Studies of CPV in *B* mesons at LHCb experiment

第5届LHCb前沿物理研讨会

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On behalf of LHCb collaboration

Outline

- Introduction
- LHCb recent CPV results in B decays
  - Measurement of A^{CP} in $B^+ \to J/\psi\pi^+$ decay
  - Measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ decay
  - Measurement of ϕ_s in $B_s^0 \to \phi\phi$ decay
  - Measurement of $\sin 2\beta$ in $B^0 \to \psi K_S^0$ decays
- Summary

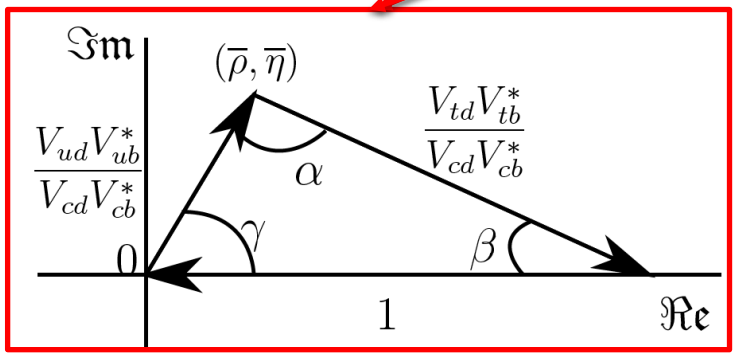
CKM in the Standard Model

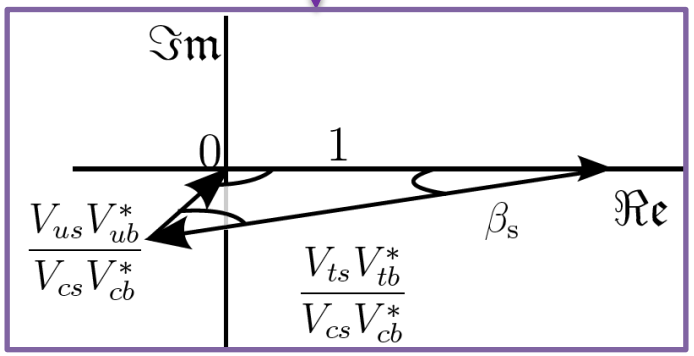
- CPV is necessary for creating the matter-antimatter asymmetry
- CPV strength given by CKM in SM is too small to explain this asymmetry

Measuring CPV observables provides excellent tests of SM:
e.g. direct CPV A^{CP}, CKM angles $[\beta, \beta_s]$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \lambda^3 e^{-i\beta} & -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

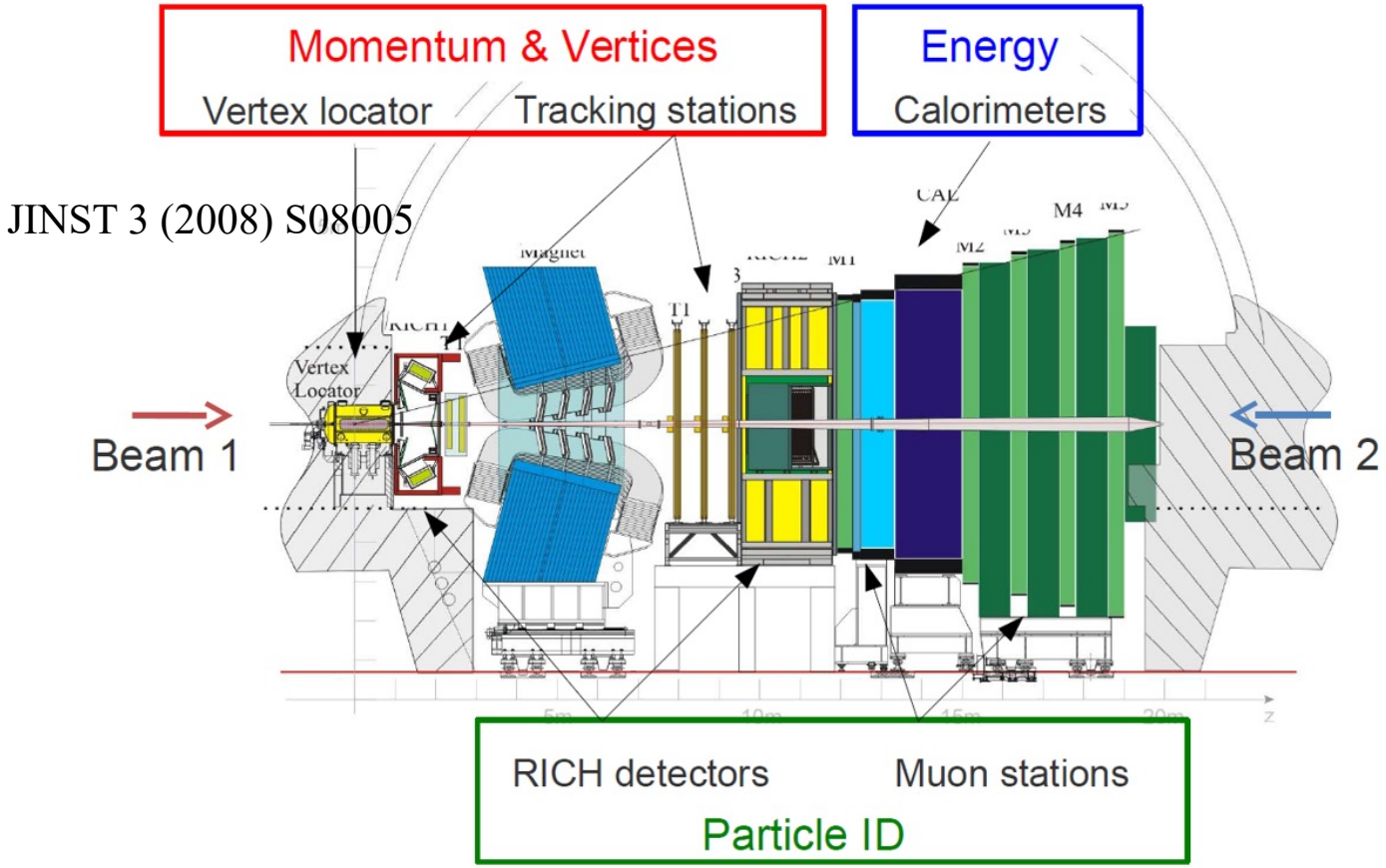
Wolfenstein parametrization $\lambda \approx 0.22$





LHCb detector

- Designed for beauty and charm physics, $2 < \eta < 5$
  - collected 3 fb^{-1} at $\sqrt{s} = 7$ TeV, 2011-2012 (Run 1)
  - collected 6 fb^{-1} at $\sqrt{s} = 13$ TeV, 2015-2018 (Run 2)



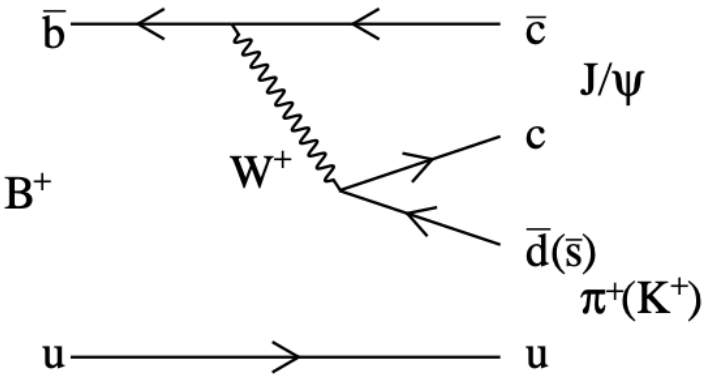
Recent CPV results with full Run 2 data

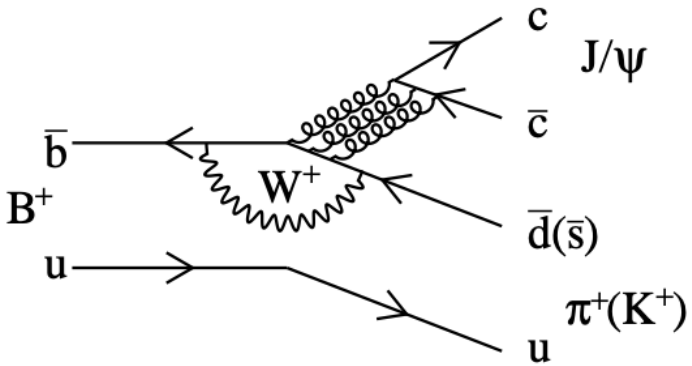
- **Measurement of A^{CP} in $B^+ \to J/\psi\pi^+$ decay**
  - ✓ Manshu Li, Shandong University, **Phys. Rev. Lett. 134 (2025) 101801**
- **Measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ decay**
  - ✓ Peilian Li, UCAS, **Phys. Rev. Lett. 132 (2024) 051802**
- **Measurement of ϕ_s in $B_s^0 \to \phi\phi$ decay**
  - ✓ Kechen Li, HTU, **Phys. Rev. Lett. 131 (2023) 171802**
- **Measurement of $\sin 2\beta$ in $B^0 \to \psi K_S^0$ decays**
  - ✓ Vukan Jevtic, TU Dortmund, **Phys. Rev. Lett. 132 (2024) 021801**

Measurement of A^{CP} in $B^+ \to J/\psi\pi^+$ decay

- CPV in $B^+ \to J/\psi(\mu^+\mu^-)\pi^+(K^+)$ decays
  - expected CPV at $\mathcal{O}(1\%)$ for $J/\psi\pi^+$ and negligible CPV for $J/\psi K^+$
    [PRD 49 (1994) 5904, PRD 52 (1995) 242]
  - ideal decay to search for direct CP violation in b decays to charmonium
  - control channel to estimate penguin effect on in $\sin 2\beta$ measurement
    [PRD 79 (2009) 014030, JHEP 03 (2015) 145]

$$\Delta A^{CP} = (a^{\text{raw}}_{J\psi\pi} - a^{\text{raw}}_{J\psi K}) - (a^{\text{det}}_{J\psi\pi} - a^{\text{det}}_{J\psi K}) - (a^{\text{PID}}_{J\psi\pi} - a^{\text{PID}}_{J\psi K})$$
$$a = (N^- - N^+)/(N^- + N^+)$$





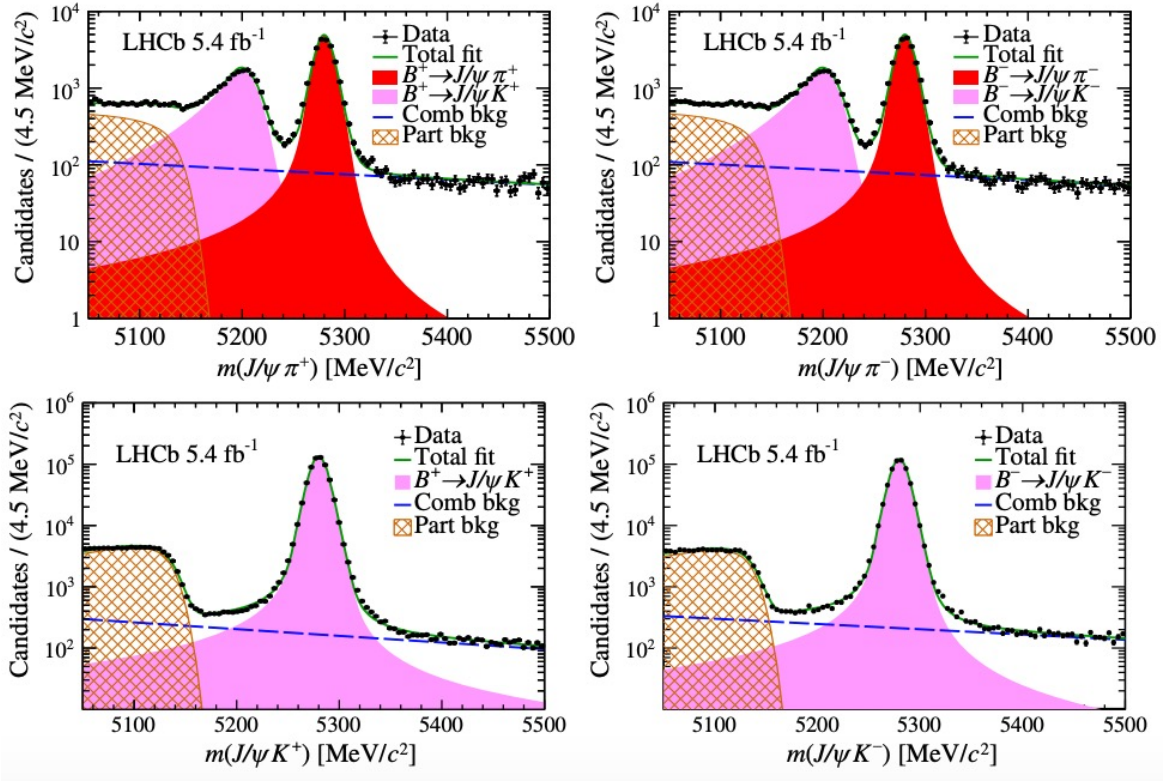
Measurement of A^{CP} in $B^+ \to J/\psi\pi^+$ decay

Measured results

$\Delta A^{CP} = (1.29 \pm 0.49 \pm 0.08)\times 10^{-2}$ (Run 2)

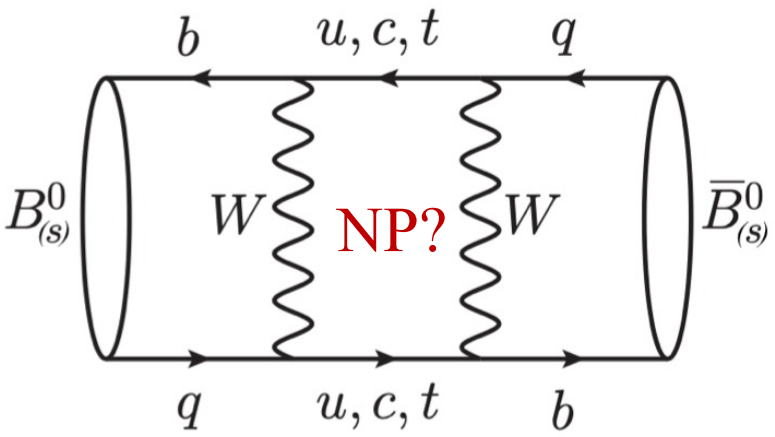
$\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08)\times 10^{-2}$ (Run 1+2)

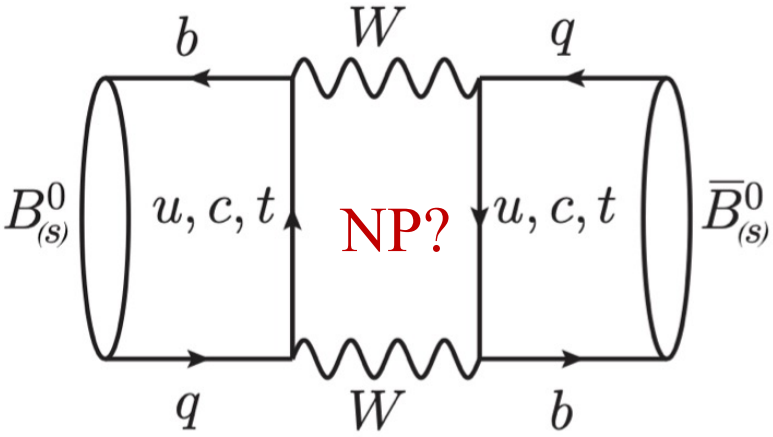
$\Longrightarrow$ 1st evidence (3.2σ) for direct CPV in the beauty decays to charmonium final states.

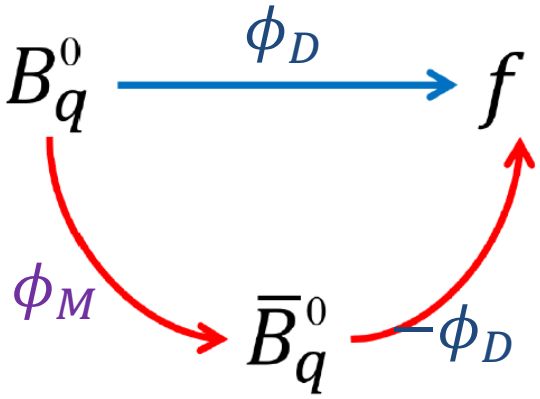


CPV in neutral B mesons

- CPV of interference between mixing and decay







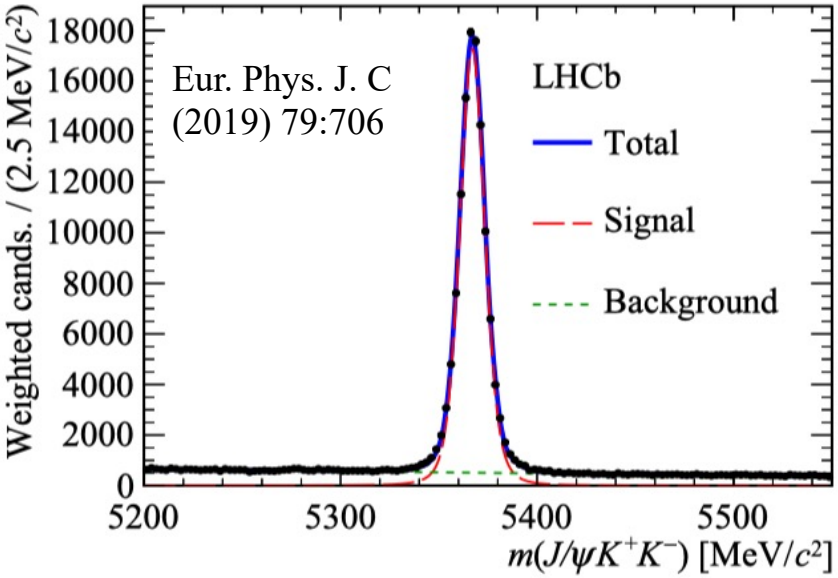
Weak phase $\phi_q = \phi_M - 2\phi_D$

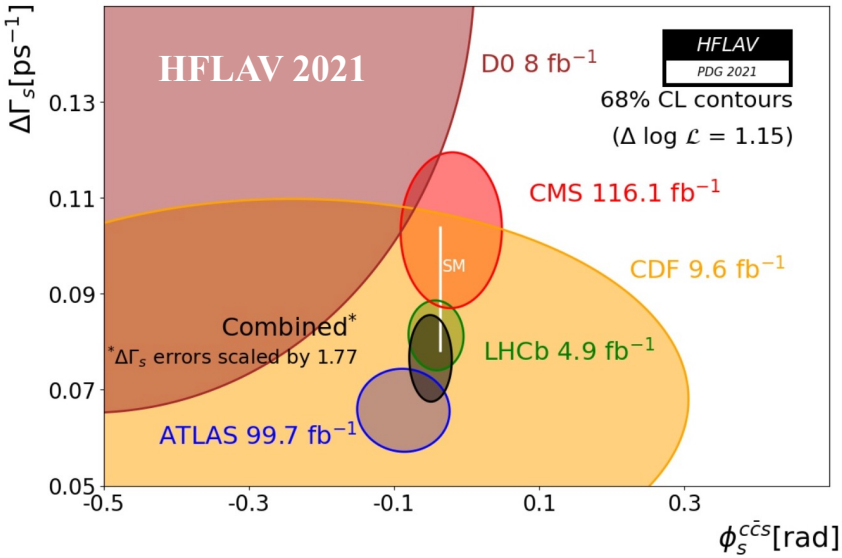
$\phi_s = -2\beta_s, \phi_d = 2\beta$

$\Delta m_q, \Gamma_q, \Delta\Gamma_q \ldots$

Measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ decay

- ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
  - precise prediction for $b \to c\bar{c}s$ decays, $\phi_s^{\text{tree}} = -2\beta_s = -37.0^{+0.6}_{-0.5}$ mrad [CKM fitter]
  - a stringent test of SM and a sensitive probe to NP in B_s^0 mixing
  - golden channel to measure $\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \Delta\phi_s^{\text{NP}}$
  - previous average $\phi_s^{c\bar{c}s} = -50 \pm 19$ mrad [HFLAV 2021]





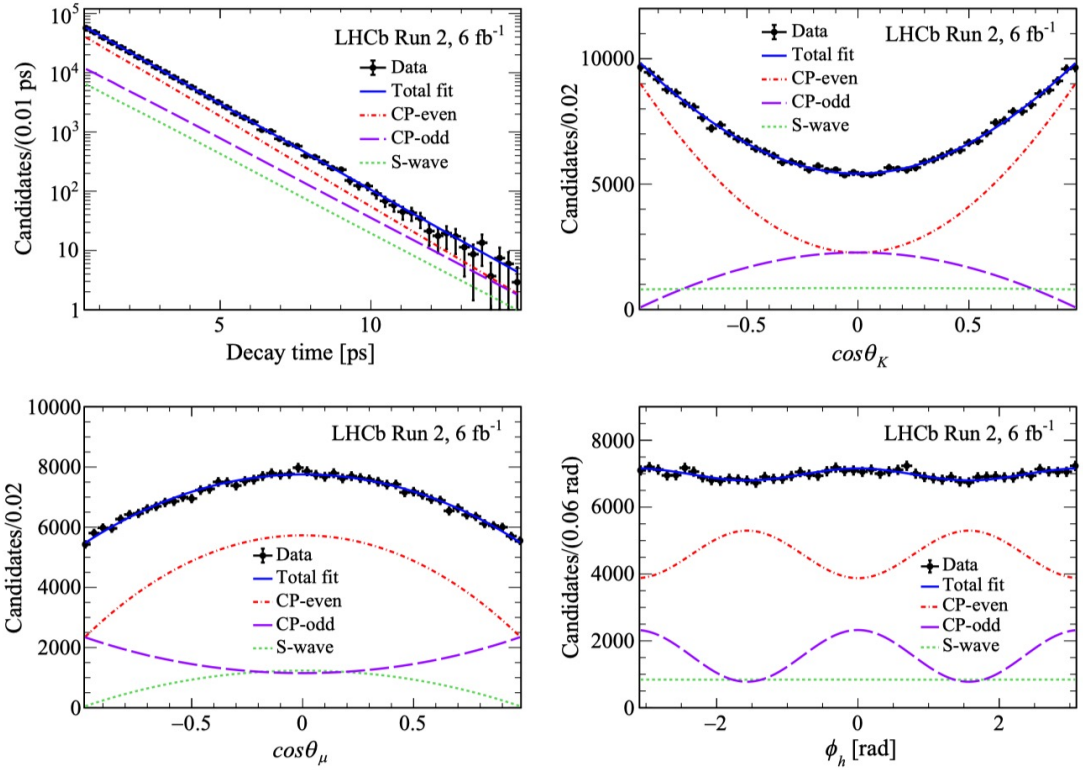
Measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ decay

Perform a time-dependent angular analysis

$$\phi_s^{J/\psi\phi} = -39 \pm 22 \pm 6 \text{ mrad}$$

$$\Delta\Gamma_s^{J/\psi\phi} = 0.085 \pm 0.004 \pm 0.002 \text{ ps}^{-1}$$

- consistent with SM, no CPV observed
- most precise measurement



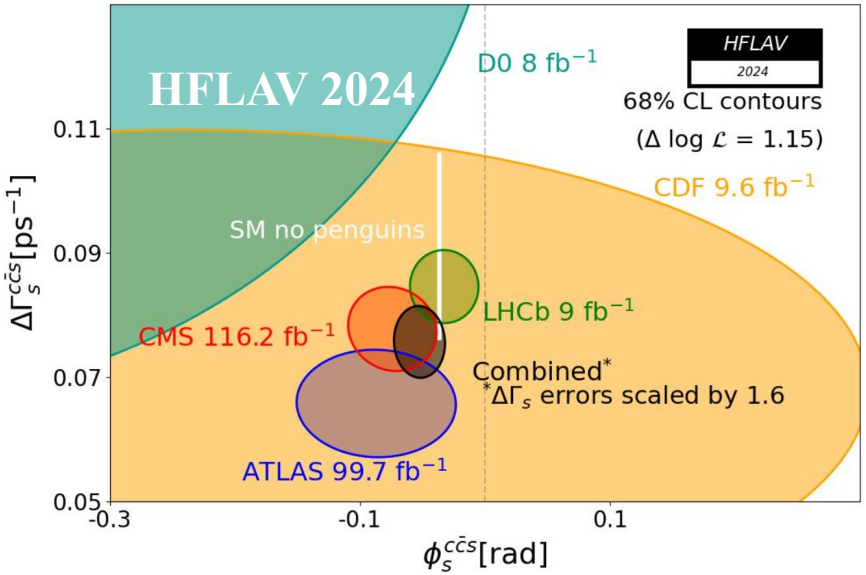
Measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ decay

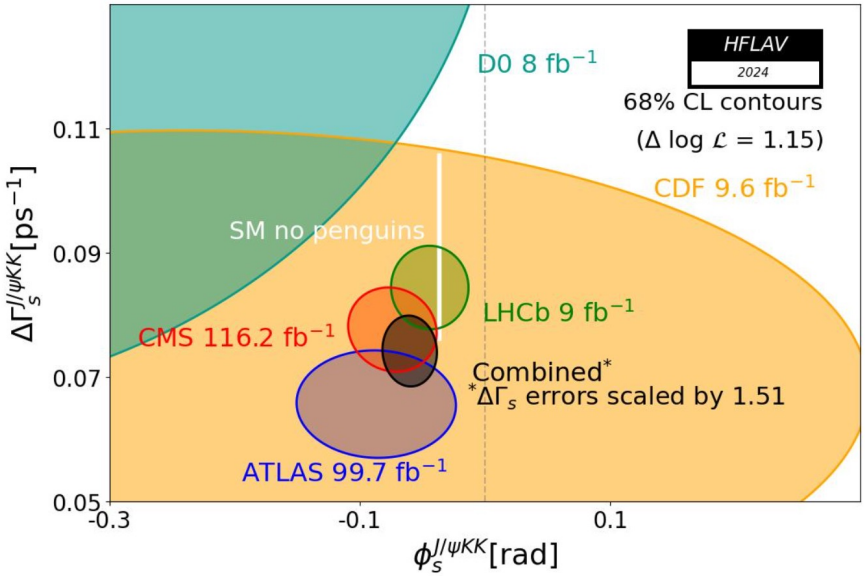
Latest combined results

$\phi_s^{c\bar{c}s} = -52 \pm 13$ mrad

$\phi_s^{J/\psi\phi} = -60 \pm 14$ mrad

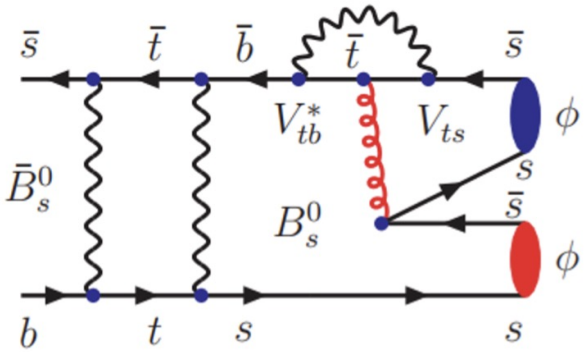
$\Longrightarrow$ 1st evidence for CPV

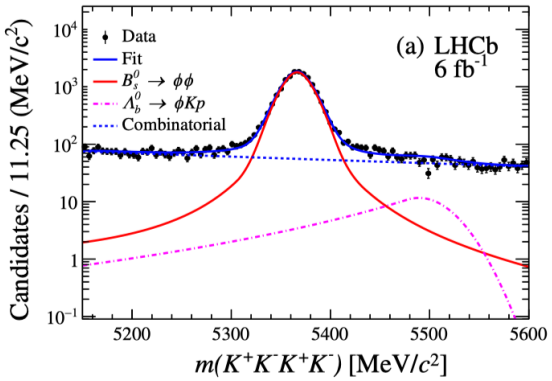


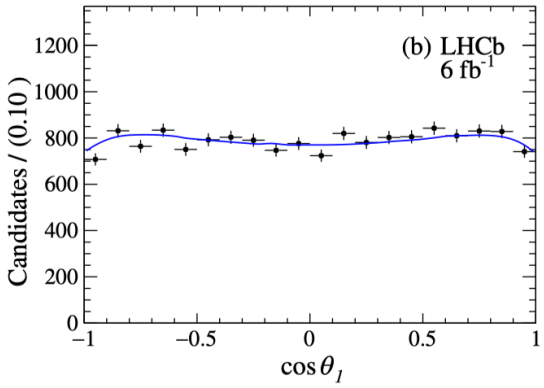


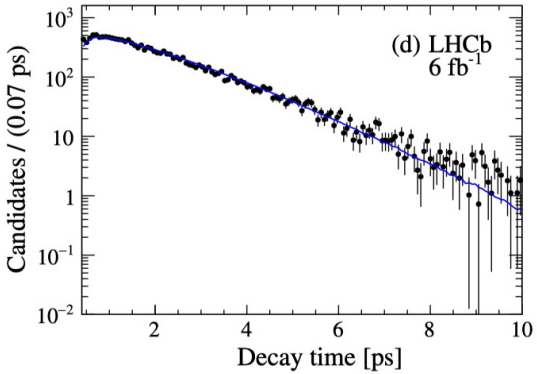
Measurement of ϕ_s in $B_s^0 \to \phi\phi$ decay

- ϕ_s in $B_s^0 \to \phi(K^+K^-)\phi(K^+K^-)$ decay
  - penguin-dominated decay via $b \longrightarrow s\bar{s}s$
  - close to zero due to a cancellation of mixing and decay weak phases
  - sensitive probe to NP in mixing and decay









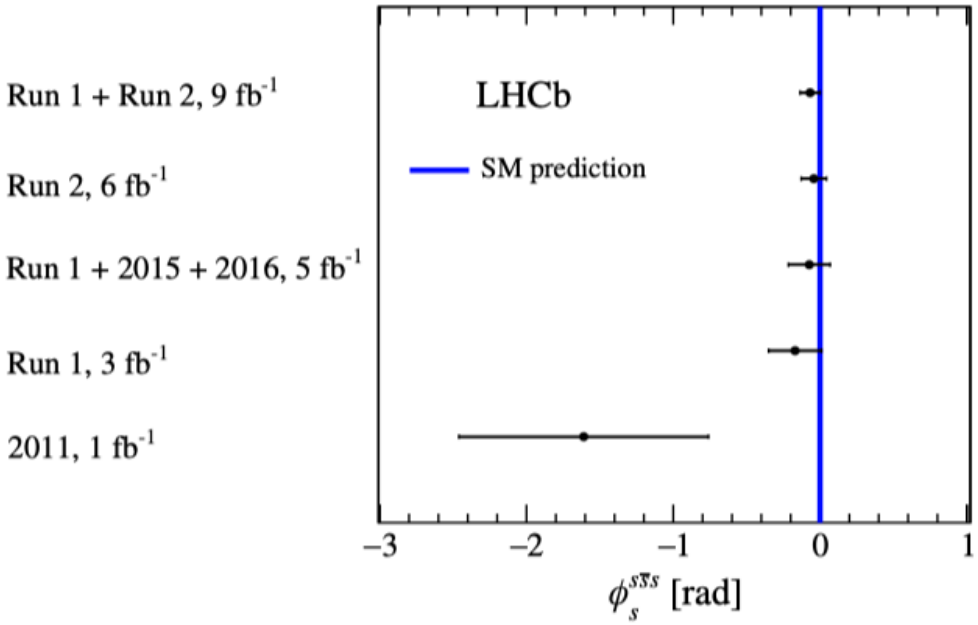
Measurement of ϕ_s in $B_s^0 \to \phi\phi$ decay

Measured results

$\phi_s^{s\bar{s}s} = -42 \pm 75 \pm 9$ mrad (Run 2)

$\phi_s^{s\bar{s}s} = -74 \pm 69$ mrad (Run 1+2)

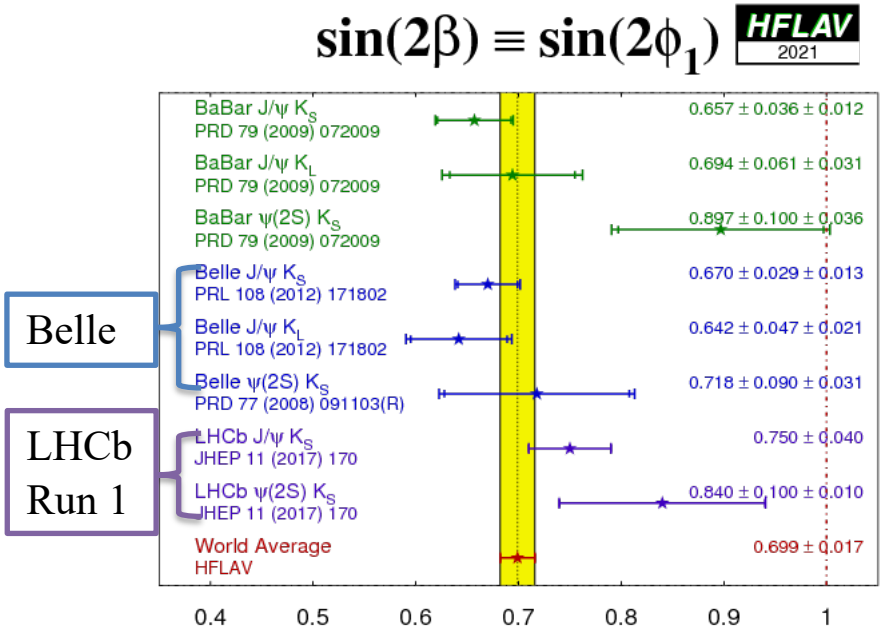
- consistent with SM, no CPV observed
- most precise measurement



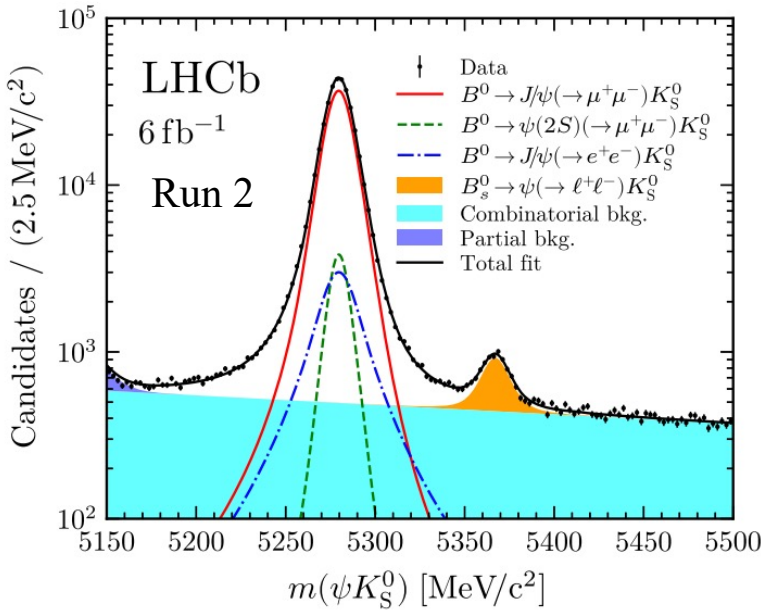
Measurement of $\sin 2\beta$ in $B^0 \to \psi K_S^0$ decays

- $\sin 2\beta$ in $B^0 \to \psi K_S^0(\pi^+\pi^-)$ decay
  - precise prediction $\sin 2\beta^{\text{tree}} = 0.7155^{+0.0079}_{-0.0071}$ [CKM fitter]
  - golden channel to measure $\sin 2\beta = \sin(2\beta^{\text{tree}} + \Delta\phi_d^{\text{penguin}} + \Delta\phi_d^{\text{NP}})$
  - previous average $\sin 2\beta = 0.699 \pm 0.017$ [HFLAV 2021]

Dominated by Belle



Update with 3 channels



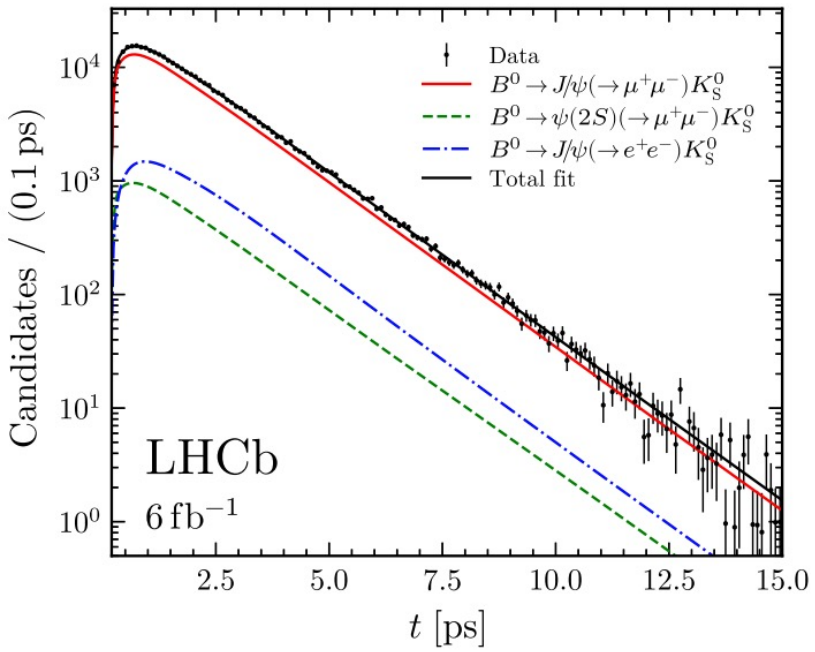
Measurement of $\sin 2\beta$ in $B^0 \to \psi K_S^0$ decays

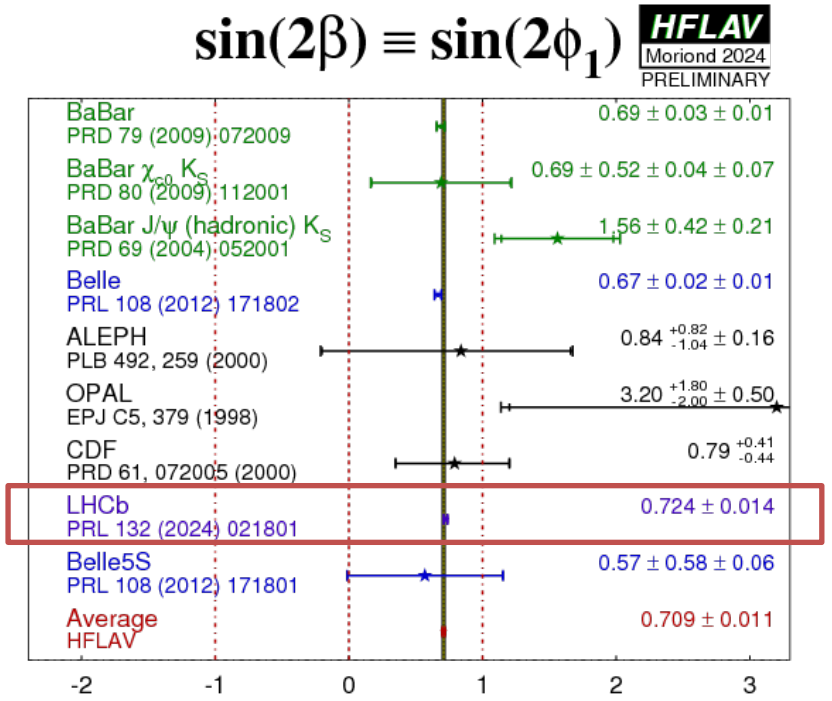
Perform a time-dependent analysis

$\sin 2\beta = 0.717 \pm 0.013 \pm 0.008$ (Run 2)

$\sin 2\beta = 0.724 \pm 0.014$ (Run 1+2)

- consistent with SM
- 1st time to dominate this measurement





Summary

- **LHCb performed CPV studies in *B* decays with full Run 2 data, giving the most precise measurements:**
  - ✓ A^{CP} in $B^+ \to J/\psi\pi^+$ decay, 1st evidence
  - ✓ ϕ_s in $B_s^0 \to J/\psi\phi$ and $B_s^0 \to \phi\phi$ decays
  - ✓ $\sin 2\beta$ in $B^0 \to \psi K_S^0$ decays, 1st time to dominate

- **Prospects for Run 3 (2024-2026) :**
  - ✓ chance to observe CPV in $B^+ \to J/\psi\pi^+$ decay
  - ✓ chance to see an evidence for ϕ_s @ LHCb
  - ✓ chance to observe CPV for ϕ_s @ LHC

Backup

Controlling the penguin effects

- $\sigma(\phi_s) \sim 0.016$ comparable with the estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$
  $\rightarrow$ Better control of penguin effect necessary!
- Combined analysis of penguin contributions in ϕ_s and ϕ_d, using SU(3) flavor symmetry J.Phys.G 48 (2021) 6, 065002
- More experimental measurements come soon!

$$\phi_d = \sin(2\beta^{\text{tree}}) + \Delta\phi_d^{\text{penguin}} + \phi_d^{\text{NP}}$$
$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$