# Recent results on CP violation at LHCb experiment

## LHCb上近期CP破坏研究结果

强子与重味物理

胡晓凡

2026/3/29

# Contents

- CKM angle $\gamma$
  - $B^+ \to DK^+$ and $B^+ \to D\pi^+$, with $\mathrm{D} \to K_S^0 h^+ h^-$
    *[LHCb-PAPER-2026-010]* **NEW!**
- Search for new physics:
  - $D^+ \to \phi(1020)^0 \pi^+$
    *[LHCb-PAPER-2026-011]* **NEW!**
  - $B^0 \to K_S^0 \mu^+ \mu^-$
    *[2603.13223]*
- Controlling penguin contribution in $\beta_s$ measurement:
  - $B^0 \to J/\psi \rho^0$
    *[2601.15646]*
  - $B_{(s)}^0 \to D_s^{\pm} D^{\mp}$
    *[LHCb-PAPER- 2025-037]* **NEW!**
- More: $B_s^0 \to D_s^- \pi^+$; measurement of $\gamma$ in $B^{\pm} \to [h^+ h^- \pi^+ \pi^-]_D h^{\pm}$ [see backups]

# CKM Matrix

- The transformation between mass & weak-interaction eigenstates:

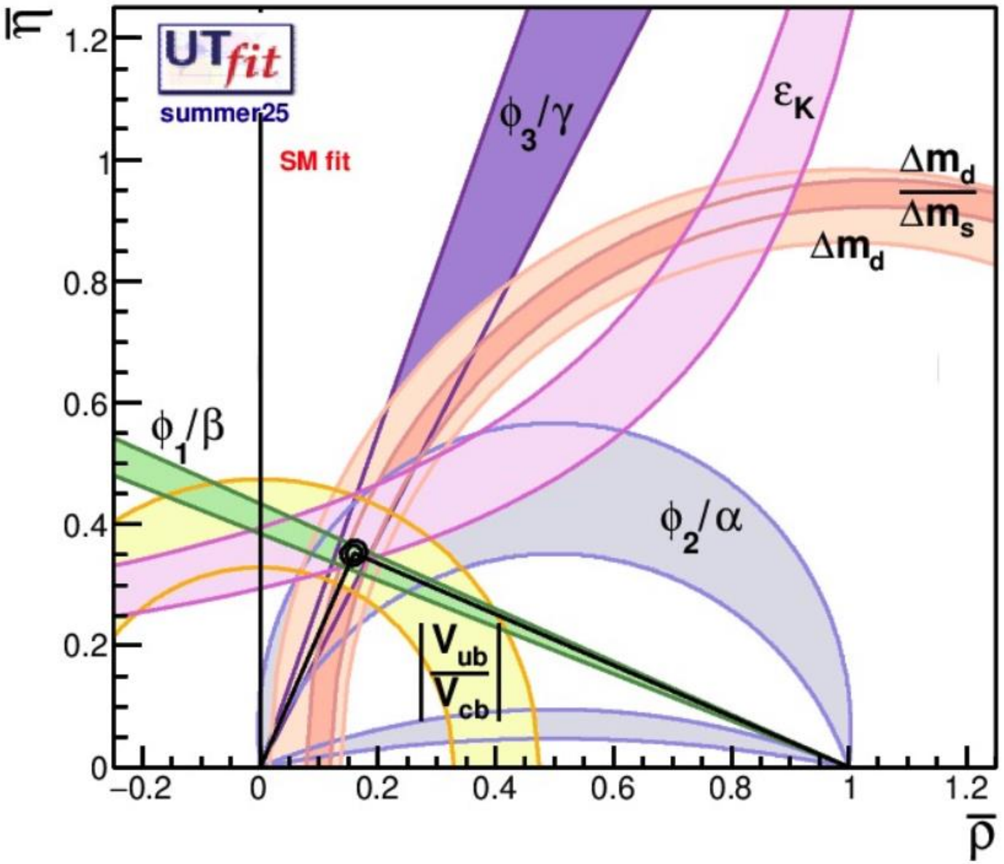
$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\, \overline{u_{Li}}\, \gamma^\mu\, (V_{\mathrm{CKM}})_{ij}\, d_{Lj}\, W_\mu^+ + \mathrm{h.c.}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitary triangle angles:

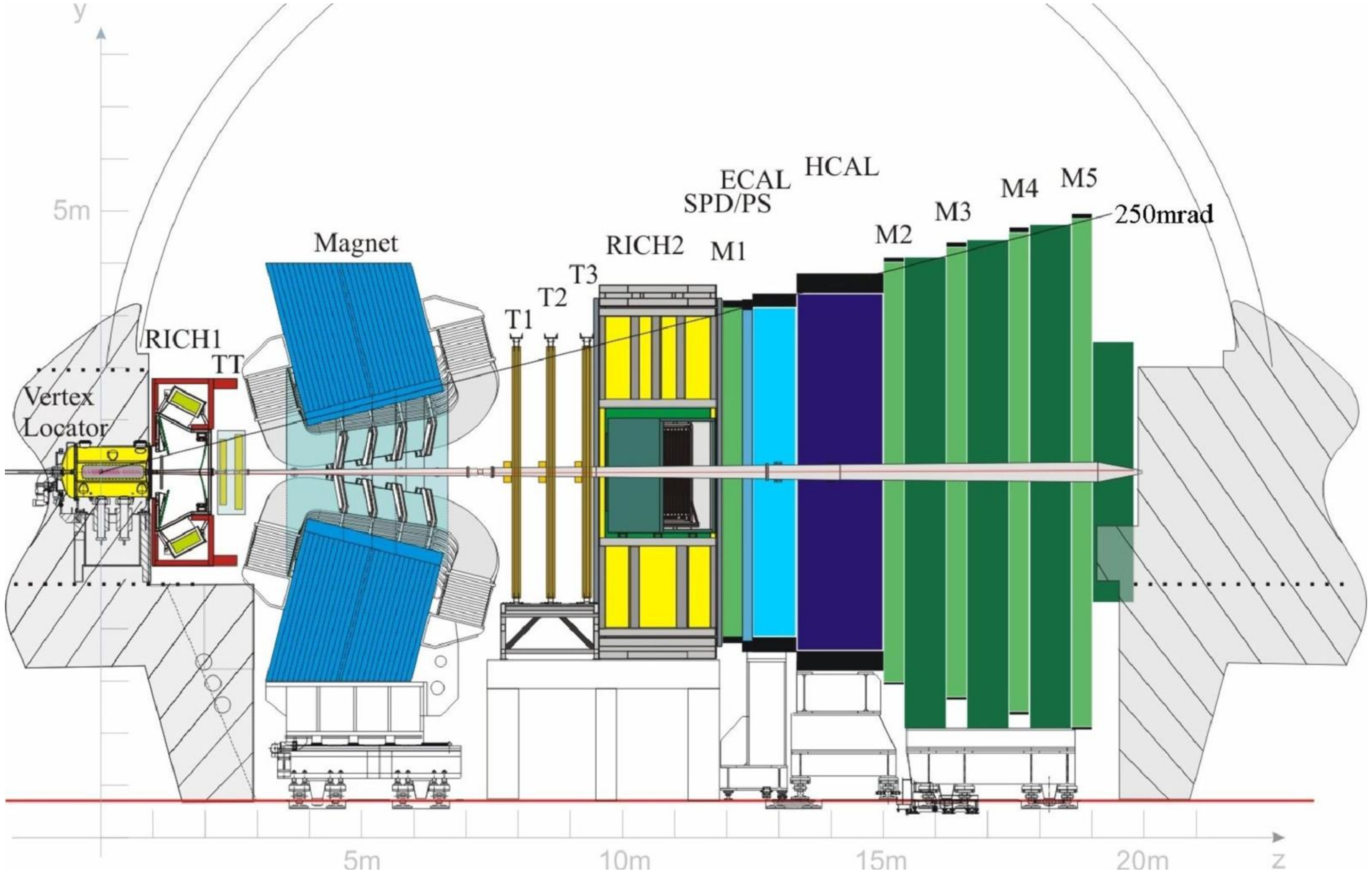
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \qquad \boldsymbol{\beta \equiv arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*})}$$

$$\boldsymbol{\gamma \equiv arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})}$$



# The LHCb Detector

- The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks.




LHCb Detector in Run 2. [JINST 3 (2008) S08005, Int. J. Mod. Phys. A30, 1530022 (2015)]

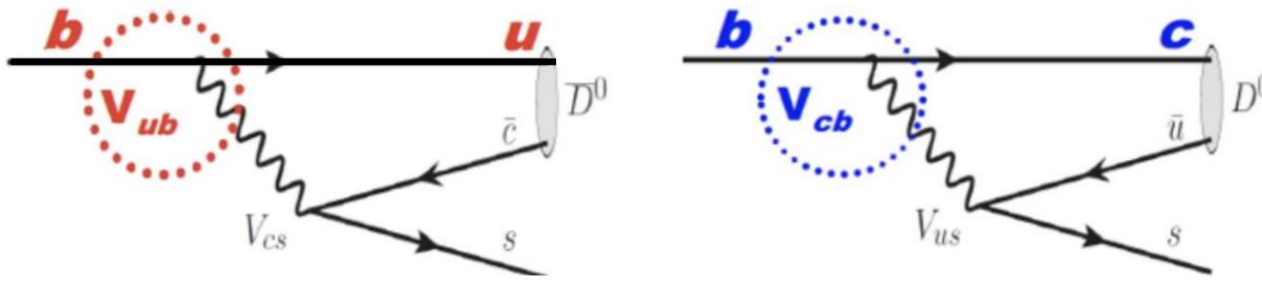
# CKM angle measurement

# Measurement of CKM angle $\gamma$: $B^+ \to Dh^+$ decays

LHCb-PAPER-2026-010
[in preparation]

RUN 3

- $B^+ \to D^0 K^+$ and $B^+ \to \bar{D}^0 K^+$ interfere, when $D^0$ ($\bar{D}^0$) decay into $K_S^0 h^+ h^-$
  - Interference between $b \to \bar{c}us$ and $c\bar{u}s$ (two tree-level, no penguin)
  - $A_B \;\propto\; A_D + r_B \exp\big(i(\delta_B + \gamma)\big)\, A_{\bar{D}}$




favoured

suppressed

$m_\pm \equiv m(K_S^0 h^\pm)$

- D meson decay amplitudes: $A_D(m_-^2, m_+^2)$ and $A_{\bar{D}}(m_-^2, m_+^2)$ dependent on final-state
  - Phase difference $\delta_D(m_-^2, m_+^2)$;
  - $|A_D(m_-^2, m_+^2)| = |A_{\bar{D}}(m_+^2, m_-^2)|$

**CPV and mixing in D decays neglected**

# $B^+ \to Dh^+$ decays: fitting procedure

LHCb-PAPER-2026-010
[in preparation]

RUN 3

- Binned fits: fits to yields of $B^+$ decays ($N_i^+$) and $B^-$ decays ($N_i^-$), in $2 \times 8 + 2 \times 2$ bins

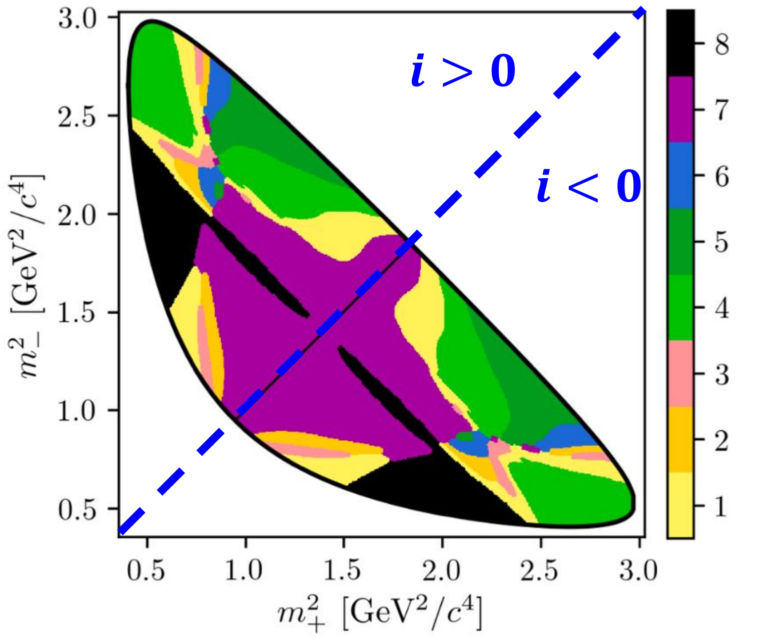
$$N_i^{\pm} \propto \left| \sqrt{F_{\mp i}} + \sqrt{F_{\pm i}}\, r_B \exp\big(i(\delta_B \pm \gamma)\big) \exp(-i\delta_{D,\mp i}) \right|^2$$

**Each bin with similar $\delta_D$**

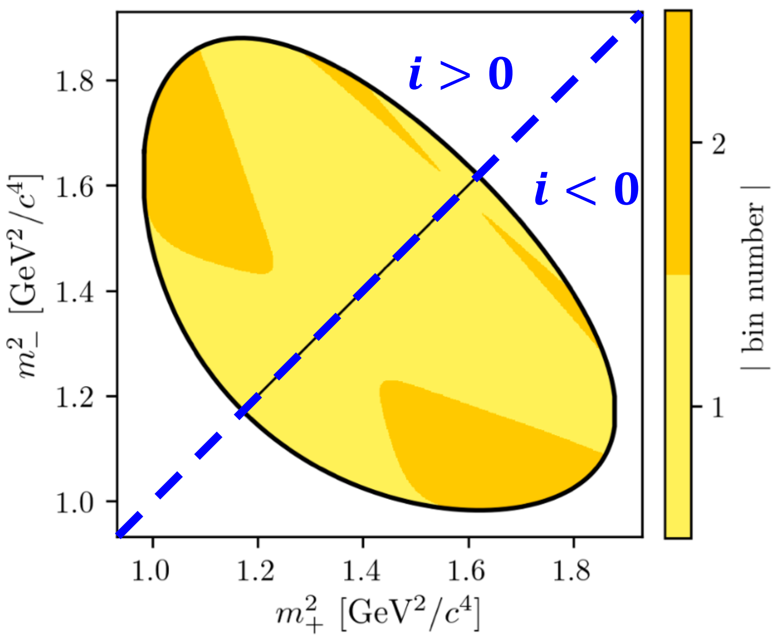
- Dataset: LHCb 2024 pp collision data ($5.8\ \mathrm{fb}^{-1}$). Background subtracted with sPlot method
- $F_i$ as floating parameters. To control $F_i$ :

**$F_i$ : fraction in the i-th bin assuming no interference**

- Control mode: $B^+ \to D\pi^+$
  - With much larger yields
  - With tiny interference
  - D mesons decaying to the same final states
  - sharing $F_i$ and $\delta_D$
- Simultaneous fit on $B^{\pm} \to D\pi^{\pm}$ and $B^{\pm} \to DK^{\pm}$ datasets




$D \to K_S^0 \pi^+ \pi^-$




$D \to K_S^0 K^+ K^-$

# $B^+ \to Dh^+$ decays: fit results

LHCb-PAPER-2026-010
[in preparation]

RUN 3

- The fit results are: (central value ± stat. ± sys. ± external)

preliminary

$$
\begin{aligned}
r_B^{DK}\cos(\delta_B^{DK}-\gamma) &= (4.81 \pm 0.88 \pm 0.20 \pm 0.23)\times 10^{-2},\\
r_B^{DK}\sin(\delta_B^{DK}-\gamma) &= (6.70 \pm 1.26 \pm 0.44 \pm 0.56)\times 10^{-2},\\
r_B^{DK}\cos(\delta_B^{DK}+\gamma) &= (-7.63 \pm 0.88 \pm 0.28 \pm 0.15)\times 10^{-2},\\
r_B^{DK}\sin(\delta_B^{DK}+\gamma) &= (-1.20 \pm 1.34 \pm 0.35 \pm 0.44)\times 10^{-2},\\
\frac{r_B^{D\pi}}{r_B^{DK}}\cos(\delta_B^{D\pi}-\delta_B^{DK}) &= (-9.44 \pm 2.51 \pm 0.57 \pm 0.69)\times 10^{-2},\\
\frac{r_B^{D\pi}}{r_B^{DK}}\sin(\delta_B^{D\pi}-\delta_B^{DK}) &= (2.76 \pm 2.99 \pm 0.19 \pm 1.21)\times 10^{-2}.
\end{aligned}
$$

External inputs:
$\delta_D$ in $D \to K_S^0\pi^+\pi^-$ (BESIII)
$\delta_D$ in $D \to K_S^0 K^+K^-$ (CLEO & BESIII)

- With the CKM angle $\gamma$ determined as:

preliminary

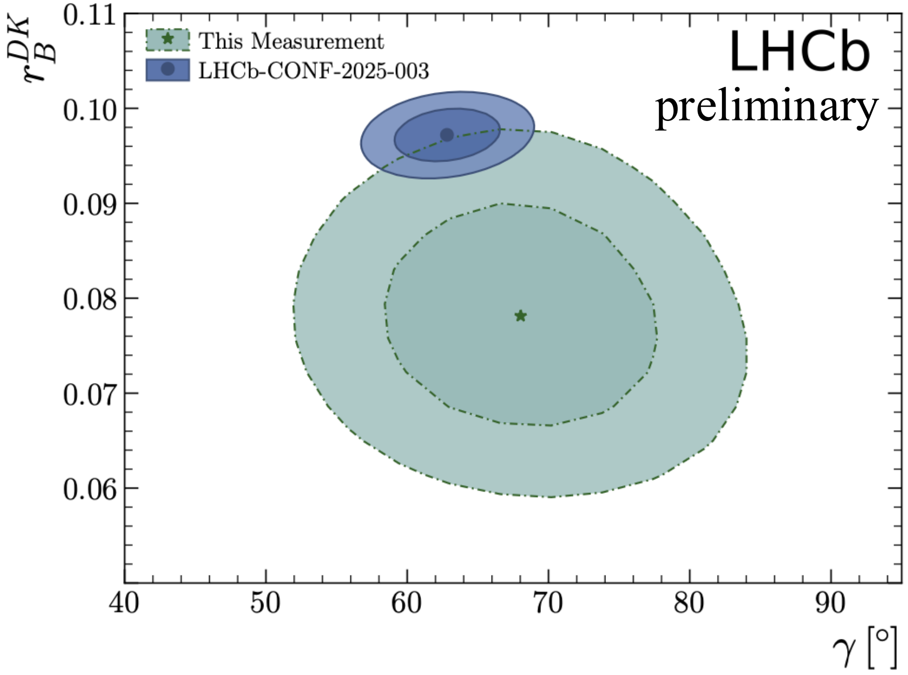
$$\gamma = (68.1 \pm 6.7)^\circ$$

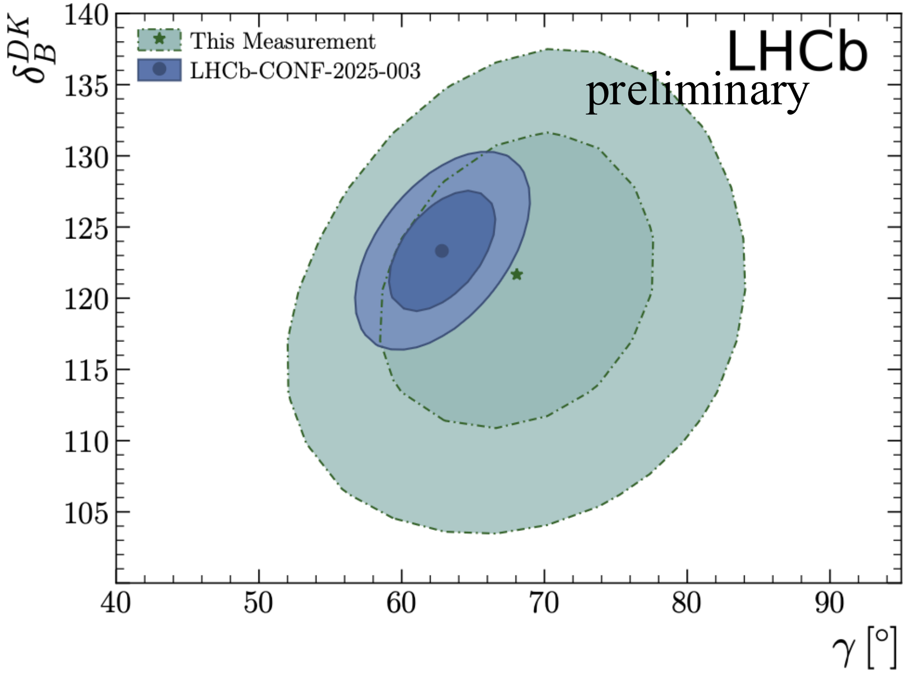
# CKM angle $\gamma$: comparison with averaged results

LHCb-PAPER-2026-010
[in preparation]

RUN 3

- Consistent with the averaged results $(62.8\pm2.6)^\circ$ reported in LHCb-CONF-2025-003



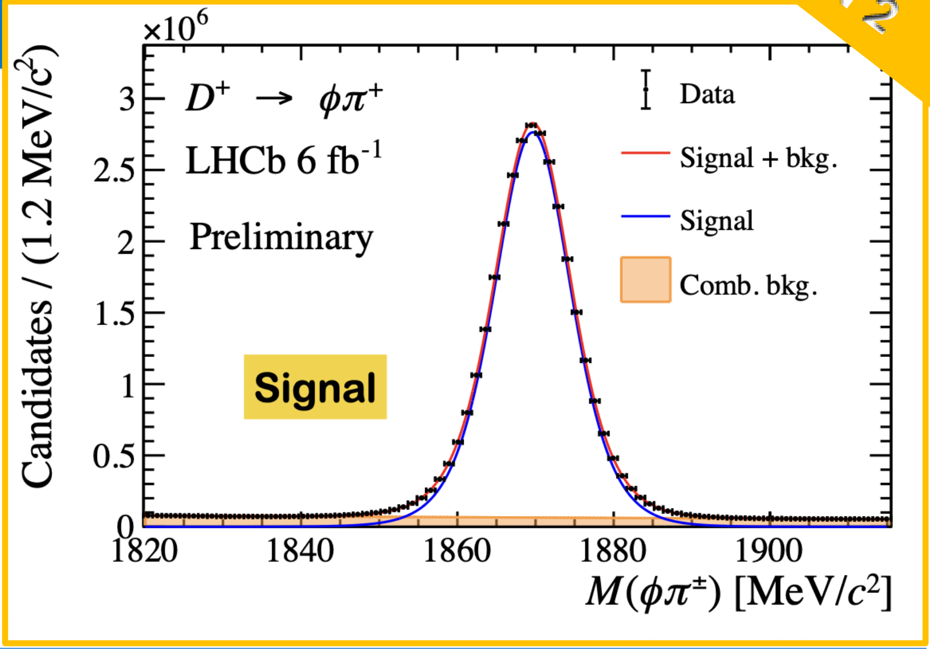
# New physics tests

# NP null test: $D^+ \rightarrow \phi(1020)^0\pi^+$

LHCb-PAPER-2026-011
[in preparation]

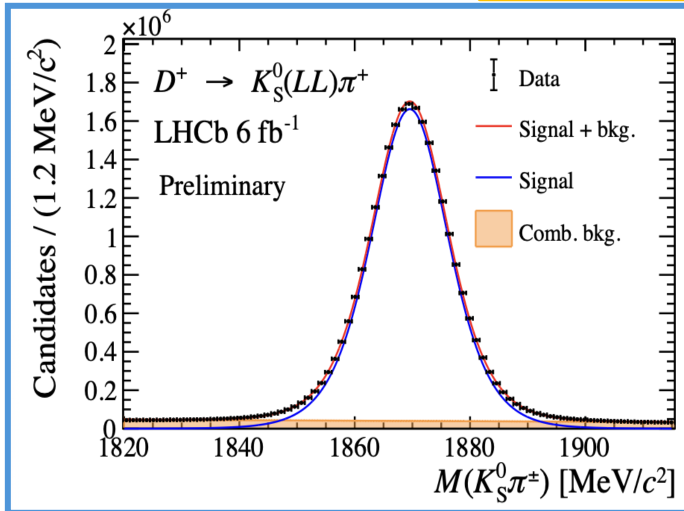
RUN 2

- Enormous data sample (~ 31M) signal decays at disposal.
- Data sample used contains all *K*+ *K*- meson combinations within 10 MeV of the $\phi$ mass. (little s-wave & interference)
- Corrections for production & det. asymmetry needed. Use $D^+ \rightarrow K_S^0\pi^+$(“favoured”). Limiting uncertainty so far. Measure the *difference* in *CP* asymmetries.

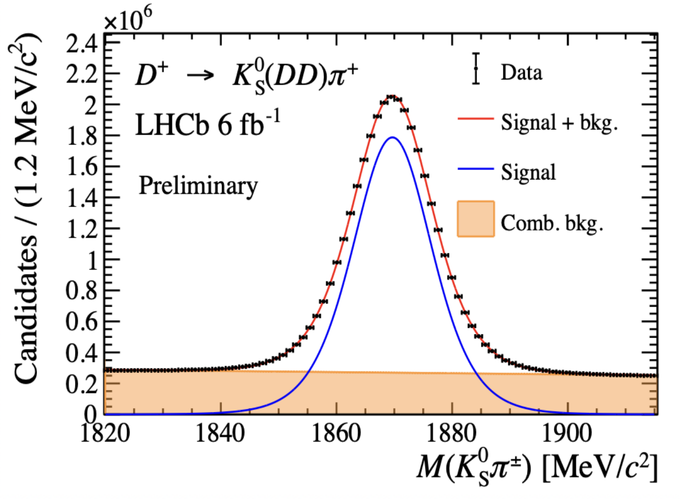



New approach: Optimise for the inclusion of $K_S^0$ with longer decay times (downstream): 50% more yields

2019: short-lived $K_S^0$ only ***PRL 122 (2019) 19, 191803***




Decaying inside the VELO




Decaying after the VELO

Control

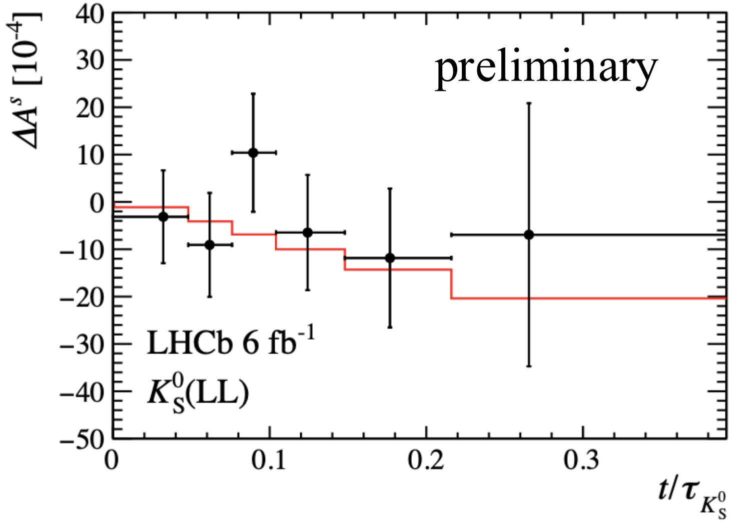
# For NP: $D^+ \to \phi(1020)^0\pi^+$

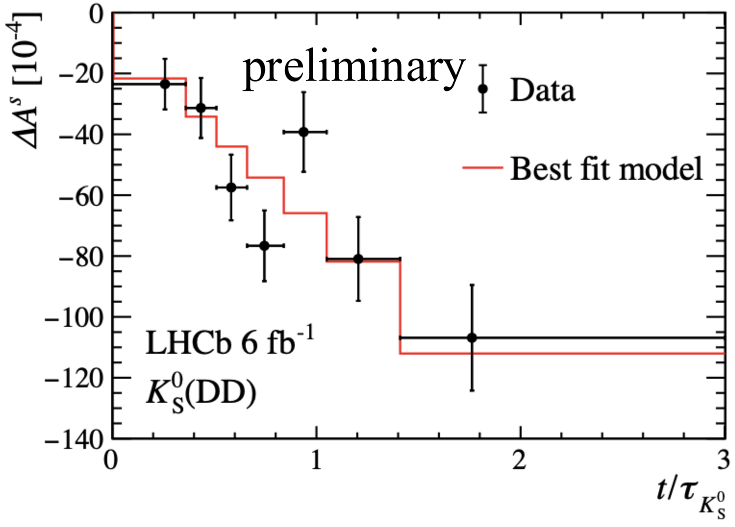
LHCb-PAPER-2026-011
[in preparation]

RUN 2

- Control mode: $D^+ \to K_S^0\pi^+$ (chi-square fit in proper-time bins)

$$\Delta A^s \equiv A^s(D^+ \to K_S^0\pi^+) - A^s(D^+ \to \phi\pi^+)$$
$$\approx A_D^s(K_S^0) - a_{CP}(D^+ \to \phi\pi^+),$$




- Preliminary result (supersedes partial Run 2 result, on par precision)

preliminary

$$a_{CP}(D^+ \to \phi\pi^+) = (0.1 \pm 4.9 \pm 1.9) \times 10^{-4}$$

**Compatible with *CP* symmetry**

- Previous result (partial Run 2): $a_{CP}(D^+ \to \phi\pi^+) = (0.5 \pm 4.2 \pm 2.9) \times 10^{-2}$ *PRL 122 (2019) 19, 191803*

# Time-dependent CPV: $B^0 \to K_S^0 \mu^+ \mu^-$

arXiv: 2603.13223

RUN 1+2

- CPV from mixing:

$$\mathcal{A}_{CP}(t) \equiv \frac{\left|A(\bar{B}_d^0(t) \to f)\right|^2 - \left|A(B_d^0(t) \to f)\right|^2}{\left|A(\bar{B}_d^0(t) \to f)\right|^2 + \left|A(B_d^0(t) \to f)\right|^2}$$
$$\approx -\boldsymbol{C}\cos(\Delta m t) + \boldsymbol{S}\sin(\Delta m t)$$

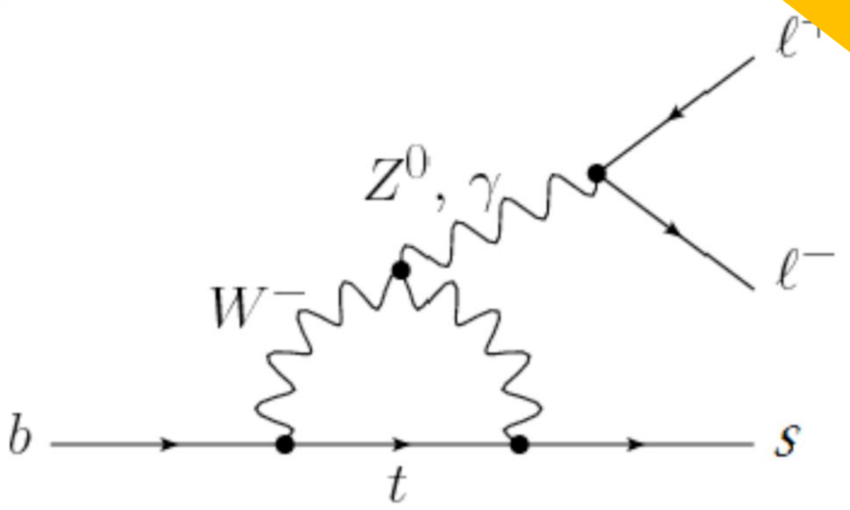
- Time-dep. CPV: measure the weak (*CP*-violating) phases, free of uncertainties related to strong phases: mixing asymmetry should be ~sin(2$\beta$)

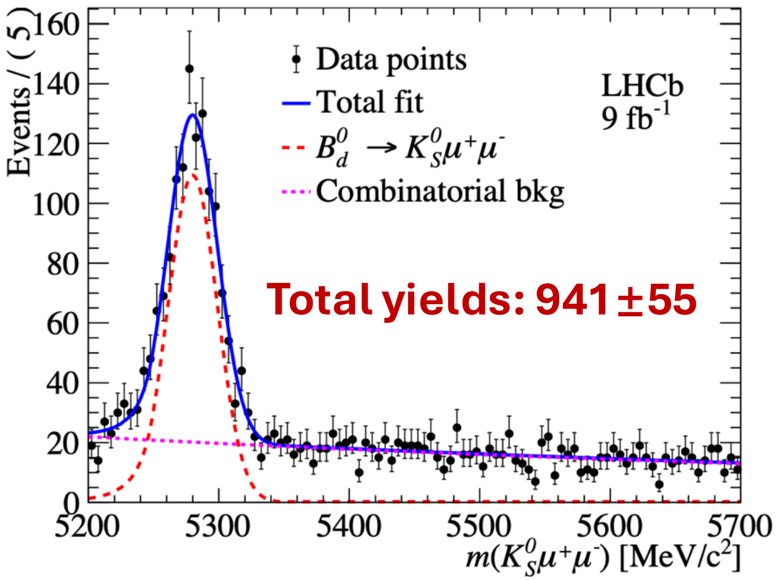
- Complete consideration requires angular analysis, but limited statistics.

(suggested by theory)

- Angle-integrated & $q^2$ "integrated" (2 large bins, veto $J/\psi$ *and* $\psi(2S)$), as first proof of principle

$$q^2 = m^2(\mu^+\mu^-)$$

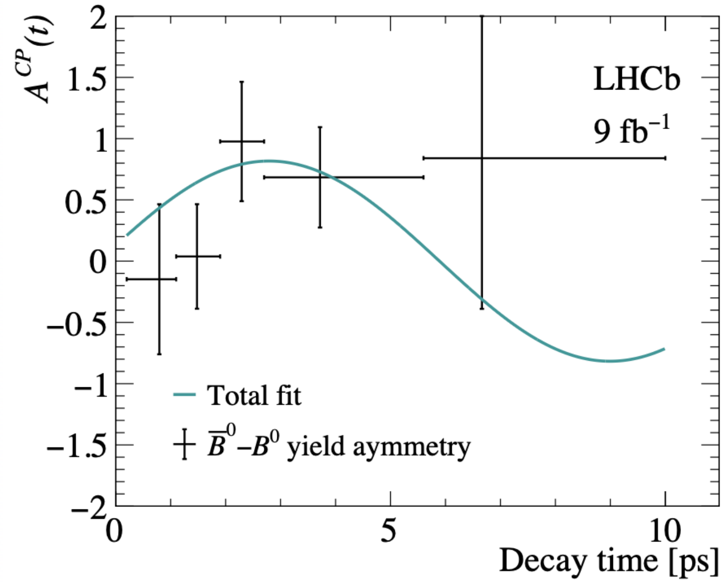


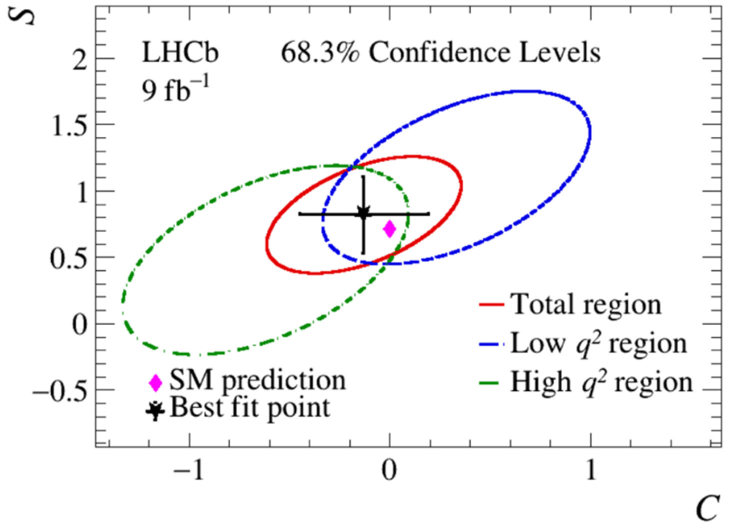



# Time-dependent CPV: $B^0 \to K_S^0 \mu^+ \mu^-$

arXiv: 2603.13223

RUN 1+2




- Can fully rely on the "golden mode" $J/\psi K_S^0$ as control channel: "only" $q^2$ is different
- Left with just enough statistics to perform the analysis after tagging

| $q^2$ range $[\text{GeV}^2/c^4]$ | $C$ | $S$ |
|---|---|---|
| Total | $-0.13 \pm 0.32$ | $+0.82 \pm 0.29$ |
| Low: $q^2 < 8.0$ | $+0.33 \pm 0.44$ | $+1.10 \pm 0.43$ |
| High: $11.0 < q^2 < 15.0$ or $q^2 > 17.5$ | $-0.62 \pm 0.47$ | $+0.48 \pm 0.47$ |

Fully compatible with SM expectation

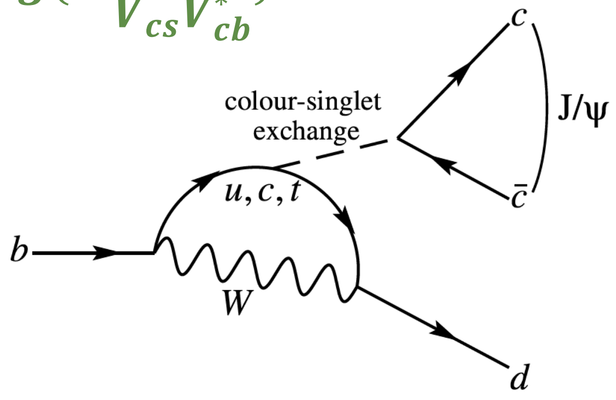
First demonstrator
valuable input to further disentangle possible NP contributions in $b \to s\ell^+\ell^-$

# Controlling subleading amplitudes in $\beta_s$ measurement

# Controlling subleading amplitudes

- Measure $\beta_s$ using $B_s^0$ decays to CP eigenstates with $b \to c\bar{c}s$ quark transition
  - Benchmark channel: $B_s^0 \to J/\psi\phi$ **dominated by tree**

$$\boldsymbol{\beta_s \equiv arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})}$$




- When measuring the time-dependent CP asymmetry:

$$\mathcal{A}_{CP}(t) = \frac{\mathcal{A}_{CP}^{dir}\cos(\Delta mt) + \boldsymbol{\mathcal{A}_{CP}^{mix}}\sin(\Delta mt)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

- Amplitude: $A(B_s^0 \to f) = A_{tree} + A_{penguin} \equiv A_{tree} \times (1 - b_f e^{i\rho_f} e^{i\gamma})$
- Assuming no penguin contribution: $b_f = 0 \;\Rightarrow\; \mathcal{A}_{CP}^{mix} = \eta_f \sin(2\beta_s + \phi^{NP})$
- Penguin pollution: $b_f \neq 0 \;\Rightarrow \mathcal{A}_{CP}^{mix} = \eta_f \sin(2\beta_s + \phi^{NP} + \Delta\phi_f)$ **($\eta_f = \pm 1$), CP eigenvalue**
- **Constrain penguin using $B_{(s)}$ decays with $b \to c\bar{c}d$ transition!**

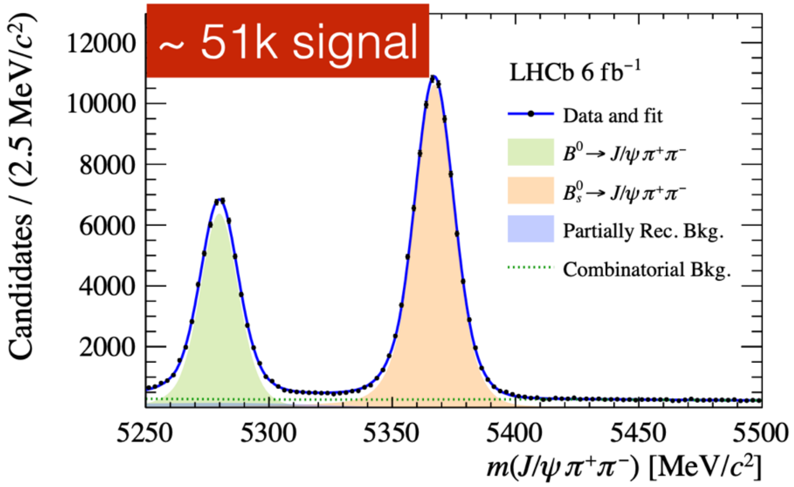
$$\boldsymbol{B^0 \to J/\psi\rho^0, \qquad \bar{B}_s^0 \to D_s^+ D^-}$$

# Observation of CPV in $B^0 \to J/\psi\rho^0$ decays

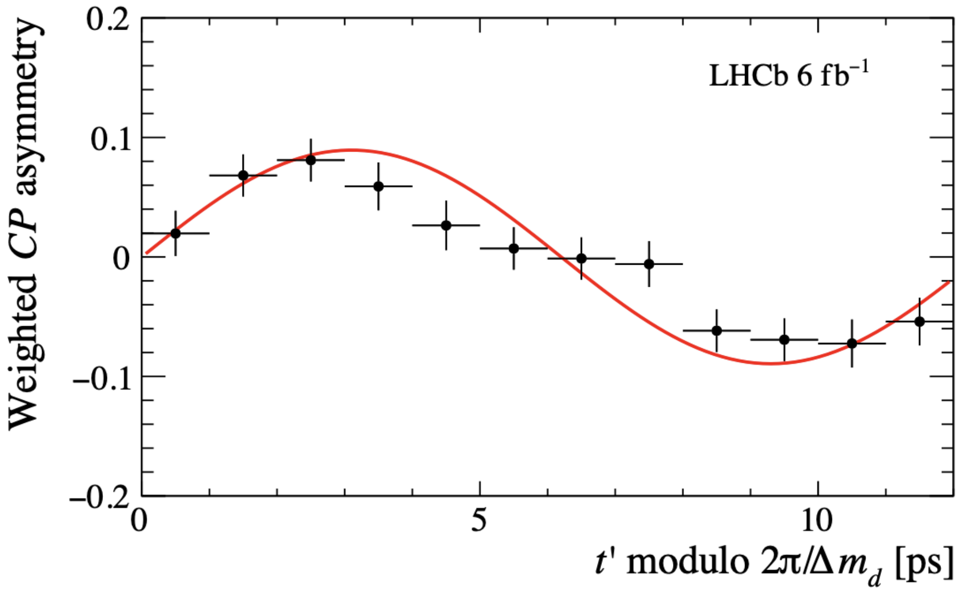
arXiv: 2601.15646

RUN 2

- Fitted m(ππ), along with 3 decay angles, capturing the different polarization components of the *p*-wave amplitude
- $2\beta_{\text{eff}}$ = 0.710 ± 0.08 ± 0.028 rad
  - First observation of time-dep. CPV in $\boldsymbol{b \to c\bar{c}d}$




- Effect due to penguins on the determination of $\phi_s$ in $B_s^0 \to J/\psi\phi$ :
- $\Delta\phi_s = (5.0 \pm 4.2)$ mrad
- Most stringent estimate of $\Delta\phi_s$ in $B_s^0 \to J/\psi\phi$ decays, hard to beat
- **Subleading amplitudes cannot be ignored in the LHC Run-3 era**

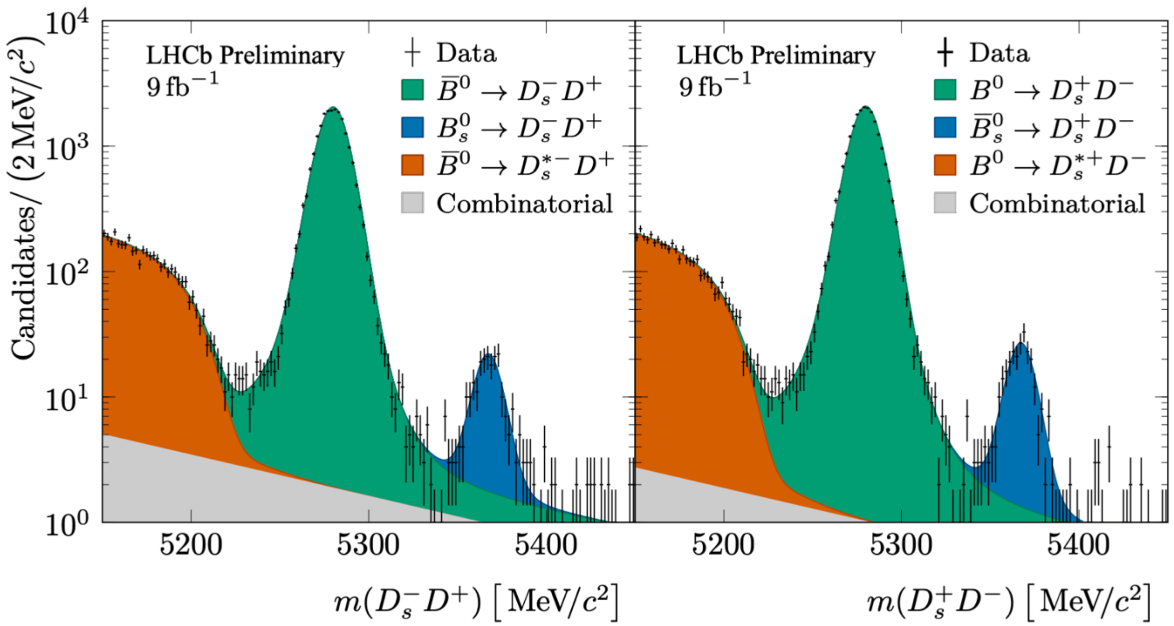


# CP asymmetries: $B^0_{(s)} \to D_s^{\pm} D^{\mp}$

LHCb-PAPER- 2025-037
[in preparation]

RUN 1+2

- $\bar{B}^0 \to D_s^- D^+$ ($b \to c\bar{c}s$) and $\bar{B}_s^0 \to D_s^+ D^-$ ($b \to c\bar{c}d$)
- Can be used to constrain penguin in $\bar{B}_s^0 \to D_s^+ D_s^-$ when determining $\phi_s$
- $\mathcal{A}_{CP} = \mathcal{A}_{\text{raw}} + \mathcal{A}_{det} + \mathcal{A}_{prod}$
  - $A_{\text{raw}}$ determined from ML fit
  - $A_{\text{det.}}$ determined using data-driven methods
  - $A_{\text{prod.}}$ cannot be neglected for $B^0$; evaluate from production cross-sections as $0.0013 \pm 0.0015$
- Results:




preliminary

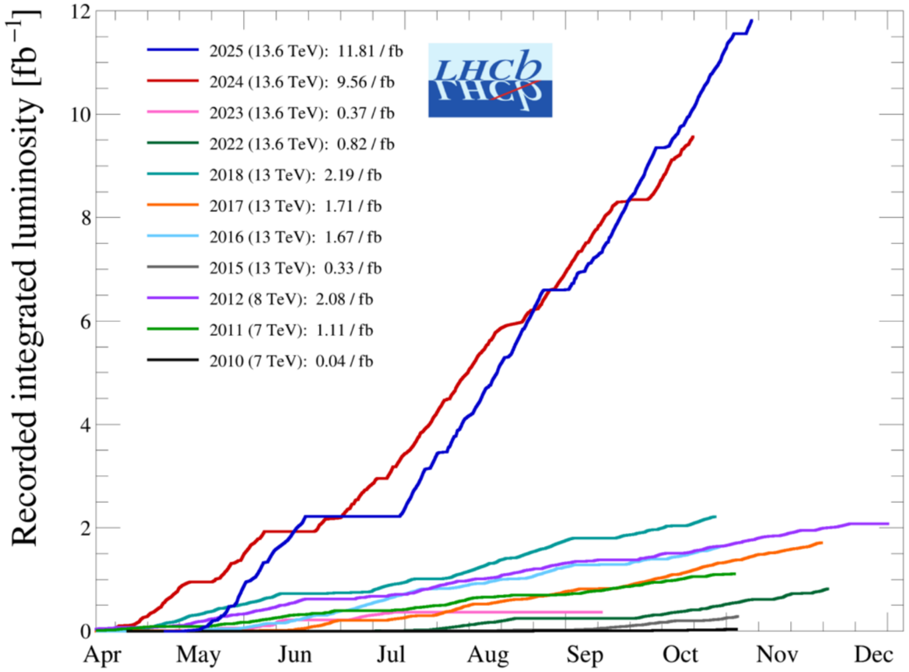
$$A_{CP}(B^0 \to D_s^- D^+) = 0.0009 \pm 0.0053 \pm 0.0040,$$ ← 4x more precise than Belle measurement

$$A_{CP}(\bar{B}_s^0 \to D_s^+ D^-) = 0.103 \pm 0.053 \pm 0.010,$$ ← first ever measurement in this channel

# Summary

- Conclusion
  - Shown new world-best, sometimes first demonstrators, results for *CP*-violating observables (i) in environments that act as clean probes for NP, (ii) new measurements on $\gamma$ and $B$ mixing
  - First results using < 1 year of data of our LHCb Run 3 detector.
    - Immediately on par or better yields than analyses of previous detector with many years of running
- Prospects
  - Total Run 3 lumi. could reach ~ $30\ \text{fb}^{-1}$ by end

*Thanks for your attention!*



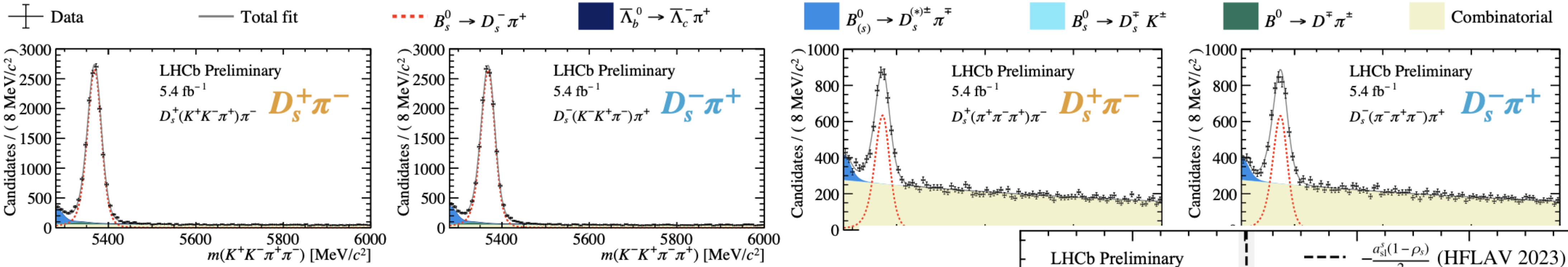

Read more: [Moriond QCD] [La Thuile] [LHC Seminar] [All that Antimatters]

# BACKUPS

Read

# Time-integrated $C\!P$ asymmetry in $B_s^0 \to D_s^- \pi^+$

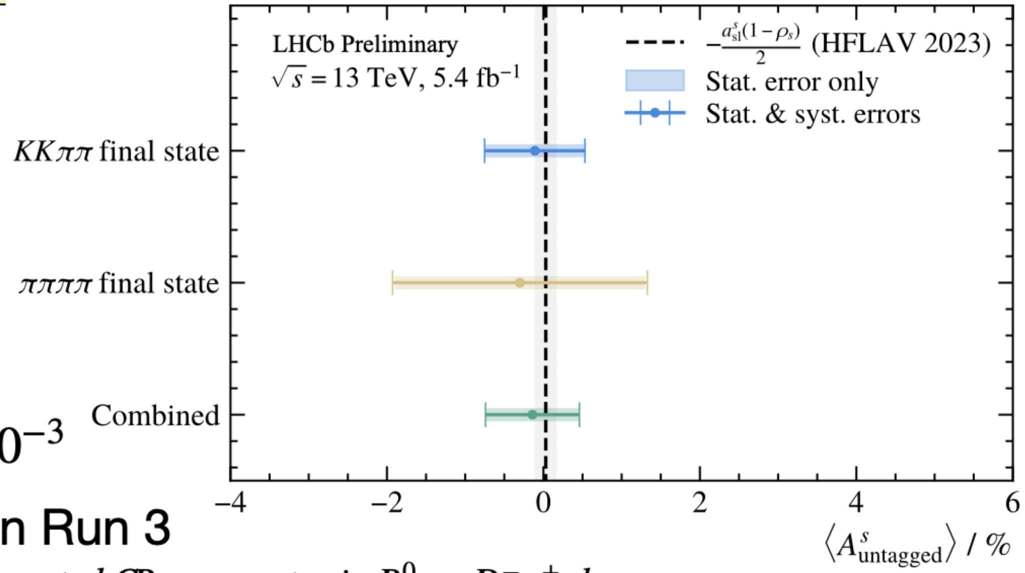
- Determine $A_{\text{raw}}$ from ML fit to $m(hh\pi\pi)$ in each mode:




- Determine terms in $A_{\text{det.}}$ from data-driven methods
  - Largest contributions: hardware trigger ($K^+K^-\pi^+$ mode); particle identification ($\pi^+\pi^-\pi^+$ mode)
  - Neglect small contributions, *e.g.*, software trigger
- Measure this asymmetry, *for the first time*, to be:

$$\langle A^s_{\text{untagged}} \rangle = \left(-1.4 \pm 5.9\,(\text{stat.}) \pm 1.1\,(\text{syst.})\right) \times 10^{-3}$$

- Statistically limited → anticipate per-mille precision in Run 3




*First measurement of the decay-time-integrated $C\!P$ asymmetry in $B_s^0 \to D_s^- \pi^+$ decays* (To be submitted to PRL)

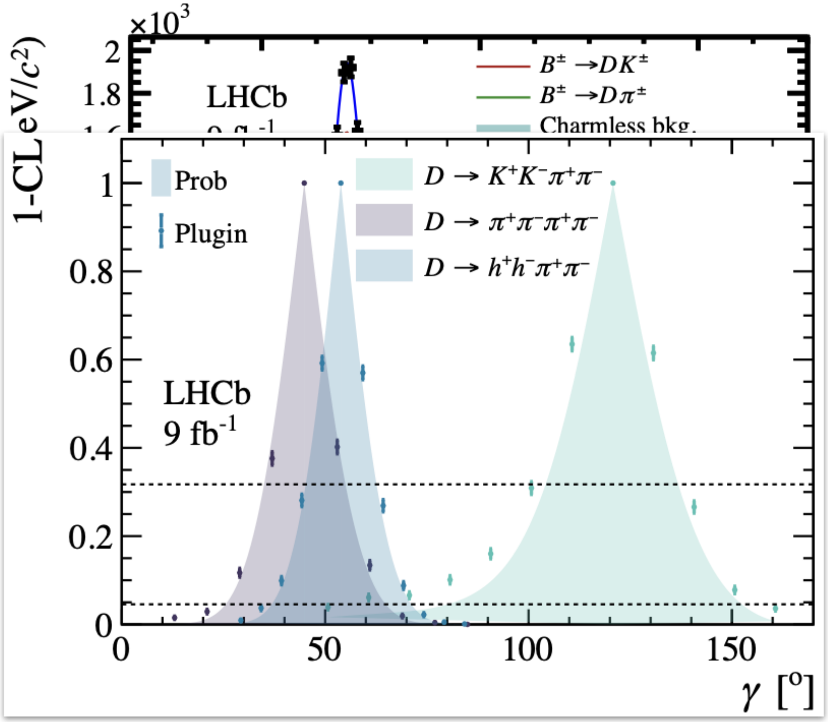
# Measuring $\gamma$ in $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- Access $\gamma$ from interference of $b \to c\bar{u}q$ (favoured) and $b \to u\bar{c}q$ (suppressed) for $q \in \{d, s\}$
  - Strong-phase difference across $D \to h^-h^+\pi^-\pi^+$ phase-space enhances sensitivity locally
- Supersedes *model-dependent* measurement from LHCb in 2023 [arxiv:2301.10328, EPJ C 83 (2023) 547]
  - Inherit selection, fit strategy, $D$ phase-space binning
  - Measure in $9\,\mathrm{fb}^{-1}$ of $pp$ collision data (Run 1+2)
- Evaluate confidence intervals in $\gamma$ from Feldman-Cousins (*Plugin method*) and Wilks' theorem (*Prob method*)

$\gamma = \left(53.9^{+9.5}_{-8.9}\right)^{\circ}$ from phase-space binning alone

$\gamma = \left(52.6^{+8.5}_{-6.4}\right)^{\circ}$ with phase-space integrated $CP$ violation effects

- This measurement is ~2x as precise as 2023 measurement
- Further improvements possible from charm mixing




[arXiv:2509.15139, JHEP 2601 (2026) 062]

*A model-independent measurement of the CKM angle $\gamma$ in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$ ($h = K, \pi$)*

# gamma

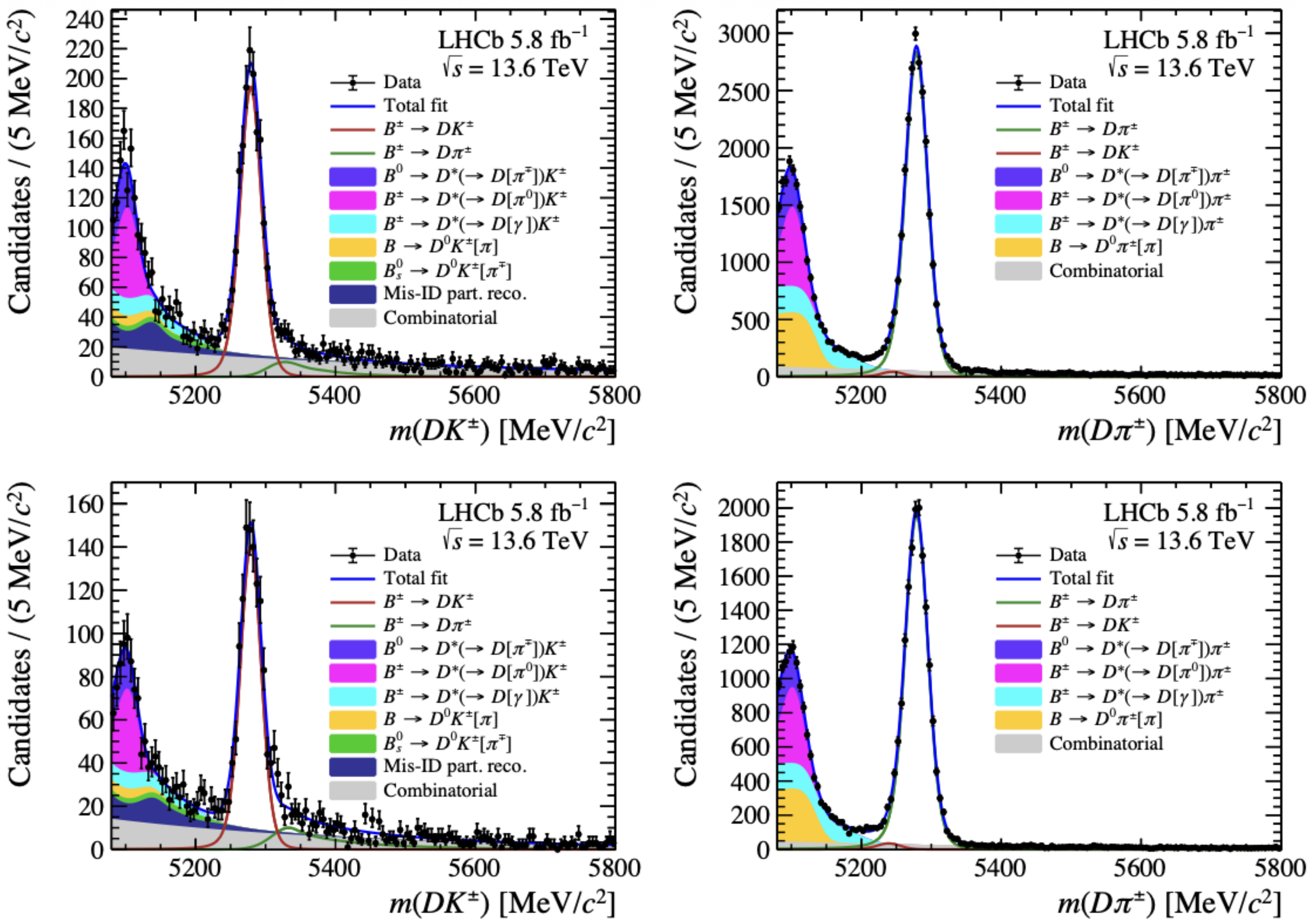
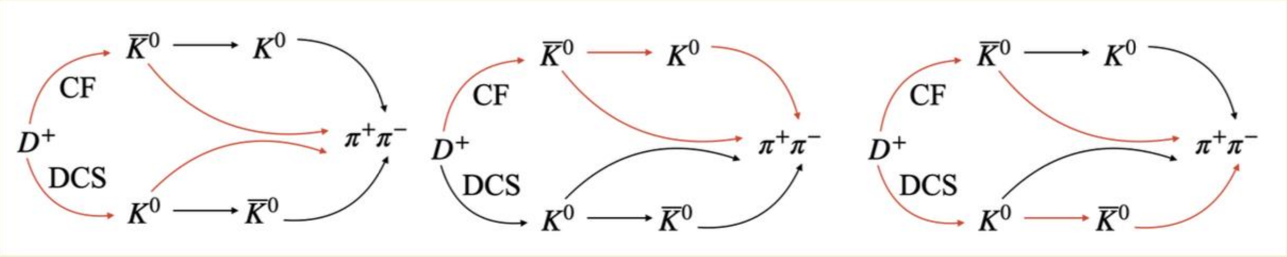



Figure 3: Fit to the $Dh^{\pm}$ invariant mass of the (left) $B^{\pm} \to DK^{\pm}$ and (right) $B^{\pm} \to D\pi^{\pm}$ decays, where $D \to K_S^0 K^+ K^-$. The top row corresponds to the *long* $K_S^0$ reconstruction and the bottom row to the *downstream* reconstruction.

Run 2

LHCb-PAPER-2026-011
in preparation

# Search for *CPV* in $D^+ \to \phi(1020)^0\pi^+$



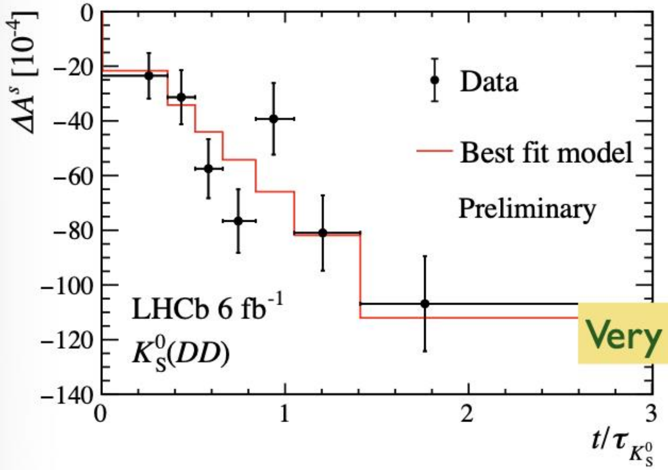

reminder: control channel, dominating uncertainty

Account for interference between DCS and CF decays, on top of kaon propagation (regeneration + CPV)

$$r_\pi\, e^{i(\delta_\pi+\varphi)} \equiv \frac{\mathcal{A}(D^+ \to K^0\pi^+)}{\mathcal{A}(D^+ \to \overline{K}^0\pi^+)}$$

from CKM

Additional parameters




Very good description

Analysis performed in bins of $K_s$ decay time, $\phi\,\pi$ sample split arbitrarily (no correlation)

Constant offset: *CPV* in the charm decay;
Decay-time dependence: result of neutral kaon

Laurent Dufour · Moriond QCD · 20

# For NP: $D^+ \to \phi(1020)^0\pi^+$

LHCb-PAPER-2026-011
[in preparation]

RUN 2

- Preliminary result (supersedes partial Run 2 result, on par precision)

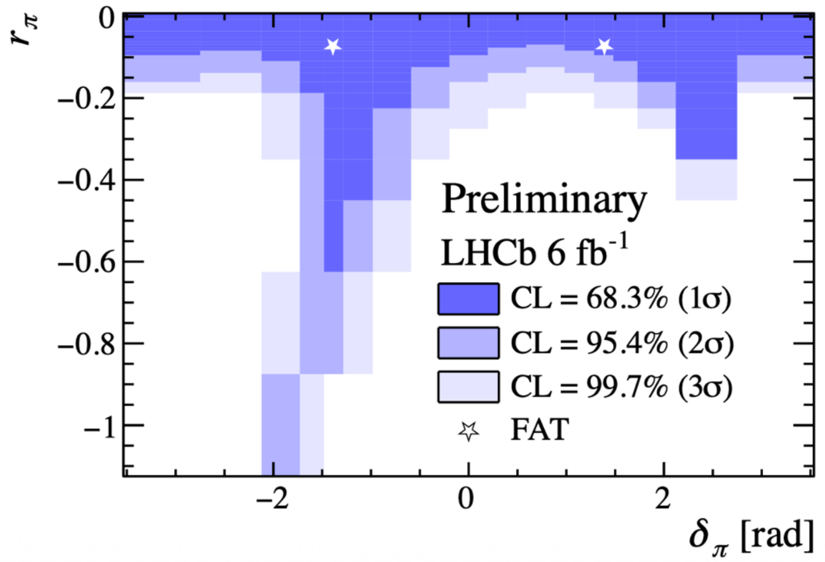
preliminary

$$a_{CP}(D^+ \to \phi\pi^+) = (0.1 \pm 4.9 \pm 1.9) \times 10^{-4}$$

  - Previous result (partial Run 2): $a_{CP}(D^+ \to \phi\pi^+) = (0.5 \pm 4.2 \pm 2.9) \times \mathbf{10^{-2}}$

*PRL 122 (2019) 19, 191803*

- uses more data compared to the previous, but now includes additional hadronic parameters of the control-mode decay (previously ignored)




Compatible with *CP* symmetry

First measurements of these hadronic parameters at the LHC

Sets standard for next analyses