Evidence of CP violation in $B^{\pm} \to J/\psi\pi^{\pm}$ decays

Manshu Li , Jie Wu

Central China Normal University

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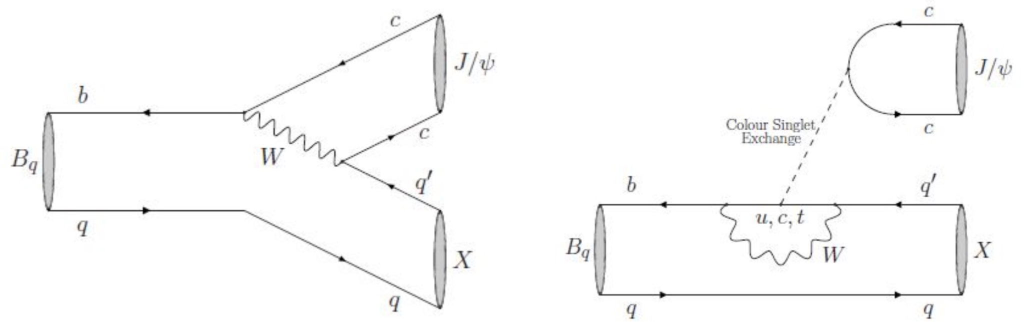
Probing CP violation in $B^+ \to J/\psi\pi^+$



$(X = \pi, K)$

$$A(B^+ \to J/\psi\pi^+) \approx \lambda^3 (T + P_c - P_t) + \lambda^3 (P_u - P_t)e^{i\gamma}$$
$$A(B^+ \to J/\psi K^+) \approx \lambda^2 (T + P_c - P_t) + \lambda^4 (P_u - P_t)e^{i\gamma}$$

- The $B^+ \to J/\psi\pi^+$ decay, proceeding via a $b \to c\bar{c}d$ transition, is enriched with penguin contributions
  - Expect $\mathcal{O}(1\%)$ direct CP violation [PRD 49 (1994) 5904, PRD 52 (1995) 242]
- Ideal place to look for yet unobserved direct CP violation in B decays to charmonia
- Important control channel to understand penguin effects that affect $\sin 2\beta$ measurement in $B^0 \to J/\psi K^0$
  [PRD 79 (2009) 014030, JHEP 03 (2015) 145]

Previous study of $B^+ \to J/\psi\pi^+$

- LHCb measured its branching fraction and CP violation relative to $B^+ \to J/\psi K^+$ using Run 1 data [JHEP 03 (2017) 036]

$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$$

$$= (3.83 \pm 0.03 \pm 0.03)\times 10^{-2}$$

$$\Delta A^{CP} \equiv A^{CP}(B^+ \to J/\psi\pi^+) - A^{CP}(B^+ \to J/\psi K^+)$$

$$= (1.82 \pm 0.86 \pm 0.14)\times 10^{-2}$$

where $A^{CP}(B^+ \to J/\psi h^+) = \frac{\Gamma(B^- \to J/\psi h^-) - \Gamma(B^+ \to J/\psi h^+)}{\Gamma(B^- \to J/\psi h^-) + \Gamma(B^+ \to J/\psi h^+)}$

- This analysis updates $\mathcal{R}_{\pi/K}$ and ΔA^{CP} using data taken in 2016-2018 ($5.4\ \mathrm{fb}^{-1}$)

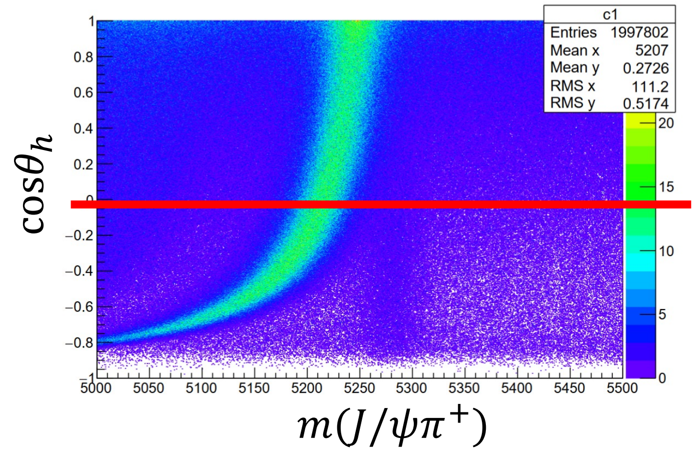
Trigger and preselection

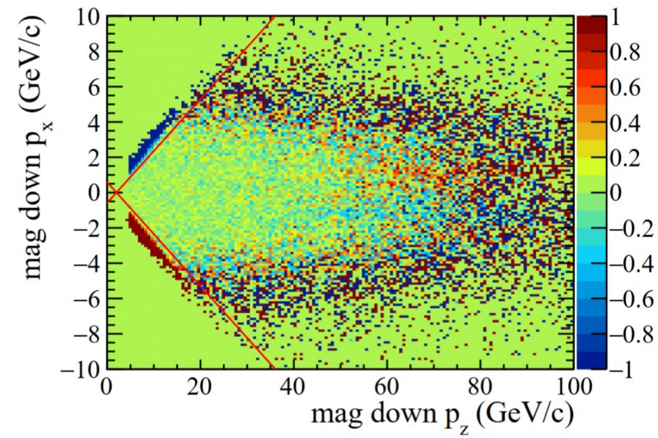
- Trigger
- Combine J/ψ and pion/kaon candidates to form $B^{\pm} \to J/\psi h^{\pm}$ candidates
- Require $cos\theta_h < 0$ to separate $B^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$

  θ_h: angle between $\vec{p}_h$ in B rest frame and $\vec{p}_B$ in the lab frame

- Remove edge regions with large raw asymmetries by requiring

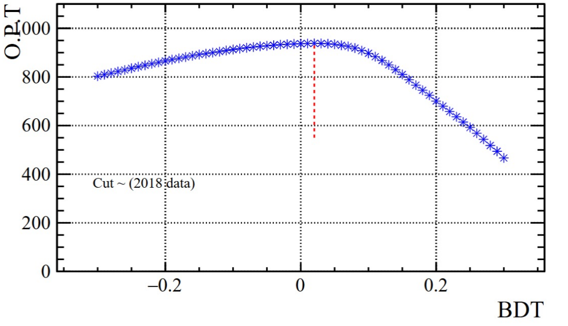
  $p_x \leq 0.294(p_z - 2\ \mathrm{GeV})$





MVA and PID selections

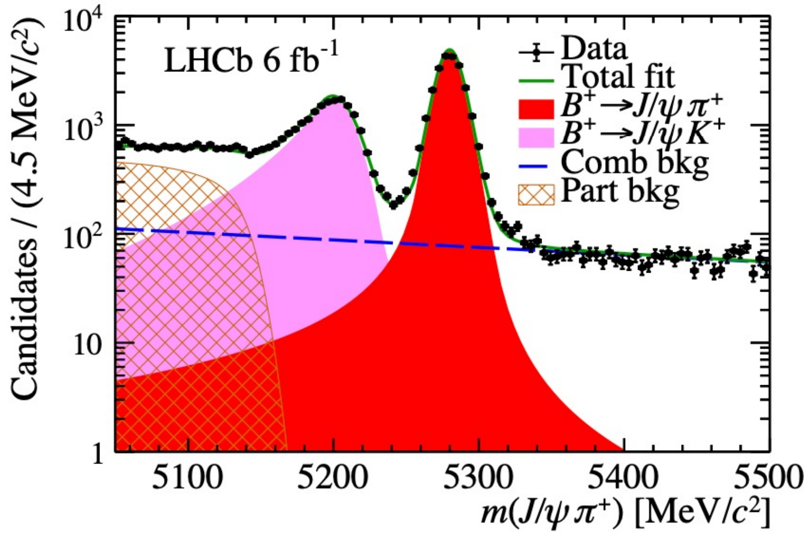
- Train a BDT for each mode and each year to suppress combinatorial background, using kinematic information
  - Optimize BDT cut to maximize significance of $B^+ \to J/\psi\pi^+$
  - Choose the same BDT efficiency for $B^+ \to J/\psi K^+$
  - Rejecting >90% of combinatorial background, with signal efficiency above 95%

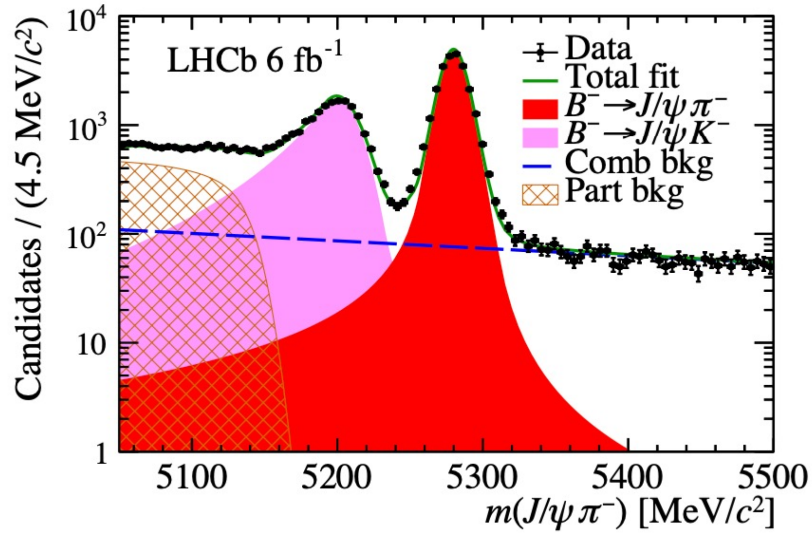


- Use hadron PID to suppress misID background
  - ✓ $\pi^{\pm}$: $probNNk < 0.6\ \&\&\ probNNpi > 0.5$, $\epsilon \approx 96\%$
  - ✓ $K^{\pm}$: $probNNk > 0.6\ \&\&\ probNNpi < 0.5$, $\epsilon \approx 92\%$
  - ✓ Reject >97% cross-feed background

$B^{\pm} \to J/\psi\pi^{\pm}$ mass fits

- Simultaneously fit B^{+} & B^{-} mass distributions for each year





(Merged plots for data in three years)

$B^{\pm} \longrightarrow J/\psi\pi^{\pm}$: Hypatia, tail parameters fixed from MC, μ & σ free

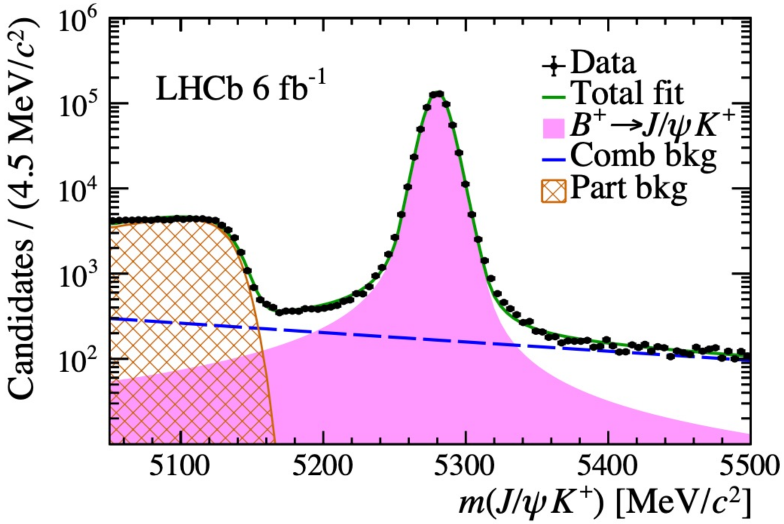
$B^{\pm} \longrightarrow J/\psi K^{\pm}$: DSCB, tail parameter fixed from MC, μ & σ free

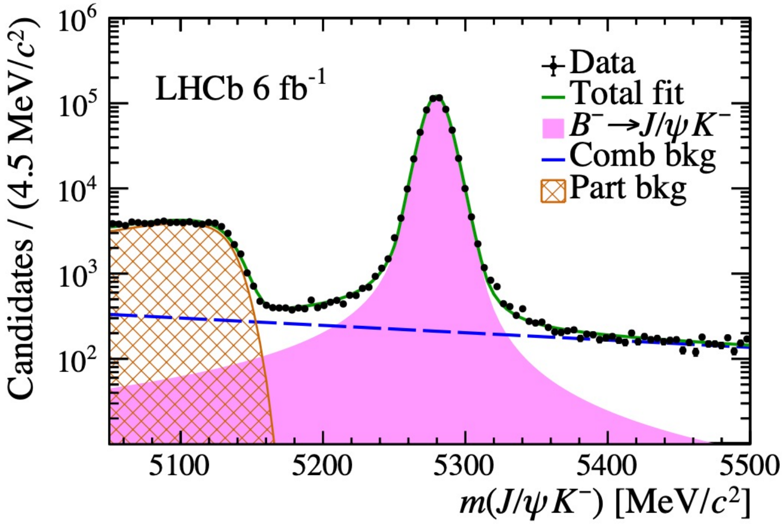
Partially reconstructed bkg: Argus convolved with Gaussian

Combinatorial bkg: exponential

$B^{\pm} \to J/\psi K^{\pm}$ mass fits

- Simultaneously fit B^{+}& B^{-} mass distributions for each year





(Merged plots for data in three years)

$B^{\pm} \longrightarrow J/\psi K^{\pm}$: Hypatia, tail parameter fixed from MC, μ & σ free

Partially reconstructed bkg: Argus convolved with Gaussian

Combinatorial bkg: exponential

Branching fraction ratios

- Signal yields obtained from mass fits
- Efficiency ratios mainly obtained from simulation

$$\mathcal{R}_{\pi/K} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N_\pi}{N_K} \times \frac{\epsilon_K}{\epsilon_\pi}$$

- Year by year

$$\mathcal{R}_{\pi/K} = \begin{cases} (3.900 \pm 0.040 \pm 0.024) \times 10^{-2} & \text{for 2016} \\ (3.858 \pm 0.039 \pm 0.022) \times 10^{-2} & \text{for 2017} \\ (3.805 \pm 0.037 \pm 0.023) \times 10^{-2} & \text{for 2018,} \end{cases}$$

- Run 2 average, using the Best Linear Unbiased Estimator method to combine

$$\mathcal{R}_{\pi/K} = (3.852 \pm 0.022 \pm 0.018)\times 10^{-2}$$

- Compatible with Run 1 result

$$\mathcal{R}_{\pi/K} = (3.83 \pm 0.03 \pm 0.03)\times 10^{-2}$$

Method to measure ΔA^{CP}

- CP asymmetries

$$A^{CP}(B^{\mp} \longrightarrow J/\psi\pi^{\mp}) = a^{\mathrm{raw}}(B^{\mp} \longrightarrow J/\psi\pi^{\mp}) - a^{\mathrm{prod}}(B^{\mp}) - a^{\mathrm{det}}(\pi^{\mp}) - a^{\mathrm{PID}}(\pi^{\mp})$$

$$A^{CP}(B^{\mp} \longrightarrow J/\psi K^{\mp}) = a^{\mathrm{raw}}(B^{\mp} \longrightarrow J/\psi K^{\mp}) - a^{\mathrm{prod}}(B^{\mp}) - a^{det}(K^{\mp}) - a^{\mathrm{PID}}(K^{\mp})$$

Raw asymmetries from mass fit

Production asymmetries largely cancelled

Detection asymmetries from D^+ control data

PID asymmetries from PIDCorr

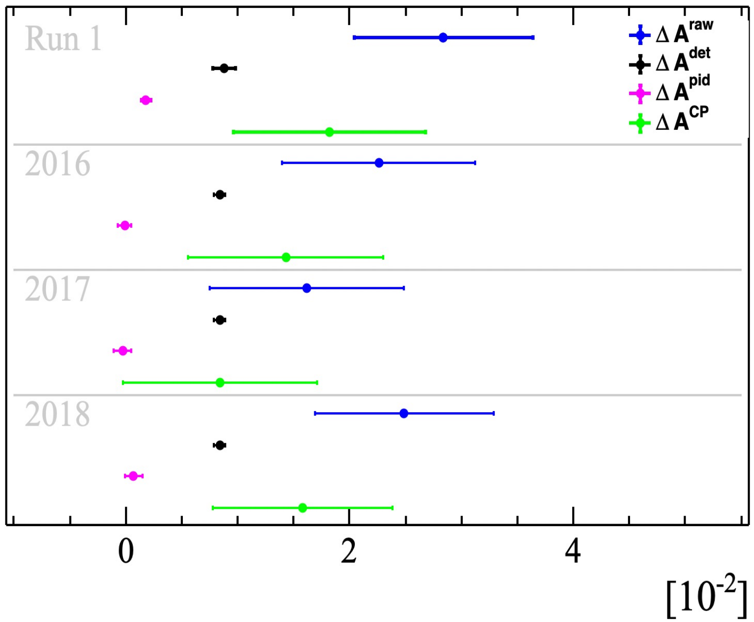
- CP asymmetry difference

$$\Delta A^{CP} \equiv A^{CP}(B^{\mp} \longrightarrow J/\psi\pi^{\mp}) - A^{CP}(B^{\mp} \longrightarrow J/\psi K^{\mp})$$

$$= \Delta a^{\mathrm{raw}} - \cancel{\Delta a^{\mathrm{prod}}} - \Delta a^{\mathrm{det}} - \Delta a^{\mathrm{PID}}$$

CP and nuisance asymmetries

- Raw asymmetries from mass fits



Note the tighter PID cuts used in Run 1 analysis resulted in a slightly larger PID asymmetry.

- Run 2 average

$$\Delta A^{CP} = (1.29 \pm 0.49 \pm 0.10)\times 10^{-2}$$

- Compatible with Run 1 result

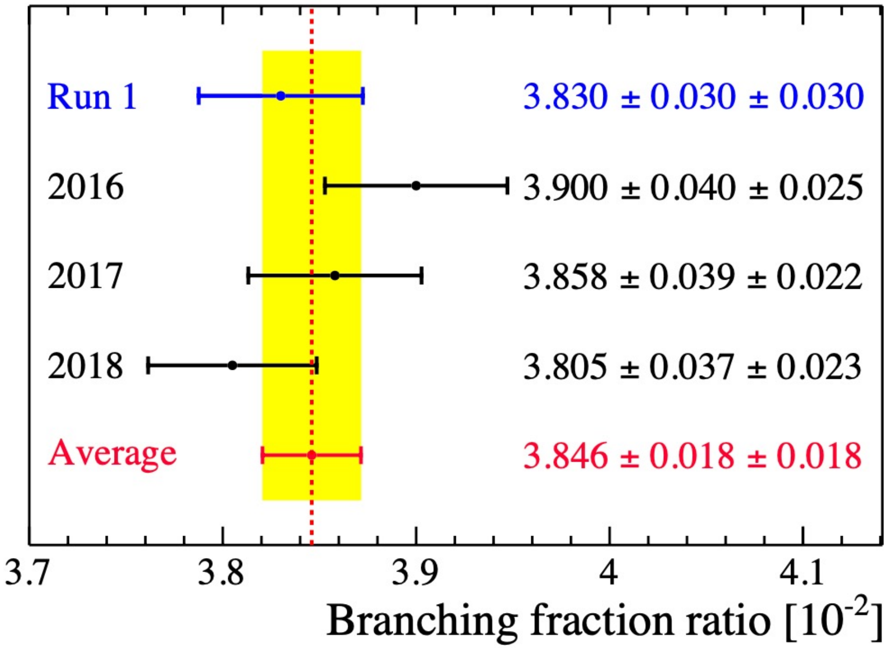
Systematic uncertainties

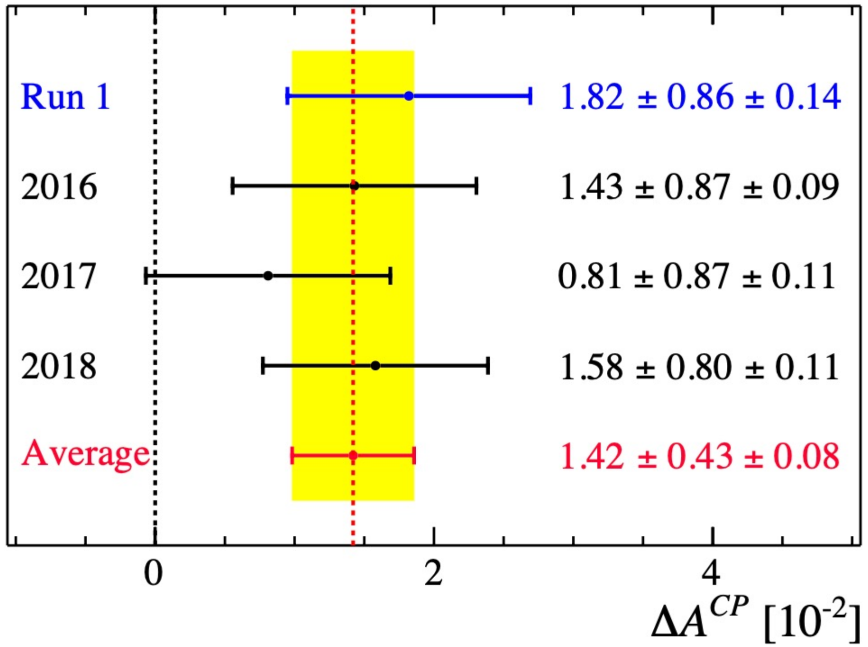
	Branching fraction ratio			CP asymmetry difference		
	2016 [%]	2017 [%]	2018 [%]	2016 [10^{-2}]	2017 [10^{-2}]	2018 [10^{-2}]
Mass fit	0.22	0.16	0.21	0.04	0.06	0.04
Trigger efficiency	0.40	0.39	0.37	-	-	-
Material budget	0.30	0.30	0.30	-	-	-
Simulation correction	0.17	0.15	0.14	-	-	-
PID	0.29	0.22	0.29	0.06	0.07	0.08
Detection asymmetry	-	-	-	0.05	0.05	0.05
Production asymmetry	-	-	-	0.02	0.02	0.02
Total	0.64	0.58	0.61	0.09	0.11	0.11

Relative uncertainty for $\mathcal{R}_{\pi/K}$ and absolute uncertainty for ΔA^{CP}

- No significant difference between mag-up and down
- No significant trend observed when tightening BDT cuts

Combination with Run 1 results





$$R_{\pi/K} = (3.846 \pm 0.018 \pm 0.018)\times 10^{-2}$$

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

First evidence for direct CP violation in beauty decays to charmonium final states (3.2σ)

Estimation of $A^{CP}(B^+ \to J/\psi\pi^+)$

- Using the LHCb measurement

$$A^{CP}(B^+ \to J/\psi K^+) = (0.09 \pm 0.27 \pm 0.07)\times 10^{-2}$$

[Phys. Rev. D 95, 052005 (2017)]

and taking into account the correlations, we get

$$A^{CP}(B^+ \to J/\psi\pi^+) = (1.51 \pm 0.50 \pm 0.11)\times 10^{-2}$$

c.f. PDG average dominated by LHCb Run 1 result

$$A^{CP}(B^+ \to J/\psi\pi^+) = (1.8 \pm 1.2)\times 10^{-2}$$

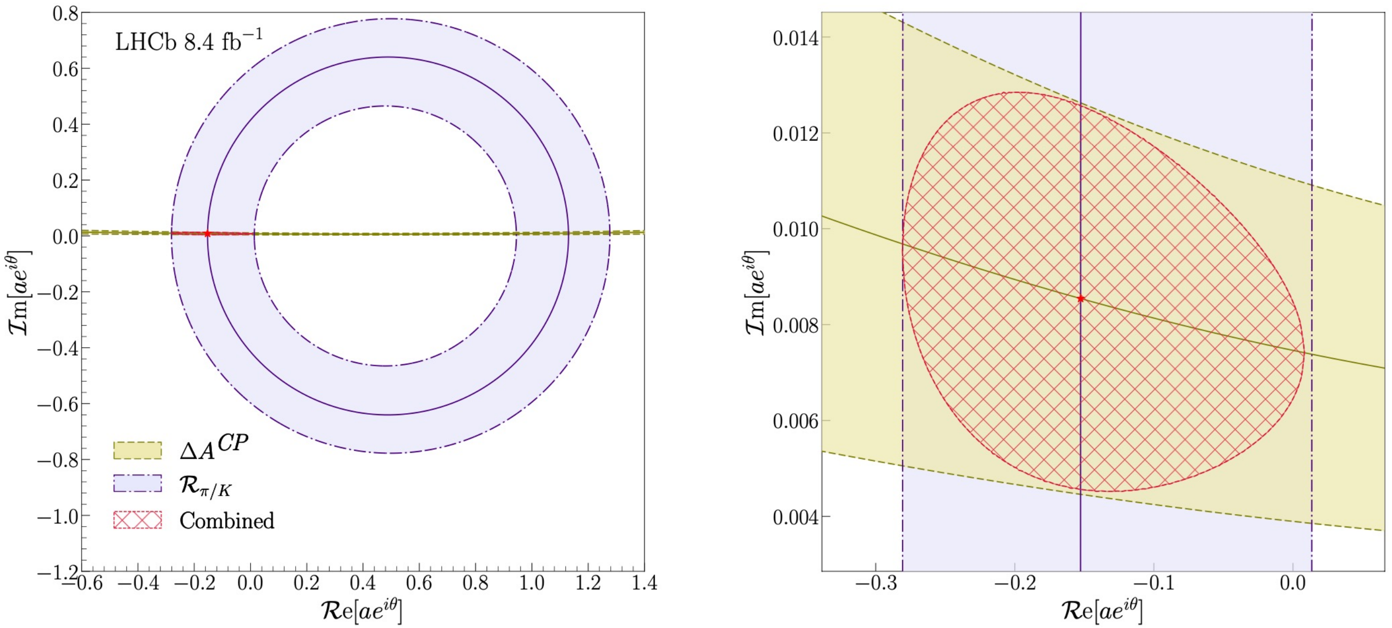
Constraints on penguin parameters

- Amplitudes for $B^+ \to J/\psi h^+ (h = \pi, K)$:

$$A(B^+ \to J/\psi\pi^+) = -\lambda\mathcal{A}(1 + ae^{i\theta}e^{i\gamma}),$$

$$A(B^+ \to J/\psi K^+) = (1 - \lambda^2/2)\mathcal{A}'(1 + \epsilon a'e^{i\theta'}e^{i\gamma}),$$

- SU(3) flavour symmetry: $a = a', \;\; \theta = \theta'.$



Conclusions

- Measurements of CP asymmetry diff. and BF ratio between $B^+ \to J/\psi\pi^+$ & $B^+ \to J/\psi K^+$ using Run 2 data

$$\Delta A^{CP} = (1.29 \pm 0.49 \pm 0.10)\times 10^{-2}$$
$$\mathcal{R}_{\pi/K} = (3.851 \pm 0.022 \pm 0.023)\times 10^{-2}$$

- Combination with Run 1 results gives 1st evidence for direct CP violation in beauty to charmonium decays!

$$\Delta A^{CP} = (1.42 \pm 0.43 \pm 0.08)\times 10^{-2}$$
$$\mathcal{R}_{\pi/K} = (3.846 \pm 0.018 \pm 0.018)\times 10^{-2}$$

Backup slides

Raw charge asymmetries

- Raw asymmetries from mass fits

	2016	2017	2018
a_{π}^{raw} (%)	0.91 ± 0.85	0.50 ± 0.85	1.42 ± 0.78
a_{K}^{raw} (%)	-1.35 ± 0.17	-1.12 ± 0.17	-1.07 ± 0.15
Δa^{raw} (%)	2.26 ± 0.86	1.62 ± 0.87	2.49 ± 0.80

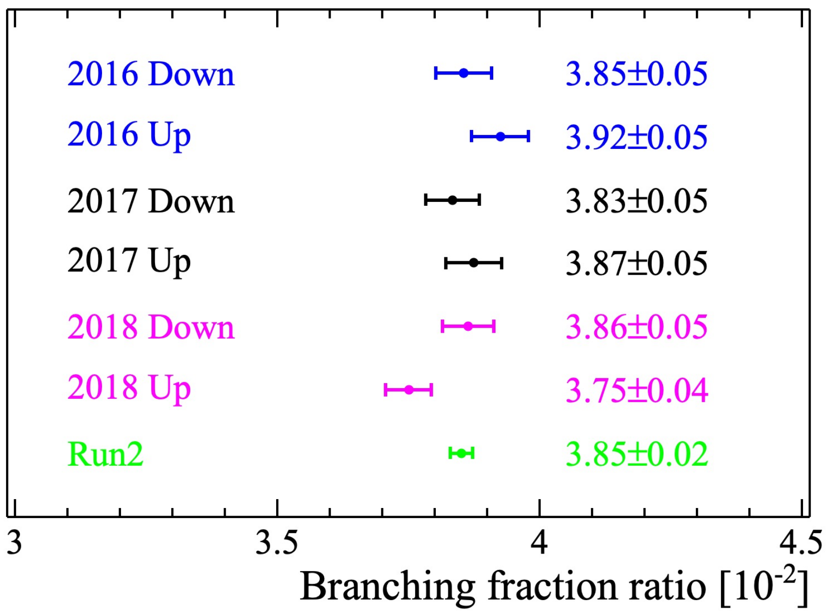
The $B^{+} \to J/\psi K^{+}$ sample is weighted to match the $B^{+} \to J/\psi \pi^{+}$ sample in p_T and η distributions, in order to cancel the B^{-}/B^{+} production asymmetry

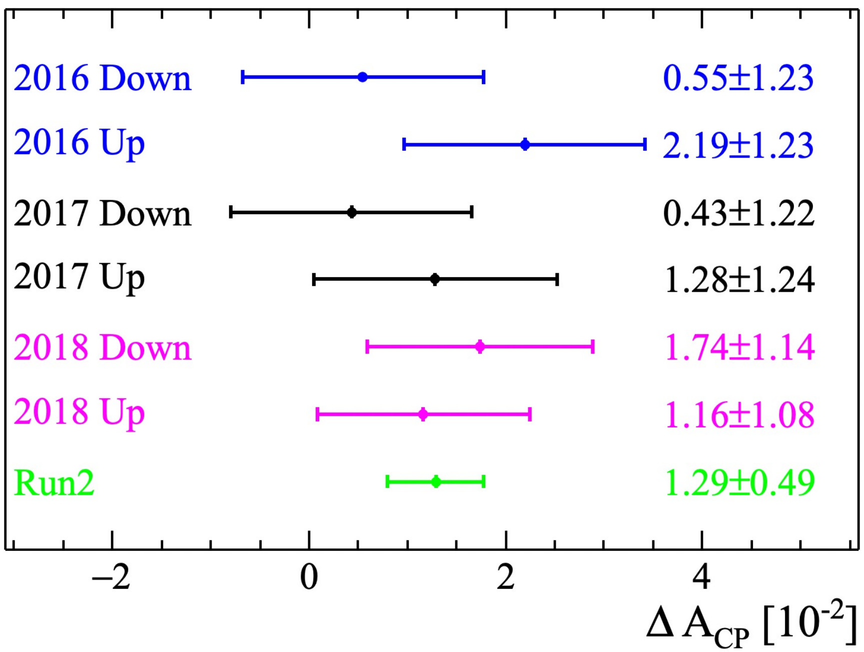
Sources of systematic uncertainties

- Mass fits: alternative signal and bkg. descriptions; different shape and position parameters for B^+ and B^-
- Trigger efficiency: difference of L0 efficiency ratios from simulation and from data, using TISTOS method
- K/π interaction: varying relevant detector material by 10%
- PID eff. and asymmetry: uncertainties of PID efficiency ratio and Δa^{PID} estimates from PIDCorr
- Detection asymmetry: uncertainty of Δa^{det} estimate
- Production asymmetry: difference of ΔA^{CP} with and w/o matching $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$ kinematics

Dependence on magnetic polarity

➤ No significant difference between mag-up and down

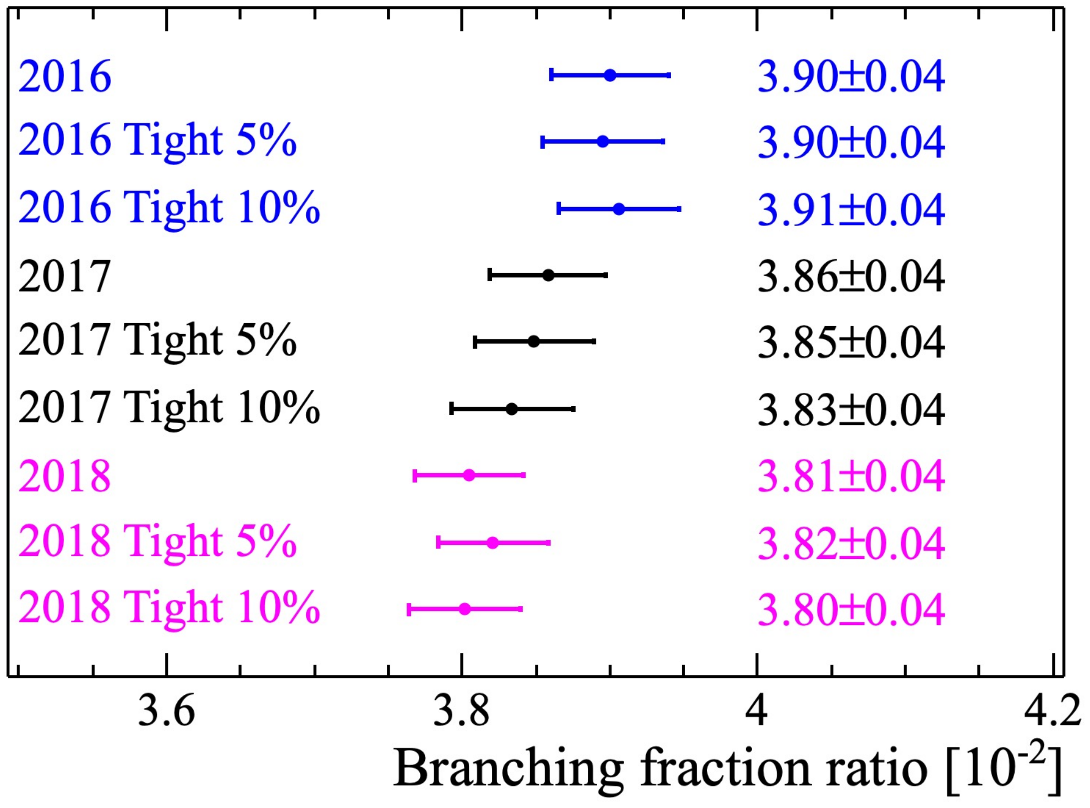




Uncertainties are statistical only

Dependence on BDT requirements

- No significant trend observed when tightening BDT cuts



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