Measurements of CKM angle γ in LHCb

Martin Tat, on behalf of the LHCb collaboration

University of Oxford

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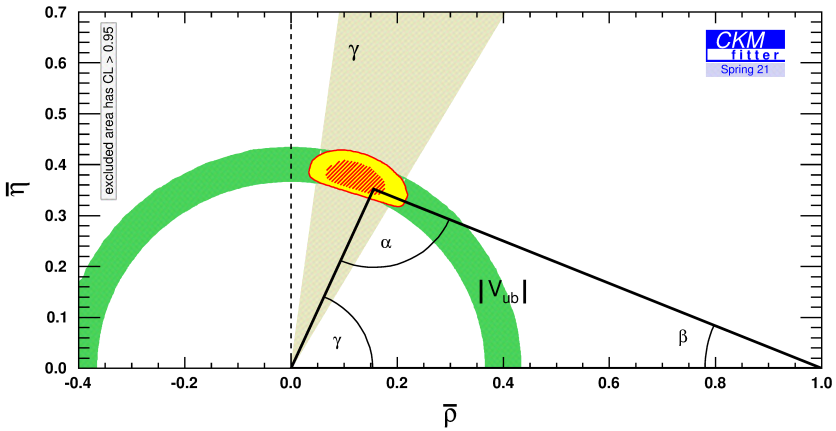
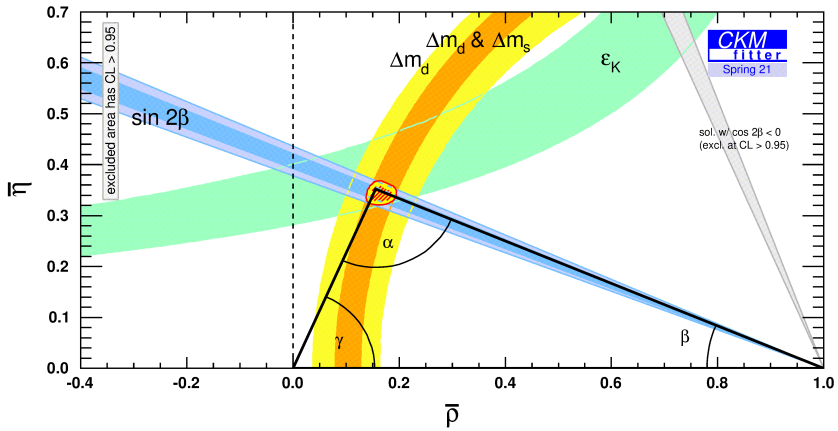
Introduction to γ and *CP* violation

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

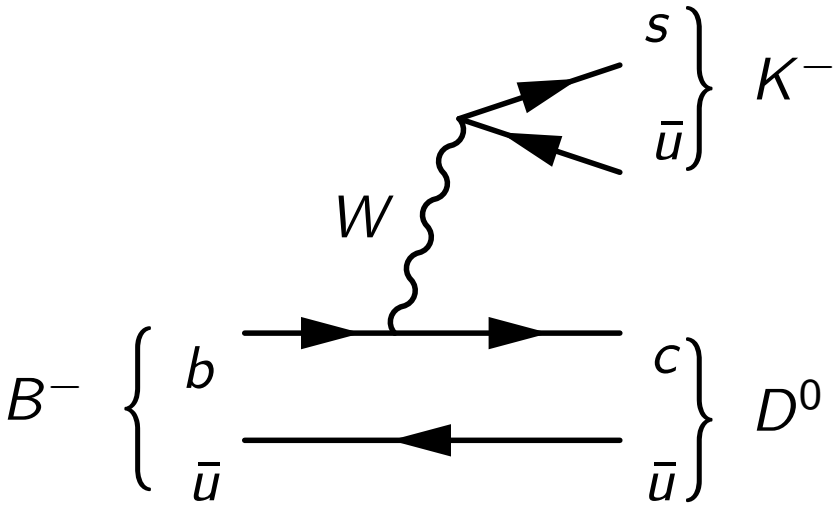


(b) Loop level: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

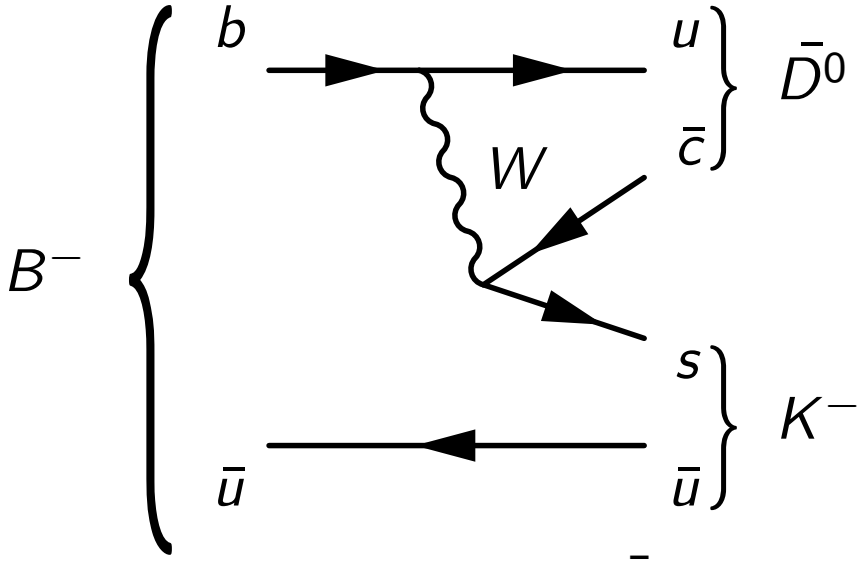
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

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

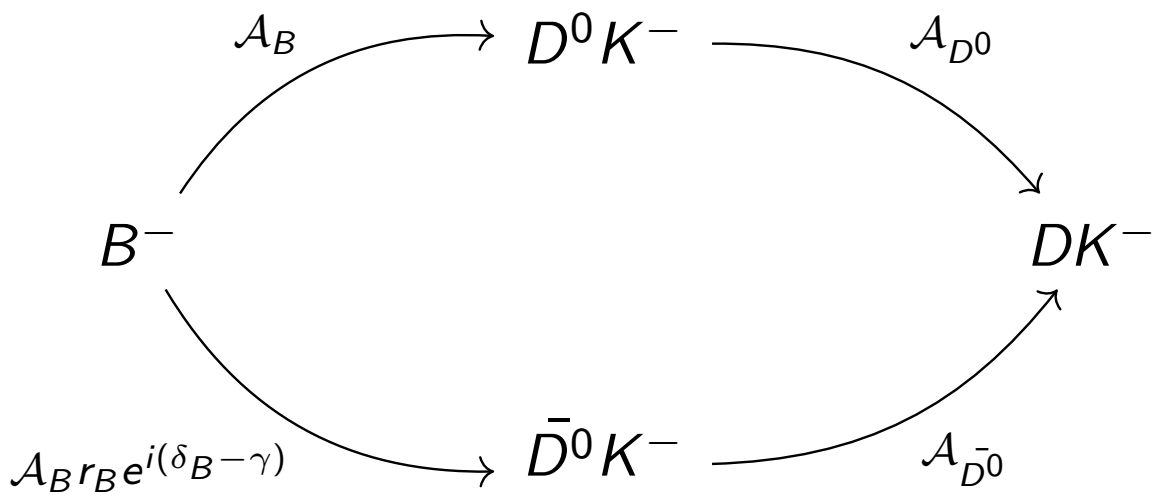
$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)}\mathcal{A}_{\bar{D}^0}\right)$$

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

Multi-body D decays

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

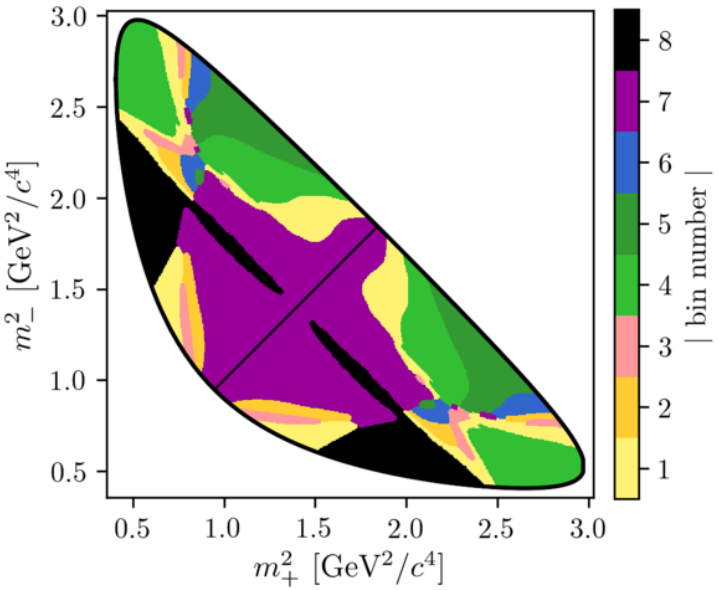
- Hadronic parameters r_D and δ_D are functions of phase space
- Compare yields of B^+ and B^- and determine the asymmetry in local phase space regions



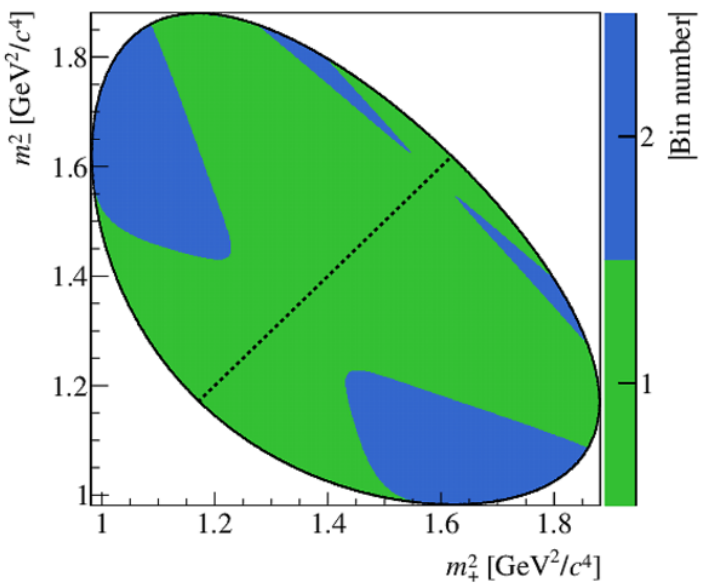
$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 r_D^2 + 2 r_B r_D \cos(\delta_B - \gamma + \delta_D)$$

Multi-body D decays

- Measurements of the amplitude-averaged δ_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 γ 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



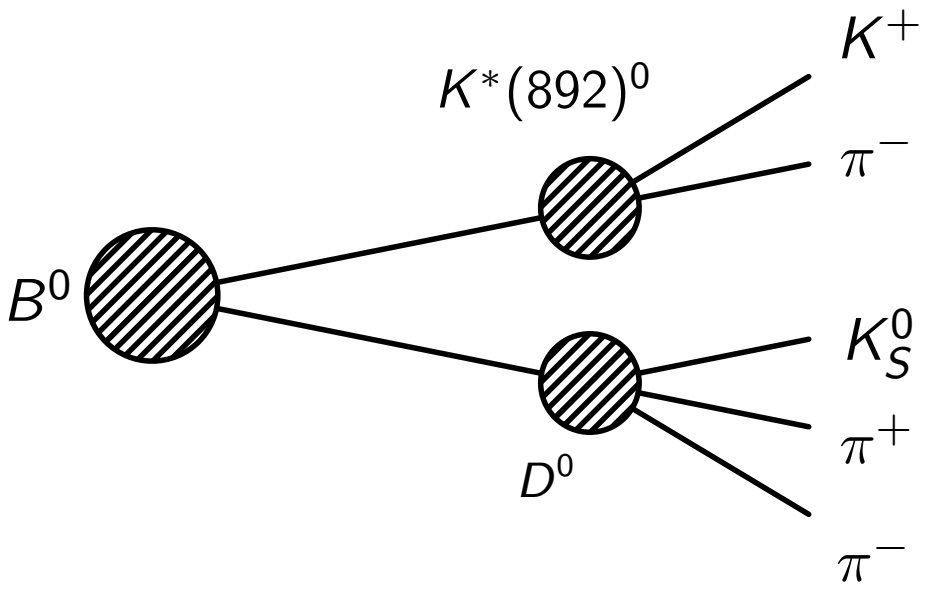
$K^0_S\pi^+\pi^-$



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

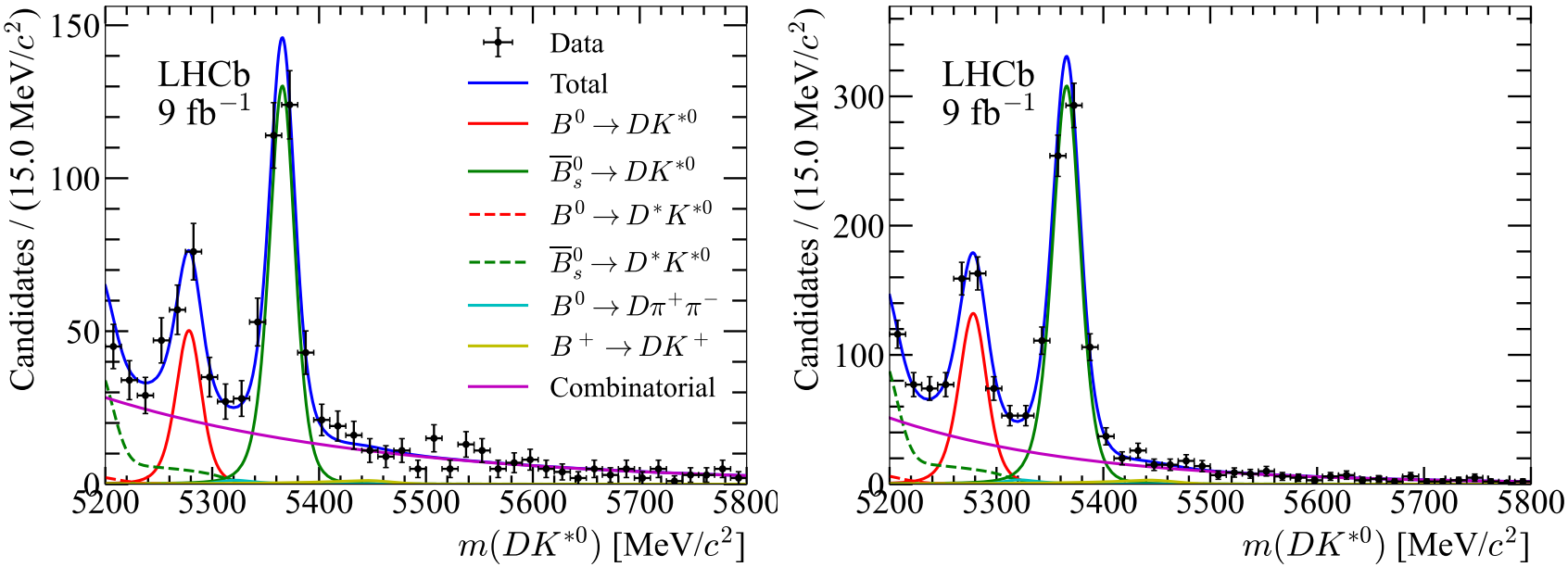
Neutral B decays

This method may be generalised to neutral B decays:



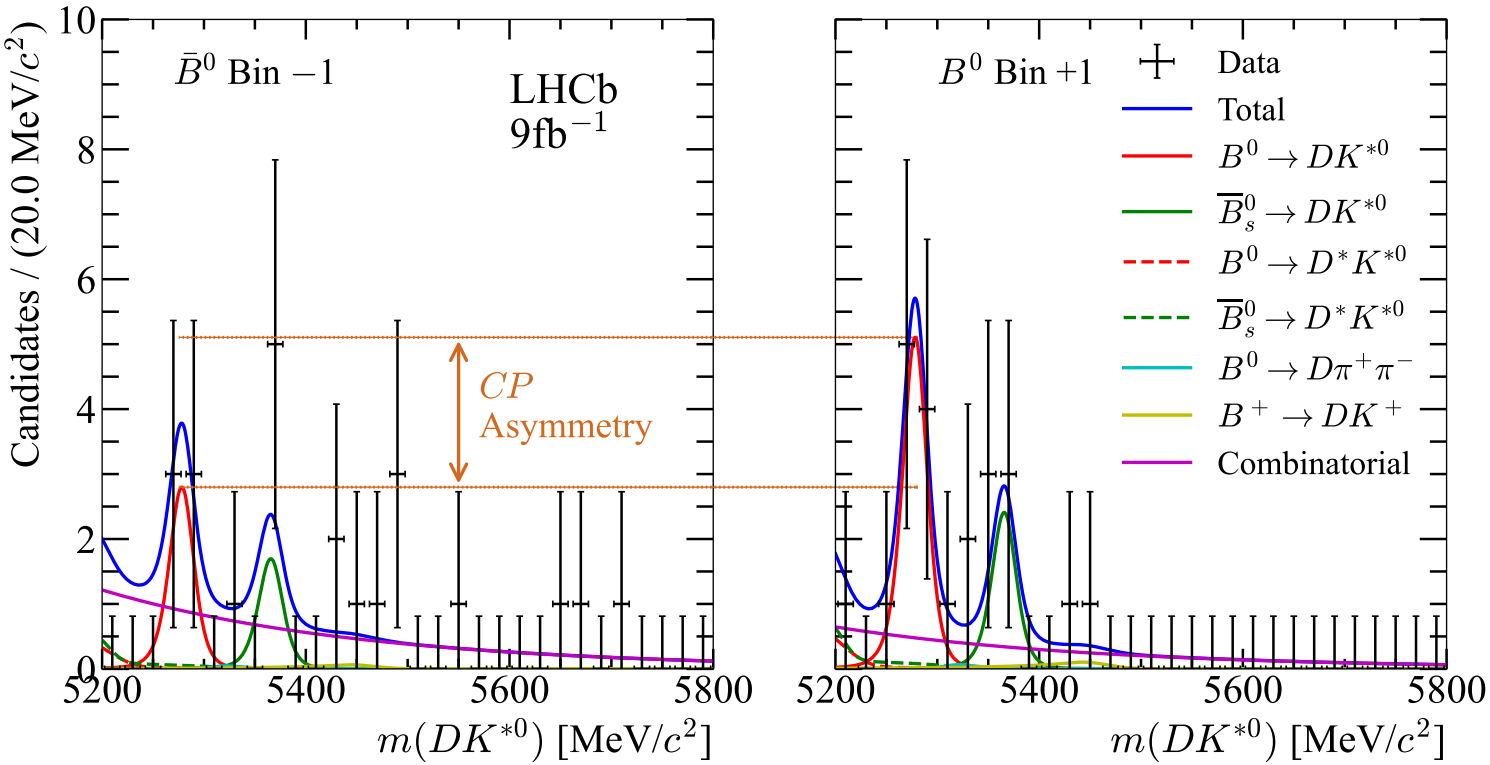
$$B^0 \to (K^0_S h^+ h^-)_D (K^+ \pi^-)_{K^*}$$

Neutral B decays



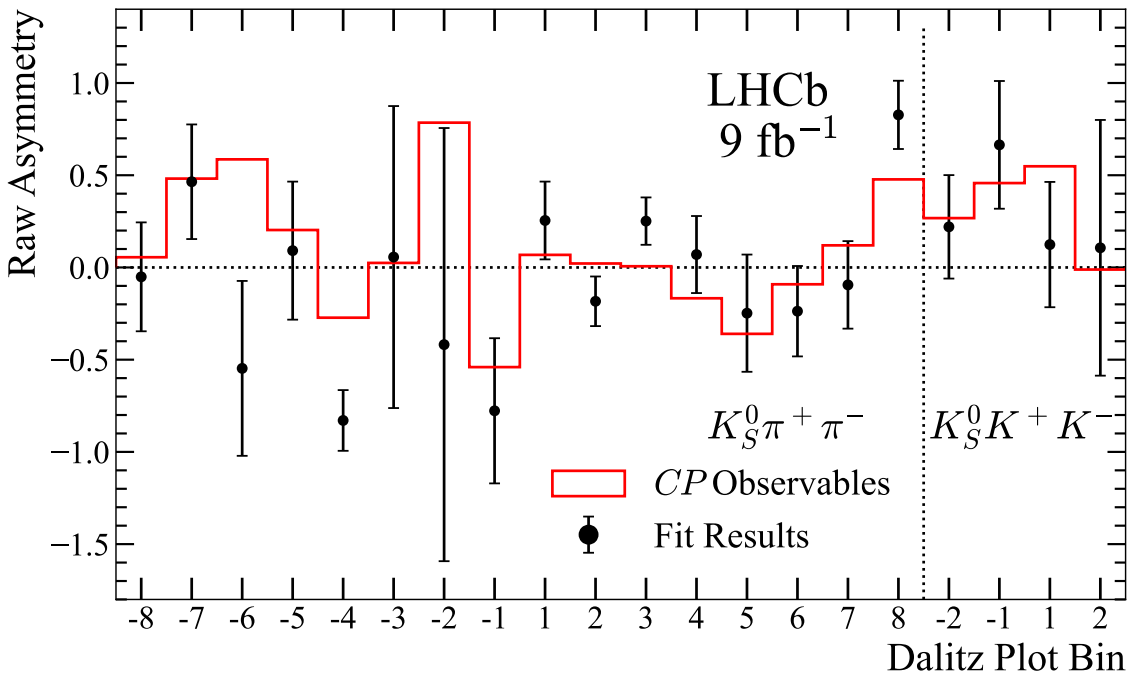
- Two separate selections of K^0_S:
  - LL (long tracks): K^0_S decays in the VELO
  - DD (downstream tracks): K^0_S decays downstream of the VELO
- $B^0 \to DK^{*0}$ candidates with $D \to K^0_S\pi^+\pi^-$ ($D \to K^0_S K^+K^-$):
  - LL: 102 ± 17 (12 ± 6)
  - DD: 288 ± 25 (32 ± 8)

Neutral B decays



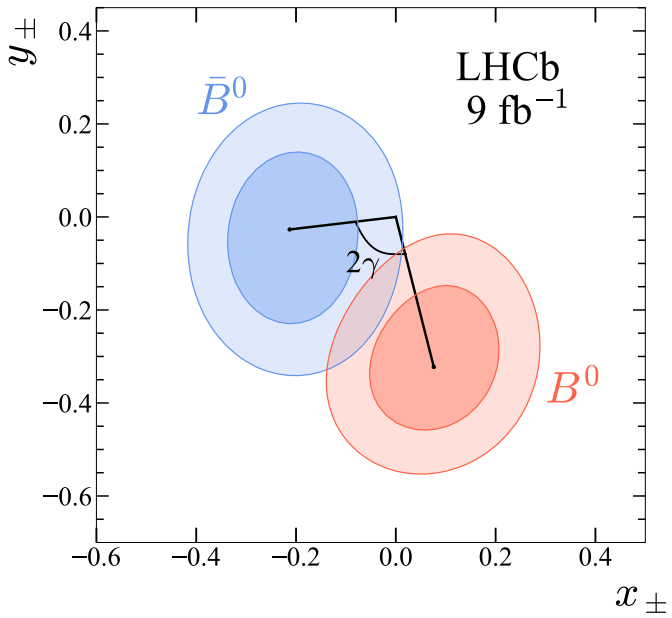
- Non-zero bin asymmetries are observed:
  - Large asymmetries are seen between B^0 ($\bar{B}^0$) bin pairs
  - No CPV is observed in B^0_s decays

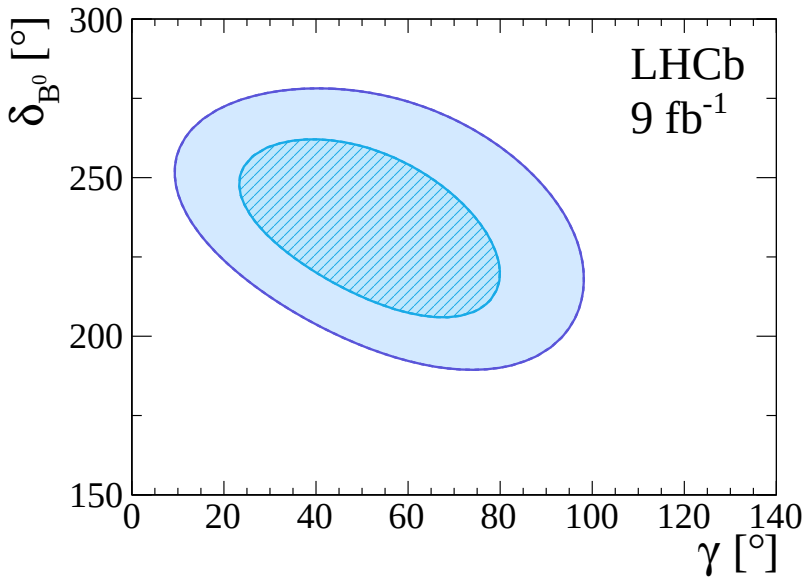
Neutral B decays



- 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:

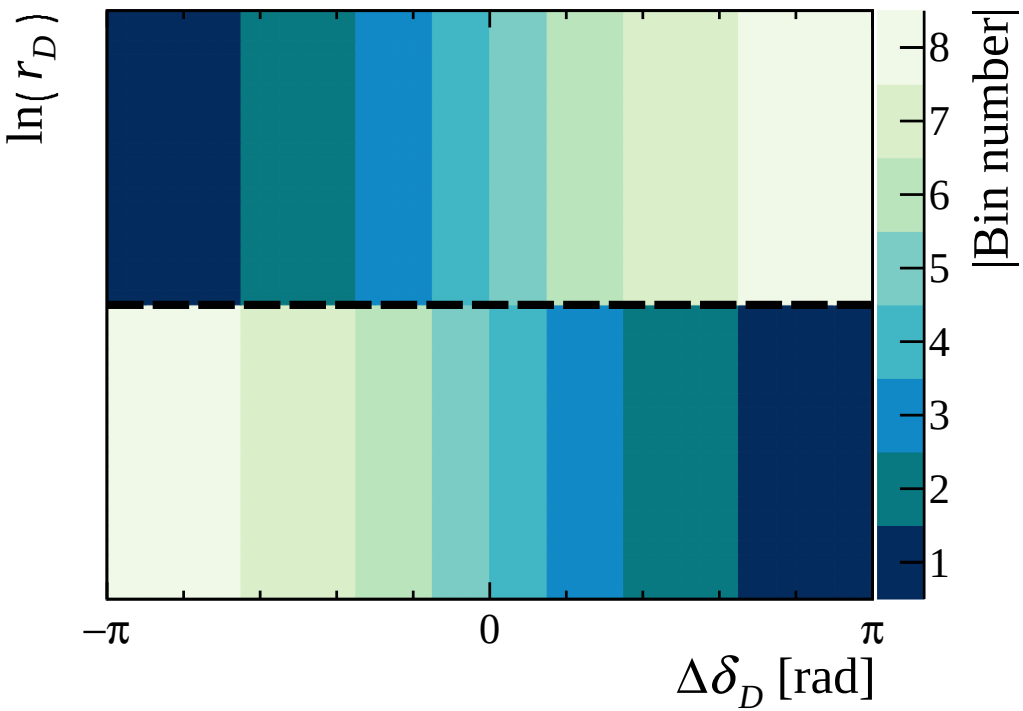
$$x_\pm \equiv r_{B^0} \cos(\delta_{B^0} \pm \gamma) \text{ and } y_\pm \equiv r_{B^0} \sin(\delta_{B^0} \pm \gamma)$$

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

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

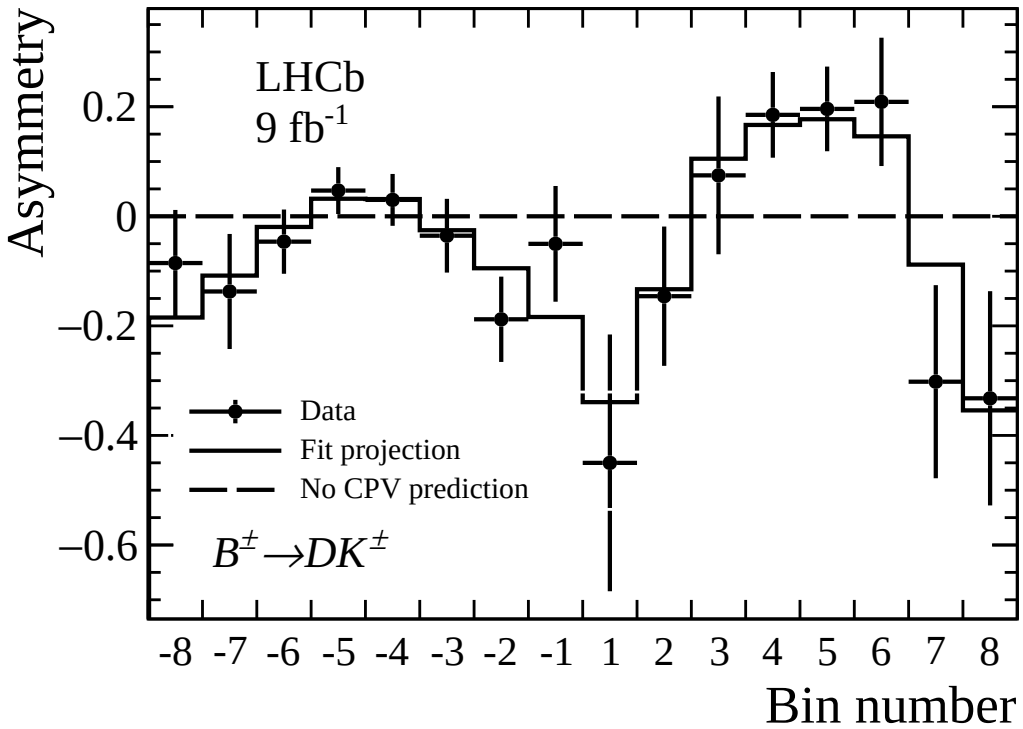
We can also consider more complicated multi-body decays: $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$

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



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

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

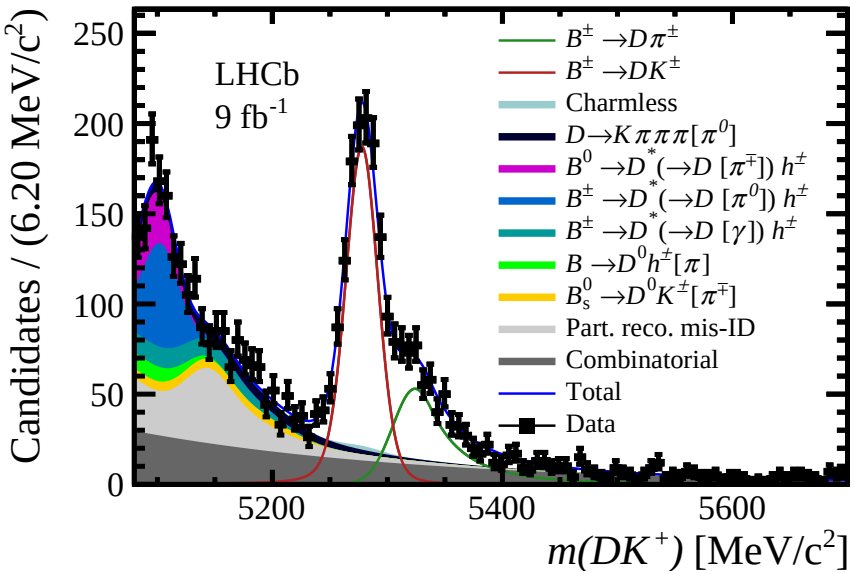


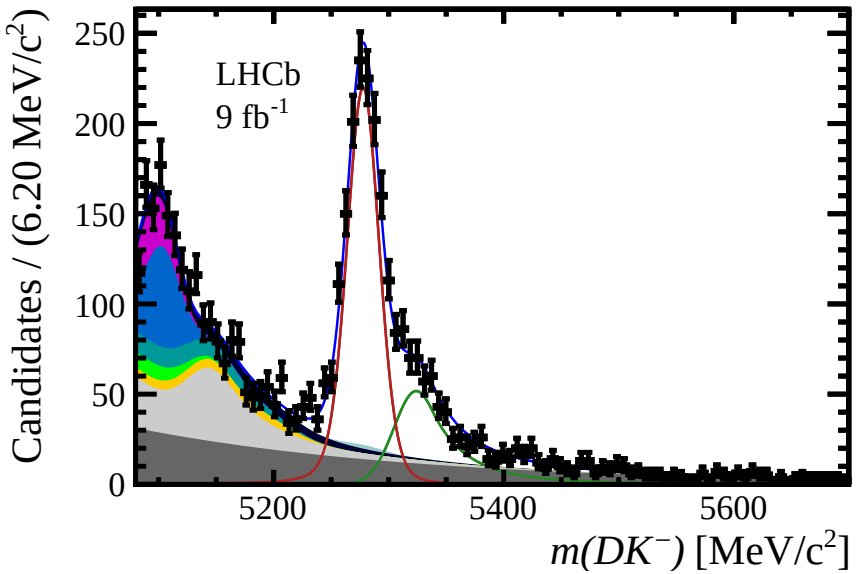
arXiv:2301.10328

- 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 γ require charm inputs, the observed bin asymmetries are model independent

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

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





arXiv:2301.10328

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

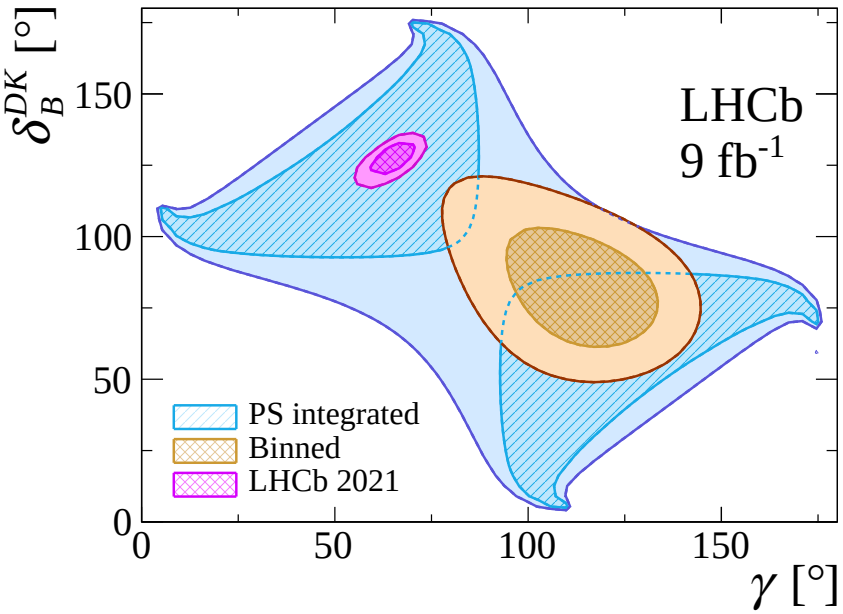
This measurement is performed on both $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D K^{\pm}$

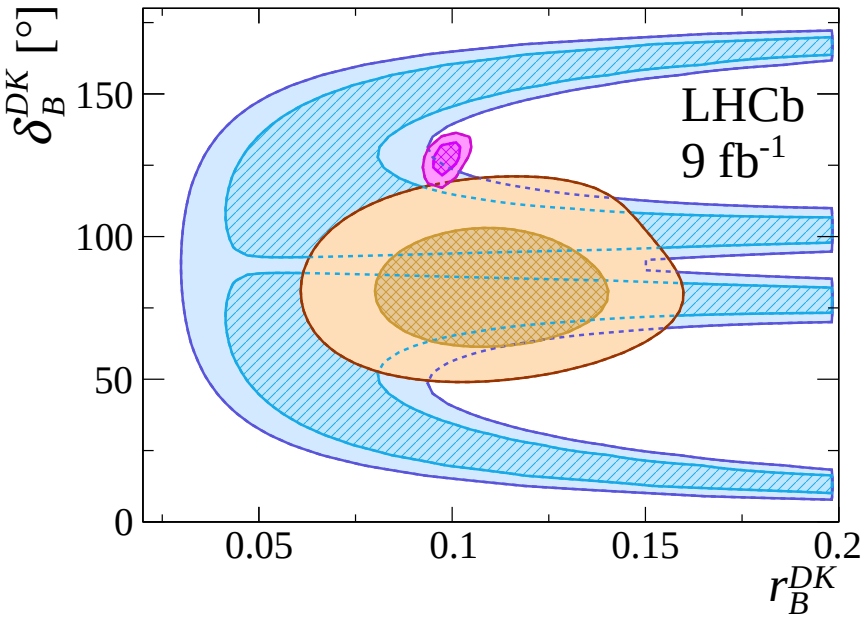
CP-violating observable	Fit results		
$A_K^{KK\pi\pi}$	0.095	± 0.023	± 0.002
$A_\pi^{KK\pi\pi}$	-0.009	± 0.006	± 0.001
$A_K^{\pi\pi\pi\pi}$	0.061	± 0.013	± 0.002
$A_\pi^{\pi\pi\pi\pi}$	-0.0082	± 0.0031	± 0.0007
$R_{CP}^{KK\pi\pi}$	0.974	± 0.024	± 0.015
$R_{CP}^{\pi\pi\pi\pi}$	0.978	± 0.014	± 0.010

Interpretation of γ

Combine phase-space binned and integrated results to obtain γ:

$$\gamma = (116^{+12}_{-14})^\circ$$





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 γ using different B and D decay combinations

2. Phase-space binned analyses is the workhorse of our γ (and charm) combination

3. I have presented two new model-independent measurements using the golden modes $D \to K^0_S h^+ h^-$:
   - $B^0 \to DK^{*0}$
   - $B^\pm \to D^* h^\pm$ with $D^* \to D\pi^0$ and $D\gamma$

4. Additionally, a binned measurement with the channel $B^\pm \to [K^+K^-\pi^+\pi^-]$ 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!