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(ON BEHALF OF LHCB, ATLAS AND CMS COLLABORATIONS)

CP VIOLATION AND MIXING IN B AND CHARM DECAYS

VIETNAM, 2023

Outline

- γ angle measurement [LHCb-CONF-2022-003]
- CPV measurements in beauty sector
  - $B_s^0 \to \phi\phi$ [arXiv:2304.06198]
  - $B_s^0 \to \psi K_s^0$ LHCB-PAPER-2023-013 (in preparation)
  - ϕ_s in $B_s^0 \to J/\psi\phi$ LHCB-PAPER-2023-016 (in preparation)
  - ϕ_s measurement in CMS [Phys. Lett. B 816 (2021) 136188] and ATLAS [Eur. Phys. J. C 81 (2021) 342]
- CPV measurements in charm sector
  - Time-integrated A_{CP} in $D^0 \to K^+K^-$ [arXiv:2209.03179]
  - Local CPV search in $D_{(s)}^+ \to K^-K^+K^-$ [arXiv:2303.04062]
  - Local CPV in $D^0 \to \pi^-\pi^+\pi^0$ [LHCB-PAPER-2023-005] (in preparation)

CP Violation

- CP violation (CPV) might occur in various ways:

1. Direct CPV

$$\left| B^0_{(s)} \rightarrow f \right|^2 \neq \left| \bar{B}^0_{(s)} \rightarrow \bar{f} \right|^2$$

$$|A_f|^2 \neq |\bar{A}_f|^2$$

* time-integrated charm analysis will be shown.

CP Violation

- CP violation (CPV) might occur in various ways:

  2. CPV in mixing

$$\left| B^0_{(s)} \longrightarrow \bar{B}^0_{(s)} \longrightarrow f \right|^2 \neq \left| \bar{B}^0_{(s)} \longrightarrow B^0_{(s)} \longrightarrow f \right|^2$$

CP Violation

- CP violation (CPV) might occur in various ways:

  3. CPV in interference :

$$\left| B^0_{(s)} \longrightarrow \bar{B}^0_{(s)} \to f \right|^2 \neq \left| \bar{B}^0_{(s)} \longrightarrow B^0_{(s)} \to f \right|^2$$

* time-dependent beauty analyses will be shown.

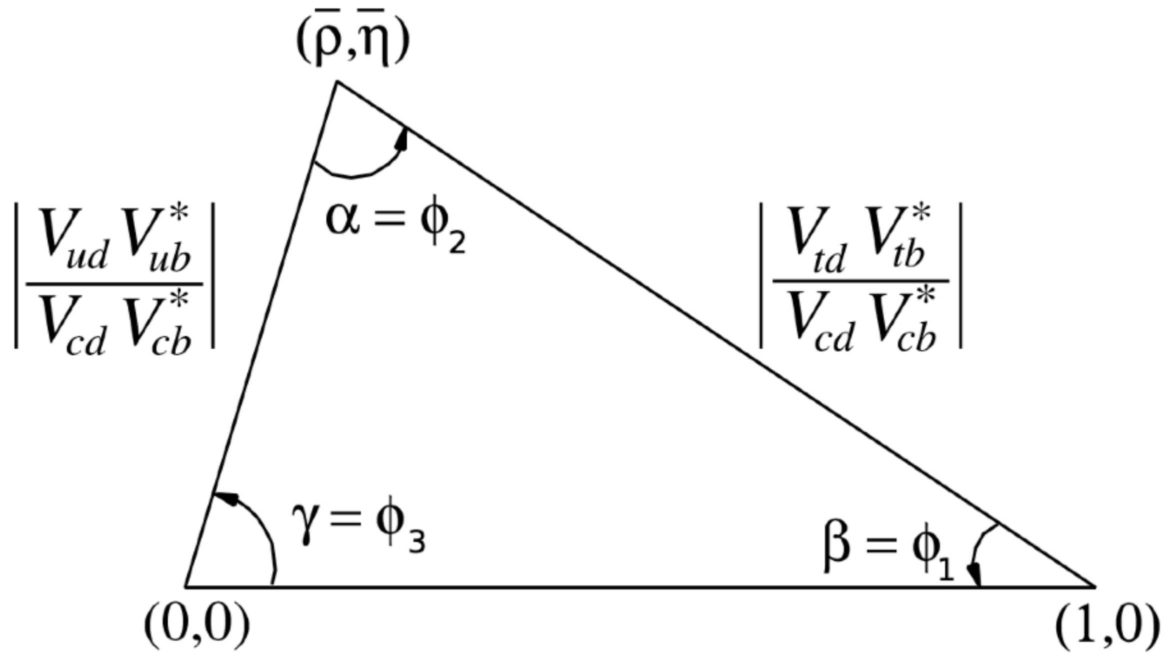
(Updated) γ angle combination

LHCb-CONF-2022-003

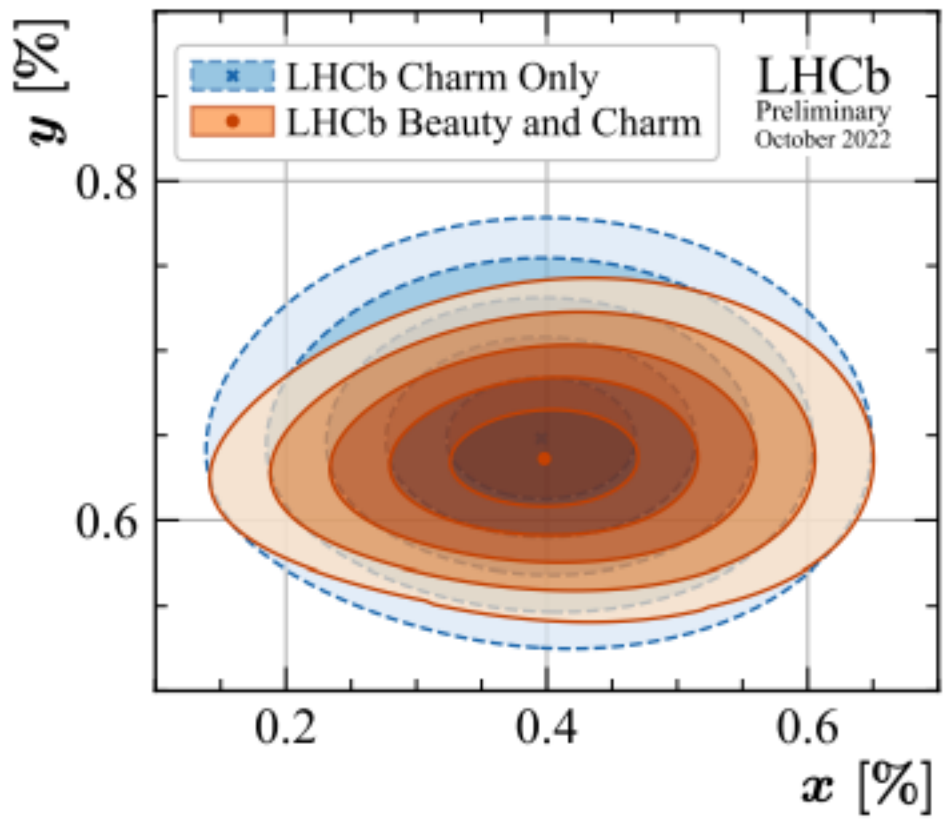
- Five new analyses added to the previous LHCb combination
- $B^{\pm} \rightarrow D[K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}]$ arXiv:2209.03692
- $B^{\pm} \rightarrow D[h^{+}h^{-}h^{0}]$ arxiv:2112.10617
- $D^{0} \rightarrow h^{+}h^{-}$ arXiv:2202.09106
- $D^{0} \rightarrow K^{+}K^{-}$ arXiv:2209.03179
- $D^{0} \rightarrow K_{s}^{0}\pi^{+}\pi^{-}$ arXiv:2208.06512

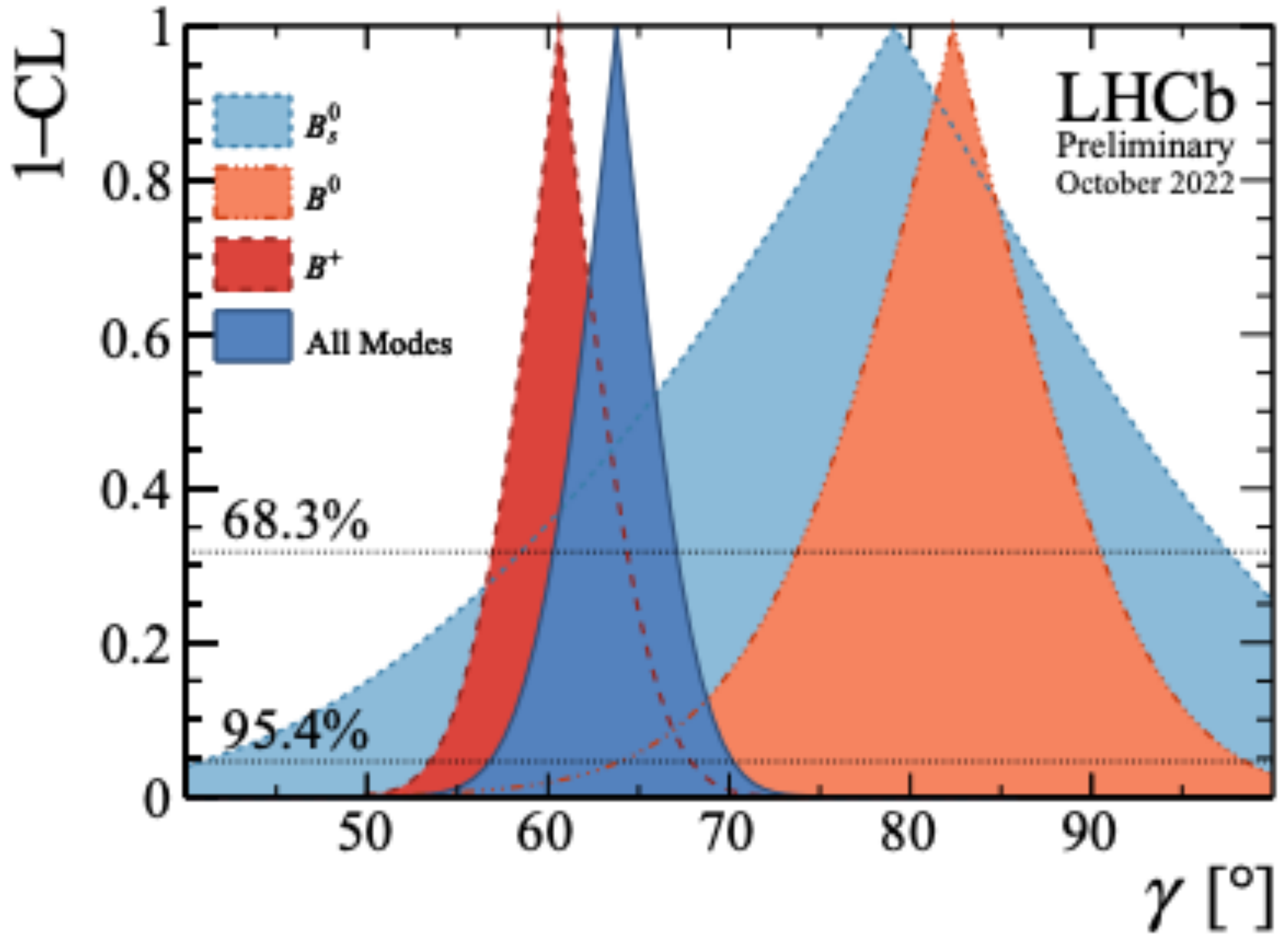
Previous combination (2021)

$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$



- $x = (0.389^{+0.50}_{-0.049})$ %
- $y = (0.636^{+0.020}_{-0.019})$ %
- $|q/p| = 0.995^{+0.015}_{-0.016}$
- $\phi = arg(q/p) = (2.5 \pm 1.2)^{\circ}$





new result

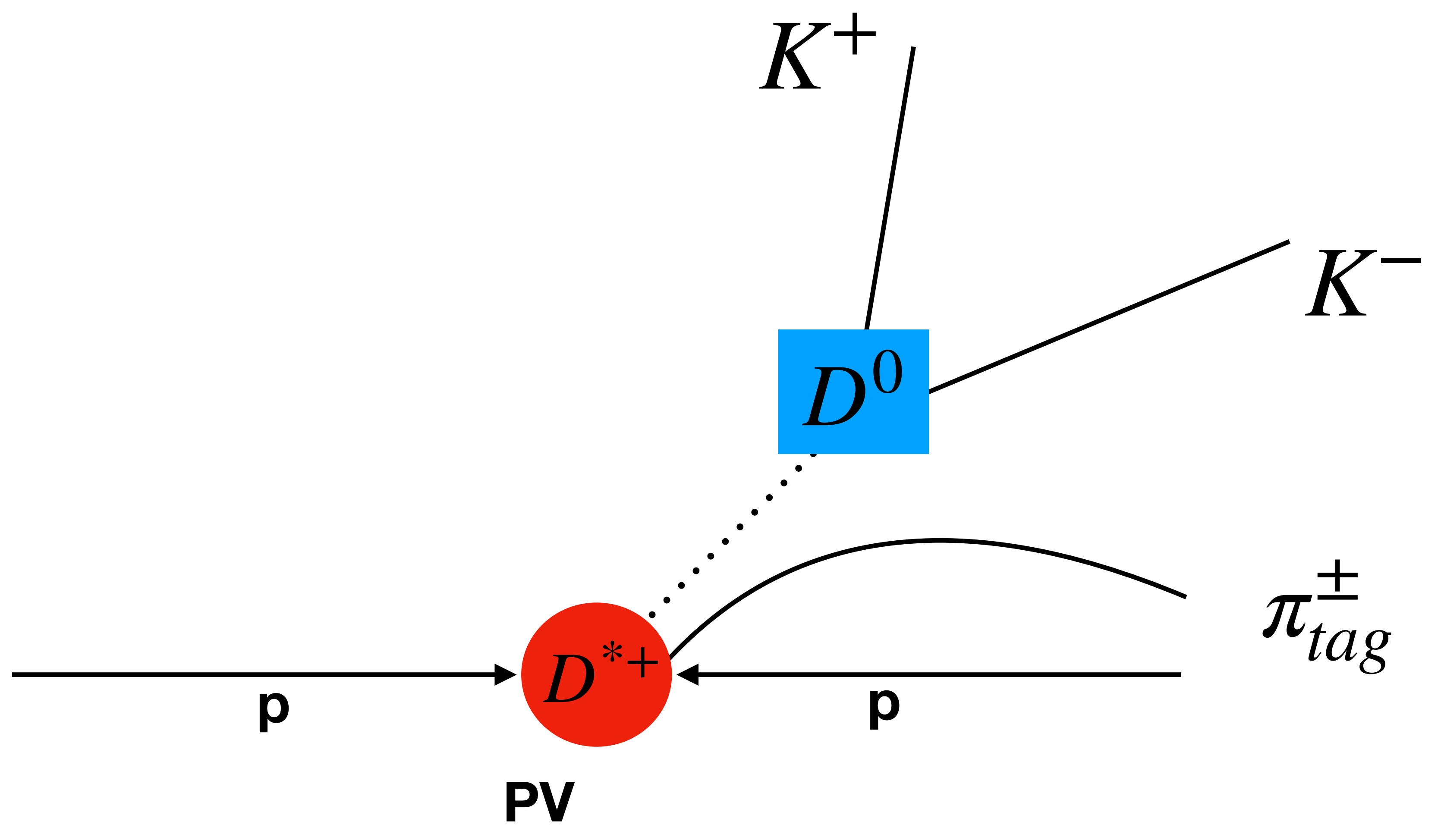
$\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$

CP Asymmetry in $D^0 \to K^-K^+$ Decays with 5.7 fb^{-1}

- Time-integrated CP asymmetry is measured using prompt $D^{*+} \to D^0(\to K^+K^-)\pi^+$ decays.

- The combination of previous LHCb measurements of $\mathcal{A}_{cp}(K^-K^+)$ and $\Delta\mathscr{A}_{CP}$ to derive direct asymmetries

- Experimental asymmetries are canceled using prompt D^+ and D_s^+ decays.



$$\mathscr{A}_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \cdot \Delta Y_f$$

Direct asym mixing asym

arXiv:2209.03179

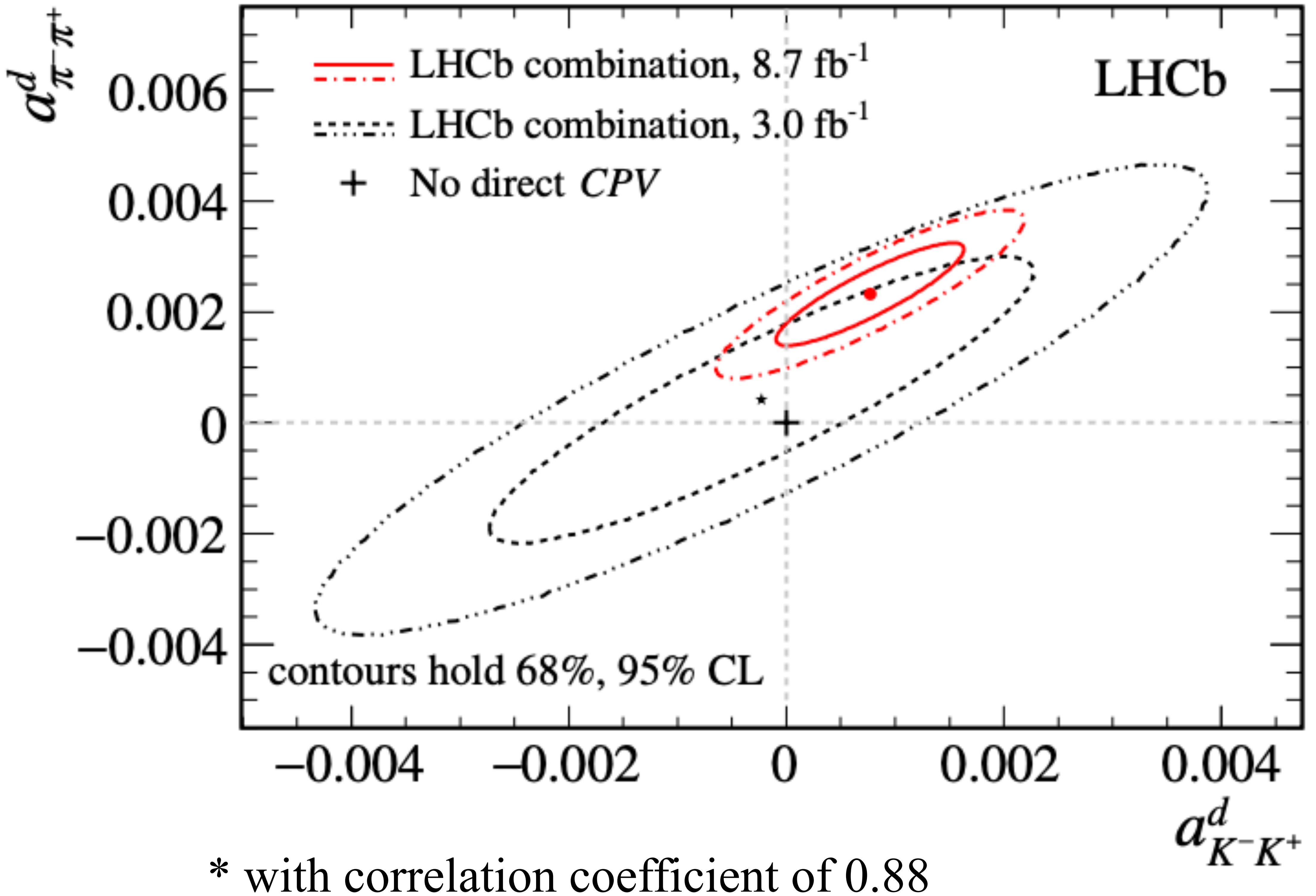
CP Asymmetry in $D^0 \to K^-K^+$ Decays with 5.7 fb^{-1}

$$\mathscr{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\ (\text{stat}) \pm 1.6\ (\text{syst})] \times 10^{-4}$$

$$\Delta A_{CP} = A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

$$a^d_{K^-K^+} = (\ 7.7\ \pm\ 5.7\ ) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (\ 23.2\ \pm\ 6.1\ ) \times 10^{-4}$$

- Evidence of CP asymmetry in $D^0 \to \pi^-\pi^+$ at the level of 3.8σ



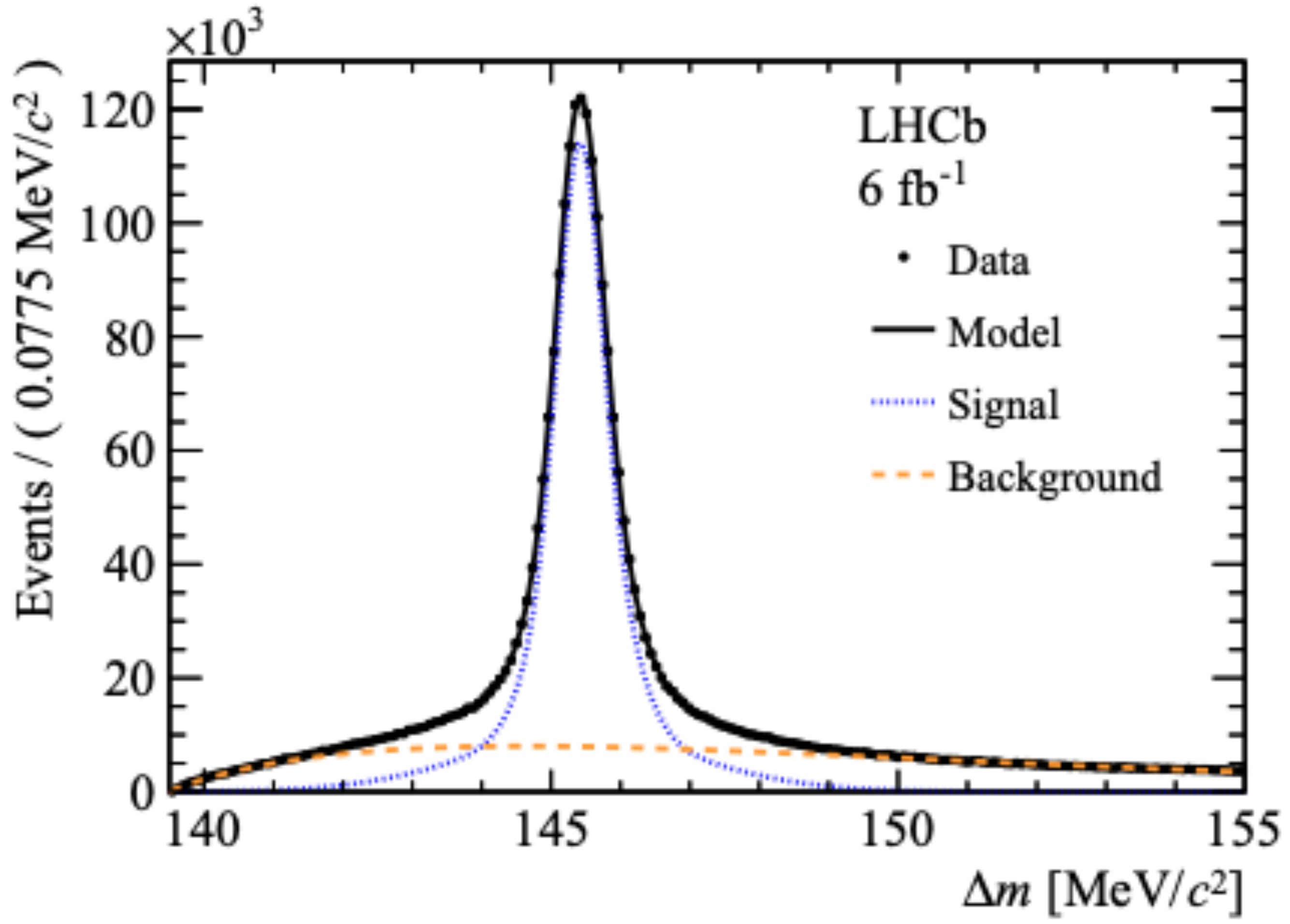
* with correlation coefficient of 0.88

** assuming mixing asymmetry is final-state independent.

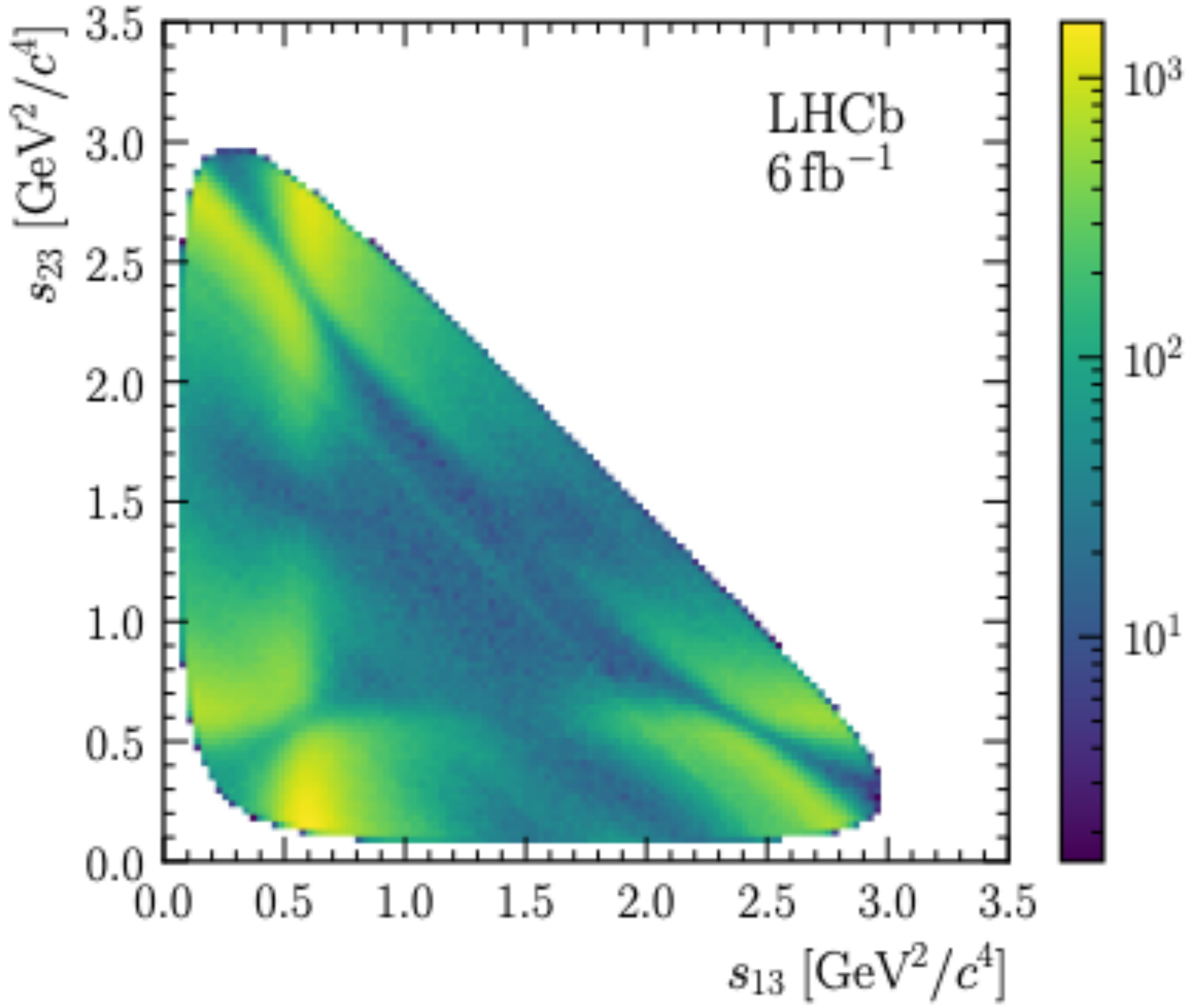
arXiv:2209.03179

CPV in $D^0 \to \pi^-\pi^+\pi^0$ Decays with 6 fb^{-1}

[LHCB-PAPER-2023-005] (in preparation)



- Dominated by the $D^0 \to \rho^{\pm}\pi^{\mp}$ amplitudes, similar to the "CP-violating" $D^0 \to \pi^-\pi^+$ decays.
- A model independent method of **energy test** is used
- Test statistics (T) to quantify local differences of D^0 and $\bar{D}^0$ candidates
  - **provide p-value** by comparing the consistency with CP symmetry.

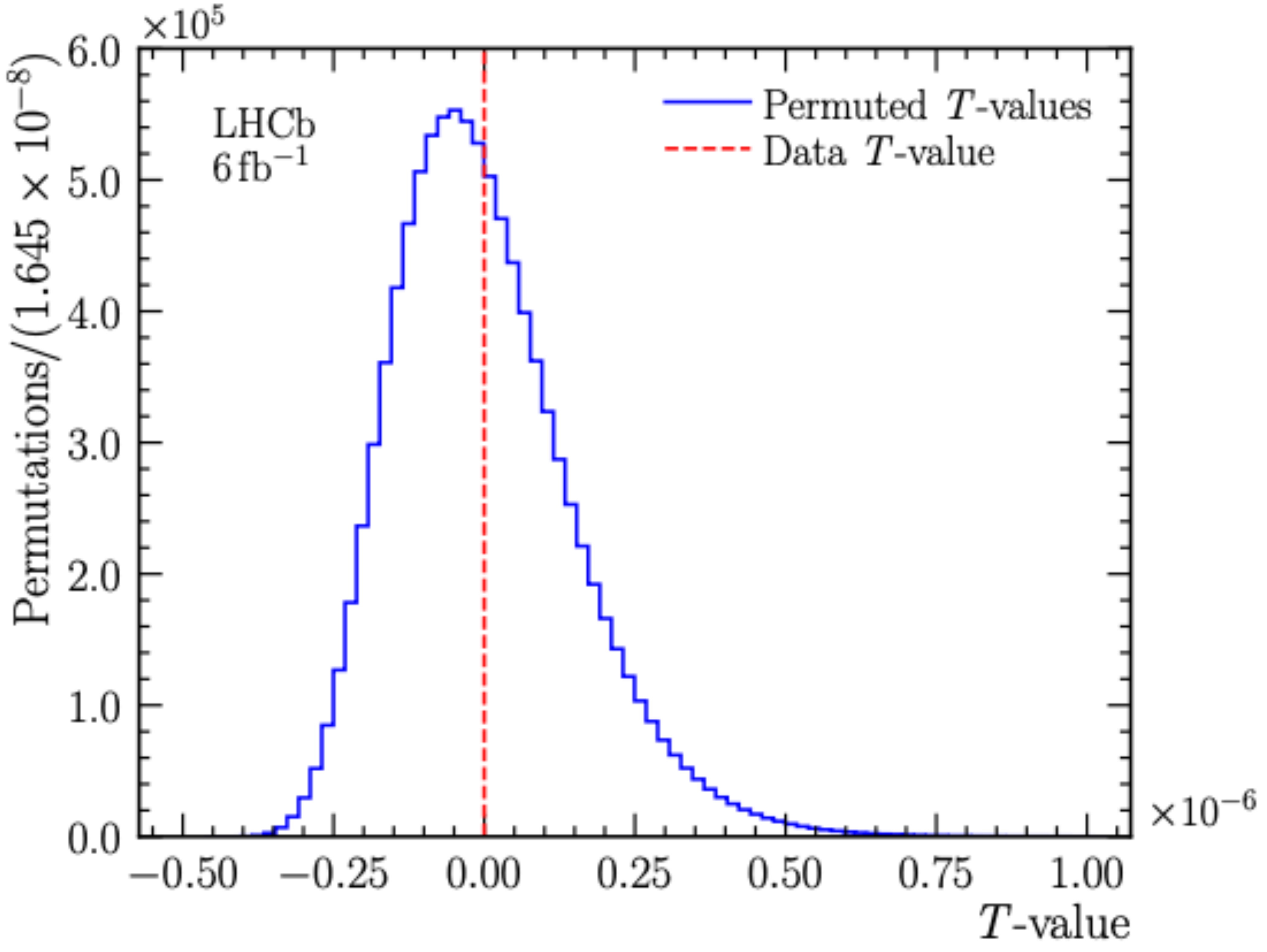


CPV in $D^0 \to \pi^-\pi^+\pi^0$ Decays with 6 fb^{-1}

[LHCB-PAPER-2023-005] (in preparation)

- Method applied to the 2.7M signal candidates
  - ~4 times of the previous analysis
- **Measured *p*-value : 62%**

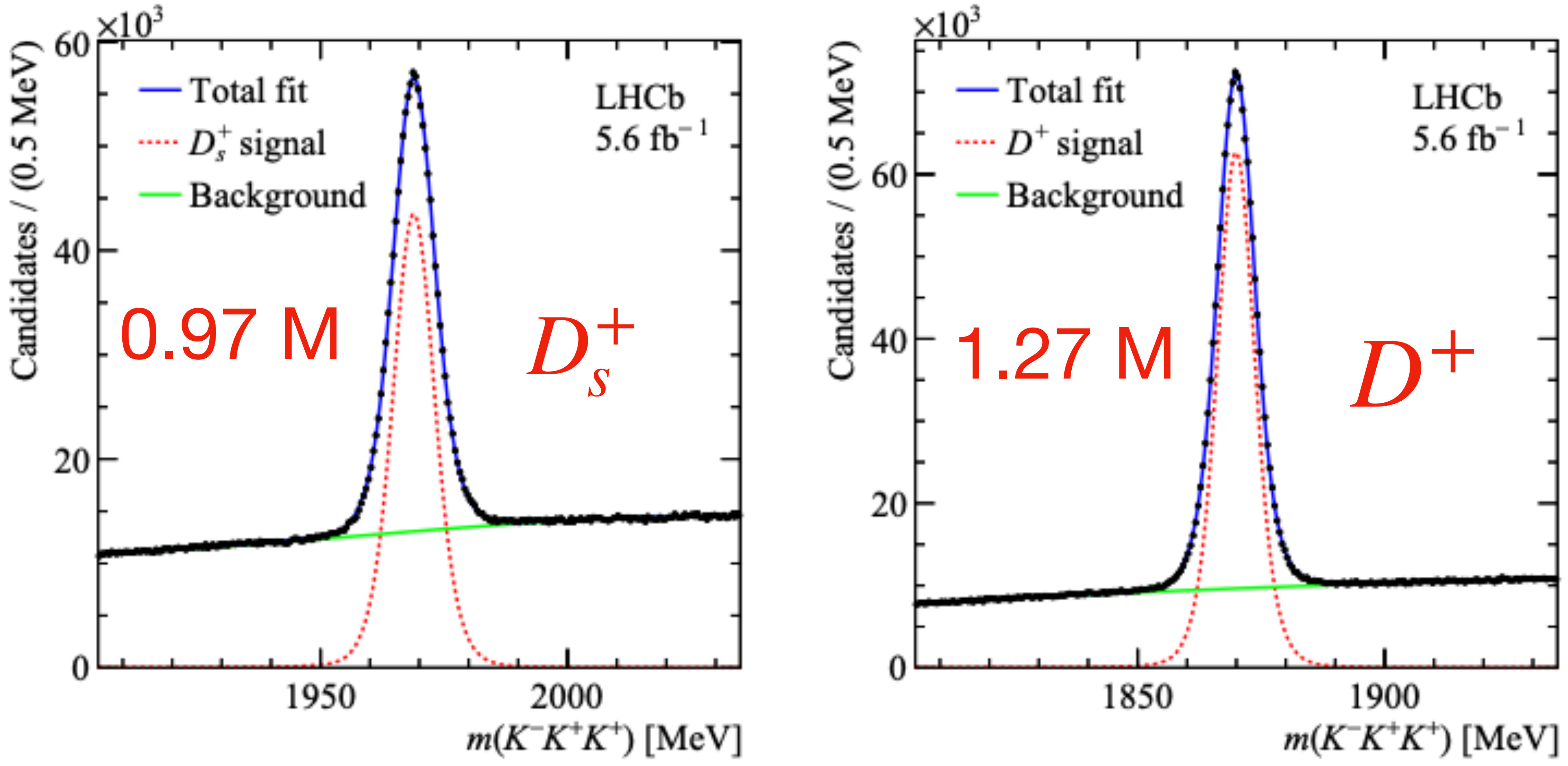
  -> no local evidence of CPV



*CP symmetry hypothesis from flavour-randomised permutations

CPV in $D^+_{(s)} \to K^-K^+K^-$ Decays with 5.6 fb^{-1}

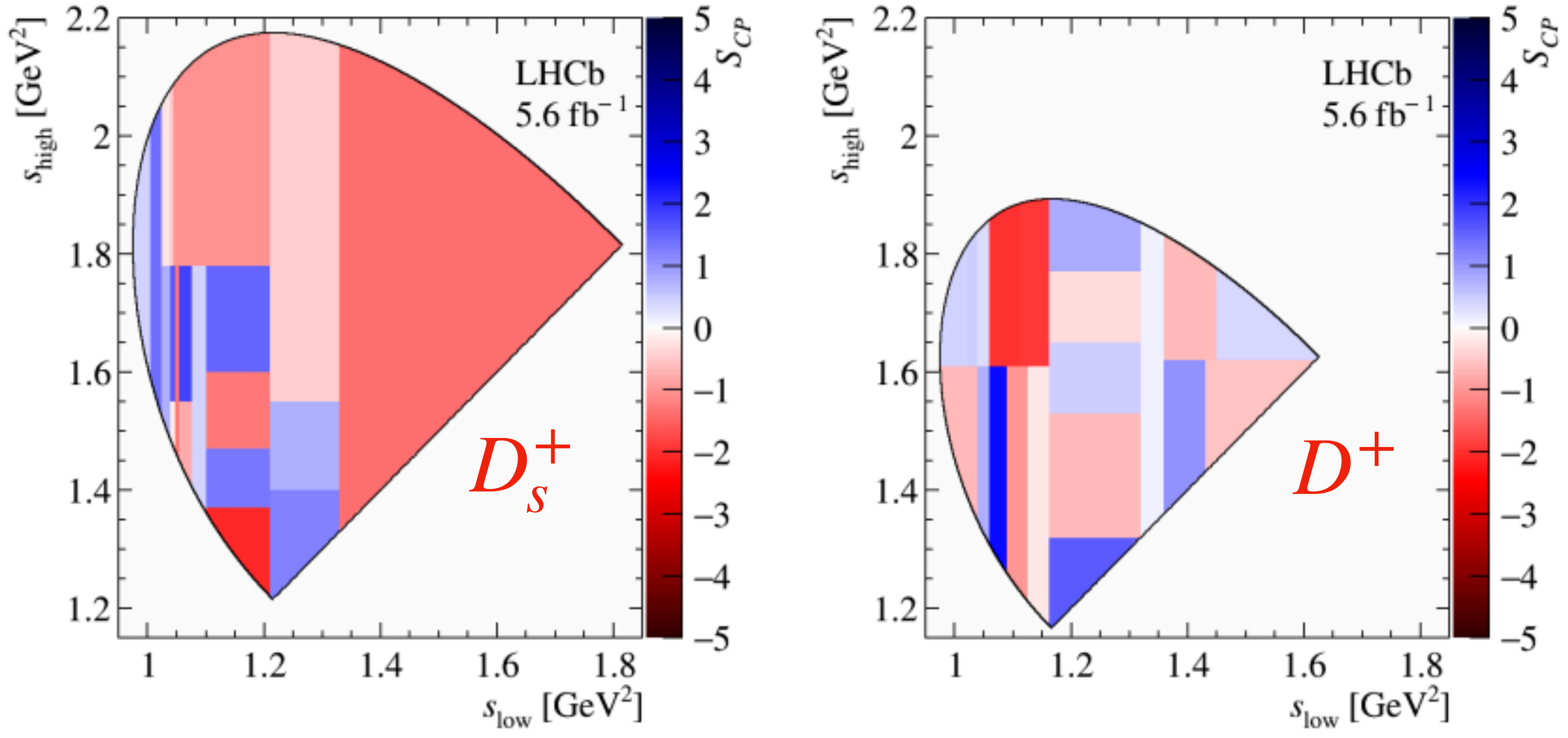
- (Double) Cabibbo-suppressed $(D_s^+)D^+ \to K^-K^+K^-$ decays.
  - (CPV is forbidden in SM -> observation indicates New Physics!) or $\mathcal{O}(10^{-3})$
- **A novel approach** is signal candidates are extracted **to search for local CP asymmetries in squared mass bins.**
- Local CP observable $\mathcal{S}_{CP}$ is extracted from signal candidates and their statistical uncertainties.



arXiv:2303.04062

CPV in $D^+_{(s)} \to K^-K^+K^-$ Decays with 5.6 fb^{-1}

- **No local CPV observed**
  - p-values are found to be (13.3%) 31.6% for $D^+_{(s)} \to K^-K^+K^-$ decays.

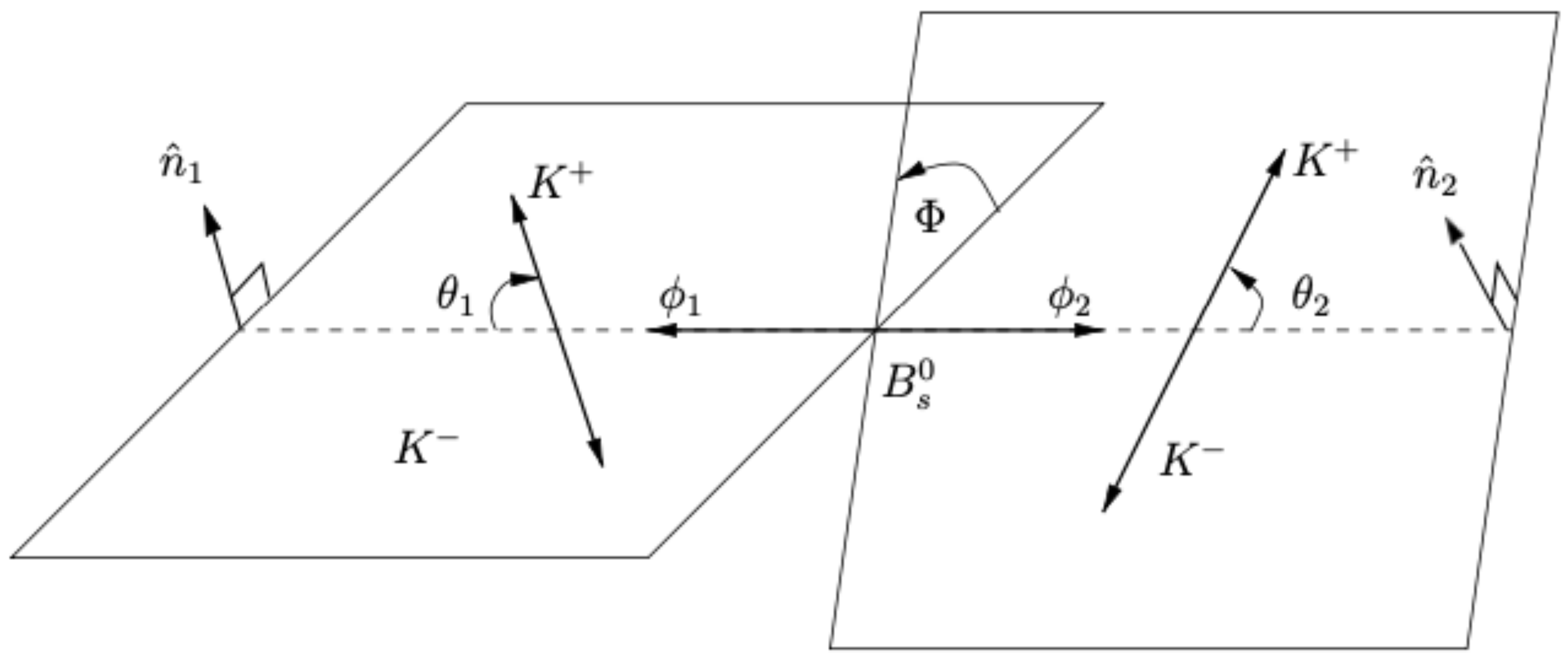


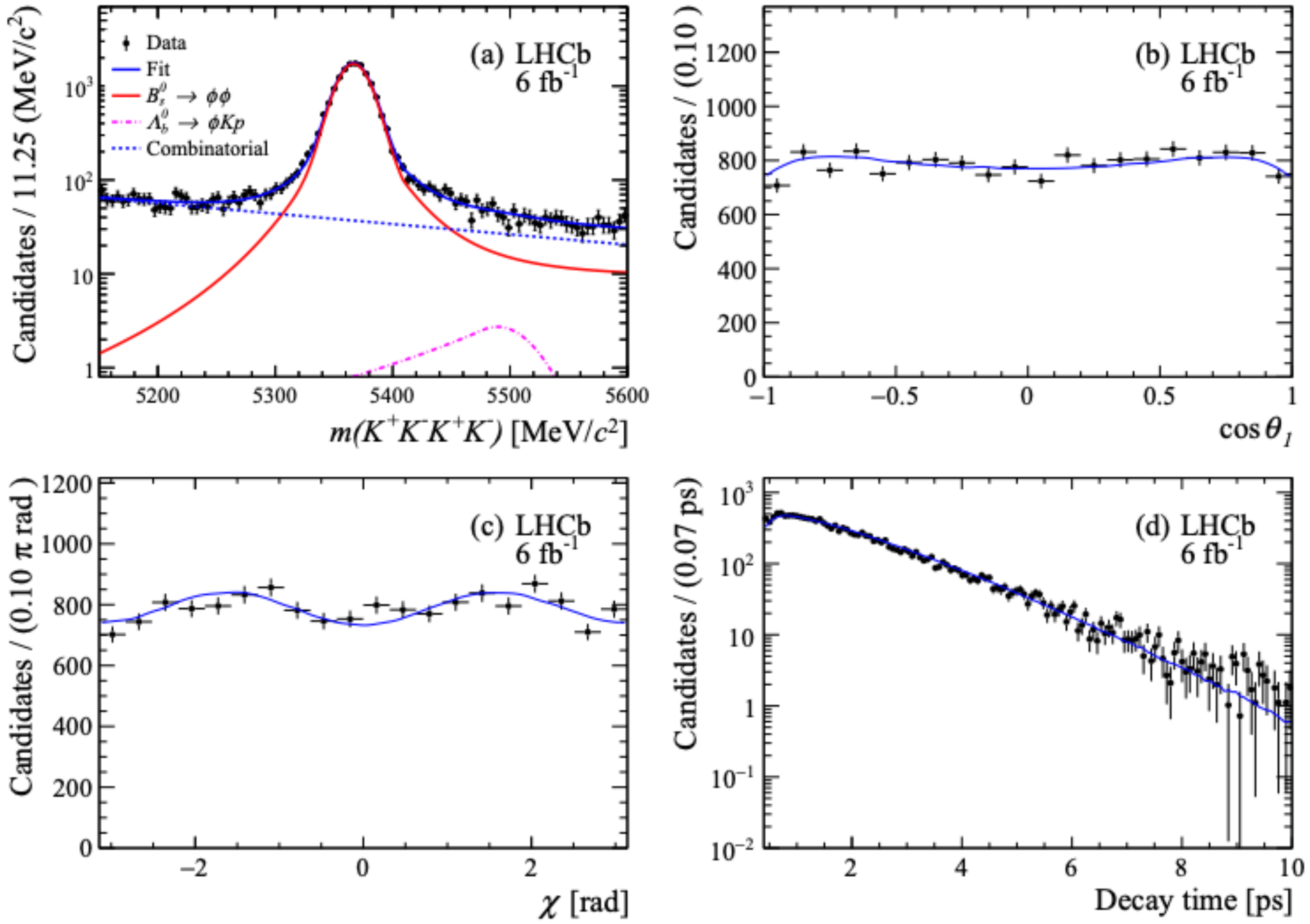
arXiv:2303.04062

$\phi_s^{s\bar{s}s}$ from $B_s^0 \to \phi\phi$ Decays with 6 fb-1

arXiv:2304.06198

- FCNC decay is produced in three linear polarization states.
  $\rightarrow$ sensitive to NP effects
- P→VV: Flavour-tagged time-dependent angular analysis
- $\phi_s^{s\bar{s}s} \approx 0$, in SM





$\phi_s^{s\bar{s}s}$ from $B_s^0 \to \phi\phi$ Decays with 6 fb^{-1}

arXiv:2304.06198

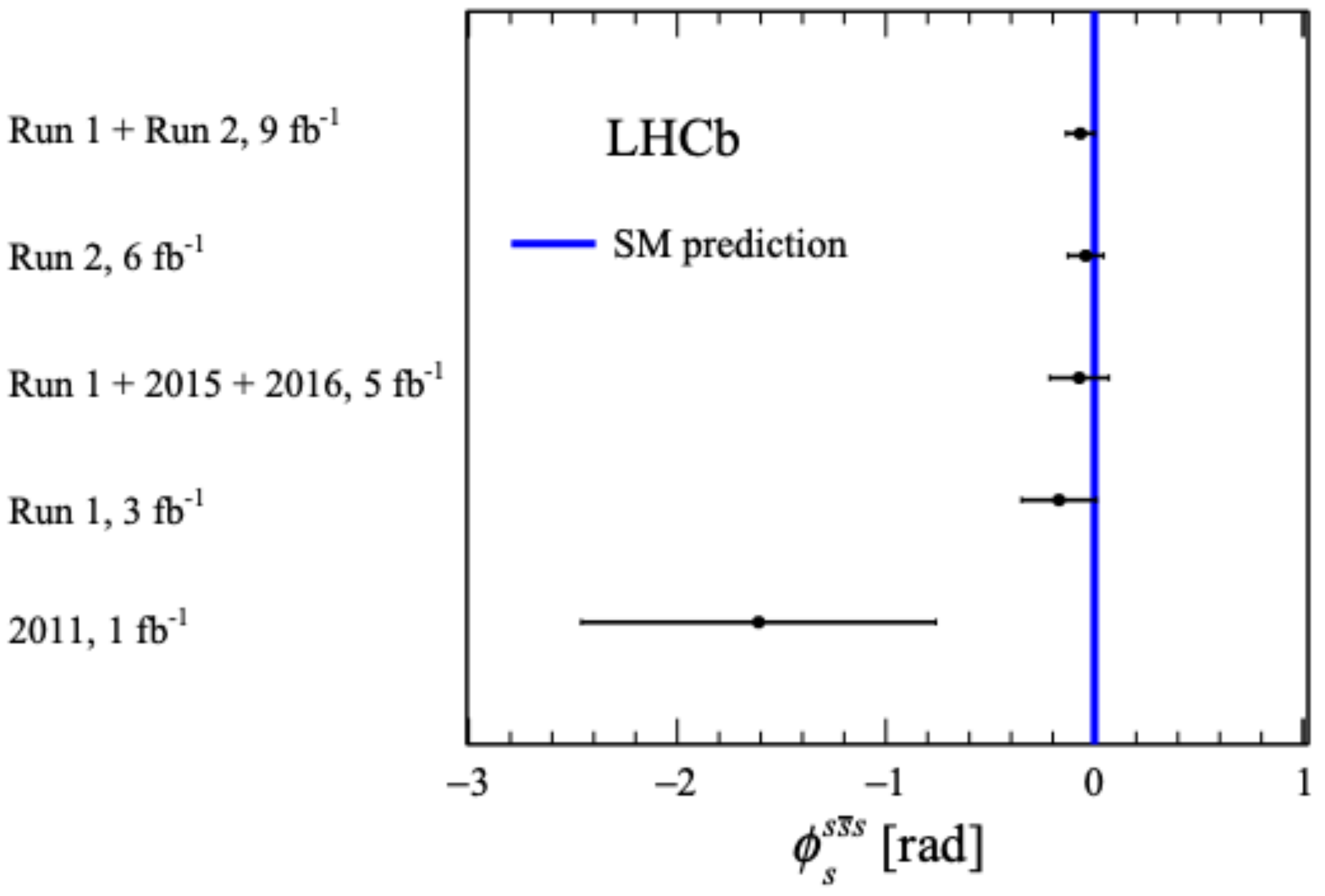
- No polarization dependence observed.

$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad

$|\lambda| = 1.004 \pm 0.030 \pm 0.009$

- The most precise measurement of CPV in any penguin dominated B decays.

- In agreement with the SM.



$\sin(2\beta)$ from $B^0 \to \psi(\to ll)K_s$ with 6 fb^{-1}

LHCB-PAPER-2023-013
(in preparation)

- CP violation is an interference of B^0 decays with and without mixing.

$$\mathscr{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S\ \sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh(1/2\Delta\Gamma_d t) + A_{\Delta\Gamma}\sinh(1/2\Delta\Gamma_d t)}$$

sin(2β) from $B^0 \to \psi(\to ll)K_s$ with 6 fb^{-1}

LHCB-PAPER-2023-013
(in preparation)

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$$= \frac{S\ \sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh(1/2\Delta\Gamma_d t) + A_{\Delta\Gamma}\sinh(1/2\Delta\Gamma_d t)} \approx S\sin(\Delta m t) - C\cos(\Delta m t) \qquad [\Delta\Gamma_d = 0]$$

$$\boxed{S_f \approx \sin(2\beta)}$$

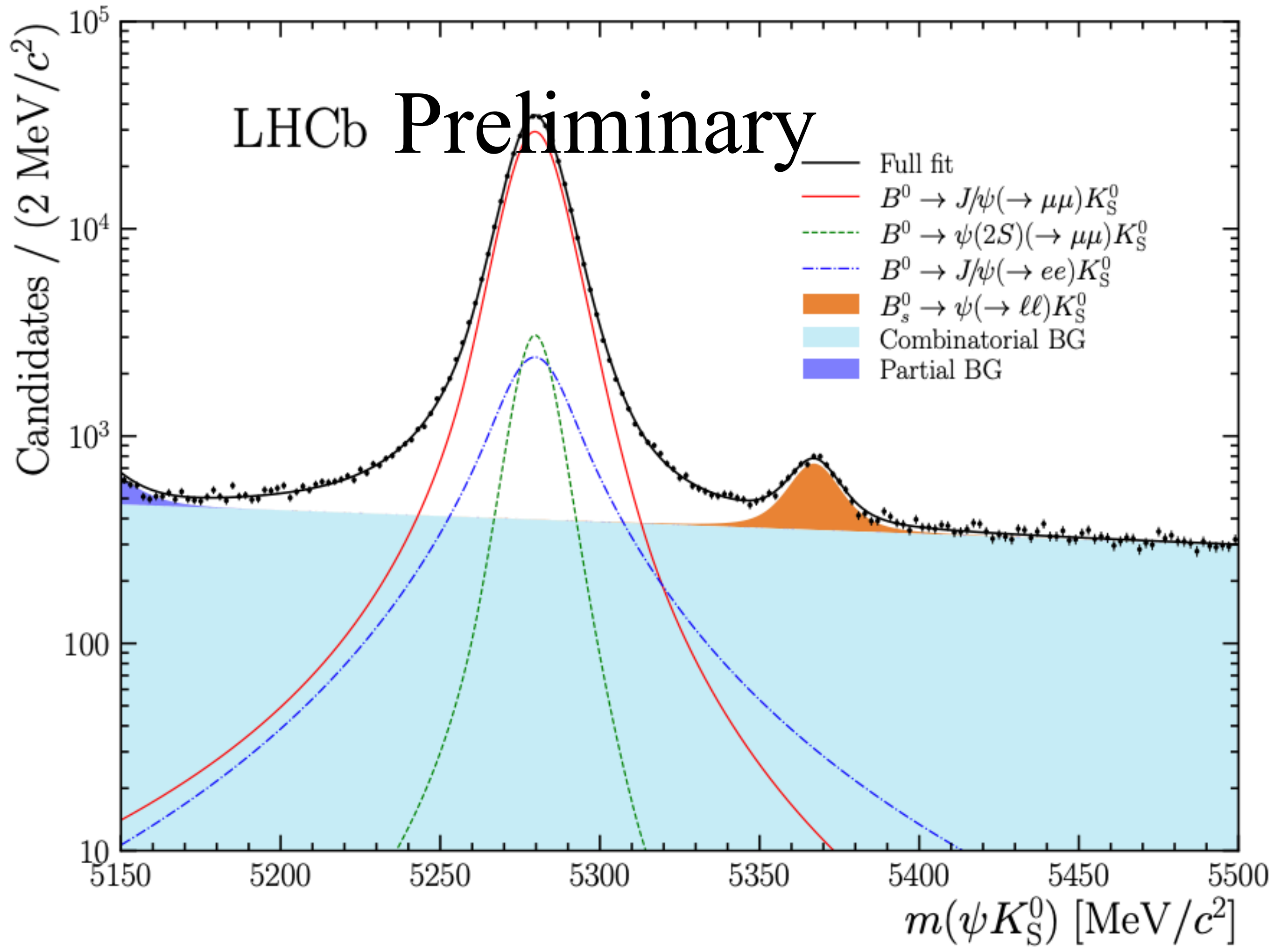
S= CPV in mixing

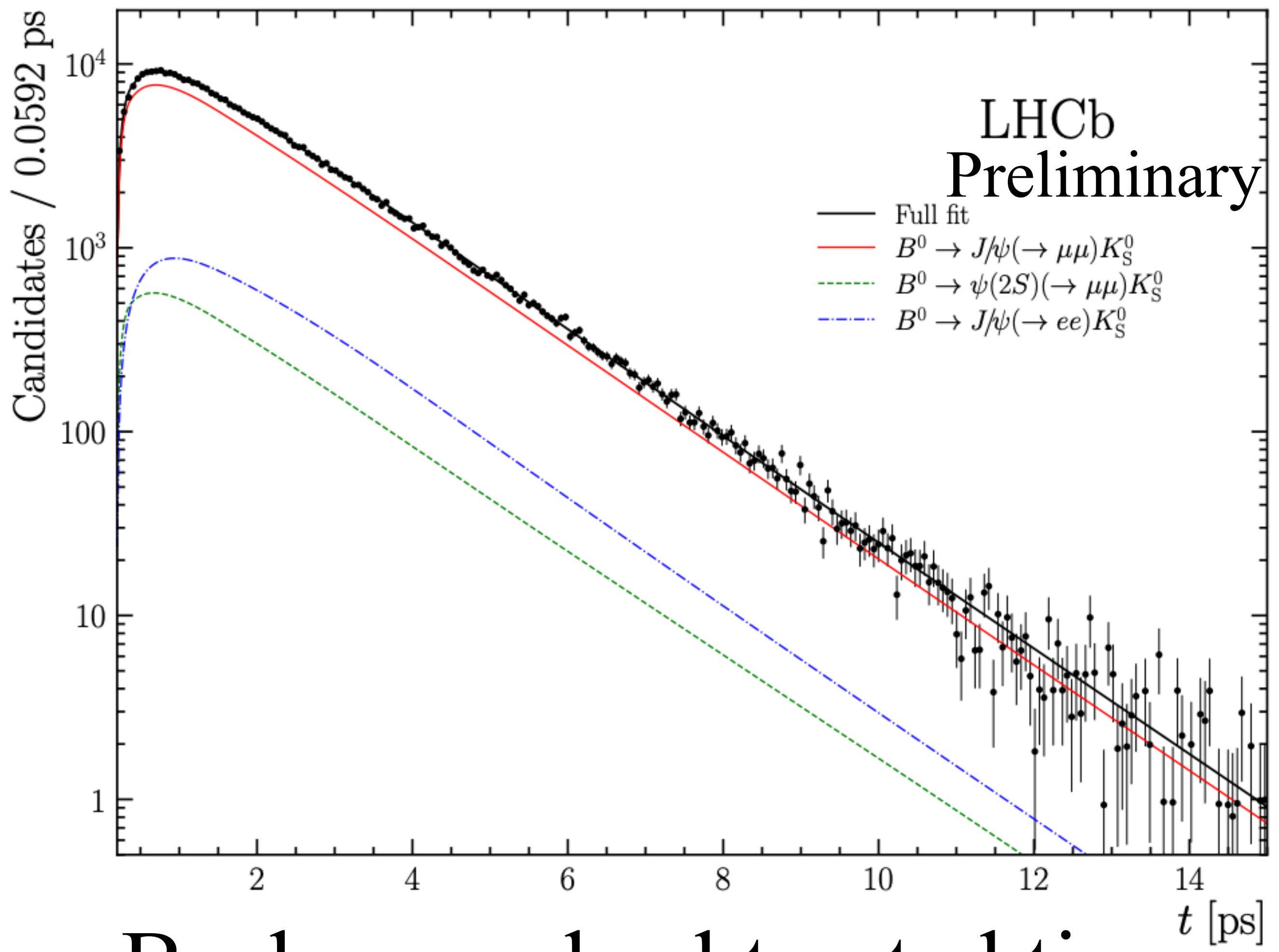
C= CPV in direct decays

$\sin(2\beta)$ from $B^0 \to \psi(\to ll)K_s$ with 6 fb^{-1}

LHCB-PAPER-2023-013
(in preparation)

- An extended maximum likelihood combined fit for 3 modes
  - $B^0 \to J/\psi(\to \mu^+\mu^-)K_s$
  - $B^0 \to \psi(2S)(\to \mu^+\mu^-)K_s$ $\quad K_s \to \pi^+\pi^-$
  - $B^0 \to J/\psi(\to e^+e^-)K_s$
- The fit is provide weights for the signal and background candidates.





Background subtracted time acceptance.

sin(2β) from $B^0 \to \psi(\to ll)K_s$ with 6 fb^{-1}

LHCB-PAPER-2023-013
(in preparation)

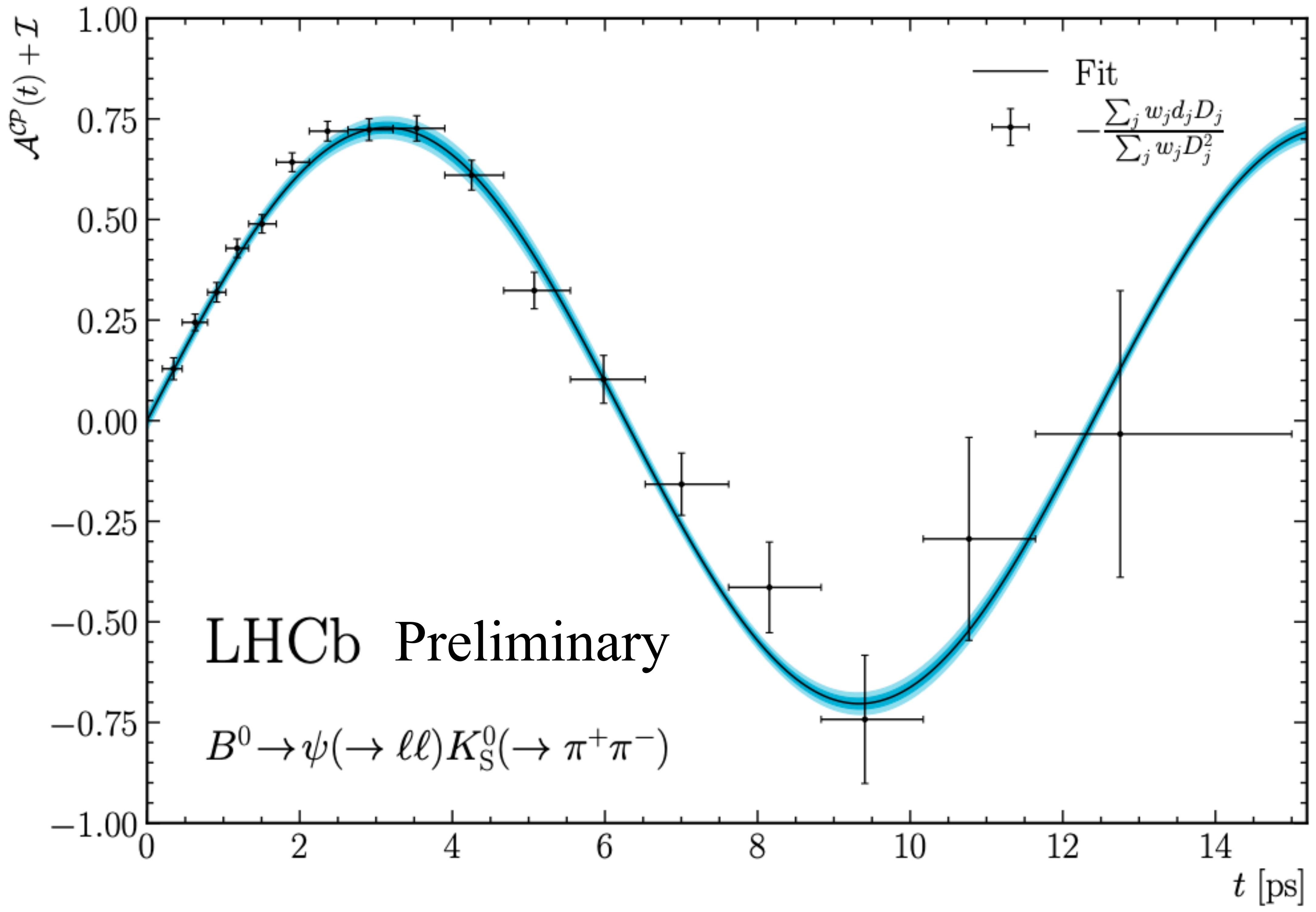
- Simultaneous fit to the three decay modes results in

$$S_{\psi K_s^0} = 0.7158 \pm 0.0133 \text{ (stat)} \pm 0.0078 \text{ (syst)}$$

$$C_{\psi K_s^0} = 0.0120 \pm 0.0123\text{(stat)} \pm 0.0029(syst)$$

- The precision of the measurement is higher than world average by HFLAV*

- Time-dependent $B^0 - \bar{B}^0$ yield asymmetry



*with a correlation coefficient of 0.44

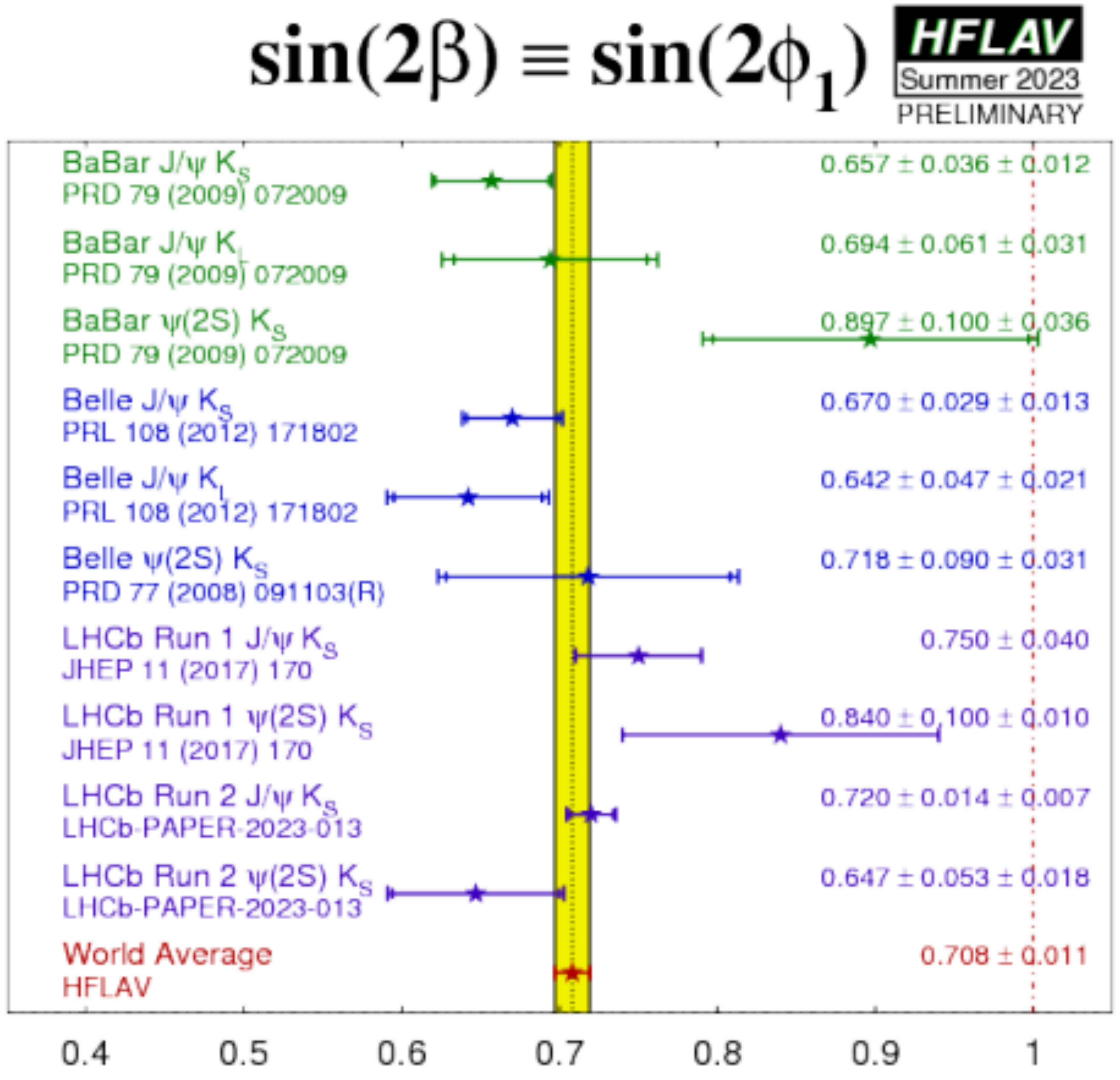
* HFLAV 2021, Eur. Phys. J. C81 (2021) 226

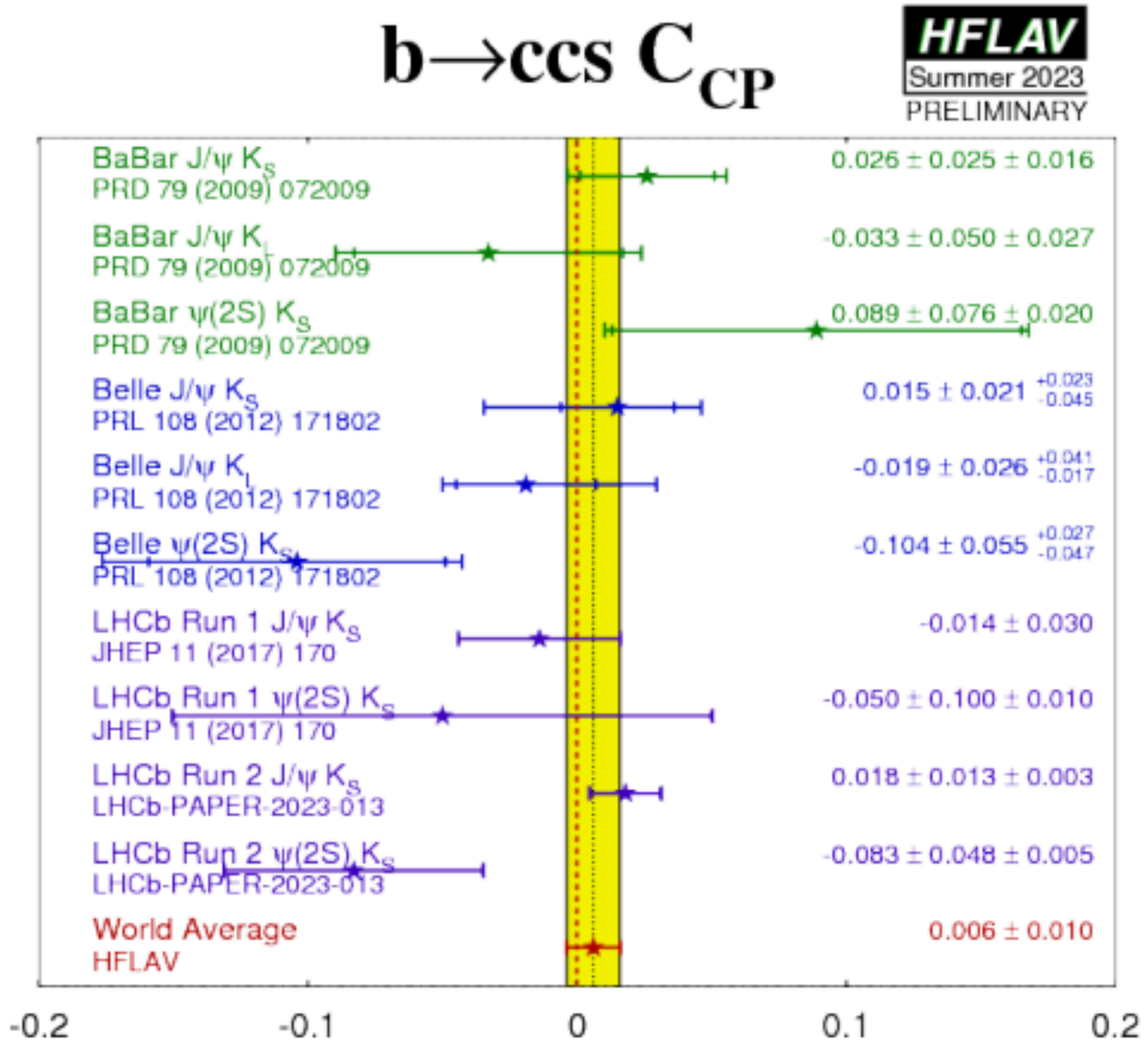
sin(2β) from $B_s^0 \to \psi K_s$ with 6 fb^{-1}

$\sin(2\beta) = 0.699 \pm 0.017 \longrightarrow \sin(2\beta) = 0.708 \pm 0.011$

$C_{CP} = 0.005 \pm 0.015 \longrightarrow C_{CP} = 0.006 \pm 0.010$

$S_f \approx \sin(2\beta)$

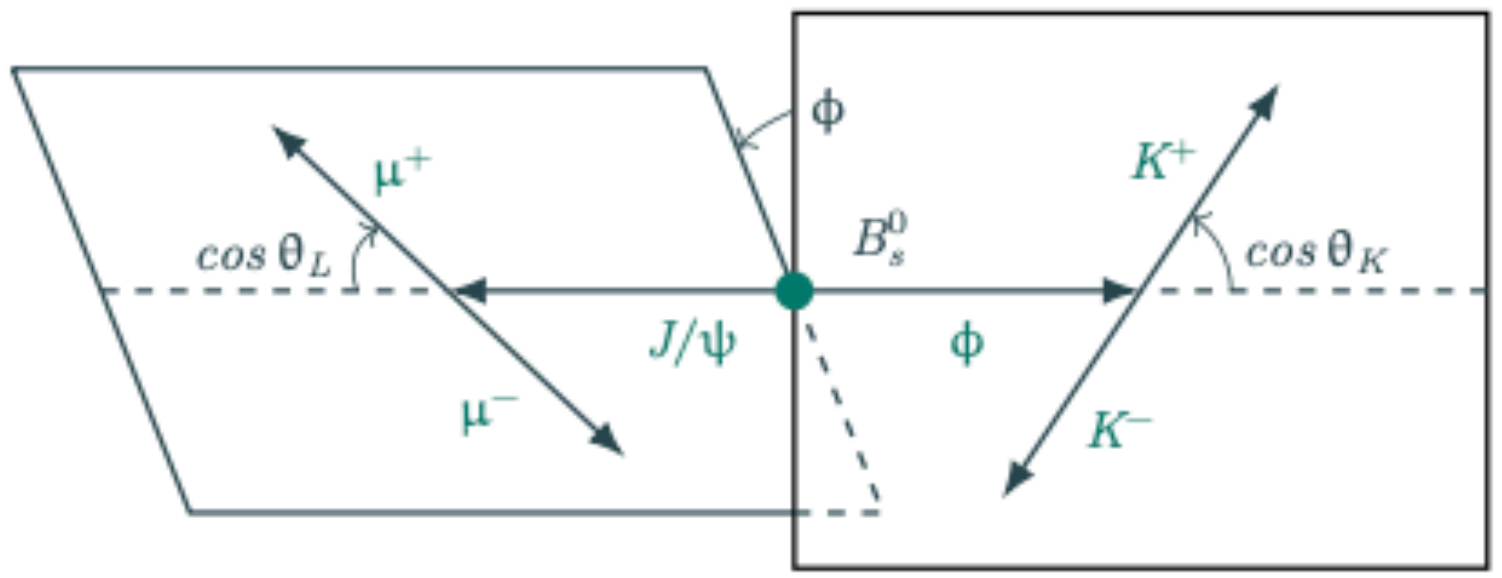


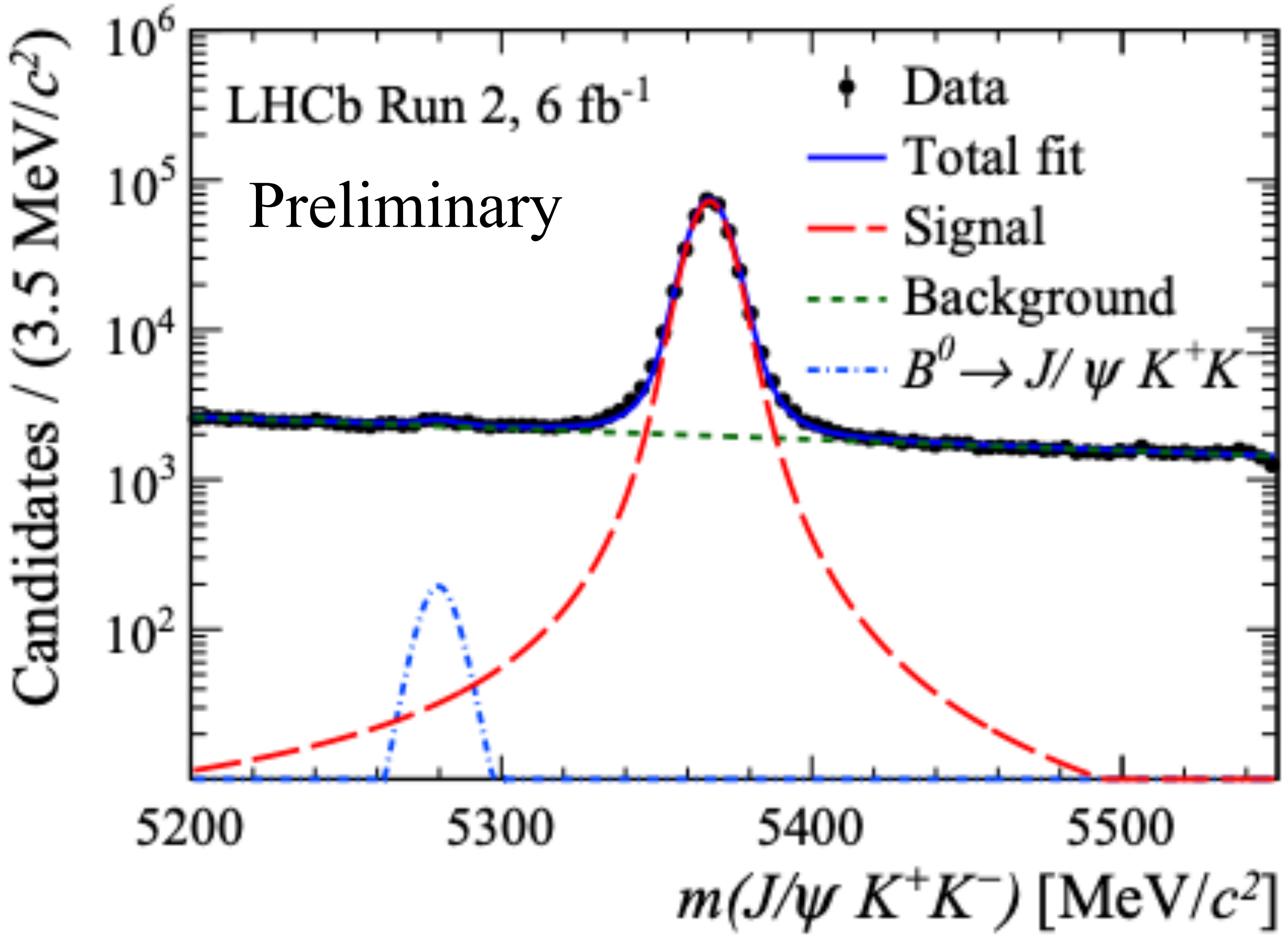


$\phi_s^{c\bar{c}s}$ from $B_s^0 \to J/\psi K^+ K^-$ Decays with 6 fb^{-1}

LHCB-PAPER-2023-016
(in preparation)

- Legacy analysis of
  - improvements in calibration of the particle identification (PID)
  - flavor tagging algorithms
  - the decay time resolution model
- P→VV time-dependent angular analysis



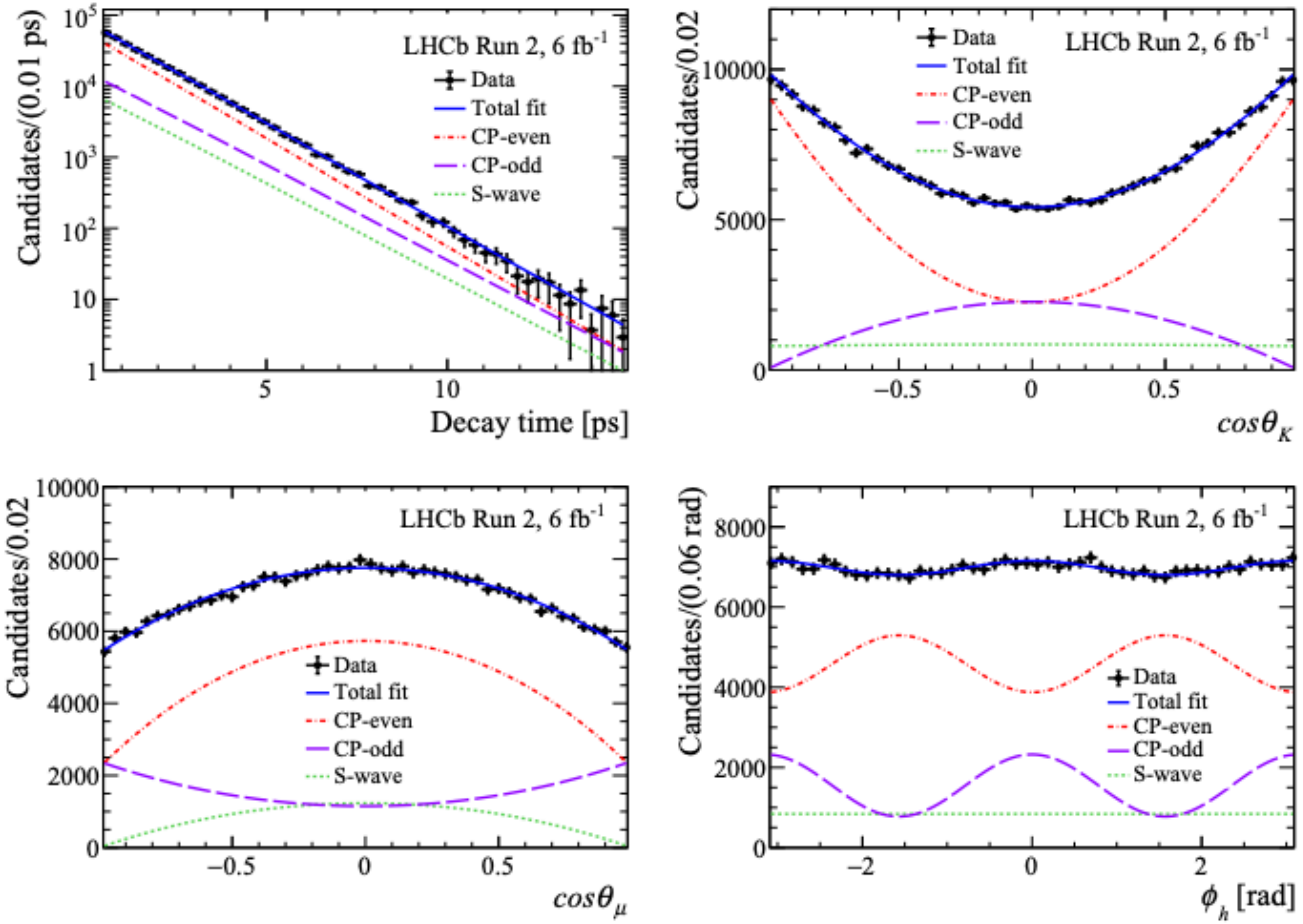


$\phi_s^{c\bar{c}s}$ from $B_s^0 \to J/\psi K^+K^-$ Decays with 6 fb^{-1}

LHCB-PAPER-2023-016
(in preparation)

- $\phi_s^{c\bar{c}c}$ = -0.039 ± 0.022 ± 0.006 [rad]
  - Most precise measurement to date
- $|\lambda|$ = 1.001 ± 0.011 ± 0.005
- $\Gamma_s - \Gamma_d = -0.0056^{+0.0013}_{-0.0015} \pm 0.0014$ [ps^{-1}]
- $\Delta\Gamma_s$ = 0.0845 ± 0.0044 ± 0.0024 [ps^{-1}]
- No CPV is observed.

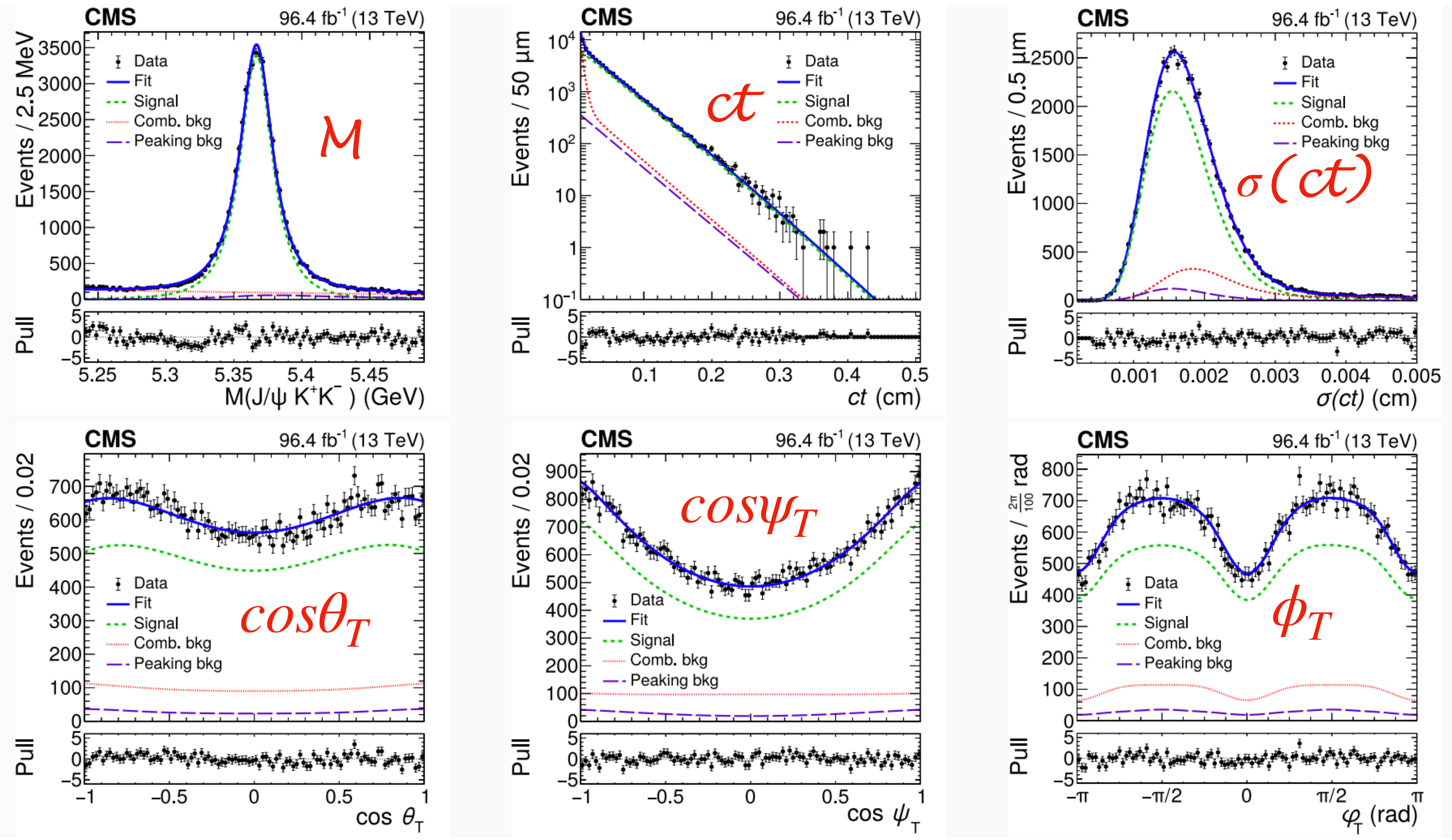
- No polarization dependence



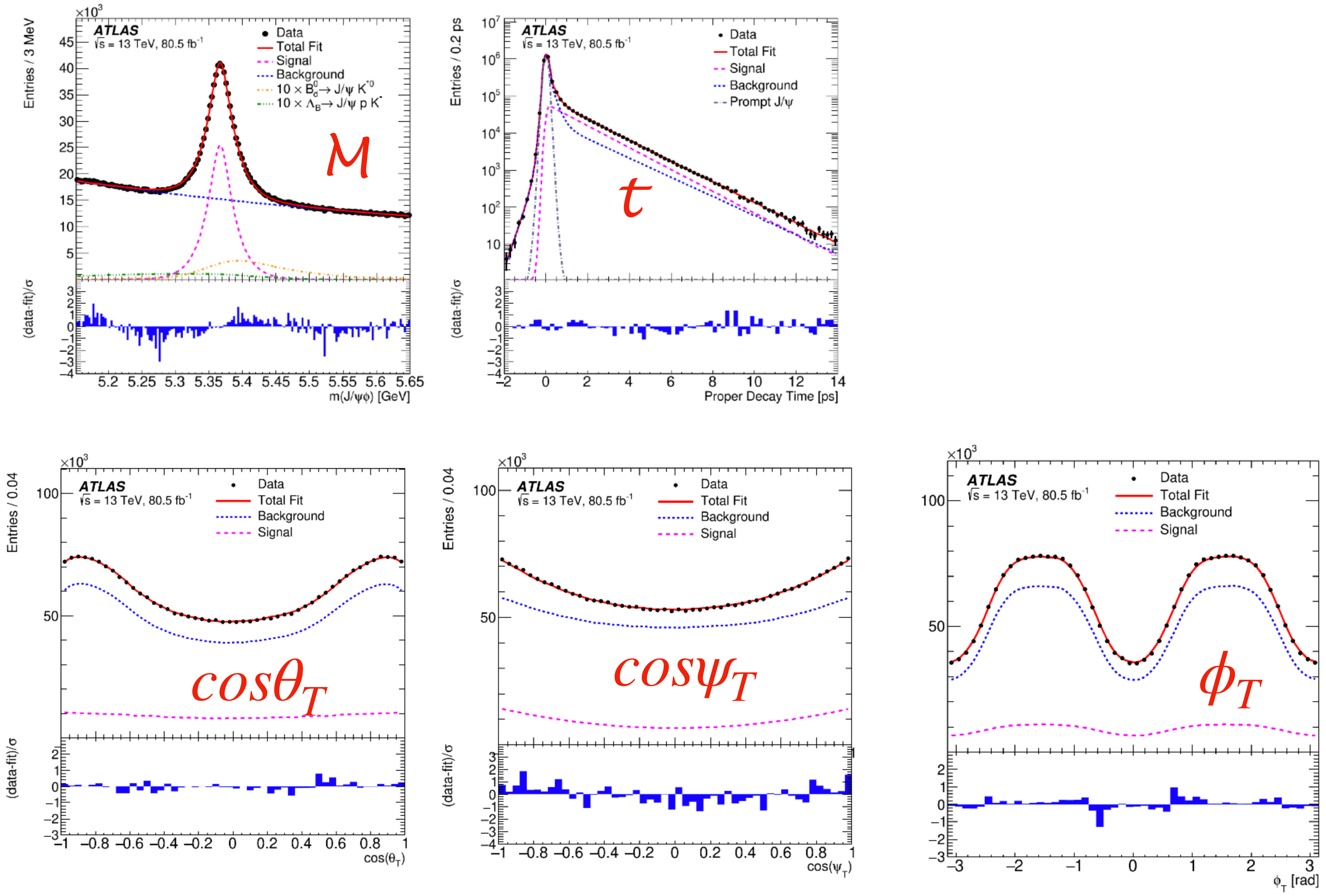
$\phi_s^{c\bar{c}s}$ from $B_s^0 \to J/\psi K^+K^-$ ATLAS and CMS

- CMS fit projections $\mathscr{L}$ = 96 fb[-1]
- SS and OS flavour tagging

- ATLAS fit projections $\mathscr{L}$ = 80.5 fb[-1]
- OS flavour tagging



Phys. Lett. B 816 (2021) 136188

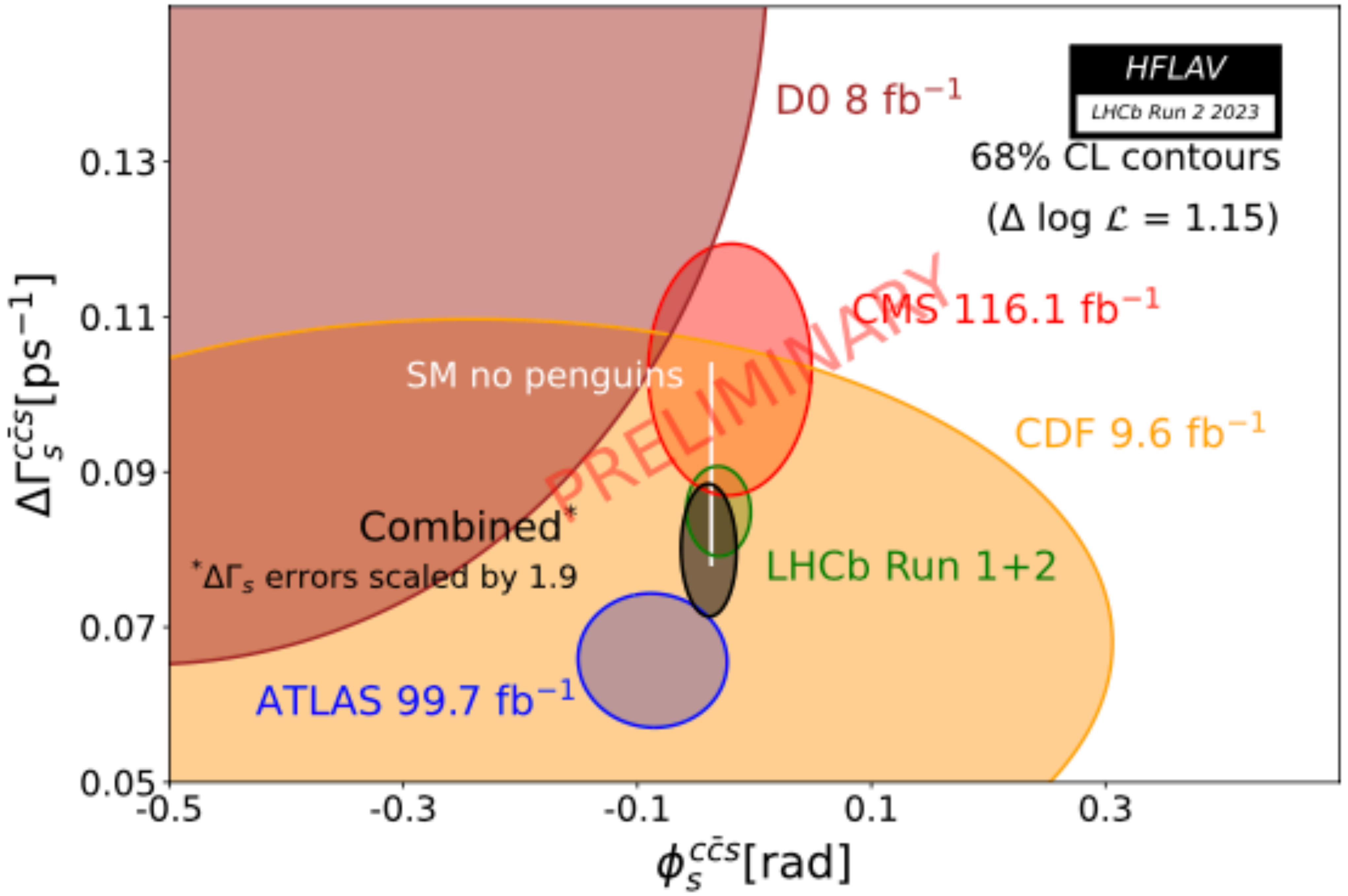


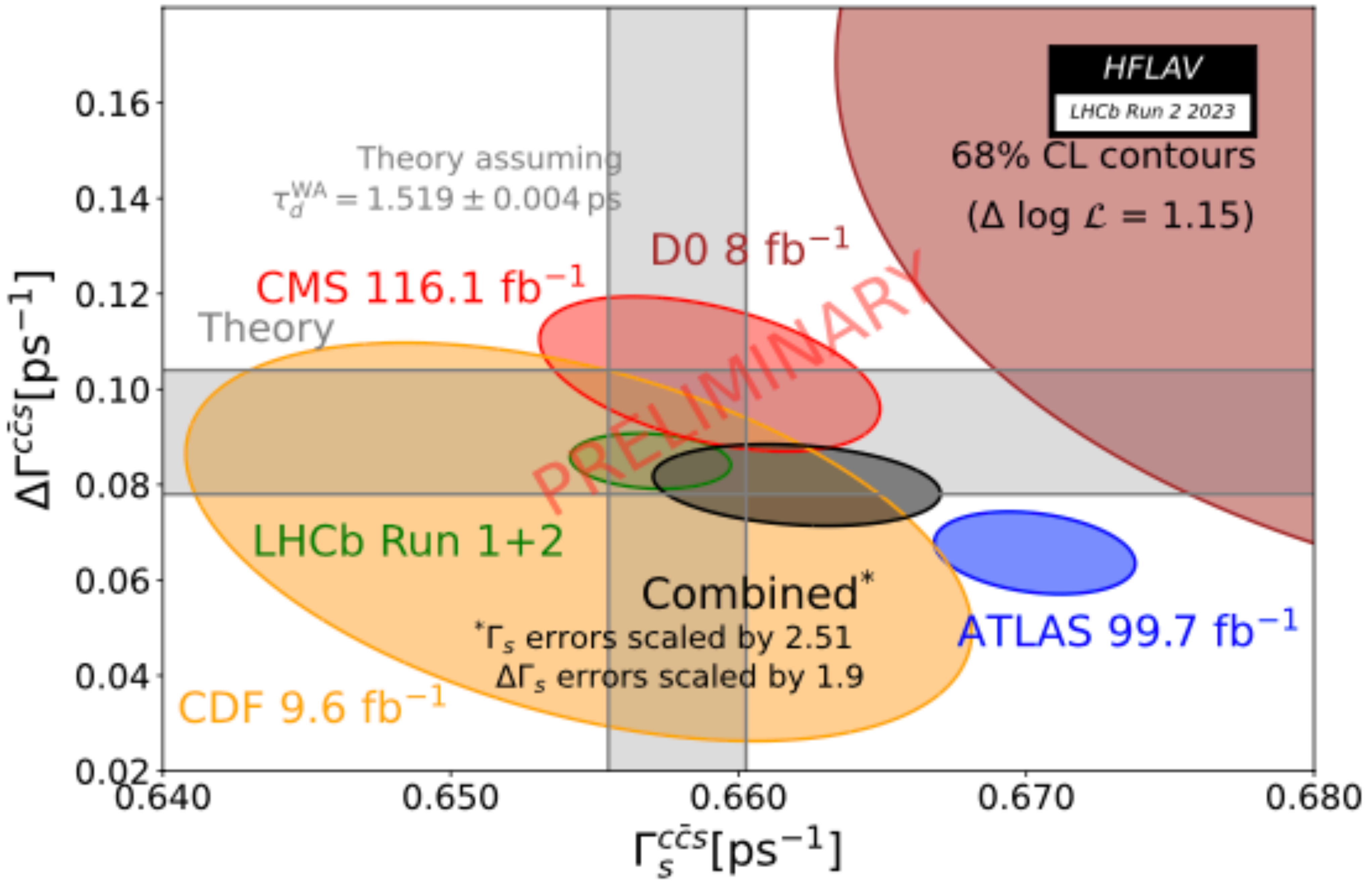
Eur. Phys. J. C 81 (2021) 342

22

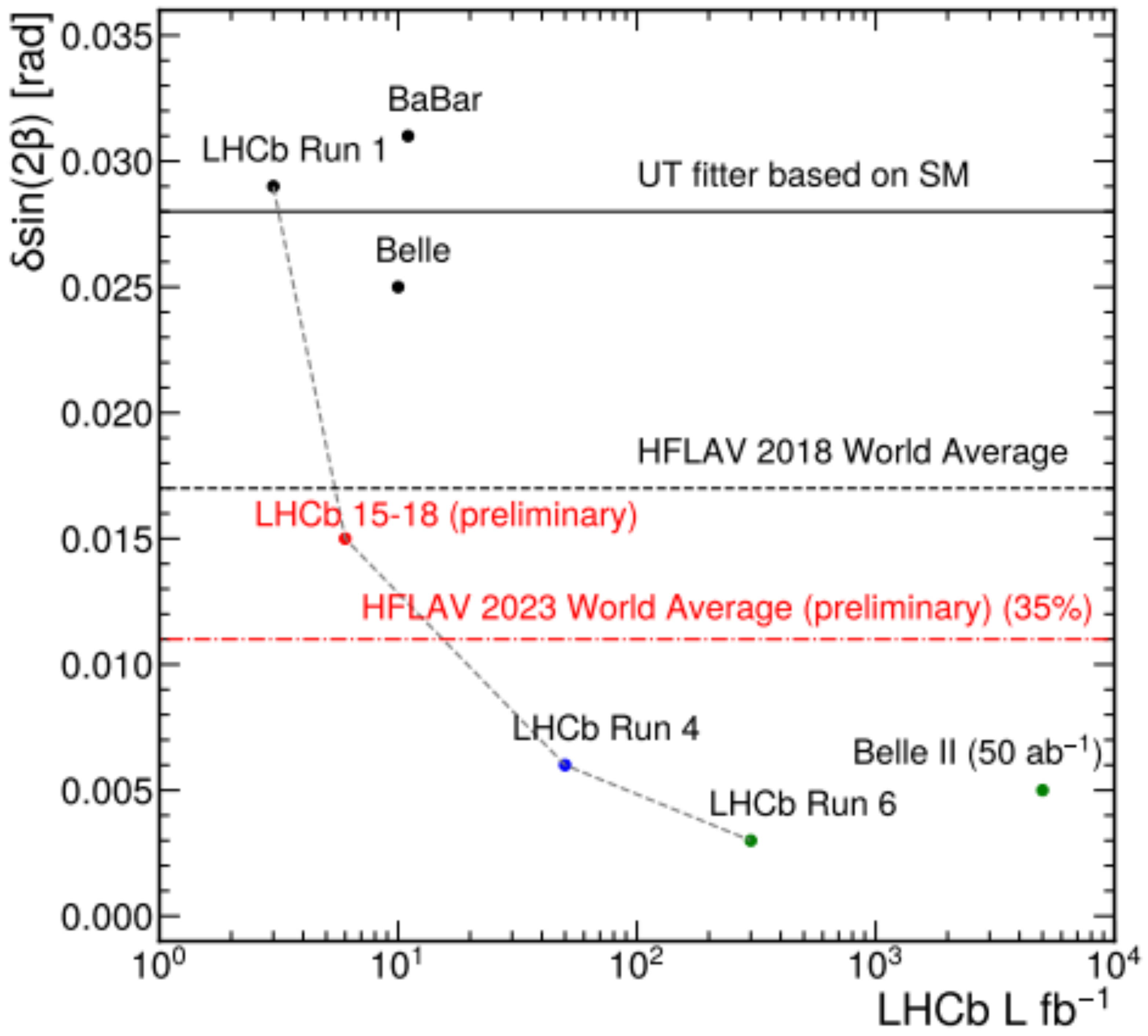
$\phi_s^{c\bar{c}s}$ HFLAV combination (2023)

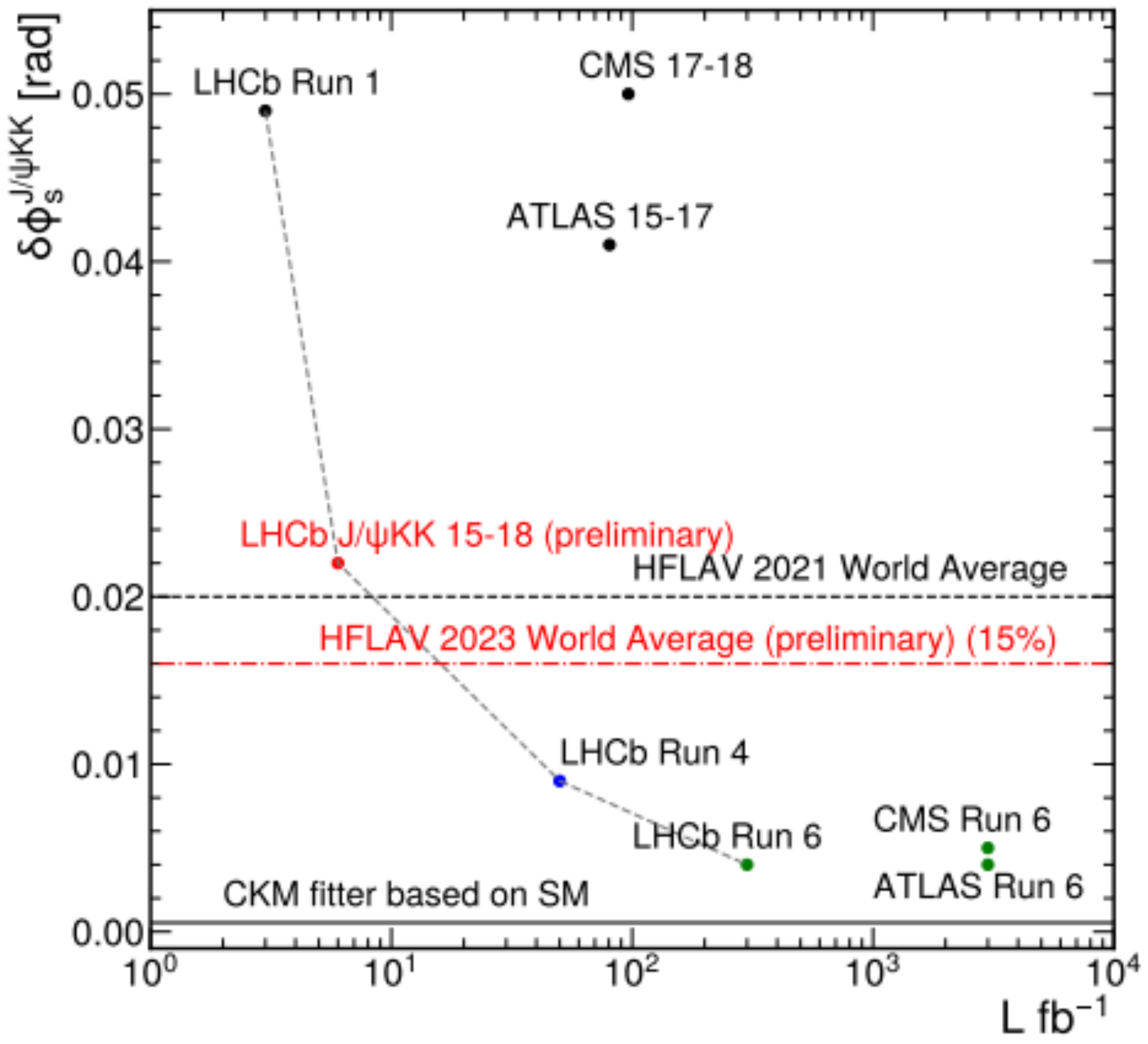
- $\phi_s^{c\bar{c}c} = -0.039 \pm 0.016$ [rad]
- $\Delta\Gamma_s = 0.080 \pm 0.006$ [ps^{-1}]
- $\Gamma_s = 0.6627 \pm 0.0036$ [ps^{-1}]





Run 3 and beyond..





LHCb-PUB-2018-009, PoS(KMI2017)005, ATL-PHYS-PUB-2018-041, CMS-PAS-FTR-18-041

Summary

- Latest time-dependent measurements of CP violation at LHCb provides **the most precise measurements**
  - $\sin(2\beta)$ $(B^0 \rightarrow \psi K_s^0)$ = 0.716 ± 0.013 ± 0.08
  - $\phi_s^{c\bar{c}c}$ with $(B_s^0 \rightarrow J/\psi K^+ K^-)$ = -0.039 ± 0.022 ± 0.006 [rad]
  - $\phi_s^{s\bar{s}s}$ with $(B_s^0 \rightarrow \phi\phi)$ = -0.042 ± 0.075 ± 0.009 [rad]
- **First evidence for direct CP violation** in $D^0 \rightarrow \pi^- \pi^+$ decays
- Upgrade I and II will help to improve (still) statistically limited analyses.