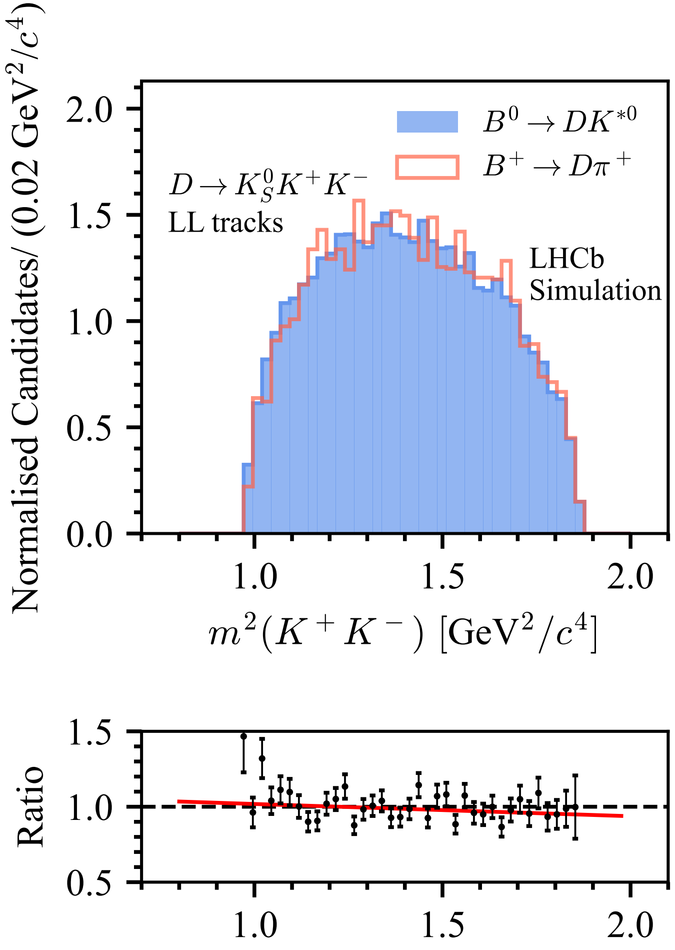
$\kappa = 0.958^{+0.005}_{-0.046}$ [11]

$B^0 \to DK^{*0}$: Dalitz plot efficiency profile

Link to paper on arXiv

- The DP efficiency profiles of $B^0 \to \left[K_S^0 h^+ h^-\right]_D K^{*0}$ and $B^+ \to \left[K_S^0 h^+ h^-\right]_D \pi^+$ decays are similar





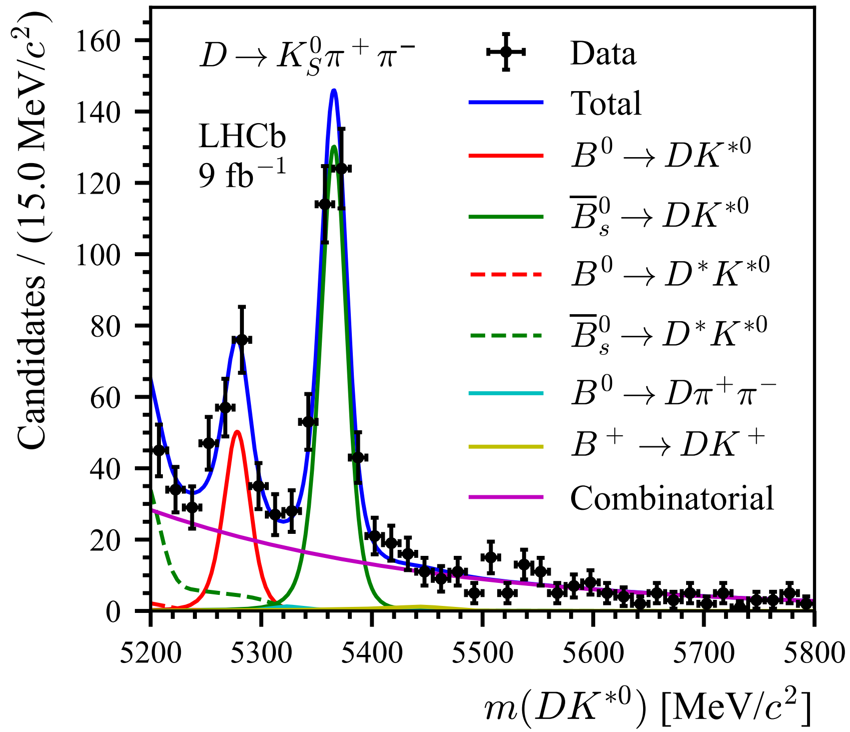
Figures from [10]

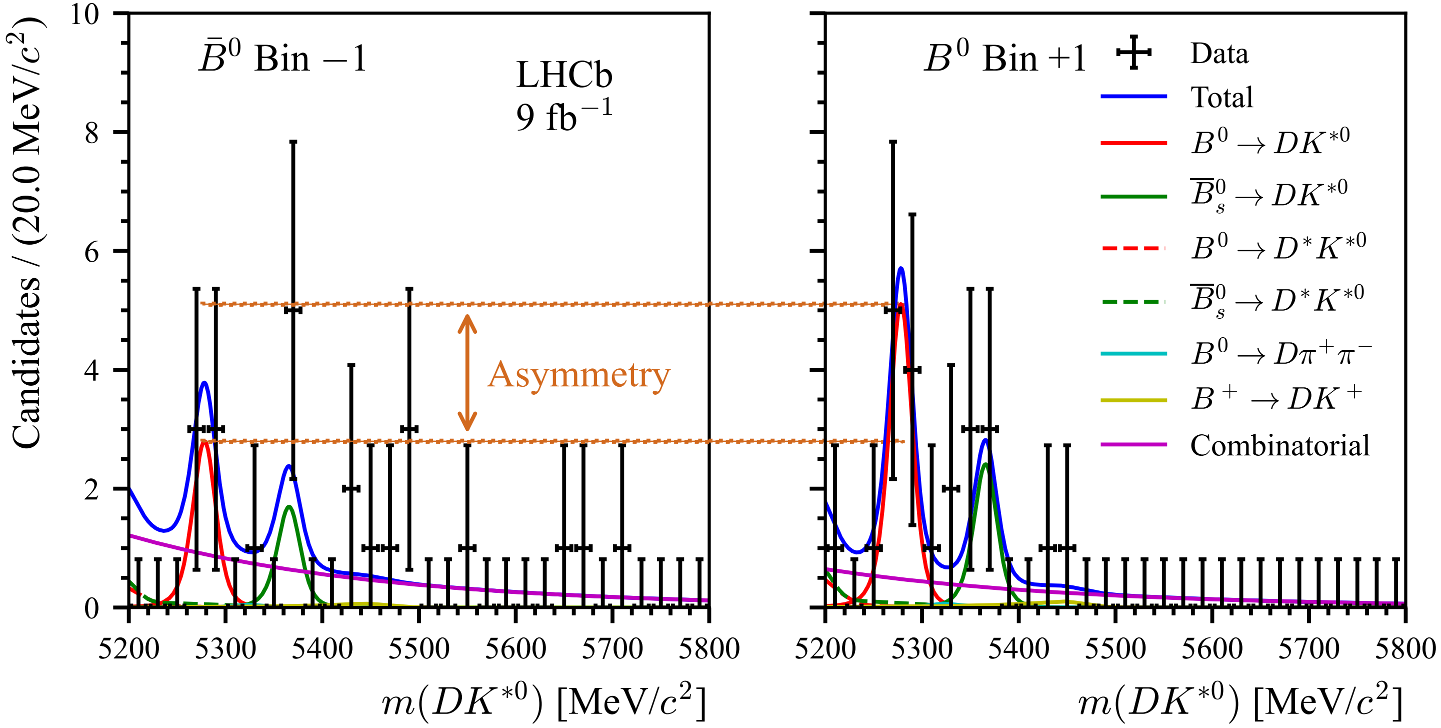
$B^0 \to DK^{*0}$: Invariant-mass fits

Link to paper on arXiv

- 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]



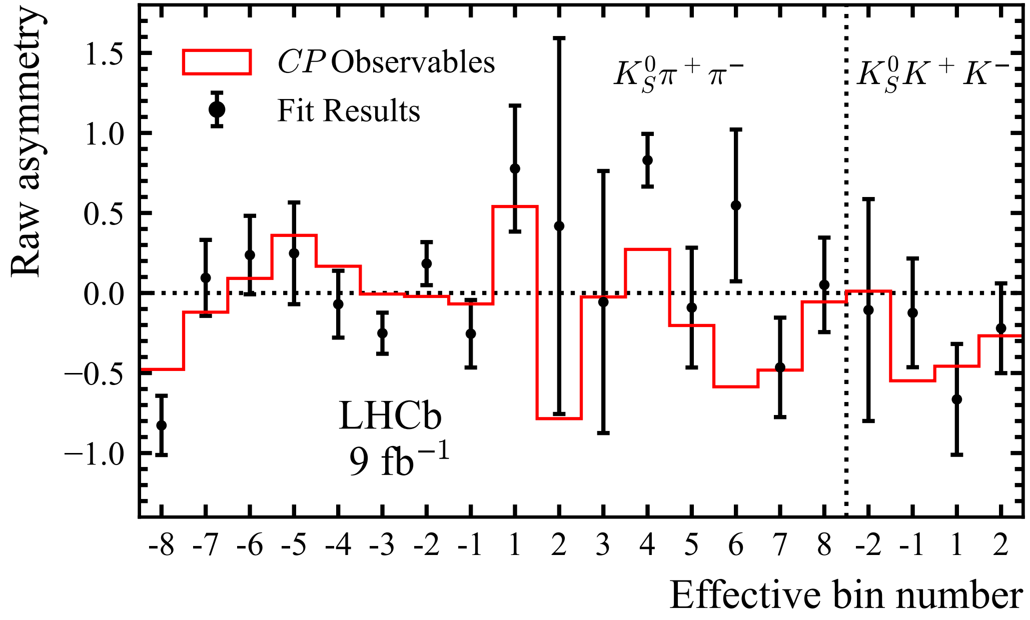


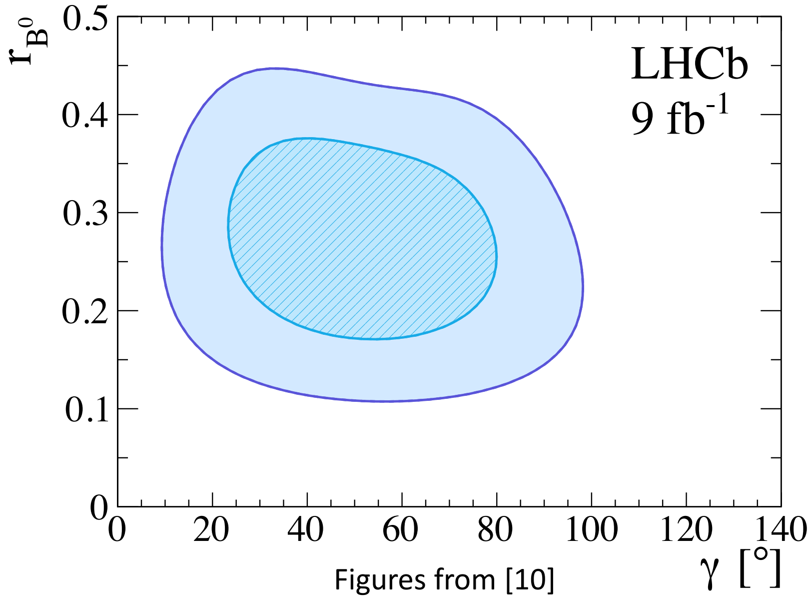
$B^0 \to DK^{*0}$: Results

Link to paper on arXiv

[12] *J. High Energ. Phys.* **2016**, 131 (2016). https://doi.org/10.1007/JHEP06(2016)131c

- Bins with large asymmetries enhance the sensitivity to γ
- Result useful in combination with measurements in $B^0 \to DK^{*0}$ decays with the ADS and GLW D-decay final states (see Seophine's talk)
- Not included in the LHCb combination yet
- Measurement supersedes Ref. [12]





Figures from [10]

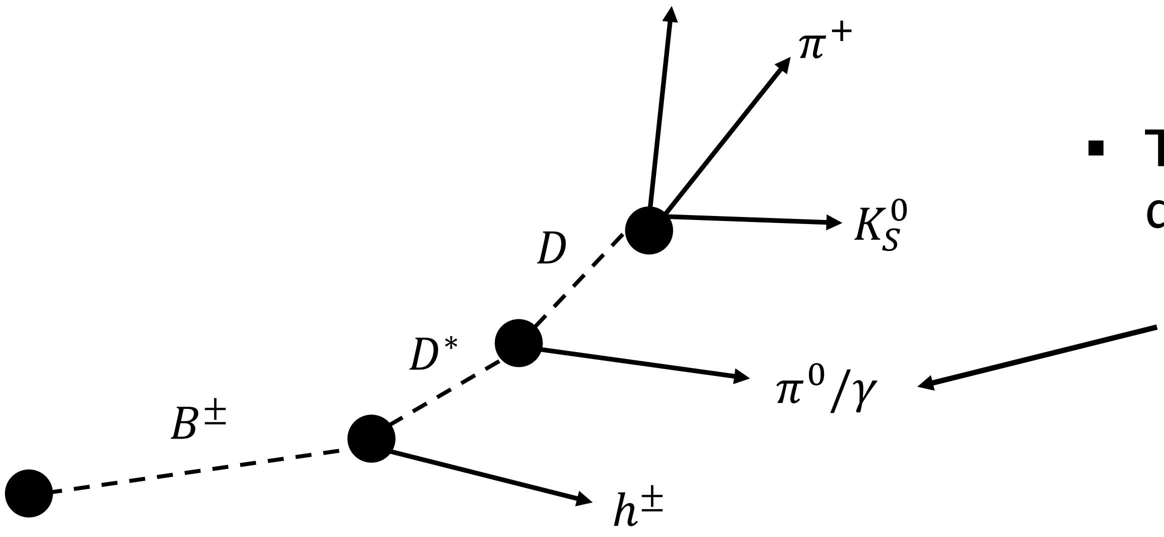
Reduces B^+/B^0 tension → $\gamma = (49^{+23}_{-18})^\circ$,

Consistent with expectations → $r_{B^0} = 0.271^{+0.068}_{-0.066}$,

$\delta_{B^0} = (236^{+19}_{-21})^\circ$.

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

[13] LHCb-PAPER-2023-012 (in preparation)
[14] LHCb-PAPER-2023-029 (in preparation)



- **Two separate measurements** with the same decay chain but different techniques
  - The neutral particle can be reconstructed [13] or not [14]
  - Negligible overlap between the analyses

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

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

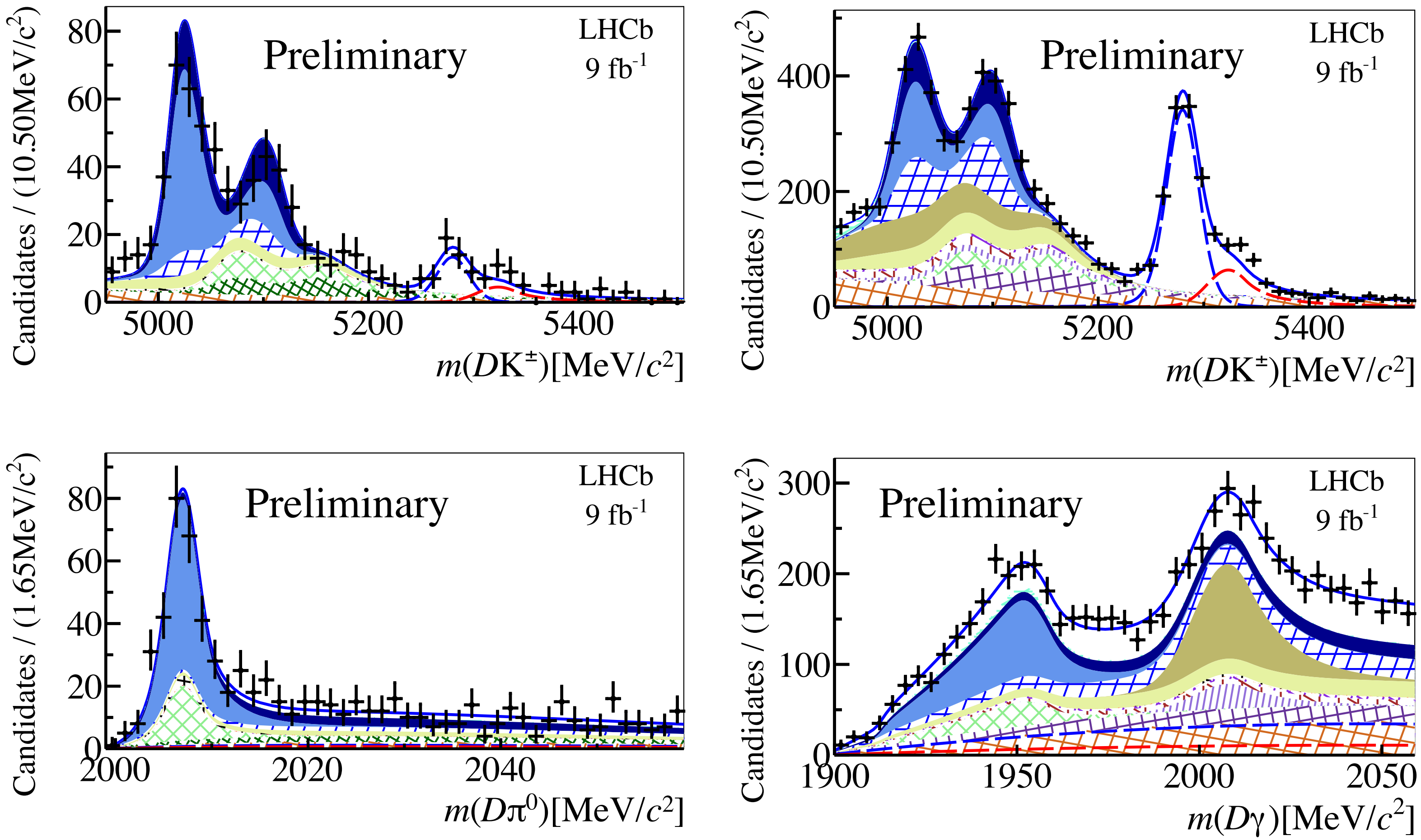
$$N_i(B^-) = h^{B^-}[F_i + (x_-^2 + y_-^2)F_{-i} \pm 2\sqrt{F_i F_{-i}}(c_i x_- + s_i y_-)]$$

Fully reconstructed $B^{\pm}\rightarrow D^{*}K^{\pm}$

LHCb-PAPER-2023-012 (in preparation)

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

Integrated fit ⟶ Binned fit ⟶ CP observables



Figures from [13]

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

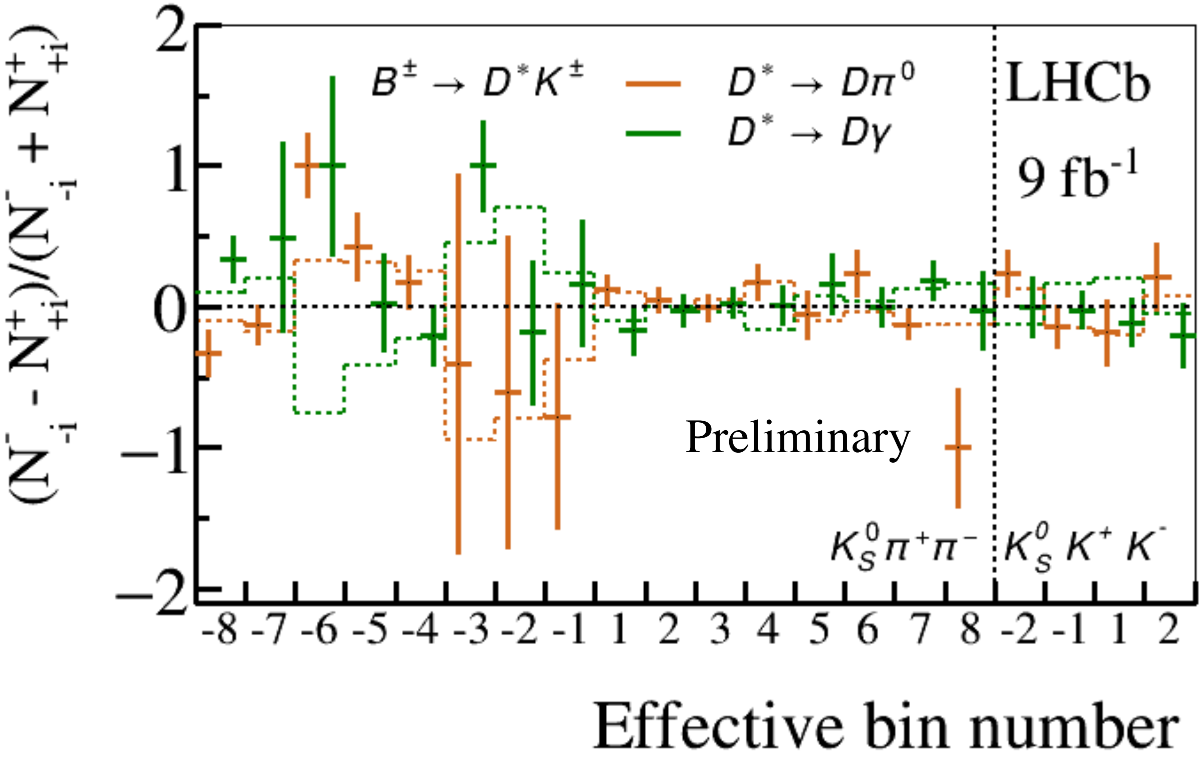
LHCb-PAPER-2023-012 (in preparation)

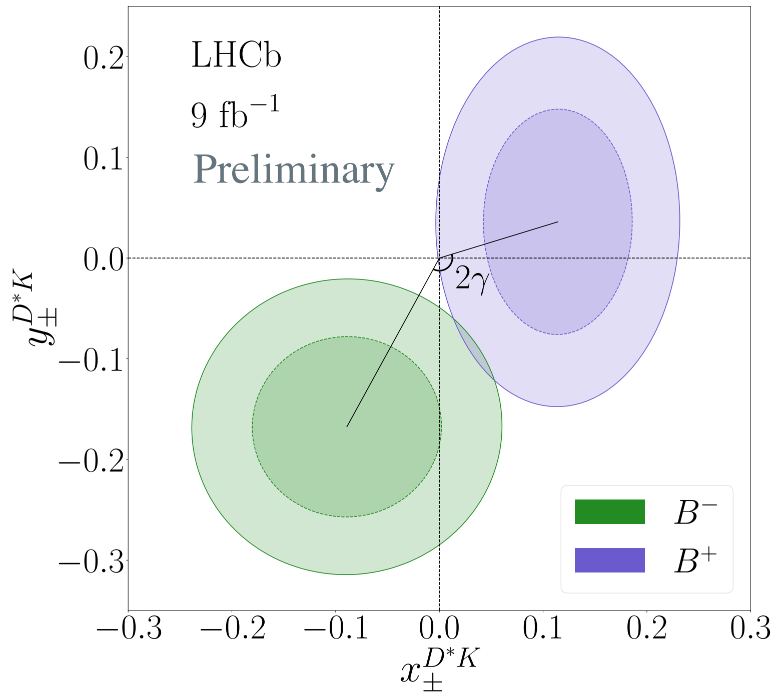
- $\mathcal{A}(\pi^0) = -\mathcal{A}(\gamma)$ observed
- γ consistent with combination

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

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

$$\delta_B^{D^*K} = (311 \pm 15)^{\circ}$$





Figures from [13]

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

LHCb-PAPER-2023-029 (in preparation)

- Blue filled shapes corresponds to signal

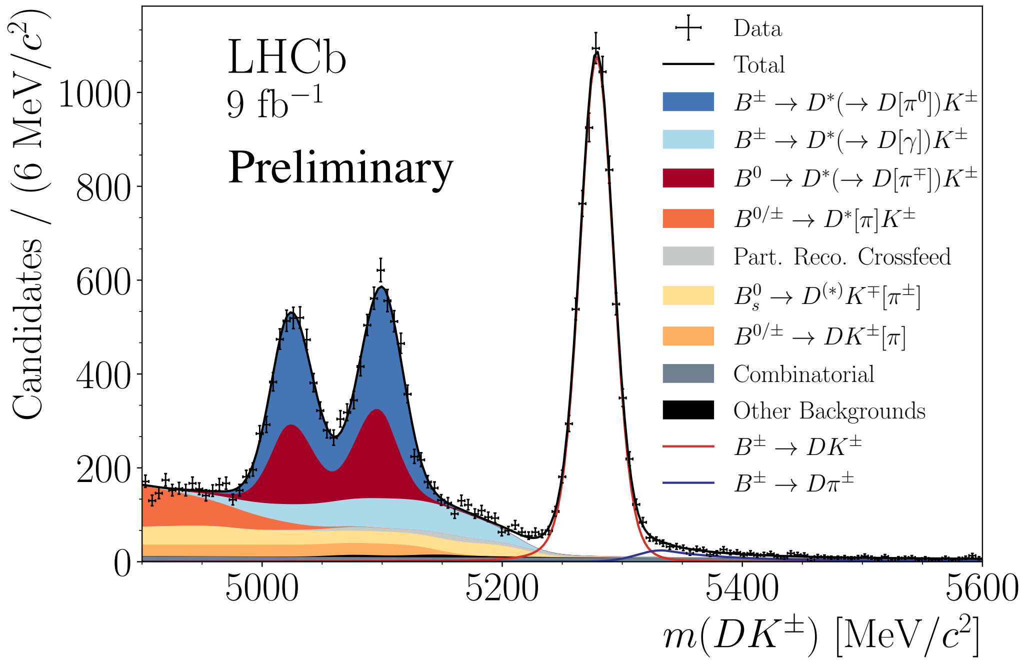
Integrated fit → Binned fit → CP observables

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

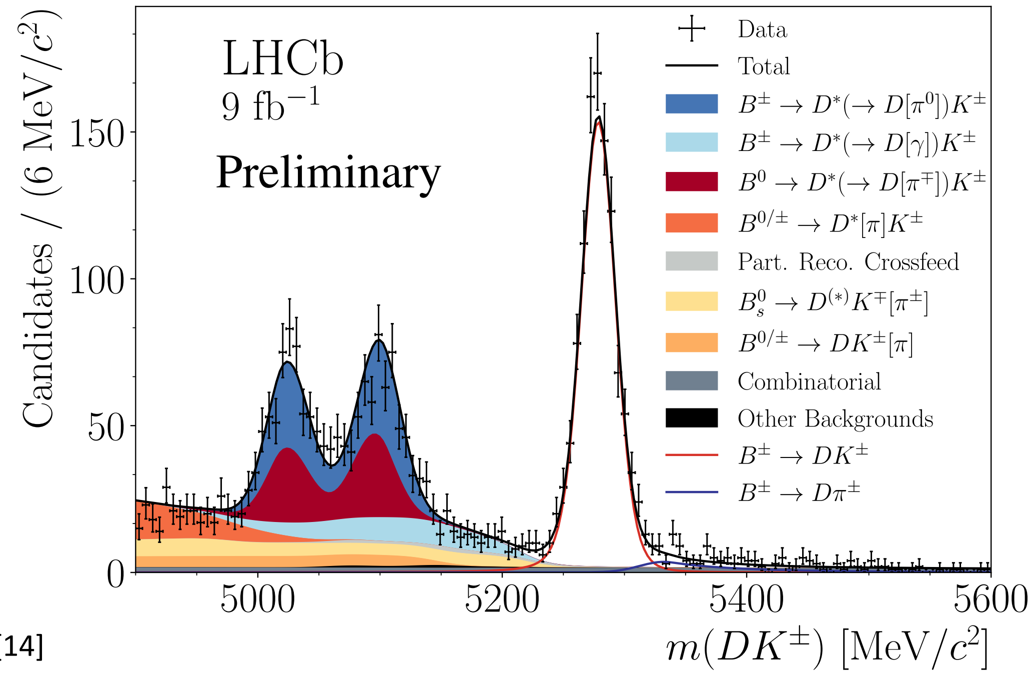
NEW

- Knowledge of the backgrounds is a large systematic uncertainty

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



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



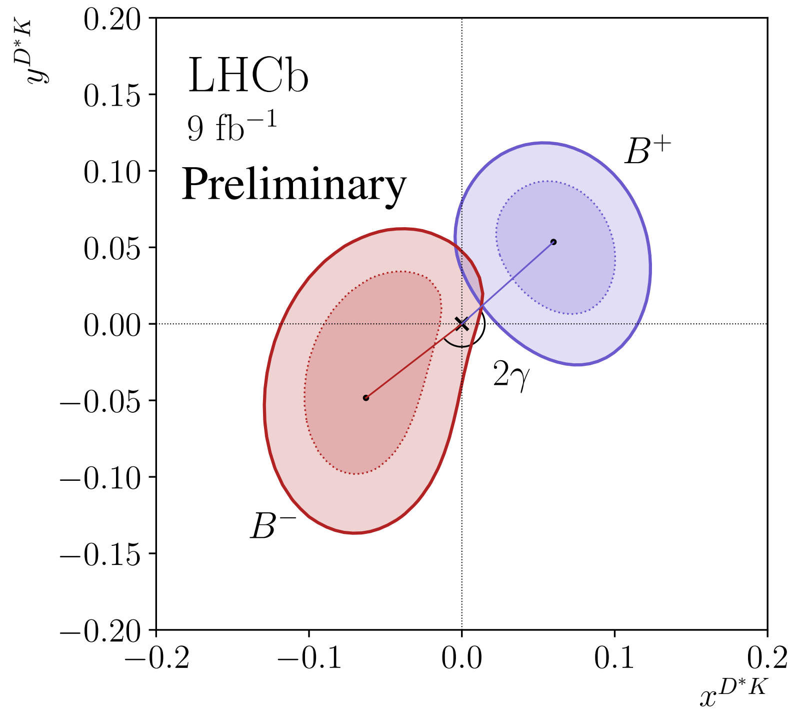
Figures from [14]

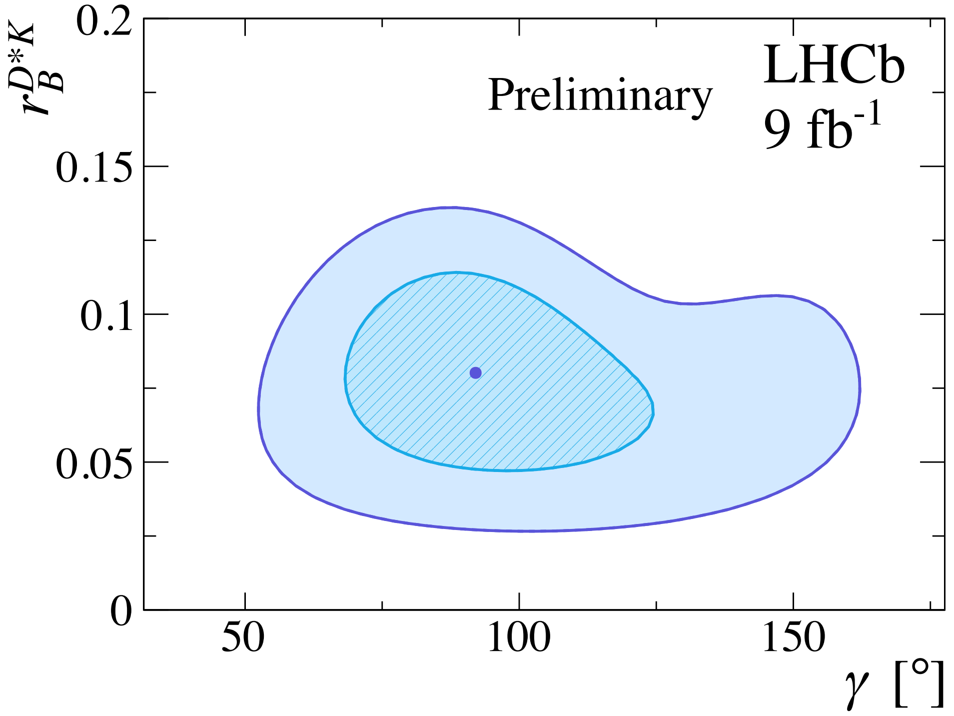
Partially reconstructed $B^{\pm} \rightarrow D^{*}K^{\pm}$

LHCb-PAPER-2023-029 (in preparation)

NEW

- 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 $\Delta\gamma \propto 1/r_{B}^{D^{*}K}$





Figures from [14]

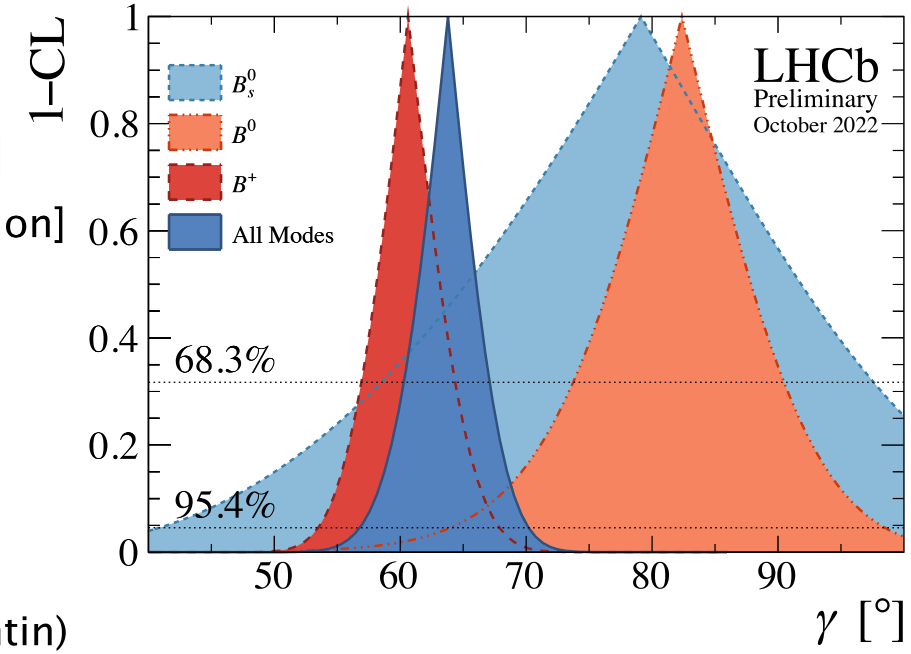
$$\gamma = (92^{+21}_{-17})^{\circ}$$

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

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

Summary

- Presented combination of direct γ measurements at LHCb [LHCb-CONF-2022-003]
- Presented 3 new LHCb γ measurements, all of which use the $D \to K_S^0 h^+ h^-$ modes
  - $B^0 \to DK^{*0}$ [https://doi.org/10.48550/arXiv.2309.05514]
  - $B^\pm \to D^* K^\pm$ (fully reconstructed) [LHCb-PAPER-2023-012, in preparation]
  - $B^\pm \to D^* K^\pm$ (partially reconstructed) [LHCb-PAPER-023-029, in preparation]

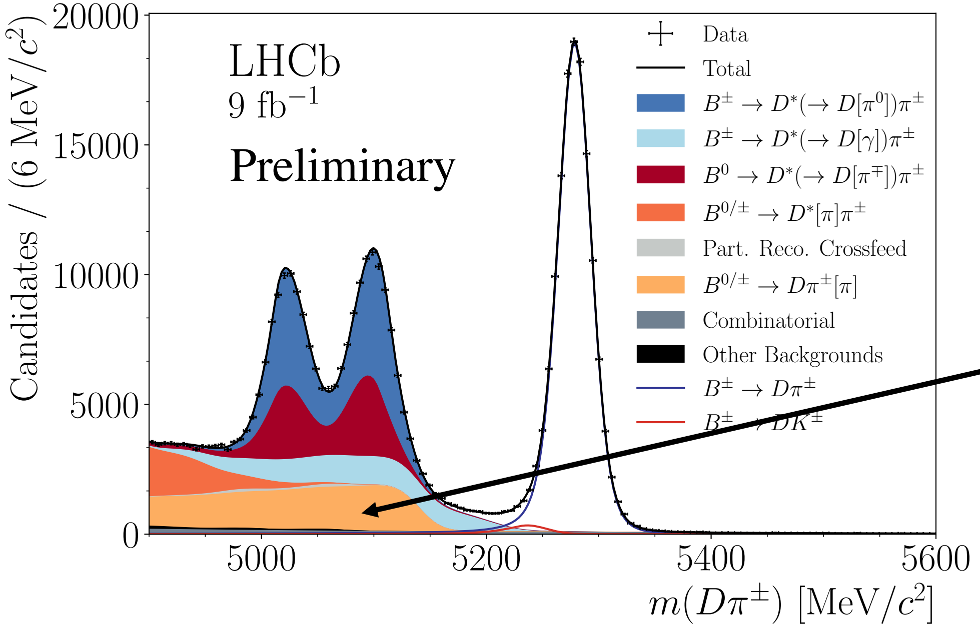


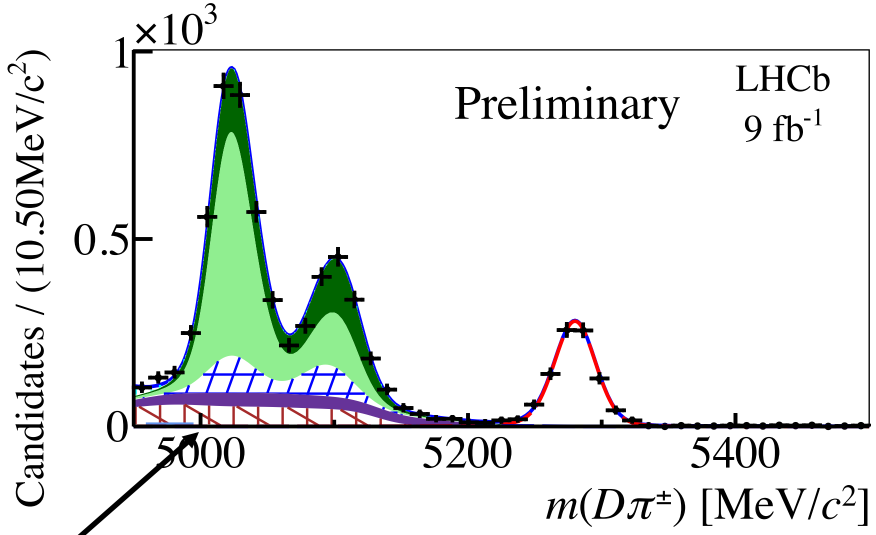
- Other LHCb γ and charm talks at CKM:
  - New results of gamma measurements in ADS, GLW–like decays at LHCb (Seophine)
  - Handling correlated systematic errors in γ measurements combination among experiments (Alex)
  - Decay–time dependent measurements of the CKM angle γ at LHCb (Quentin)
  - Mixing and indirect CPV in charm decays at LHCb (Federico)
  - Direct CPV in D mesons decays at LHCb (Jolanta)

Backup: Correlation between the fully and partially reconstructed measurements

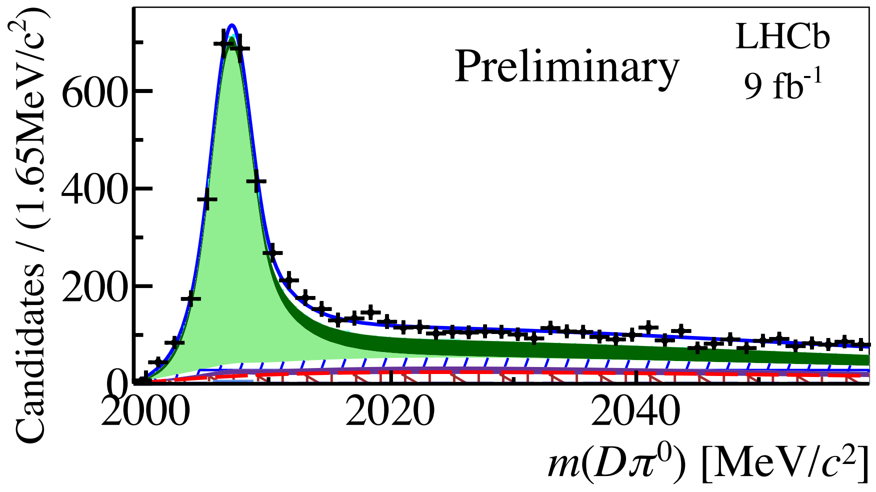
- Signal yield overlap: 17%
- Purity effect in fully reconstructed: 42%
- Purity effect in partially reconstructed: 53%
- Total: <4%

Plots display invariant masses in $B^+ \to D\pi^+$ mode

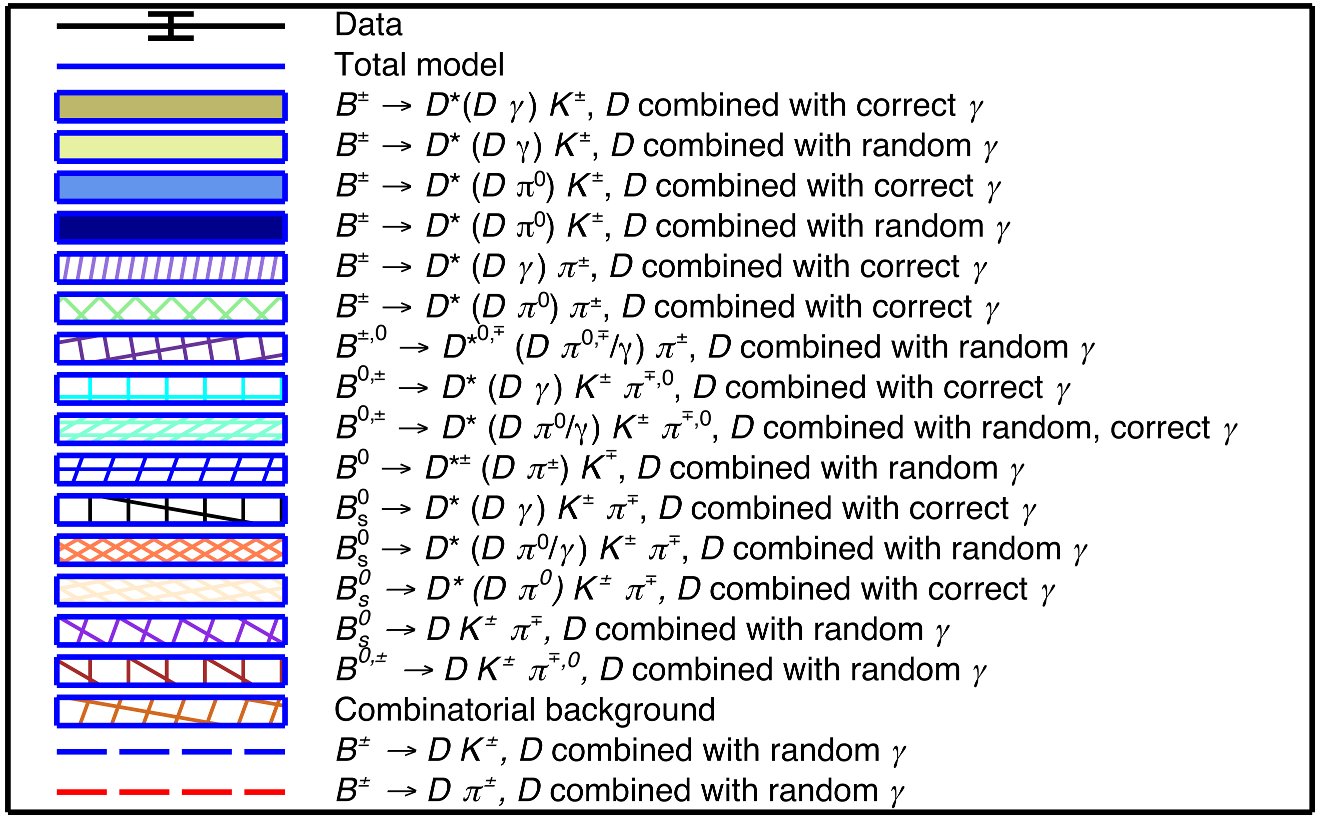


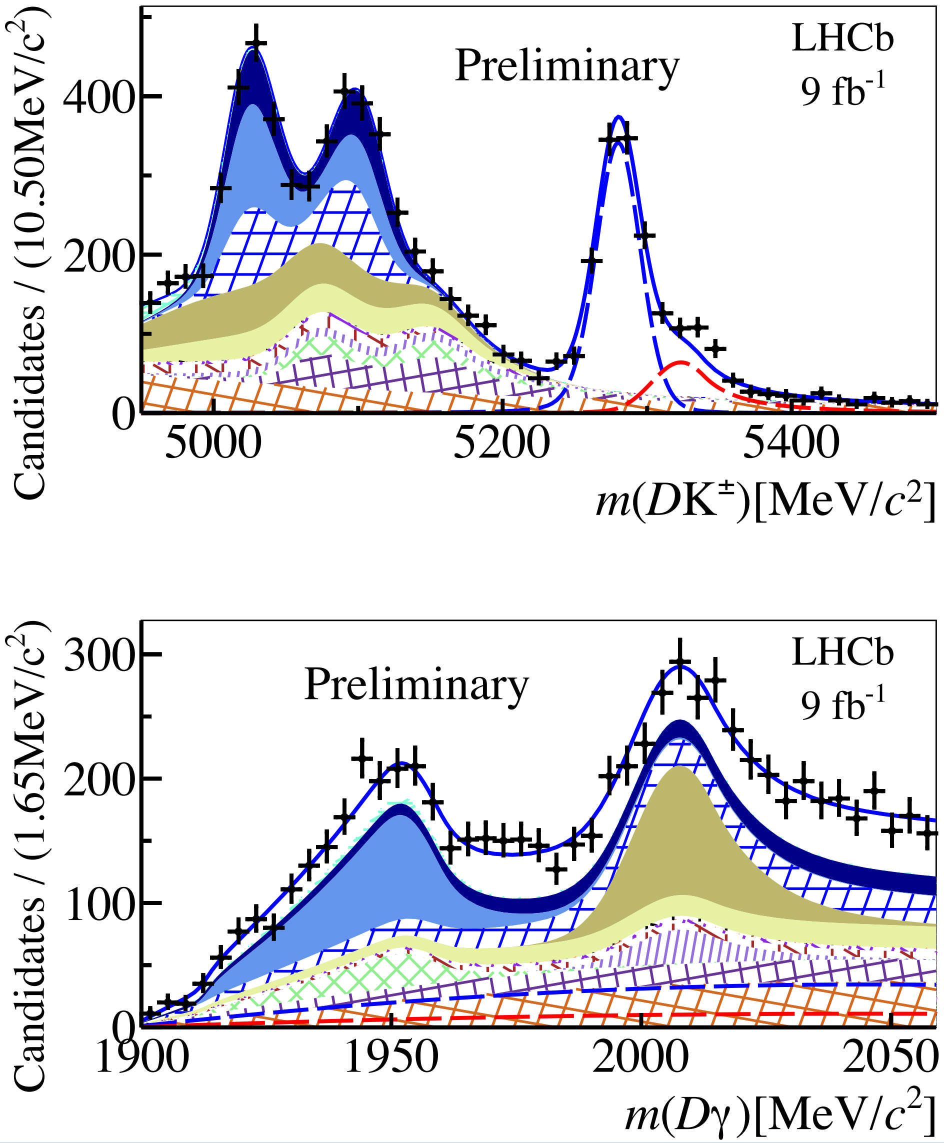


$B \to D\pi + \pi^0$



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





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