Time Independent CPV at LHCb

Michael K. Wilkinson
of the University of Cincinnati
on behalf of the LHCb collaboration

LHCP

5 June 2024

Introduction

- Charge-Parity (CP) symmetry = natural laws the same for (anti-)matter
  - C changes particles for anti-particles, e.g., $Q \rightarrow -Q$
  - P reverses spatial handedness, $\vec{x} \rightarrow -\vec{x}$
  - CP symmetry apparently exact for electromagnetic and strong interactions
  - CP violation (CPV) seen in weak interactions
- CPV in the Standard Model (SM) comes from a single parameter in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, which determines the size of the couplings between quark flavors
- **Not nearly large enough to explain observed (anti-)matter asymmetry!** Prompts searches for sources Beyond the SM (BSM)

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Sources of CPV

1. CPV in decay ("direct")

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

- Defined by different rates of charge-conjugated decay for hadron M:

$$\mathcal{A}_{f^\pm} \equiv \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)}$$

- The only possible source of CPV for baryons and charged mesons

2. CPV in mixing

- Comes from differences in mass and flavor eigenstates for neutral meson M:

$$|M_{1,2}\rangle = p|M^0\rangle + q|\bar{M}^0\rangle, \qquad |p|^2 + |q|^2 = 1$$
$$|q/p| \neq 1 \Rightarrow \text{CPV}$$

- The only source in charged-current semileptonic neutral-meson decays

3. CPV in interference between $M^0 \to f$ and $M^0 \to \bar{M}^0 \to f$

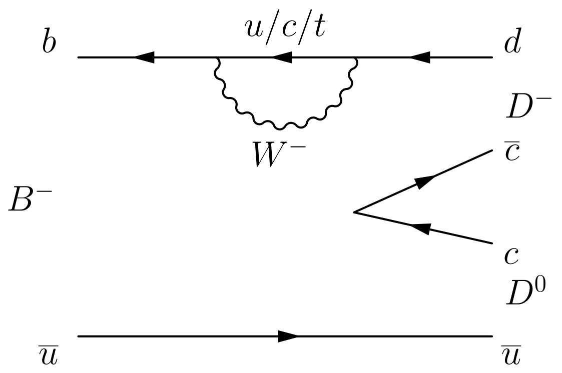
Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

JHEP 09 (2023) 202 [arXiv:2306.09945]

- Search for direct CP violation, $\mathcal{A}^{CP}$
- Arises from interference between decay amplitudes
- Predicted to be small in SM, up to 1% for $b \to c\bar{c}s$ and up to 5% for $b \to c\bar{c}d$
- Also, measure two BF ratios, $R(D^-D^0/D_s^-D^0)$ & $R(D^{*-}D^0/D^-D^0)$

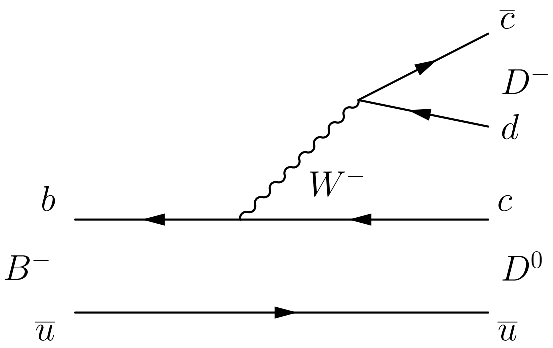
$$\mathcal{A}^{CP} \equiv \frac{\Gamma\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) - \Gamma\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}{\Gamma\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) + \Gamma\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}$$

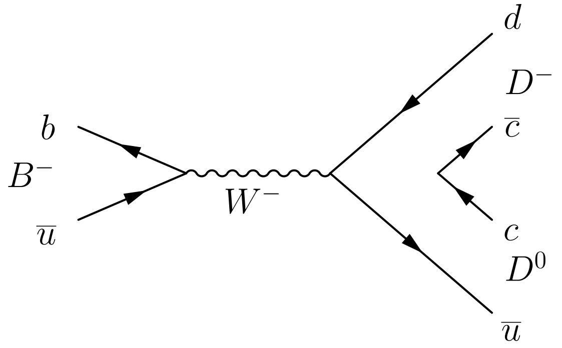
Decay	World Average $\mathcal{A}^{CP}$ [%]
$B^- \to D_s^- D^0$	-0.4 ± 0.7
$B^- \to D_s^{*-} D^0$	-
$B^- \to D_s^- D^{*0}$	-
$B^- \to D^- D^0$	1.6 ± 2.5
$B^- \to D^- D^{*0}$	13 ± 18
$B^- \to D^{*-} D^0$	-6 ± 13
$B^- \to D^{*-} D^{*0}$	-15 ± 11



$$R(D^-D^0/D_s^-D^0) \equiv \frac{\mathcal{B}(B^- \to D^-D^0)}{\mathcal{B}(B^- \to D_s^-D^0)} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}$$

$$R(D^{*-}D^0/D^-D^0) \equiv \frac{\mathcal{B}(B^- \to D^{*-}D^0)}{\mathcal{B}(B^- \to D^-D^0)} \frac{\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-)\mathcal{B}(\overline{D}^0 \to K^+\pi^-)}{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}$$

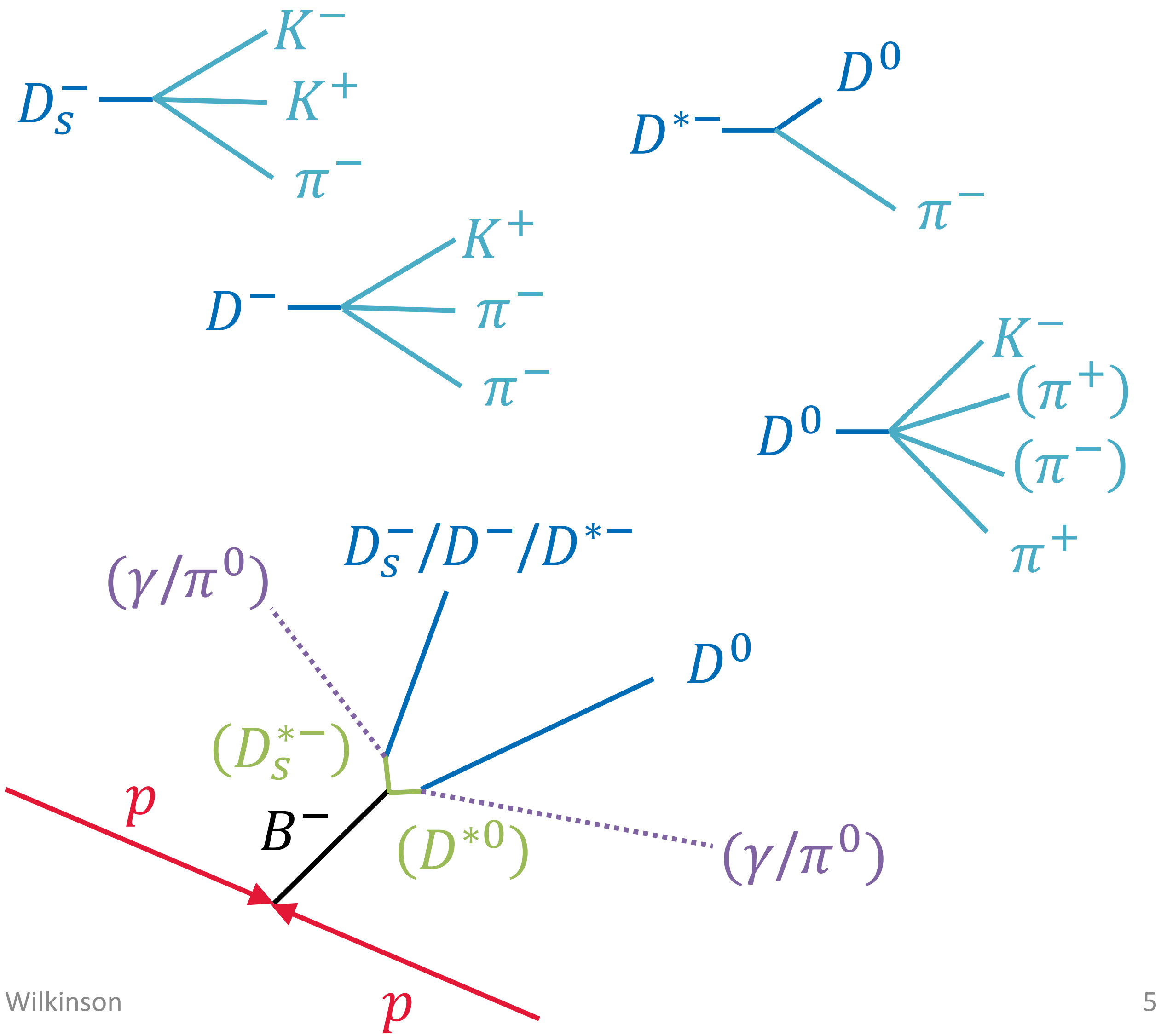




Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

JHEP 09 (2023) 202 [arXiv:2306.09945]

- 9 fb^{-1} of data (Run 1 + 2)
- Reconstruct $D_s^- D^0$, $D^- D^0$, or $D^{*-} D^0$ final states
- Partially reconstruct intermediate $D_s^{*-/0} \to D(\gamma/\pi^0)$ decays (contributes broad structure to invariant mass)



Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

- $\mathcal{A}^{CP} = \mathcal{A}_{\mathrm{raw}} - \mathcal{A}_{\mathrm{P}} - \mathcal{A}_{\mathrm{D}}$
  - Calculate raw asymmetry ($\mathcal{A}_{\mathrm{raw}}$) from yields and correct by the production and detection asymmetries ($\mathcal{A}_{\mathrm{P}}$ and $\mathcal{A}_{\mathrm{D}}$) to get $\mathcal{A}^{CP}$
  - $\mathcal{A}_{\mathrm{P}}$ and $\mathcal{A}_{\mathrm{D}}$ evaluated with kinematically-weighted calibration data
- Branching fraction ratios are measured for fully-reconstructed decays where we achieve high precision
  - Calculated using efficiency-corrected yields
  - Efficiency from data-corrected simulation

JHEP 09 (2023) 202 [arXiv:2306.09945]

$$\mathcal{A}_{\mathrm{raw}} \equiv \frac{N\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) - N\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}{N\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) + N\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}$$

$$\mathcal{A}_{\mathrm{P}} \equiv \frac{\sigma(B^-) - \sigma(B^+)}{\sigma(B^-) + \sigma(B^+)}$$

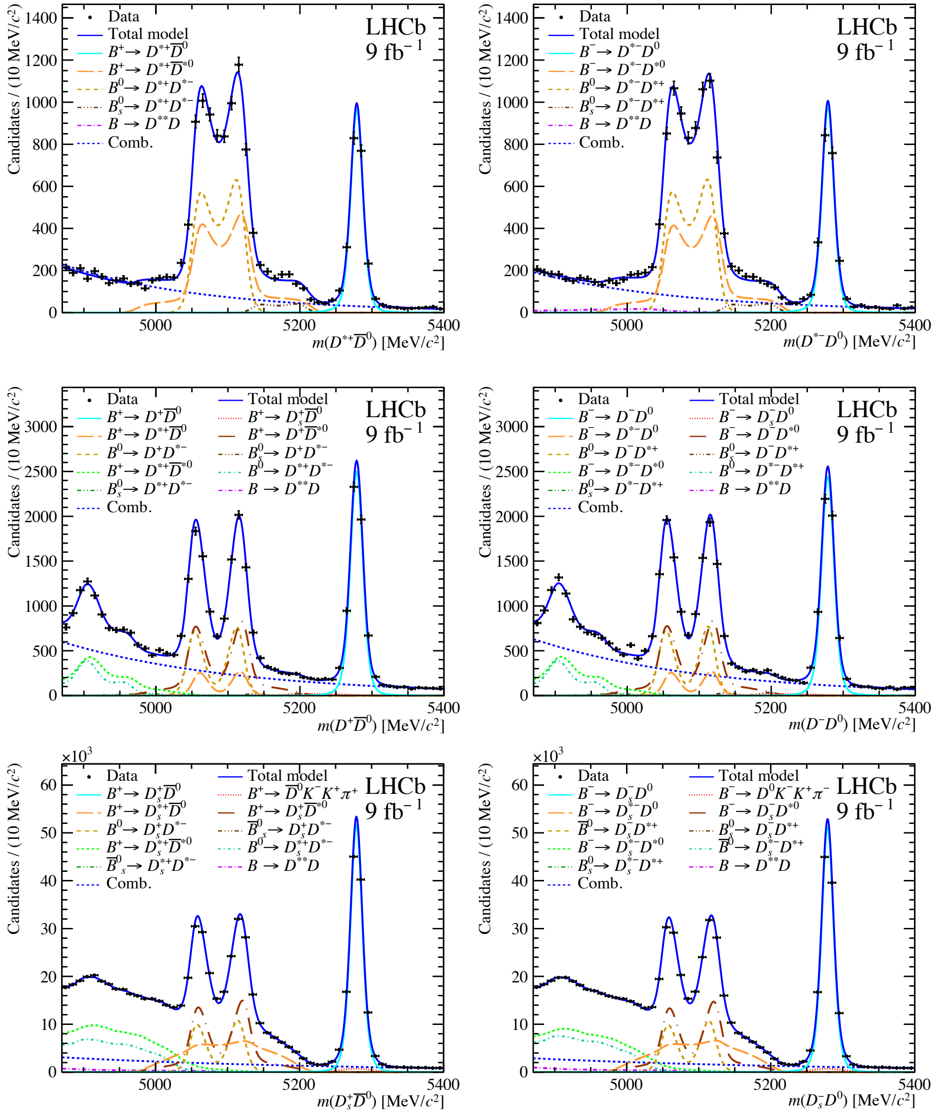
$$\mathcal{A}_{\mathrm{D}} \equiv \frac{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) - \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) + \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}$$

$$R(D^-D^0/D_s^-D^0) = \frac{N(B^- \to D^-D^0)}{N(B^- \to D_s^-D^0)} \frac{\varepsilon(B^- \to D_s^-D^0)}{\varepsilon(B^- \to D^-D^0)}$$

$$R(D^{*-}D^0/D^-D^0) = \frac{N(B^- \to D^{*-}D^0)}{N(B^- \to D^-D^0)} \frac{\varepsilon(B^- \to D^-D^0)}{\varepsilon(B^- \to D^{*-}D^0)}$$

Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

- $\mathcal{A}^{CP} = \mathcal{A}_{\text{raw}} - \mathcal{A}_{\text{P}} - \mathcal{A}_{\text{D}}$
- Fit $m\left(D_{(s)}^{(*)-} D^{(*)0}\right)$ to extract $\mathcal{A}_{\text{raw}}$
  - Asymmetry extracted from simultaneous fit to both charges
  - Background asymmetries constrained to improve resolution
- Extract $\mathcal{A}_{\text{P}}$ by kinematically weighting previous LHCb result from $B^+ \to J/\psi K^+$
- Extract $\mathcal{A}_{\text{D}}$ (dominated by K^- nuclear interaction) using independent, kinematically weighted calibration samples of D^+, D^{*+}, and B decays



Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

- $R(D^-D^0/D_s^-D^0)$ & $R(D^{*-}D^0/D^-D^0)$
  - Agree with world averages
  - Higher precision

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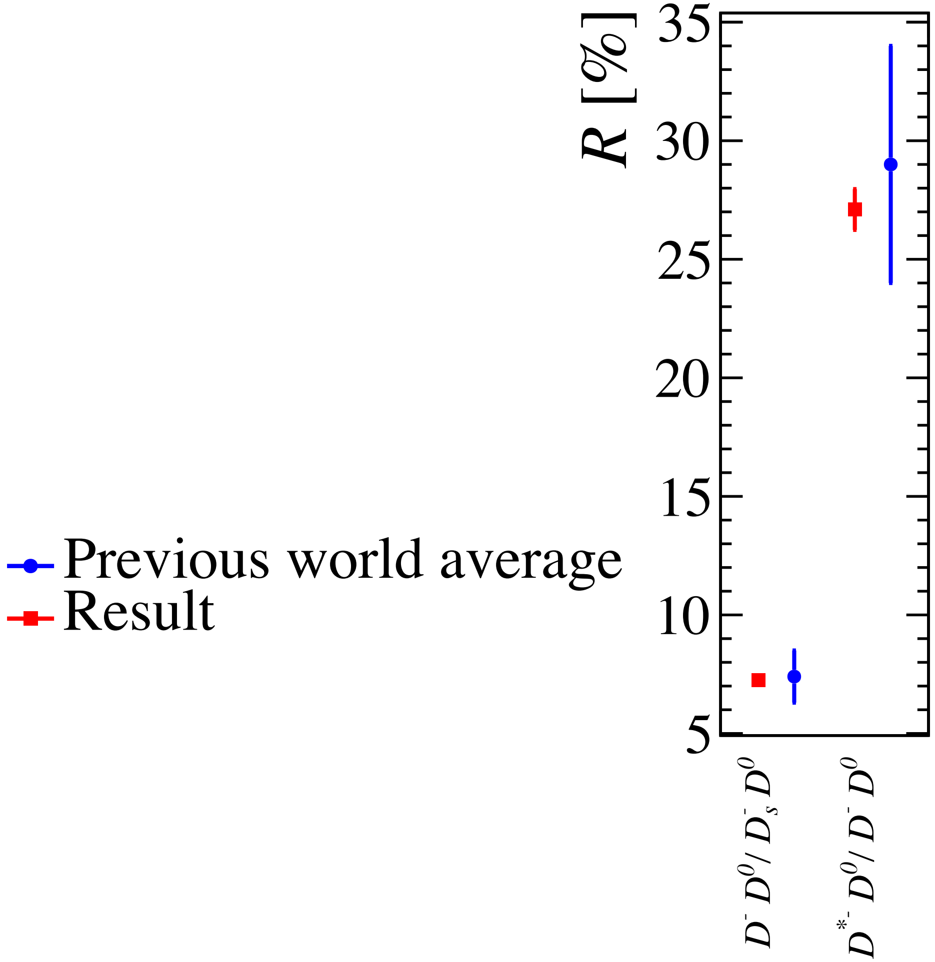

Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

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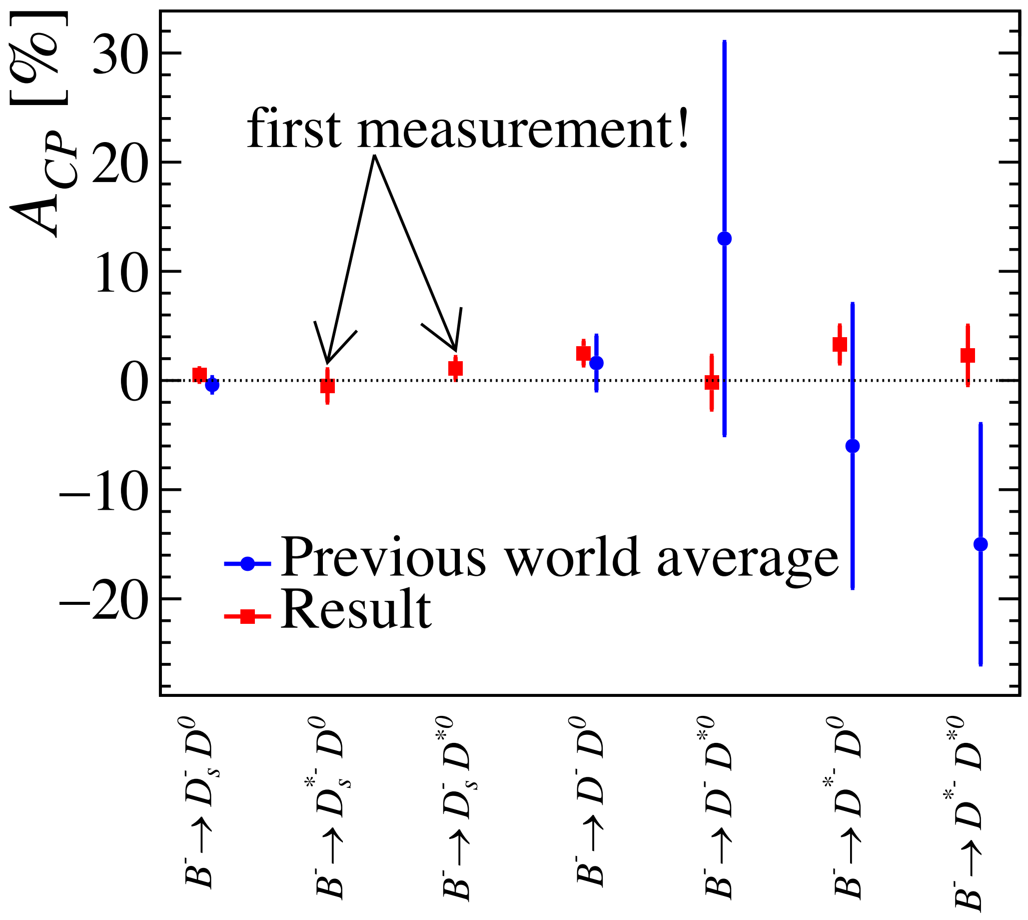
- $R(D^-D^0/D_s^-D^0)$ & $R(D^{*-}D^0/D^-D^0)$
  - Agree with world averages
  - Higher precision
- $\mathcal{A}^{CP}$
  - No evidence of CP violation found
  - More precise than world averages
  - $\mathcal{A}^{CP}(B^- \to D_{(s)}^- D^0)$ agree with and supersede previous LHCb measurement
- Substantially improve knowledge of B^- meson decays, helping to constrain BSM physics

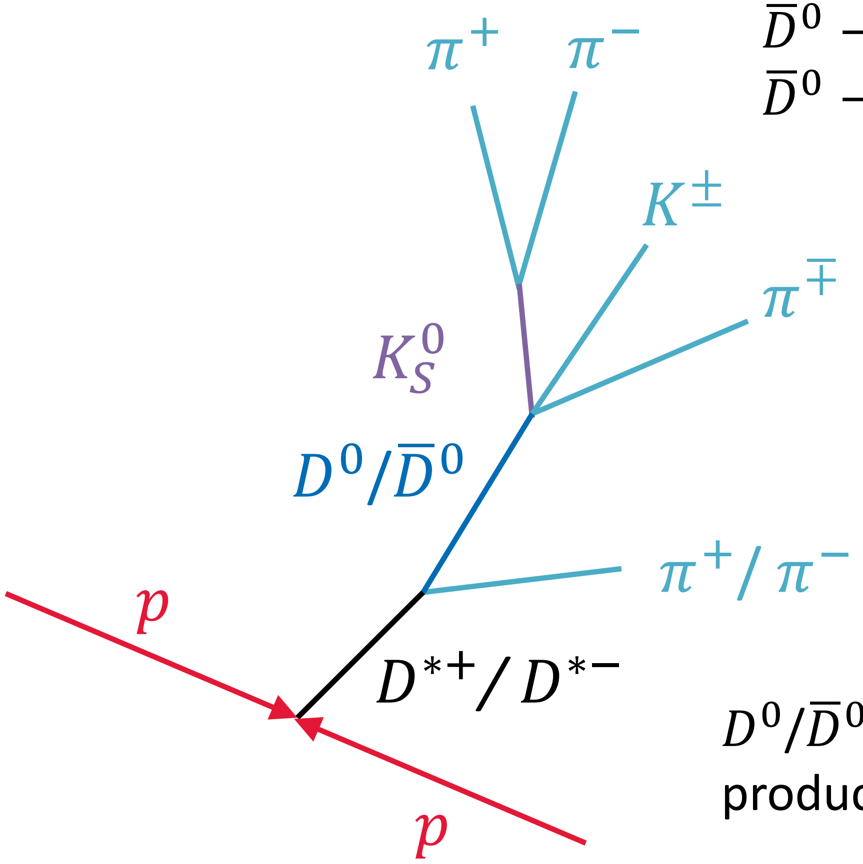


Search for CP violation in the phase space of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays with the energy test

JHEP 03 (2024) 107 [arXiv:2310.19397]

- CPV in charm decays is expected to be small in the SM
- Observed for the first time in 2019 by LHCb in singly Cabibbo-suppressed (SCS) decay modes [1], unclear whether consistent with the SM
- $D^0 \to K_S^0 K^\pm \pi^\mp$ decays are dominated by SCS amplitudes, previously studied in amplitude analysis by LHCb [2], and contain other CP-sensitive amplitudes

$D^0 \to K_S^0 K^+ \pi^-$ (OS)
$D^0 \to K_S^0 K^- \pi^+$ (SS)
$\overline{D}^0 \to K_S^0 K^+ \pi^-$ (SS)
$\overline{D}^0 \to K_S^0 K^- \pi^+$ (OS)



$D^0/\overline{D}^0$ tagged at production by π^+/π^-

1. Phys. Rev. Lett. 122 (2019) 211803, arXiv:1903.08726
2. Phys. Rev. D 93 (2016) 052018, arXiv:1509.06628

Search for CP violation in the phase space of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays with the energy test

JHEP 03 (2024) 107 [arXiv:2310.19397]

- The energy test quantifies whether two multi-dimensional datasets are consistent with the same underlying distribution
- Test statistic T near zero for no CPV, large for significant CPV
- Significance determined by comparing found T-value to null distribution
  - Repeatedly run the test with the D^0, $\overline{D}^0$ flavors randomly assigned = null dist.
  - The p-value = fraction of permutation samples with T-value > the found value

$$T \equiv \frac{1}{2n(n-1)} \sum_{i,j \neq i}^{n} \psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{i,j \neq i}^{\bar{n}} \psi_{ij} - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi_{ij}$$

Sum over n D^0 pairs, $\bar{n}$ $\overline{D}^0$ pairs, and $n, \bar{n}$ D^0-$\overline{D}^0$ pairs

$$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$$

$$d_{ij}^2 = \left(s_{12,i} - s_{12,j}\right)^2 + \left(s_{13,i} - s_{13,j}\right)^2 + \left(s_{23,i} - s_{23,j}\right)^2$$

$$s_{12} = m^2\left(K_S^0 K^\pm\right), s_{13} = m^2\left(K_S^0 \pi^\mp\right), s_{23} = m^2\left(K^\pm \pi^\mp\right)$$

d_{ij}^2 is the square of the Euclidean distance between candidates

δ sets the distance scale (optimized for max. sensitivity)

Search for CP violation in the phase space of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays with the energy test

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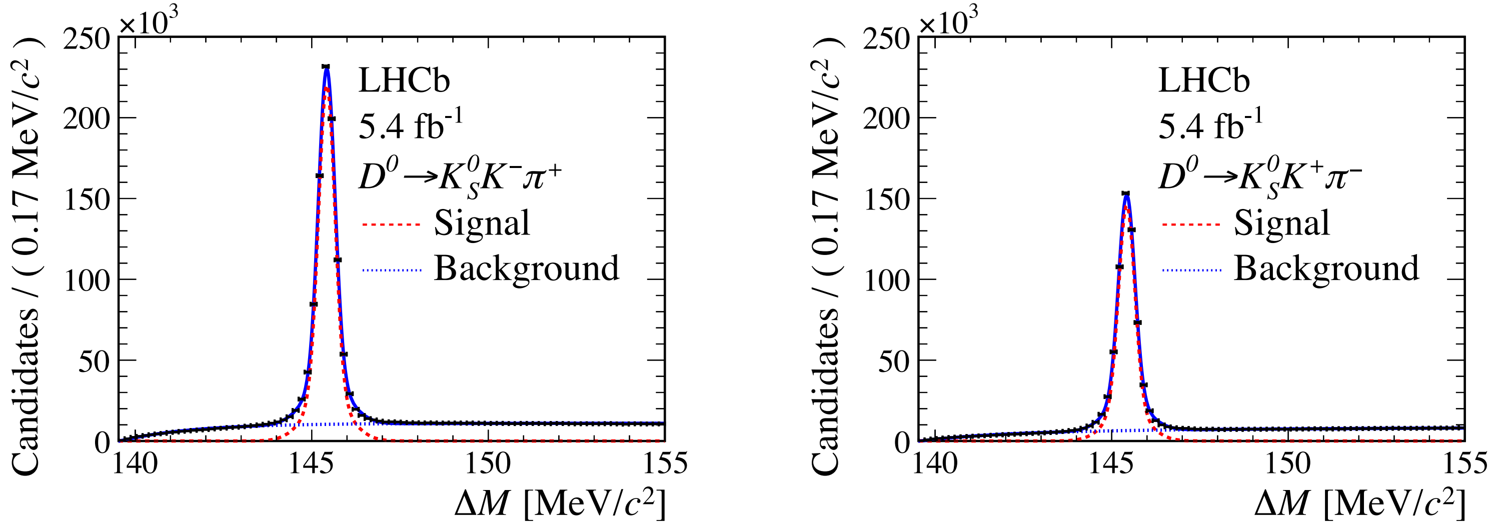
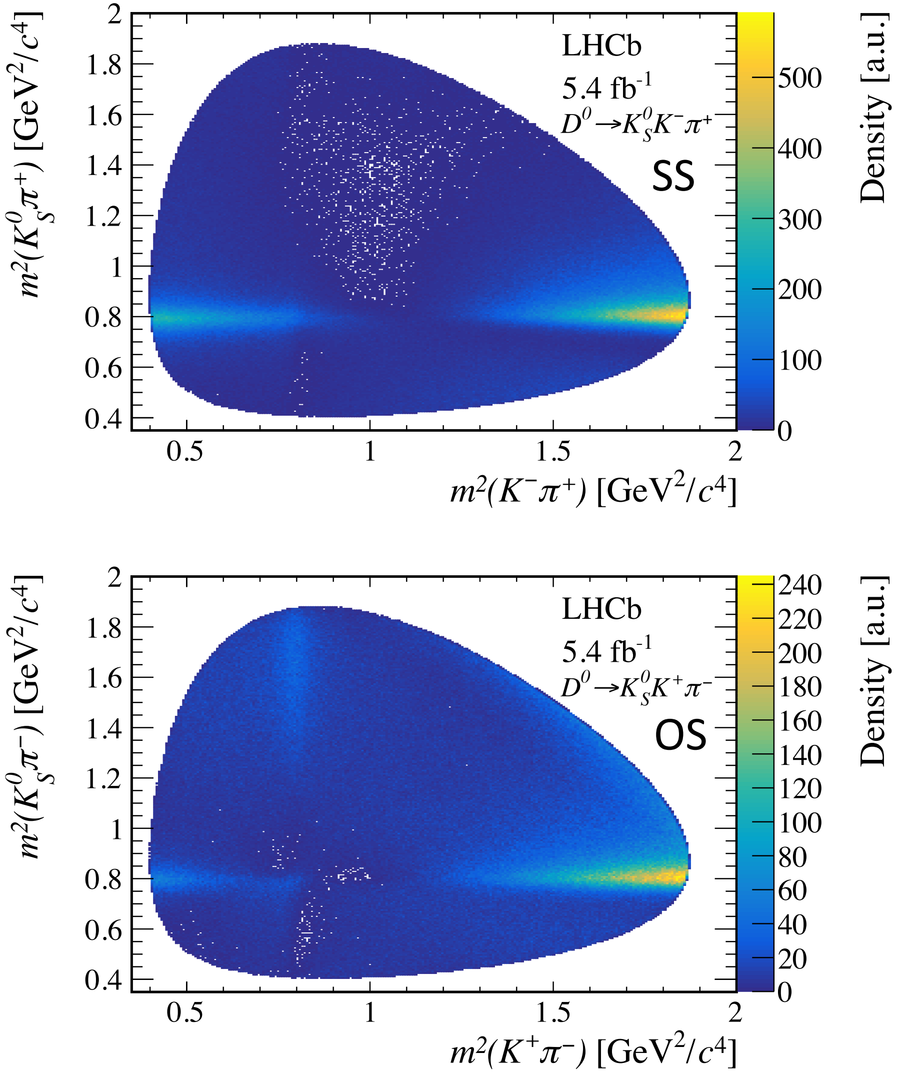
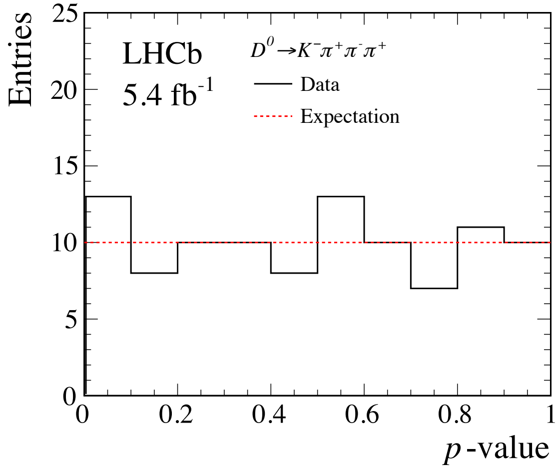


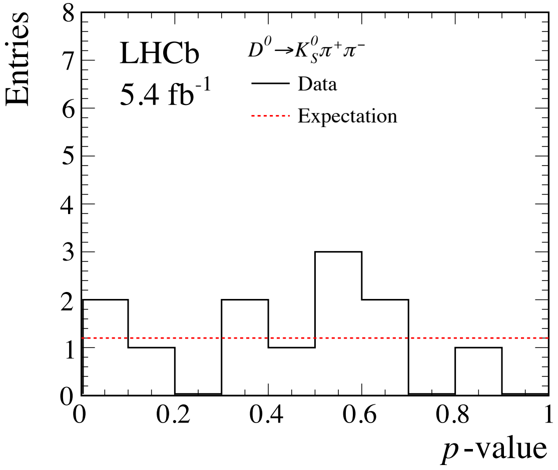


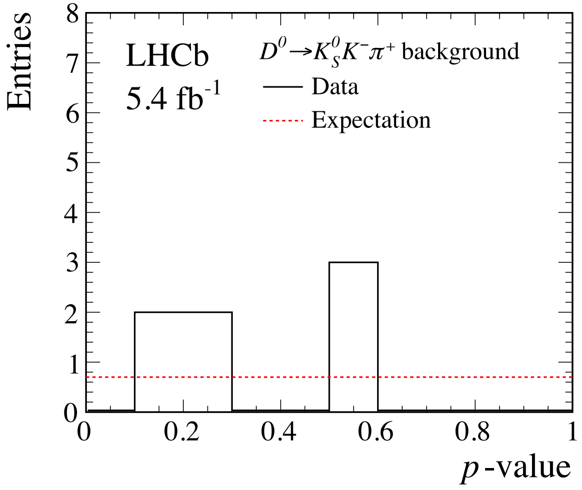
- Largest sample of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays ever studied
- 5.4 fb^{-1} of data (Run 2)
- Selections achieve signal purity $\approx$ 91%
- Contributions from $K^{*\pm} \to K_S^0 \pi^\pm$ clearly visible as horizontal band in SS and OS Dalitz plots
- Contributions from $K^{*0} \to K^+ \pi^-$ clearly visible as vertical band in OS Dalitz plot

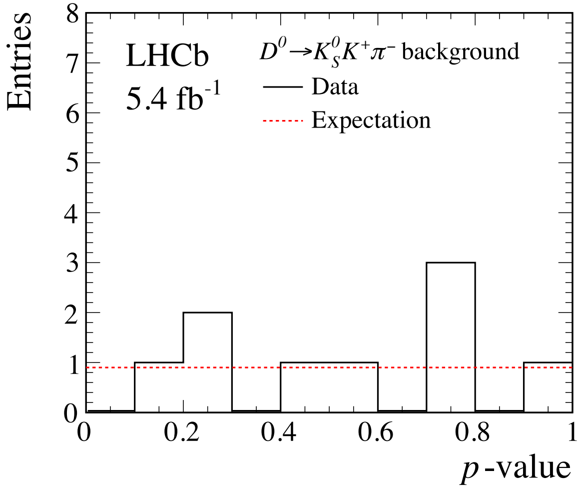
Search for CP violation in the phase space of $D^0 \to K_S^0 K^\pm \pi^\mp$ decays with the energy test

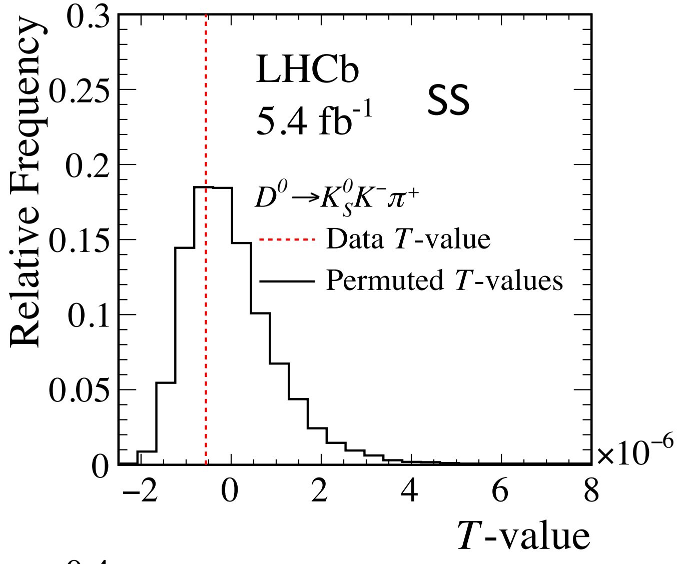
[JHEP 03 (2024) 107](#) [arXiv:2310.19397]

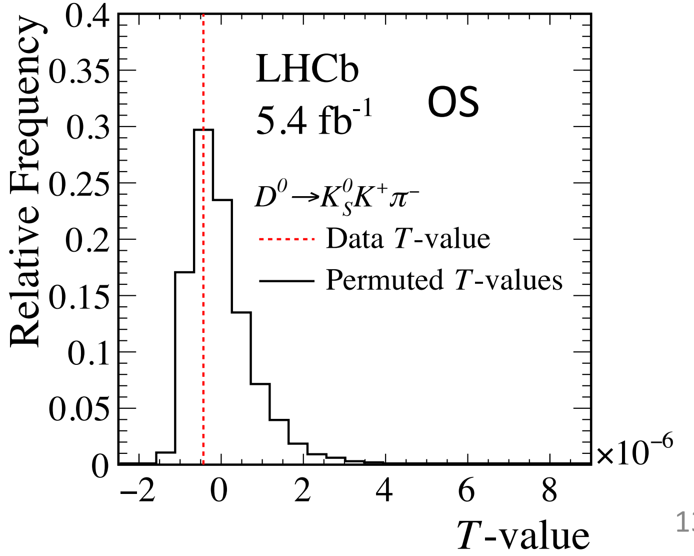












- Method found to be free of bias by comparing to subsets of control and background-enhanced samples
  - $D^0 \to K^-\pi^+\pi^-\pi^+, D^0 \to K_S^0\pi^+\pi^-$
  - Invariant-mass sidebands
- No evidence for CP-violation (p-values 70%, 66% for SS, OS)

Conclusions

- Measured CPV in $B^- \to D_{(s)}^{(*)-} D^{(*)0}$ and $D^0 \to K_S^0 K^\pm \pi^\mp$ decays
  - *JHEP* 09 (2023) 202 [arXiv:2306.09945]
  - *JHEP* 03 (2024) 107 [arXiv:2310.19397]
- Found no evidence of CPV in these decays
- These measurements are statistically limited
  - We expect ≈5x greater integrated luminosity in Run 3+4
  - And we expect much larger hadron-trigger efficiency in Run 3+4
  - ∴ we expect $\gtrapprox$10x greater statistics in near future!

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FIN

BACKUP

Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

- $\mathcal{A}_{\mathrm{D}} = \mathcal{A}_{K\pi} + \mathcal{A}_{\pi} + \mathcal{A}_{\mathrm{PID}} + \mathcal{A}_{\mathrm{TIS}} + \mathcal{A}_{\mathrm{TOS}}$
- Weight calibration samples to match signal kinematics
- $\mathcal{A}_{K\pi}$
  - Difference in raw asymmetry between $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$
  - Corrected for $\overline{K}^0$ asymmetry
- $\mathcal{A}_{\pi}$ from $D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$
- $\mathcal{A}_{\mathrm{PID}}$
  - Induced by tight particle identification (PID) requirements
  - From $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ without PID requirements
- $\mathcal{A}_{\mathrm{TIS}}, \mathcal{A}_{\mathrm{TOS}}$
  - Induced by hardware trigger requirements
  - From $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $B \to \overline{D}^0\mu^+\nu_\mu X$

$$\mathcal{A}_{\mathrm{D}} \equiv \frac{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) - \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) + \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}$$

Decay	$\mathcal{A}_{\mathrm{raw}}$	$\mathcal{A}_{\mathrm{P}}$	$\mathcal{A}_{\mathrm{D}}$
$D_s^- D^0$	$-1.3 \pm 0.2 \pm 0.1$	$-1.1 \pm 0.3 \pm 0.3$	-0.7 ± 0.2
$D_s^{*-} D^0$	$-2.4 \pm 1.1 \pm 0.9$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D_s^- D^{*0}$	$-0.8 \pm 0.8 \pm 0.4$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D^- D^0$	$1.5 \pm 1.0 \pm 0.2$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^- D^{*0}$	$-1.3 \pm 2.0 \pm 1.3$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^{*-} D^0$	$2.4 \pm 1.6 \pm 0.2$	$-1.2 \pm 0.4 \pm 0.3$	0.2 ± 0.3
$D^{*-} D^{*0}$	$1.3 \pm 2.1 \pm 1.6$	$-1.1 \pm 0.5 \pm 0.3$	0.1 ± 0.2

Values of $\mathcal{A}_{\mathrm{raw}}$, $\mathcal{A}_{\mathrm{P}}$, and $\mathcal{A}_{\mathrm{D}}$ in percent, averaged over all D^0 decay modes and data-taking periods. The uncertainties on $\mathcal{A}_{\mathrm{raw}}$ are statistical and systematic, respectively. The first uncertainty on $\mathcal{A}_{\mathrm{P}}$ contains all sources of uncertainty except that on $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$, which is the second uncertainty.

Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

- $\mathcal{A}_{\mathrm{D}} = \mathcal{A}_{K\pi} + \mathcal{A}_{\pi} + \mathcal{A}_{\mathrm{PID}} + \mathcal{A}_{\mathrm{TIS}} + \mathcal{A}_{\mathrm{TOS}}$
- Weight calibration samples to match signal kinematics
- $\mathcal{A}_{K\pi}$
  - Difference in raw asymmetry between $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$
  - Corrected for $\overline{K}^0$ asymmetry
- $\mathcal{A}_{\pi}$ from $D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$
- $\mathcal{A}_{\mathrm{PID}}$
  - Induced by tight particle identification (PID) requirements
  - From $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ without PID requirements
- $\mathcal{A}_{\mathrm{TIS}}, \mathcal{A}_{\mathrm{TOS}}$
  - Induced by hardware trigger requirements
  - From $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $B \to \overline{D}^0\mu^+\nu_\mu X$

$$\mathcal{A}_{\mathrm{D}} \equiv \frac{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) - \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}{\varepsilon\left(B^- \to D_{(s)}^{(*)-} D^{(*)0}\right) + \varepsilon\left(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0}\right)}$$

Final state	$D_s^- D^0$		$D^- D^0$		$D^{*-} D^0$	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
$\mathcal{A}_{\mathrm{P}}$	0.42	0.43	0.41	0.43	0.48	0.48
$\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$	0.30	0.30	0.30	0.30	0.30	0.30
$\mathcal{A}_{K\pi}$	0.28	0.11	0.04	0.04	0.10	0.00
$\mathcal{A}_{\pi}$	0.09	0.09	0.06	0.06	0.18	0.17
$\mathcal{A}_{\mathrm{PID}}$	0.29	0.03	0.25	0.11	0.55	0.10
$\mathcal{A}_{\mathrm{TIS}}$	0.08	0.10	0.08	0.10	0.09	0.11
$\mathcal{A}_{\mathrm{TOS}}$	0.01	0.03	0.01	0.02	0.01	0.01
Weighting	0.01	0.00	0.04	0.00	0.01	0.00
Part. rec. weighting	0.03	0.02	0.02	0.01	0.03	0.01
Total	0.67	0.55	0.58	0.55	0.82	0.61

Systematic uncertainties on the corrections for $\mathcal{A}^{CP}$ in percent, averaged over all D0 decay modes.

Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons

$$\mathcal{A}^{CP}(B^- \to D_s^- D^0) = (+0.5 \pm 0.2 \pm 0.5 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D_s^{*-} D^0) = (-0.5 \pm 1.1 \pm 1.0 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D_s^- D^{*0}) = (+1.1 \pm 0.8 \pm 0.6 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^- D^0) = (+2.5 \pm 1.0 \pm 0.4 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^- D^{*0}) = (-0.2 \pm 2.0 \pm 1.4 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^{*-} D^0) = (+3.3 \pm 1.6 \pm 0.6 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^{*-} D^{*0}) = (+2.3 \pm 2.1 \pm 1.7 \pm 0.3)\%$$

Values of $\mathcal{A}^{CP}$ where the first uncertainty is statistical, the second is systematic, and third is from $\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$.

D^0 decay mode	Run 1	Run 2	Run 1+2
$K^-\pi^+$	$6.88 \pm 0.24 \pm 0.12$	$7.35 \pm 0.12 \pm 0.11$	$7.22 \pm 0.11 \pm 0.10$
$K^-\pi^+\pi^-\pi^+$	$6.93 \pm 0.38 \pm 0.23$	$7.40 \pm 0.18 \pm 0.15$	$7.30 \pm 0.16 \pm 0.14$
Combined	$6.89 \pm 0.20 \pm 0.12$	$7.36 \pm 0.10 \pm 0.10$	$7.25 \pm 0.09 \pm 0.09$

Values of $R(D^-D^0/D_s^-D^0)/10^{-2}$ for each D^0 decay mode, for Run 1 and Run 2 and the combined measurement. The first uncertainty is statistical and the second is systematic

D^0 decay mode	Run 1	Run 2	Run 1+2
$K^-\pi^+$	$0.328 \pm 0.023 \pm 0.011$	$0.256 \pm 0.009 \pm 0.005$	$0.271 \pm 0.008 \pm 0.005$
$K^-\pi^+\pi^-\pi^+$	$0.316 \pm 0.033 \pm 0.015$	$0.272 \pm 0.012 \pm 0.008$	$0.278 \pm 0.012 \pm 0.007$
Combined	$0.324 \pm 0.019 \pm 0.010$	$0.262 \pm 0.007 \pm 0.005$	$0.271 \pm 0.007 \pm 0.005$

Values of $R(D^{*-}D^0/D^-D^0)$ for each D^0 decay mode, for Run 1 and Run 2 and the combined measurement. The first uncertainty is statistical and the second is systematic