technische universität dortmund

FSP LHCb Erforschung von Universum und Materie

Decay-time-dependent measurements of the CKM angle γ at LHCb

Quentin Führing

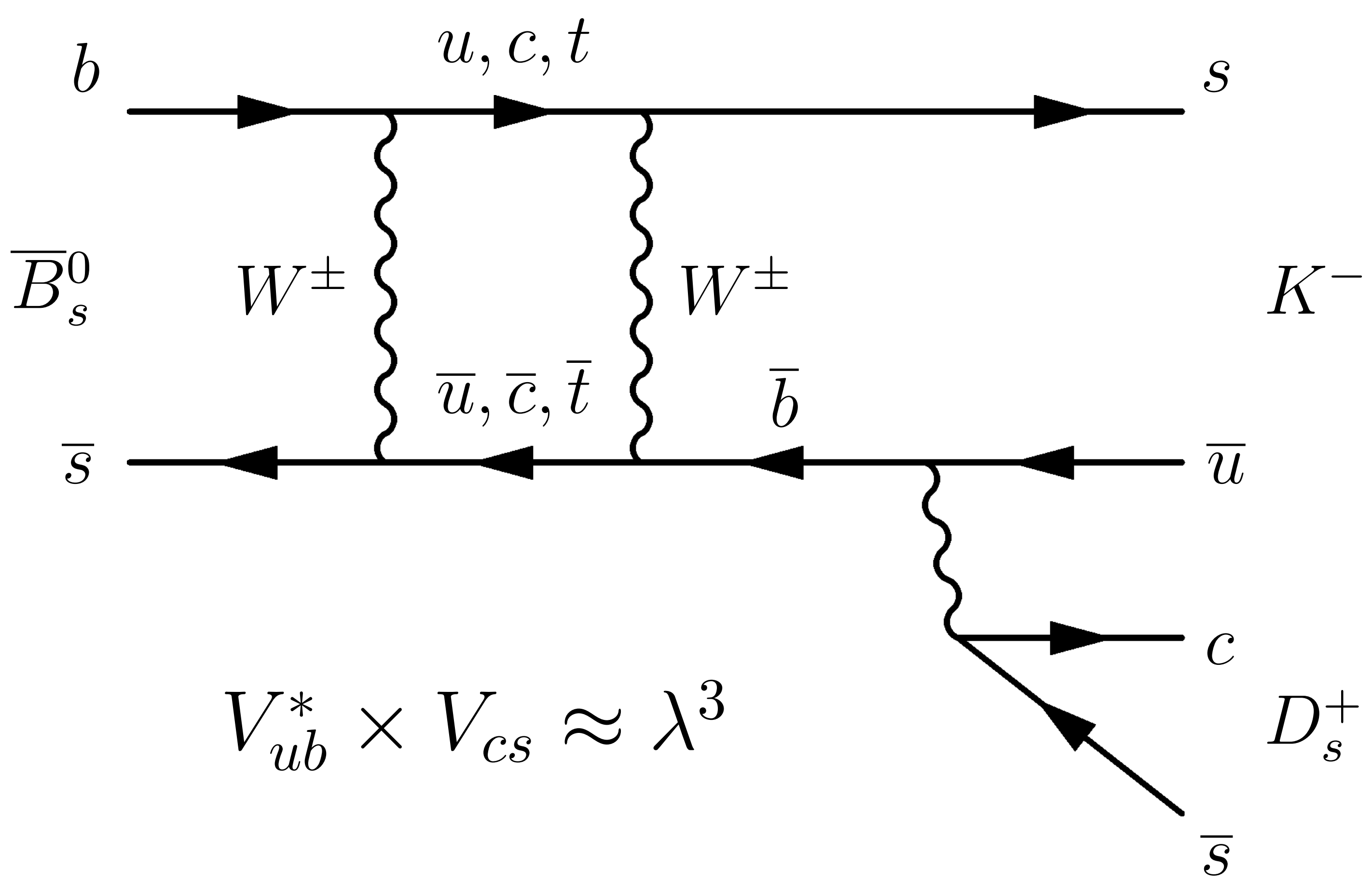
On behalf of the LHCb collaboration

12th International Workshop on the CKM Unitarity

September 19th 2023

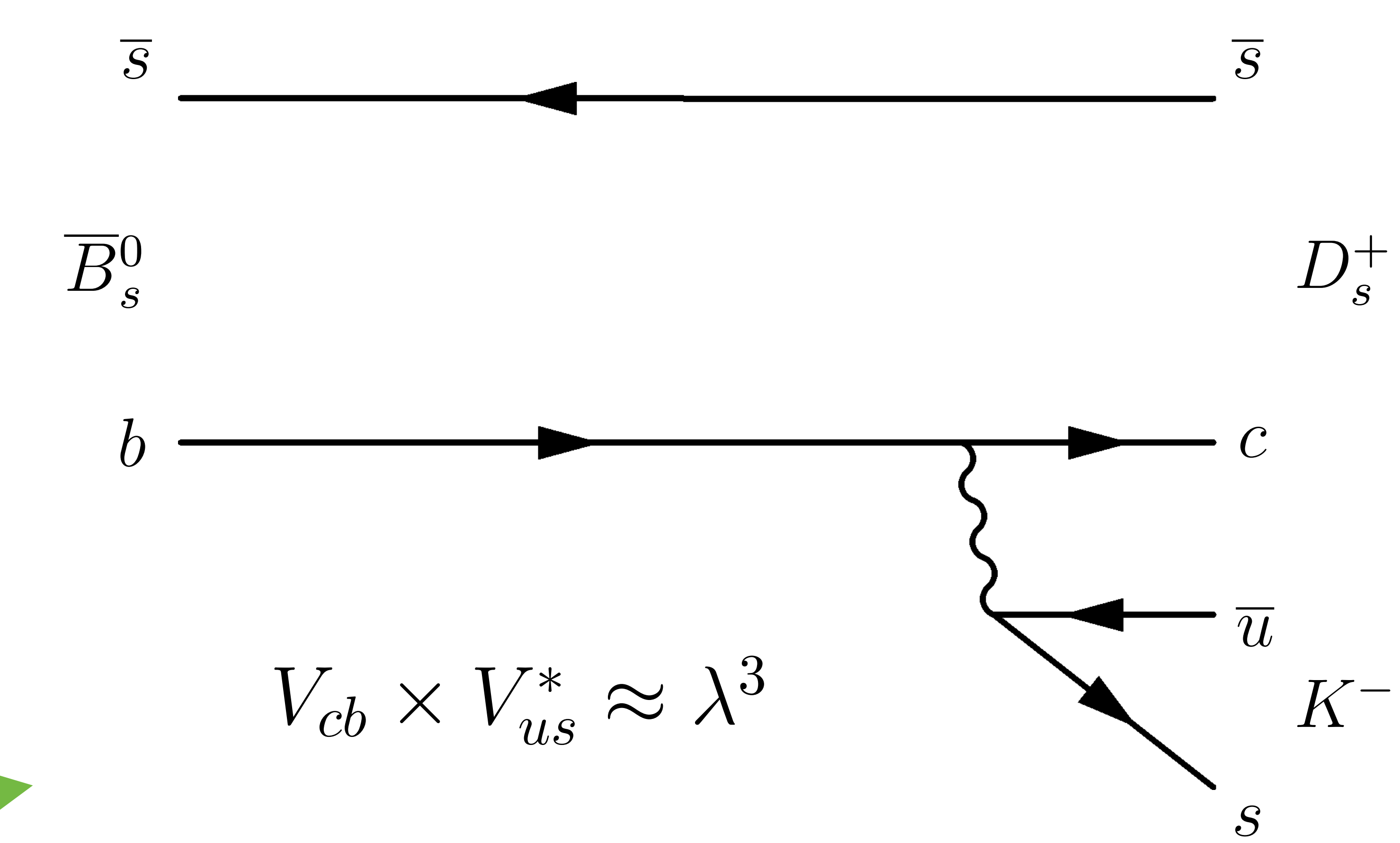
Decay-time dependent measurements of γ

- **Interference of direct decay and decay after mixing**
  - Accessible in relative phase
- **Limited sensitivity in $B^0 \to D^\mp \pi^\pm$-like decays**
- **Good sensitivity in $B_s^0 \to D_s^\mp K^\pm$-like decays**
  - Large interference effects



Relative phase:

$\gamma - 2\beta_s$



Decay-time dependent measurements of γ

- **Measurement of four decay rates gives access to:**
  - Relative phase $\gamma - 2\beta_s$
  - Strong phase difference δ
  - Amplitude ratio r_{D_sK}

$$\Gamma\left(B_s^0(t) \to f/\bar{f}\right) \sim \mathrm{e}^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_{f/\bar{f}}\cos\left(\Delta m_s t\right) + A_{f/\bar{f}}^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{f/\bar{f}}\sin\left(\Delta m_s t\right)\right)$$

$$C_f = C_{\bar{f}} = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2} \qquad A_f^{\Delta\Gamma} = \frac{-2\, r_{D_sK}\cos\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2} \qquad S_f = \frac{2\, r_{D_sK}\sin\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2}$$

$$A_{\bar{f}}^{\Delta\Gamma} = \frac{-2\, r_{D_sK}\cos\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2} \qquad S_{\bar{f}} = \frac{2\, r_{D_sK}\sin\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r_{D_sK}^2}$$

The LHCb experiment

[4] LHCb-CONF-2023-004
[6] Int. J. Mod. Phys. A 30, 1530022 (2015)
[7] Eur. Phys. J. C 73, 2431 (2013)

The LHCb experiment

- **Single-arm forward spectrometer**
  - Precision measurements of b and c decays
- **Good decay-time resolution**
  - VertexLocator close to interaction region
  - Average resolution below 50 fs [4]
- **Good hadron identification**
  - Only $10\,\%$ $\pi \to K$ misID at $95\,\%$ K efficiency [6]
  - Important for the hadronic final-states
  - Ingredient to flavour tagging

Figure taken from [4]

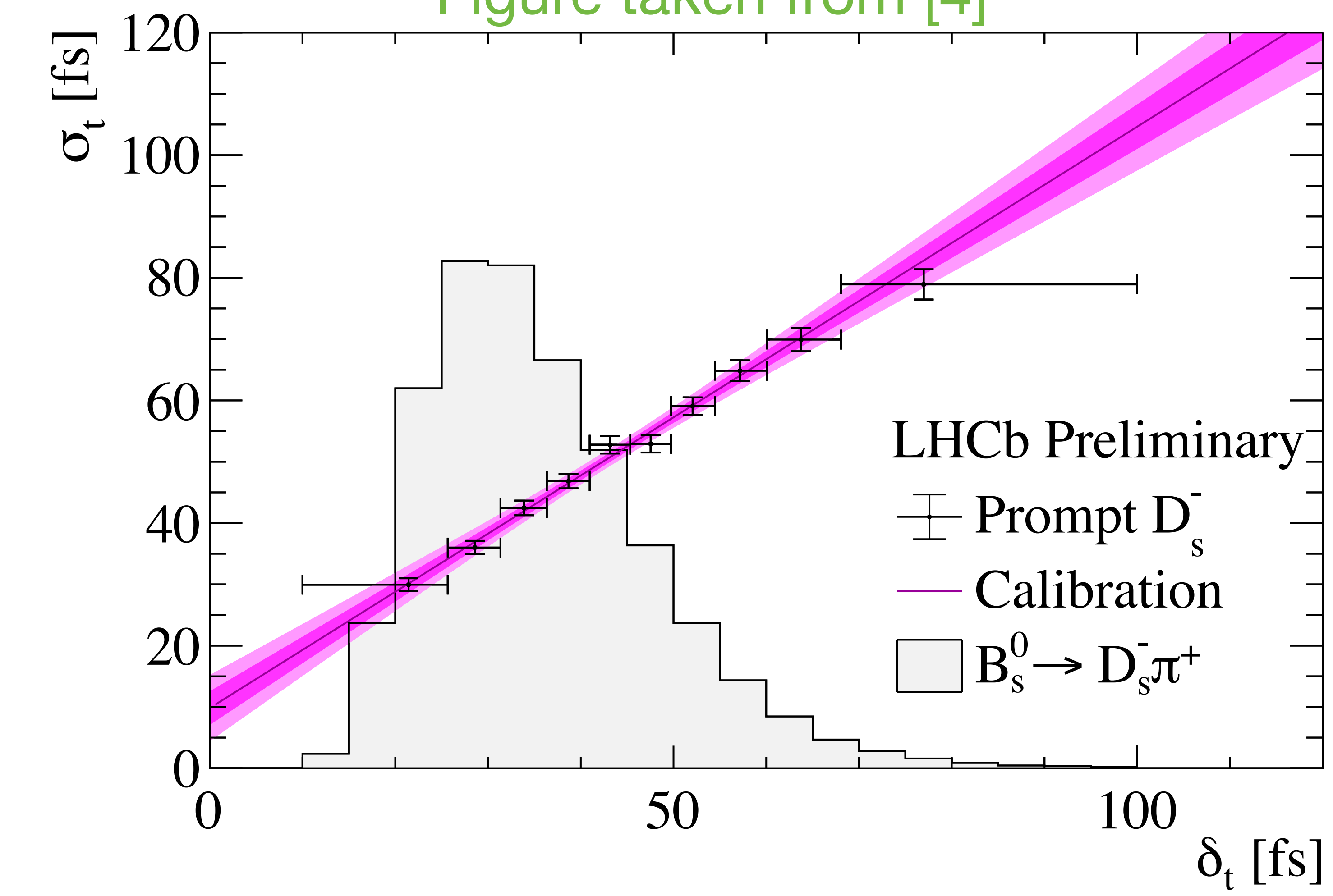
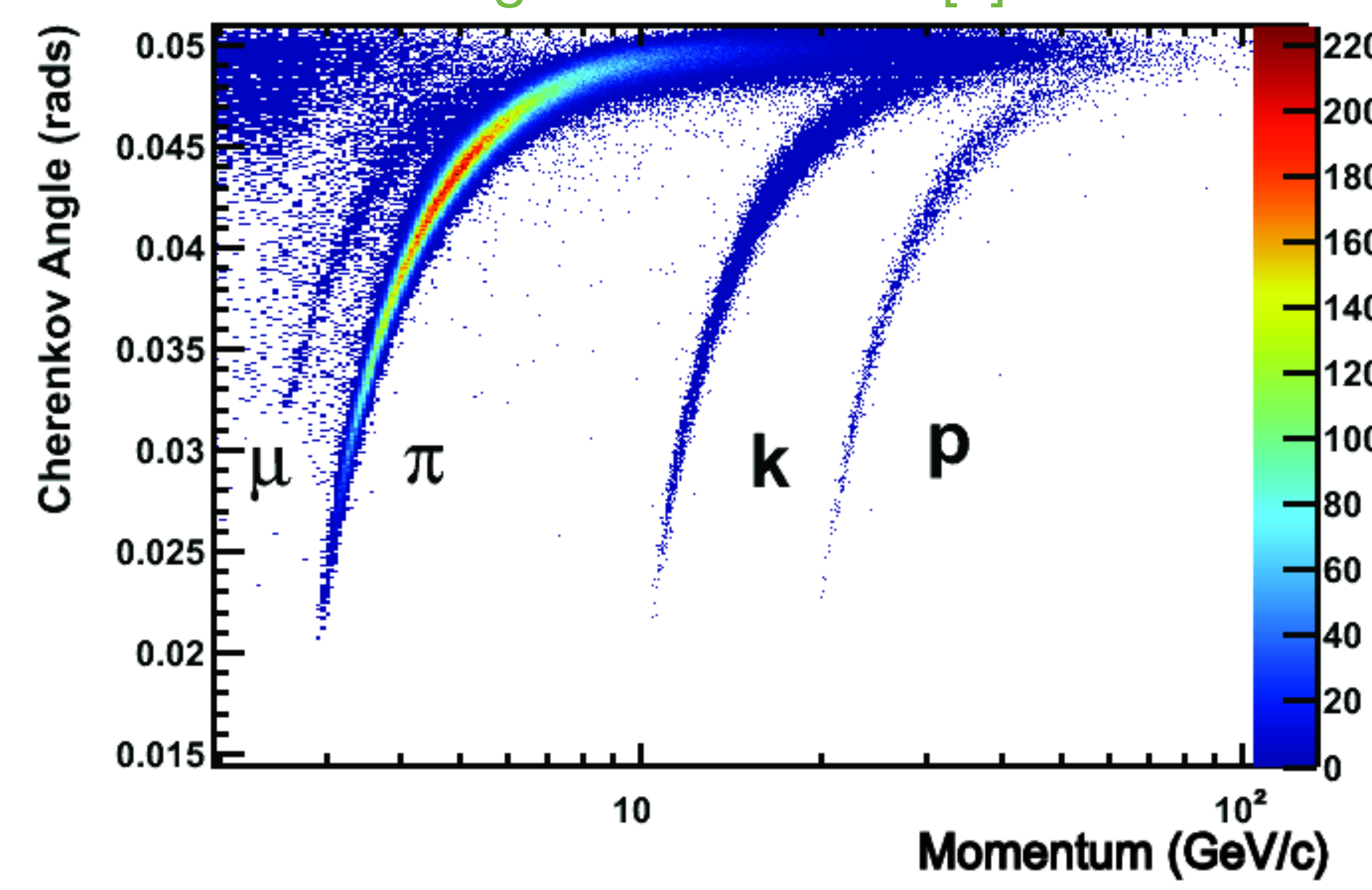
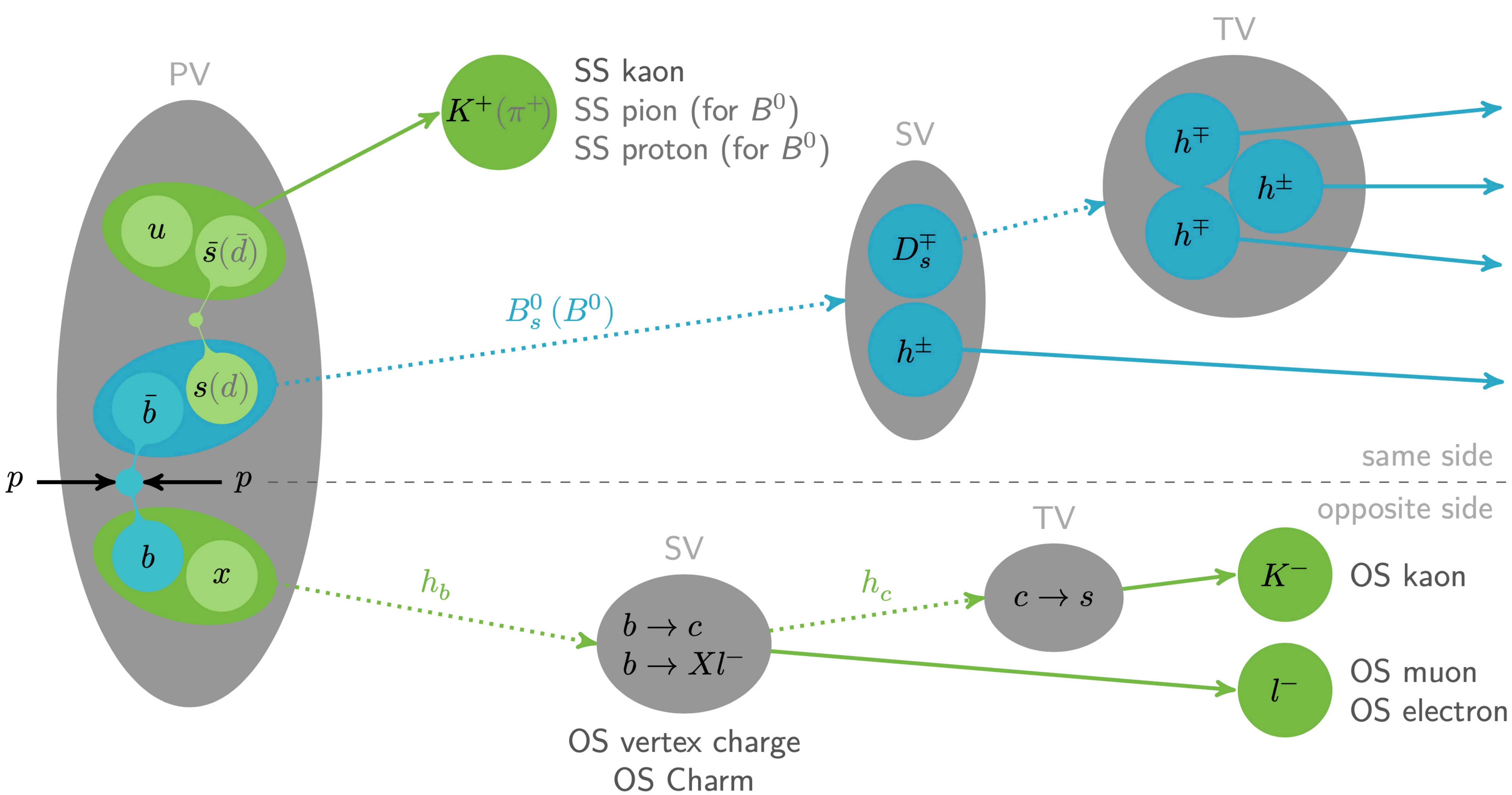


Figure taken from [7]



Flavour tagging at LHCb

- **Flavour tagging estimates initial flavour**
  - Exploits various fragmentation processes
  - MVA-based mistag probability
- **Reduction of effective sample size**
  - Tagging efficiency
  - Dilution from mistagged candidates



$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot \left(1 - 2\,\omega(\eta)\right)^2$$

$$\sigma\left(A_{CP}\right) \sim \frac{1}{\sqrt{\varepsilon_{\text{eff}} \cdot N}}$$

TD B_s^0 measurements at LHCb

[8] Nat. Phys. 18, 1–5 (2022)

- **Signal extraction**
- **Careful handling of:**
  - Flavour tagging calibration
  - Decay-time resolution
  - Decay-time acceptance

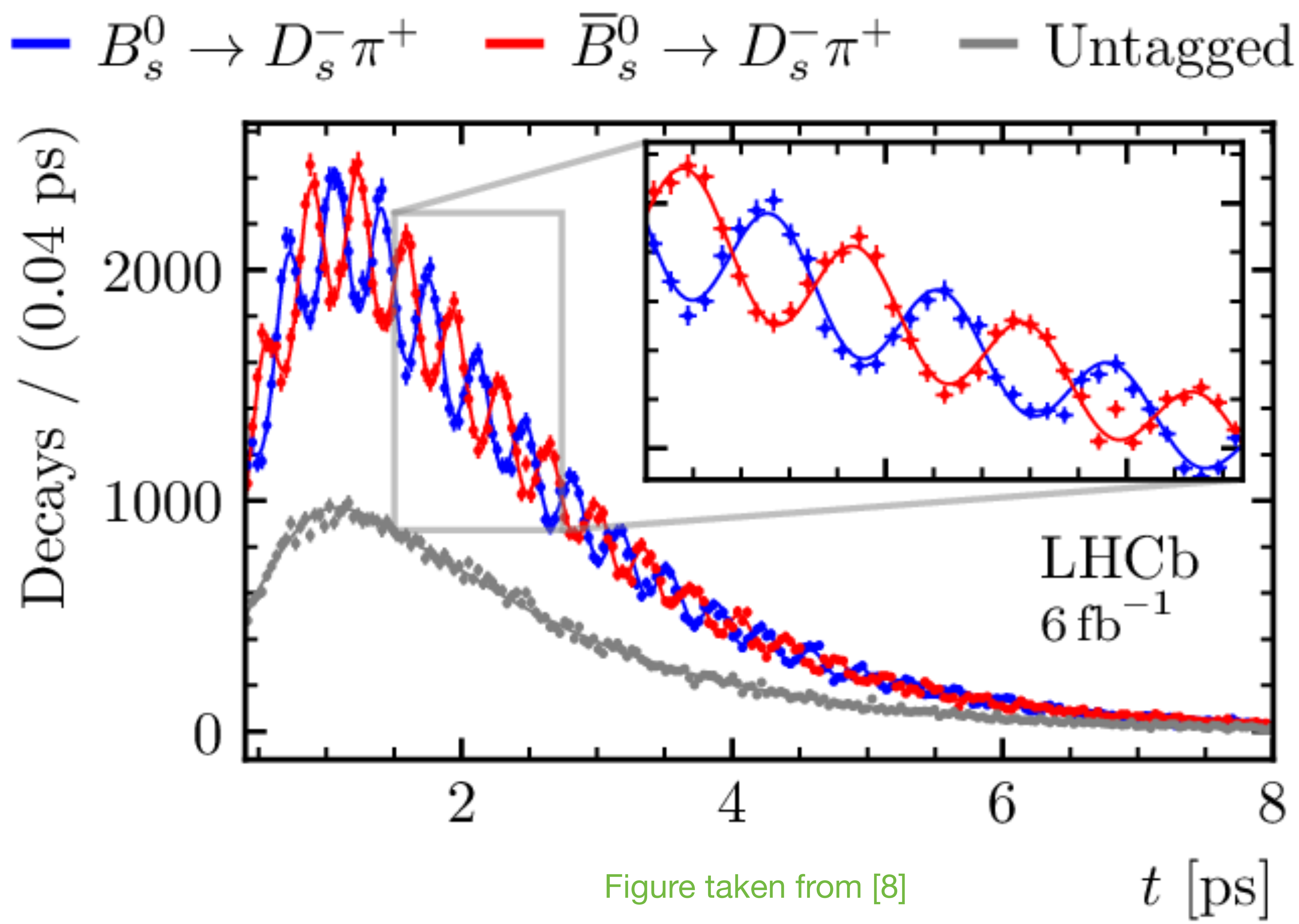


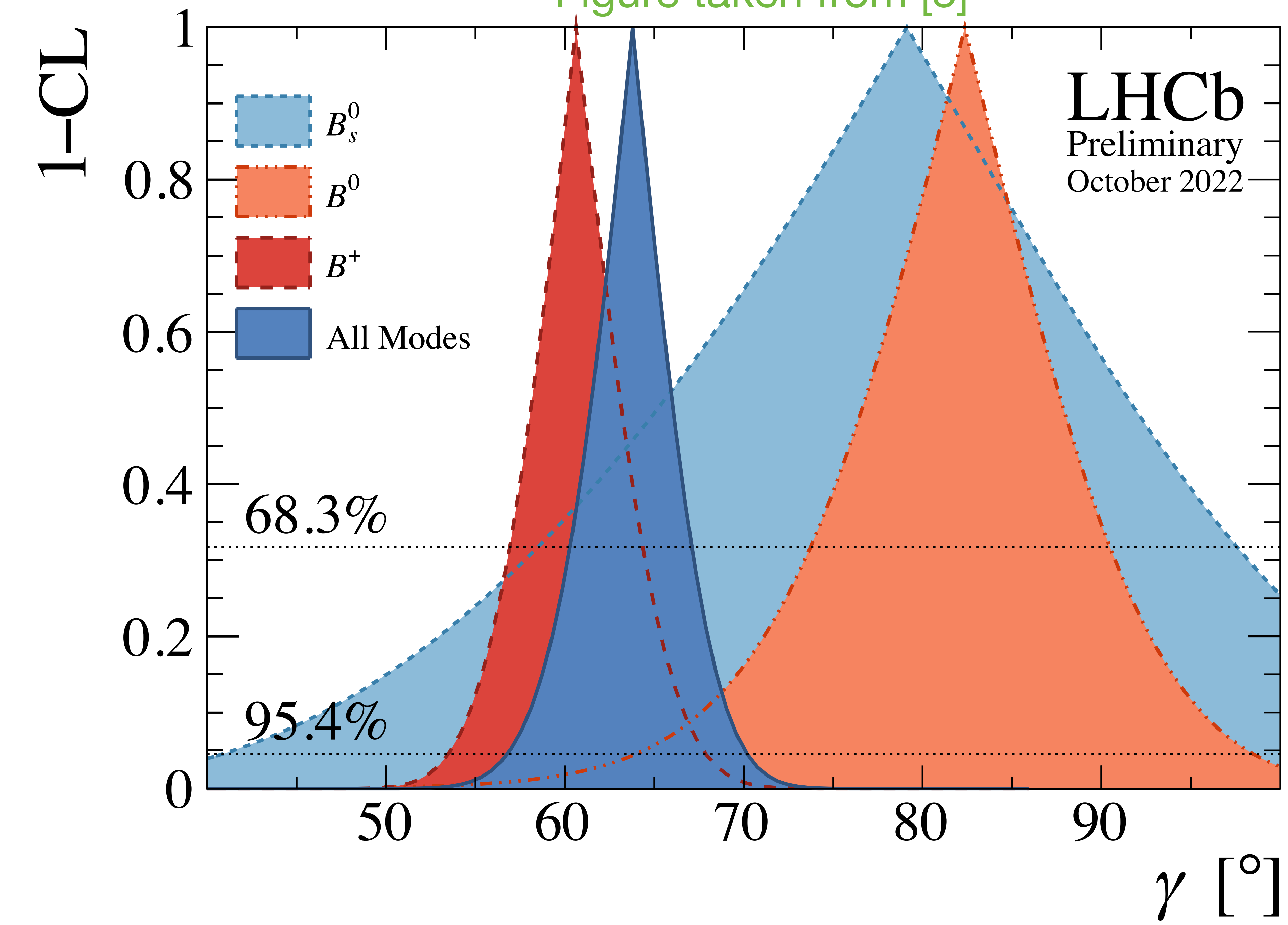
Figure taken from [8]

[1] JHEP 06 (2018) 084
[2] JHEP 03 (2018) 059
[3] JHEP 03 (2021) 137
[4] LHCb-CONF-2023-004
[5] LHCb-CONF-2022-003

TD measurements of γ at LHCb

- Time-dependent measurements of γ
  - $B^0 \to D^{\mp}\pi^{\pm}$ (Run1, 3 fb^{-1}) [1]
  - $B_s^0 \to D_s^{\mp}K^{\pm}$ (Run1, 3 fb^{-1}) [2]
  - $B_s^0 \to D_s^{\mp}K^{\pm}\pi^{\mp}\pi^{\pm}$ (Run1+2, 9 fb^{-1}) [3]
  - $B_s^0 \to D_s^{\mp}K^{\pm}$ NEW! (Run2, 6 fb^{-1}) [4]

Figure taken from [5]



- Small tensions
  - Charged vs neutral
  - Within B_s^0 measurements
  - Time-dependent vs integrated

Table taken from [5]

Method	Value [°]	68.3% CL Uncertainty	68.3% CL Interval	95.4% CL Uncertainty	95.4% CL Interval
Time-dependent	79	$^{+21}_{-23}$	$[56, 100]$	$^{+51}_{-48}$	$[31, 130]$
Time-integrated	63.3	$^{+3.7}_{-3.9}$	$[59.4, 67.0]$	$^{+7.1}_{-7.8}$	$[55.5, 70.4]$

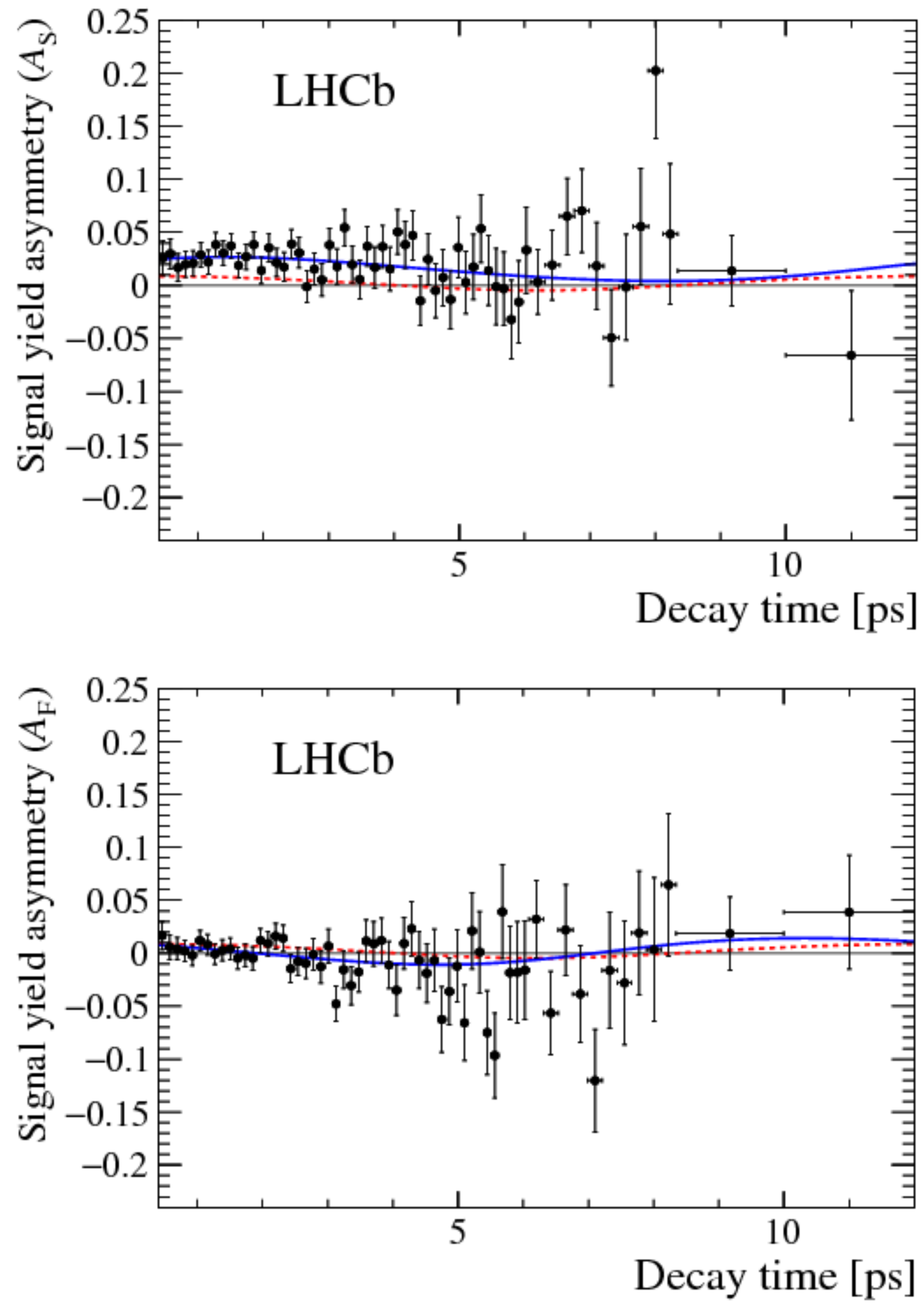
Overview on previous measurements

[1] JHEP 06 (2018) 084

$B^0 \to D^{\mp}\pi^{\pm}$ - Run1 [1]

- **2011 & 12 data ($3\,\mathrm{fb}^{-1}$)**
- **Large statistics**
  - 479000 ± 700 candidates
  - $\varepsilon_{\mathrm{eff}} = (5.59 \pm 0.01)\,\%$
- **Minor sensitivity to γ**
  - Amplitude ratio $r_{D\pi} \approx 0.02$
  - Negligible $\Delta\Gamma \approx 0$

$\gamma \in [5^\circ, 86^\circ] \cup [185^\circ, 266^\circ]$ at 68 % CL

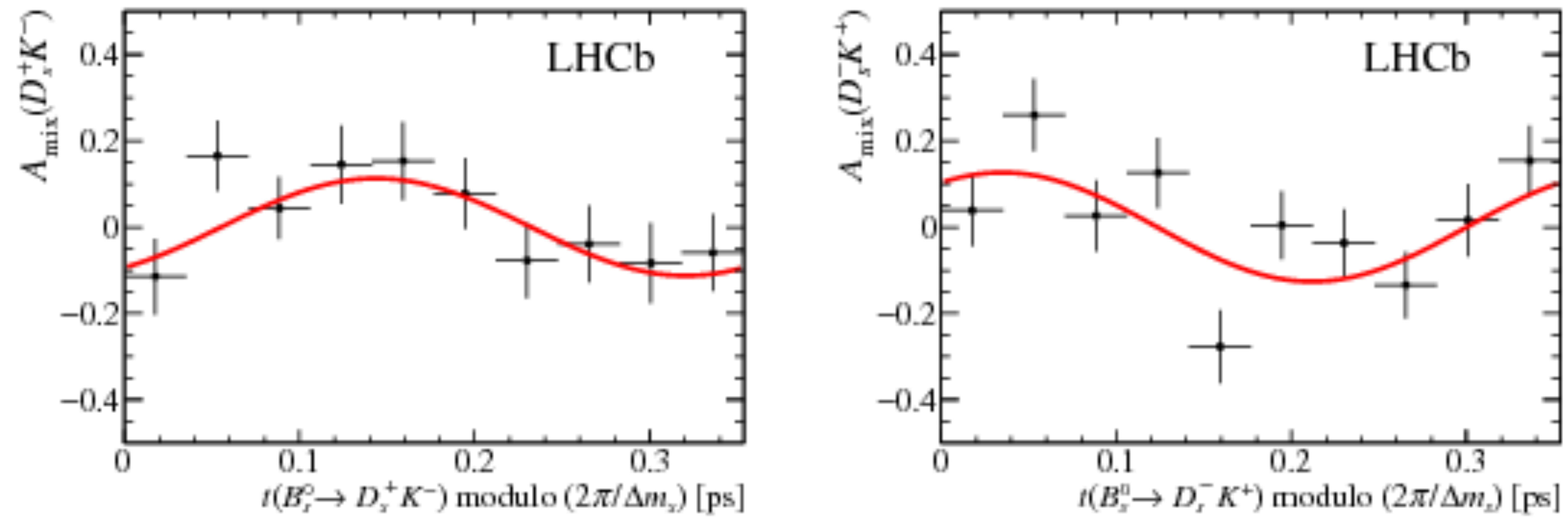


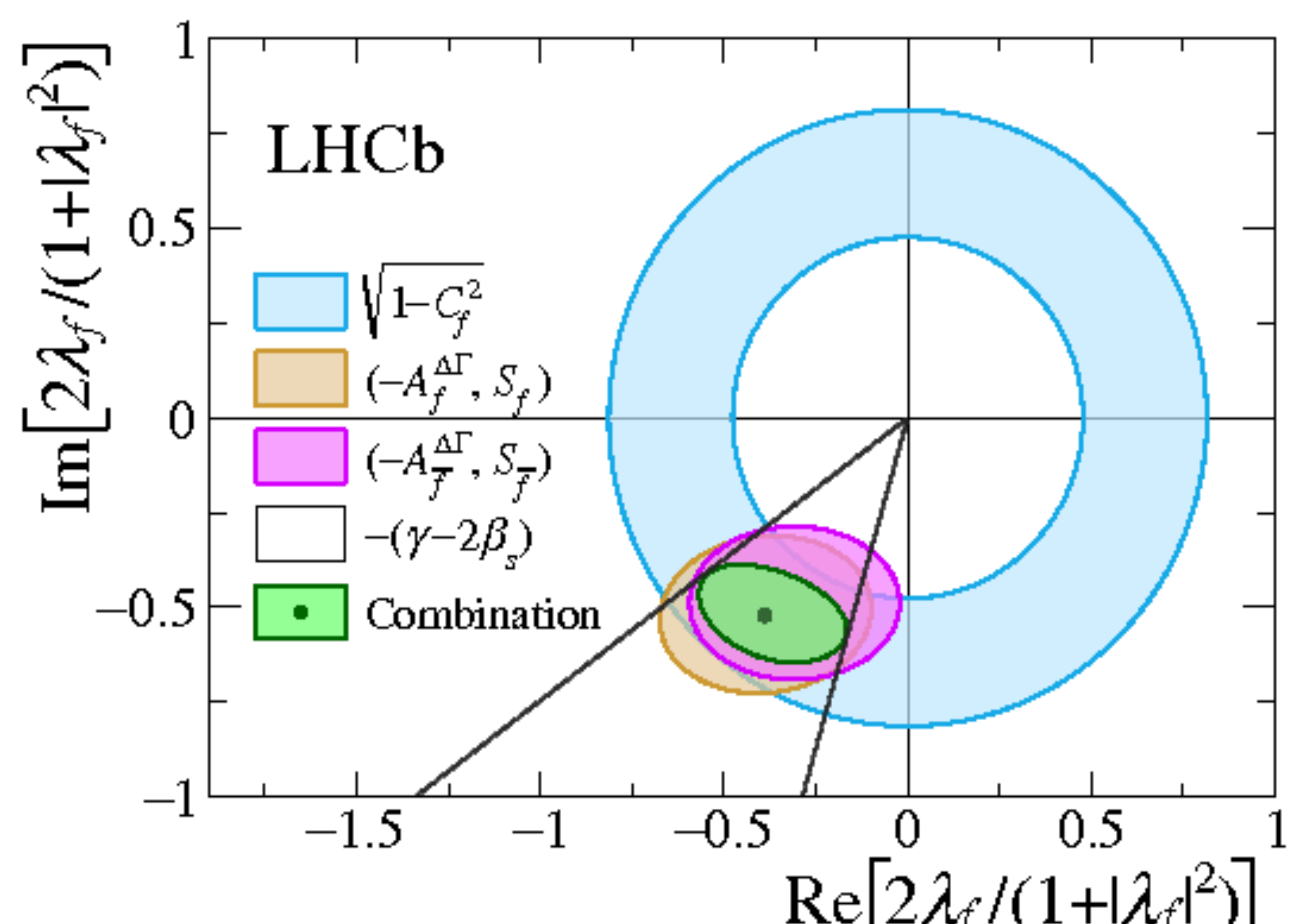
[2] JHEP 03 (2018) 059

$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run1 [2]

- **2011 & 12 data ($3\,\mathrm{fb}^{-1}$)**
  - 5955 ± 90 candidates
  - $\varepsilon_{\mathrm{eff}} = (5.80 \pm 0.25)\,\%$
- **High sensitivity to γ**
  - Amplitude ratio $r_{D_sK} \approx 0.4$

$$C_f = \quad 0.73 \pm 0.14 \pm 0.05$$
$$A_f^{\Delta\Gamma} = \quad 0.39 \pm 0.28 \pm 0.15$$
$$A_{\bar{f}}^{\Delta\Gamma} = \quad 0.31 \pm 0.28 \pm 0.15$$
$$S_f = -\,0.52 \pm 0.20 \pm 0.07$$
$$S_{\bar{f}} = -\,0.49 \pm 0.20 \pm 0.07$$



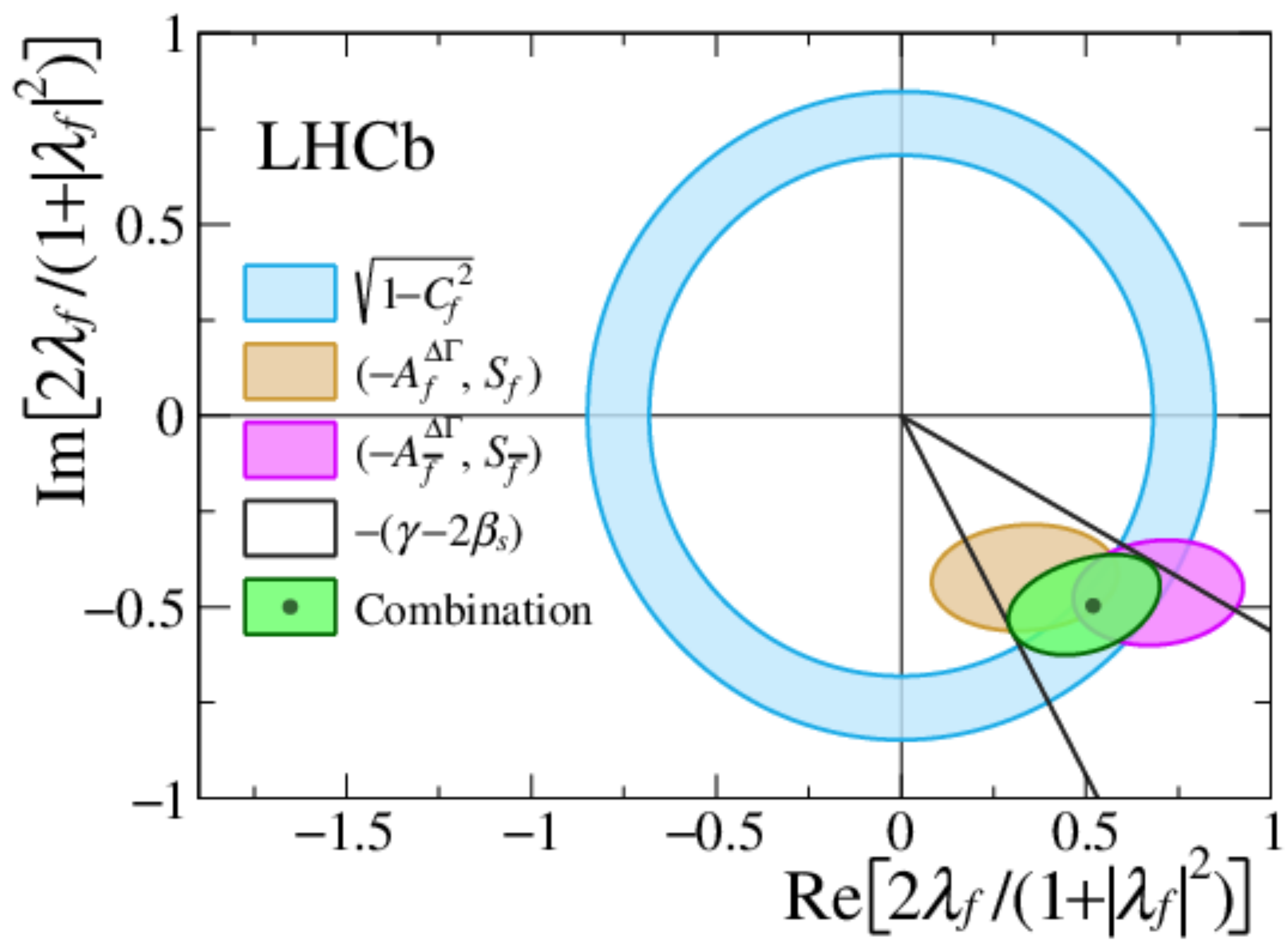


$$\gamma = \left(128^{+17}_{-22}\right)^{\circ}$$

$B_s^0 \to D_s^{\mp} K^{\pm} \pi^{\mp} \pi^{\pm}$ - Run1 & 2 [3]

[3] JHEP 03 (2021) 137

- Full LHCb dataset (Run1 & 2, $9\,\text{fb}^{-1}$)
  - 7500 ± 100 candidates
  - $\varepsilon_{\text{eff}} = (5.71 \pm 0.40)\,\%$ (Run1)
  - $\varepsilon_{\text{eff}} = (6.52 \pm 0.17)\,\%$ (Run2)
- Two strategies
  1. Phase-space integrated analysis



$$C_f = 0.631 \pm 0.096 \pm 0.032$$

$$A_f^{\Delta\Gamma} = -0.334 \pm 0.232 \pm 0.097 \qquad A_{\bar{f}}^{\Delta\Gamma} = -0.695 \pm 0.215 \pm 0.081$$

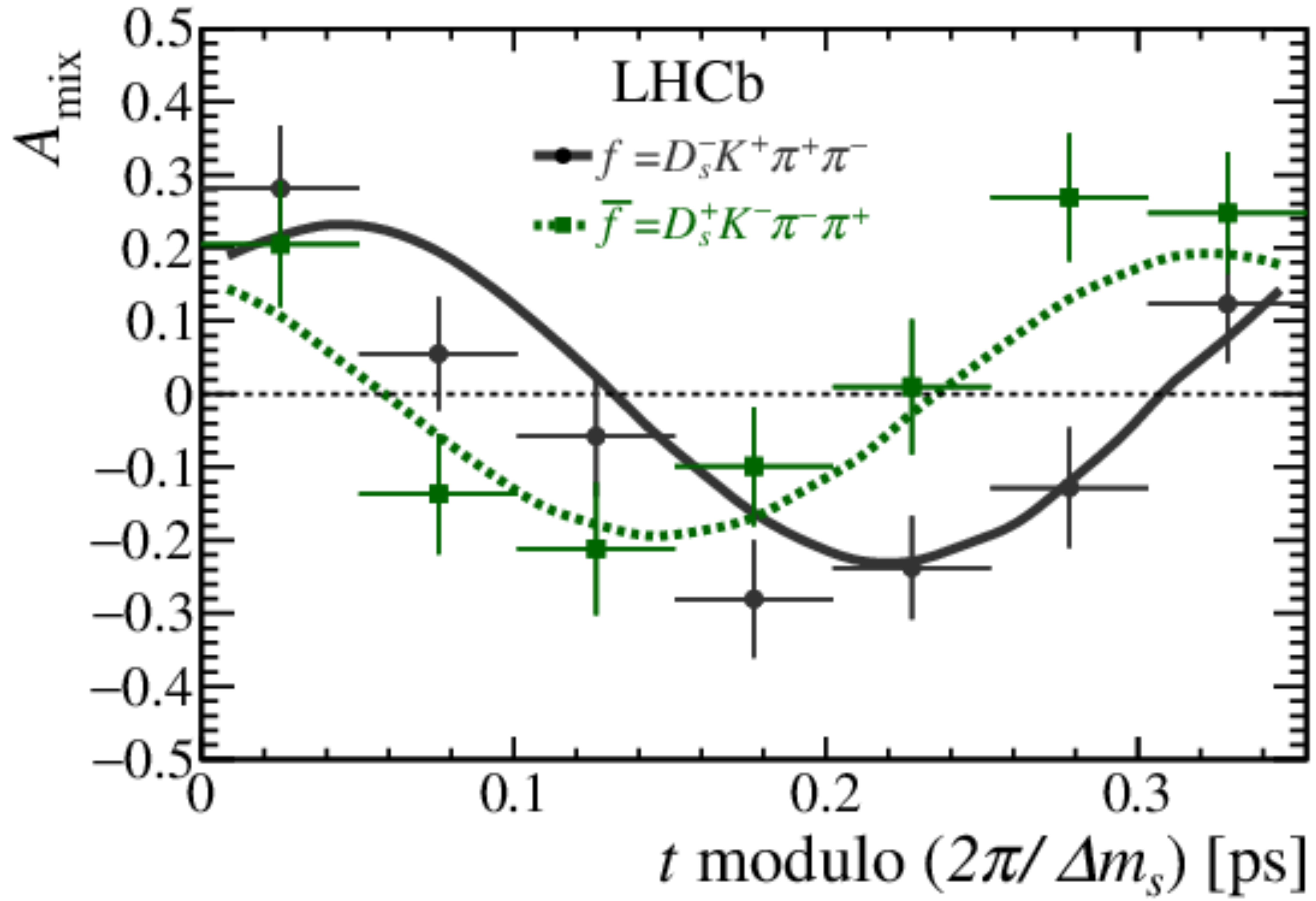
$$S_f = -0.424 \pm 0.135 \pm 0.033 \qquad S_{\bar{f}} = -0.463 \pm 0.134 \pm 0.031$$

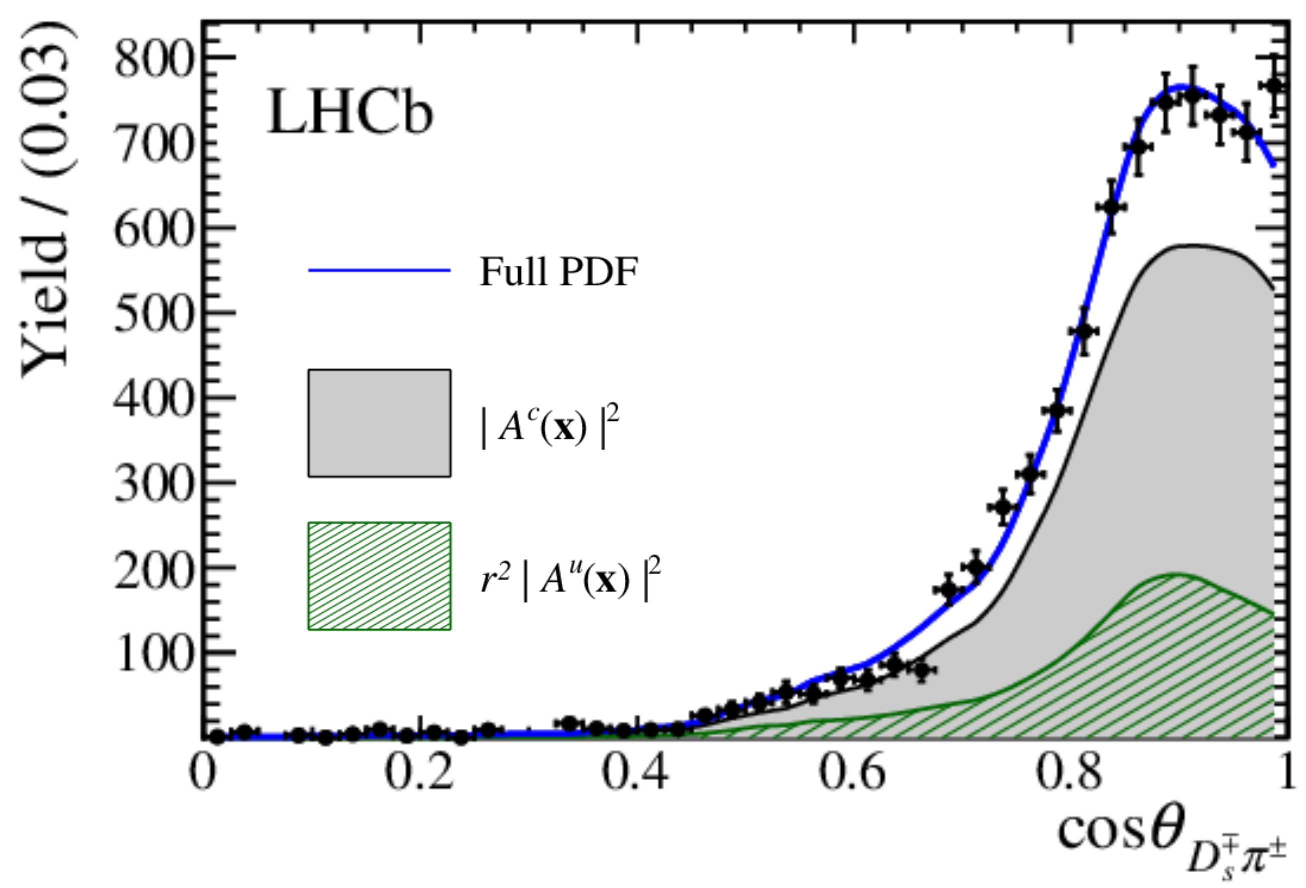
$$\gamma = \left(44^{+20}_{-13}\right)^\circ$$

$B_s^0 \to D_s^{\mp} K^{\pm} \pi^{\mp} \pi^{\pm}$ - Run1 & 2 [3]

[3] JHEP 03 (2021) 137

- Full LHCb dataset (Run1 & 2, $9\,\mathrm{fb}^{-1}$)
  - 7500 ± 100 candidates
  - $\varepsilon_{\mathrm{eff}} = (5.71 \pm 0.40)\,\%$ (Run1)
  - $\varepsilon_{\mathrm{eff}} = (6.52 \pm 0.17)\,\%$ (Run2)
- Two strategies
  2. Model-dependent amplitude analysis





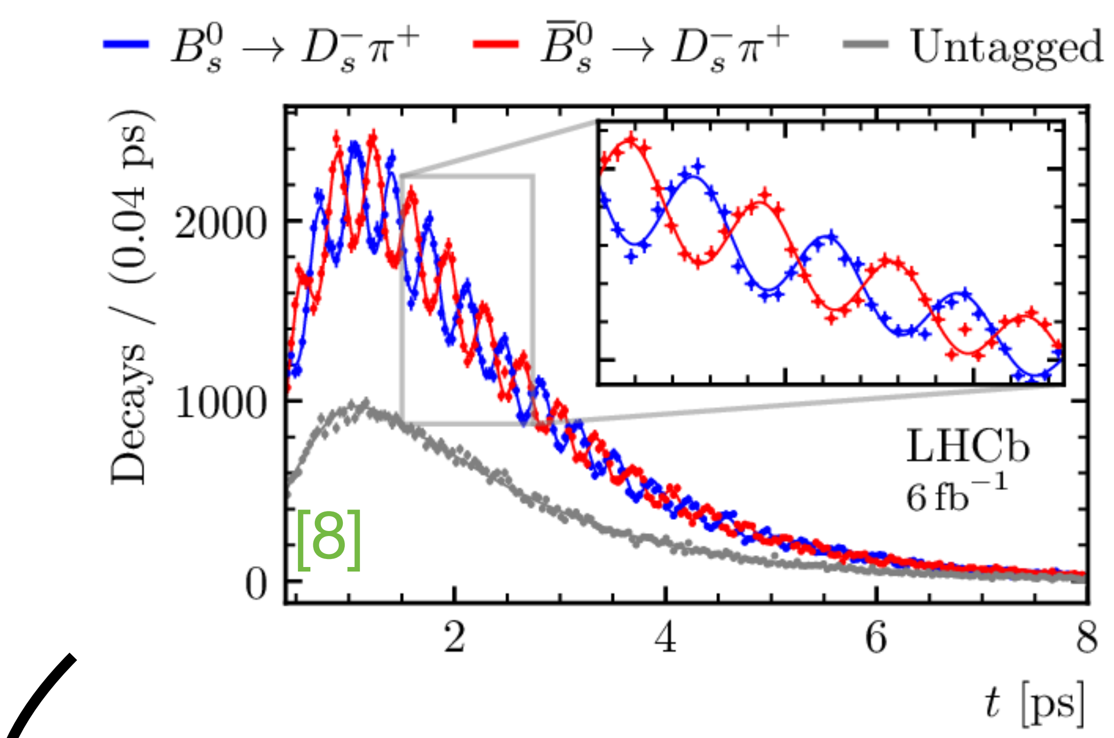
$$\gamma = \left(44 \pm 12\right)^{\circ}$$

Analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$ decays in the LHCb Run2 dataset

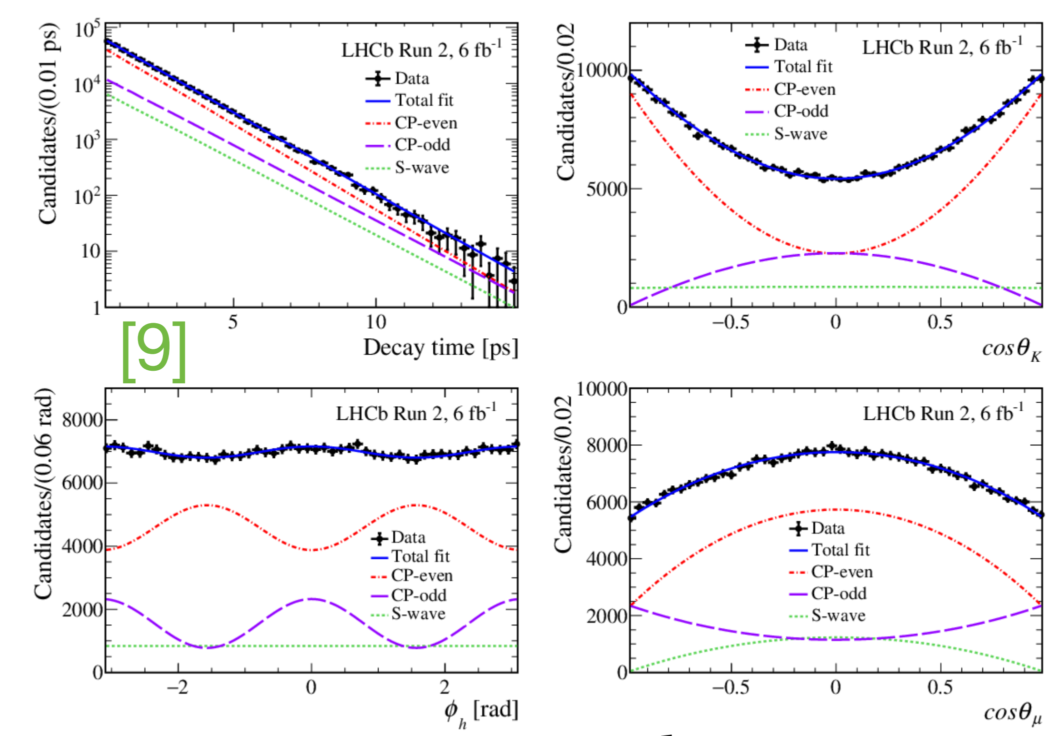
$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2

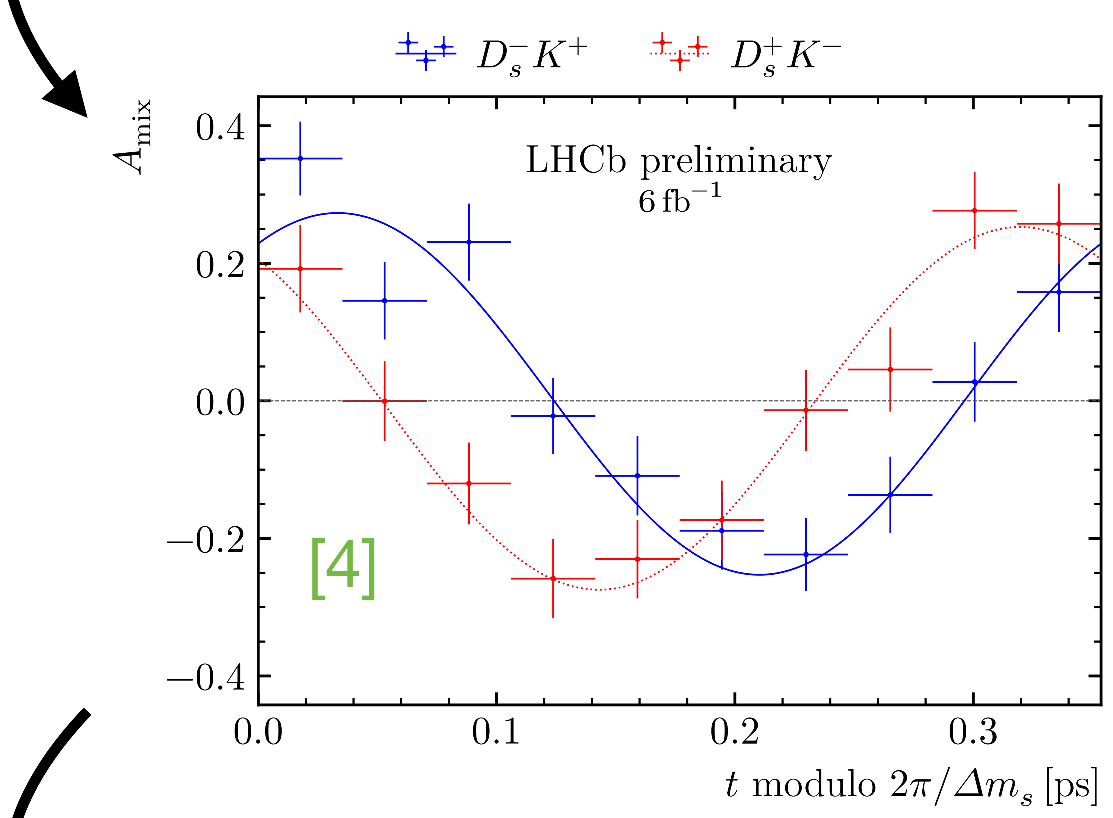
- **Three time-dependent legacy measurements coming together**
  - $B_s^0 \to D_s^- \pi^+$ Run2 [8]
  - $B_s^0 \to D_s^{\mp} K^{\pm}$ Run2 [4]
  - $B_s^0 \to J/\psi K^+ K^-$ Run2 [9]
- **Most precise TD measurement of γ**

WG4, Mon 14:45



Inputs (Δm_s, calibrations)



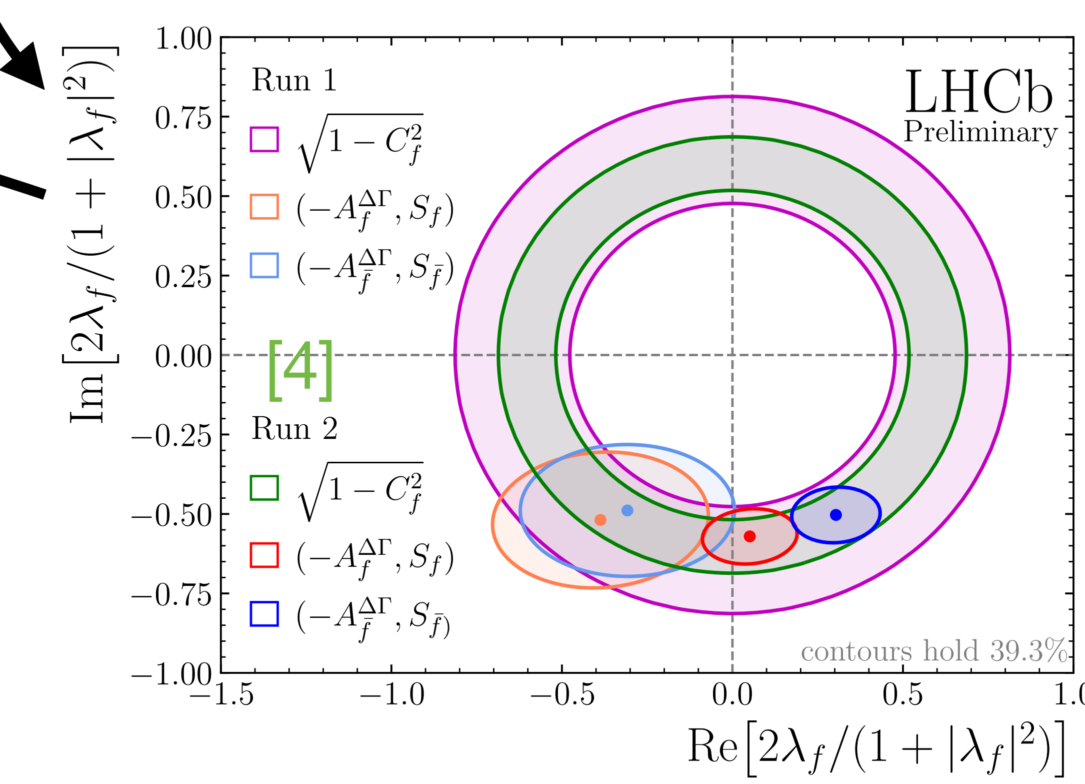


Five CP observables

ϕ_s

$\gamma - \phi_s$

γ



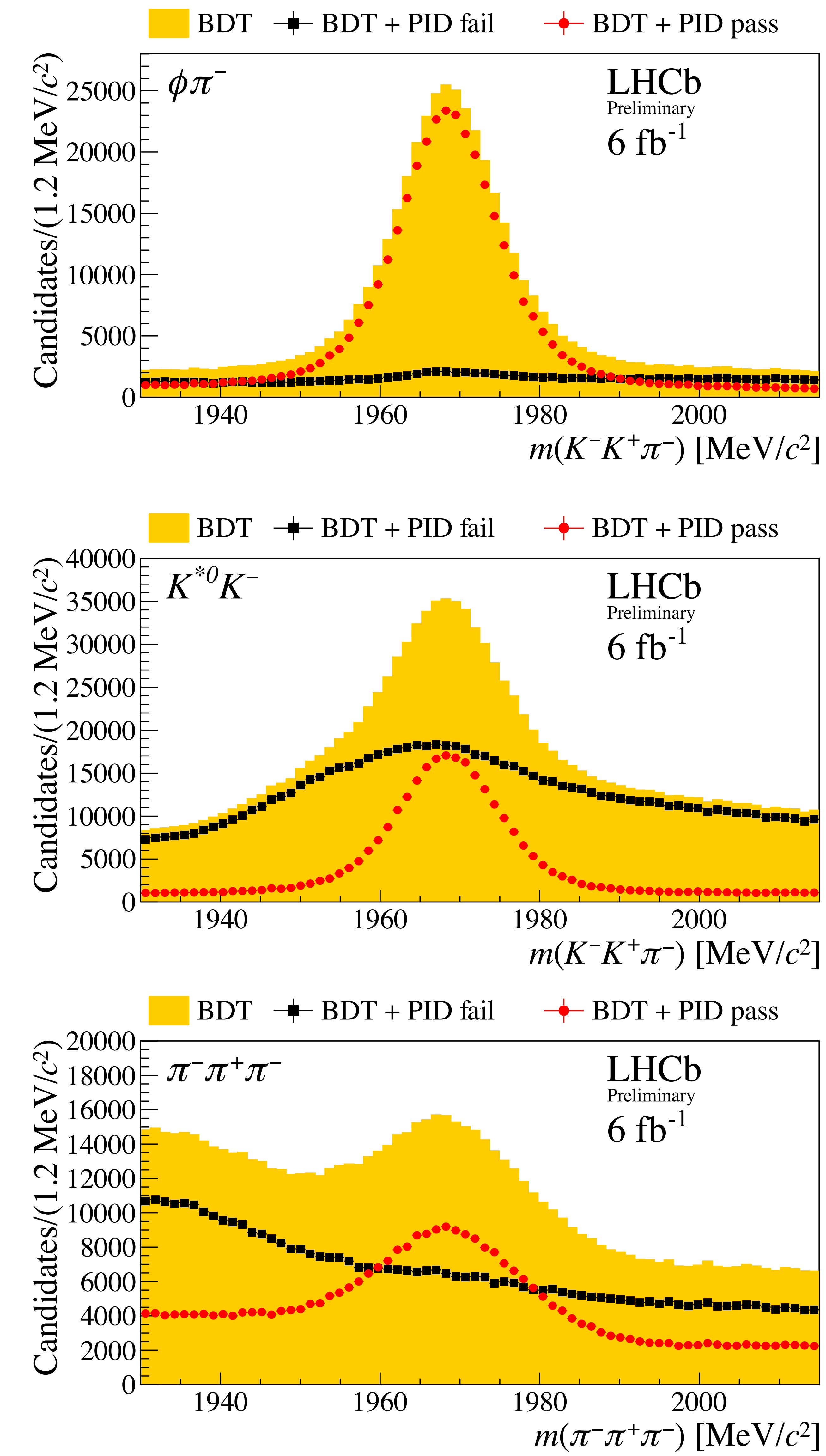
[4] LHCb-CONF-2023-004
[8] Nat. Phys. 18, 1–5 (2022)
[9] LHCb-PAPER-2023-016, submitted to Phys. Rev. Lett.

[4] LHCb-CONF-2023-004

$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Signal

- D_s^- **reconstructed in five modes**
  - Different levels of contamination
  - $\phi(1020)\pi^-$
  - $K^-\pi^+\pi^-$
  - $K^{*0}(892)K^-$
  - $\pi^-\pi^+\pi^-$
    - $K^-K^+\pi^-$ (nonresonant)

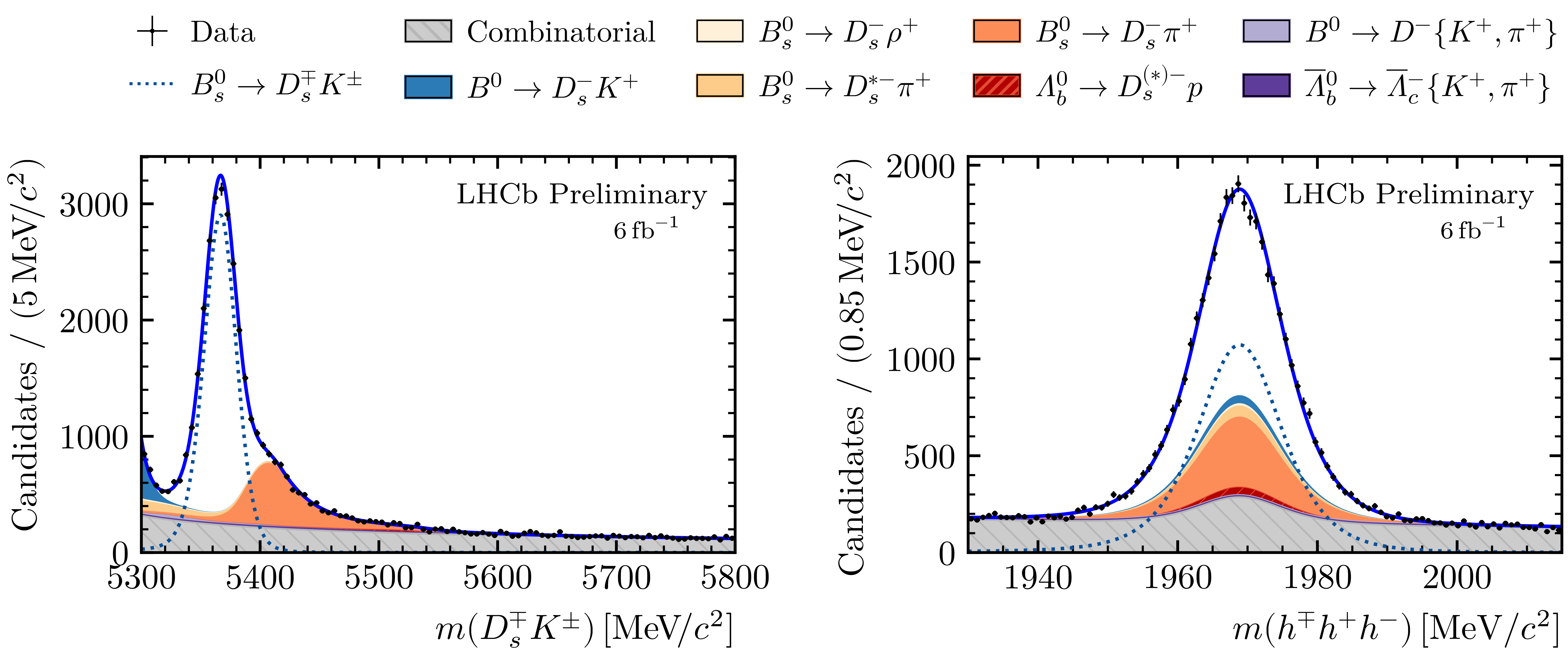
- **Selection**
  - BDT to reduce combinatorial
  - Various specific vetoes
  - FD requirements to suppress non-D_s^- backgrounds
  - Sample split by hadron PID $h \in \{K, \pi\}$



$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Signal

[4] LHCb-CONF-2023-004
[10] Eur. Phys. J. C 82, 393 (2022)

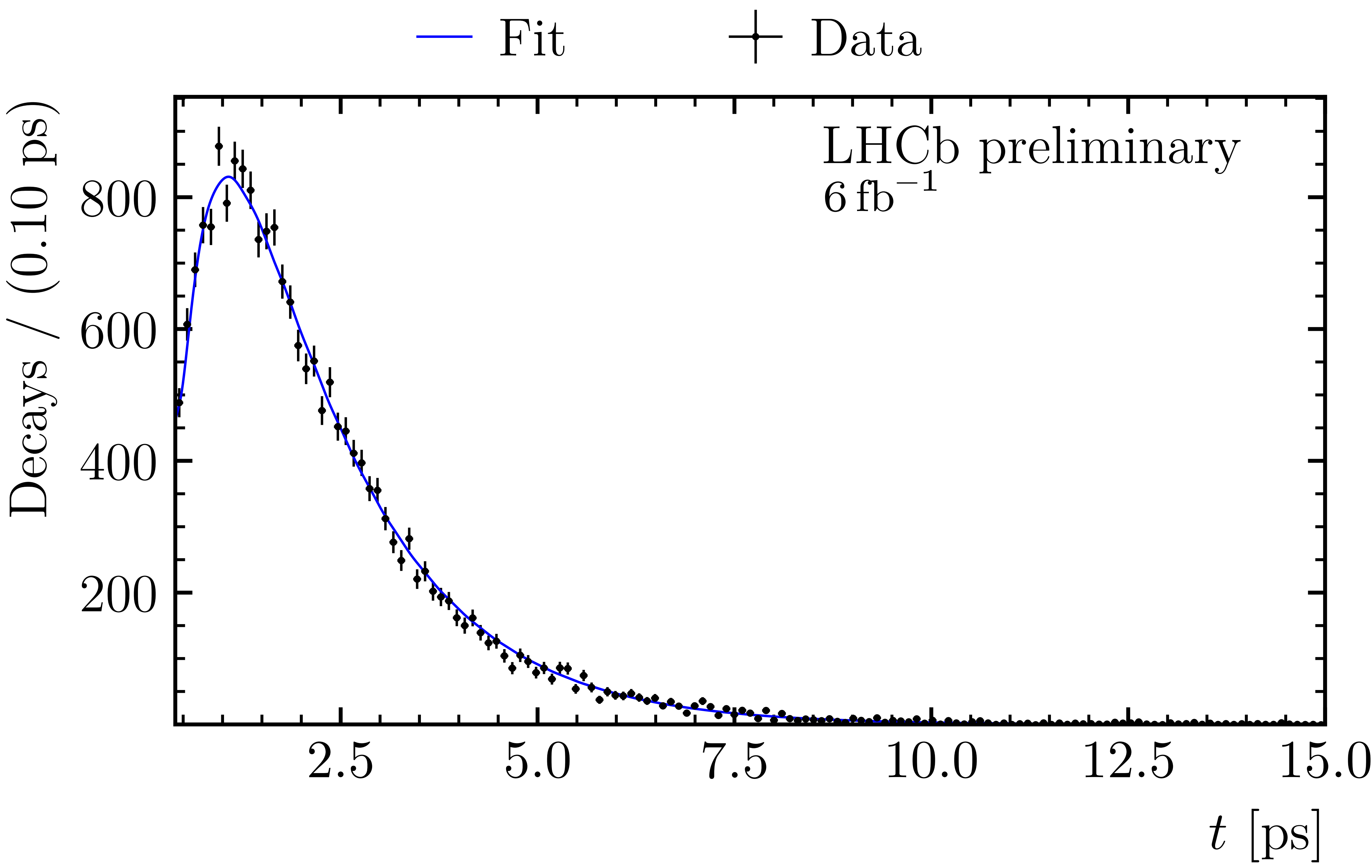
- **Invariant mass fit to extract sWeights** [10]
  - 2-dimensional
  - Simultaneous for all D_s^- modes and years (2015+16, 2017, 2018)
  - 20950 ± 180 candidates



$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Fit

[4] LHCb-CONF-2023-004
[9] LHCb-PAPER-2023-016 (submitted to Phys. Rev. Lett.)
[11] LHCb-PUB-2018-004

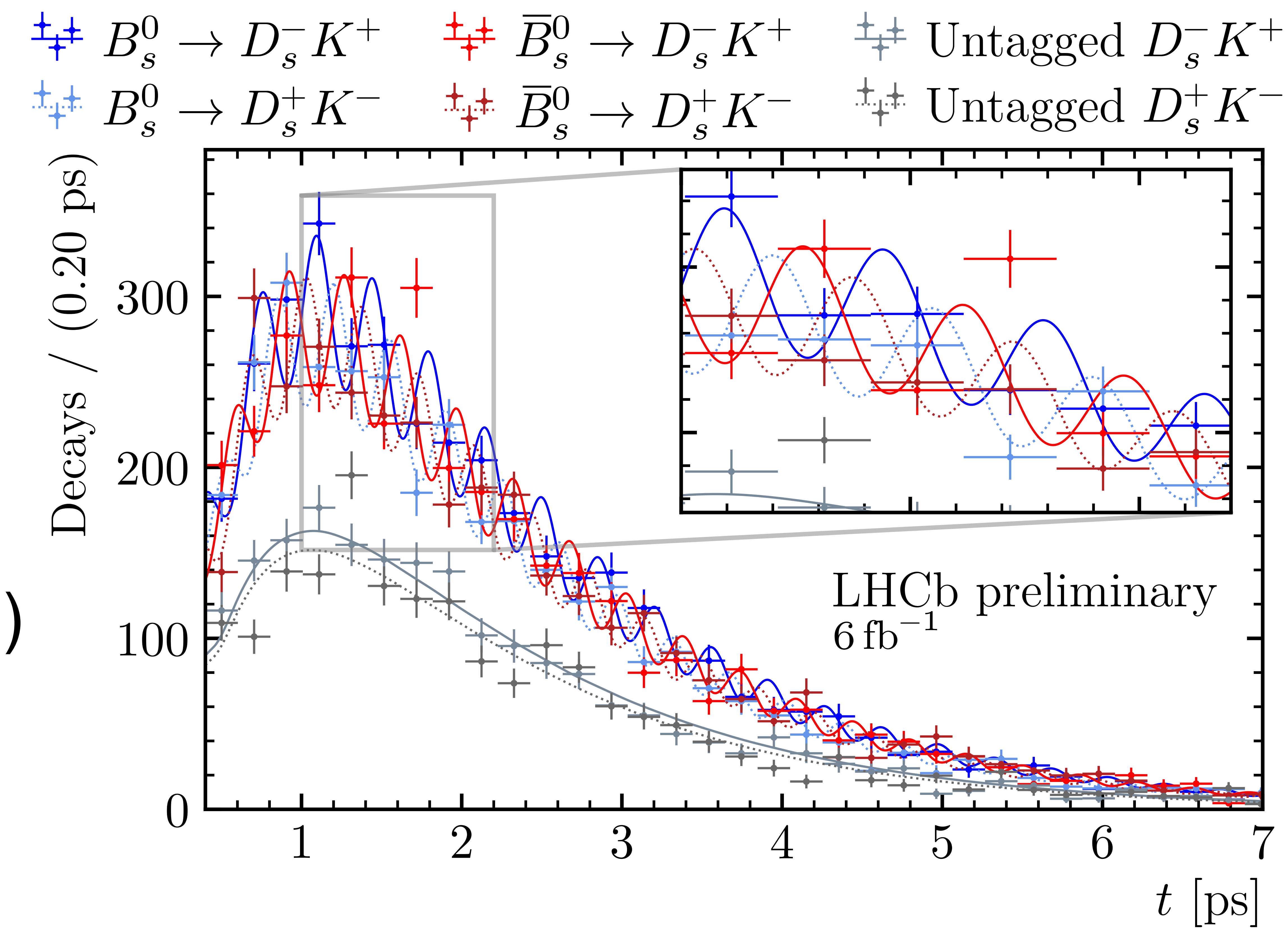
- **Simultaneous fit of all modes and years**
- **Inputs from $B_s^0 \to D_s^- \pi^+$**
  - Resolution calibration
  - VELO alignment correction
  - Decay-time acceptance with small simulation-based corrections
  - Tagging calibration ($\varepsilon_{\text{eff}} = (6.10 \pm 0.15)\,\%$)
  - Production asymmetry and Δm_s
- **External inputs**
  - Γ_s and $\Delta\Gamma_s$ [9]
  - Detection asymmetry [11]



$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Fit

[4] LHCb-CONF-2023-004
[9] LHCb-PAPER-2023-016 (submitted to Phys. Rev. Lett.)
[11] LHCb-PUB-2018-004

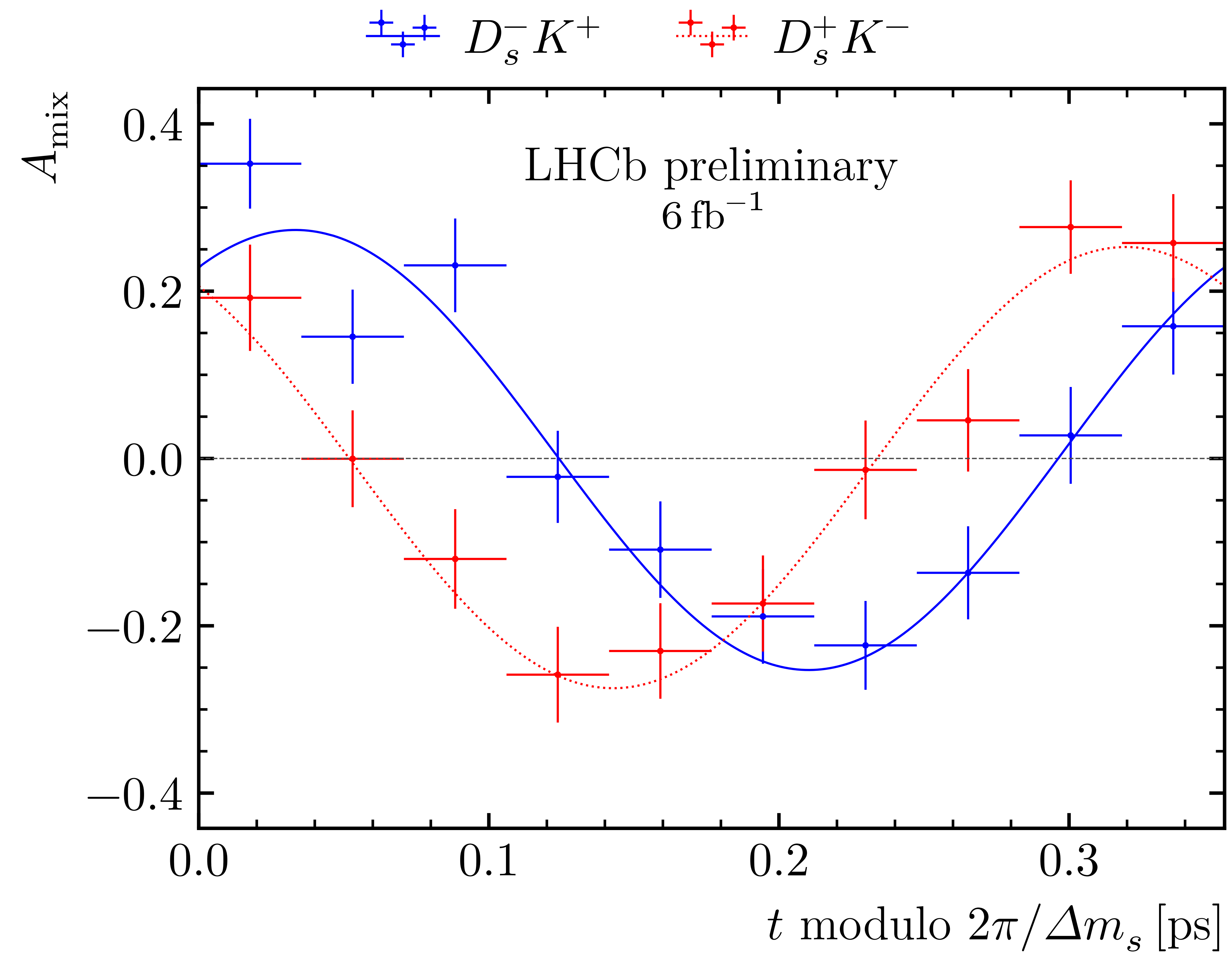
- Simultaneous fit of all modes and years
- Inputs from $B_s^0 \to D_s^- \pi^+$
  - Resolution calibration
  - VELO alignment correction
  - Decay-time acceptance with small simulation-based corrections
  - Tagging calibration ($\varepsilon_{\text{eff}} = (6.10 \pm 0.15)\,\%$)
  - Production asymmetry and Δm_s
- External inputs
  - Γ_s and $\Delta\Gamma_s$ [9]
  - Detection asymmetry [11]



$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Fit

[4] LHCb-CONF-2023-004

- **Uncertainties improved beyond statistics**
  - e.g. improvement in FT
- **Systematics also reduced**
- **Significant $C\!P$ violation in the interference**
  $S_f \neq -S_{\bar{f}}$ at $8.8\,\sigma$



$$C_f = 0.791 \pm 0.061 \pm 0.022$$

$$A_f^{\Delta\Gamma} = 0.051 \pm 0.134 \pm 0.037 \qquad A_{\bar{f}}^{\Delta\Gamma} = 0.303 \pm 0.125 \pm 0.036$$

$$S_f = -0.571 \pm 0.084 \pm 0.023 \qquad S_{\bar{f}} = -0.503 \pm 0.084 \pm 0.025$$

$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Systematics

[4] LHCb-CONF-2023-004

- **Systematics evaluated**
  - Peseudoexperiment studies
  - Data-driven approaches
  - Bootstrapping simulation

Source	C_f	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
Δm_s	0.007	0.004	0.004	0.108	0.103
Detection asymmetry	—	0.079	0.083	0.006	0.007
Multivariate fit	0.045	0.095	0.121	0.088	0.112
Flavour tagging	0.256	0.026	0.028	0.012	0.070
Decay-time resolution model	0.195	0.002	0.003	0.058	0.167
Decay-time bias	0.062	0.027	0.046	0.188	0.167
Decay-time acceptance, Γ_s, $\Delta\Gamma_s$	0.006	0.225	0.231	0.003	0.003
Decay-time acceptance ratios	0.001	0.018	0.018	—	—
Neglecting correlations	0.137	0.081	0.054	0.135	0.043
Total	0.358	0.273	0.285	0.278	0.294

- **Further checks**
  - Simulation-based closure tests
  - Analysis performed in subsamples
- **No systematic limitation expected in Run3**

$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Results

[4] LHCb-CONF-2023-004
[9] LHCb-PAPER-2023-016, submitted to Phys. Rev. Lett.

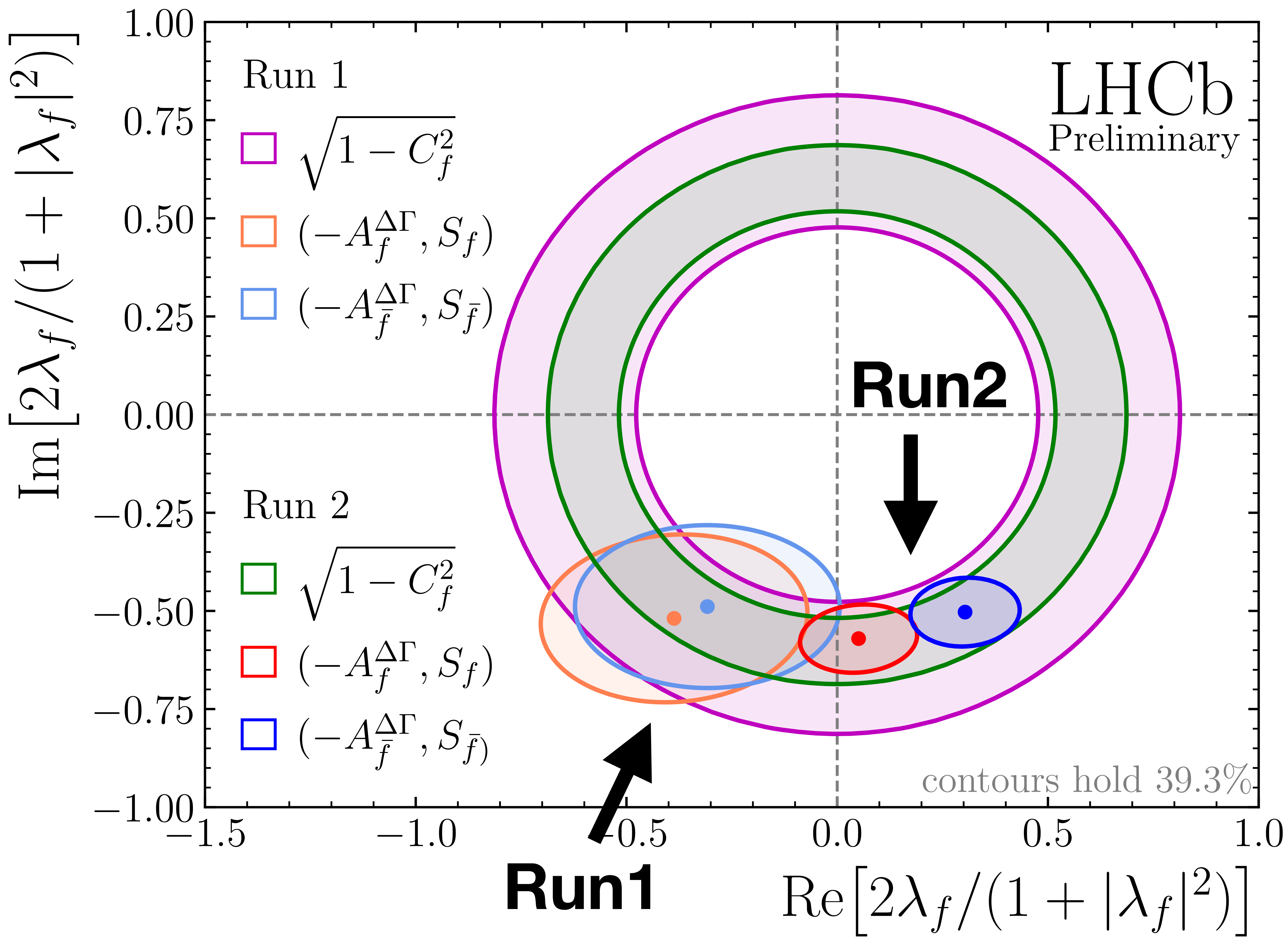
- **Extraction of physics parameters**
  - External input [9]

    $-2\beta_s = \phi_s = (-0.031 \pm 0.018)\,\text{rad}$

- **Run2 standalone result:**

$$\gamma = (74 \pm 11)^{\circ}$$

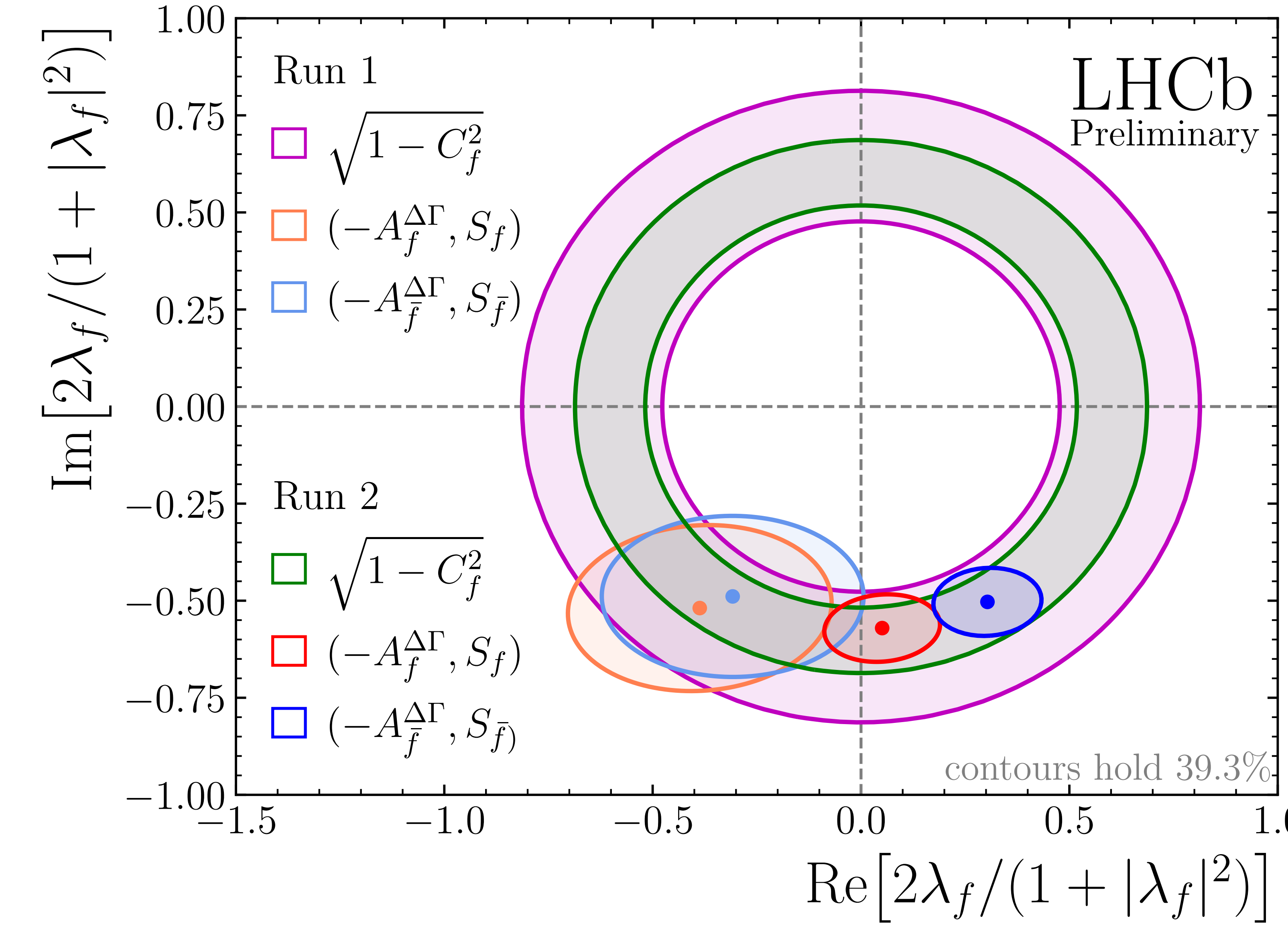
$$\delta = (346.9 \pm 6.6)^{\circ} \qquad r_{D_sK} = 0.327 \pm 0.038$$

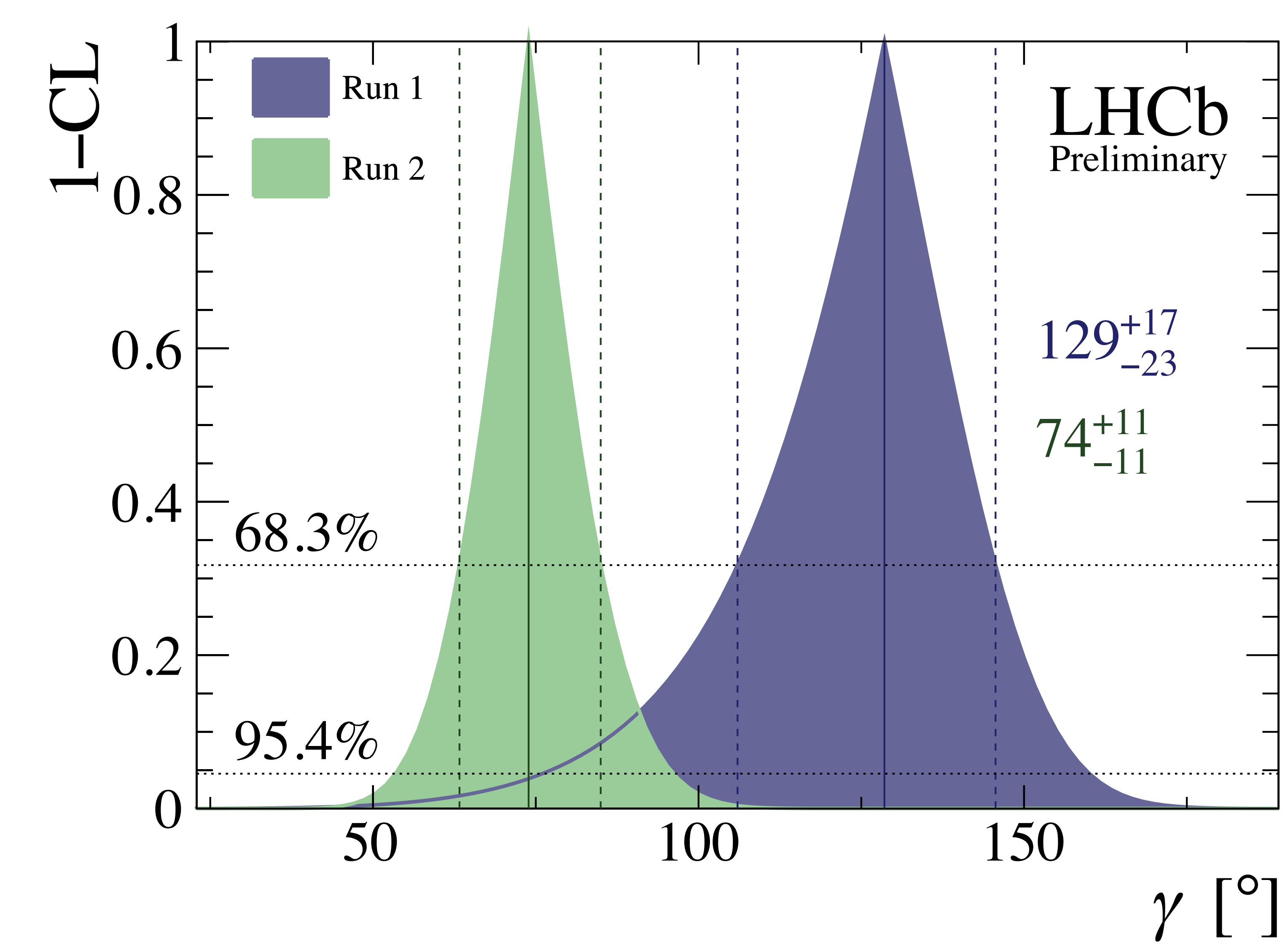


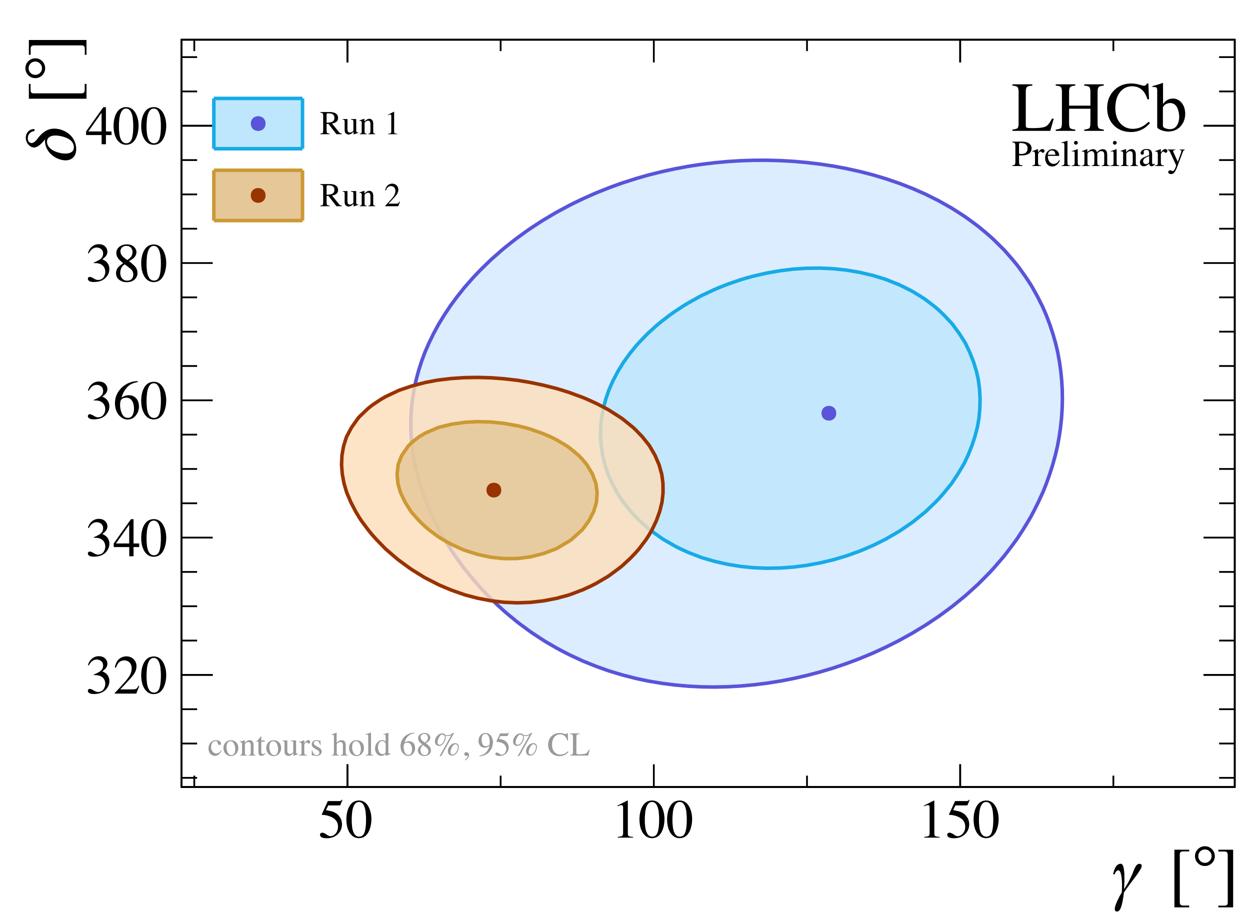
[2] JHEP 03 (2018) 059
[4] LHCb-CONF-2023-004

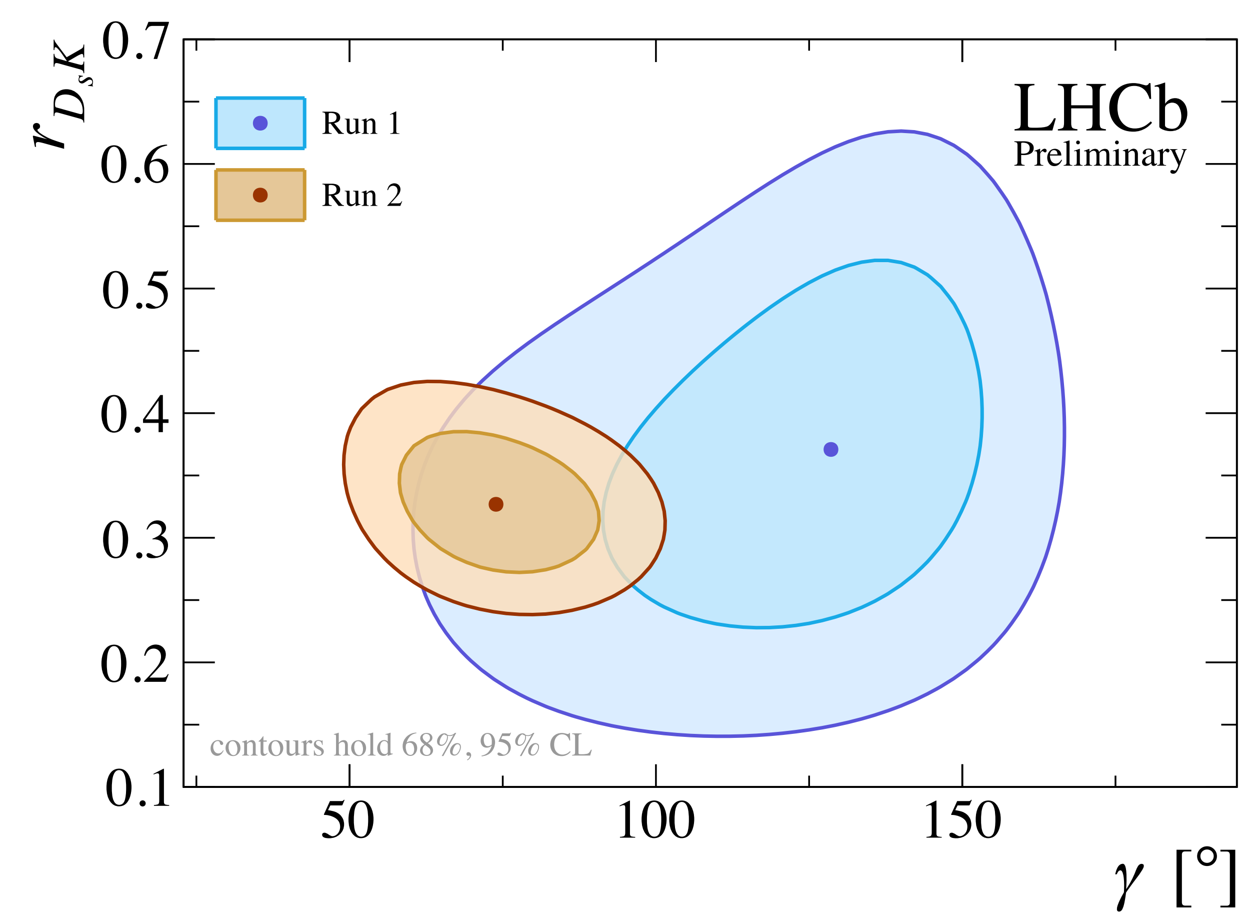
$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2 [4] - Results

- **Compatibility to Run1 [2] at $1.3\,\sigma$**
  - Driven by γ at $2\,\sigma$ and Re[λ_f]
  - r_{D_sK} and δ at $0.6\,\sigma$ each
- **Updated machinery reproduces Run1 result [2]**
- **Combination in preparation**









Summary

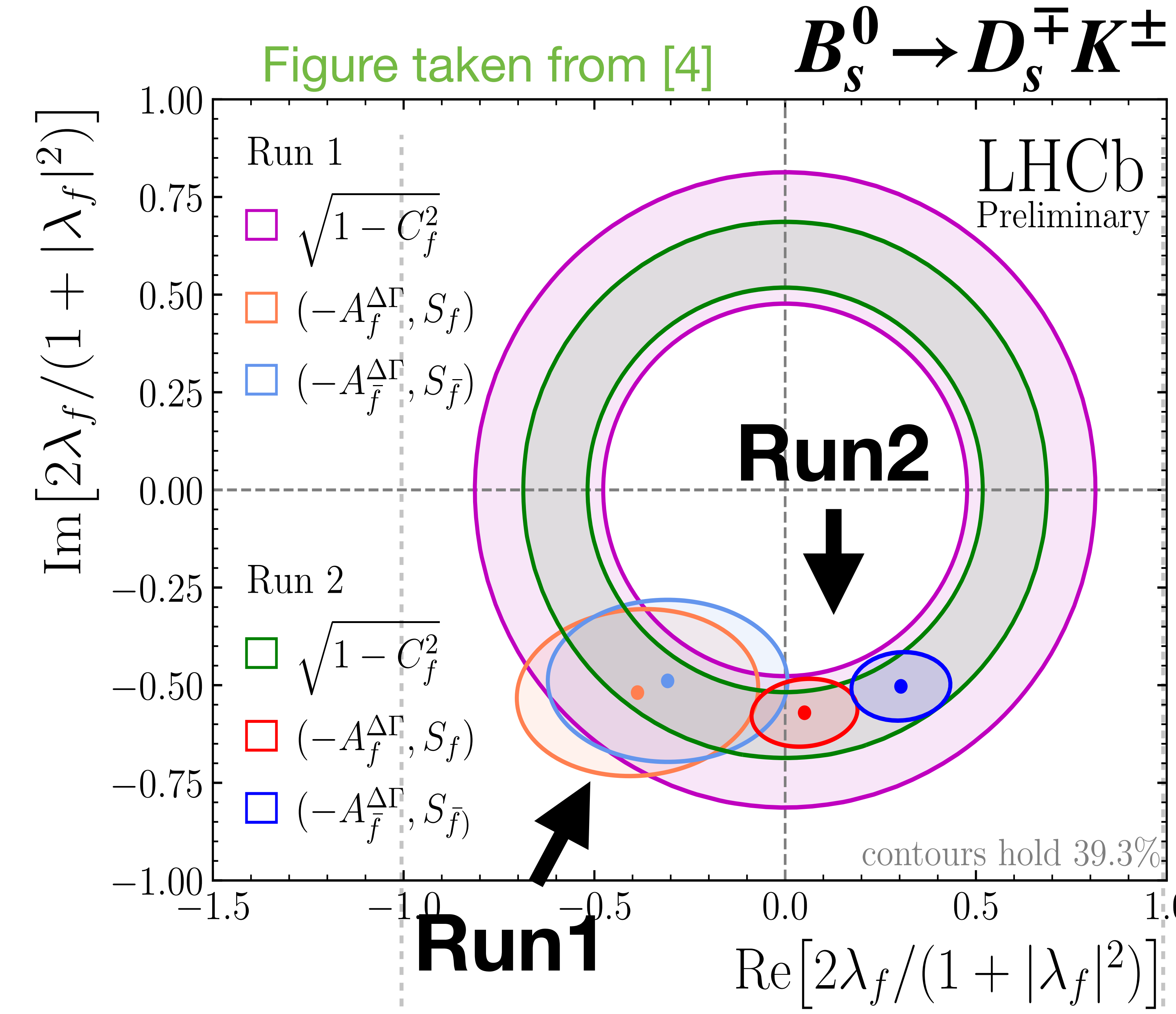
Summary

- New TD analysis of $B_s^0 \to D_s^{\mp} K^{\pm}$ decays in LHCb Run2 data set: [4]

$$\gamma_{D_s^{\mp}K^{\pm}}^{6\,\mathrm{fb}^{-1}} = (74 \pm 11)^{\circ}$$

- Combinations with new result in preparation

Figure taken from [4]



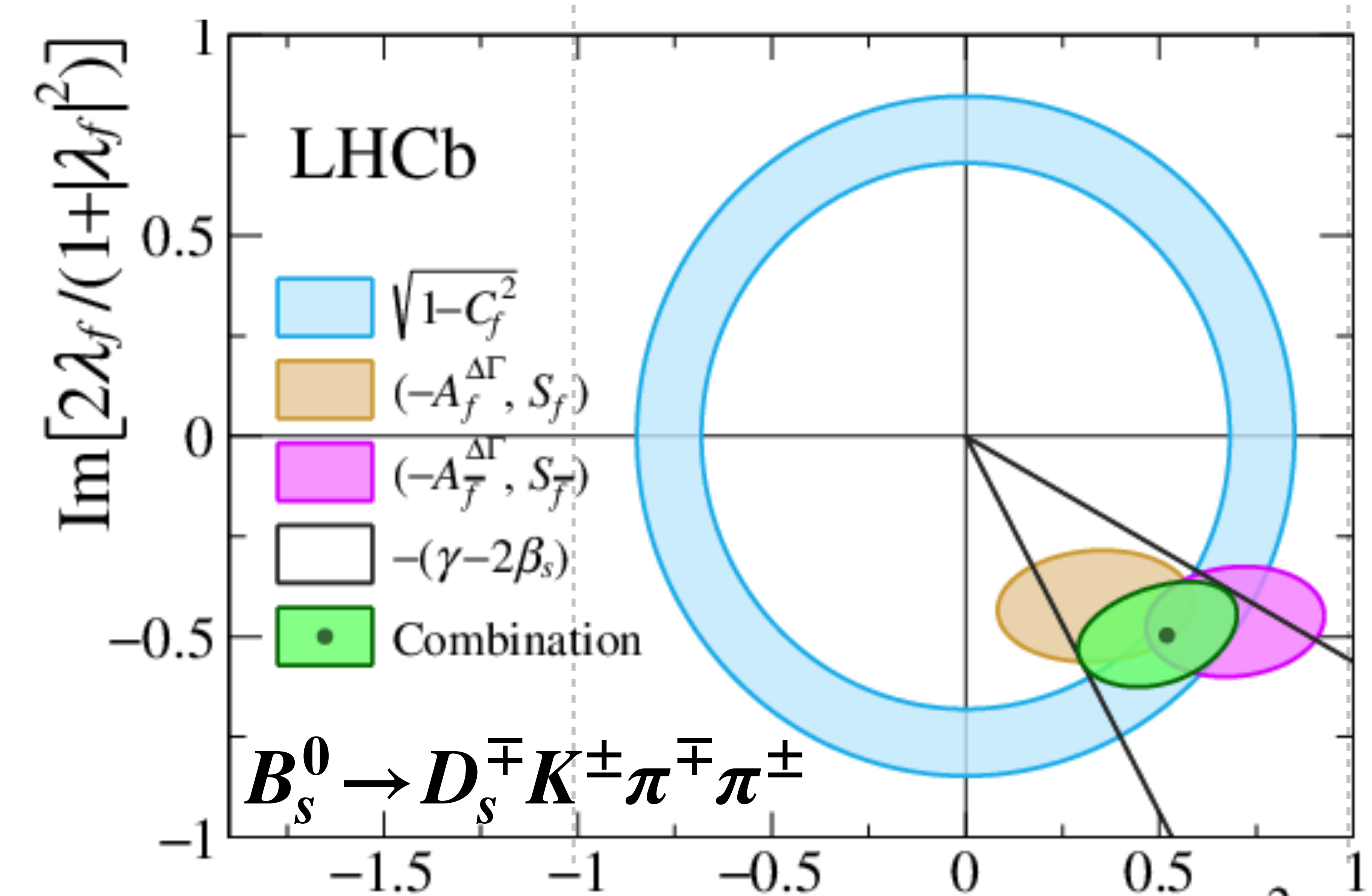


Figure taken from [3]

[1] JHEP 06 (2018) 084
[2] JHEP 03 (2018) 059
[3] JHEP 03 (2021) 137
[4] LHCb-CONF-2023-004
[5] LHCb-CONF-2022-003
[6] Int. J. Mod. Phys. A 30, 1530022 (2015)
[7] Eur. Phys. J. C 73, 2431 (2013)
[8] Nat. Phys. 18, 1–5 (2022)
[9] LHCb-PAPER-2023-016, submitted to Phys. Rev. Lett. (Presentation: WG4, Mon 14:45)
[10] Eur. Phys. J. C 82, 393 (2022)
[11] LHCb-PUB-2018-004