# Measurements of CKM angle $\gamma$ in LHCb

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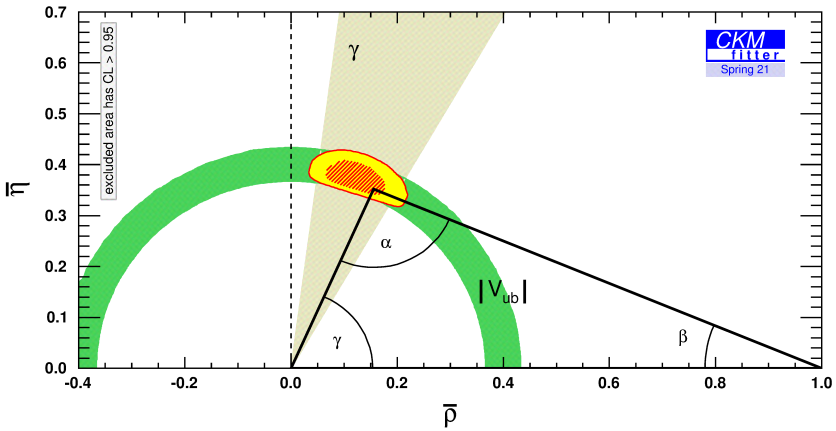
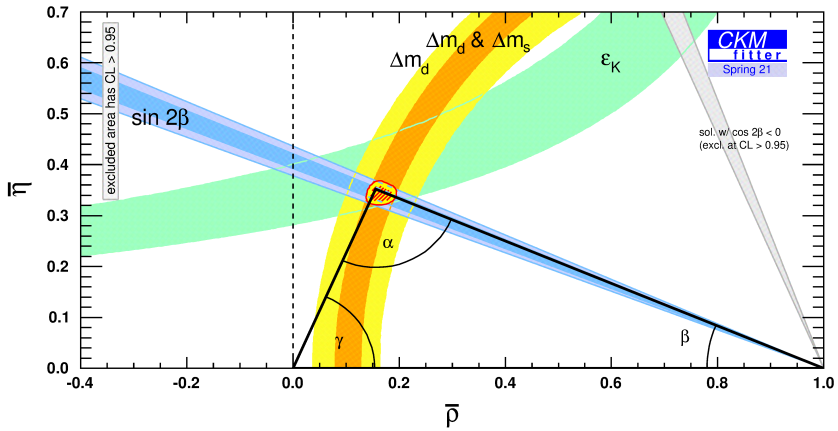
# Introduction to $\gamma$ and *CP* violation

- CPV in SM is described by the Unitary Triangle, with angles $\alpha$, $\beta$, $\gamma$
- 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: $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^\circ$

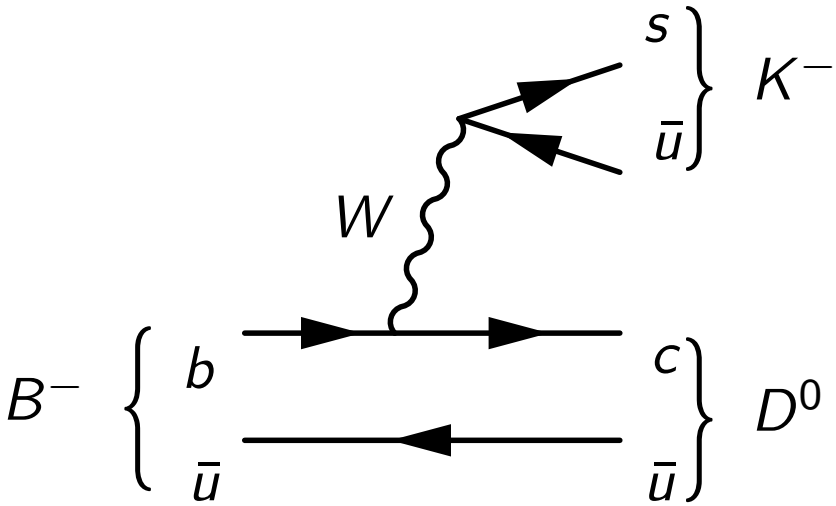



**(b)** Loop level: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

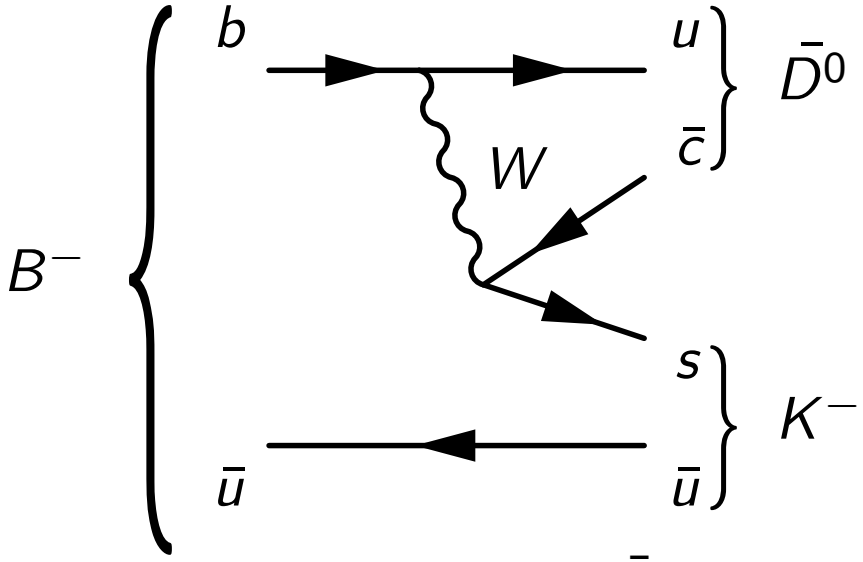
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

# Sensitivity through interference

Measure $\gamma$ 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 $\gamma$

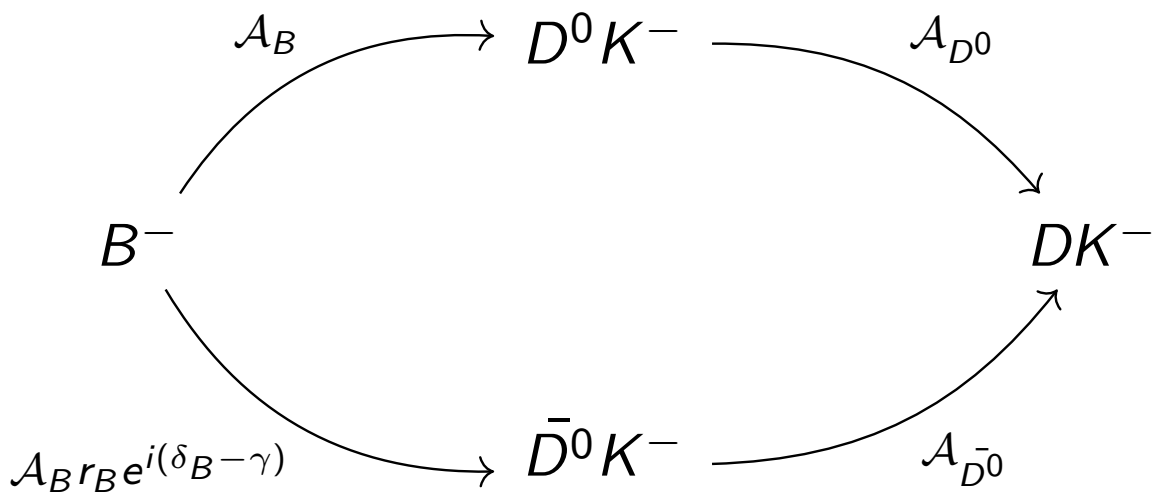
$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)}\mathcal{A}_{\bar{D}^0}\right)$$

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

# Multi-body $D$ decays

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

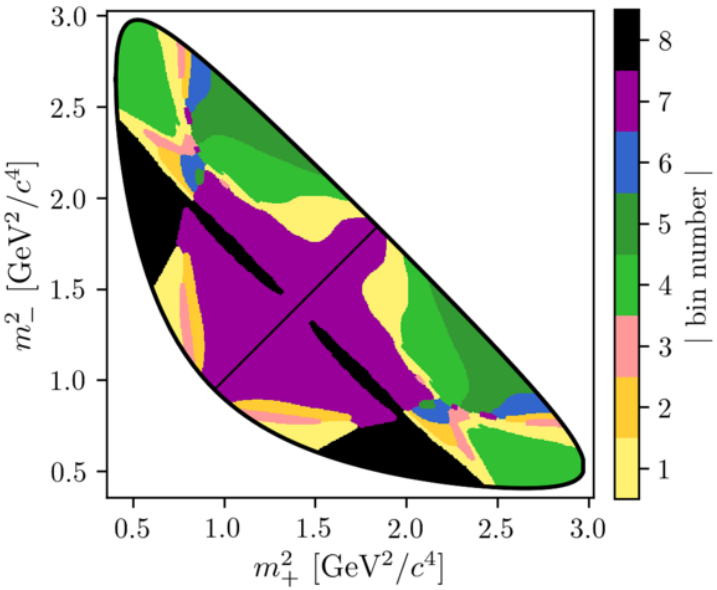
- Hadronic parameters $r_D$ and $\delta_D$ are functions of phase space
- Compare yields of $B^+$ and $B^-$ and determine the asymmetry in local phase space regions



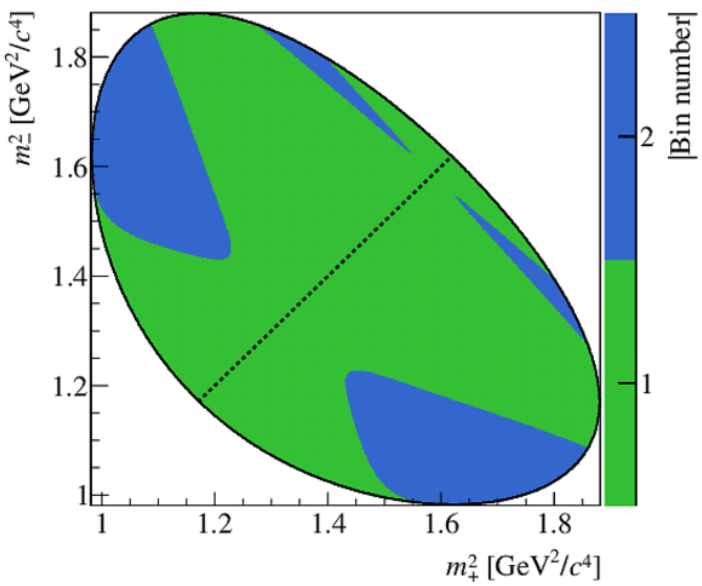

$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 r_D^2 + 2 r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

# Multi-body $D$ decays

- Measurements of the amplitude-averaged $\delta_D$, $c_i$ and $s_i$, have been measured directly at:
  - CLEO Phys. Rev. **D82** (2010) 112006
  - BESIII Phys. Rev. **D101** (2020) 112002
- The value of $\gamma$ obtained will be model independent
- $\gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$ with $B^\pm \to [K^0_S h^+ h^-]_D h^\pm$ JHEP **02** (2021) 0169




$K^0_S\pi^+\pi^-$

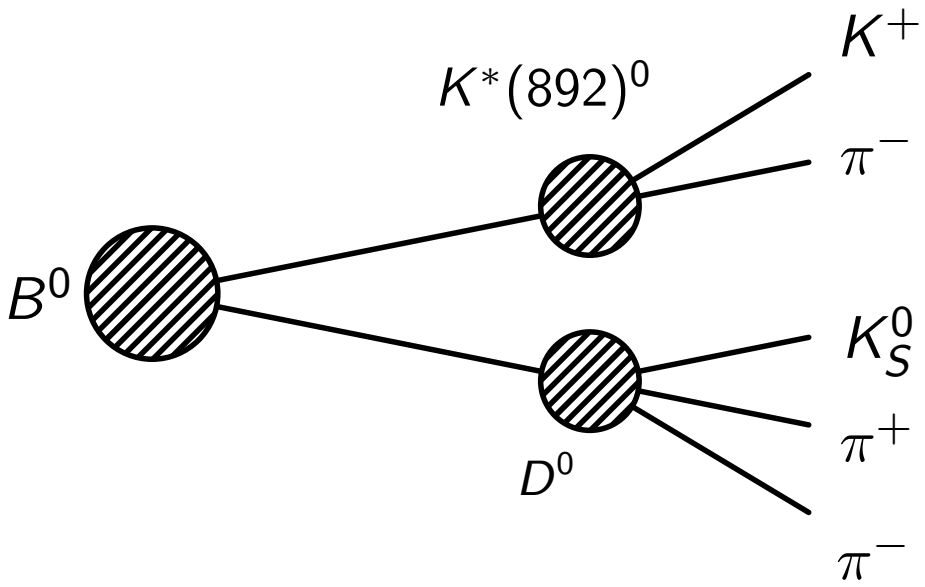



$K^0_S K^+ K^-$

# Neutral $B$ decays

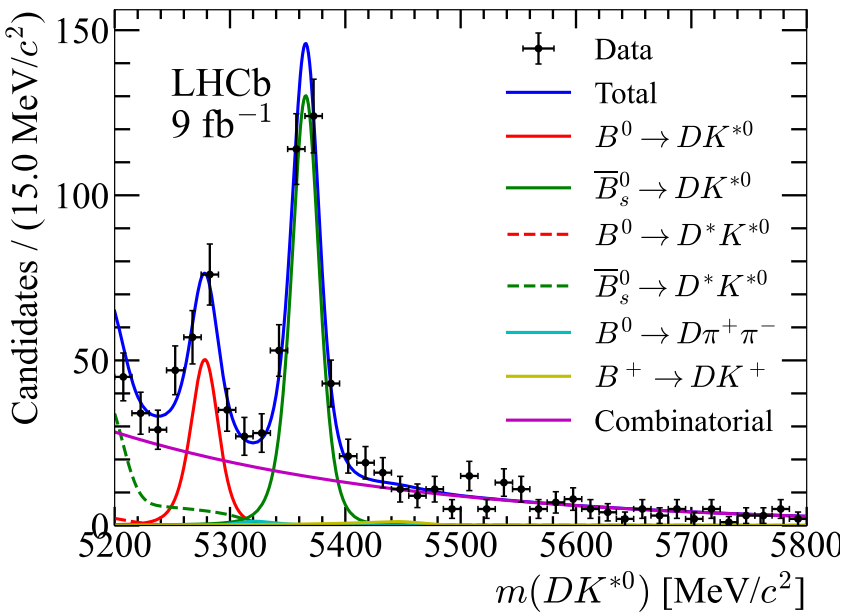
This method may be generalised to neutral $B$ decays:

LHCb-PAPER-2023-009 New preliminary results!

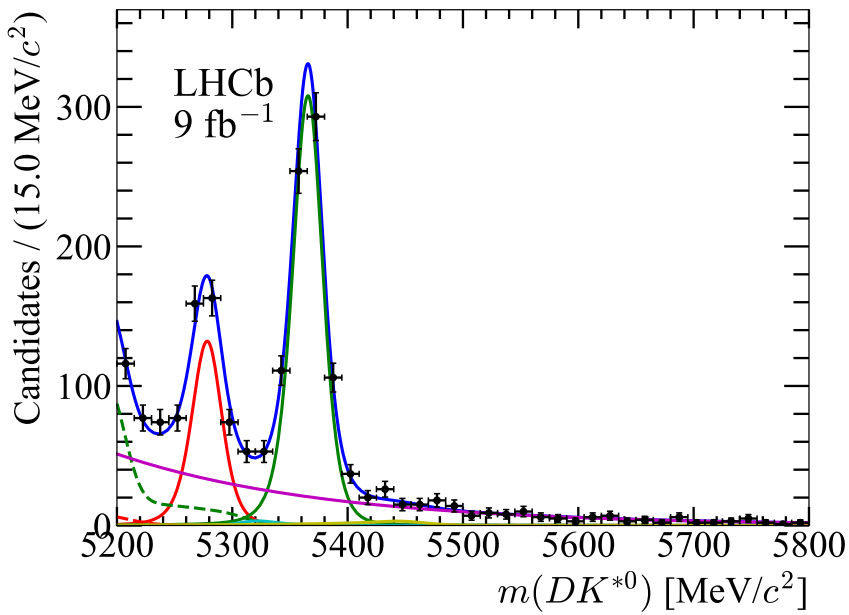



$$B^0 \to (K^0_S h^+ h^-)_D (K^+\pi^-)_{K^*}$$

# Neutral $B$ decays



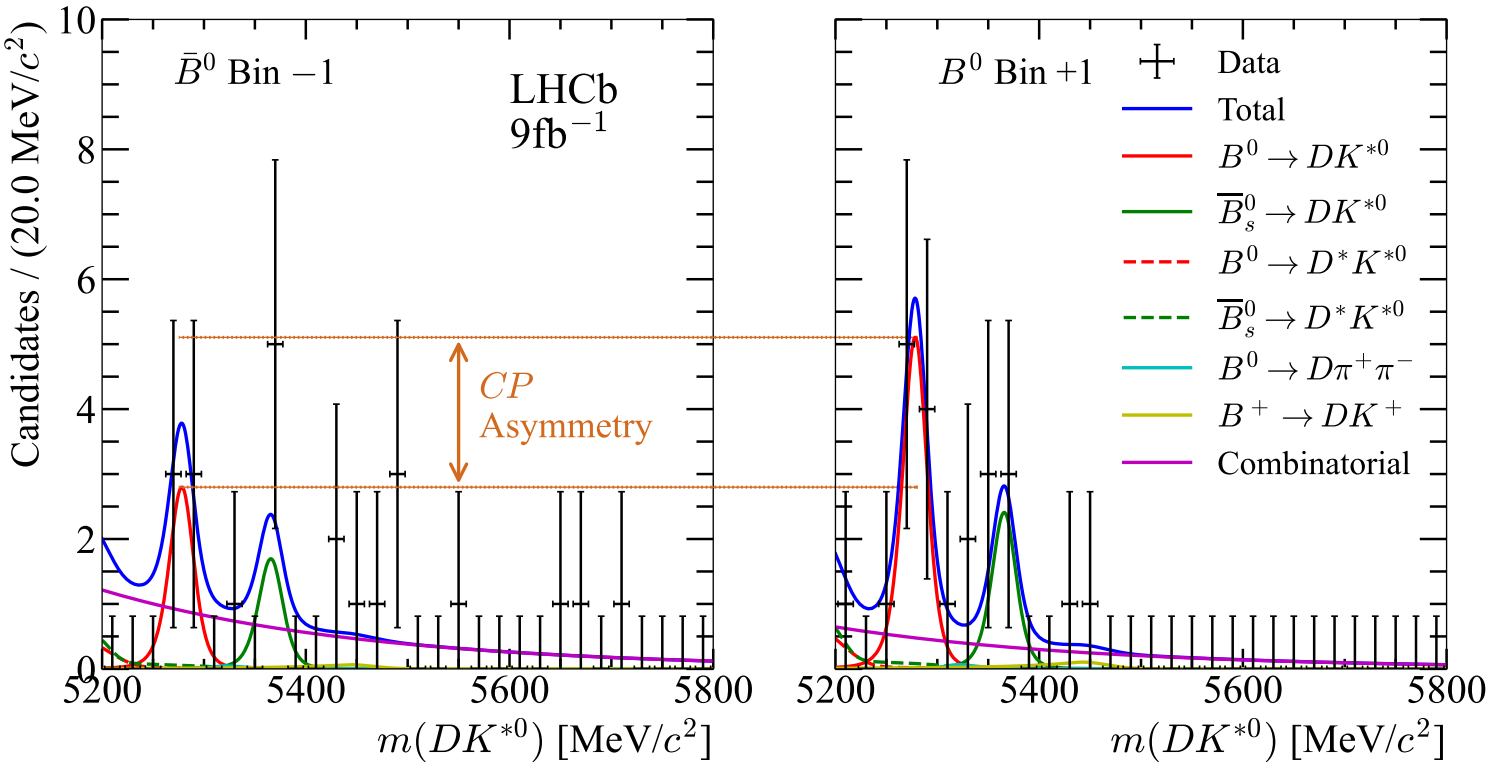

LL




DD

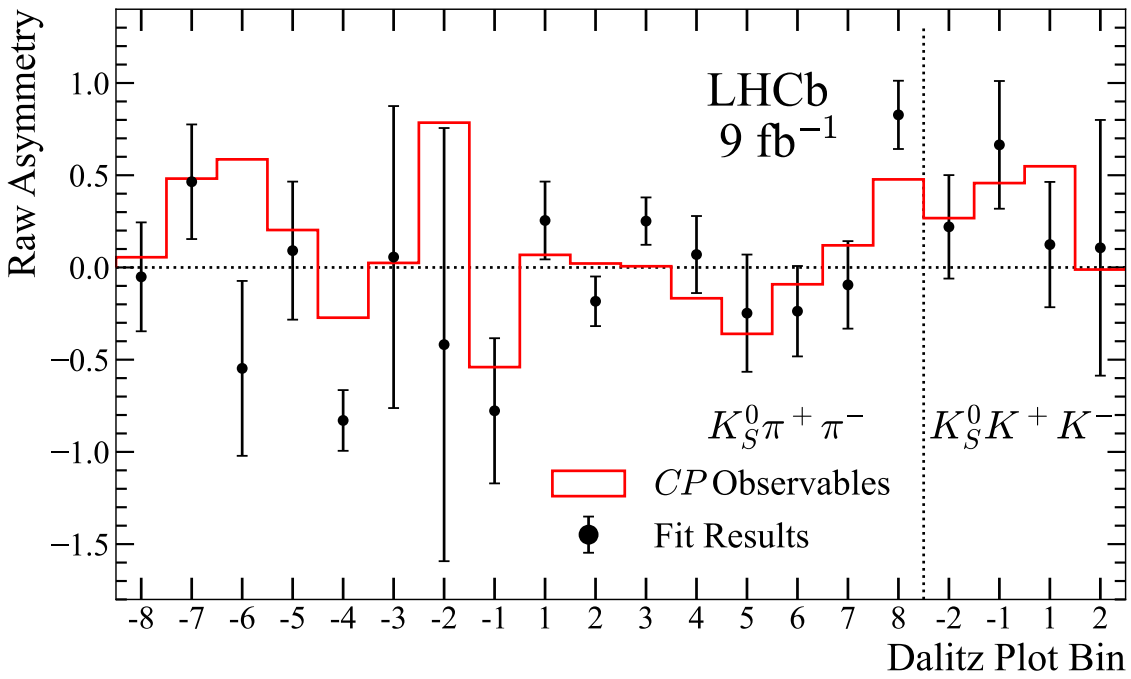
- Two separate selections of $K^0_S$:
  - LL (long tracks): $K^0_S$ decays in the VELO
  - DD (downstream tracks): $K^0_S$ decays downstream of the VELO
- $B^0 \to DK^{*0}$ candidates with $D \to K^0_S\pi^+\pi^-$ ($D \to K^0_S K^+K^-$):
  - LL: $102 \pm 17$ ($12 \pm 6$)
  - DD: $288 \pm 25$ ($32 \pm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

# Neutral $B$ decays



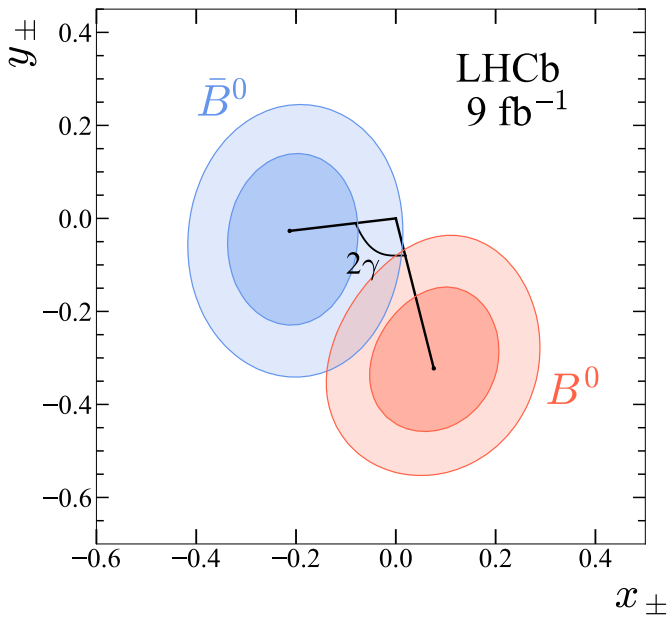

- Non-zero bin asymmetries are observed:
  - Large asymmetries are seen between $B^0$ ($\bar{B}^0$) bin pairs
  - No CPV is observed in $B^0_s$ decays

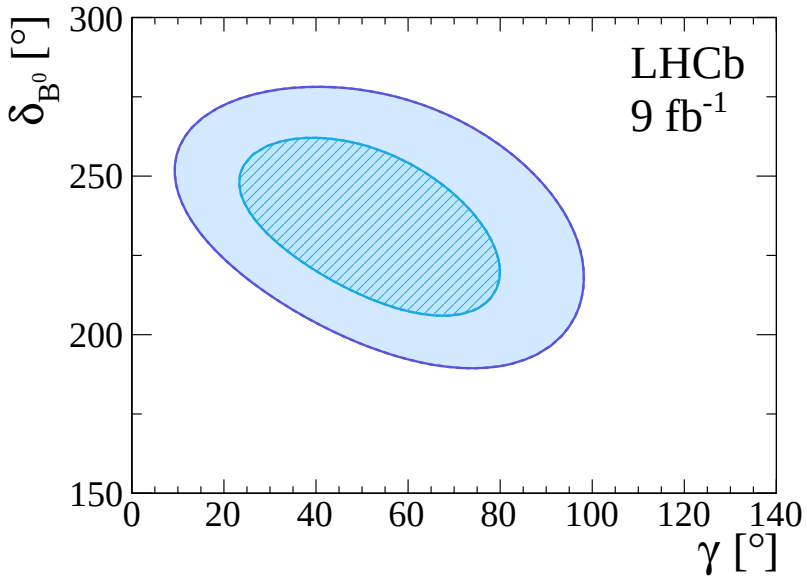
# Neutral $B$ decays




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

# Neutral $B$ decays




- Measured $CP$-violating observables:

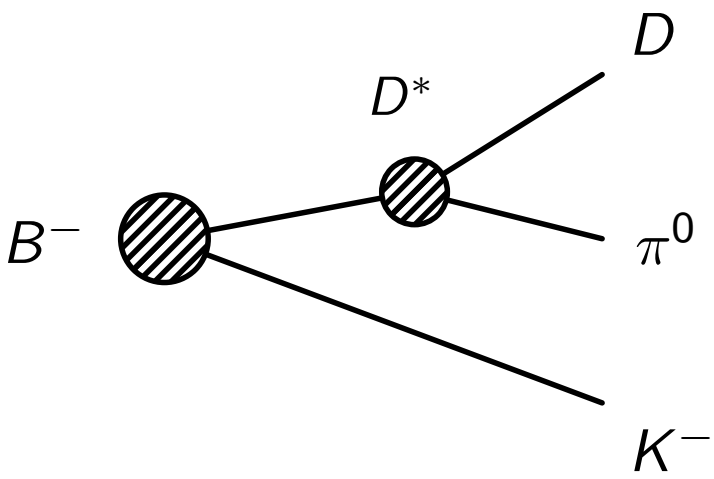
$$x_\pm \equiv r_{B^0} \cos(\delta_{B^0} \pm \gamma) \text{ and } y_\pm \equiv r_{B^0} \sin(\delta_{B^0} \pm \gamma)$$

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

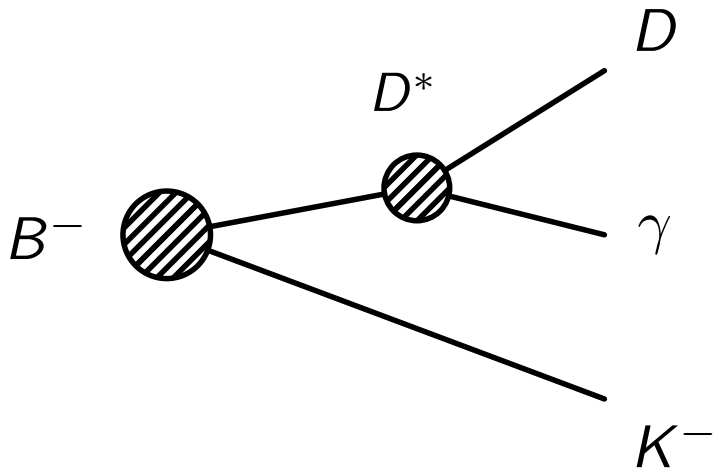
# $B$ decays to excited $D^*$ final states

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

LHCb-PAPER-2023-012 **New preliminary results!**




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

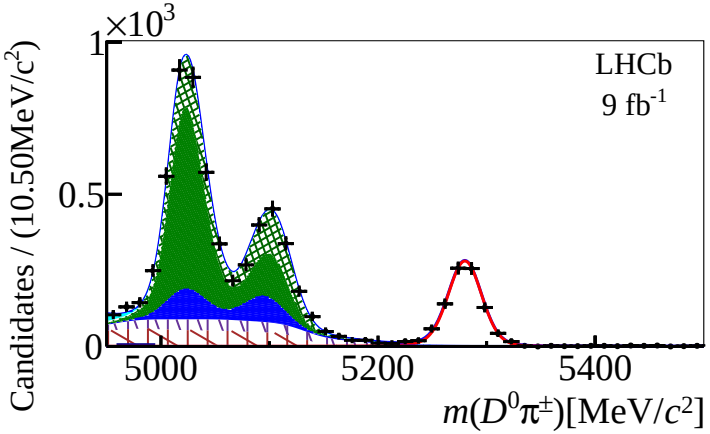


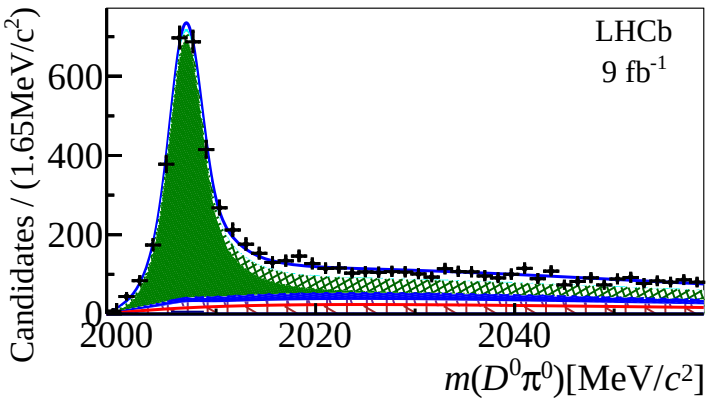

$B^- \to [D\gamma]_{D^*} K^-$

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

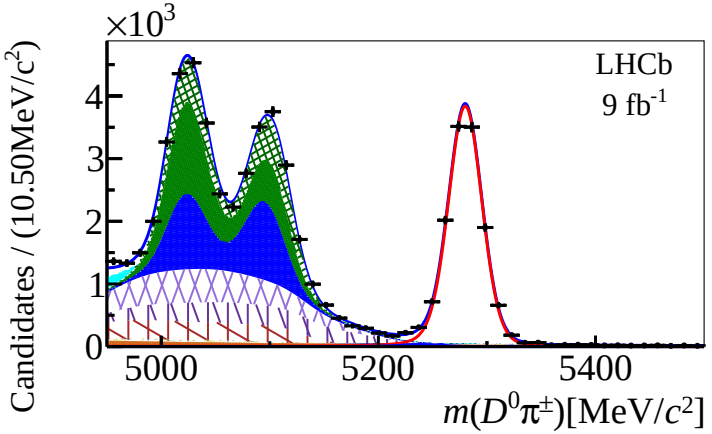
The relative signal swap results in opposite $CP$ asymmetries between $D^* \to D\pi^0$ and $D^* \to D\gamma$

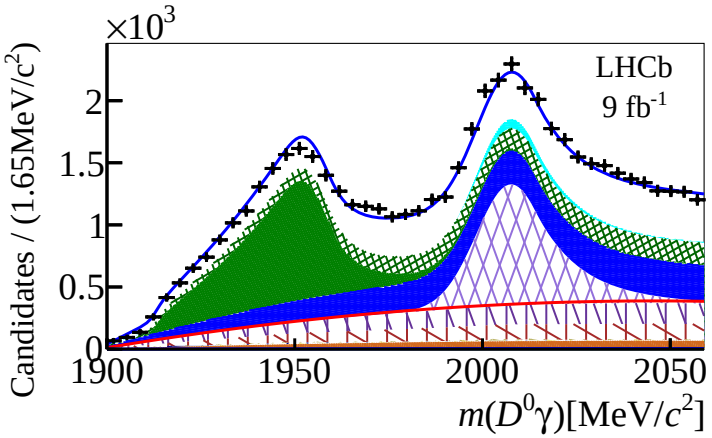
# $B$ decays to excited $D^*$ final states



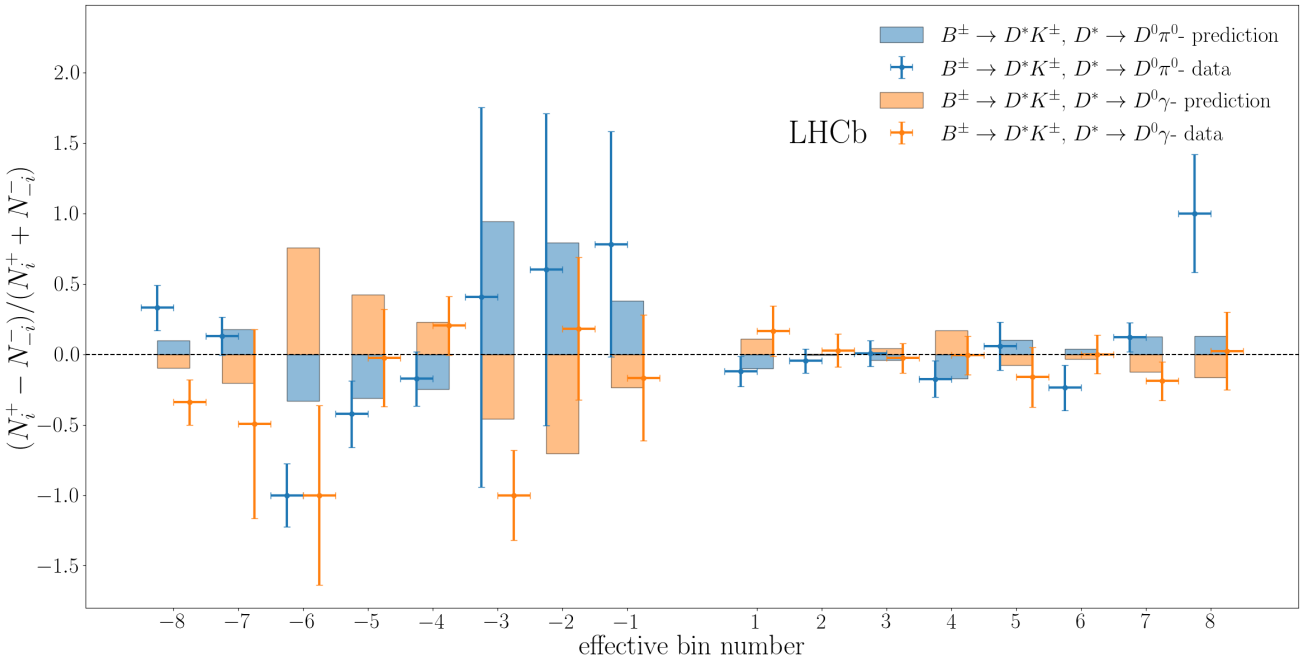

$D^* \to D\pi^0$



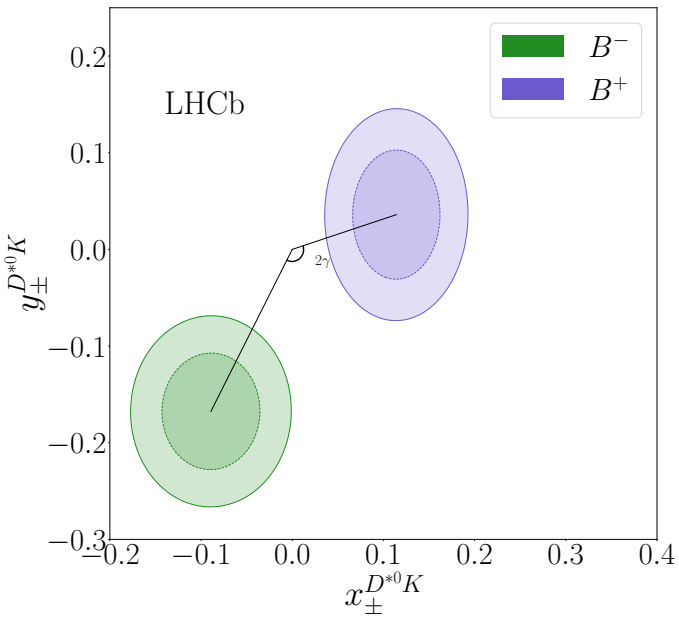

**(a)** $D^* \to D\gamma$

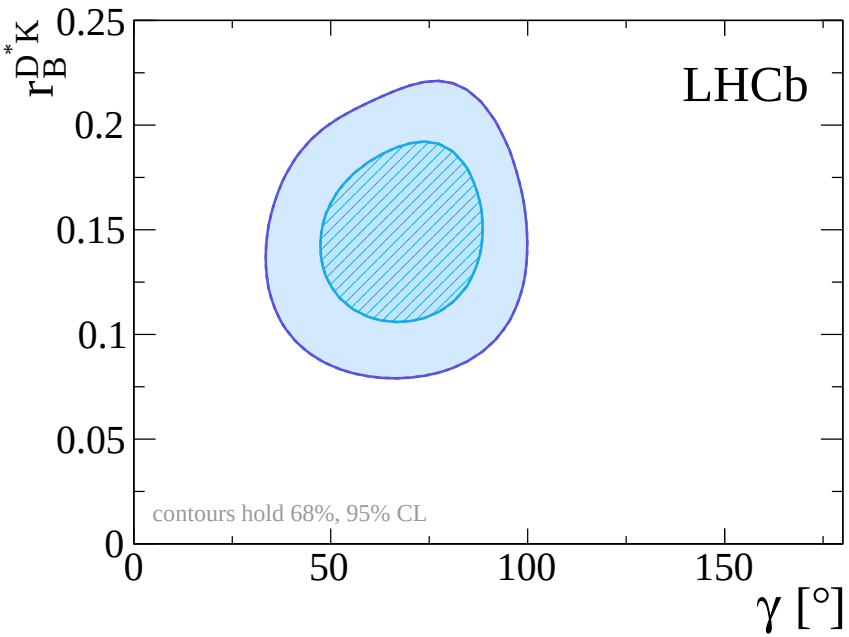
# $B$ decays to excited $D^*$ final states




- 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 opposite in magnitude

# $B$ decays to excited $D^*$ final states



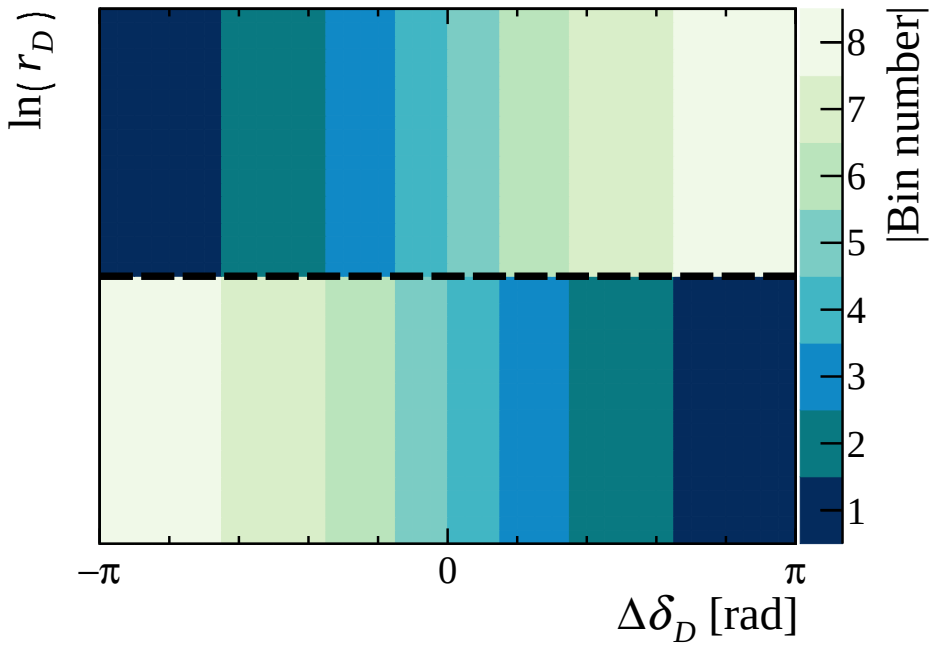

These results provide strong constraints on $\gamma$:

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

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

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!

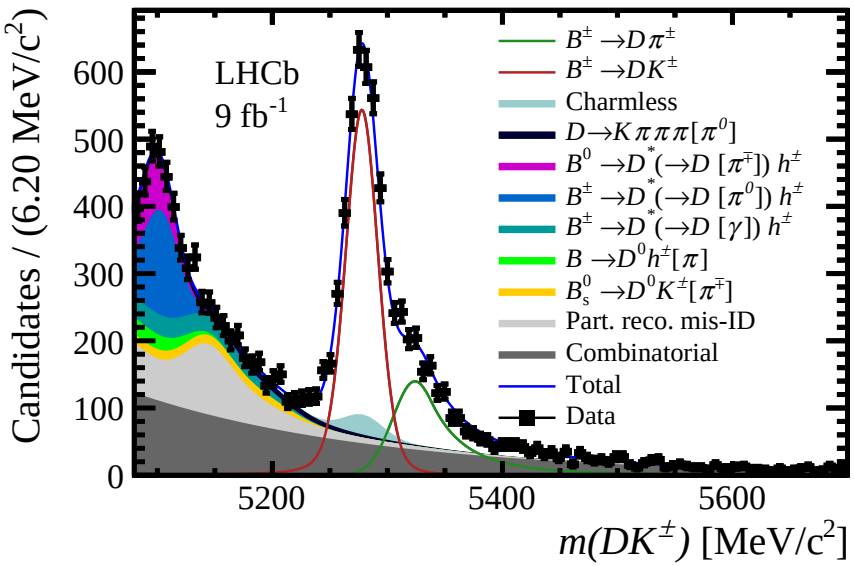


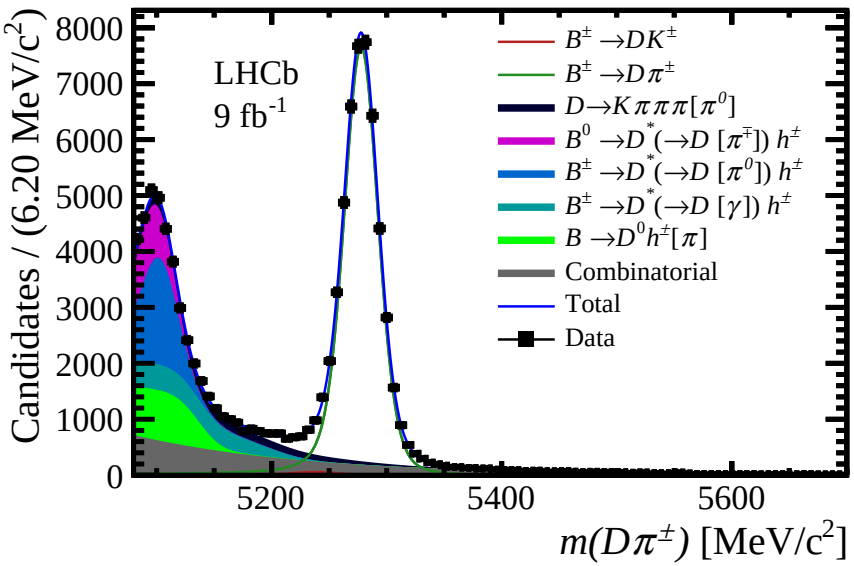

Bins $i < 0$ on top, $i > 0$ below

LHCb-PAPER-2022-037, arXiv:2301.10328 (accepted by EPJC)

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

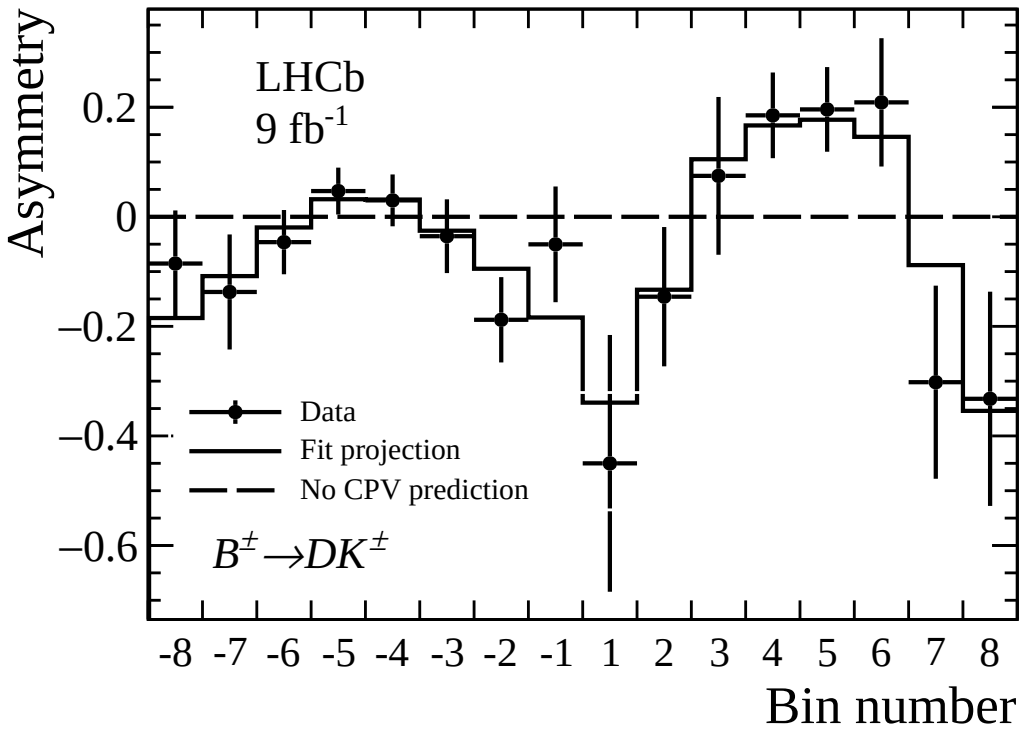
Fully charged final state $\implies$ Highly suitable for LHCb




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

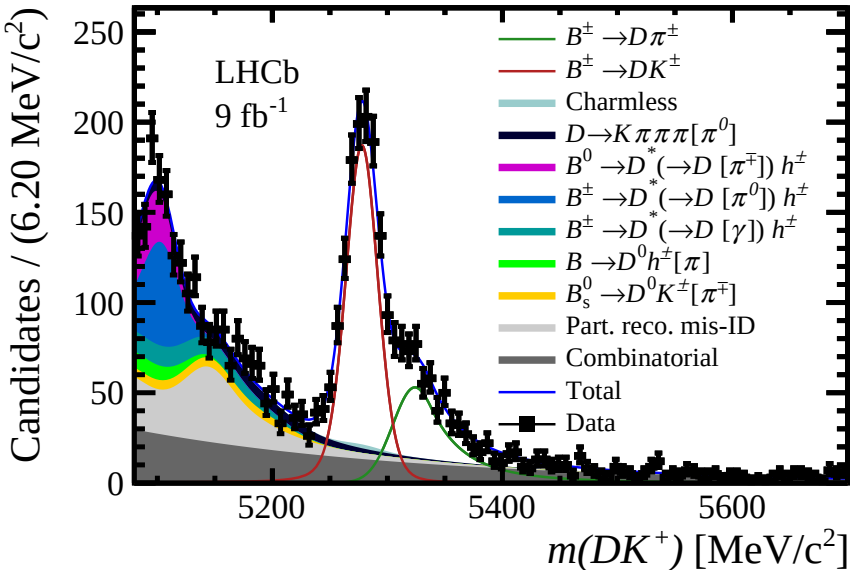
# Phase-space binned $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

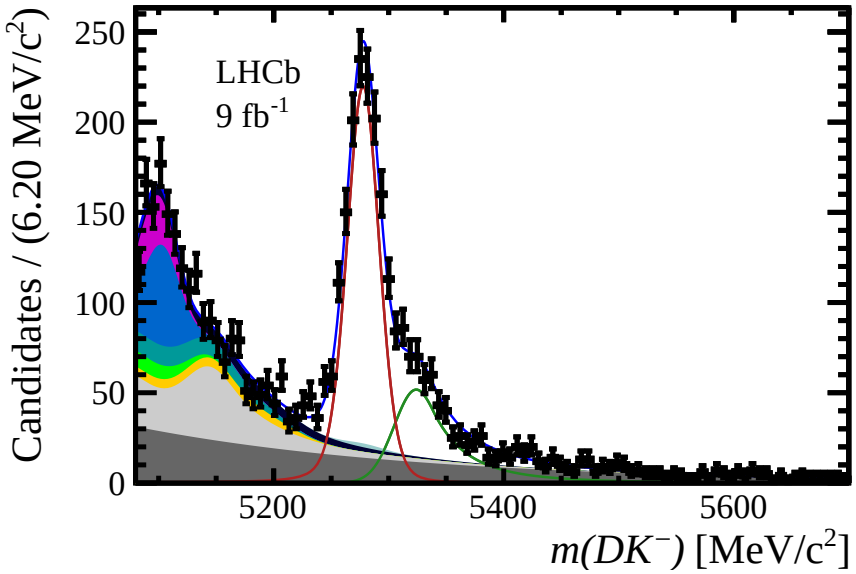



- Clear bin asymmetries are seen, and the non-trivial distribution is driven by the change in strong phases across phase space
- While the interpretation of $\gamma$ require charm inputs, the observed bin asymmetries are model independent

# 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



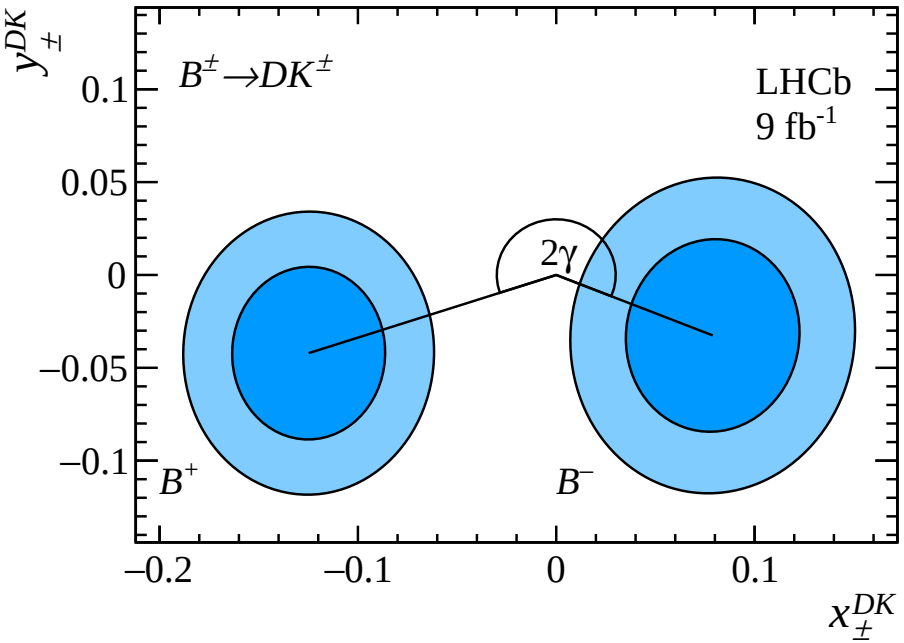



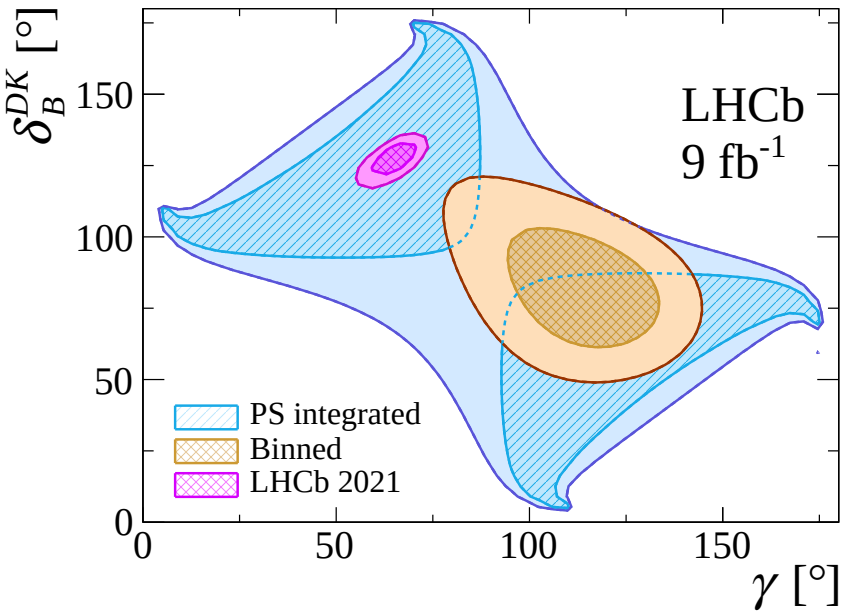

More $B^-$ candidates because $D^0 \to K^+K^-\pi^+\pi^-$ is predominantly *CP*-even

# Interpretation of $\gamma$

From the phase-space binned asymmetries, we obtain:

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




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

# Summary and conclusion

1. LHCb has produced several measurements of $\gamma$ using different $B$ and $D^{(*)}$ decay combinations

2. Phase-space binned analyses using the golden mode $D \to K^0_S\pi^+\pi^-$ provide the most powerful constraints for our $\gamma$ combination

3. I have 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 $D\gamma$

4. Additionally, a binned measurement with the channel $B^\pm \to [K^+K^-\pi^+\pi^-]K^\pm$ has been performed for the first time
   - Model-dependent result has some tension with current world average
   - Need external inputs for charm strong-phases from BESIII!

# Summary and conclusion

Thanks for your attention!