γ measurements in ADS and GLW(-like) decays at LHCb

Fidan Suljik

University of Oxford

on behalf of the LHCb collaboration

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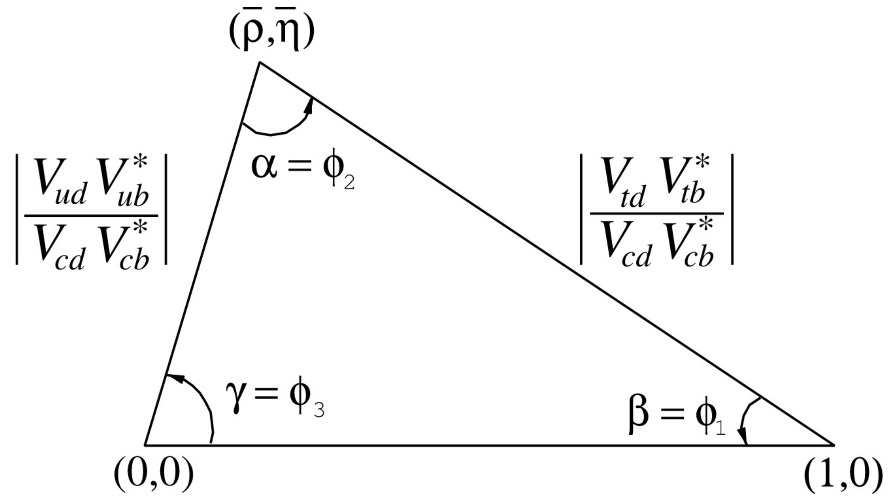
[1] Phys. Rev. **D98** (2018) 030001

- Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Unitarity of V_{CKM} represented by a **triangle**[1] **in the complex plane**

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



- Weak phase $\boldsymbol{\gamma}$ is the only angle **easily accessible at tree level**

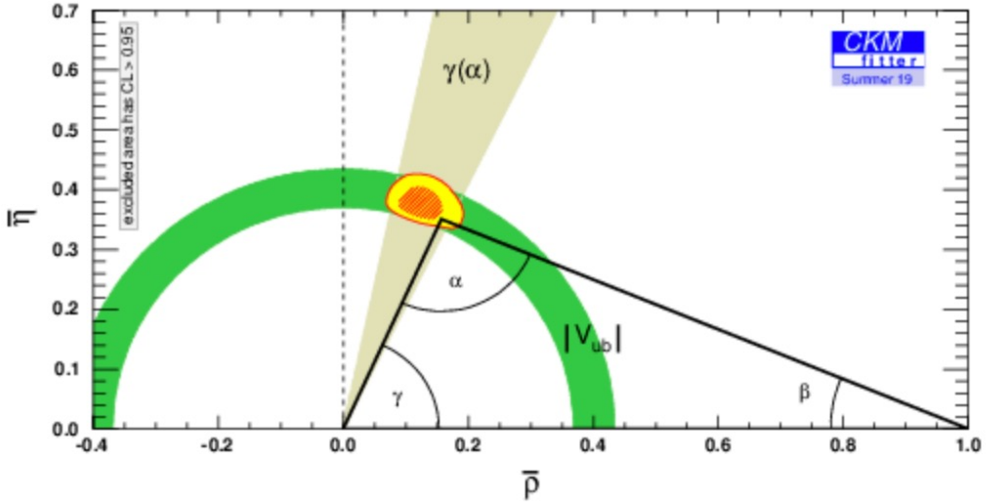
$$\gamma = \arg\left(-\frac{V_{ud}\, V_{ub}^{*}}{V_{cd}\, V_{cb}^{*}}\right)$$

- Theoretical uncertainty on γ is negligible

$$\frac{\delta\gamma}{\gamma} \sim 10^{-7}$$

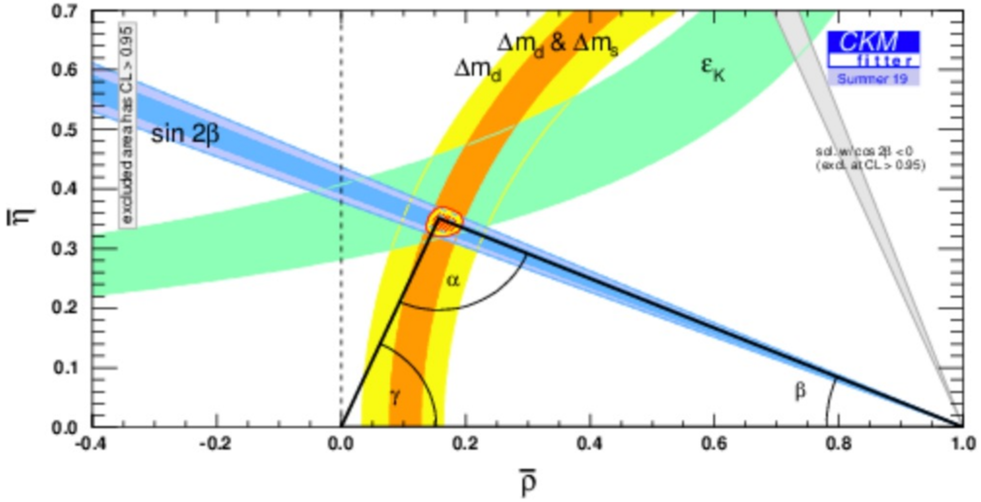
[2] Phys. Rev. **D91** (2015) 073007, http://ckmfitter.in2p3.fr/

Tree-level (direct measurement)



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

Loop-level (indirect measurement)

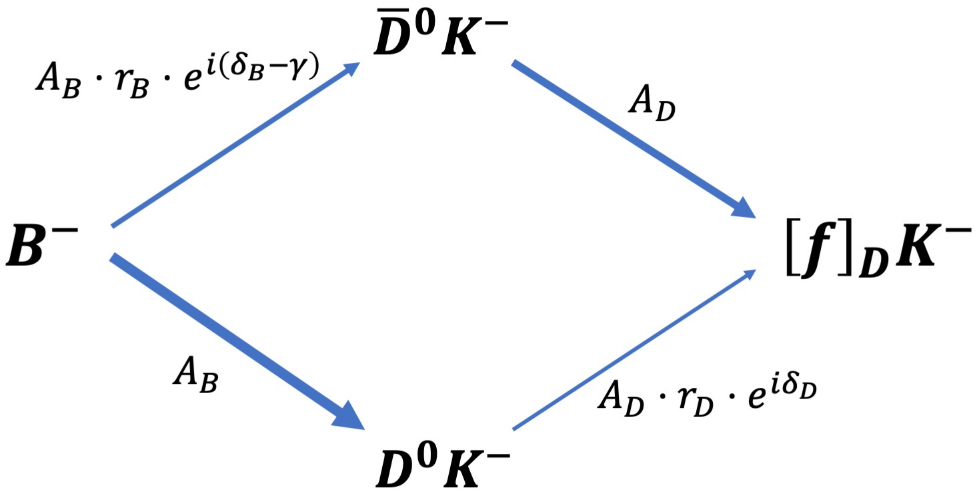


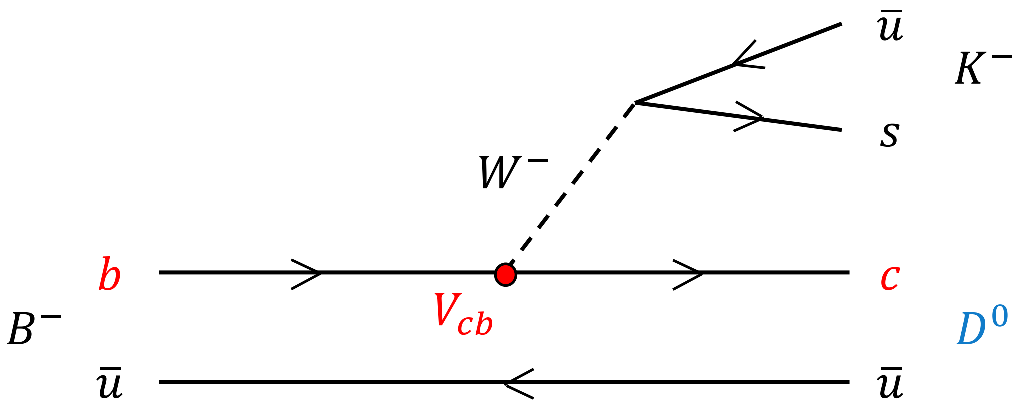
$\gamma = \left(65.66^{+0.90}_{-2.65}\right)^{\circ}$

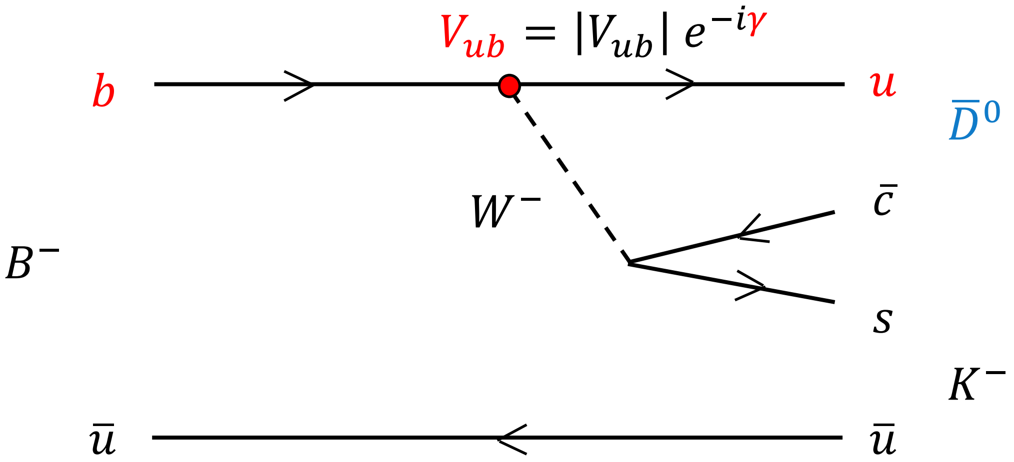
CKMfitter[2] Summer 2019

- Direct measurements of γ at tree-level are expected to be benchmarks of the Standard Model
- Indirect measurements consist of global fits to the unitary triangle, where some inputs include loop processes and assuming closed triangle. New Physics expected to contribute through loop processes
- A discrepancy between direct and indirect measurements would be a clear sign of New Physics

- Direct measurements of the CKM angle γ in $B \to DK$ decays
- The D meson is a superposition of D^0 and $\overline{D}^0$ states, which are reconstructed in common final states
- Both D^0 and $\overline{D}^0$ should be able to decay to the same final state
- Interference between $b \to cW$ and $b \to uW$ transitions gives sensitivity to γ







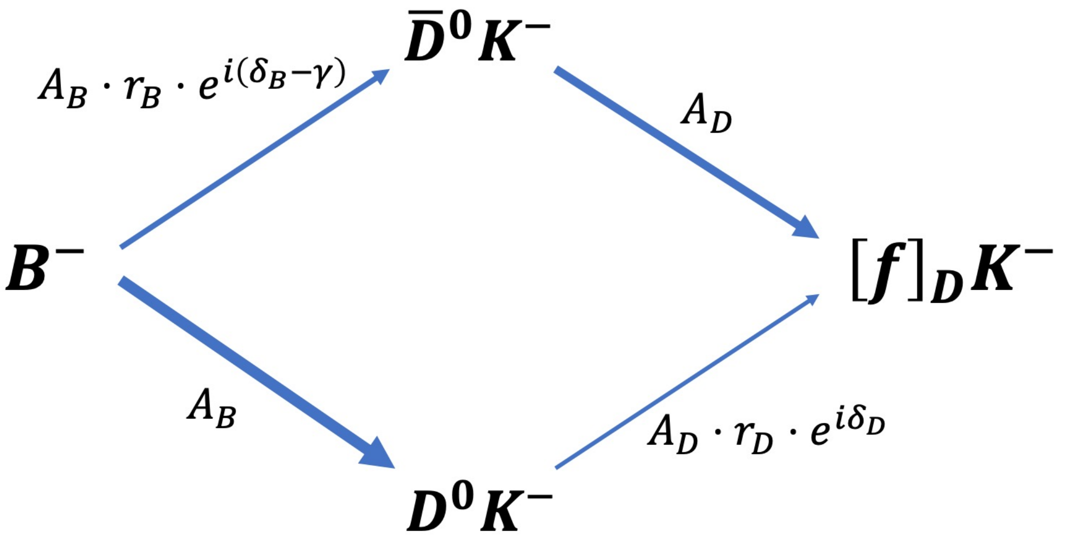
[3] Phys. Rev. Lett. **78** (1997) 3257

- **ADS[3] decays**
  - **Cabibbo-favoured (CF) / doubly Cabibbo-suppressed (DCS)**: $D \to K^-\pi^+, D \to \pi^-K^+$

$$R_{ADS} = \frac{N(B^- \to [\pi^-K^+]_D K^-)}{N(B^- \to [K^-\pi^+]_D K^-)} = r_B^2 + r_D^2 + 2\, r_B\, r_D \cos(\delta_B + \delta_D) \cos(\gamma)$$

$$A_{ADS} = \frac{N(B^- \to DK^-) - N(B^+ \to DK^+)}{N(B^- \to DK^-) + N(B^+ \to DK^+)} = \frac{2\, r_B\, r_D \sin(\delta_B + \delta_D) \sin(\gamma)}{R_{ADS}}$$

  - External inputs: r_D, δ_D
  - Measure yields of favoured and suppressed decays
  - Measure rate asymmetries between B^- and B^+
  - Maximal interference due to similar sized amplitudes



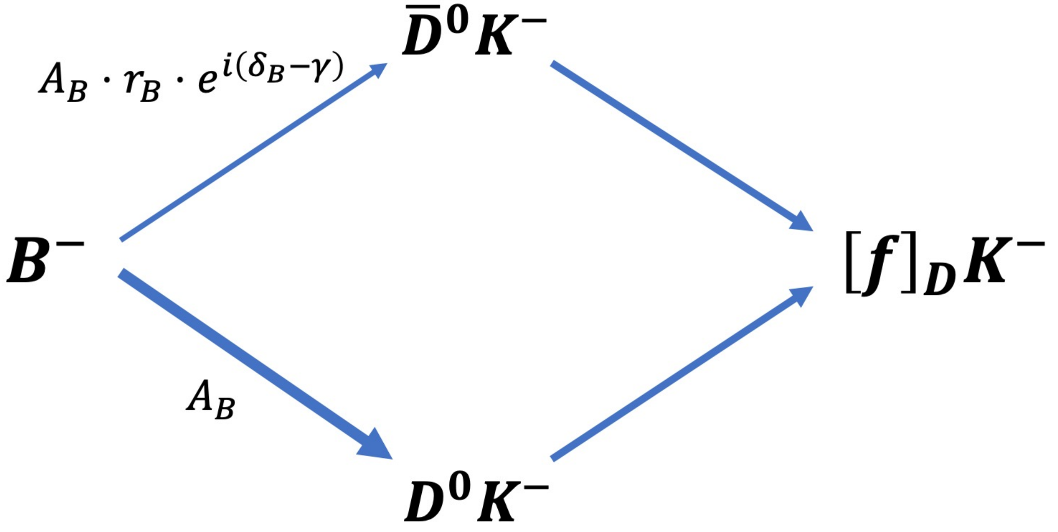
[4] Phys. Lett. **B253** (1991) 483
[5] Phys. Lett. **B265** (1991) 172

- **GLW[4,5] decays**
  - **CP eigenstates**: $D \to K^- K^+, D \to \pi^- \pi^+$

$$R_{CP+} = \frac{N(B \to [KK]_D K)}{N(B \to [K\pi]_D K)} \frac{\Gamma(D \to K\pi)}{\Gamma(D \to KK)} = 1 + r_B^2 + 2\, r_B \cos(\delta_B) \cos(\gamma)$$

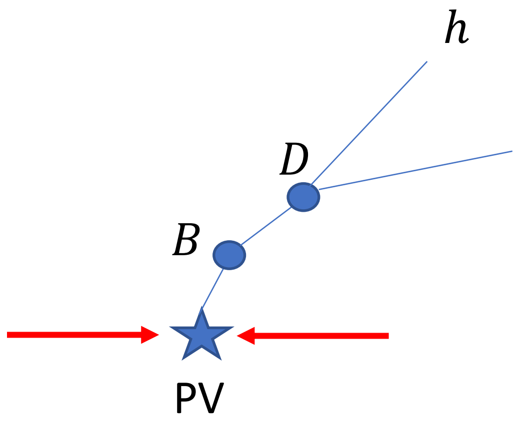
$$A_{CP+} = \frac{N(B^- \to DK^-) - N(B^+ \to DK^+)}{N(B^- \to DK^-) + N(B^+ \to DK^+)} = \frac{2\, r_B \sin(\delta_B) \sin(\gamma)}{R_{CP+}}$$

  - Relatively smaller observable CP violation due to amplitudes of different sizes



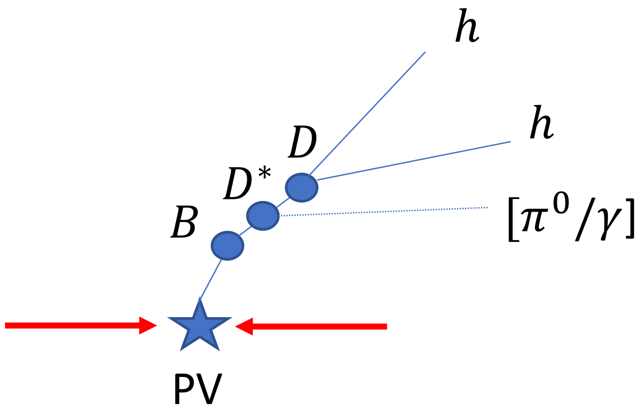
- ADS/GLW analysis in $B^{\pm} \to D^{(*)}h^{\pm}$ decays

- **Partially reconstructed** $D^* \to D^0\ [\pi^0/\gamma]$ **included as signal**
    - Larger yields using the partial reconstruction method
    - Measurements of the ADS $B^{\pm} \to D^* h^{\pm}$ first of their kind



- 28 CP observables measured with world-best precision

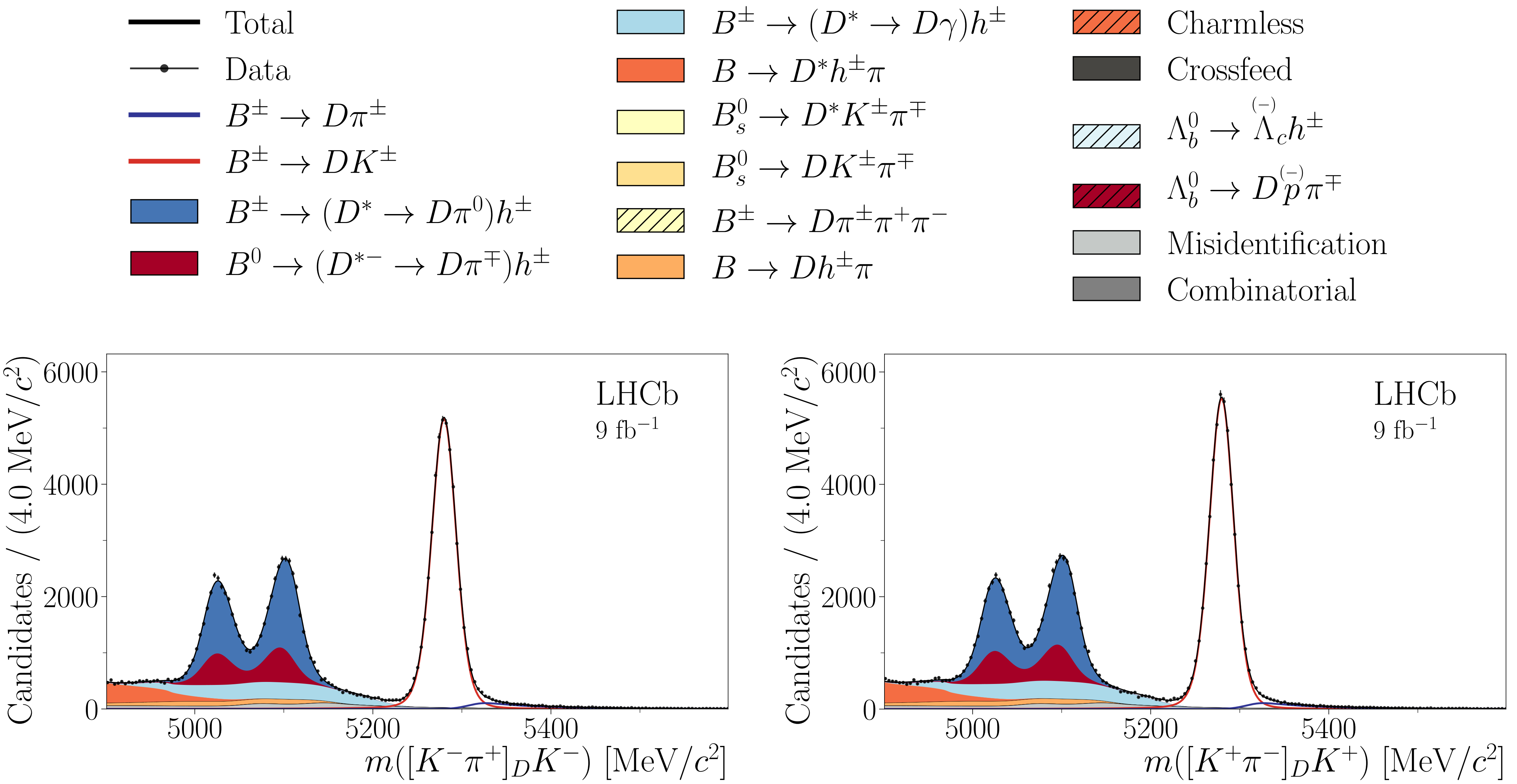
$$A_K^{CP,\gamma} = \frac{\Gamma(B^- \to ([h^+h^-]_D\gamma)_{D^*}K^-) - \Gamma(B^+ \to ([h^+h^-]_D\gamma)_{D^*}K^+)}{\Gamma(B^- \to ([h^+h^-]_D\gamma)_{D^*}K^-) + \Gamma(B^+ \to ([h^+h^-]_D\gamma)_{D^*}K^+)}$$



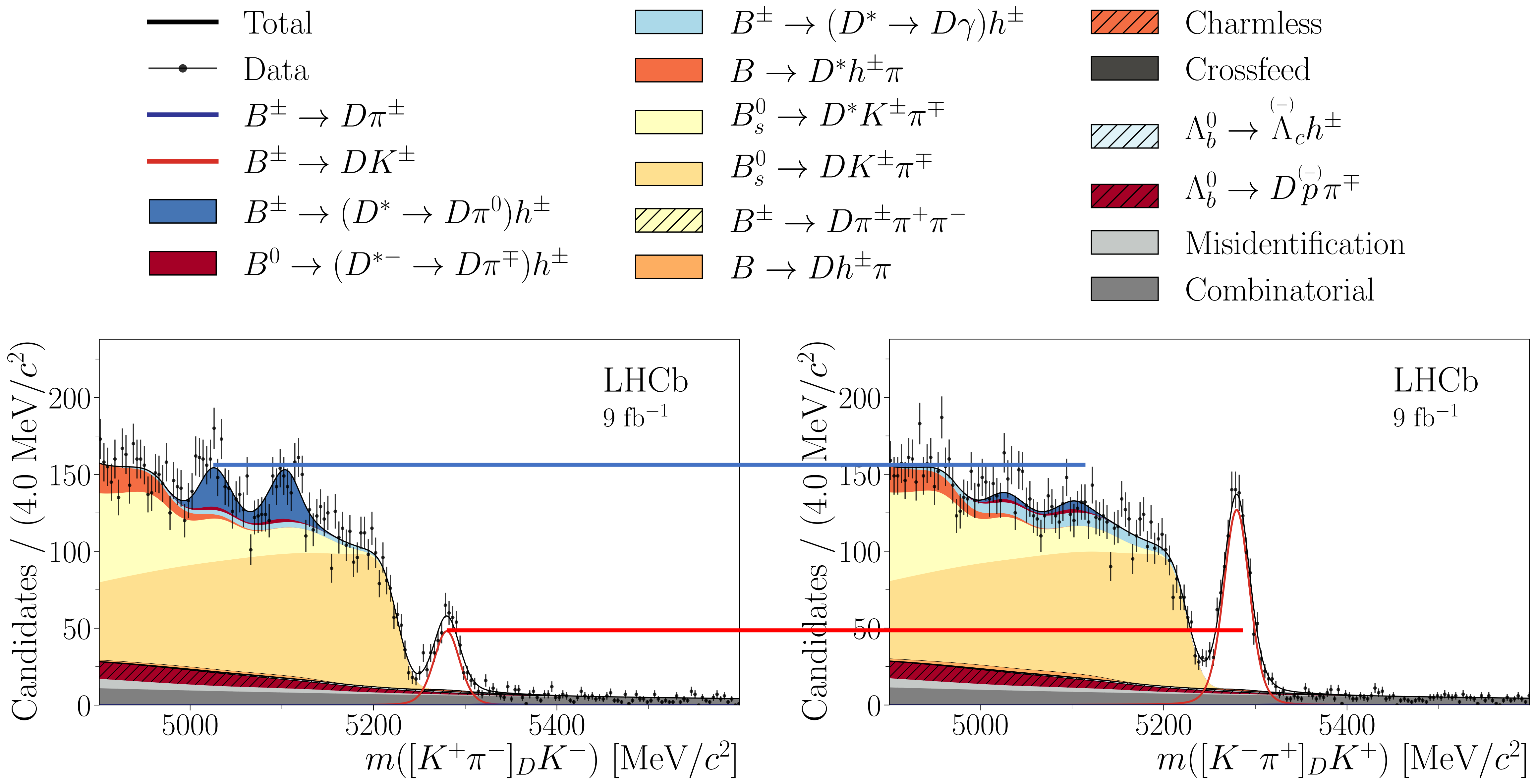
- **First observation** of the ADS $B^{\pm} \to (D\pi^0)_{D^*}\pi^{\pm}$ decay with a 6.1σ significance

$B^\pm \to D^{(*)}K^\pm$, $D \to K^\pm\pi^\mp$

JHEP **04** (2020) 081

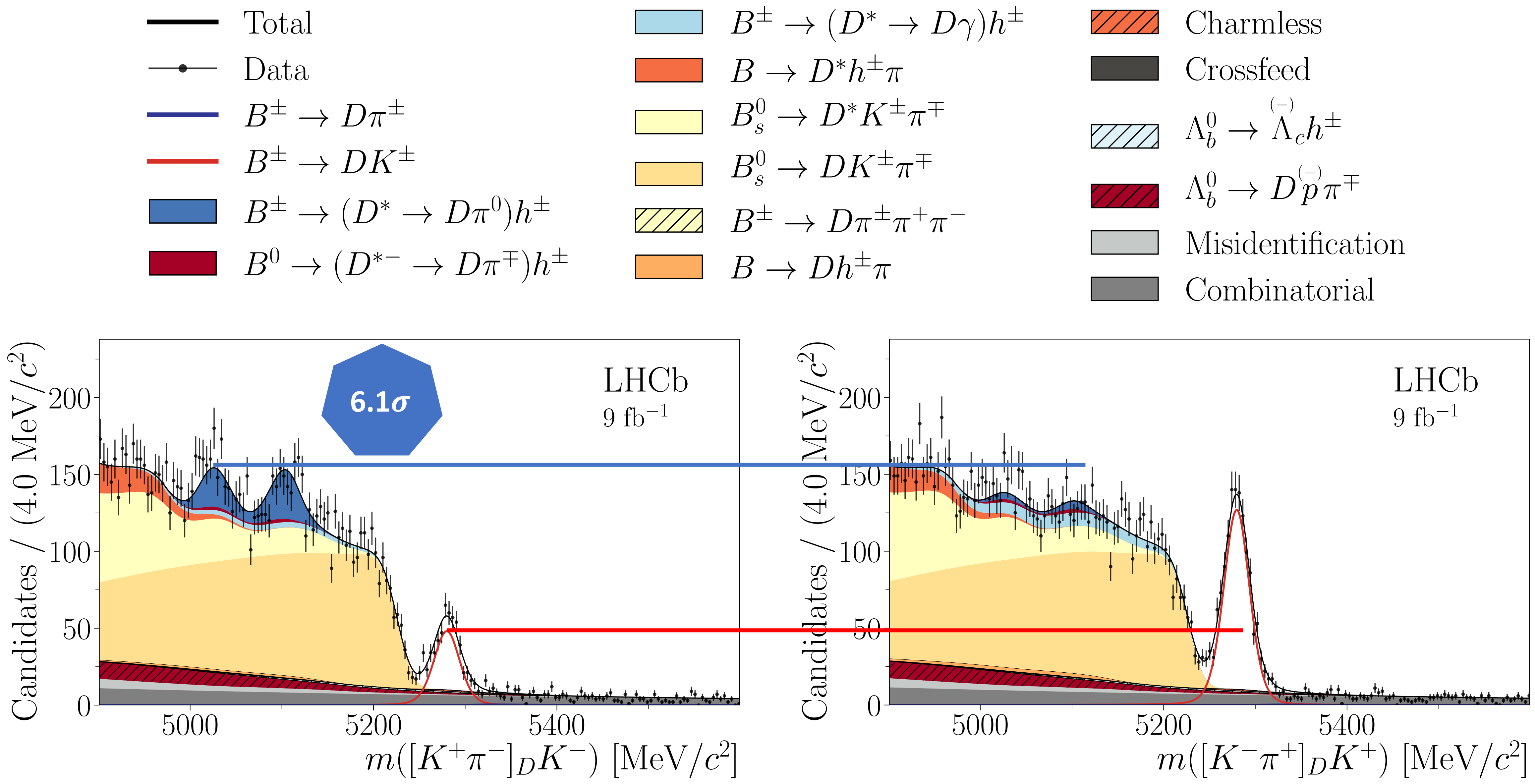


JHEP **04** (2020) 081



$B^\pm \to D^{(*)}K^\pm$, $D \to K^\mp\pi^\pm$

JHEP **04** (2020) 081



$B^{\pm} \to D^{(*)}K^{\pm}$, $D \to h^+h^-$

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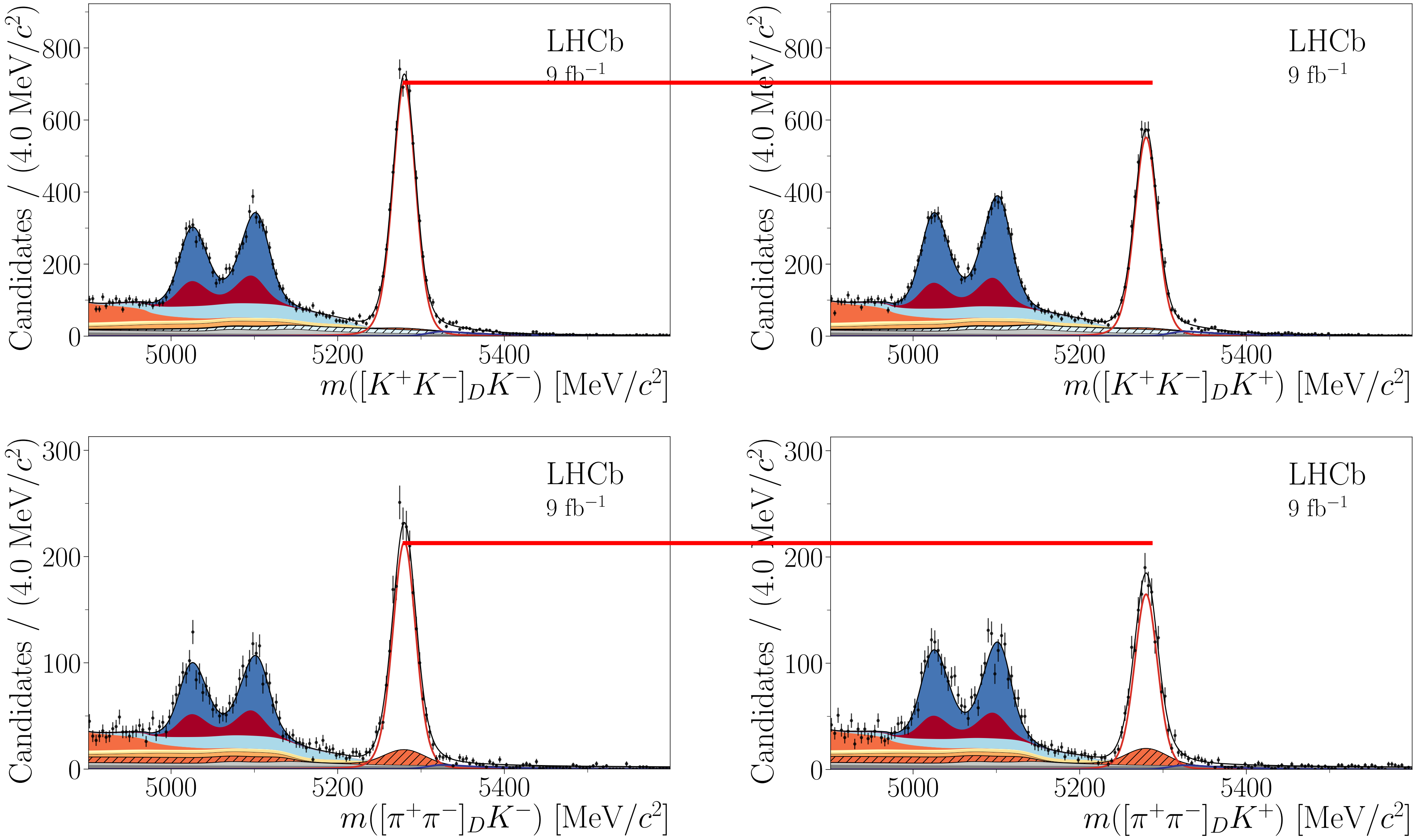


$B^{\pm} \to DK^{\pm}$: interpretation

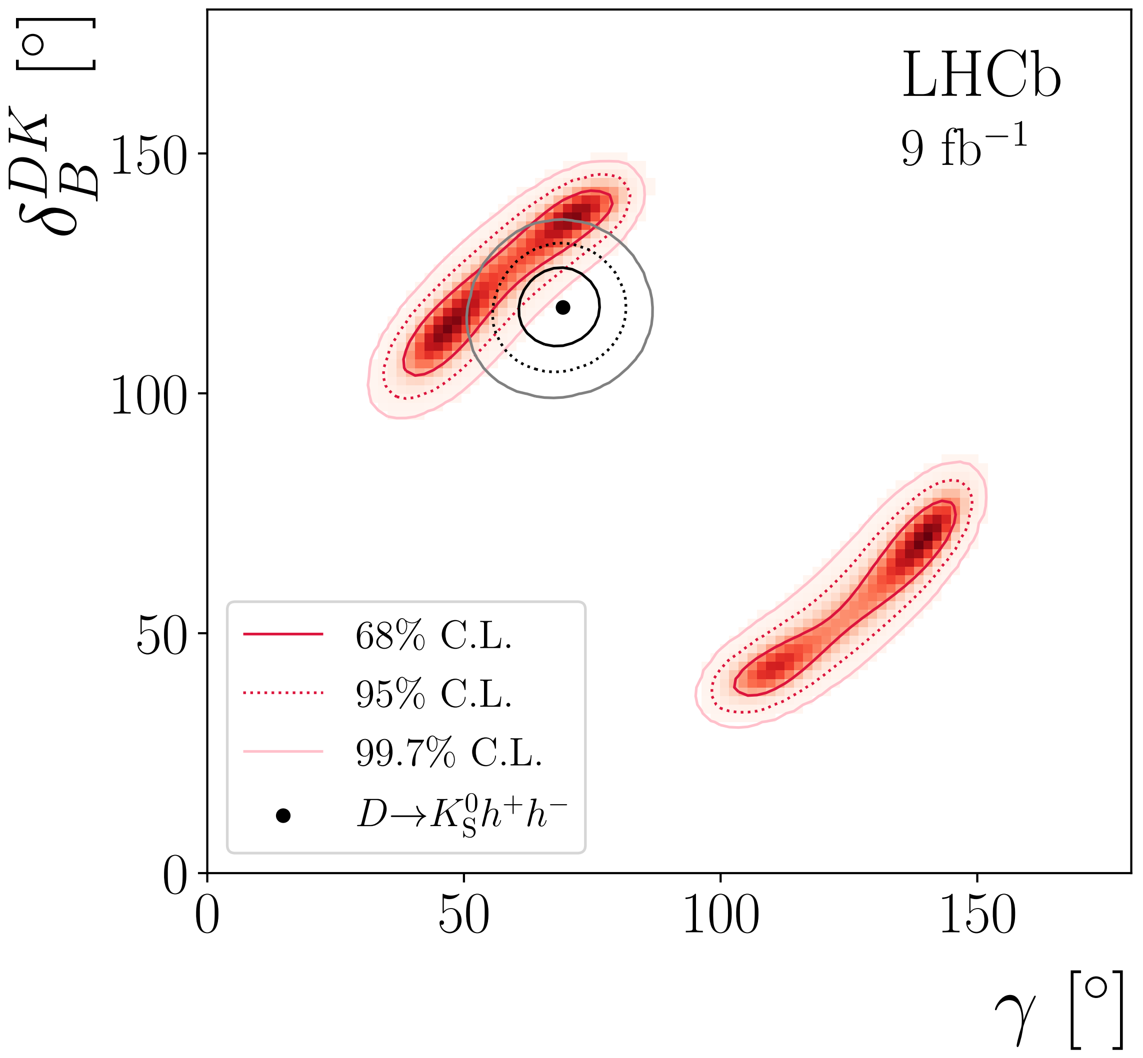
JHEP **04** (2020) 081
[6] Eur. Phys. J. **C81** (2021) 226, https://hflav.web.cern.ch

- **Multiple solutions** due to the trigonometric nature of the equations that relate the CP observables to the physics parameters of interest

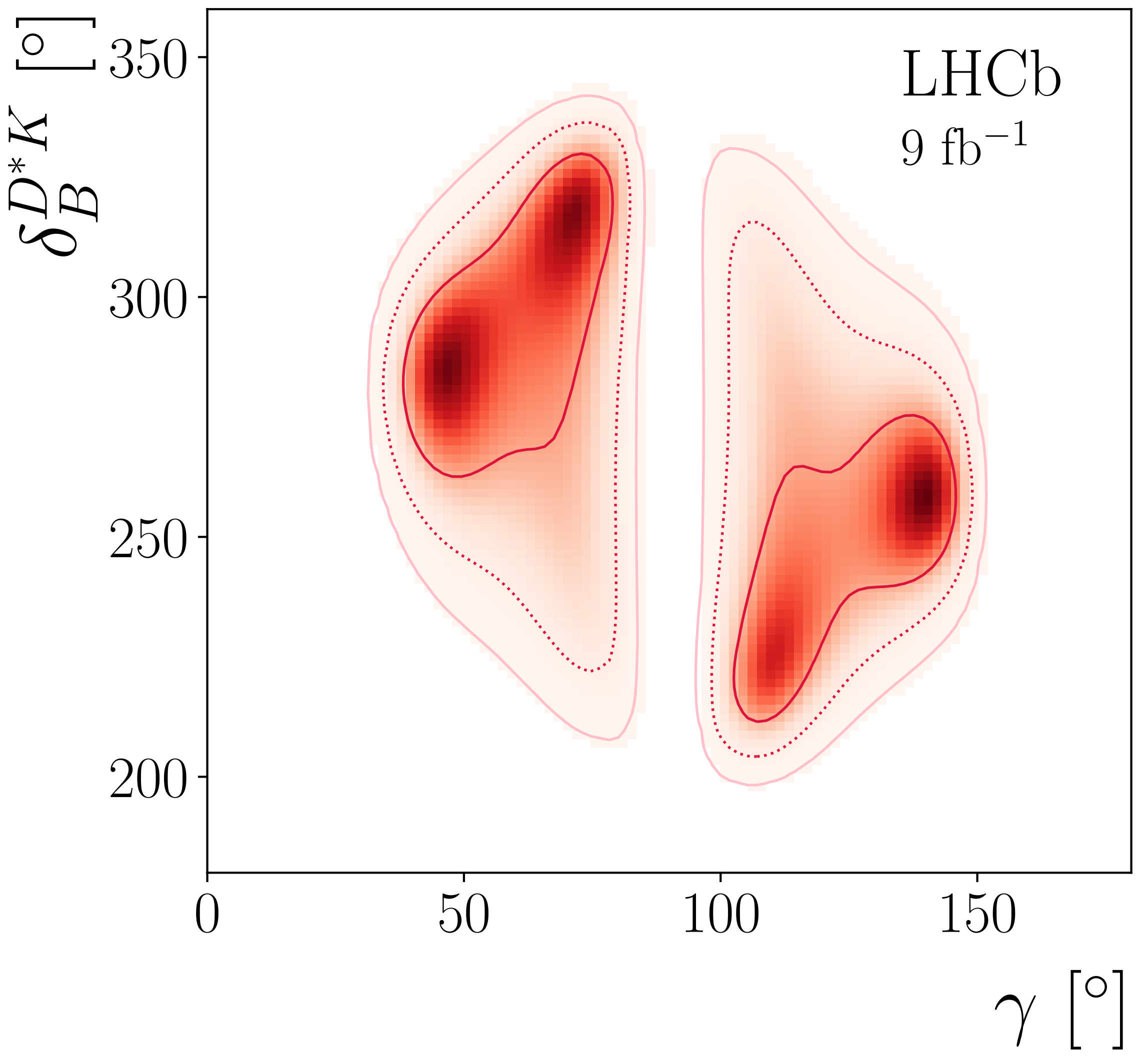
- **External inputs** needed for r_D, δ_D, charm mixing[6]

- In order to break the multiple solutions, combine with results from $D \to K_S^0 h^+ h^-$, yielding:

$$\gamma = (61.8 \pm 4.0)^{\circ}$$



- **Multiple solutions** due to the trigonometric nature of the equations that relate the CP observables to the physics parameters of interest
- **External inputs** needed for r_D, δ_D, charm mixing
- The multiple solutions cannot be broken yet
- Work ongoing on the corresponding $D \to K_S^0 h^+ h^-$ decays in order to be able to add a constraint for $B \to D^* h$ decays



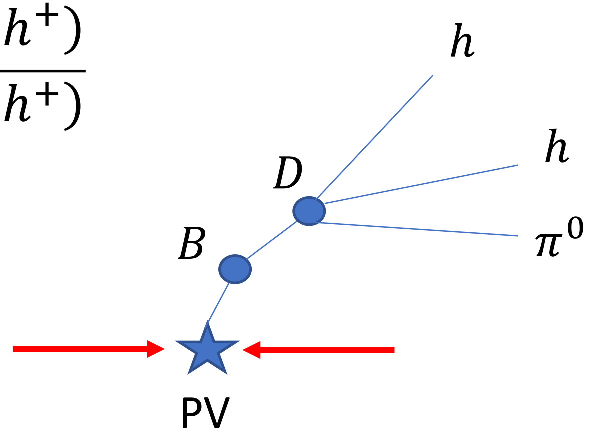
$B^{\pm} \to Dh^{\pm}$, $D \to h^{\pm}h^{\mp}\pi^0$

LHCb-PAPER-2021-036 (in preparation)
[7] JHEP **05** (2021) 164

- ADS modes

$$R_{ADS(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^+ \to [\pi^+ K^- \pi^0]_D h^+)}{\Gamma(B^- \to [K^- \pi^+ \pi^0]_D h^-) + \Gamma(B^+ \to [K^+ \pi^- \pi^0]_D h^+)}$$

$$A_{ADS(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) - \Gamma(B^+ \to [\pi^+ K^- \pi^0]_D h^+)}{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^+ \to [\pi^+ K^- \pi^0]_D h^+)}$$



- Admixtures of CP-even and CP-odd eigenstates: **quasi-GLW**
  - Dilution factors as external inputs (measured at CLEO-c and BESIII using correlated $D\overline{D}$ pairs at the $\psi(3770)$ resonance[7])

$$R_{K/\pi}^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D K^-) + \Gamma(B^+ \to [hh\pi^0]_D K^+)}{\Gamma(B^- \to [hh\pi^0]_D \pi^-) + \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}$$

$$R_{F+}^{KK\pi^0} \approx R_{K/\pi}^{KK\pi^0} / R_{K/\pi}^{K\pi\pi^0}$$

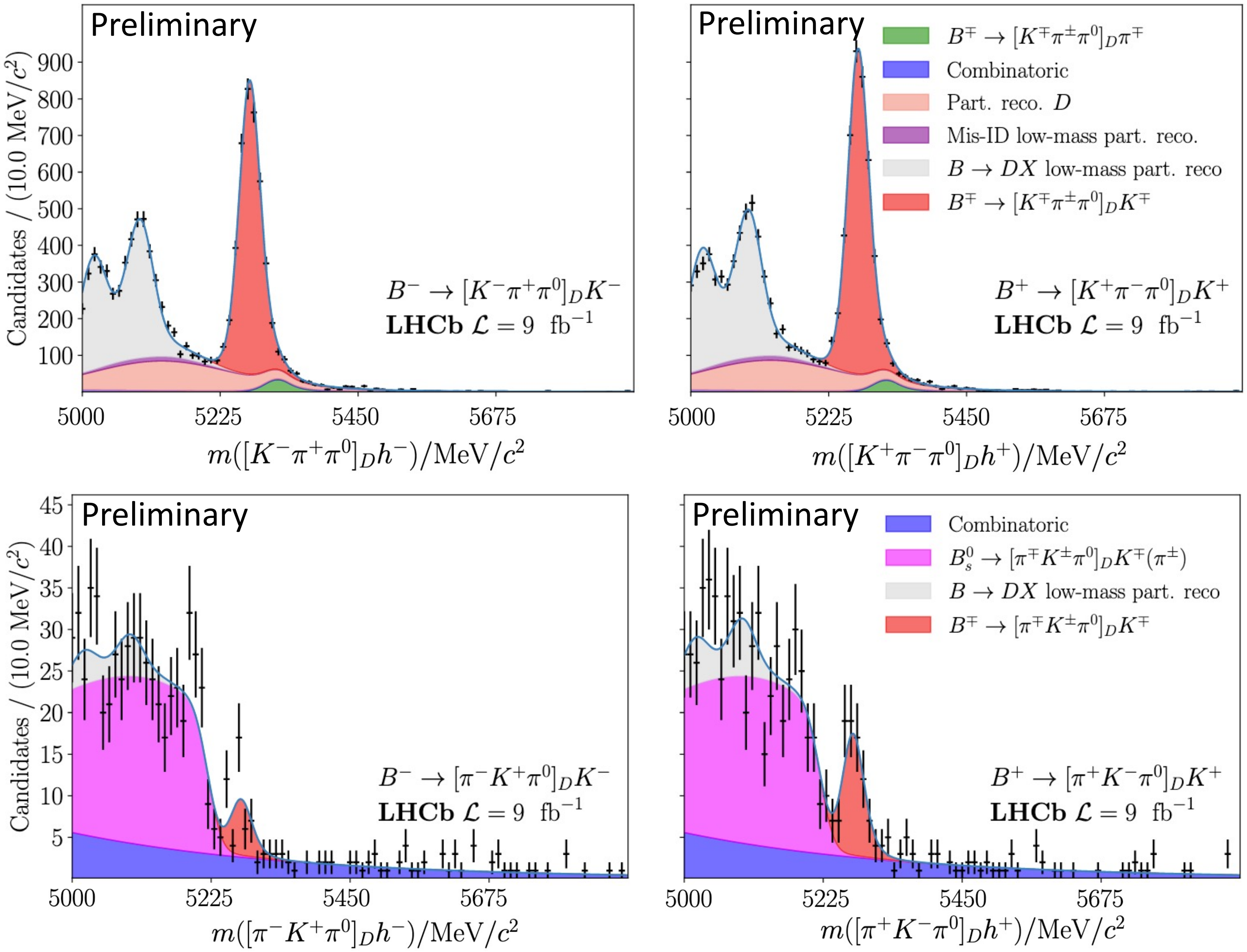
$$R_{F+}^{\pi\pi\pi^0} \approx R_{K/\pi}^{\pi\pi\pi^0} / R_{K/\pi}^{K\pi\pi^0}$$

$$A_{F+(h)}^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D h^-) - \Gamma(B^+ \to [hh\pi^0]_D h^+)}{\Gamma(B^- \to [hh\pi^0]_D h^-) + \Gamma(B^+ \to [hh\pi^0]_D h^+)}$$

- **First observation** of the suppressed mode with >7.0σ significance

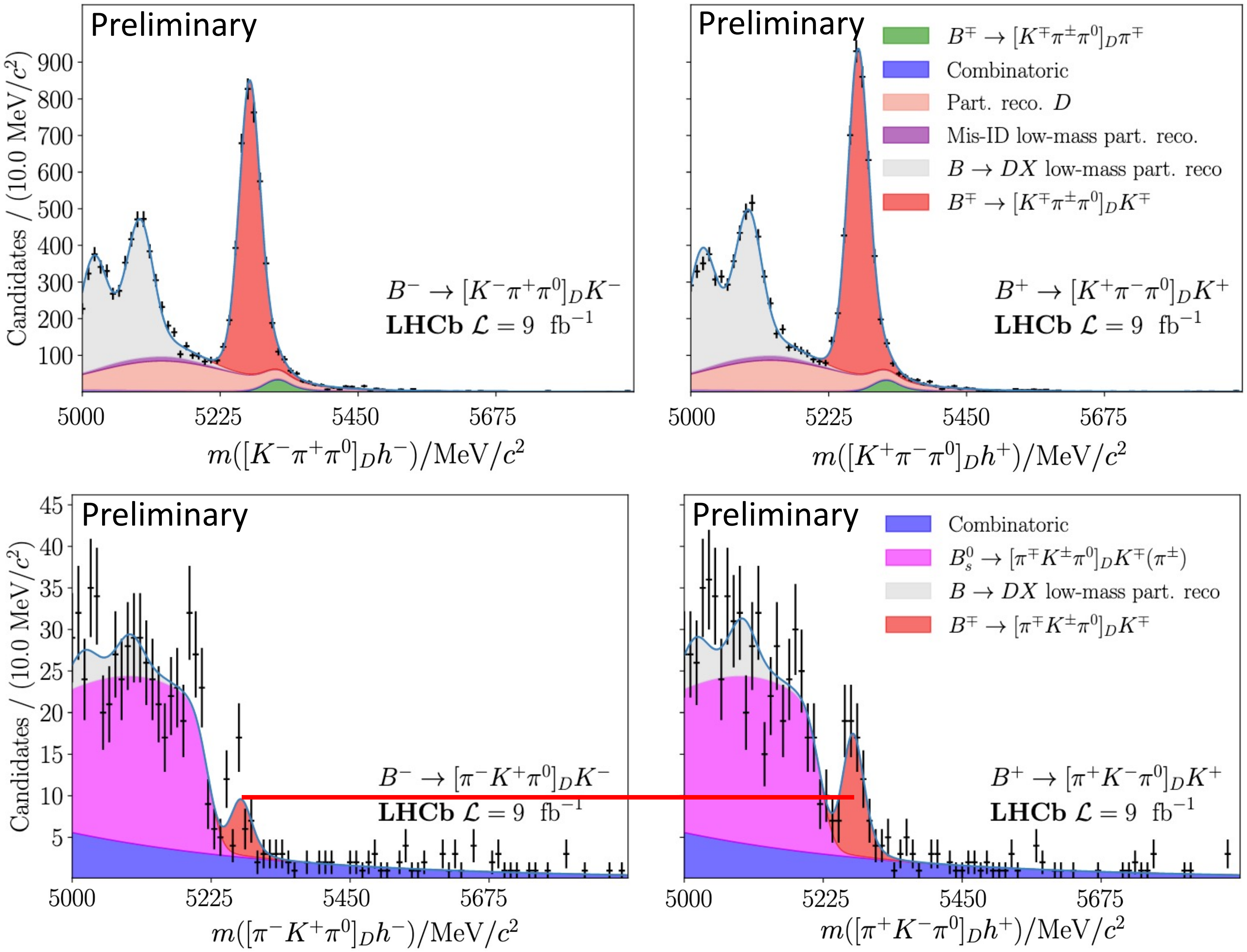
$B^{\pm} \to D h^{\pm}$, $D \to h^{\pm} h^{\mp} \pi^{0}$

LHCb-PAPER-2021-036 (in preparation)



$B^{\pm} \to Dh^{\pm}$, $D \to h^{\pm}h^{\mp}\pi^{0}$

LHCb-PAPER-2021-036 (in preparation)



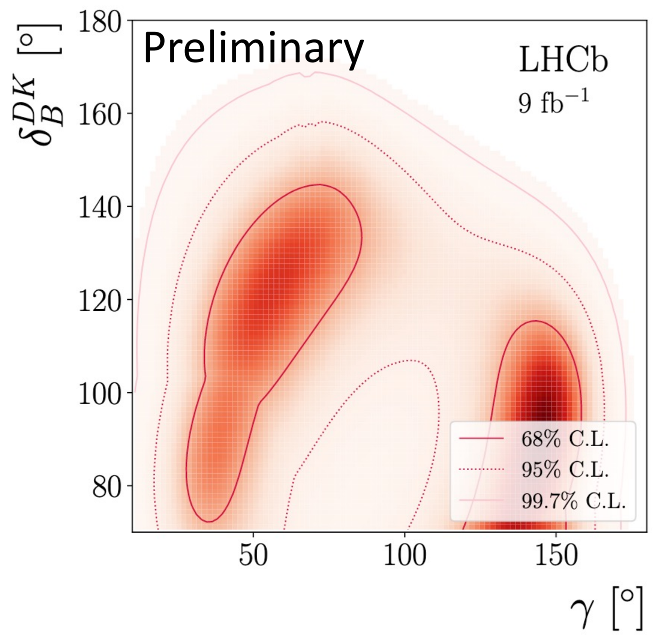
>7.0σ

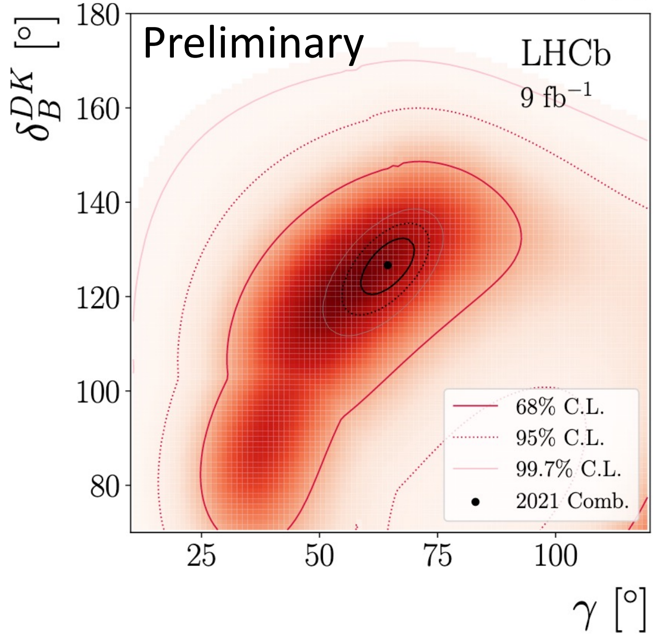
- Profile likelihood method to evaluate the confidence intervals
- **Multiple solutions** expected due to the trigonometric nature of the equations that relate the CP observables to the physics parameters of interest
- Global minimum at $\gamma = (145^{+9}_{-39})°$
- Second solution in good agreement with the current value of γ

$$\gamma = (56^{+24}_{-19})°$$

$$\delta_B = (122^{+19}_{-23})°$$

$$r_B = \left(9.25^{+1.04}_{-0.85}\right) \times 10^{-2}$$





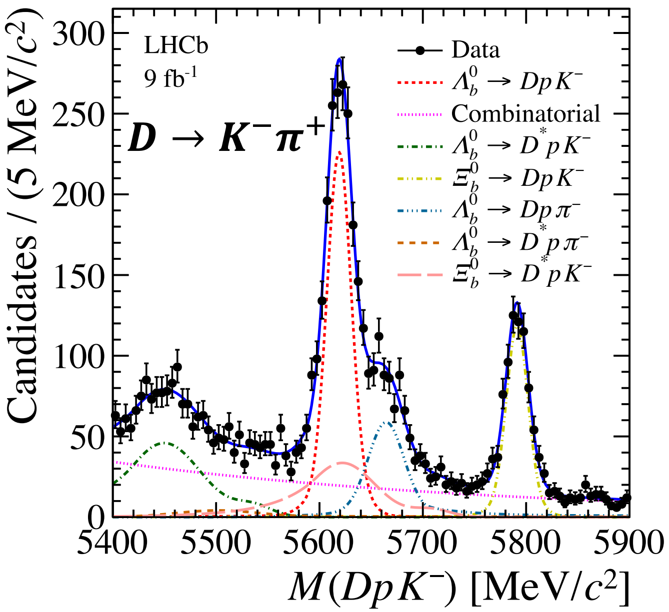
$\Lambda_b^0 \to DpK^-, D \to K\pi$

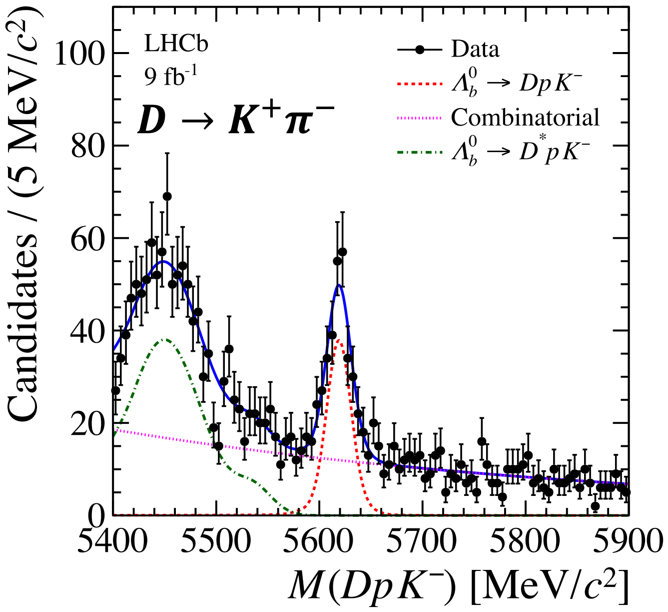
arXiv:2109.02621

- **First observation** of the suppressed $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ decay

- Branching fraction ratio measurement

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to [K^-\pi^+]_D pK^-)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-)}$$



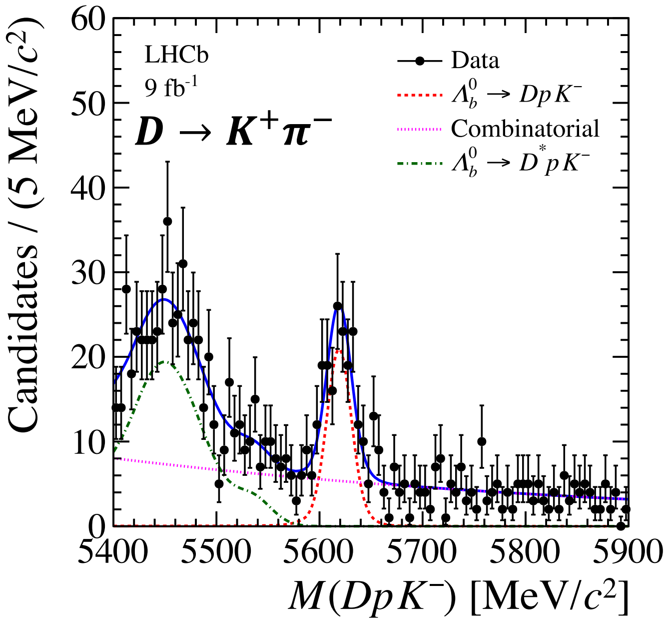


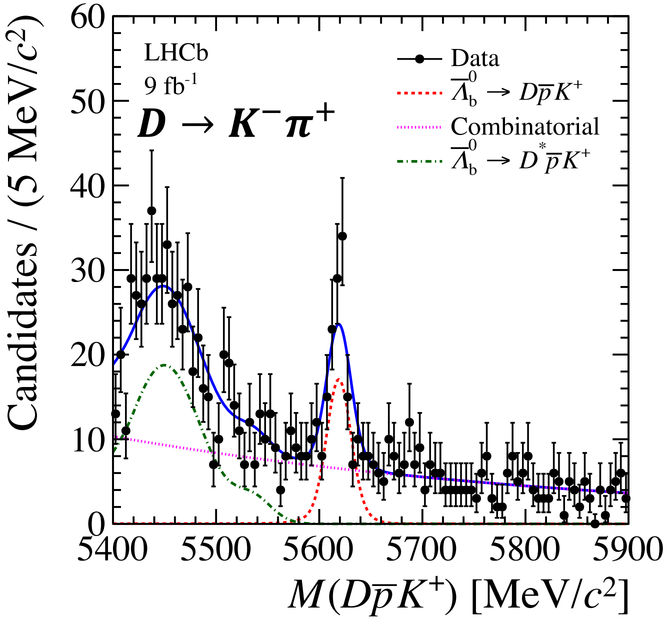
$\Lambda_b^0 \to DpK^-, D \to K\pi$

arXiv:2109.02621

- CP asymmetry measurement

$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}$$





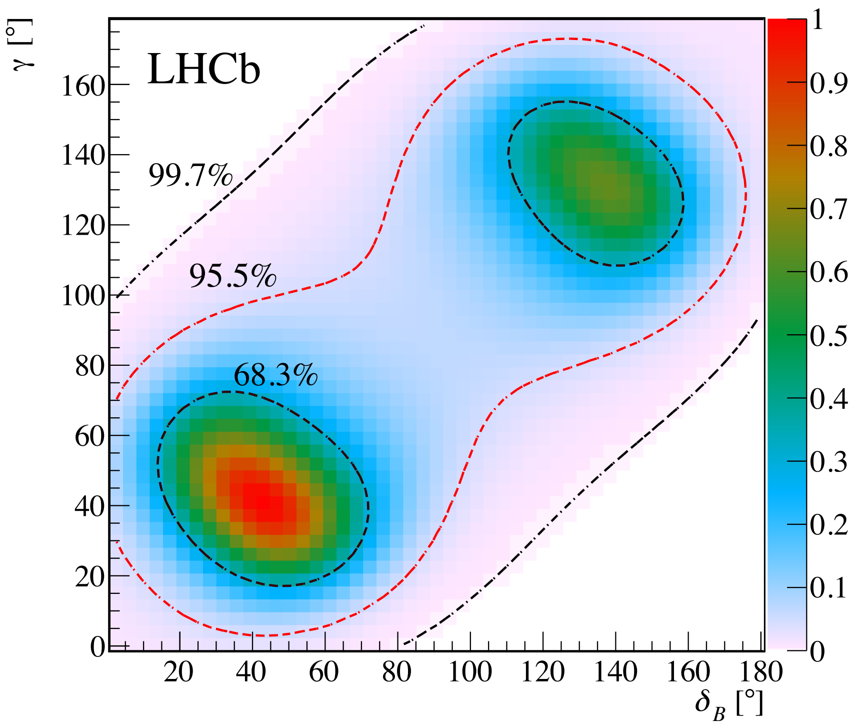
- **Towards sensitivity to γ**: higher yields and more decay modes will improve sensitivity to γ

- Interesting to study CP violation in baryons, which is under studied compared to the meson sector

[8] JHEP **11** (2017) 156

- **Ongoing analyses** with the full Run 1+2 LHCb dataset such as in $B \to DK^*$ decays
- Strategy to cover all B and D decay **combinations** to improve sensitivity to γ, e.g. using $B^\pm \to DK^{*\pm}$ decays
- Important to perform analyses in sub-dominant channels as systematic uncertainties and backgrounds are different and therefore provide **further constraints and cross-checks**
- Future γ combinations will include recent and future results to **further improve precision** on γ

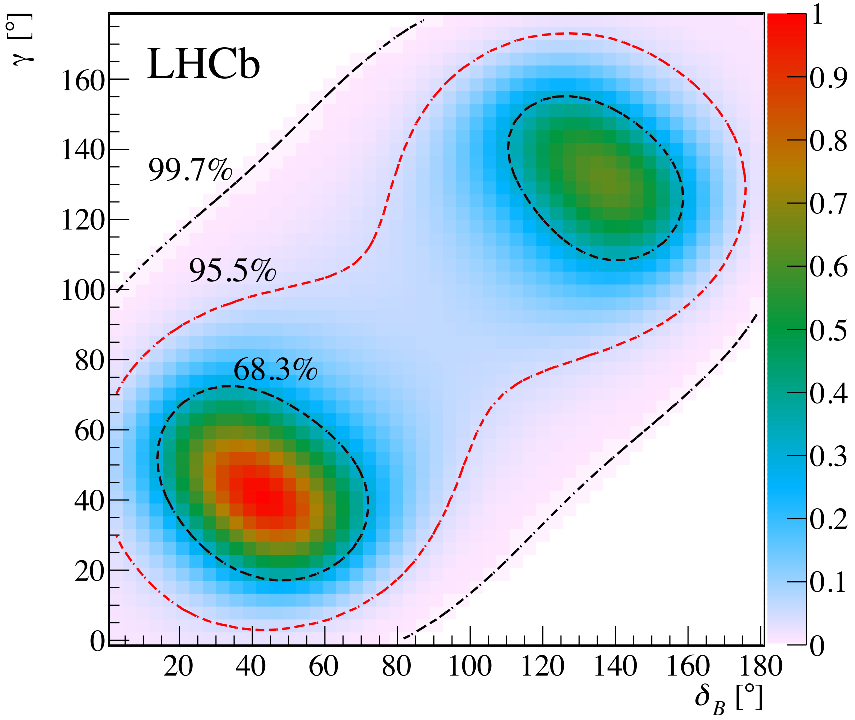
$B^\pm \to DK^{*\pm}$ (partial Run 2 result[8])



[9] Eur. Phys. J. **C73** (2013) 2373
[10] arXiv:1808.08865

- **Ongoing analyses** with the full Run 1+2 LHCb dataset such as in $B \to DK^*$ decays
- Strategy to cover all B and D decay **combinations** to improve sensitivity to γ, e.g. using $B^\pm \to DK^{*\pm}$ decays
- Important to perform analyses in sub-dominant channels as systematic uncertainties and backgrounds are different and therefore provide **further constraints and cross-checks**
- Future γ combinations will include recent and future results to **further improve precision** on γ
- More data to be collected during Run 3 and beyond with expectations[9,10] to measure γ with a precision of less than 1°

$B^\pm \to DK^{*\pm}$ (partial Run 2 result)



Precision in 2013	LHCb 2018	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
~10–12°	4°	1°	0.35°

Conclusions

- Recent ADS/GLW measurements from LHCb presented
  - $B^{\pm} \to D^{(*)}h^{\pm}, D \to h^{+}h^{-}$ JHEP **04** (2020) 081
  - $B^{\pm} \to Dh^{\pm}, D \to h^{\pm}h^{\mp}\pi^{0}$ LHCb-PAPER-2021-036 (in preparation)
  - $\Lambda_b^0 \to DpK^{-}, D \to K\pi$ arXiv:2109.02621
- First observations of suppressed modes
- Strong constraints added to γ and expected sensitivity for Run 1-2 of about $4°$ achieved
- Most recent and future results will contribute to the next γ combinations
- Future runs will provide more data and allow for more precise measurements ($< 1°$) to test the Standard Model