Recent measurements of the CKM angle γ at LHCb

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on behalf of the LHCb collaboration

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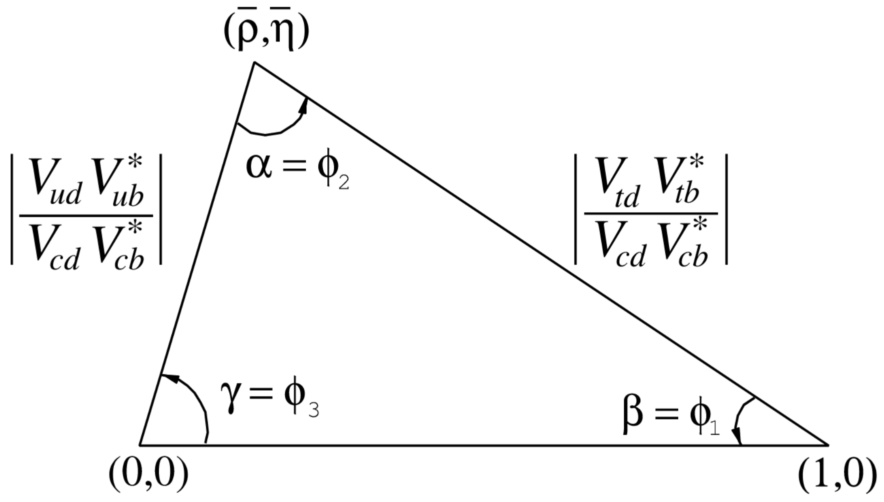
[1] Phys. Rev. **D98** (2018) 030001
[2] JHEP **01** (2014) 051

- 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**

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



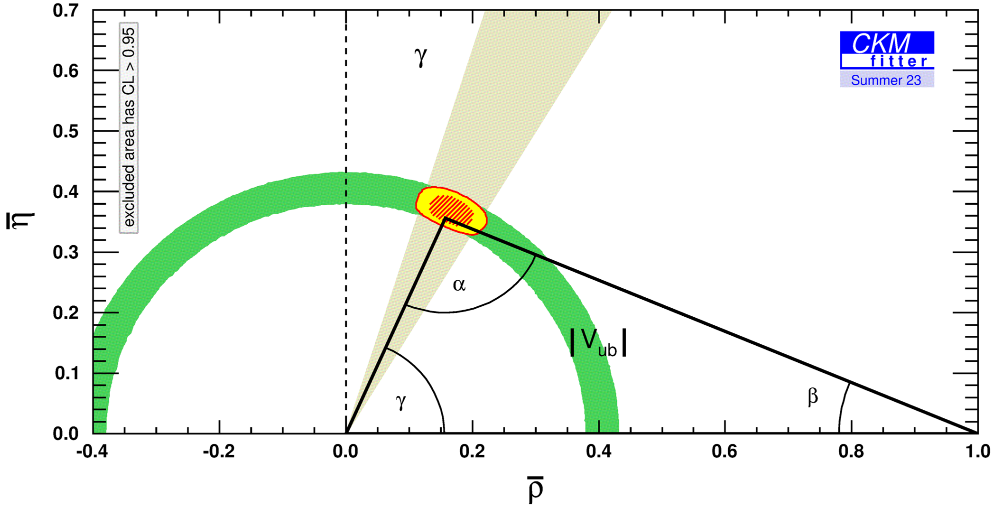
- Weak phase $\boldsymbol{\gamma}$ is the only angle **easily accessible at tree level**

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

- Hadronic parameters can be determined from data
  => **theoretical uncertainty** within the Standard Model on γ is **negligible**[2]

[3] Phys. Rev. **D91** (2015) 073007, http://ckmfitter.in2p3.fr/
[4] Phys. Rev. **D107** (2023) 052008 (arXiv:2206.07501)

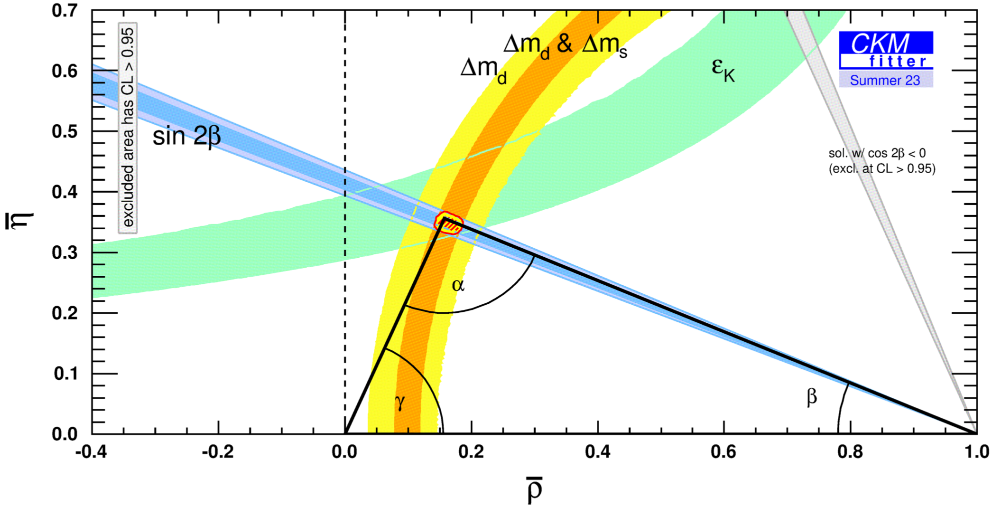
Tree-level (direct measurement)[3]



$$\gamma = \left(66.4^{+2.8}_{-3.0}\right)^\circ$$

World average (HFLAV[4])

Loop-level (indirect measurement)[3]

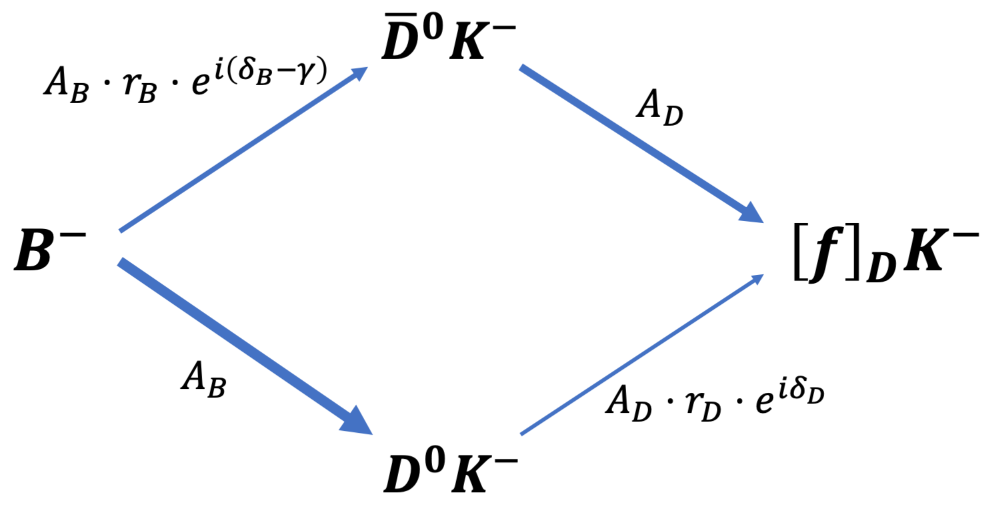


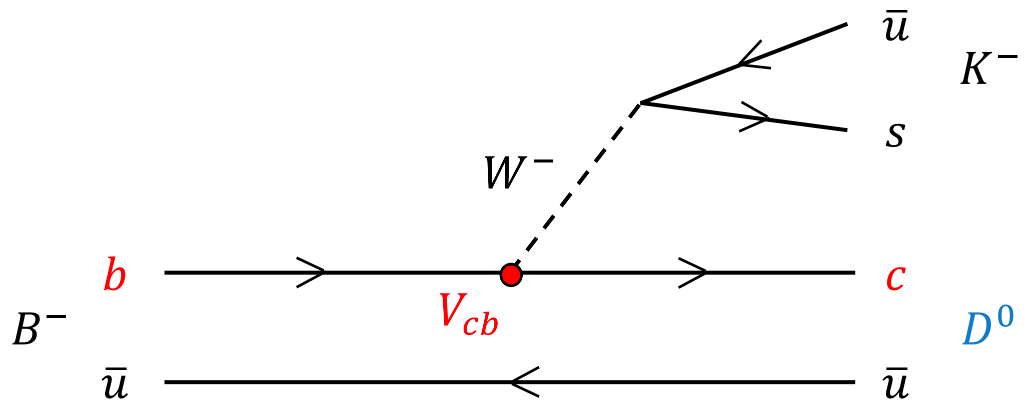
$$\gamma = \left(66.29^{+0.72}_{-1.86}\right)^\circ$$

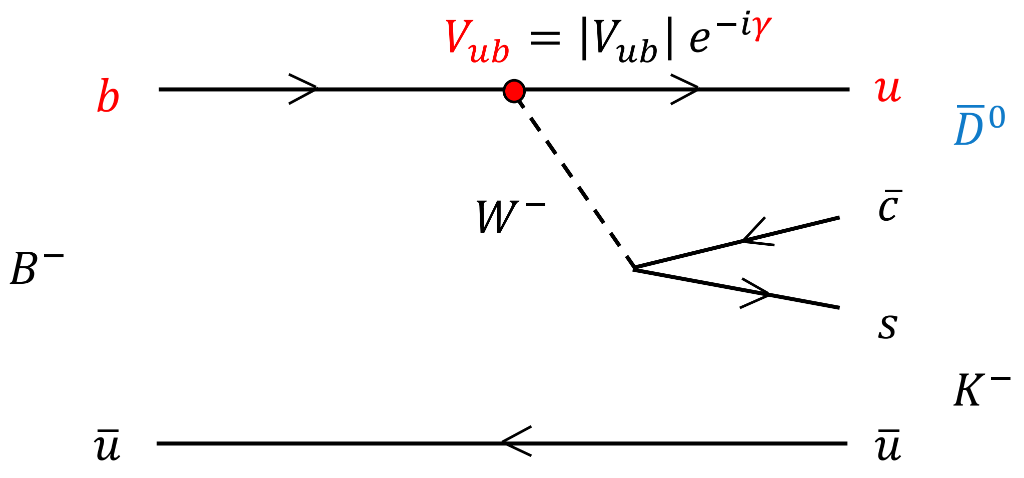
- Direct measurements of γ at tree level are expected to be benchmarks of the Standard Model
- Indirect measurements consist of global fits to the unitary triangle. Inputs include loop processes, where New Physics effects are expected to contribute

A discrepancy between direct and indirect measurements would be a clear sign of New Physics

- The D meson is a superposition of D^0 and $\bar{D}^0$ states, which are reconstructed in common final states
- Both D^0 and $\bar{D}^0$ need to be able to decay to the same final state
- Interference between $b \to cW$ and $b \to uW$ transitions gives sensitivity to γ





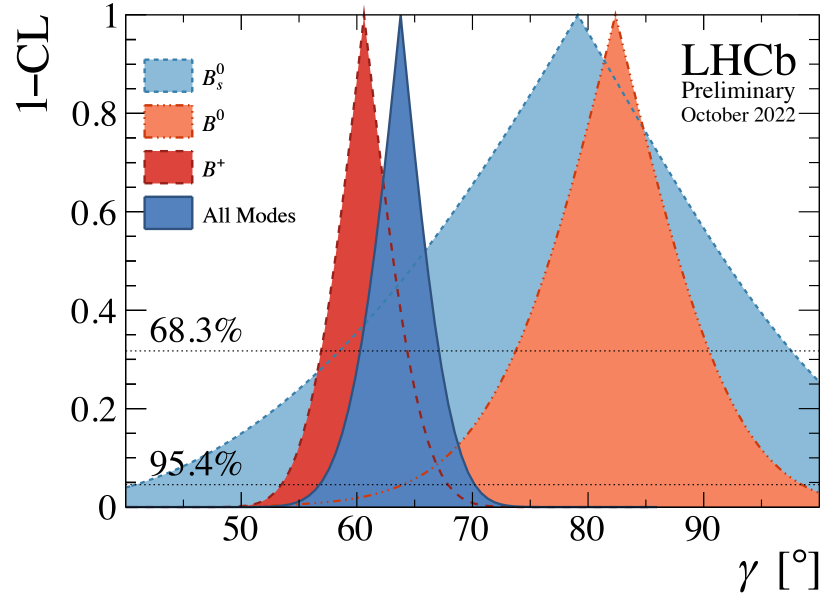


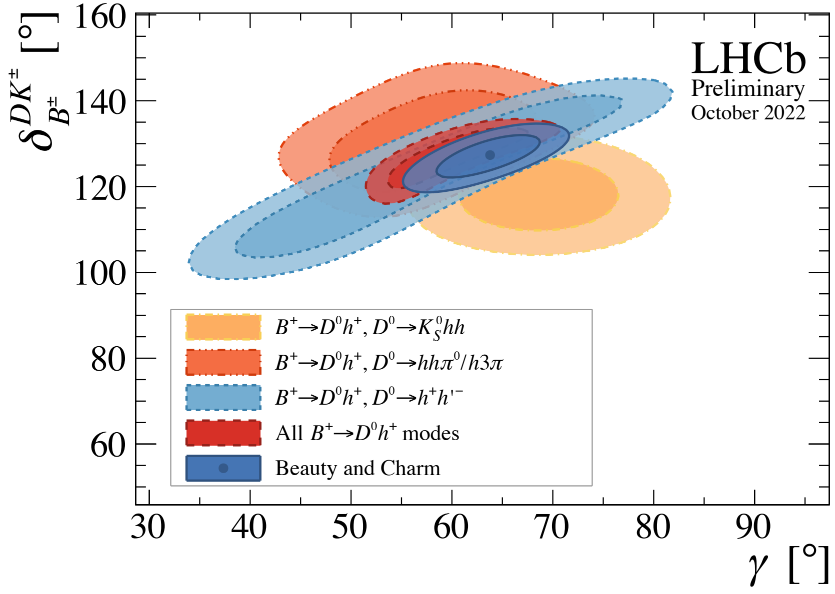
[5] LHCb-CONF-2022-003
[6] JHEP **02** (2021) 169

- LHCb γ+charm combination[5] 2022

$$\boldsymbol{\gamma = (63.8^{+3.5}_{-3.7})^\circ}$$

- Expected sensitivity for Run 1-2 of about 4° surpassed
- World average dominated by LHCb
- Golden channel: $B^\pm \to DK^\pm$
  - Most precise measurement from a single analysis to date in $B^\pm \to [K_s h^+ h^-]_D\, h'^\pm$ decays at LHCb[6]: $\gamma = (68.7^{+5.2}_{-5.1})^\circ$
- Strategy to cover all B and D decay **combinations** to improve overall sensitivity to γ
- Important to perform analyses in sub-dominant channels to provide further constraints and cross-checks
  - Different systematic uncertainties (important for the future)
  - Different background contributions





- LHCb γ+charm combination[7] 2024 includes recent measurements

- Recent measurements with other B decays
  - $B^{\pm} \to D^{*} K^{\pm}$
  - $B^{0} \to D K^{*0}$
  - $B^{\pm} \to D K^{*\pm}$

- Different families of D decays used
  - $D \to h^{+}h^{-}(h^{+}h^{-})$: narrow but multiple solutions
  - $D \to K_S^0 h^{+}h^{-}$: wide single solution

- Time-dependent measurement
  - $B_s^0 \to D_s^{\mp} K^{\pm}$

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^{\pm} \to D h^{\pm}$	$D \to h^{\pm} h'^{\mp}$	[35]	Run 1&2	*As before*
$B^{\pm} \to D h^{\pm}$	$D \to h^{+} h^{-} \pi^{+} \pi^{-}$	[19]	Run 1&2	**New**
$B^{\pm} \to D h^{\pm}$	$D \to K^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$	[36]	Run 1&2	*As before*
$B^{\pm} \to D h^{\pm}$	$D \to h^{\pm} h'^{\mp} \pi^{0}$	[37]	Run 1&2	*As before*
$B^{\pm} \to D h^{\pm}$	$D \to K_S^0 h^{+} h^{-}$	[38]	Run 1&2	*As before*
$B^{\pm} \to D h^{\pm}$	$D \to K_S^0 K^{\pm} \pi^{\mp}$	[39]	Run 1&2	*As before*
$B^{\pm} \to D^{*} h^{\pm}$	$D \to h^{\pm} h'^{\mp}$ (PR)	[35]	Run 1&2	*As before*
$B^{\pm} \to D^{*} h^{\pm}$	$D \to K_S^0 h^{+} h^{-}$ (PR)	[20]	Run 1&2	**New**
$B^{\pm} \to D^{*} h^{\pm}$	$D \to K_S^0 h^{+} h^{-}$ (FR)	[21]	Run 1&2	**New**
$B^{\pm} \to D K^{*\pm}$	$D \to h^{\pm} h'^{\mp}$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to D K^{*\pm}$	$D \to h^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$	[22]†	Run 1&2	**Updated**
$B^{\pm} \to D K^{*\pm}$	$D \to K_S^0 h^{+} h^{-}$	[22]†	Run 1&2	**New**
$B^{\pm} \to D h^{\pm} \pi^{+} \pi^{-}$	$D \to h^{\pm} h'^{\mp}$	[40]	Run 1	*As before*
$B^{0} \to D K^{*0}$	$D \to h^{\pm} h'^{\mp}$	[23]	Run 1&2	**Updated**
$B^{0} \to D K^{*0}$	$D \to h^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$	[23]	Run 1&2	**Updated**
$B^{0} \to D K^{*0}$	$D \to K_S^0 h^{+} h^{-}$	[24]	Run 1&2	**Updated**
$B^{0} \to D^{\mp} \pi^{\pm}$	$D^{+} \to K^{-} \pi^{+} \pi^{+}$	[41]	Run 1	*As before*
$B_s^0 \to D_s^{\mp} K^{\pm}$	$D_s^{+} \to h^{+} h^{-} \pi^{+}$	[25, 42]†	Run 1&2	**Updated**
$B_s^0 \to D_s^{\mp} K^{\pm} \pi^{+} \pi^{-}$	$D_s^{+} \to h^{+} h^{-} \pi^{+}$	[43]	Run 1&2	*As before*

[8] Phys. Lett. B **253** (1991) 483
[9] Phys. Lett. B **265** (1991) 172

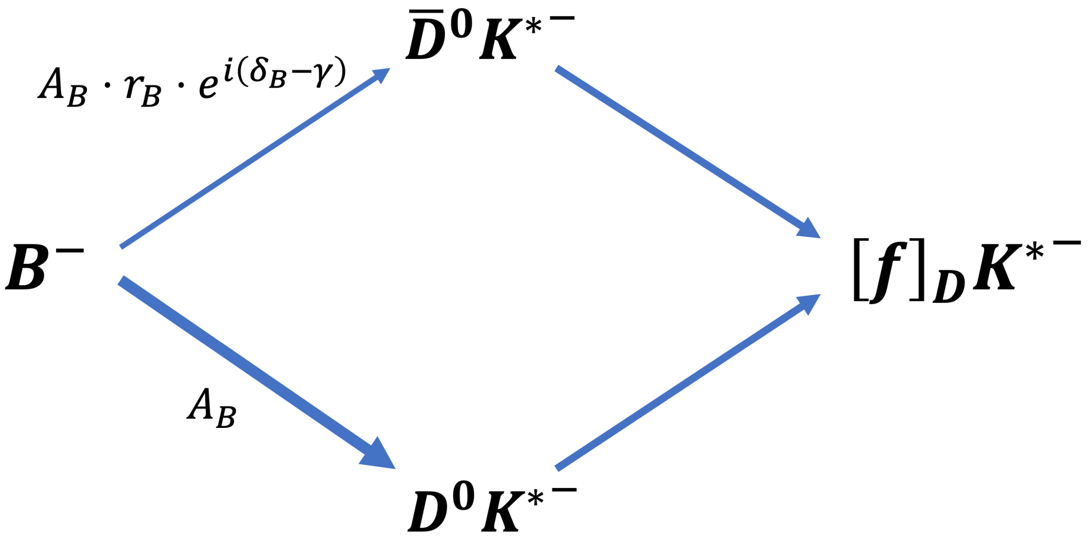
- ***CP*-even eigenstates**[8,9]
  - $\boldsymbol{D \to K^+K^-, D \to \pi^+\pi^-, D \to \pi^+\pi^-\pi^+\pi^-}$

Coherence factor (for non-resonant K^* contribution)

$$R_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^{*-}) + \Gamma(B^+ \to [h^+h^-]_D K^{*+})}{\Gamma(B^- \to [K^-\pi^+]_D\, K^{*-}) + \Gamma(B^+ \to [K^+\pi^-]_D\, K^{*+})} \frac{\mathcal{B}(D^0 \to K^-\pi^+)}{\mathcal{B}(D^0 \to h^+h^-)} = 1 + r_B^2 + 2\,\kappa\, r_B \cos(\delta_B)\cos(\gamma)$$

$$A_{CP+} = \frac{\Gamma(B^- \to [h^+h^-]_D K^{*-}) - \Gamma(B^+ \to [h^+h^-]_D K^{*+})}{\Gamma(B^- \to [h^+h^-]_D K^{*-}) + \Gamma(B^+ \to [h^+h^-]_D K^{*+})} = \frac{2\,\kappa\, r_B \sin(\delta_B)\sin(\gamma)}{R_{CP+}}$$

- Measure rate ratios to the favoured mode
- Measure rate asymmetries between B^- and B^+
- Relatively smaller observable CP violation due to amplitudes of different sizes
- Measure CP observables, directly related to physics parameters



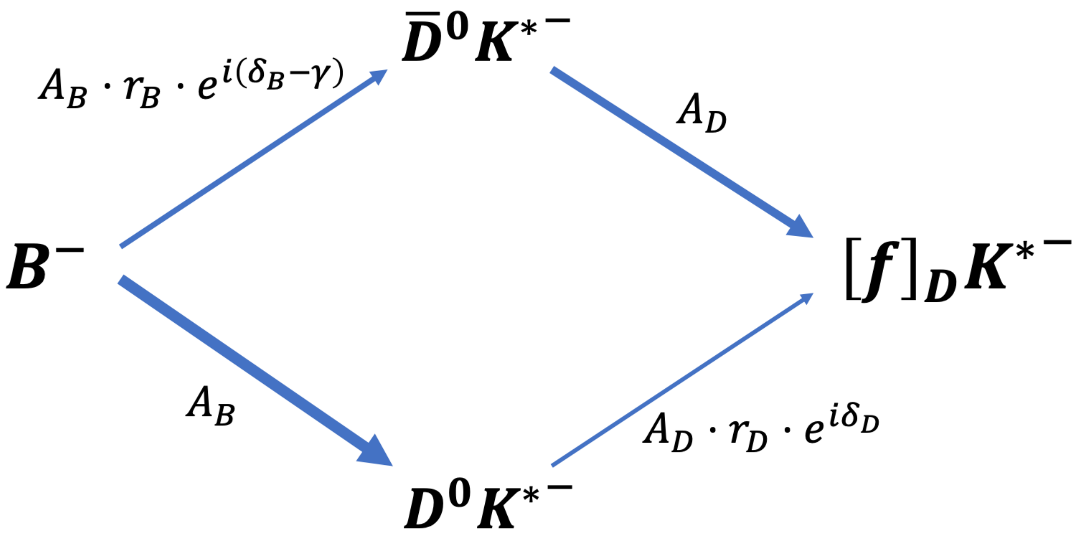
[10] Phys. Rev. Lett. **78** (1997) 3257

- **non-CP eigenstates**[10]
  - **Cabibbo-favoured (CF) / doubly Cabibbo-suppressed (DCS)**: $\boldsymbol{D \to K^- \pi^+, D \to \pi^- K^+}$
    $\boldsymbol{D \to K^- \pi^+ \pi^- \pi^+, D \to \pi^- K^+ \pi^- \pi^+}$

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

$$A_{ADS} = \frac{\Gamma(B^- \to [\pi^- K^+]_D K^{*-}) - \Gamma(B^+ \to [\pi^+ K^-]_D K^{*+})}{\Gamma(B^- \to [\pi^- K^+]_D K^{*-}) + \Gamma(B^+ \to [\pi^+ K^-]_D K^{*+})} = \frac{2\,\kappa\, r_B\, r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{R_{ADS}}$$

- External inputs: D decay parameters r_D, δ_D
- Maximal interference due to similar sized amplitudes



[11] Phys. Rev. D **68** (2003) 054018
[12] Phys. Rev. D **70** (2004) 072003
[13] Phys. Rev. D **82** (2010) 112006
[14] Phys. Rev. D **101** (2020) 112002
[15] Phys. Rev. D **102** (2020) 052008
[16] Phys. Rev. Lett. **124** (2020) 241802

- **Three-body self-conjugate final states**[11,12]
  - $\boldsymbol{D \to K_S^0\pi^+\pi^-, D \to K_S^0K^+K^-}$: complex system of resonances
  - The kinematics of the D decay can be represented in 2D in a Dalitz plot
  - CP observables

$$x_\pm = r_B \cdot \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \cdot \sin(\delta_B \pm \gamma)$$
$$x_\pm + iy_\pm = r_B \cdot e^{i(\delta_B \pm \gamma)}$$

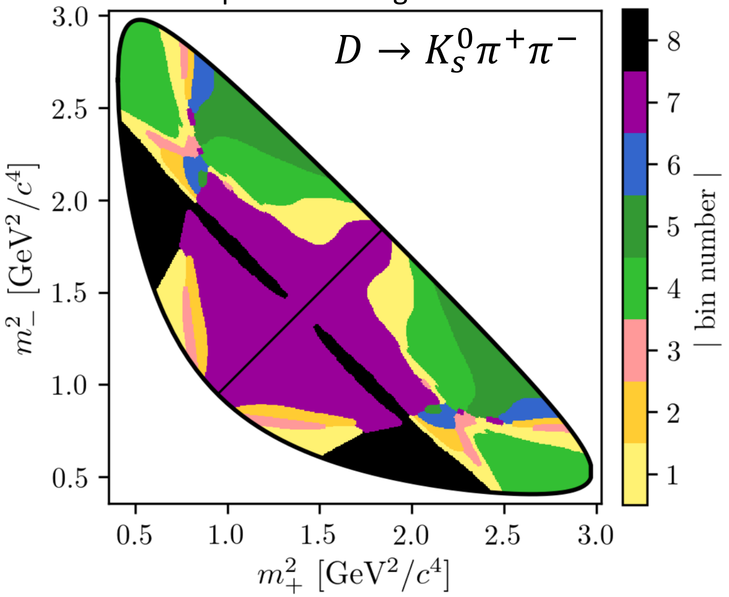
  - Interference appears as different distributions of the D meson Dalitz plot for B^- and B^+ → counting experiment in each bin
  - Yields in each Dalitz bin

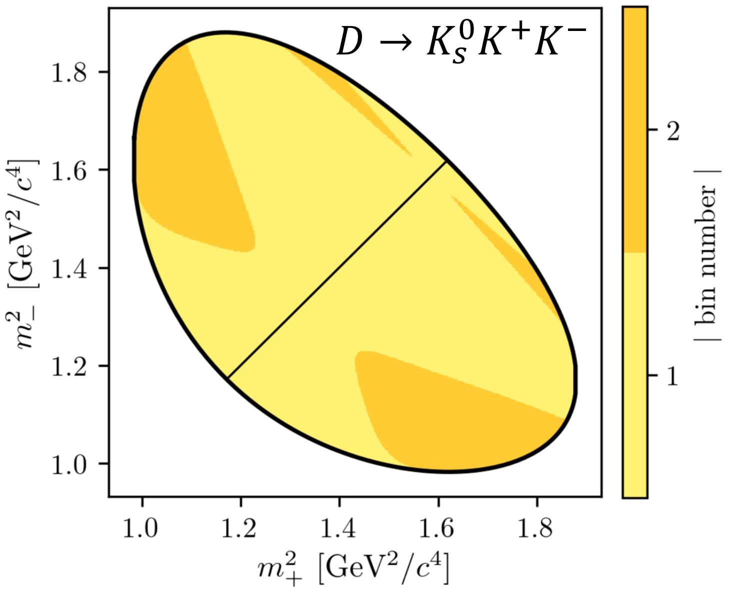
$$N^-_{\pm i} \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\kappa\sqrt{F_i F_{-i}}\,(x_-\,c_{\pm i} + y_-\,s_{\pm i})$$

Fractional yield of flavour-tagged D^0

Strong-phase differences (input from CLEO[13]+BESIII[14,15,16])

optimal binning scheme[13]



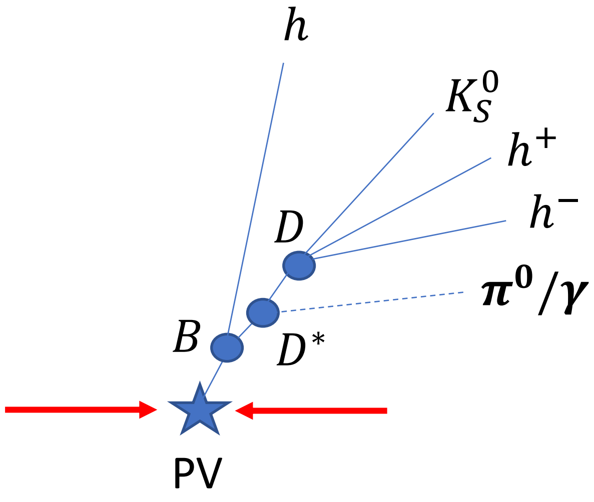


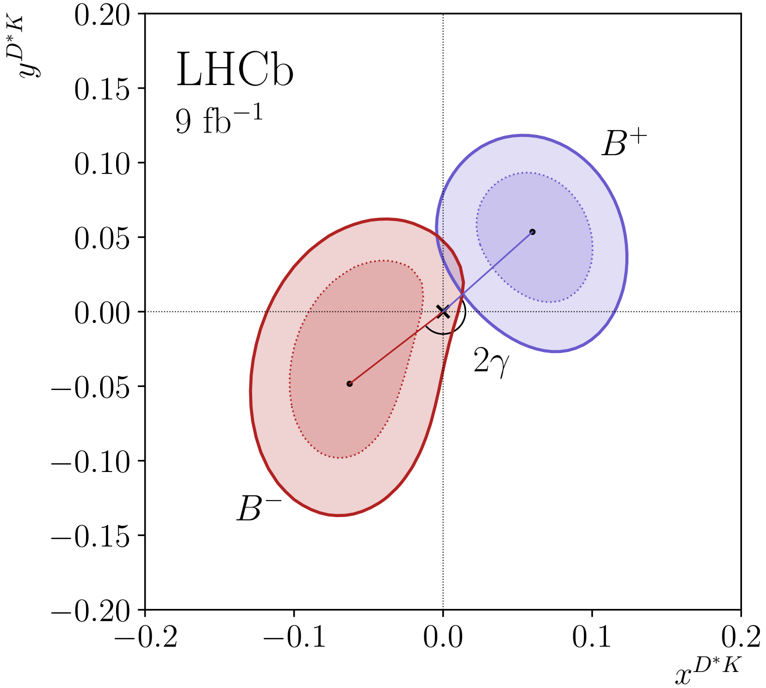
JHEP **02** (2024) 118
[17] JHEP **12** (2023) 013 [18] JHEP **04** (2021) 081

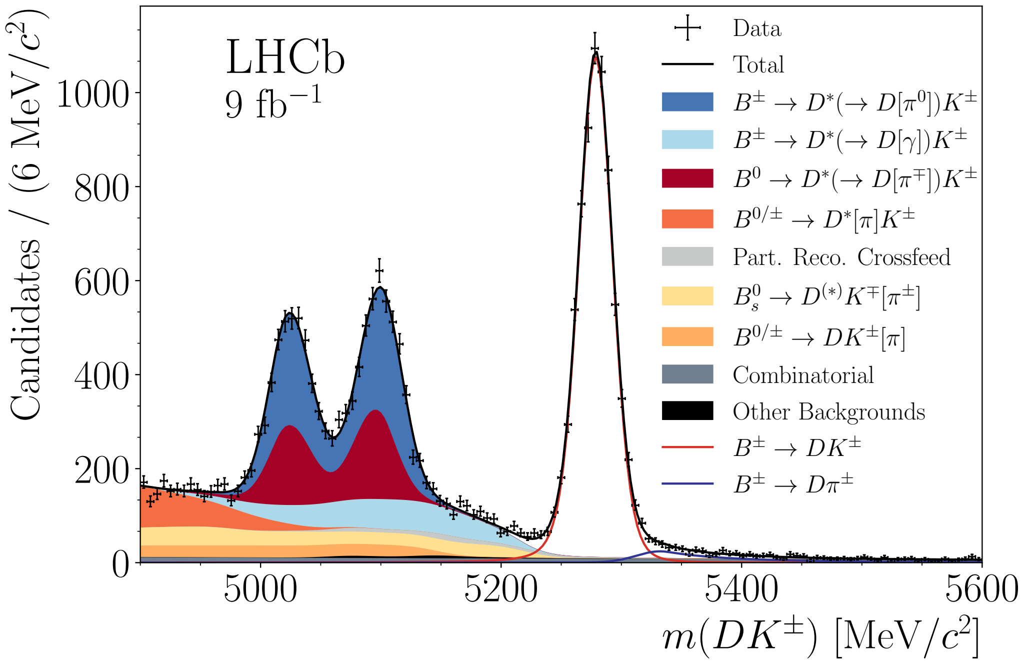
- Measurement of γ in $B^{\pm} \to D^* h^{\pm}$ with $D^* \to D\pi^0/\gamma, D \to K_S^0 h^+ h^-$ decays

- Partially reconstructed D^* meson, where $\boldsymbol{\pi^0/\gamma}$ is not reconstructed. Measurement performed in Dalitz bins of the D decay phase space. Also performed the corresponding fully reconstructed measurement[17] and the $D \to h^+ h^-$ analysis[18]

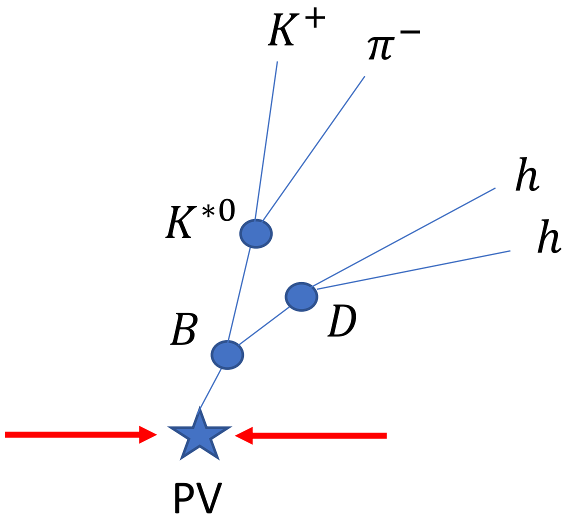
- The physics parameters of interest can be interpreted from the measured CP observables $x_{\pm}, y_{\pm}$: $\boldsymbol{\gamma = (92^{+21}_{-17})^\circ}$



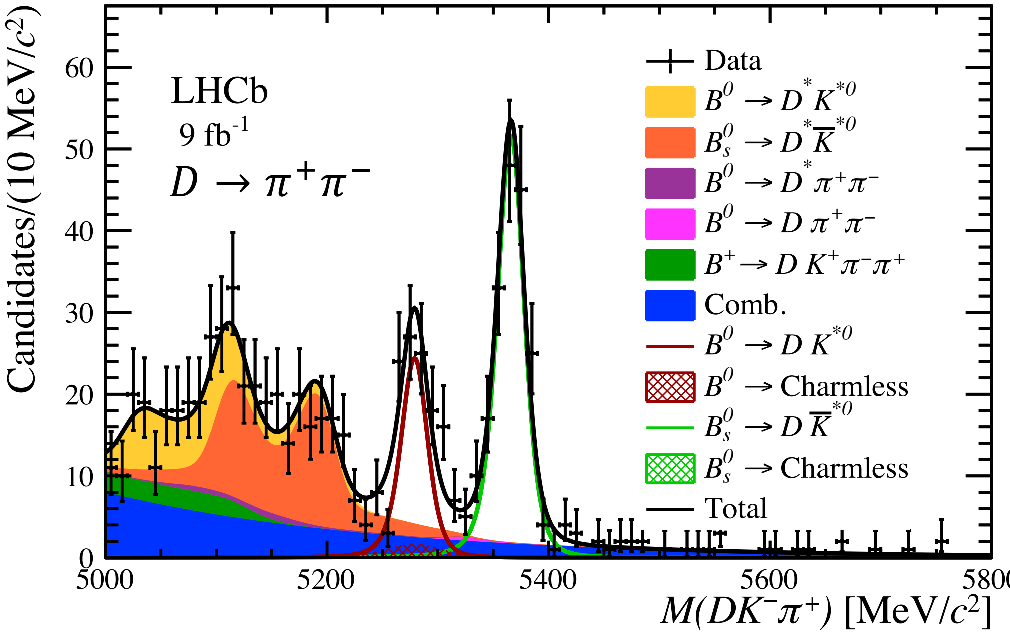




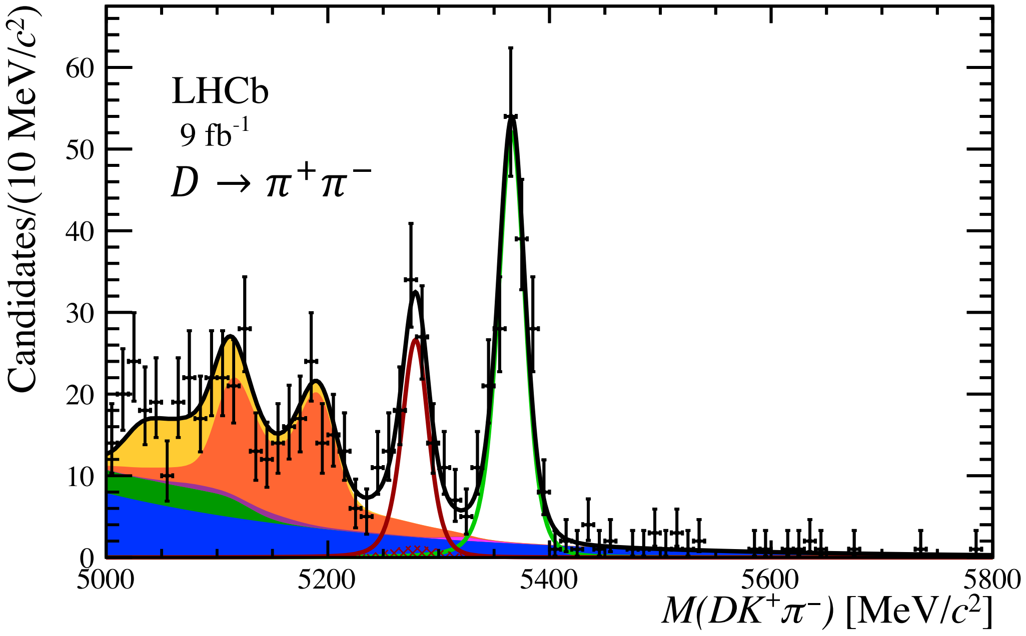
- Measurement of γ in $B^0 \to [h^+h^-(h^+h^-)]_D K^{*0}$ decays
- Simultaneous fit for each D meson final state and each B^0 flavour, which is tagged using the kaon child from the K^{*0}
- CP-violating observables measured in $B^0_{(s)} \to DK^{*0}$



$\overline{B}^0$



B^0



$B^0 \to DK^{*0}, D \to h^+h^-(h^+h^-)$

JHEP **05** (2024) 025
[19] Eur. Phys. J. **C84** (2024) 206

- The physics parameters of interest can be interpreted from the measured CP-violating observables, B_s^0 results consistent with no CP violation

- **Multiple solutions** due to trigonometric equations relating CP observables to physics parameters. Solution compatible with world average:

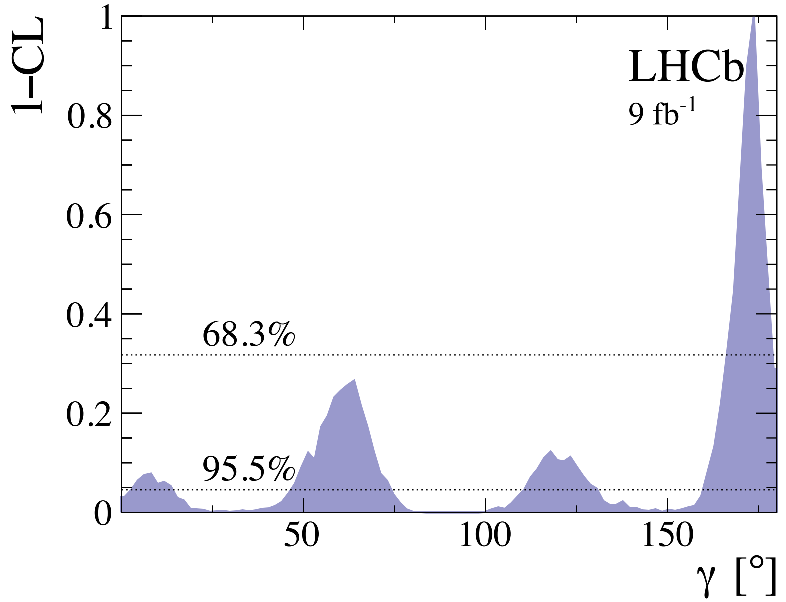
$$\boldsymbol{\gamma = (61.7 \pm 8.0)^\circ}$$

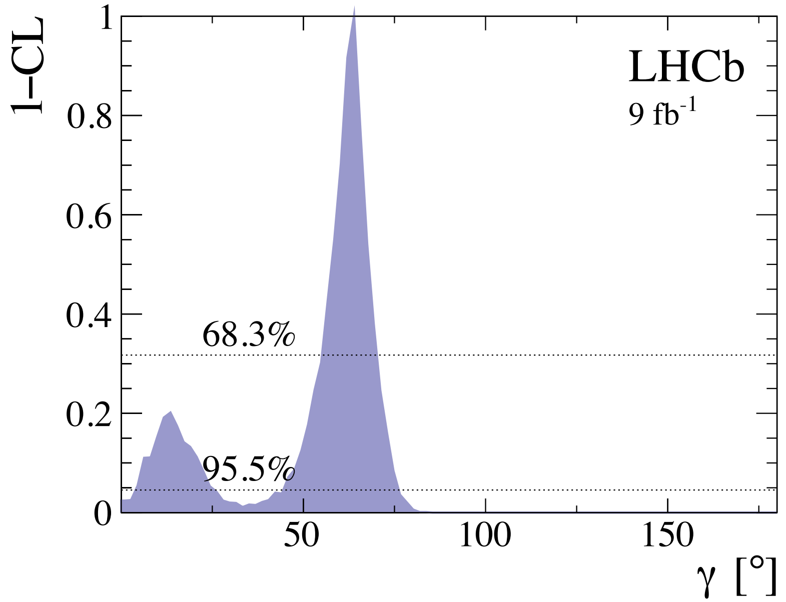
- **Combining** with $B^0 \to [K_S^0 h^+ h^-]_D K^{*0}$ measurement[19] removes two solutions and strengthens the one consistent with the world average, yielding:

$$\boldsymbol{\gamma = \left(63.2^{+6.9}_{-8.1}\right)^\circ}$$

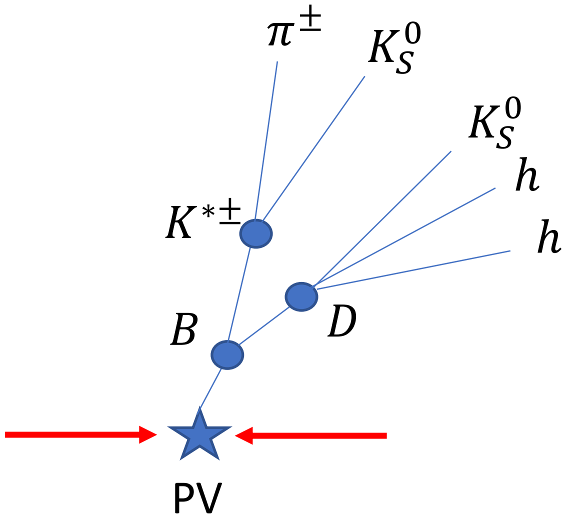
- Result for γ consistent with LHCb γ combination

- Measurement of γ in B^0 decays coming closer to the average value obtained with $B^\pm$ decays



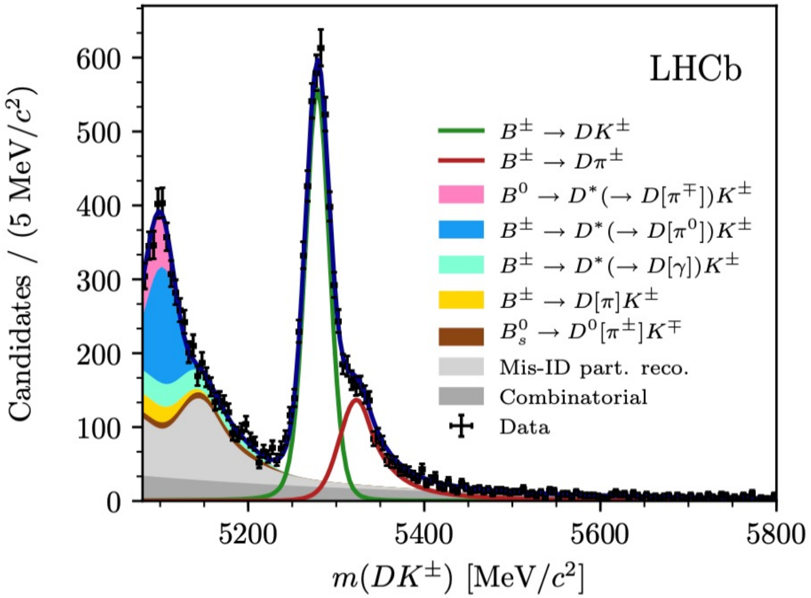


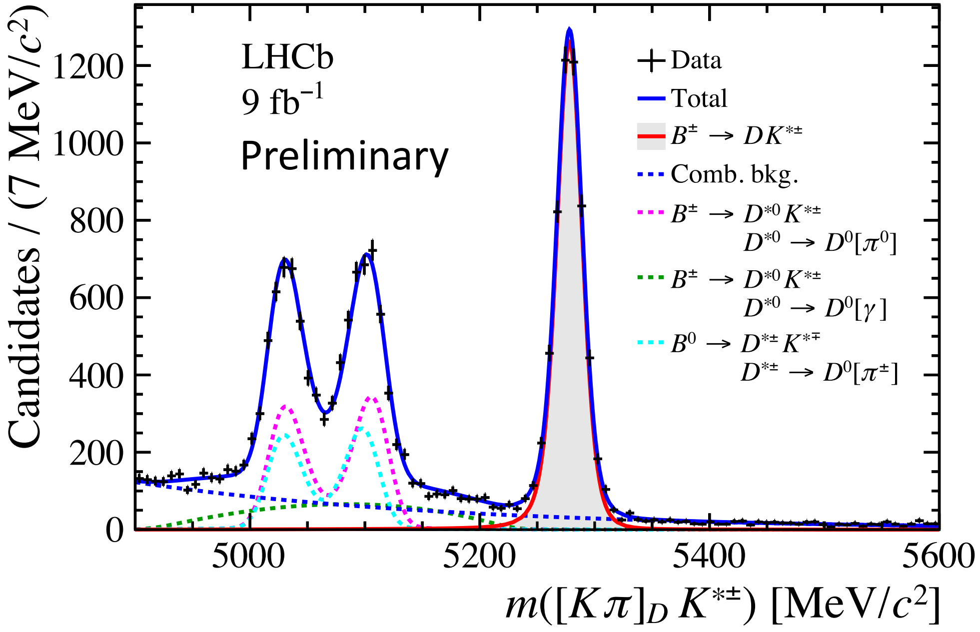
- Measurement of γ in $B^{\pm} \to DK^{*\pm}$ decays, **comprehensive** study:
  - $D \to h^+h^-(h^+h^-)$
  - $D \to K_S^0 h^+h^-$ ← first measurement at LHCb in this channel



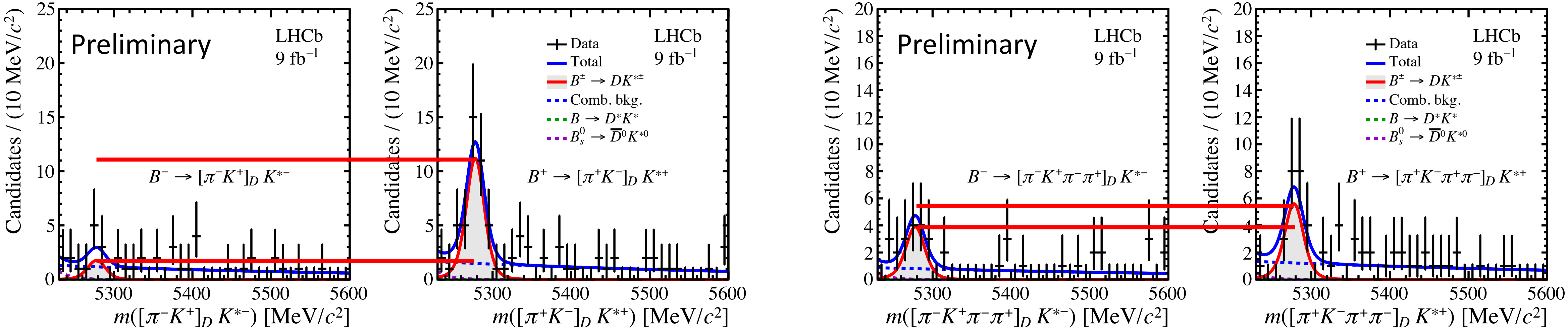
- Advantages of this channel compared to golden channel:
  - **Clean signal peak**
  - **No mis-ID component**
  - Lower partially reconstructed backgrounds

$B^{\pm} \to [K_s h^+h^-]_D\ h'^{\pm}$ analysis[6]





- Simultaneous fit for the different categories defined by B charge and D decay mode to measure the CP observables



- Small asymmetries within the favoured modes, while larger asymmetries observed for the suppressed modes and CP-eigenstates modes

- CP observables measured for **all three types of *D* decay modes considered** in this analysis

- **First observation** of the suppressed $B^{\pm} \to [\pi^{\pm} K^{\mp}]_D K^{*\pm}$ and $B^{\pm} \to [\pi^{\pm} K^{\mp} \pi^{\pm} \pi^{\mp}]_D K^{*\pm}$ decays

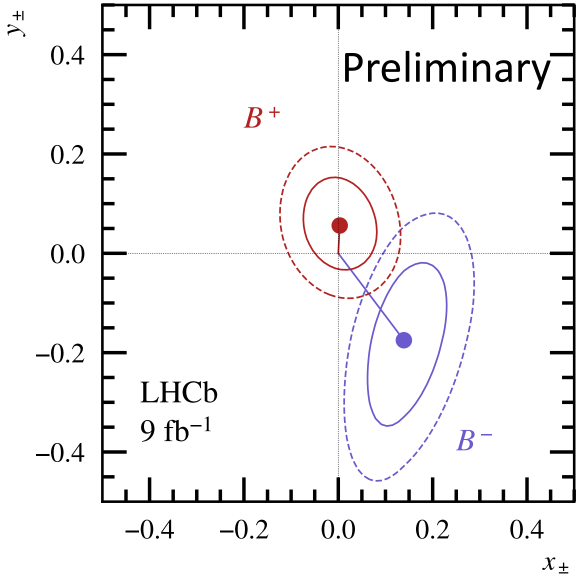
$B^{\pm} \to DK^{*\pm}$

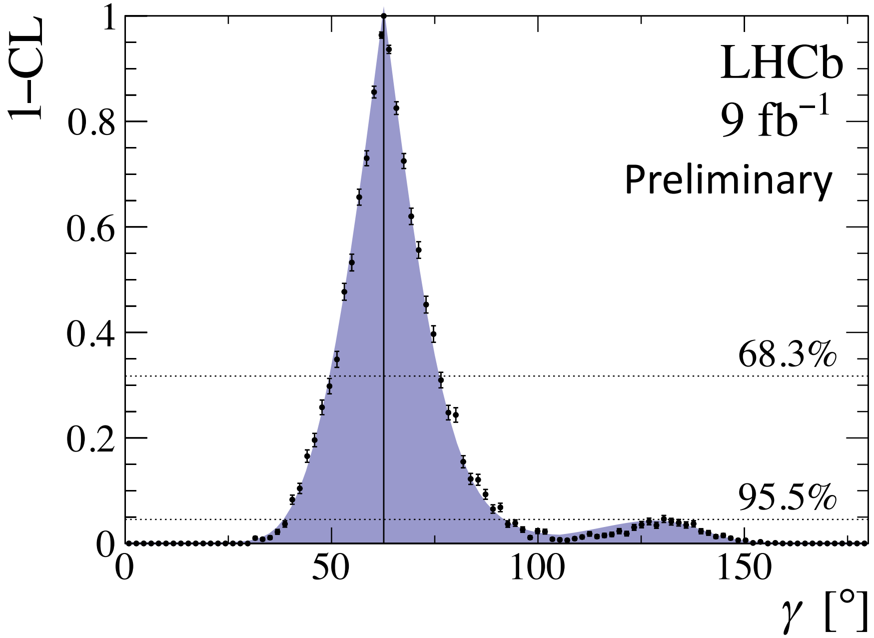
- The physics parameters of interest can be interpreted from the measured CP-violating observables

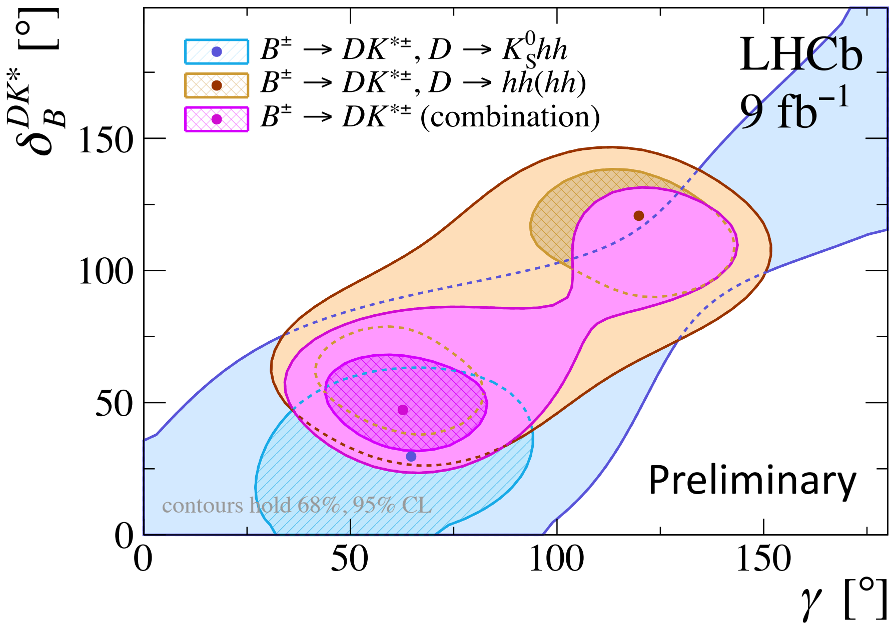
$$\boldsymbol{\gamma = (63 \pm 13)^{\circ}}$$

- Model-independent results, using strong-phase c_i, s_i inputs from CLEO and BESIII

- Result for γ consistent with world average

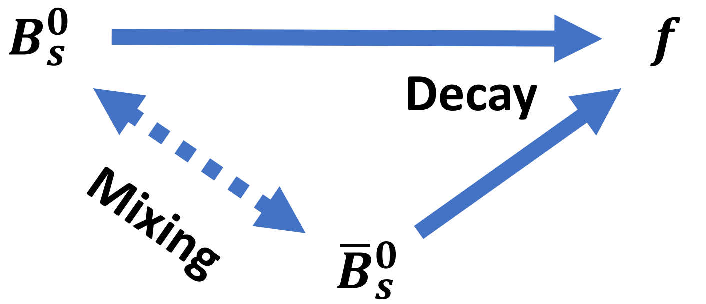


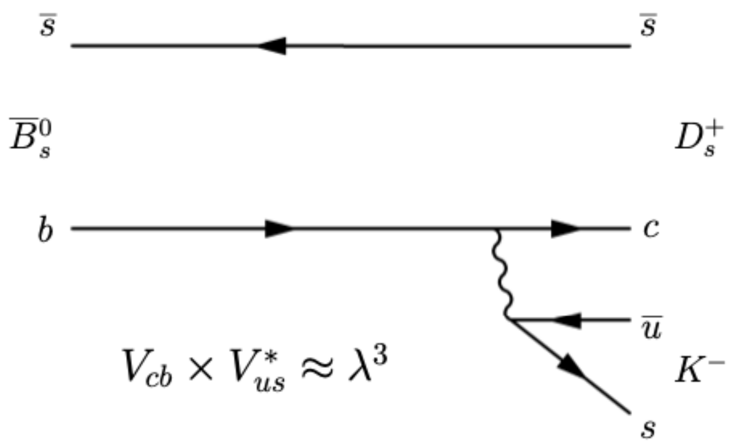


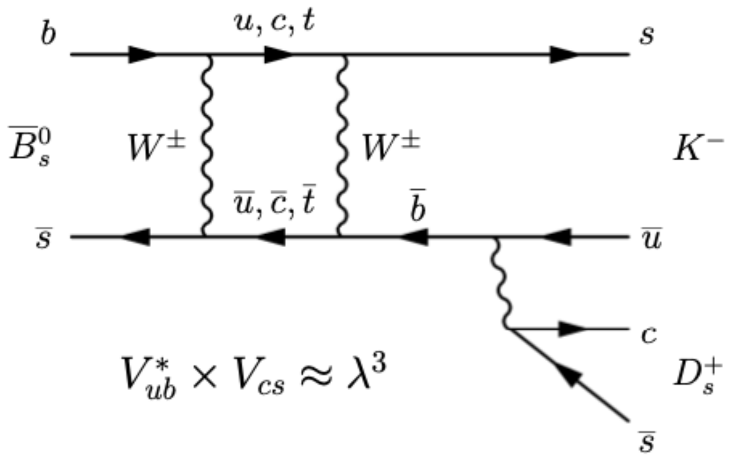


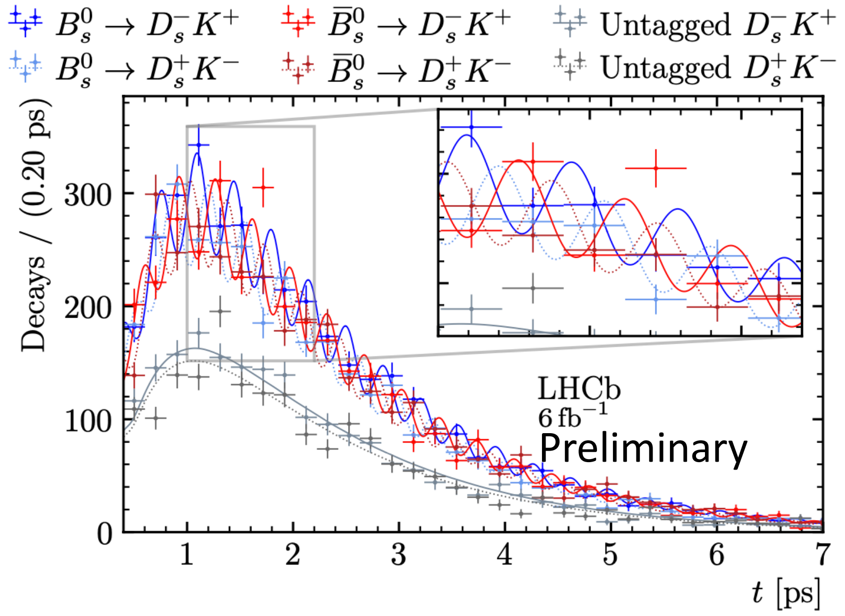
Time dependent $B_s^0 \to D_s^{\mp} K^{\pm}$

- CP-violating parameters measured in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays
- Interference between mixing and decay amplitudes
  - **Time dependent**
- CP-violating observables functions of γ and mixing phase β_s
  - $\gamma - 2\beta_s$
- Initial flavour of the B meson determined using **flavour tagging**



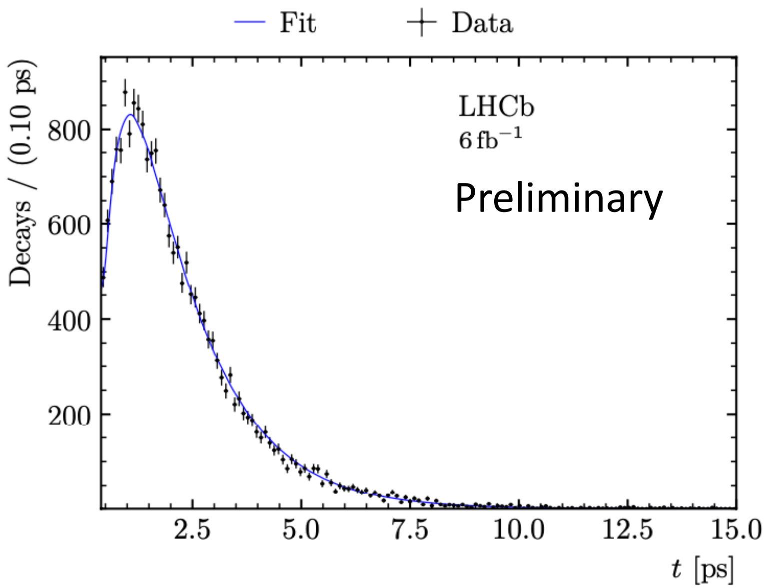


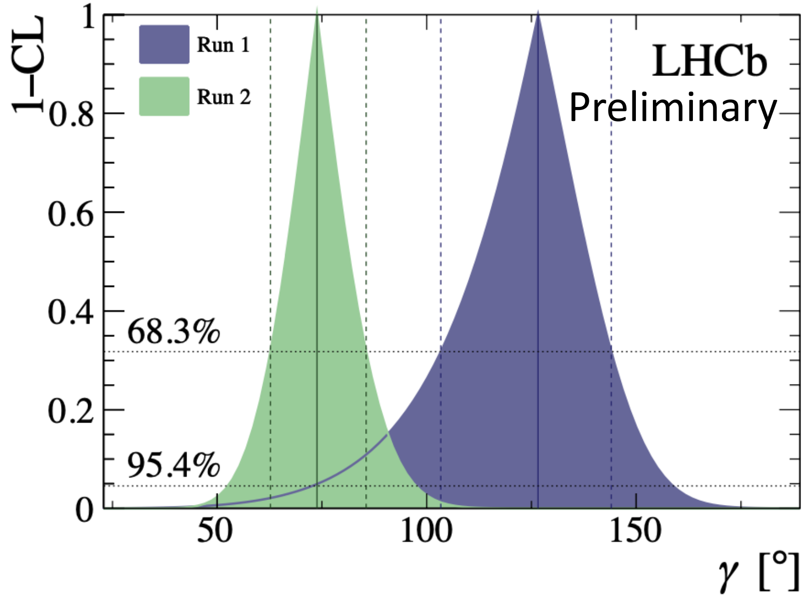


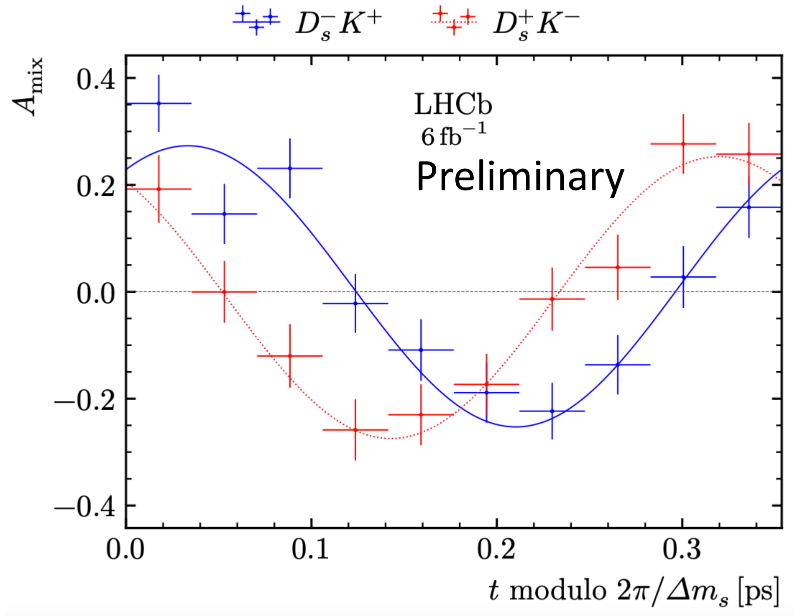


Time dependent $B_s^0 \to D_s^{\mp} K^{\pm}$

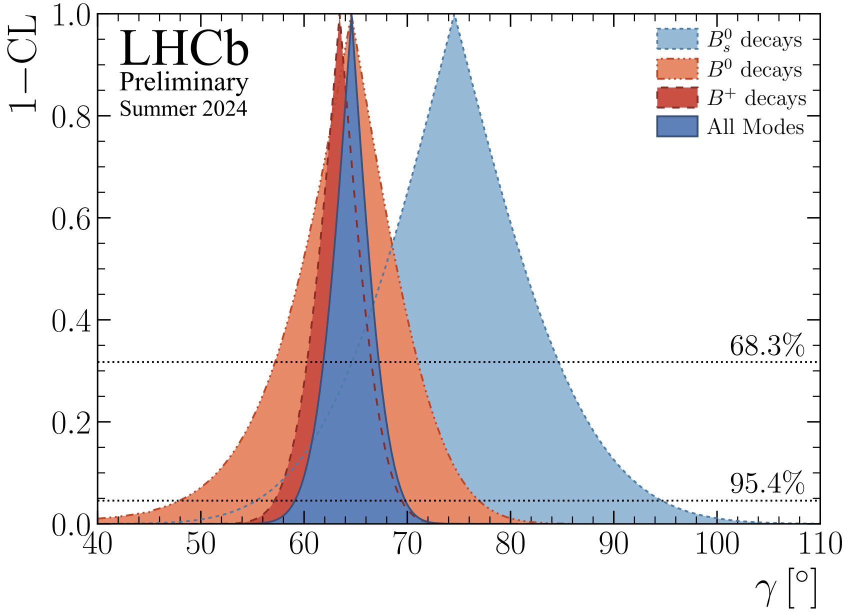
- Signal obtained from 2D fit in $\mathrm{m}(B_s^0)$ and $\mathrm{m}\left(D_s^{\mp}\right)$ with *sPlot* technique
- Fit to **decay-time distribution** of background-subtracted $B_s^0 \to D_s^{\mp} K^{\pm}$ signal to determine the CP observables
- Result for γ when combining with Run 1: $\boldsymbol{\gamma = \left(81^{+12}_{-11}\right)^{\circ}}$
- Most precise determination of γ in B_s^0 meson decays

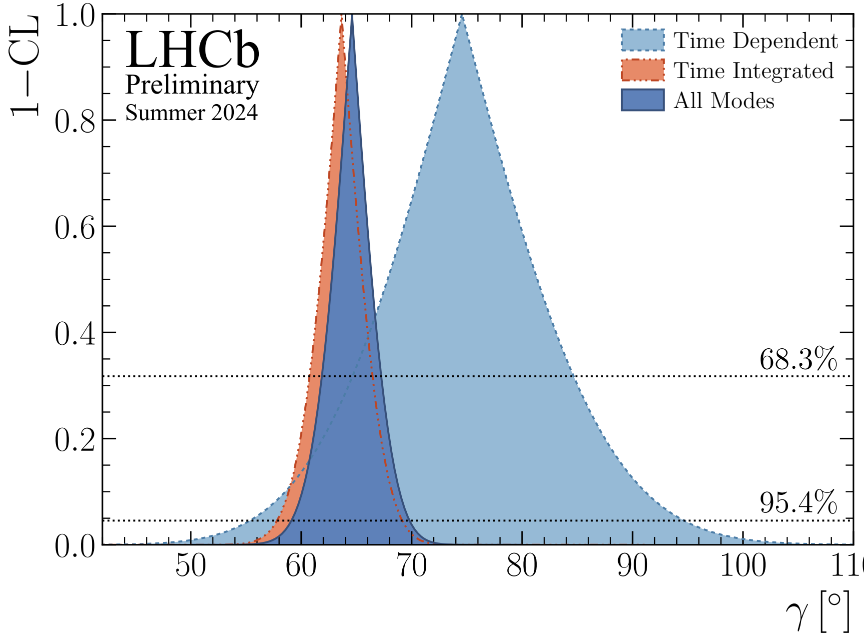


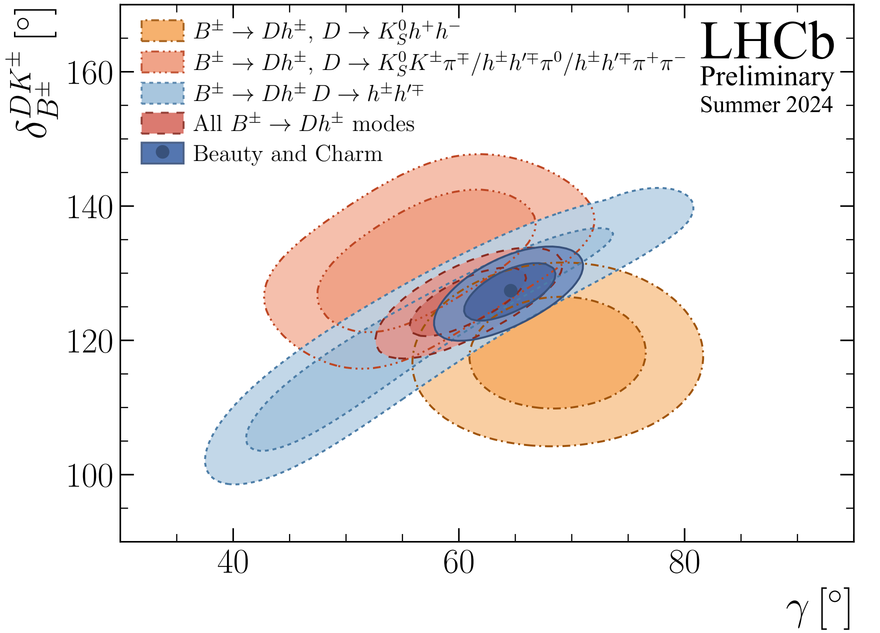




- LHCb γ+charm combination 2024 $\quad \boldsymbol{\gamma = (64.6 \pm 2.8)^\circ}$
- World's most precise direct determination of γ. Expected sensitivity for Run 1-2 of about 4° surpassed
- Result for γ from neutral B^0 decays now closer to the value obtained in charged $B^\pm$ decays
- Consistency between B species now more evident





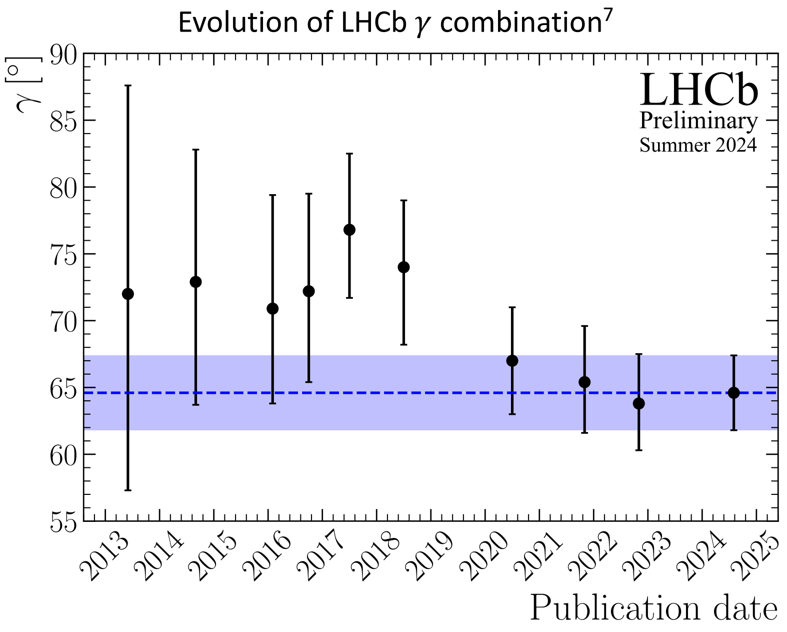


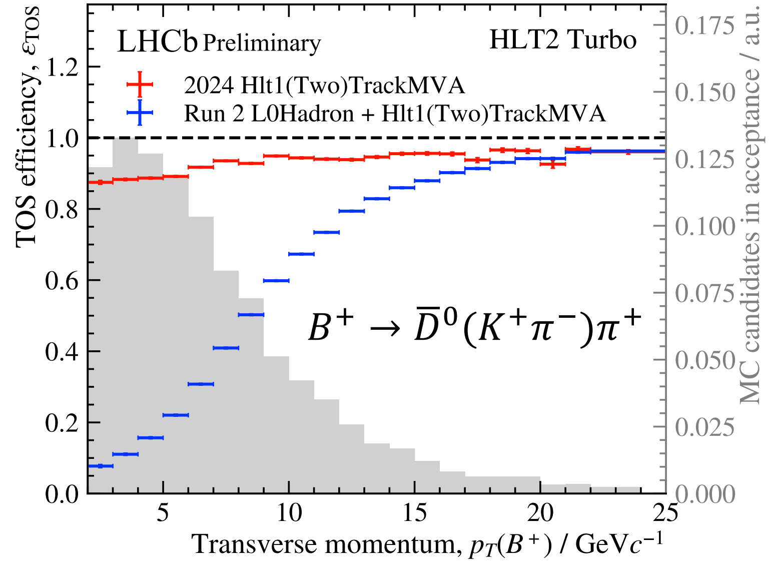
[20] Eur. Phys. J. **C73** (2013) 2373
[21] arXiv:1808.08865
[22] LHCb-FIGURE-2024-030

- Recent γ measurements included in the latest LHCb combination, **further improving the precision**
- Strategy to cover all B and D decay **combinations** to improve sensitivity to γ, providing **further constraints** and cross-checks
- Only a few more Run 2 results still to be completed
- **Statistically limited**: a precision of less than 1° is expected[20,21] with **more data** to be collected in Run 3 and beyond

Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
1°	0.35°

- **Removal of hardware trigger** in Run 3 good for hadronic final states such as those used for γ measurements, with large increase in yields at low momentum[22]





Conclusions

- Presented recent **measurements of the CKM angle γ at LHCb**:
  - $B^{\pm} \to D^{*}h^{\pm}, D^{*} \to D\pi^{0}/\gamma, D \to K_S^0 h^+ h^-$ — JHEP **02** (2024) 118
  - $B^{0} \to DK^{*0}, D \to h^+h^-(h^+h^-)$ — JHEP **05** (2024) 025
  - $B^{\pm} \to DK^{*\pm}, D \to h^+h^-(h^+h^-), K_S^0 h^+ h^-$ — LHCb-PAPER-2024-023 (in preparation)
  - $B_s^0 \to D_s^{\mp}K^{\pm}$ — LHCb-PAPER-2024-020 (in preparation)
  - LHCb γ+charm combination 2024 — LHCb-CONF-2024-004

- Strong impact from **combination with** measurements of $\boldsymbol{\gamma}$ **from the same $\boldsymbol{B}$ decay channels**

- Expected sensitivity of about $4°$ for Run 1-2 surpassed

$$\boldsymbol{\gamma = (64.6 \pm 2.8)°}$$

- More precise determination of γ in the future, which is a standard candle measurement of CP violation in the Standard Model

Thank you


35th Rencontres de Blois
Château de Blois, October 20-25, 2024