Measurements of CKM angle γ in LHCb

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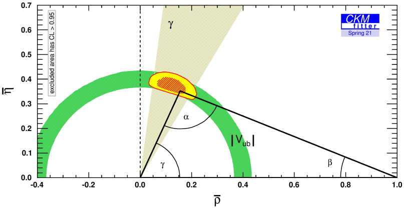
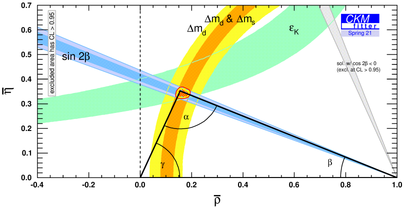
Introduction to γ and *CP* violation

- CPV in SM is described by the Unitary Triangle, with angles α, β, γ
- The angle $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is very important:
  1. Negligible theoretical uncertainties: Ideal SM benchmark
  2. Accessible at tree level: Indirectly probe New Physics that enter loops
  3. Compare with a global CKM fit: Is the Unitary Triangle a triangle?



(a) Tree level: $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^\circ$

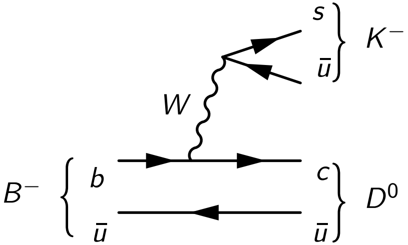


(b) Loop level: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

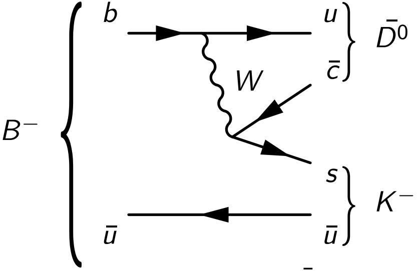
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



Favoured $B^- \to D^0 K^-$



Suppressed $B^- \to \bar{D}^0 K^-$

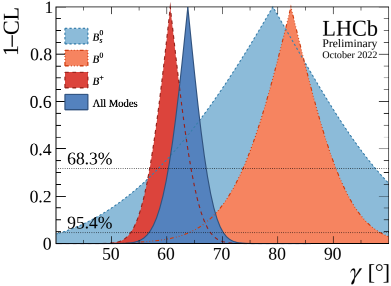
- Superposition of D^0 and $\bar{D}^0$
  - Consider $D^0/\bar{D}^0$ decays to the same final state, such as $D \to K^+K^-$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)}\mathcal{A}_{\bar{D}^0}\right)$$
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

Summary of LHCb γ measurements

Our most precise knowledge of γ comes from the combination of γ and charm mixing parameters

LHCb-CONF-2022-003



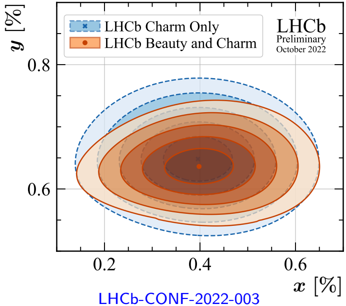
LHCb-CONF-2022-003

Most precise determination from a single experiment: $\gamma = (63.8^{+3.5}_{-3.7})^\circ$
Contributions from the $B^\pm$ dominate, but all measurements are consistent

Summary of LHCb γ measurements

Our most precise knowledge of γ comes from the combination of γ and charm mixing parameters

LHCb-CONF-2022-003

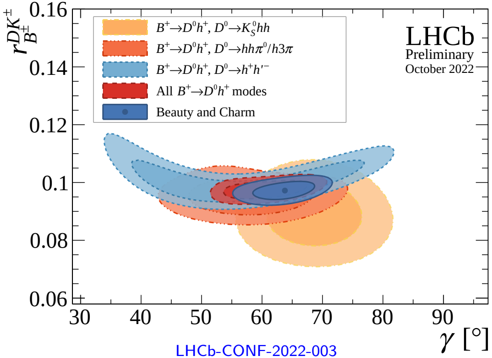


LHCb-CONF-2022-003

Mixing effects to γ measurements are approaching the statistical sensitivity

The simultaneous fit improves the knowledge of y significantly

Summary of LHCb γ measurements

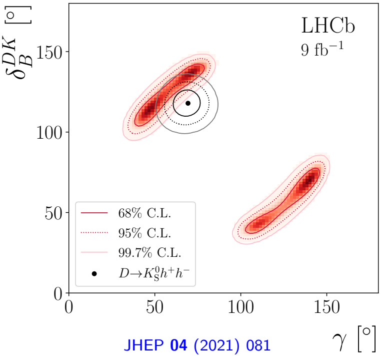


LHCb-CONF-2022-003

The γ combination is mainly driven by $B^\pm \to Dh^\pm$, where:

- $D \to K^+K^-$, $\pi^+\pi^-$, $K^\mp\pi^\pm$
- $D \to K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$
- $D \to K^\mp\pi^\pm\pi^-\pi^+$

Summary of LHCb γ measurements



JHEP **04** (2021) 081

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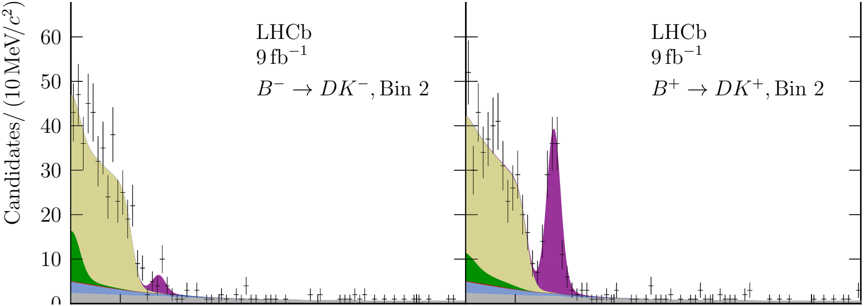
Summary of LHCb γ measurements



arXiv:2209.03692

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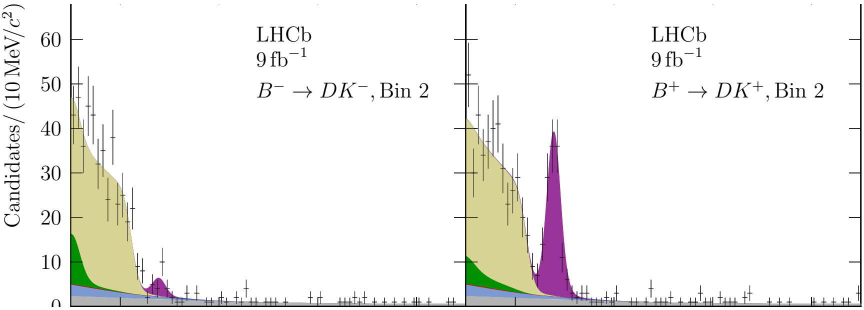
$\rightarrow$ $D \to K^\mp\pi^\pm\pi^-\pi^+$

Summary of LHCb γ measurements



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The γ combination is mainly driven by $B^\pm \to Dh^\pm$, where:

- $D \to K^+K^-$, $\pi^+\pi^-$, $K^\mp\pi^\pm$
- $D \to K^0_S\pi^+\pi^-$, $K^0_SK^+K^-$
- $D \to K^\mp\pi^\pm\pi^-\pi^+$

These multi-body decays are analysed in local regions of phase space

Multi-body D decays

This talk: Focus on multi-body D decays, where interference effects vary across phase space

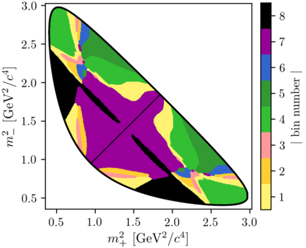
- Strong-phase difference δ_D is a function of phase space
- Compare yields of B^+ and B^- and determine the asymmetry in local phase space regions

$$\begin{tikzcd}
 & D^0K^- \arrow[dr, bend left, "\mathcal{A}_{D^0}(\Phi)"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0K^- \arrow[ur, bend right, "\mathcal{A}_{\bar{D}^0}(\Phi)"'] &
\end{tikzcd}$$

$$|\mathcal{A}(B^-)|^2 \propto |\mathcal{A}_{D^0}(\Phi)|^2 + r_B^2|\mathcal{A}_{\bar{D}^0}(\Phi)|^2 + 2r_B|\mathcal{A}_{D^0}(\Phi)||\mathcal{A}_{\bar{D}^0}(\Phi)|\cos(\delta_B - \gamma + \delta_D)$$

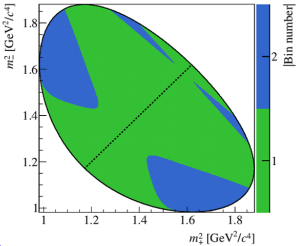
Multi-body D decays

- Interpretation of γ from the multi-body charm decays require external inputs of the charm strong-phase differences
- The three-body decays $D \to K_S^0 h^+ h^-$ have been studied extensively, using an optimised phase-space binning:
  - CLEO Phys. Rev. **D82** (2010) 112006
  - BESIII Phys. Rev. **D101** (2020) 112002
- With charm inputs from CLEO and BESIII, the measurement of γ becomes model independent



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

JHEP **02** (2021) 0169

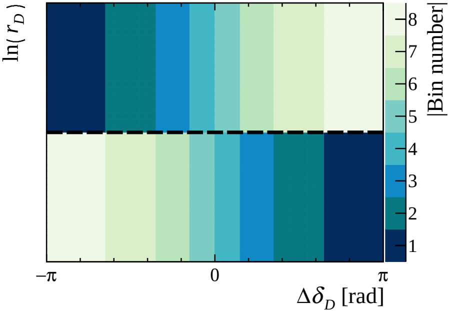


$K_S^0K^+K^-$

Can also consider more complicated multi-body decays:

$$B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$$

- Phase space is 5-dimensional...
- ...use an amplitude model to determine an efficient binning scheme!

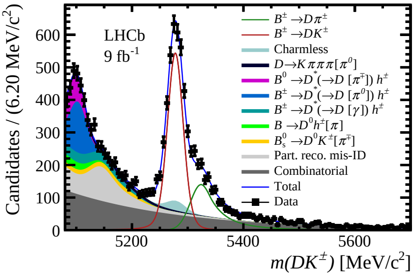


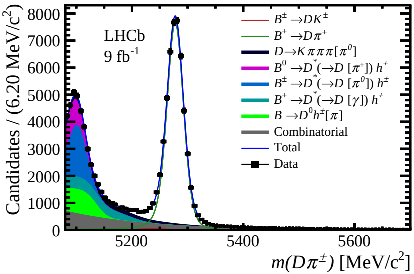
Bins $i < 0$ on top, $i > 0$ below

Eur. Phys. J. C **83**, 547 (2023)

Phase-space binned $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

Fully charged final state $\Longrightarrow$ Highly suitable for LHCb

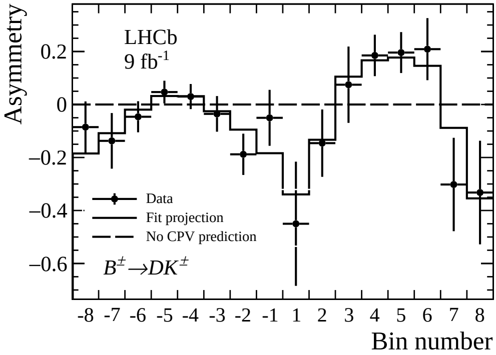




Eur. Phys. J. C **83**, 547 (2023)

- $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ signal yield:
  - $B^{\pm} \to DK^{\pm}$: 3026 ± 38
  - $B^{\pm} \to D\pi^{\pm}$: 44349 ± 218

Phase-space binned $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$



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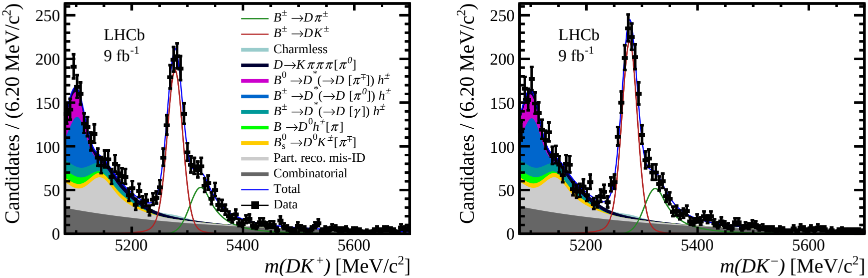
- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong-phase differences across phase space
- While the interpretation of γ require charm inputs, the observed bin asymmetries are model independent

Phase-space integrated $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

Additionally, one can measure the phase-space integrated asymmetries and measure additional *CP*-violating observables



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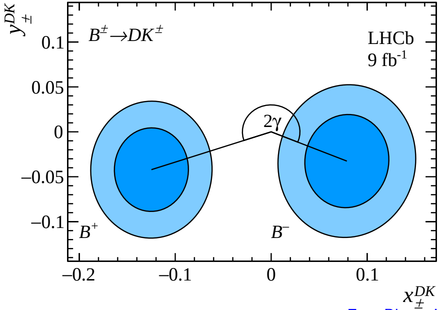
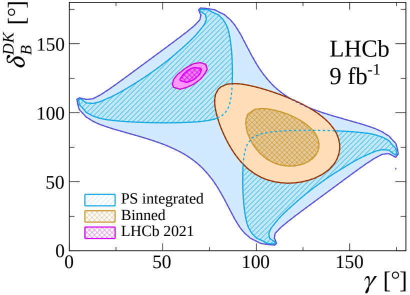
More B^- candidates because $D^0 \to K^+K^-\pi^+\pi^-$ is predominantly <u>*CP*-even</u> (Phys. Rev. D **107** 032009)

From the phase-space binned asymmetries, we obtain:

- $\gamma = (116^{+12}_{-14})^{\circ}$
- $\delta_D^{DK} = (81^{+12}_{-14})^{\circ}$
- $r_B^{DK} = 0.110^{+0.020}_{-0.020}$





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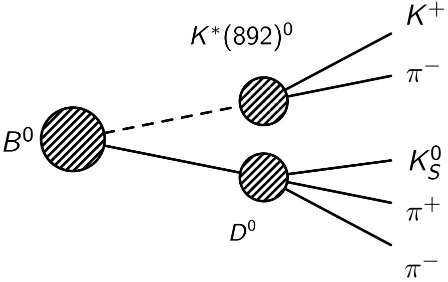
These results are model dependent, and will be updated once BESIII strong-phase inputs are available

Neutral B decays

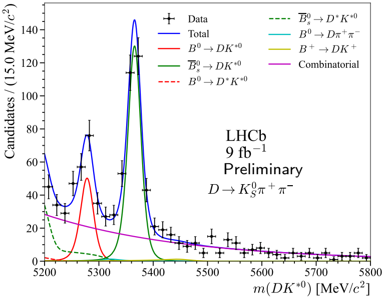
This method works analogously with neutral B decays:

LHCb-PAPER-2023-009 (in preparation) New results!

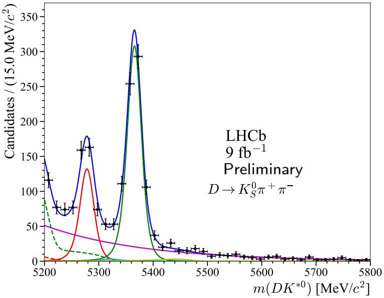


$$B^0 \to (K_S^0 h^+ h^-)_D (K^+\pi^-)_{K^*}$$

This results supersedes that of JHEP **08** (2016) 137



LL

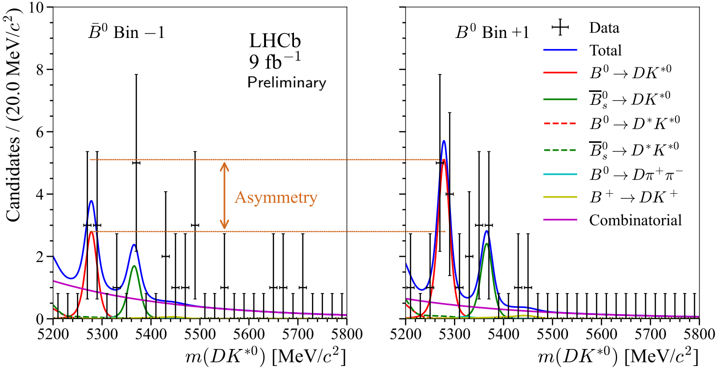


DD

LHCb-PAPER-2023-009

- Two separate selections of K^0_S:
  - LL (long tracks): K^0_S decays in the VELO
  - DD (downstream tracks): K^0_S decays downstream of the VELO
- $B^0 \to DK^{*0}$ candidates with $D \to K^0_S\pi^+\pi^-$ ($D \to K^0_S K^+K^-$):
  - LL: 102 ± 17 (12 ± 6)
  - DD: 288 ± 25 (32 ± 8)

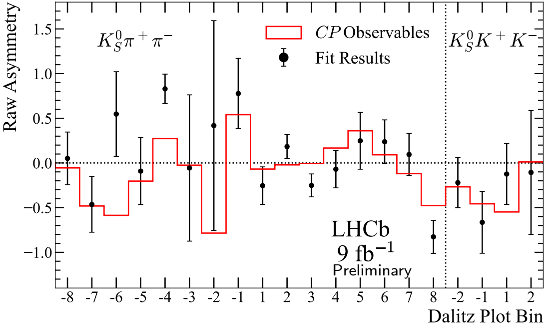
Neutral B decays



LHCb-PAPER-2023-009

- Non-zero bin asymmetries are observed:
  - Large asymmetries are seen between B^0 ($\bar{B}^0$) bin pairs
  - No CPV is expected in B_s^0 decays, and no such CPV is observed

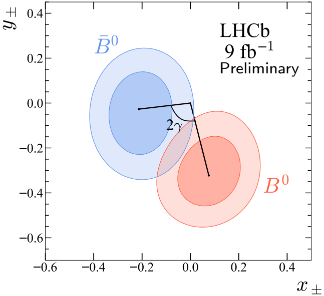
Neutral B decays

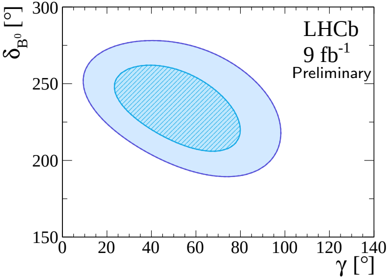


LHCb-PAPER-2023-009

- Non-zero bin asymmetries are observed:
    - Large asymmetries are seen between B^0 ($\bar{B}^0$) bin pairs
    - No CPV is expected in B_s^0 decays, and no such CPV is observed
- Asymmetries differ in size and magnitude across bins of phase space

Neutral B decays





LHCb-PAPER-2023-009

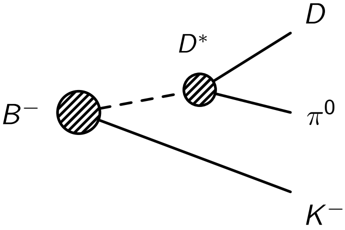
- Measured CP-violating observables:

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

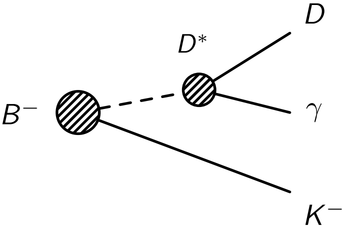
- Measured value of γ is consistent with world average:
  - $\gamma = (49 \pm 20)^\circ$
  - $\delta_{B^0} = (236 \pm 19)^\circ$
  - $r_{B^0} = 0.27 \pm 0.07$

$B^- \to D^* K^-$ decays are also a powerful probe of CPV:

LHCb-PAPER-2023-012 (in preparation) New results!



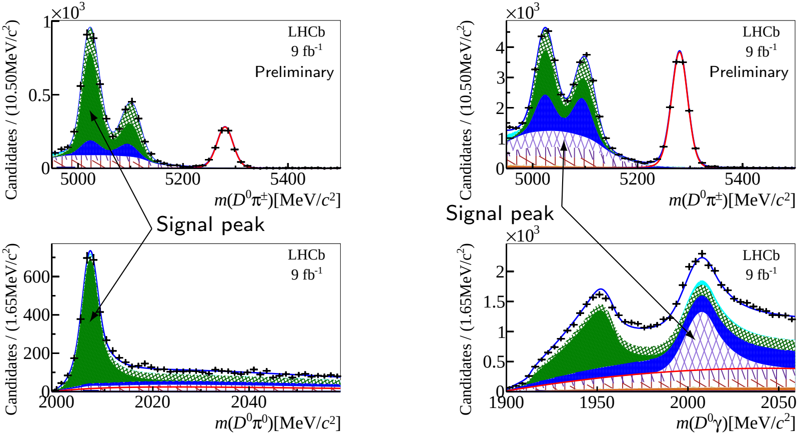
$B^- \to [D\pi^0]_{D^*} K^-$



$B^- \to [D\gamma]_{D^*} K^-$

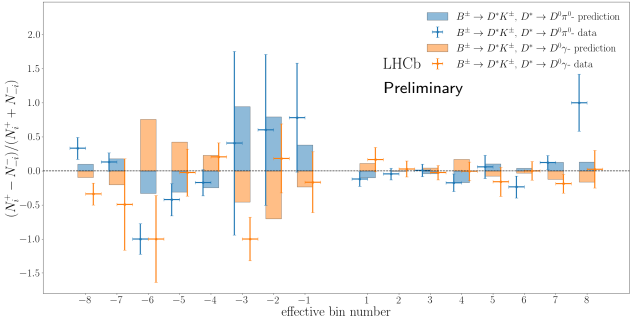
$$\mathcal{A}(B^-) \propto \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0) \quad \mathcal{A}(B^-) \propto \mathcal{A}(D^0) - r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$

The relative sign swap, due to the phase difference of π between π^0 and γ, results in opposite CP asymmetries between $D^* \to D\pi^0$ and $D^* \to D\gamma$



$D^* \to D\pi^0$ **(a)** $D^* \to D\gamma$

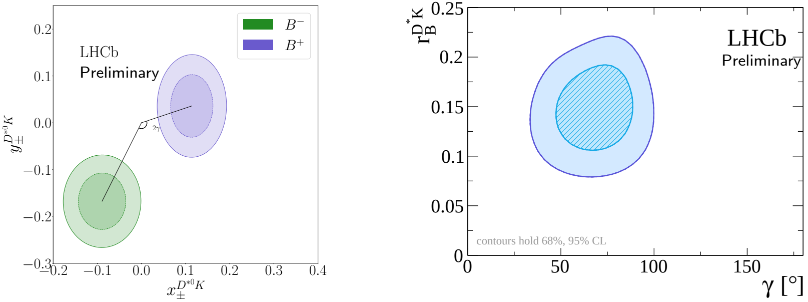
LHCb-PAPER-2023-012



LHCb-PAPER-2023-012

- Good agreement between individual bin asymmetries and the combined *CP* fit
- Bin asymmetries between $D^* \to D\pi^0$ and $D^* \to D\gamma$ are generally <u>opposite</u> in sign

B decays to excited D^* final states



LHCb-PAPER-2023-012

These results provide strong constraints on γ:

- $\gamma = (69 \pm 14)^\circ$
- $\delta_B^{D^*K} = (311 \pm 15)^\circ$
- $r_B^{D^*K} = 0.15 \pm 0.03$

Summary and future prospects

In summary:

1. LHCb performed several measurements of γ, using a set of complementary B and $D^{(*)}$ decay combinations
2. Phase-space binned analyses using the golden mode $D \to K_S^0\pi^+\pi^-$ provide the most powerful constraints for our γ combination
3. A binned measurement with the channel $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ has been performed for the first time
    - Need external inputs for charm strong-phases from BESIII
4. I have also presented two new model-independent measurements:
    - $B^0 \to DK^{*0}$ with $K^{*0} \to K^+\pi^-$
    - $B^\pm \to D^* h^\pm$ with $D^* \to D\pi^0$ and $D\gamma$

Summary and future prospects

Future prospects:

1. The measurements I have presented today will make valuable improvements to future γ combinations
2. Measurements are still dominated by statistical uncertainties, and are expected to reduce significantly at the end of Run 3
3. We expect more time-dependent results, such as $B_s^0 \to D_s^- K^+$ with Run 2, that will be interesting to compare with results from $B^\pm/B^0$

Thanks for your attention!