Recent results on CPV from b-hadron to charmonium decays at LHCb

LHCb实验底强子到粲偶素衰变的CP破坏

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Outline

- Introduction
  - The CKM Matrix
  - Penguin pollution
  - Constraining penguin using $b \to c\bar{c}d$
- Branching fraction: $B^0 \to J/\psi\pi^0$ [JHEP 05 (2024) 065]
- CPV and branching fraction: $B_s^0 \to J/\psi\overline{K}^*(892)^0$ [arXiv: 2506.22090, JHEP10(2025)173]
- **Evidence of direct CPV**: $B^+ \to J/\psi\pi^+$ [PRL 134, 101801 (2025)]
- **Evidence of direct CPV**: $\Lambda_b^0 \to J/\psi p\pi^-$ [arXiv: 2509.16103]

CKM Matrix

- The transformation between mass & weak-interaction eigenstates:

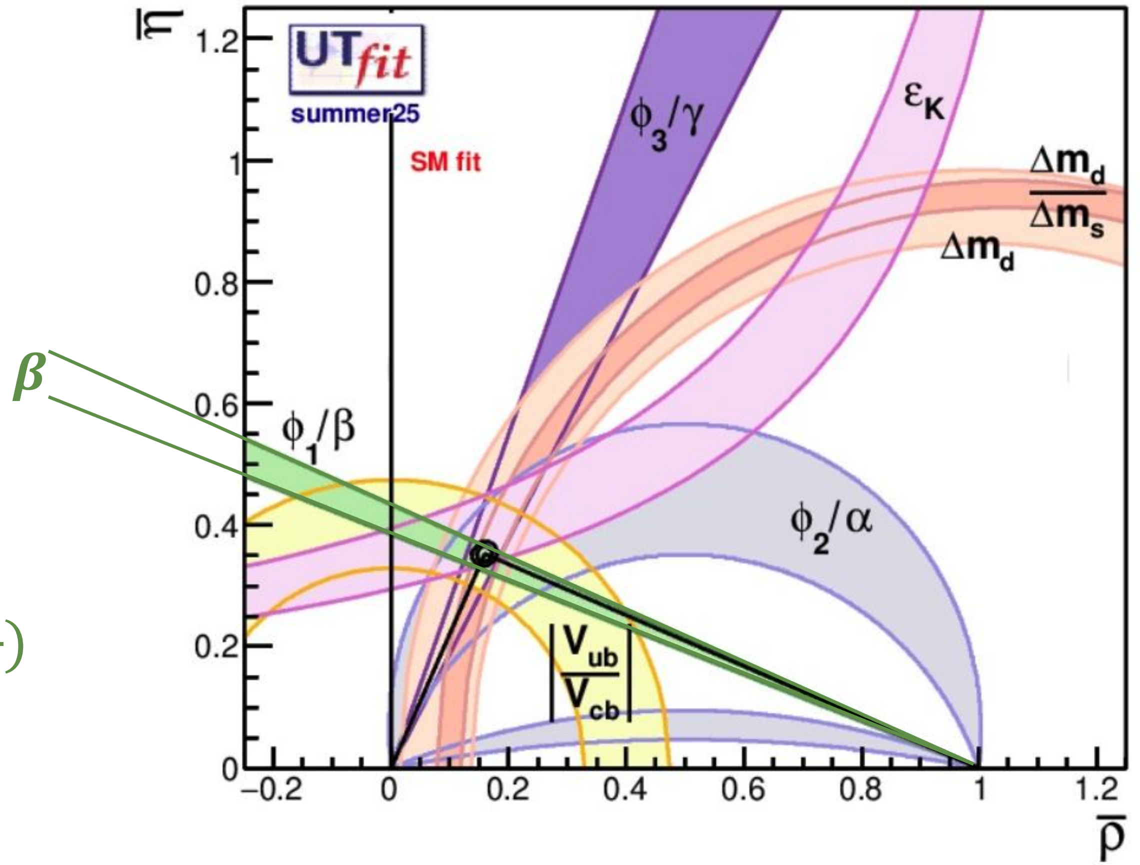
$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_{Li}} \gamma^\mu (V_{\mathrm{CKM}})_{ij} d_{Lj} W^+_\mu + \mathrm{h.c.}$$

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

- Unitary triangle angles:

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

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



Precision test of the Standard Model: CKM angle β

- Measure β using B_d^0 decays to CP eigenstates with $b \to c\bar{c}s$ quark transition
  - Benchmark channel: $B^0 \to J/\psi K^0$
  - Amplitude: $A(B_d^0 \to f) = A_{tree} + A_{penguin} \equiv A_{tree} \times (1 - b_f e^{i\rho_f} e^{i\gamma})$
- When measuring the time-dependent CP asymmetry:

$$\mathcal{A}_{CP}(t) \equiv \frac{|A(B_d^0(t) \to f)|^2 - |A(\overline{B}_d^0(t) \to f)|^2}{|A(B_d^0(t) \to f)|^2 + |A(\overline{B}_d^0(t) \to f)|^2}$$

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

- Assuming no penguin contribution: $b_f = 0 \quad \Rightarrow \quad \mathcal{A}_{CP}^{mix} = \eta_f \sin(2\beta + \phi^{NP})$

($\eta_f = \pm 1$, CP eigenvalue)

- Penguin pollution: $b_f \neq 0 \quad \Rightarrow \mathcal{A}_{CP}^{mix} = \eta_f \sin(2\beta + \phi^{NP} + \Delta\phi_f)$
- **The penguin contribution b_f is hard to calculate theoretically!**

Needs experimental methods

Enhanced penguin diagram in $b \to c\bar{c}d$ processes

Wolfenstein parameter: $\lambda \sim 0.23$

$b \to c\bar{c}s$:

$$A_f \sim (V_{cs}^* V_{cb})T + (V_{us}^* V_{ub})P^u$$

$$A\lambda^2 \qquad (\rho - i\eta)A\lambda^4$$

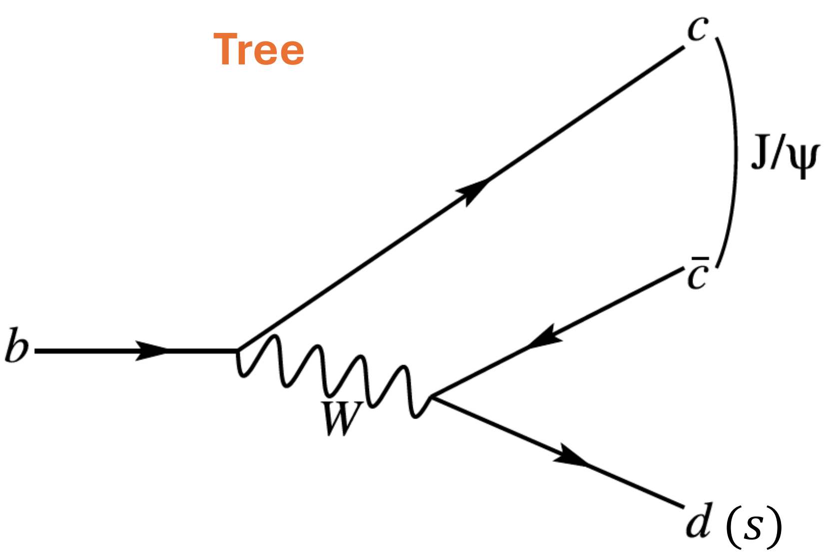
$b \to c\bar{c}d$:

$$A_f \sim (V_{cd}^* V_{cb})T + (V_{td}^* V_{tb})P^t$$

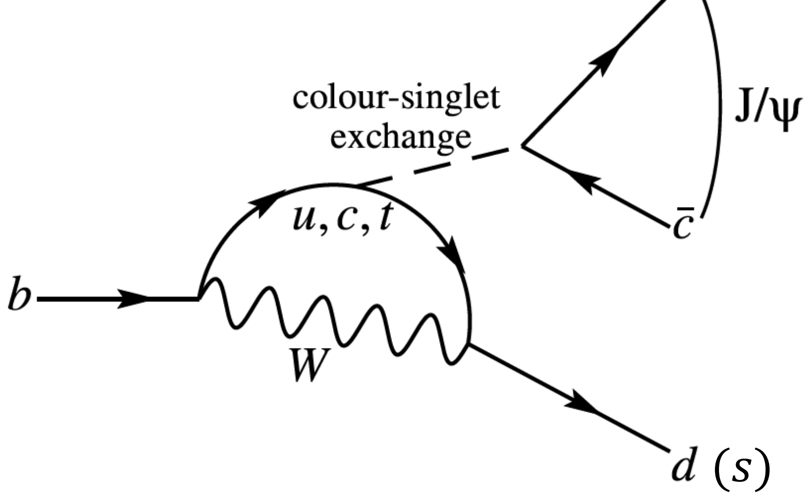
$$-A\lambda^3 \qquad (1 + \rho + i\eta)A\lambda^3$$

Enhanced penguin contribution!

Tree



Gluonic penguin



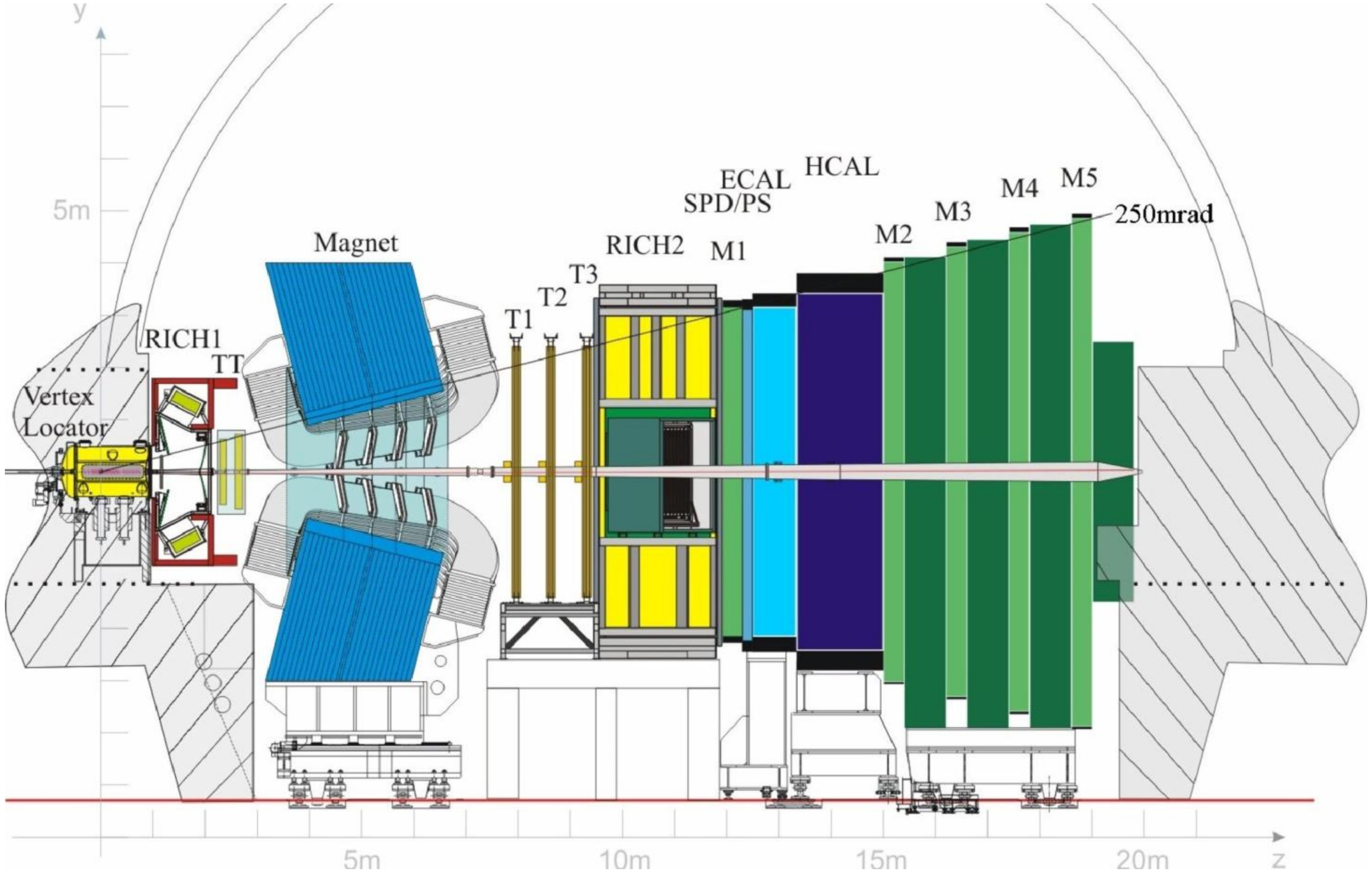
Two experimental observables in $\boldsymbol{b \to c\bar{c}d}$ to constrain penguin in $b \to c\bar{c}s$

- Branching fraction
- CP asymmetry from decay

$SU(3)$ symmetry assumed

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.



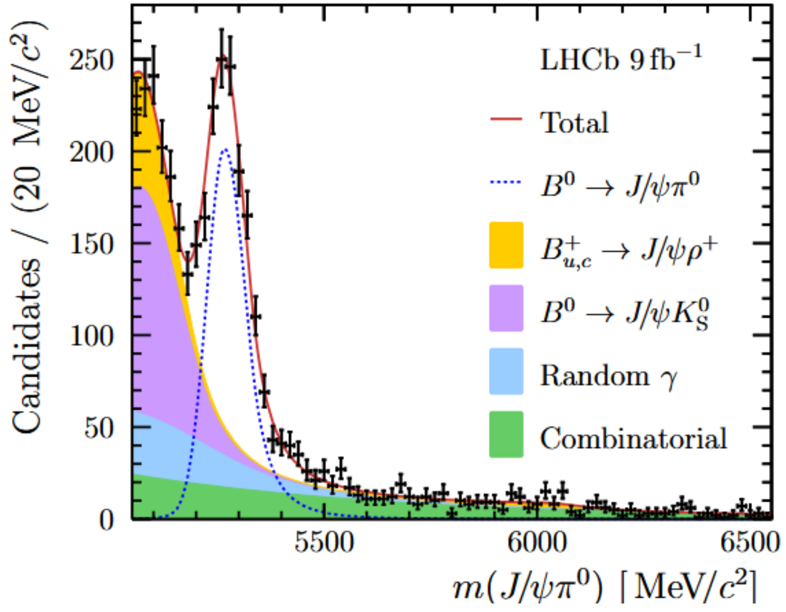
LHCb Detector in Run 2. [JINST 3 (2008) S08005, Int. J. Mod. Phys. A30, 1530022 (2015)]

Branching fraction of the $B^0 \to J/\psi\pi^0$ decays

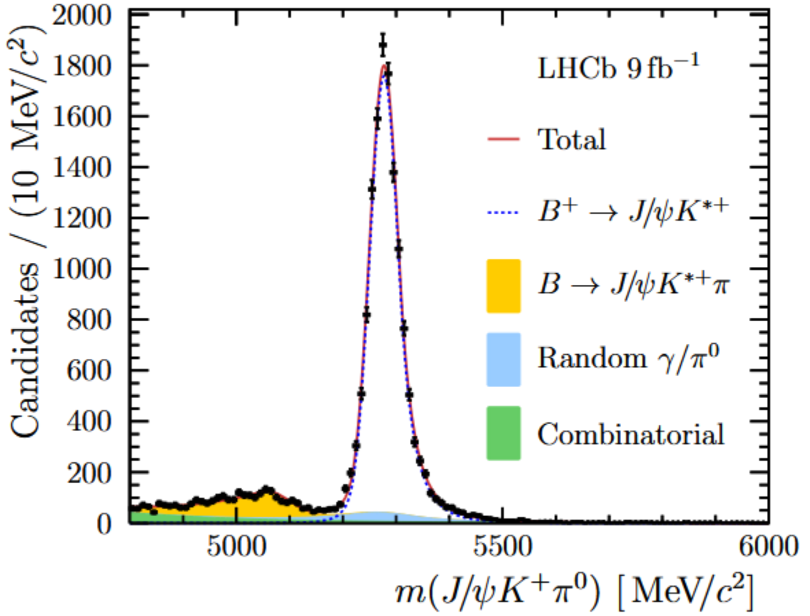
JHEP 05 (2024) 065

- LHCb Run1 (2011–12) + Run2 (2015–2018)

1232±55 $B^0 \to J/\psi\pi^0$ signal yields



13052±115 $B^+ \to J/\psi K^{*+}$ signal yields



- Results:

$$\mathcal{R} = \frac{N_{B^0\to J/\psi\pi^0}}{N_{B^+\to J/\psi K^{*+}}} \times \frac{\epsilon_{B^+\to J/\psi K^{*+}}}{\epsilon_{B^0\to J/\psi\pi^0}} \times \mathcal{B}_{K^{*+}\to K^+\pi^0}$$
$$= (1.153 \pm 0.053\ (\text{stat.}) \pm 0.048\ (\text{syst.})) \times 10^{-2}.$$

$$\mathcal{B}_{B^0\to J/\psi\pi^0} = (1.670 \pm \underbrace{0.077}_{\text{stat.}} \pm \underbrace{0.069}_{\text{sys.}} \pm \underbrace{0.095}_{\text{external}}) \times 10^{-5}$$

Total uncertainty: 0.14×10^{-5}

Competitive with the most precise single measurement!

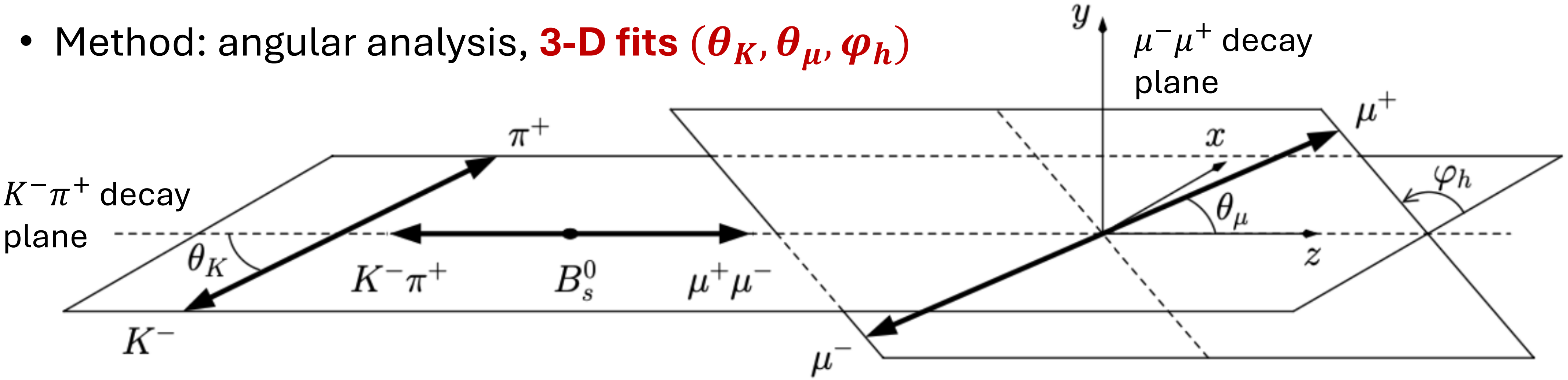
- Belle: $(1.62 \pm 0.13) \times 10^{-5}$
[Phys.Rev.D 98 (2018) 11, 112008]

Hopefully CP measurements in Run 3

CPV in the $B_s^0 \to J/\psi \overline{K}^*(892)^0(\to K^-\pi^+)$ decay

arXiv: 2506.22090
JHEP10(2025)173

- Dataset: LHCb Run-2 data
- Method: angular analysis, **3-D fits $(\theta_K, \theta_\mu, \varphi_h)$**



Angular distribution:

$$\mathrm{PDF}(\theta_K,\theta_\mu,\varphi_h) = \sum_{\alpha_\mu=\pm1} \left| \sum_{\lambda,J}^{|\lambda|<J} \sqrt{\frac{2J+1}{4\pi}} \mathcal{H}_\lambda^J e^{-i\lambda\varphi_h} d^1_{\lambda,\alpha_\mu}(\theta_\mu) d^1_{-\lambda,0}(\theta_K) \right|^2$$

Helicity $\lambda = 0, \pm1$ for $\overline{K}^{*0}$ or J/ψ

Angular momentum between $K^-\pi^+$: $L = 1$ (p-wave)

Amplitudes:

$$A_0 = \mathcal{H}_0^1,$$
$$A_\parallel = \frac{1}{\sqrt{2}}(\mathcal{H}_{+1}^1 + \mathcal{H}_{-1}^1),$$
$$A_\perp = \frac{1}{\sqrt{2}}(\mathcal{H}_{+1}^1 - \mathcal{H}_{-1}^1),$$
$$A_S = \mathcal{H}_0^0.$$

Integrate $|A|^2$ over phase-space to get widths Γ

$B_s^0 \to J/\psi \bar{K}^*(892)^0$: CPV observables

arXiv: 2506.22090
JHEP10(2025)173

- Observables:

$$\mathcal{A}_k^{CP} = \frac{\bar{\Gamma}_k - \Gamma_k}{\bar{\Gamma}_k + \Gamma_k}, \qquad k = 0, ||, \perp, S$$

- Results:

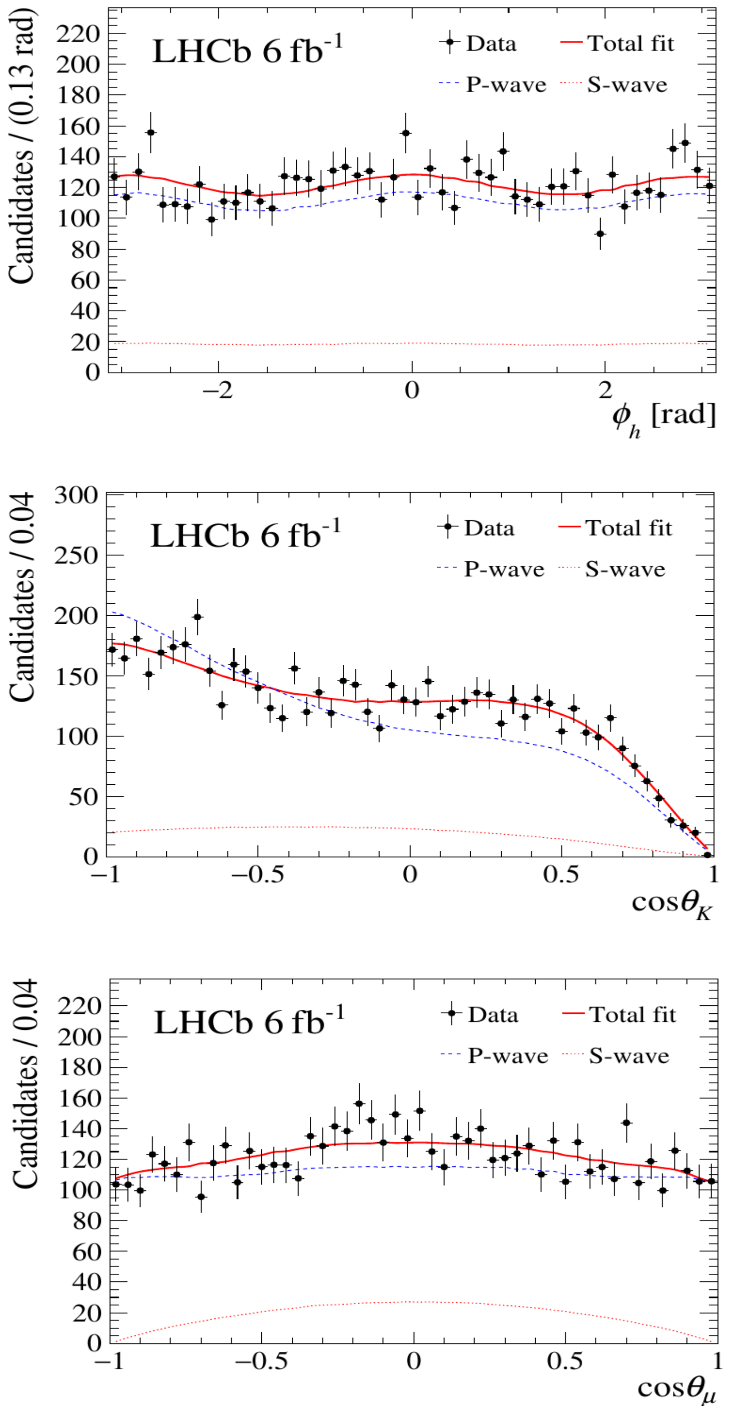
$$\mathcal{A}_0^{CP} = 0.014 \pm 0.029\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst}),$$
$$\mathcal{A}_{||}^{CP} = -0.055 \pm 0.065\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst}),$$
$$\mathcal{A}_{\perp}^{CP} = 0.060 \pm 0.057\,(\mathrm{stat}) \pm 0.016\,(\mathrm{syst}).$$

- After combination with LHCb Run-1 results:

JHEP 11 (2015) 082

$$\mathcal{A}_0^{CP} = 0.021 \pm 0.026\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst}),$$
$$\mathcal{A}_{||}^{CP} = -0.073 \pm 0.060\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst}),$$
$$\mathcal{A}_{\perp}^{CP} = 0.057 \pm 0.049\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst}).$$

No evidence of CP violation found



$B_s^0 \to J/\psi \bar{K}^*(892)^0$: Branching fraction

arXiv: 2506.22090
JHEP10(2025)173

$$\frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = \boxed{\frac{N_{B_s^0}}{N_{B^0}}} \times \boxed{\frac{\varepsilon'_{B^0}}{\varepsilon'_{B_s^0}}} \times \boxed{\frac{\zeta_{B^0}}{\zeta_{B_s^0}}} \times \boxed{\frac{f_d}{f_s}},$$

N – Signal yield
ε' – detection efficiency obtained from simulation
ζ – correction from data & simulation discrepancy and angular fraction
f – fragmentation fraction

- Results: $$\frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = (3.08 \pm 0.11\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.10\,(\frac{f_d}{f_s}))\%.$$

$$\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0}) = \frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} \times C \times \mathcal{B}(B^0 \to J/\psi K^{*0})_{\text{Belle}}$$
$$= (4.07 \pm 0.15\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.13\,(\frac{f_d}{f_s}) \pm 0.45\,(\mathcal{B}_{B^0})) \times 10^{-5}.$$

Correction to Belle result:
$C = 1.026 \pm 0.016$

- After combination with LHCb Run-1 result: *(JHEP 11 (2015) 082)*

$$\frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = (3.12 \pm 0.09\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.10\,(\frac{f_d}{f_s}))\%.$$

$$\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0}) = (4.13 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.14\,(\frac{f_d}{f_s}) \pm 0.45\,(\mathcal{B}_{B^0})) \times 10^{-5}.$$

With the best precision!

LHCb Run 1: $$\frac{\mathcal{B}(B_s^0 \to J/\psi \bar{K}^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = (2.99 \pm 0.25) \times 10^{-5}$$

CP asymmetry difference of $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ decays

PRL 134, 101801 (2025)

- LHCb Run2 data
- $\Delta\mathcal{A}_{CP} = \Delta\mathcal{A}_{\text{raw}} - \Delta\mathcal{A}_{det} - \Delta\mathcal{A}_{PID}$
- $\Delta\mathcal{A}_{\text{raw}} = \mathcal{A}_{\text{raw}}(B^+ \to J/\psi\pi^+) - \mathcal{A}_{\text{raw}}(B^+ \to J/\psi K^+)$

$$\Delta\mathcal{A}^{CP} = \begin{cases} (1.43 \pm 0.87 \pm 0.09) \times 10^{-2} & (2016), \\ (0.81 \pm 0.87 \pm 0.11) \times 10^{-2} & (2017), \\ (1.58 \pm 0.80 \pm 0.11) \times 10^{-2} & (2018), \end{cases}$$

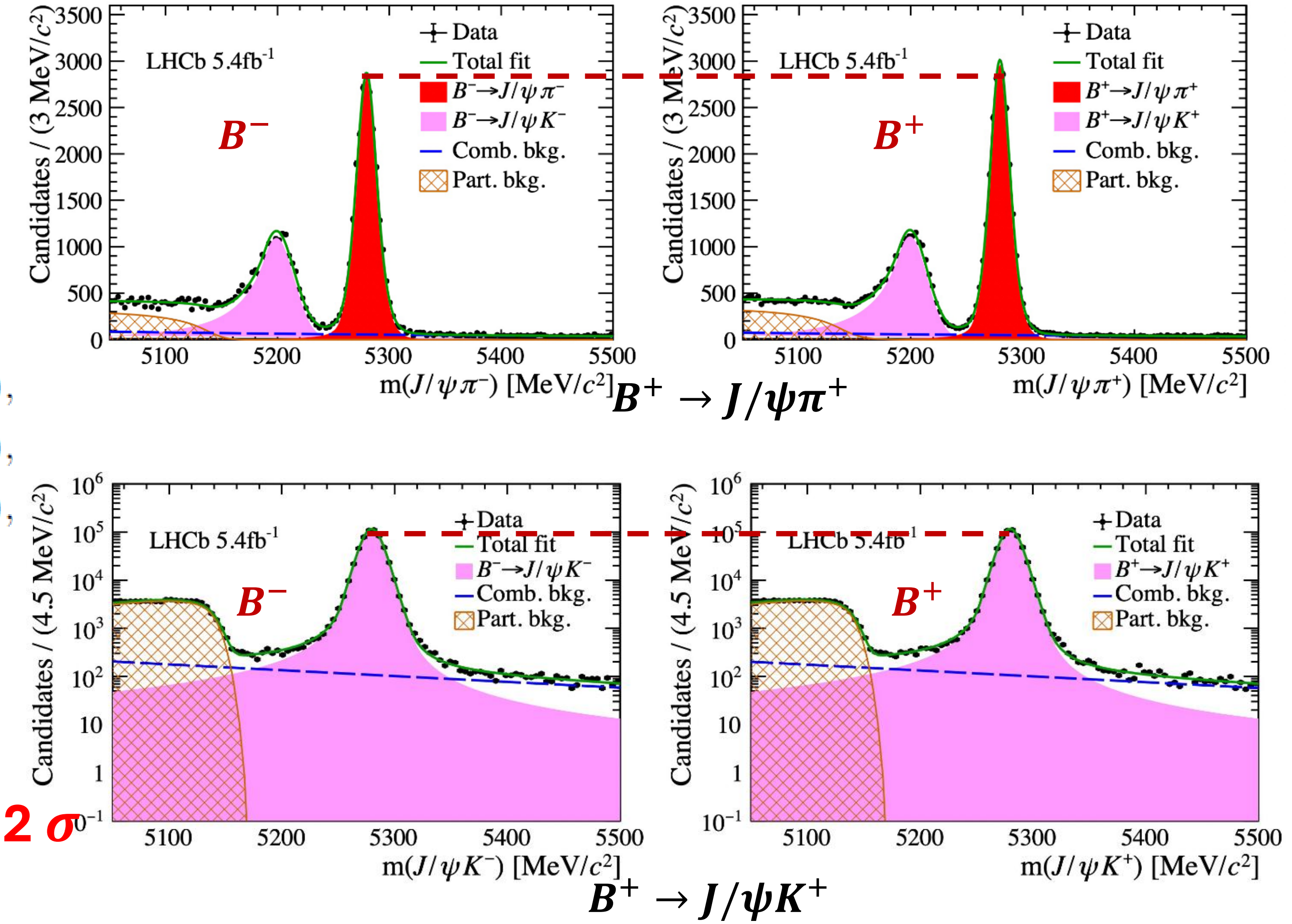
- Run-2 result:

$$\Delta\mathcal{A}_{\text{CP}} = (1.29 \pm 0.49 \pm 0.08)\%$$

Combined with Run 1:

$$\boldsymbol{\Delta\mathcal{A}_{CP} = (1.42 \pm 0.43 \pm 0.08)\%}$$ **3.2 σ**

First evidence of CP violation in B hadron to charmonium decays!



Branching fraction ratio

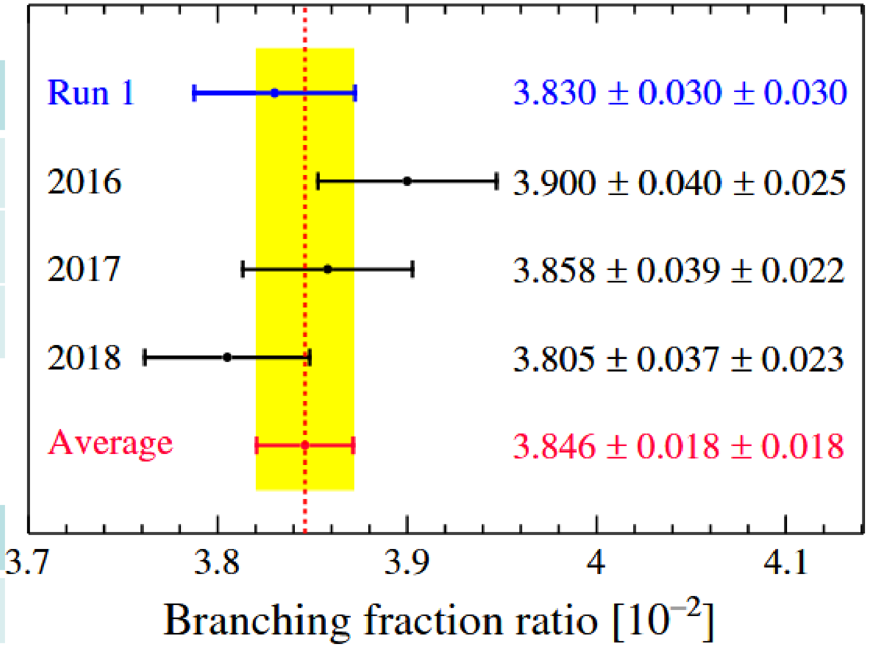
PRL 134, 101801 (2025)

- Signal Yields:

	2016	2017	2018
N_π	15500 ± 140	15140 ± 140	18130 ± 150
N_K	371700 ± 600	367300 ± 600	454100 ± 700
N_π/N_K (%)	4.170 ± 0.038	4.121 ± 0.039	3.993 ± 0.034

- Efficiencies:

	2016	2017	2018
ϵ_π/ϵ_K	0.935 ± 0.004	0.936 ± 0.004	0.953 ± 0.005



$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N_\pi}{N_K} \times \frac{\epsilon_K}{\epsilon_\pi} = (3.852 \pm 0.022 \pm 0.018) \times 10^{-2}$$

Combined with Run 1: $\mathcal{R}_{\pi/K} = \ (\mathbf{3.846} \ \pm \ \mathbf{0.018} \ \pm \ \mathbf{0.018}) \times \mathbf{10^{-2}}$

Important for constraining penguin contribution in $b \to c\bar{c}s$ processes!

Constraints to penguin parameters a and θ

PRL 134, 101801 (2025), supplementary

- Decay amplitudes: $\frac{\text{penguin}}{\text{tree}} \equiv -b_f e^{i\rho_f} e^{i\gamma}$, $= a e^{i\theta} e^{i\gamma}\ (b \to c\bar{c}d)$; $= \epsilon a' e^{i\theta'} e^{i\gamma}\ (b \to c\bar{c}s)$

$$A(B^+ \to J/\psi \pi^+) = -\lambda A_{tree}(1 + a e^{i\theta} e^{i\gamma}),\ A(B^+ \to J/\psi K^+) = \left(1 - \frac{\lambda^2}{2}\right) A'_{tree}(1 + \epsilon a' e^{i\theta'} e^{i\gamma})$$

  - Assuming SU(3) symmetry: $a = a', \theta = \theta'$ $\quad \lambda \sim 0.23,\ \epsilon \equiv \frac{\lambda^2}{1-\lambda^2} = 0.056$

68% CL:

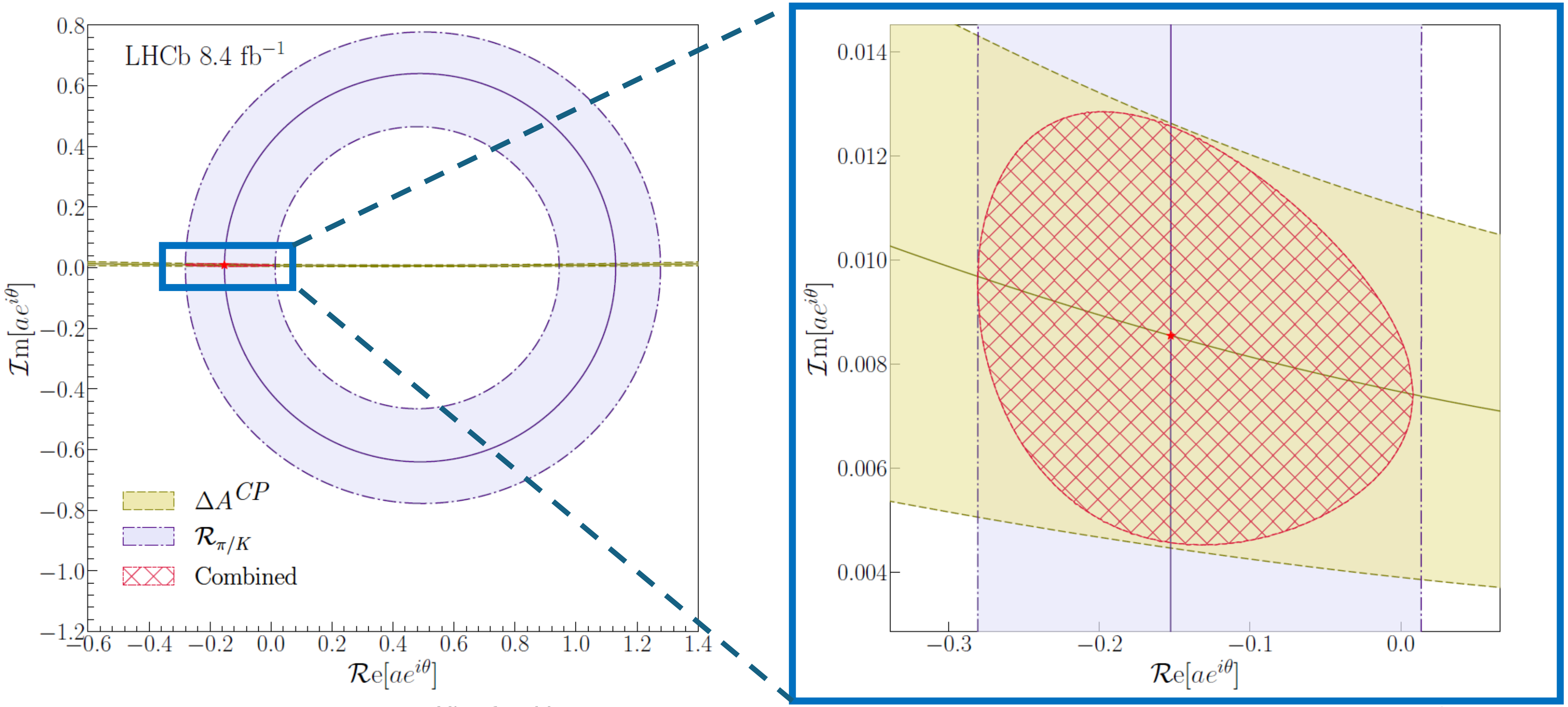
External results:

$$\frac{A'_{tree}}{A_{tree}} = 1.32 \pm 0.07$$

(*J. Phys. G:* **48 (2021)** 065002)

$\gamma = (64.6 \pm 2.8)^\circ$

(LHCb-CONF-2024-004)

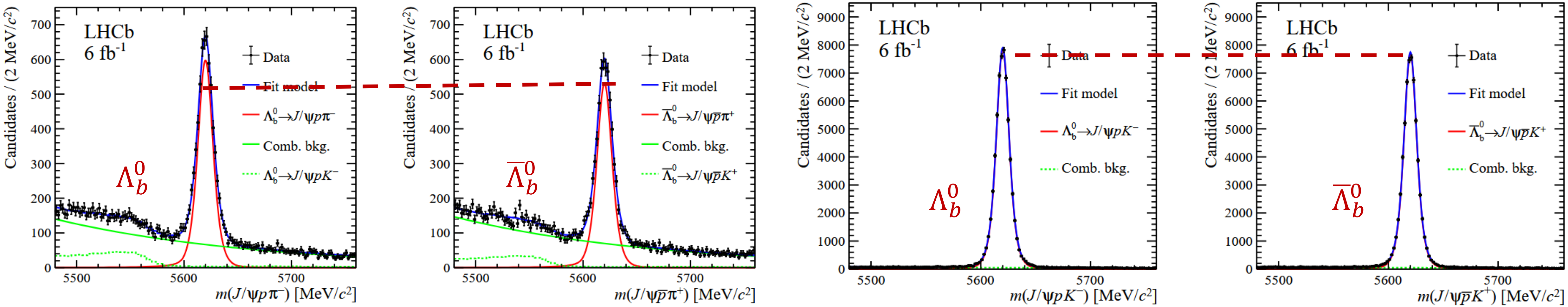


CPV difference in $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays

arXiv: 2509.16103
Submitted to Sci. Bull.

[New!]

- Measurement of the CP asymmetry difference $\Delta\mathcal{A}_{CP}$
  - $\Delta\mathcal{A}_{CP} = \mathcal{A}_{\text{raw}}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{\text{raw}}\left(\Lambda_b^0 \to J/\psi pK^-\right) + A_{\text{D}}(K^-) - A_D(\pi^-)$
  - LHCb Run2:



(10853 ± 134) yields
$\mathcal{A}_{raw}(\Lambda_b^0 \to J/\psi p\pi^-) = (5.94\ \pm\ 1.14)$ %

(125380 ± 372) yields
$\mathcal{A}_{raw}(\Lambda_b^0 \to J/\psi pK^-) = (0.98\ \pm 0.30)$ %

  - $\Delta\mathcal{A}_{CP} = (4.03 \pm 1.18(\text{stat.}) \pm 0.23(\text{sys.}))\%$ **3.3 σ**
  - Combined with Run 1: $\Delta\mathcal{A}_{CP} = (4.31 \pm 1.06 \pm 0.28)\%$ **3.9 σ**

First evidence of CP violation in b baryon to charmonium decays!

Run 1 results: ***JHEP 07 (2014) 103***
$\Delta\mathcal{A}_{CP} = (5.7 \pm 2.4 \pm 1.2)\%$
$\mathcal{R}_{\pi/K} = (8.24 \pm 0.25 \pm 0.42) \times 10^{-2}$

Triple-product asymmetry (TPA) of the $\Lambda_b^0 \to J/\psi p \pi^-$ decay

arXiv: 2509.16103
Submitted to Sci. Bull.

[New!]

- Triple product:

$$\Lambda_b^0: \quad C_T \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{\pi^-})$$
$$\overline{\Lambda}_b^0: \quad \bar{C}_T \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\bar{p}} \times \vec{p}_{\pi^+})$$

- Define an asymmetry

$$\mathcal{A}_{\hat{T}} \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

- Under CP: $C_T \to -\bar{C}_T,\ \mathcal{A}_{\hat{T}} \to \bar{\mathcal{A}}_{\hat{T}}$
- CP violation variable:

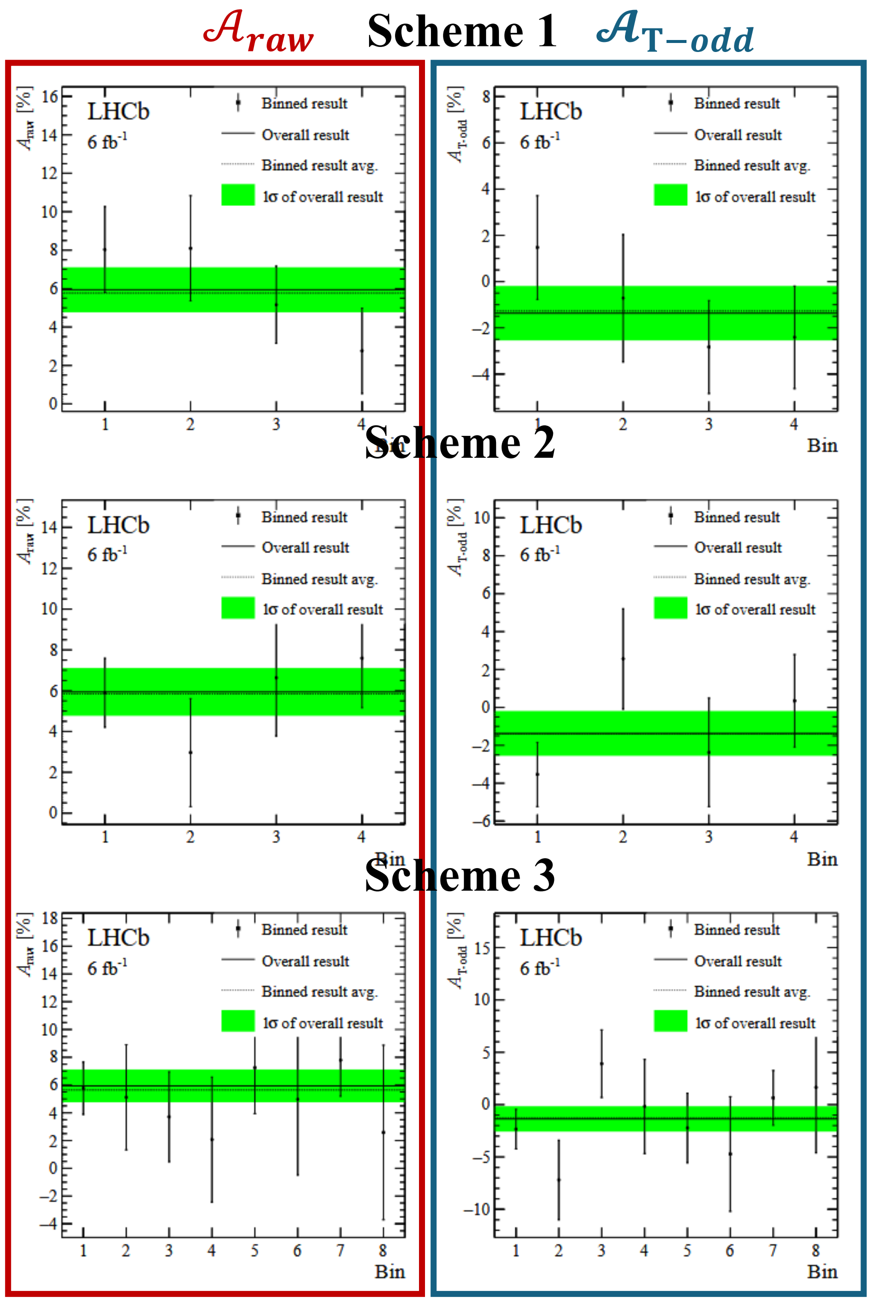
$$\mathcal{A}_{\mathrm{T-odd}} \equiv \frac{1}{2}(\mathcal{A}_{\hat{T}} - \bar{\mathcal{A}}_{\hat{T}})$$

$$\mathcal{A}_{\mathrm{T-odd}} = (-1.37 \pm 1.15 \pm 0.21)\ \%$$

(no evidence of TPA found)

Localised CP asymmetries

arXiv: 2509.16103
Submitted to Sci. Bull
[New!]

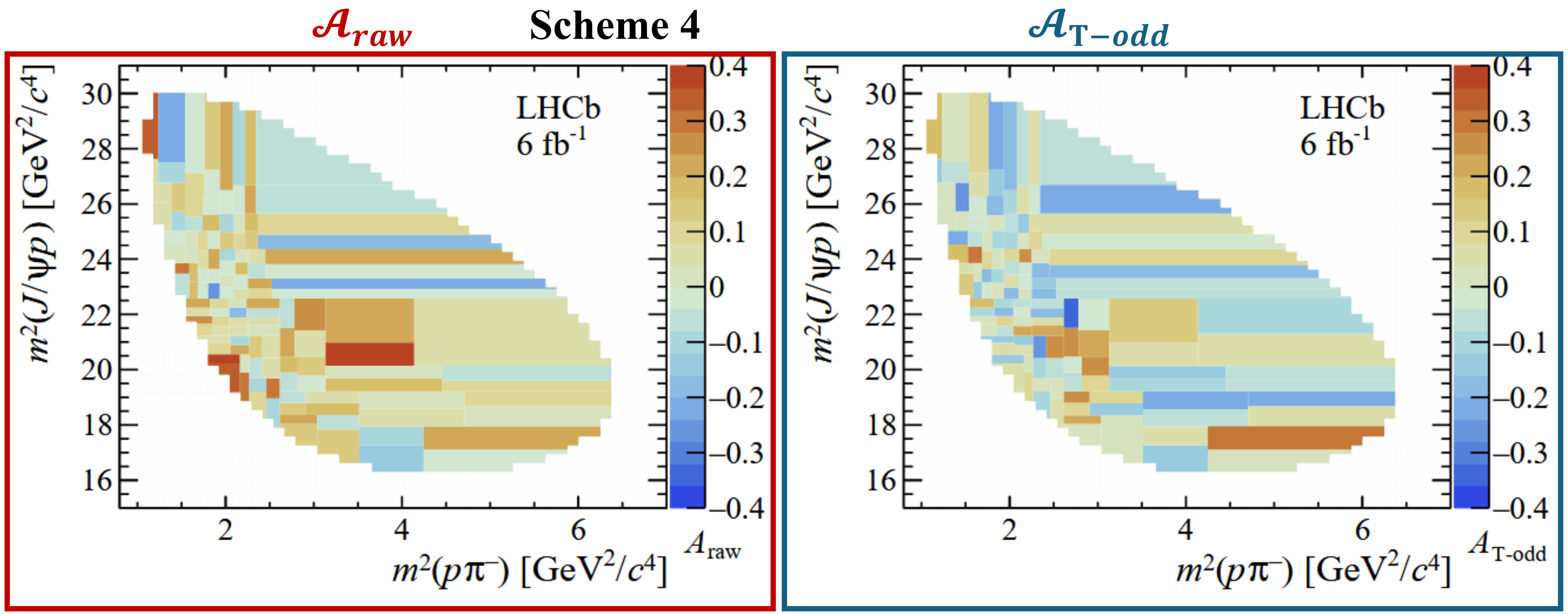


- Measurement of local CP asymmetry with **4 binning schemes**
  - 1: Split the $J/\psi p\pi^-$ data sample evenly in Dalitz-plot (4 bins)
  - 2: Split according to resonances in $M(p\pi^-)$ spectrum (4 bins)
  - 3: Split binning scheme 2 further, according to boosting angle $\theta_{p\pi}$ (8 bins)
  - 4: Split evenly into 128 bins
- Both raw asymmetry $\mathcal{A}_{raw}$ and triple-product asymmetry $\mathcal{A}_{\mathrm{T-odd}}$ are measured
- No significant variation of asymmetries across the phase space

Localised CP asymmetries – multiple bins in PHSP

arXiv: 2509.16103
Submitted to
Sci. Bull.

- Scheme 4: Split the phase space evenly into 128 bins (~90 candidates each bin)



- No significant variation of asymmetries across the phase space

Summary

- Conclusion
  - Branching fraction of $B^0 \to J/\psi\pi^0$: a first step towards its CPV analysis at LHCb
  - Branching fraction and CPV of $B_s^0 \to J/\psi\overline{K}^*(892)^0$: most precise values to date
  - Branching ratio and CPV of $B^+ \to J/\psi\pi^+$: first evidence of CPV, constraints to penguin parameters
  - CPV of $\Lambda_b^0 \to J/\psi p\pi^-$: first evidence of CPV
- Prospects
  - LHCb Run3 (started in 2023)
    - Higher integrated luminosity (25–30 fb^{-1}), significantly larger dataset
  - CP violation in pentaquarks?
    - Both statistical method and amplitude analysis can be used

Thanks for your attention!

BACKUPS

Wolfenstein parametrization

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

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} .$$

CKM angle gamma

arXiv:hep-ph/9903455
CERN-TH/99-78

- Take $B^0 \to J/\psi K^0$ as example ($b \to c\bar{c}s$):

$$A(B_d^0 \to J/\psi\, K_S) = \lambda_c^{(s)}\left(A_{cc}^{c'} + A_{pen}^{c'}\right) + \lambda_u^{(s)} A_{pen}^{u'} + \lambda_t^{(s)} A_{pen}^{t'}\,,$$

$$\lambda_q^{(s)} \equiv V_{qs}V_{qb}^* \tag{2}$$

are the usual CKM factors. Making use of the unitarity of the CKM matrix and applying the Wolfenstein parametrization [9], generalized to include non-leading terms in λ [10], we obtain

$$A(B_d^0 \to J/\psi\, K_S) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}'\left[1 + \left(\frac{\lambda^2}{1-\lambda^2}\right) a' e^{i\theta'} e^{i\gamma}\right], \tag{3}$$

where

$$\mathcal{A}' \equiv \lambda^2 A\left(A_{cc}^{c'} + A_{pen}^{ct'}\right), \tag{4}$$

with $A_{pen}^{ct'} \equiv A_{pen}^{c'} - A_{pen}^{t'}$, and

$$a' e^{i\theta'} \equiv R_b\left(1 - \frac{\lambda^2}{2}\right)\left(\frac{A_{pen}^{ut'}}{A_{cc}^{c'} + A_{pen}^{ct'}}\right). \tag{5}$$

- For $B_s^0 \to J/\psi \bar{K}^0$ ($b \to c\bar{c}d$):

$$A(B_s^0 \to J/\psi\, K_S) = -\lambda\,\mathcal{A}\left[1 - a\, e^{i\theta} e^{i\gamma}\right],$$

$$\mathcal{A} \equiv \lambda^2 A\left(A_{cc}^{c} + A_{pen}^{ct}\right)$$

$$a\, e^{i\theta} \equiv R_b\left(1 - \frac{\lambda^2}{2}\right)\left(\frac{A_{pen}^{ut}}{A_{cc}^{c} + A_{pen}^{ct}}\right)$$

- For $B^+ \to J/\psi \pi^+$ or $J/\psi K^+$:
  - $a = a',\ \theta = \theta'$
  - Normalization factors

$$\frac{\mathcal{A}'}{\mathcal{A}} = f_{B_d \to K}/f_{B_d \to \pi} = 1.32 \pm 0.07$$

Form factors:

$$f_{B_d\to\pi}^{+}(m_{J/\psi}^2) = 0.487 \pm 0.018\,,$$
$$f_{B_d\to K}^{+}(m_{J/\psi}^2) = 0.645 \pm 0.022\,,$$

Precision test of β_s

https://arxiv.org/pdf/2505.06102

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

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

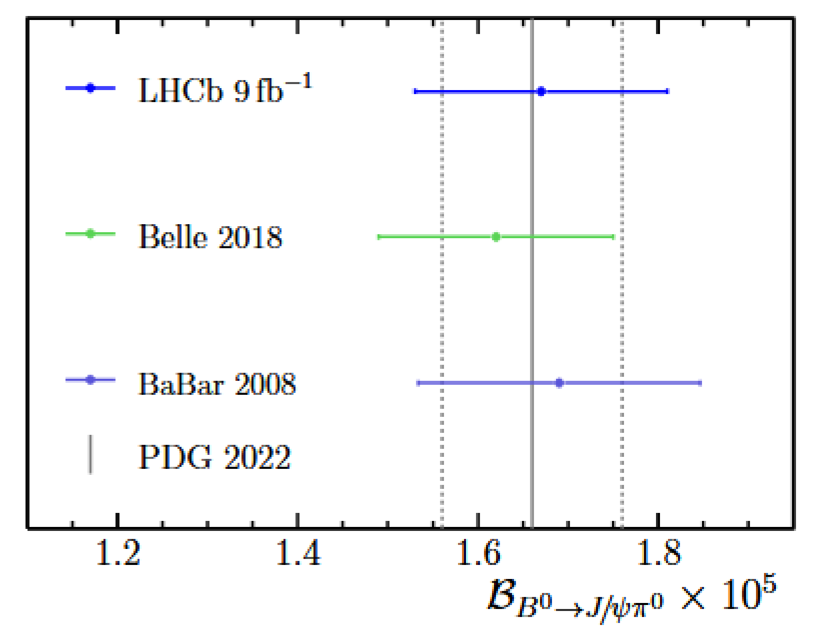
- When measuring the time-dependent CP asymmetry:

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

- 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!**

	$\sin 2\beta$	$\sin 2\beta_s$
Global fit result	$0.7155^{+0.0079}_{-0.0071}$ ***(CKMFitter)***	$0.03757^{+0.00057}_{-0.00054}$ ***(CKMFitter)***
Average from $\mathcal{A}_{CP}^{mix}$	0.699 ± 0.015 ***(UTfit 2025)***	0.052 ± 0.013 ***(HFLAV Winter 2024)***

B to Jpsi pi0



- Measurement by Belle, Babar, and global average

- Global fit of B+ -> Jpsi K*+

The current world-average for the normalisation branching fraction of $(1.43 \pm 0.08) \times 10^{-3}$ [12] includes seven measurements performed using K^{*+} candidates with a reconstructed mass within a $100\,\mathrm{MeV}/c^2$ mass window or smaller of the known K^{*+} mass [40–46]. The Belle analysis [42] is the only to measure the yield for resonant decays but estimates the contributions from nonresonant decays at the level of 5.2% in the K^* mass region. Including the nonresonant contributions, the uncertainty-weighted average of the normalisation branching fraction increases to

$$\mathcal{B}_{B^+ \to J/\psi K^{*+}} = (1.449 \pm 0.083) \times 10^{-3}.$$

Angular correction to $B_s^0 \to J/\psi \bar{K}^*(892)^0$

- Angular correlation factor

$$\zeta \equiv c_{\text{decay}} / F^{\text{P}}_{\text{decay}}$$

$$F^{\text{P}}_{\text{decay}} = \frac{\sum_{k=1}^{6} \xi_k a_k}{\sum_{k=1}^{10} \xi_k a_k C_k},$$

$$c_{\text{decay}} = \frac{\sum_{k=1}^{6} \xi_k a_k(\vec{A}_{\text{data}})}{\sum_{k=1}^{6} \xi_k a_k(\vec{A}_{\text{sim}})}.$$

$$\frac{\zeta_{B^0}}{\zeta_{B^0_s}} = 1.015 \pm 0.034\,(\text{stat}) \pm 0.017\,(\text{syst}).$$

acceptance correction $$\xi_k = \int \varepsilon(\Omega_{\text{hel}}) G_k(\Omega_{\text{hel}}) \text{d}\Omega_{\text{hel}}$$

Index k	Amplitude product a_k	Angular function $G_k(\Omega_{\text{hel}})$
1 (0)	$\lvert A_0\rvert^2$	$\frac{9}{16\pi}\cos^2\theta_K(1-\cos^2_{\theta_\mu})$
2 (∥)	$\lvert A_\parallel\rvert^2$	$\frac{9}{32\pi}(1-\cos^2\theta_K)(1-(1-\cos^2_{\theta_\mu})\cos^2\phi_h)$
3 (⊥)	$\lvert A_\perp\rvert^2$	$\frac{9}{32\pi}(1-\cos^2\theta_K)((1-\cos^2_{\theta_\mu})\cos^2\phi_h+\cos^2_{\theta_\mu})$
4	$\mathcal{Im}(A_\parallel^* A_\perp)$	$\frac{9}{16\pi}(1-\cos^2\theta_K)(1-\cos^2_{\theta_\mu})\sin(2\phi_h)$
5	$\mathcal{Re}(A_0^* A_\parallel)$	$\frac{9\sqrt{2}}{16\pi}\cos\theta_K\cos_{\theta_\mu}\sqrt{(1-\cos^2\theta_K)(1-\cos^2_{\theta_\mu})}\cos\phi_h$
6	$\mathcal{Im}(A_0^* A_\perp)$	$\frac{9\sqrt{2}}{16\pi}\cos\theta_K\cos_{\theta_\mu}\sqrt{(1-\cos^2\theta_K)(1-\cos^2_{\theta_\mu})}\sin\phi_h$
7 (S)	$\lvert A_S\rvert^2$	$\frac{3}{16\pi}(1-\cos^2_{\theta_\mu})$
8	$\mathcal{Re}(A_S^* A_\parallel)$	$\frac{3\sqrt{6}}{16\pi}\cos_{\theta_\mu}\sqrt{(1-\cos^2\theta_K)(1-\cos^2_{\theta_\mu})}\cos\phi_h$
9	$\mathcal{Im}(A_S^* A_\perp)$	$\frac{3\sqrt{6}}{16\pi}\cos_{\theta_\mu}\sqrt{(1-\cos^2\theta_K)(1-\cos^2_{\theta_\mu})}\sin\phi_h$
10	$\mathcal{Re}(A_S^* A_0)$	$\frac{3\sqrt{3}}{8\pi}\cos\theta_K(1-\cos^2_{\theta_\mu})$

P-wave

Index k	Amplitude product a_k	Normalised weight ξ_k/ξ_1
1	$\lvert A_0\rvert^2$	1
2	$\lvert A_\parallel\rvert^2$	1.4249 ± 0.0073
3	$\lvert A_\perp\rvert^2$	1.4489 ± 0.0074
4	$\lvert A_\parallel\rvert\lvert A_\perp\rvert\sin(\delta_\parallel-\delta_\perp)$	-0.0013 ± 0.0043
5	$\lvert A_0\rvert\lvert A_\parallel\rvert\cos(\delta_\parallel)$	-0.0189 ± 0.0029
6	$\lvert A_0\rvert\lvert A_\perp\rvert\sin(\delta_\perp)$	0.0027 ± 0.0028
7	$\lvert A_S\rvert^2$	1.2485 ± 0.0062
8	$\lvert A_S\rvert\lvert A_\parallel\rvert\cos(\delta_S-\delta_\parallel)$	-0.0412 ± 0.0040
9	$\lvert A_S\rvert\lvert A_\perp\rvert\sin(\delta_S-\delta_\perp)$	0.0072 ± 0.0040
10	$\lvert A_S\rvert\lvert A_0\rvert\cos(\delta_S)$	-0.6919 ± 0.0096

P-wave

$B_s^0 \to J/\psi \bar{K}^*(892)^0$: correction for Belle results

- Belle uses B mesons from $\Upsilon(4S) \to B^0\bar{B}^0$ to measure

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$$\mathcal{B}(B^0 \to J/\psi K^{*0})_{\text{Belle}} = (1.29 \pm 0.05\,(\text{stat}) \pm 0.13\,(\text{syst})) \times 10^{-3}.$$

- In that analysis, the production ratio $R^{+/0} \equiv \Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\bar{B}^0)$ was assumed to be 1.
- Measured ratio: $R^{+/0} = 1.052 \pm 0.031$
- Correction factor: $C = \left(1 + R^{+/0}\right)/2 = 1.026 \pm 0.016$

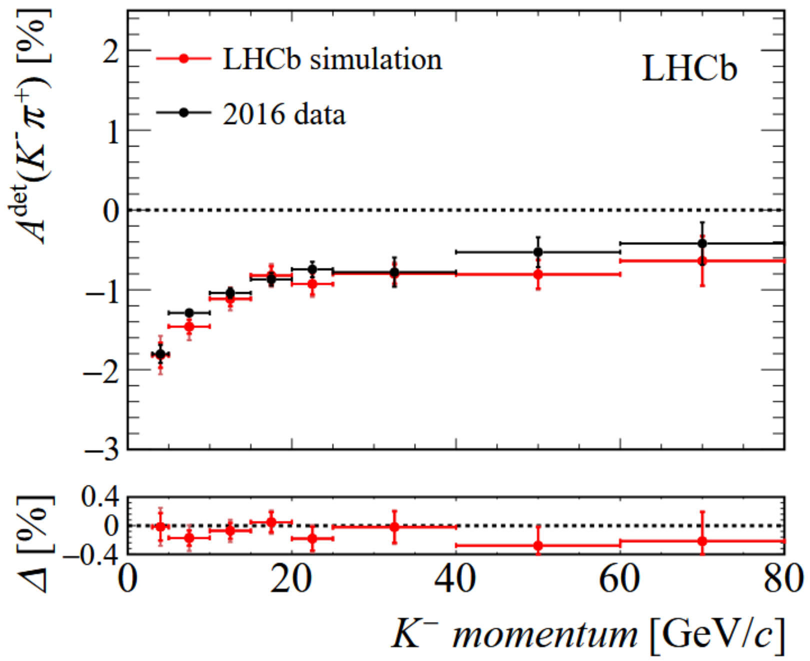
HFLAV 2023

Detection asymmetries

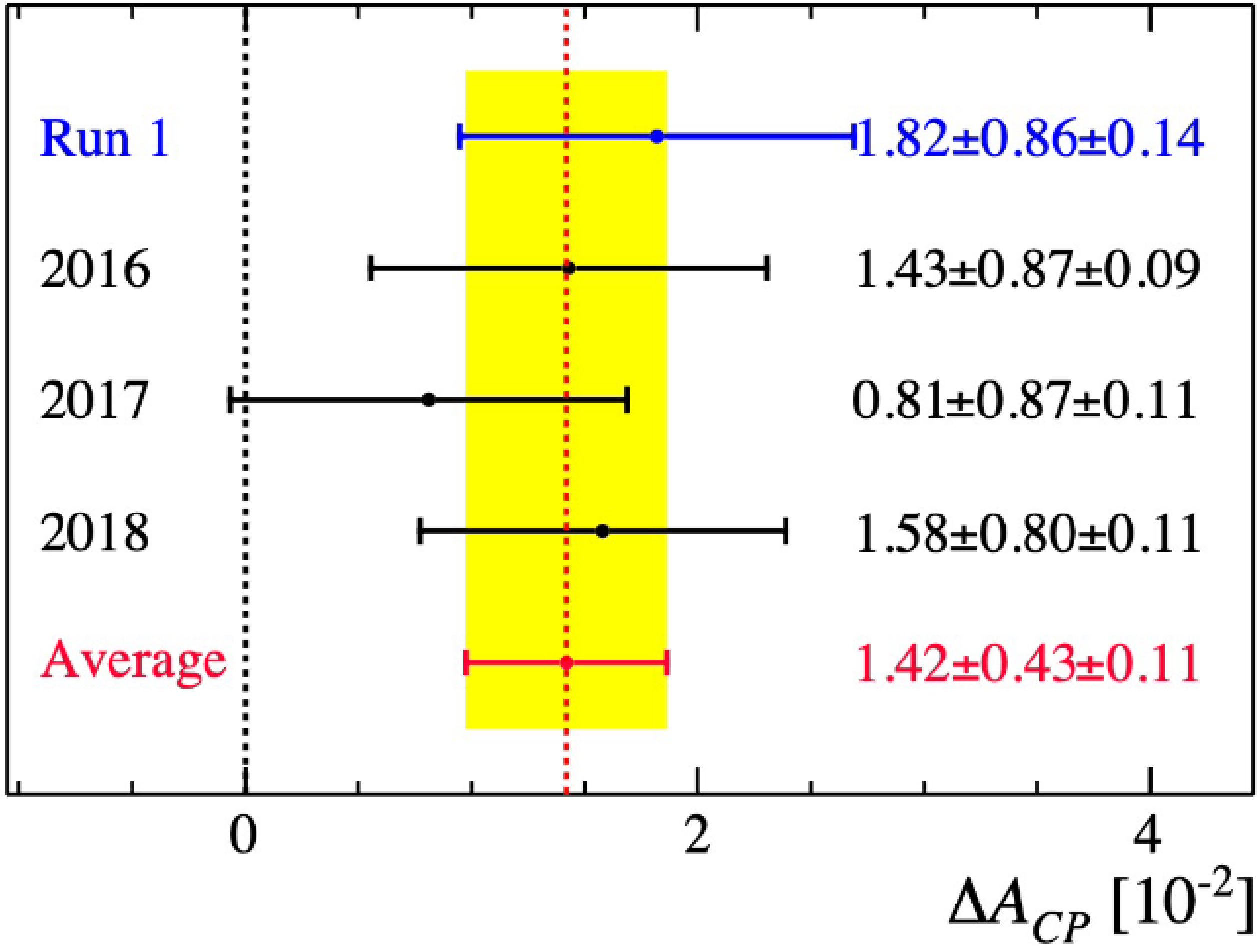
- Methods from LHCb-PUB-2018-004
- Using D meson decays

$$A^{\mathrm{det}}(K^-\pi^+) = A^{\mathrm{raw}}(D^+ \to K^-\pi^+\pi^+) - A^{\mathrm{raw}}(D^+ \to \overline{K}^0\pi^+) - A(K^0),$$

- Calibration dataset from LHCb during 2016–2018



$B^+ \to J/\psi\pi^+$: CP asymmetry of each year

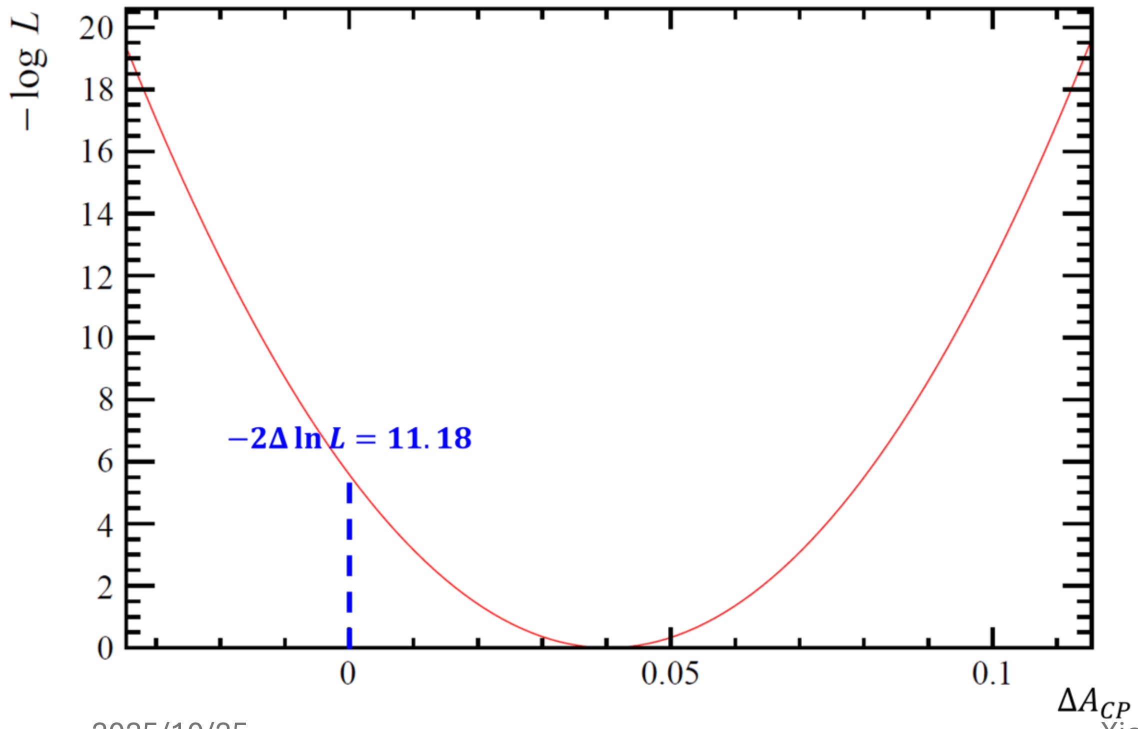


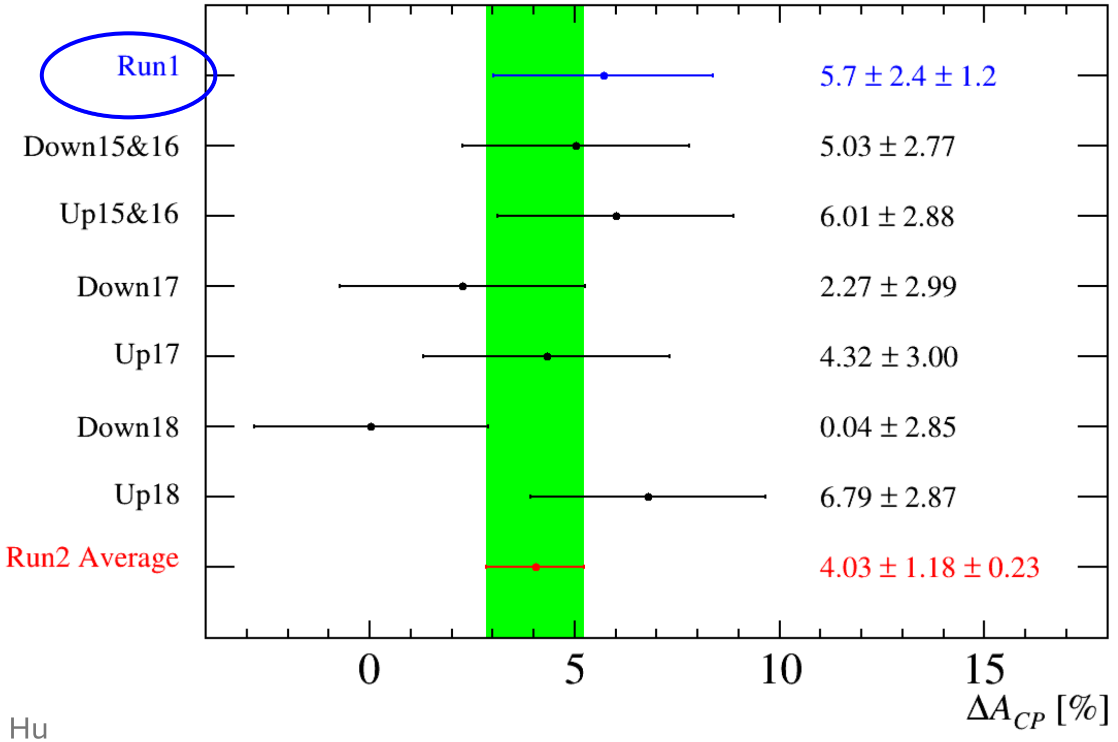
CPV difference in $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$

[LHCb-PAPER-2025-021], in preparation **[New!]**

- Significance level from Wilks's theorem: $\sqrt{-2\Delta\ln\mathcal{L}} = \mathbf{3.3\sigma}$
- Results in different years/polarities compatible with overall results, as well as run-1 result
- Combined with the LHCb Run1 results with the Best Linear Unbiased Estimate (BLUE) method
  - $\Delta\mathcal{A}_{CP} = (4.31 \pm 1.06 \pm 0.28)\%$ $\mathbf{3.9\sigma}$

First evidence of CP violation in b-baryon to charmonium decays!





Combination with Run-1 results

- Combination of $\Delta\mathcal{A}_{CP}$
- Run-1 result (JHEP 07 (2014) 103): **(5.7 ± 2.4 ± 1.2)%**
- Best Linear Unbiased Estimation (BLUE) method is used for sys. uncertainty

Source	Run 1 [%]	Run 2 [%]	Correlation assumption
Stat.	2.4	1.18	0%
signal shape	0.14	0.016	100%
comb. bkg	0.71	0.012	100%
Detection asymmetry	0.85	0.040	0%
Mis-id $J/\psi K^+\pi^-$ background	–	0.013	0%
Binding Λ_b^0 peak parameters	–	0.21	0%
Reweighting	–	0.017	0%
PID asymmetry	–	0.074	0%

Combined result: $\boldsymbol{\Delta\mathcal{A}_{CP}}$ **= (4.31 ± 1.06(stat.) ± 0.28(sys.))%** $\boldsymbol{3.9\,\sigma}$

The BLUE method

- Total result $\hat{a}$ and total variance $\hat{\sigma}^2$:

$$\hat{a} = \sum_{i}^{n} w_i a_i,$$

$$\hat{\sigma}^2 = \sum_{i,j}^{n} w_i V_{ij} w_j.$$

- The total **covariance matrix** is calculated as

$$V_{ij} = V_{ij}^{\mathrm{stat}} + V_{ij}^{u} + V_{ij}^{c}$$

- ▶ Diagonal: $V_{ii} = \sigma_{i,\mathrm{tot}}^2$
- ▶ Non-diagonal: $V_{ij} = V_{ji} = \rho_{ij}\sigma_{i,c}\sigma_{j,c}$ ($\rho \in [-1, 1]$ is the correlation coefficient)

- Weights:

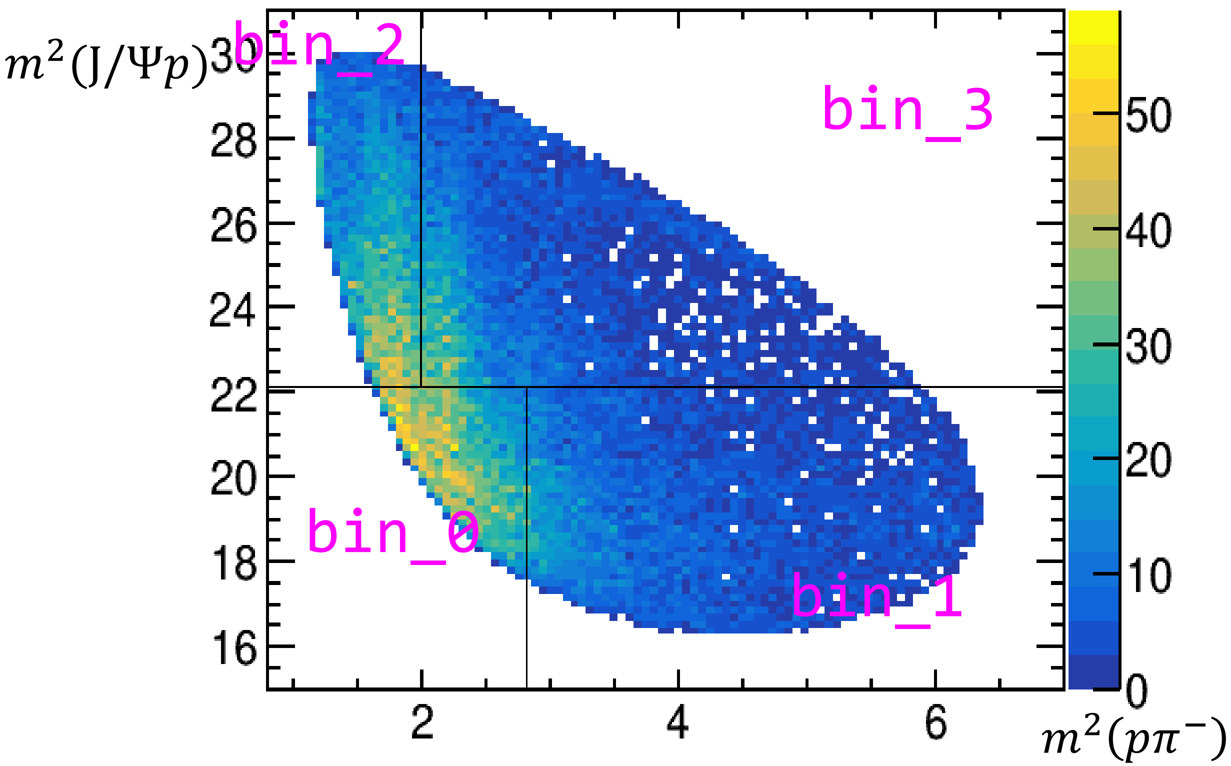
$$w_i = \frac{\sum_j (V^{-1})_{ij}}{\sum_{ij} (V^{-1})_{ij}}$$

Summary of combination:

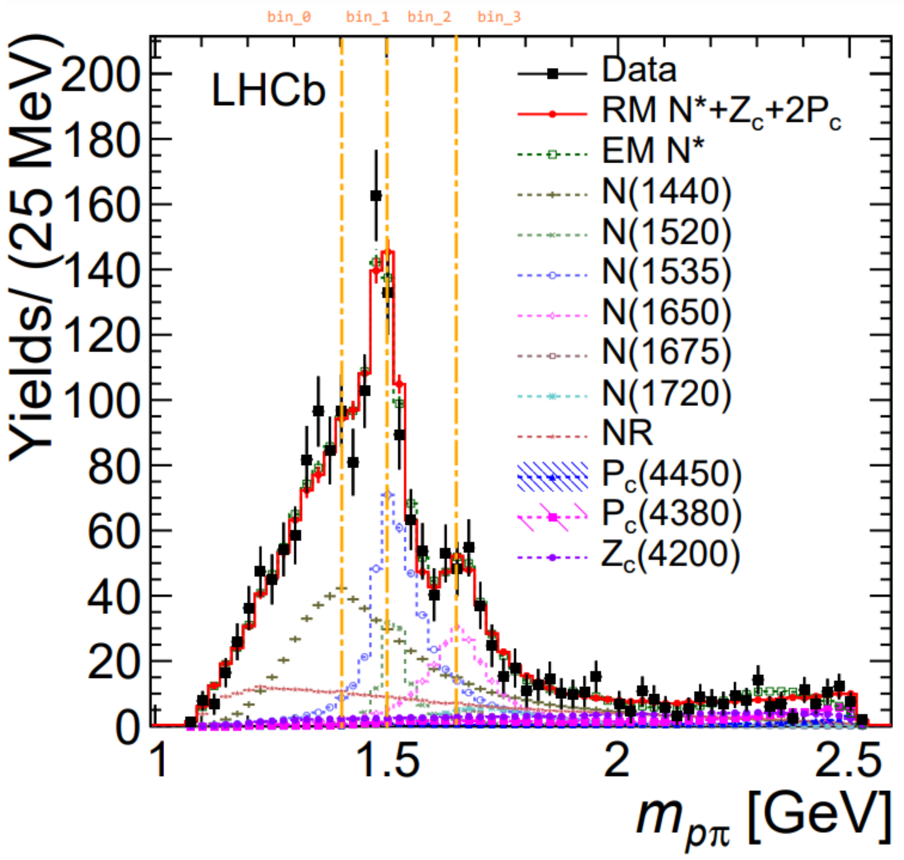
1. Construct the covariance matrix, calculate its inverse, and then the weights.
2. Average the measured values using the weights.
3. Calculate each component of uncertainties:
   - ▶ Statistical: $\hat{\sigma}_{\mathrm{stat}} = \sqrt{\sum_i w_i^2 V_{ii}^{\mathrm{stat}}} = \sqrt{\sum_i w_i^2 \sigma_{i,\mathrm{stat}}^2}$
   - ▶ Systematic, uncorrelated: $\hat{\sigma}_{\mathrm{u}} = \sqrt{\sum_i w_i^2 V_{ii}^{u}} = \sqrt{\sum_i w_i^2 \sigma_{i,\mathrm{u}}^2}$
   - ▶ Systematic, correlated: $\hat{\sigma}_{\mathrm{c}} = \sqrt{\sum_{ij} w_i w_j V_{ij}^{c}}$

Binning schemes

- Scheme 1



- Scheme 2



Significance

- Look-elsewhere effects for 128 bins:

Global significance	3σ	5σ
Local significance requirement	4.3σ	5.9σ

$$
\begin{aligned}
&P(1 \text{ or more bins } p\text{-value} \le t;\ 128 \text{ bins}) \\
=&1 - P(128 \text{ bins } p\text{-value} > t) \\
=&1 - [P(p\text{-value} > t)]^{128} = 1 - [1-t]^{128},
\end{aligned}
$$