CP violation in Charm

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CPV in Charm

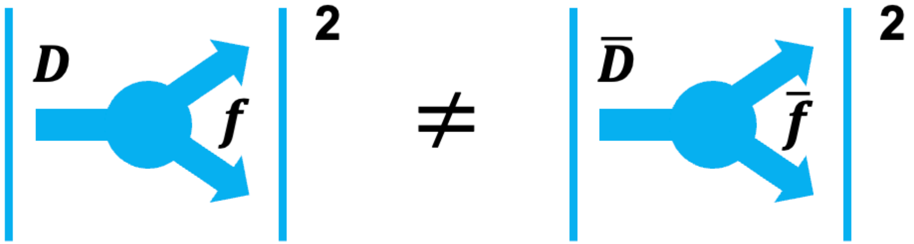
- Charm is only up-type quark with observable mixing and CPV effect, providing a unique sensitivity to possible new physics in up-type quark decays and complementing bottom and strange quark decays.
- In the charm sector, Cabibbo-favored and doubly Cabibbo-suppressed decays are dominated by a single diagram, leading to only tiny expected CP violation.
- Singly Cabibbo-suppressed decays receive comparable contributions from tree and penguin diagrams, making CP violation observable.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

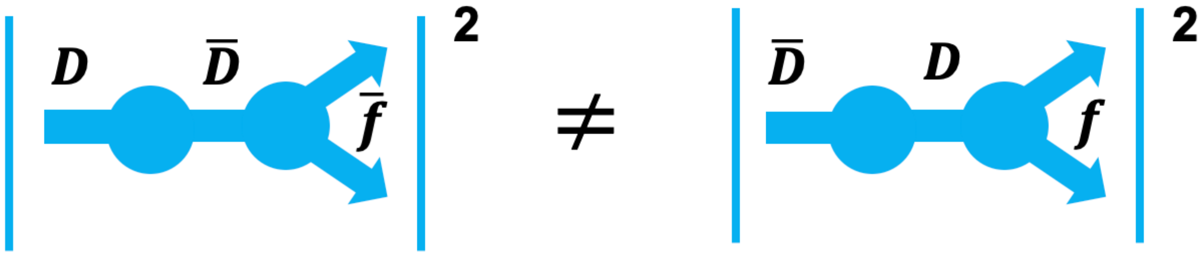
- CPV in the charm system is proportional to $2Im\left[\left(\frac{V_{cb}V_{ub}^*}{V_{cd}V_{ud}^*}\right)\right] \sim 10^{-3}$, a sizeable CPV could indicate BSM physics.

3 types of CP violation

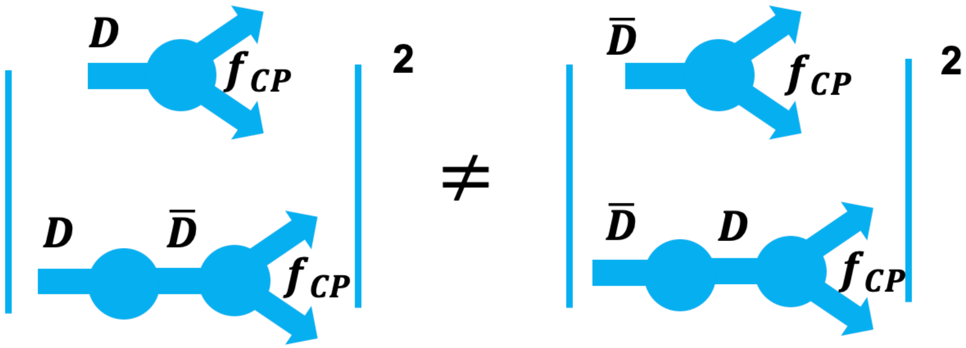
- CPV in decay
  - $\Gamma(D \to f) \neq \Gamma(\bar{D} \to \bar{f})$



- CPV in mixing
  - $\Gamma(D^0 \to \bar{D}^0) \neq \Gamma(\bar{D}^0 \to D^0)$

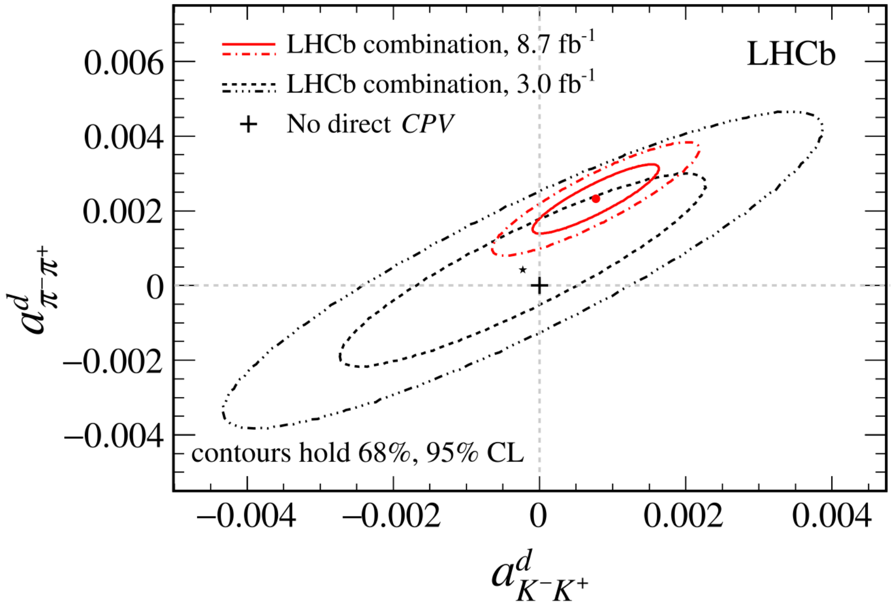


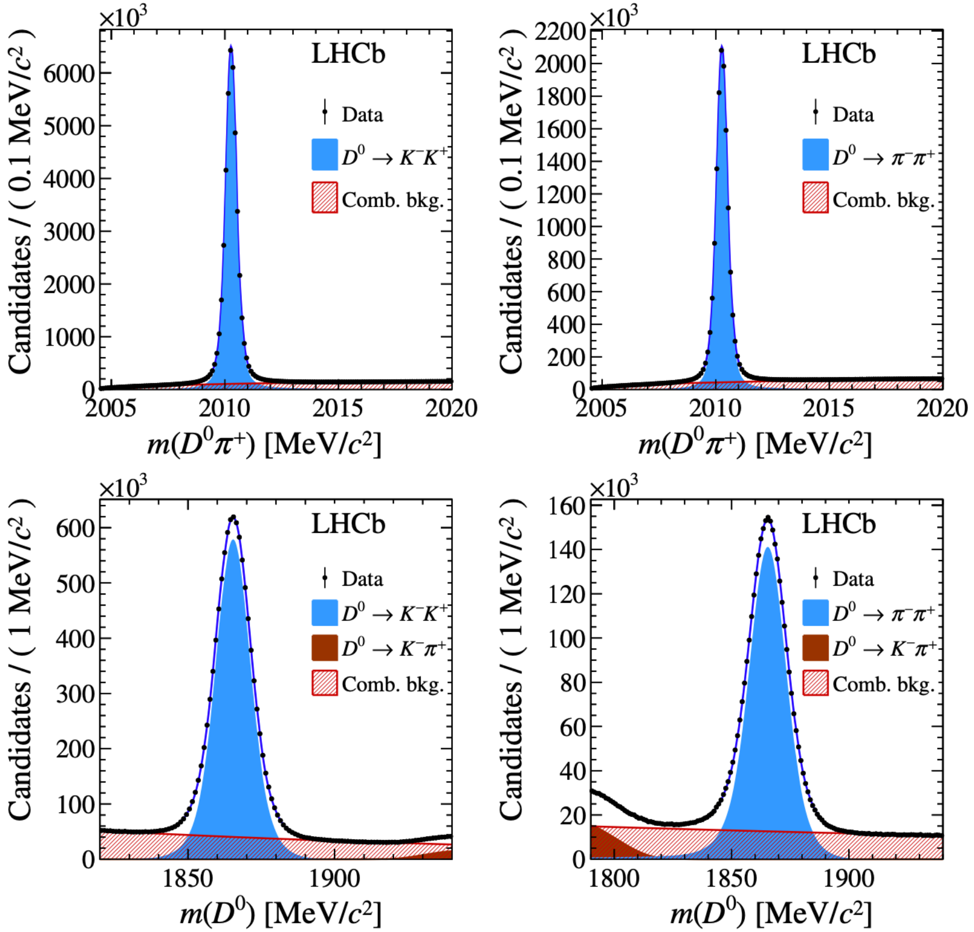
- CPV in interference between mixing and decay
  - $\Gamma(D^0 \to f_{CP}) \neq \Gamma(\bar{D}^0 \to f_{CP})$



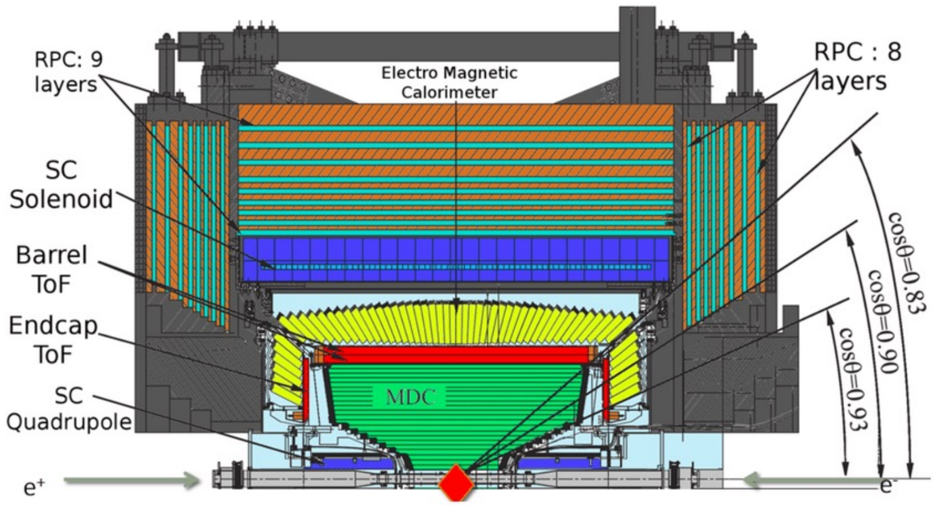
Experimental status

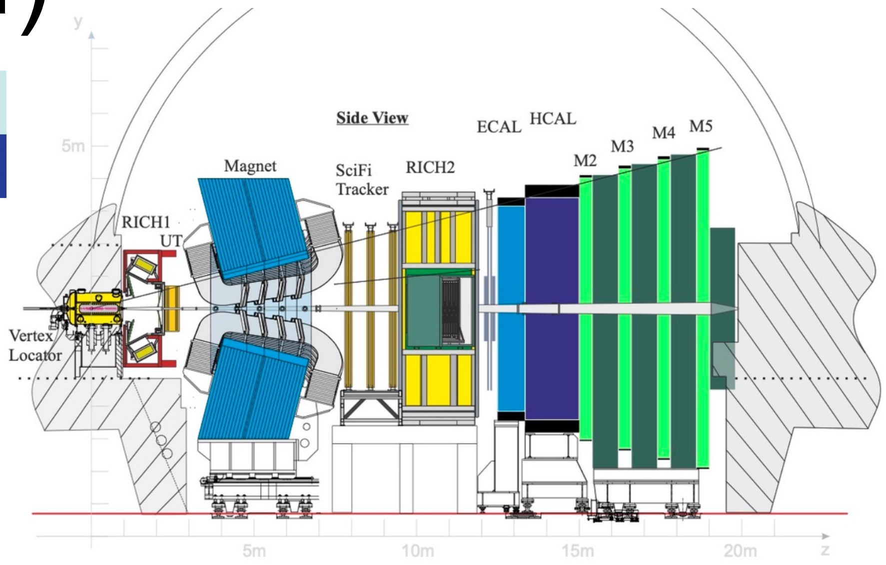
- First charm CPV observed in 2019 [PRL 122, 211803 (2019)]
  - $\Delta A_{CP} = A_{CP}(K^+K^- - \pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$ 5.3σ
- Evidence of CPV in 2023 [PRL 131, 091802 (2023)]
  - $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1)\times 10^{-4}$ 3.8σ

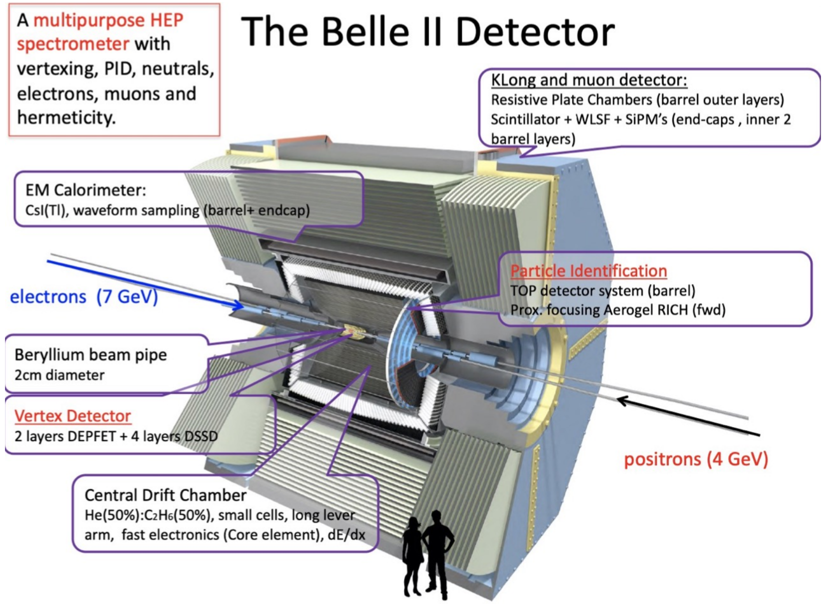


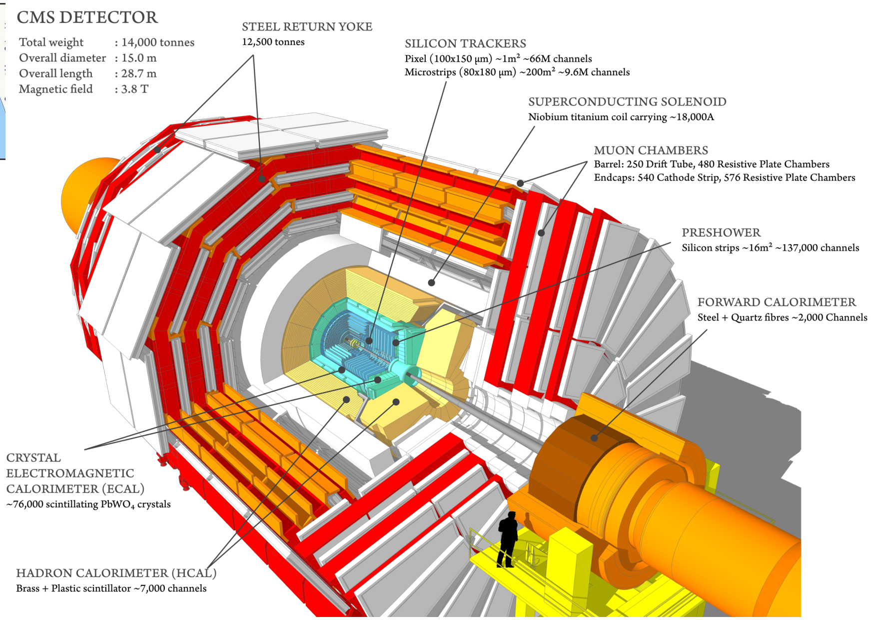


BESIII LHCb CMS and Belle (II)









Time dependent CPV in $D^0 \to K^- \pi^+$

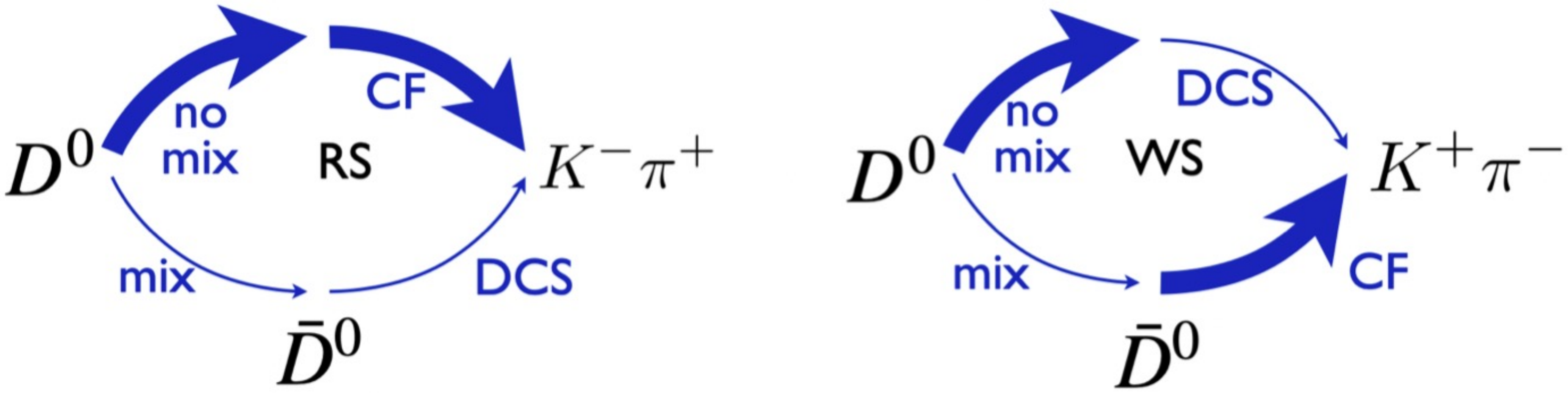
JHEP03(2025)149

PRD 111 (2025) 012001

CPV in $D^0 \to K^-\pi^+$

- The time evolution of D^0 and $\bar{D}^0$ is described by $i\frac{d}{dt}\begin{pmatrix}|D^0(t)\rangle \\ |\bar{D}^0(t)\rangle\end{pmatrix} = \underbrace{\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}}_{\hat{\mathcal{H}}=\hat{M}-\frac{i}{2}\hat{\Gamma}}\begin{pmatrix}|D^0(t)\rangle \\ |\bar{D}^0(t)\rangle\end{pmatrix}$
- The ratio of decay rates $R^{\pm}_{K\pi}$ of WS and RS is sensitive to mixing parameters x_{12} and y_{12}

$$R^-_{K\pi} = \frac{\Gamma(\bar{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} \qquad R^+_{K\pi} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\bar{D}^0 \to K^+\pi^-)} \qquad x_{12} = \frac{2|M_{12}|}{\Gamma}, y_{12} = \frac{|\Gamma_{12}|}{\Gamma}$$



arXiv:2506.15584

CPV in $D^0 \to K^-\pi^+$

- The time dependent ratio can be given by

$$R^{\pm}_{K\pi}(t) = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2$$

CP even: $R_{K\pi}$, $c_{K\pi}$, $c'_{K\pi}$

$$R_{K\pi} = \frac{R^{+}_{K\pi} + R^{-}_{K\pi}}{2}$$

$$c_{K\pi} \approx y_{12} cos\phi^{\Gamma}_{f} cos\Delta_f + x_{12} cos\phi^{M}_{f} sin\Delta_f$$

$$c'_{K\pi} \approx \frac{1}{4}(x^2_{12} + y^2_{12})$$

CP odd: $A_{K\pi}$, $\Delta c_{K\pi}$, $\Delta c'_{K\pi}$

$$A_{K\pi} = \frac{R^{+}_{K\pi} - R^{-}_{K\pi}}{R^{+}_{K\pi} + R^{-}_{K\pi}}$$

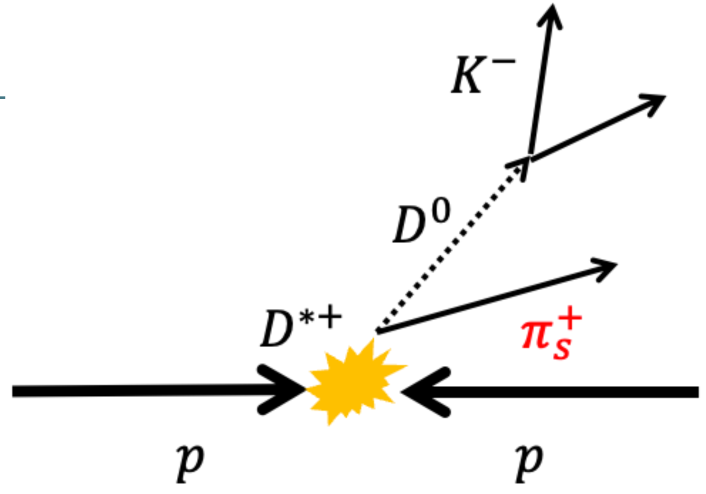
$$\Delta c_{K\pi} \approx x_{12} sin\phi^{M}_{f} cos\Delta_f - y_{12} sin\phi^{\Gamma}_{f} sin\Delta_f$$

$$\Delta c'_{K\pi} \approx \frac{1}{2} x_{12} y_{12} \sin(\phi^{M}_{f} - \phi^{\Gamma}_{f})$$

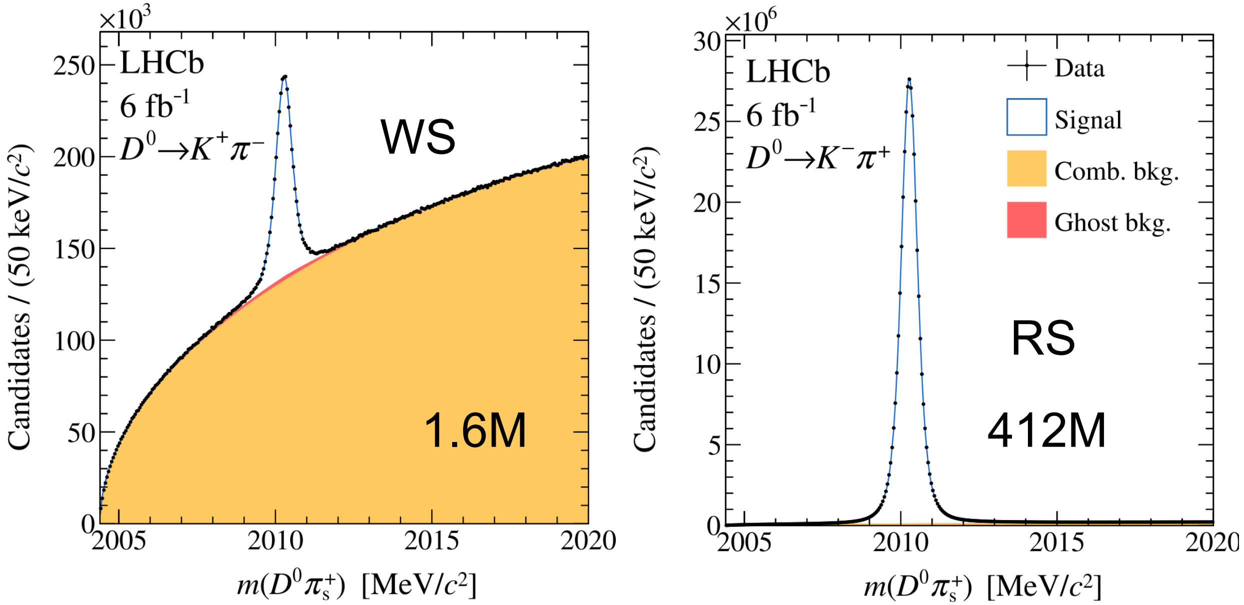
The weak phase $\phi^{\Gamma}_{f}, \phi^{M}_{f}$(also denote as $\phi^{\Gamma}_{2}, \phi^{M}_{2}$) , and strong phase are defined in PRD 103, 053008(2021)

CPV in $D^0 \to K^-\pi^+$ （Prompt）

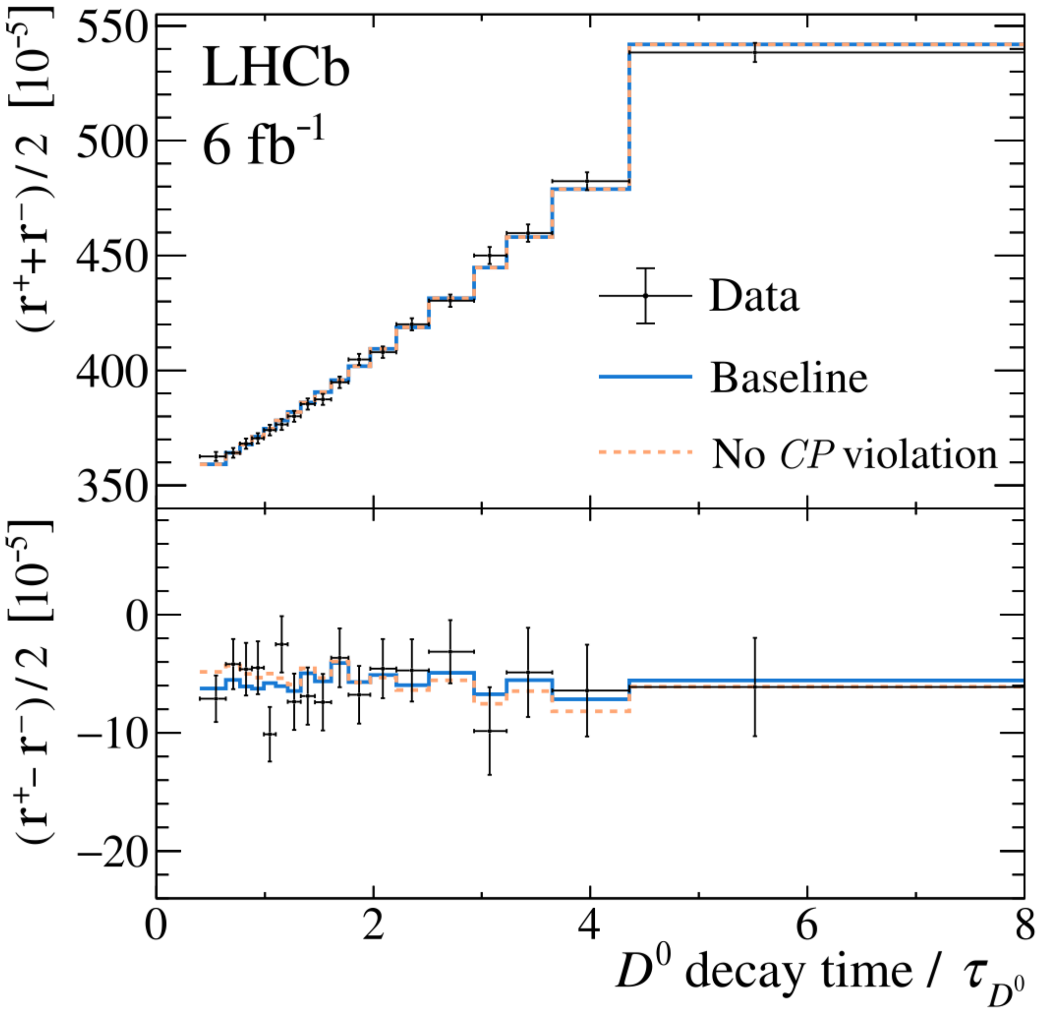
PRD 111 (2025) 012001



- Full Run2 data (6fb^{-1})
- D^0 from prompt $D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$
- Samples divided in bins of:
  - D^0 final states: $K^-\pi^+$ and $K^+\pi^-$
  - 3 Data taking period
  - 18 D^0 decay time intervals
- Simultaneous fit to WS and RS sample



CPV in $D^0 \to K^-\pi^+$ （Prompt)



$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

- Significance of quadratic term $c'_{K\pi}$: 3.4σ
- Consistent with CP symmetry

CPV in $D^0 \to K^-\pi^+$ （Doubly tagged)

- Run2 data ($5.4\ \mathrm{fb}^{-1}$)
- D^0 from $B \to D^{*+}(\to D^0\,\pi^+)\mu^- X$
  - Smaller sample size
  - Larger purity
  - Sensitive to lower D^0 decay time region
- Sample divided in bins of decay time and D^0 final states

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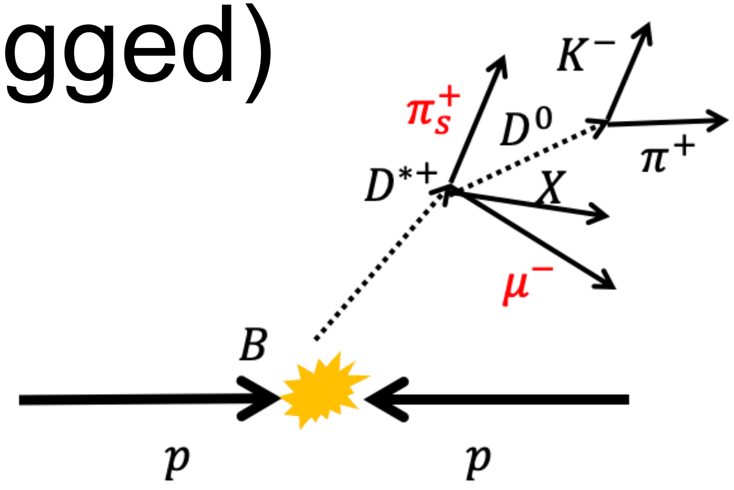
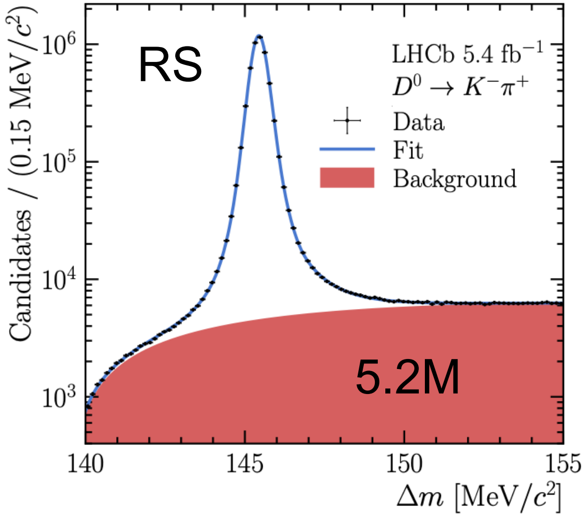
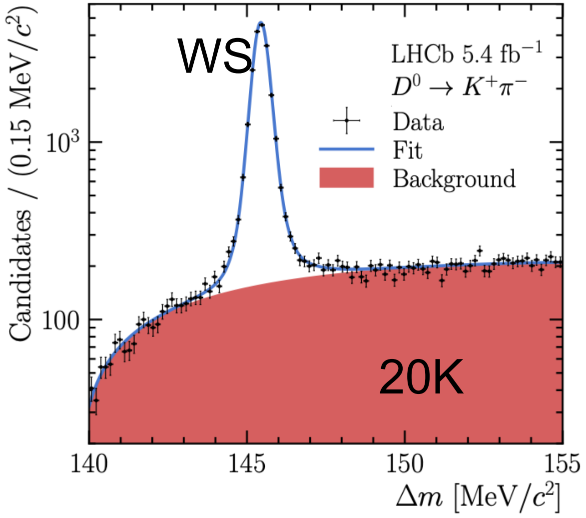
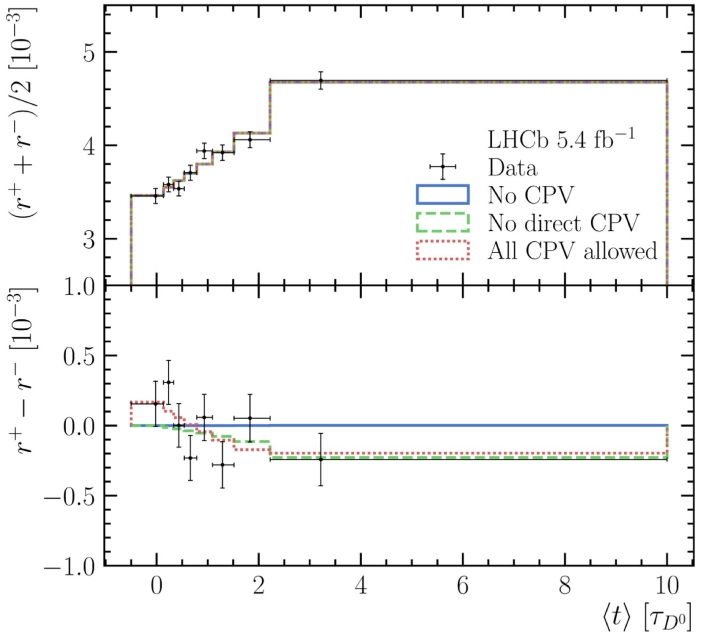






$$\Delta M = M(D^{*+}) - M(D^0)$$



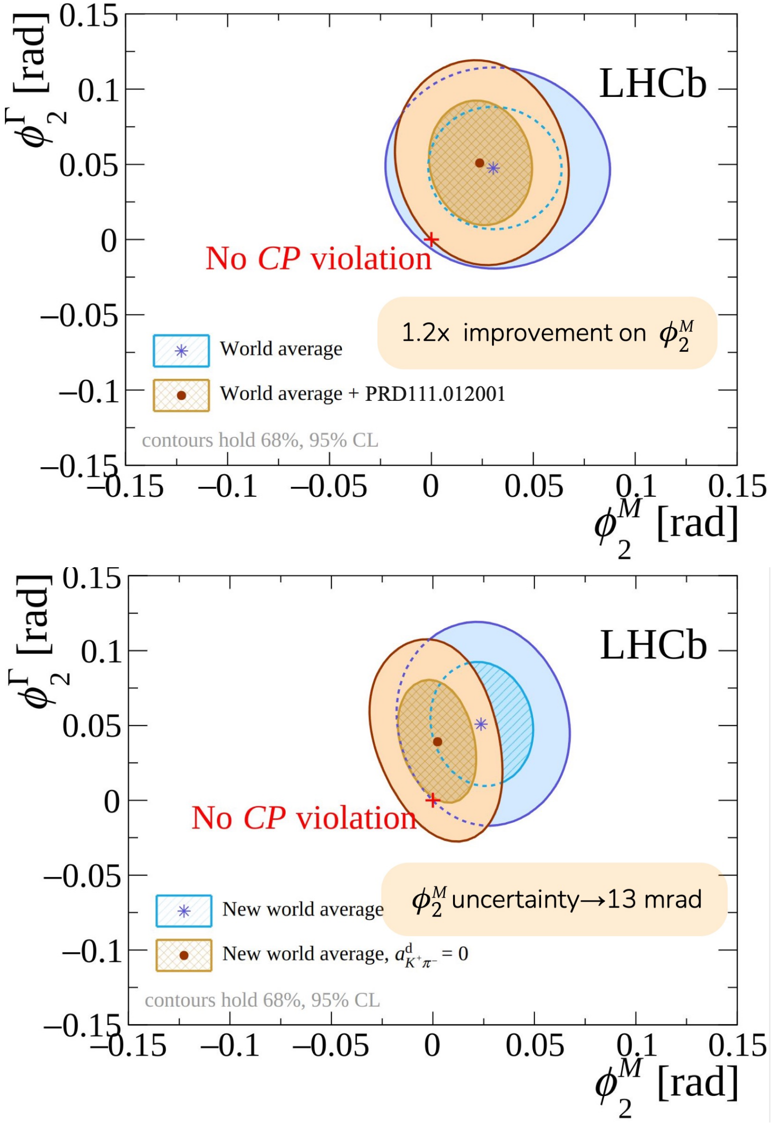
Consistent with CP symmetry

CPV in $D^0 \to K^-\pi^+$

From R. Ribatti

- The final results for both prompt and doubly tagged analysis
- Combined Run1 and Run2 results

	Prompt	Doubly tagged
$R_{K\pi}$	$(342.7 \pm 1.9)\times10^{-5}$	$(347.0 \pm 5.1)\times10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3)\times10^{-4}$	$(5.5 \pm 1.5)\times10^{-3}$
$c'_{K\pi}$	$(12.0 \pm 3.5)\times10^{-6}$	$(1.2 \pm 2.4)\times10^{-5}$
$A_{K\pi}$	$(-6.6 \pm 5.7)\times10^{-3}$	$(0.9 \pm 1.5)\times10^{-2}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4)\times10^{-4}$	$(-1.3 \pm 1.5)\times10^{-3}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6)\times10^{-6}$	$(1.2 \pm 2.4)\times10^{-5}$



Time dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

PRL.133.101803 (2024)

Time dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

PRL.133.101803 (2024)

- Time dependent asymmetry for D^0 meson decaying to CP eigenstate

$$A_{CP}(f_{CP},t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\overline{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\overline{D}^0\to f_{CP}}(t)} \approx a_{f_{CP}}^{dir} + \Delta Y_{f_{CP}} \frac{t}{\tau_D}$$

- The gradient $\Delta Y_{f_{CP}}$ can be defined in terms of the Universal CPV parameter $\Delta Y \equiv \eta_{f_{CP}} \Delta Y_{f_{CP}}$

- For multibody D^0 decays, an effective time-dependent asymmetry is defined:

$$\Delta Y_f^{eff} = \left(2F_+^f - 1\right)\Delta Y$$

F_+^f : CP even fraction of the decay $D^0 \to f$

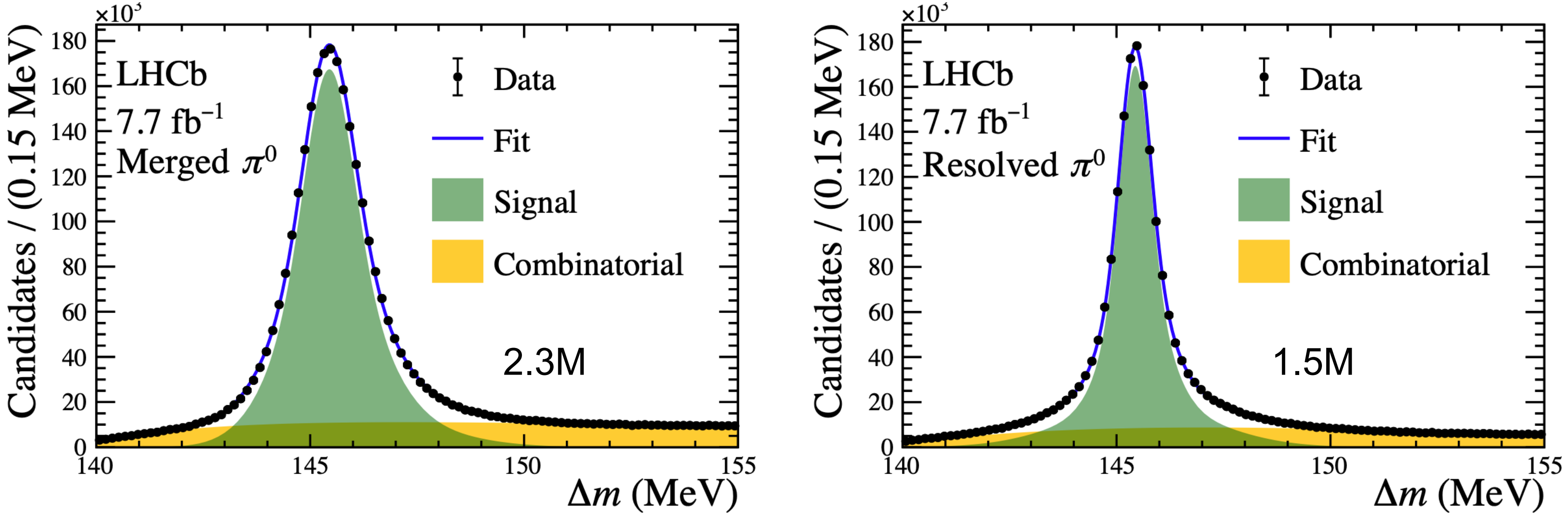
- Experimentally:

$$A_{raw}(t) = \frac{N_{D^0}(t) - N_{\overline{D}^0}(t)}{N_{D^0}(t) + N_{\overline{D}^0}(t)} = a_{f_{CP}}^{dir} + \Delta Y_{eff} \frac{t}{\tau_D} + A_{det}(t) + A_{prod}(t)$$

- Per-event kinematic weighting procedure to correct nuisance asymmetries

Time dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

- Full Run2 + 2012 dataset (7.7fb^{-1})
- D^0 from prompt decay $D^{*+} \to D^0\pi^+_{tag}$
- π^0 reconstructed as Merged (γ clusters in the same ECAL cell) or Resolved (γ clusters in different cell)
- Signal yields are extracted from fit to $\Delta m \equiv m(D^{*+}) - m(D^0)$



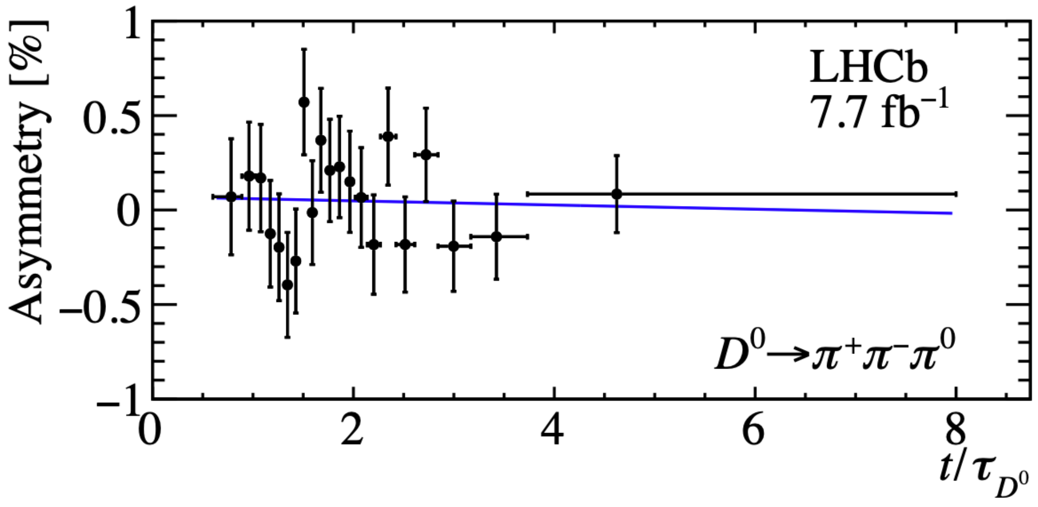
Time dependent CPV in $D^0 \to \pi^+\pi^-\pi^0$

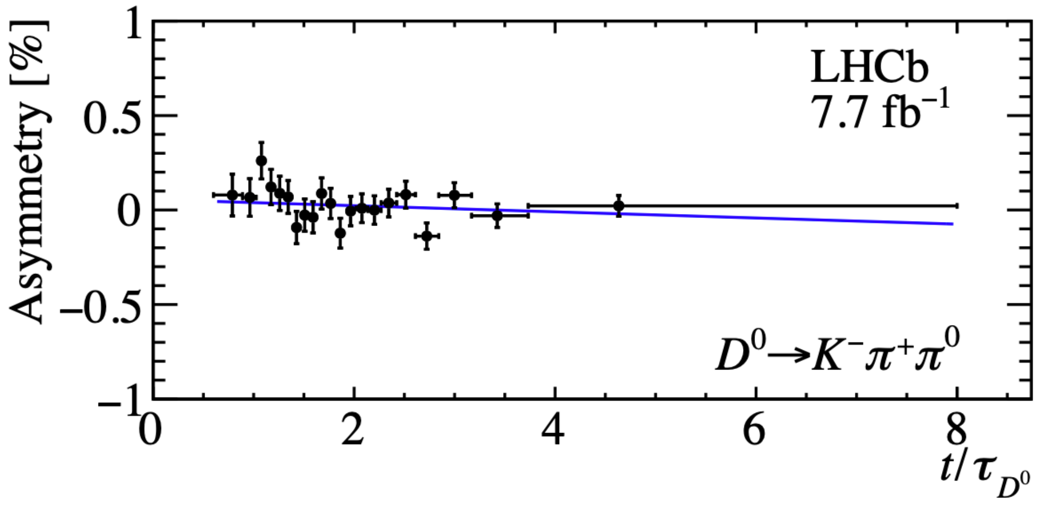
- A_{CP} extracted from fit to Δm in each t/τ_D bin (21 bins)
  - Simultaneously fit to $D^0/\bar{D}^0$ sample, with shared shape parameters
  - Mean decay time calculated as a weighted average of all candidates in that bin
- Linear fit to $A_{CP}(t)$ to extract $\Delta Y_f^{eff} = \left(2F_+^f - 1\right)\Delta Y$
- $\mathrm{A_{CP}(t)}$ for control channel $D^0 \to K^-\pi^+\pi^0$ is also measured

$F_+^f = 0.973 \pm 0.017$ (CLEO-*c*)

$$\Delta Y_{\pi\pi\pi}^{eff} = (-1.2 \pm 6.0 \pm 2.3)\times 10^{-4}$$

$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4)\times 10^{-4}$$





No evidence of CPV is found

CPV in $D^0 \to K_s^0 K^{\pm}\pi^{\mp}$

JHEP03(2024)107

CPV in $D^0 \to K_S^0 K^\pm \pi^\mp$

JHEP03(2024)107

- Multibody decays allow to access many intermediate processes
- Dalitz plot of a three body decay can be used to study localized CPV
- A model independent unbinned method: Energy test is used to search for asymmetries in local phase space
- Test statistic:

Sensitive to local asymmetry, but not global asymmetry

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

All pairs of D^0 candidates — All pairs of $\bar{D}^0$ candidates — All pairs of $D^0 - \bar{D}^0$ pairs

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

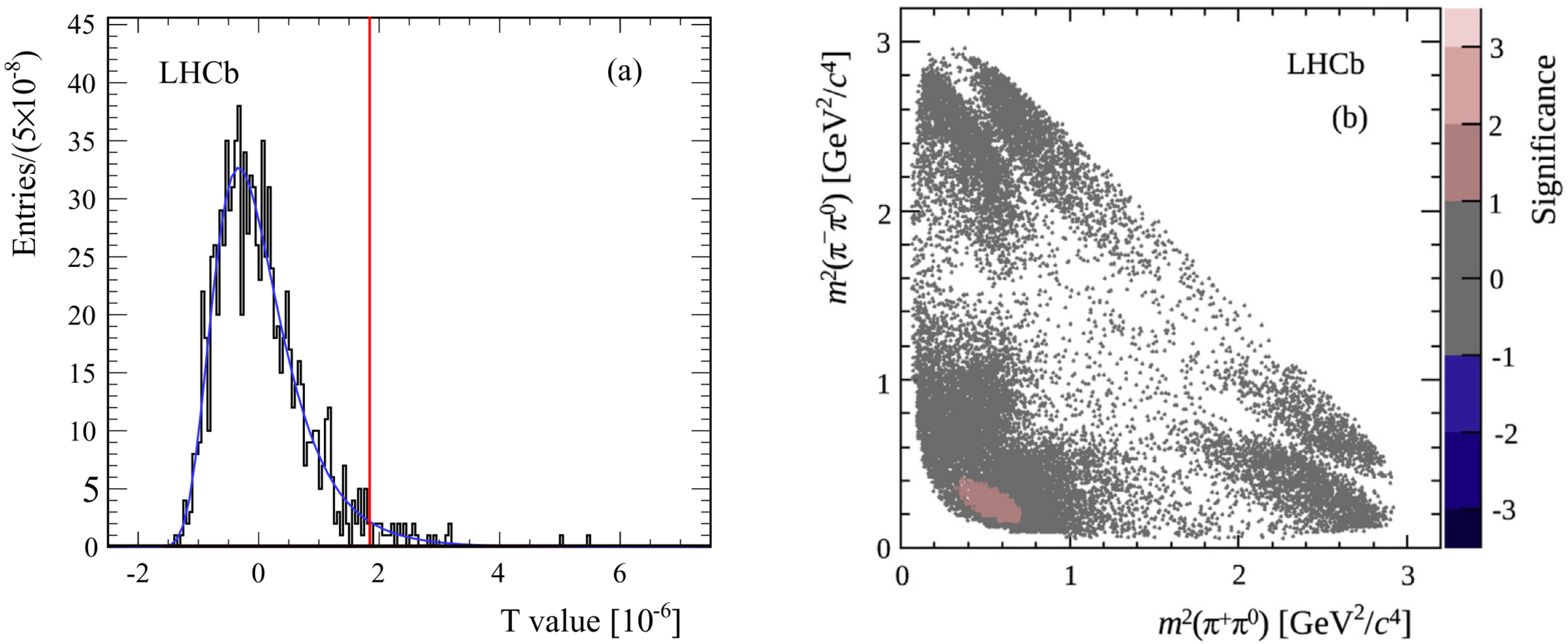
Euclidean distance: $d_{ij}^2 = \left(s_{12,i} - s_{12,j}\right)^2 + \left(s_{13,i} - s_{13,j}\right)^2 + \left(s_{23,i} - s_{23,j}\right)^2$

Metric parameter δ: the distance scale probed, optimized to maximize the sensitivity to CPV

CPV in $D^0 \to K_S^0 K^\pm \pi^\mp$

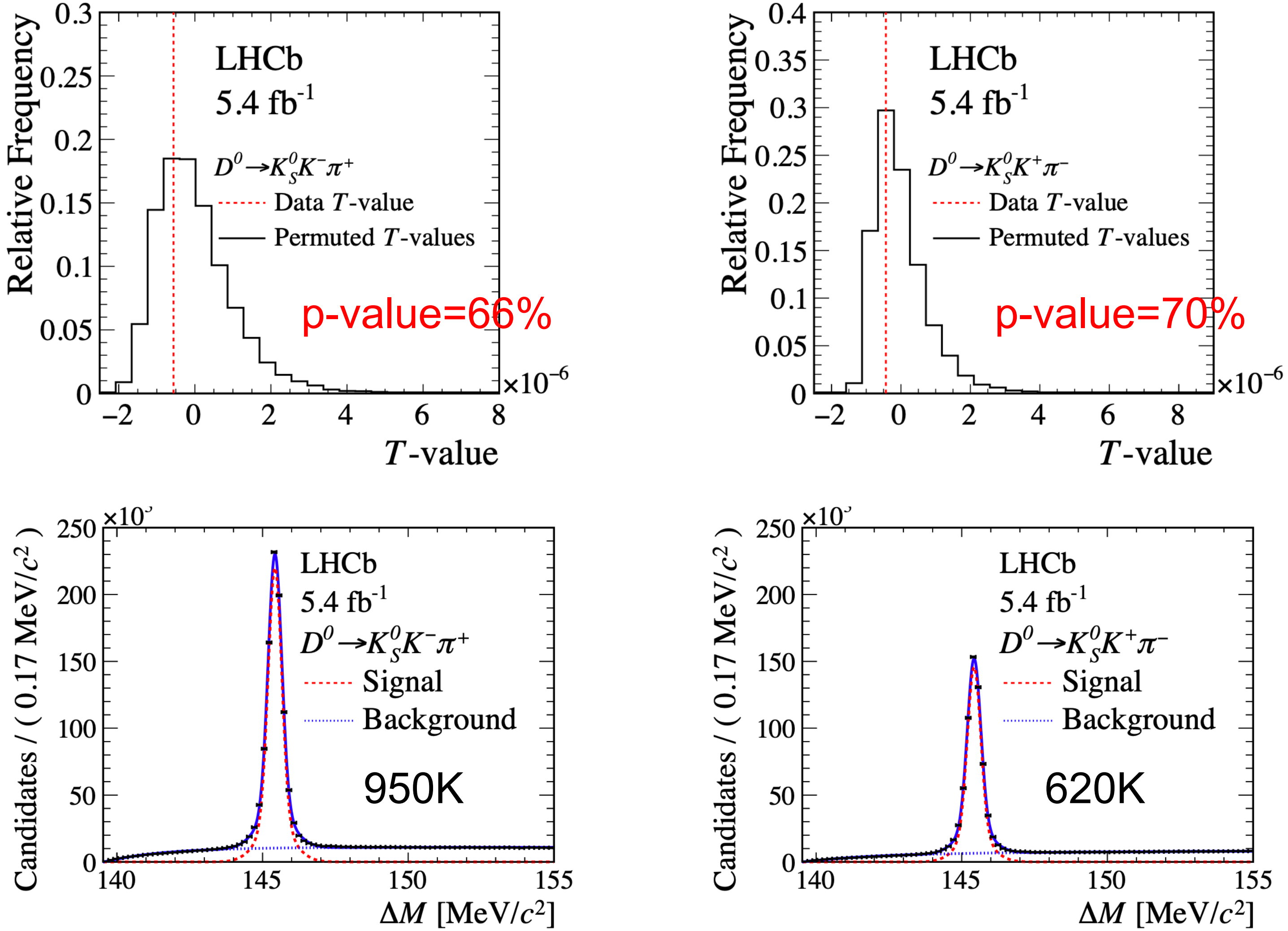
- Non-CPV samples are obtained by assigning flavor to $D^0/\overline{D}^0$ sample randomly (permutation method).
- Compare T from data with that from non-CPV samples
- The fraction of the non-CPV sample with T greater than that observed in data is the p-value

Physics Letters B 740 (2015) 158–167



CPV in $D^0 \to K_S^0 K^{\pm}\pi^{\mp}$

- Run2 dataset (5.4fb^{-1})
- Purity estimated by fitting to $\Delta m \equiv m(D^{*+}) - m(D^0)$ spectrum
- Combinatorial background studied using Δm sideband samples, physics background studied with simulation. No background asymmetry is observed
- Two control channels $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K_S^0\pi^-\pi^+$ used to study detector effect and potential biases



No evidence of CPV

Direct CPV in $D^+ \to K^+K^-\pi^+$

PRL.133.251801 (2024)

Direct CPV in $D^+ \to K^+K^-\pi^+$

PRL.133.251801 (2024)

- The physics variable we are interested in is

$$A_{CP} = \frac{\Gamma(H \to f) - \Gamma(\bar{H} \to \bar{f})}{\Gamma(H \to f) + \Gamma(\bar{H} \to \bar{f})} \propto sin\Delta\phi \sin\Delta\delta$$

- Experimentally, the variable easily accessed is

$$A_{raw} = \frac{N(H \to f) - N(\bar{H} \to \bar{f})}{N(H \to f) + N(\bar{H} \to \bar{f})}$$

- The nuisance asymmetry must be taken into account

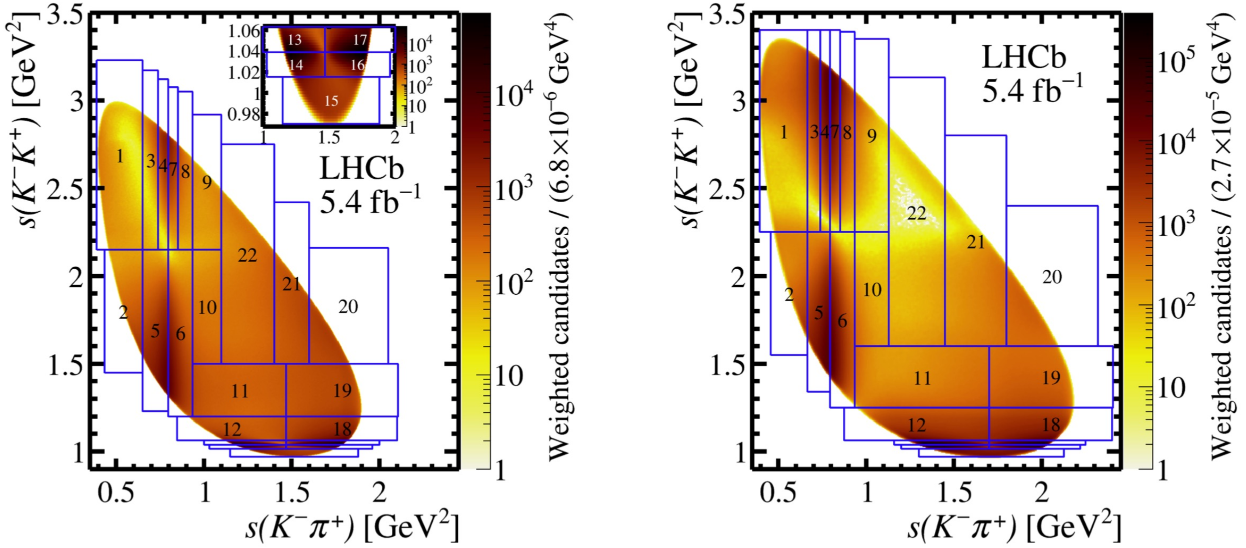
$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

- A control channel is introduced to cancel the leading-order nuisance asymmetries, and the CP asymmetry difference between the two modes is given by

$$\Delta A_{CP} = A_{CP}^{signal} - A_{CP}^{control} = \Delta A_{raw} - \Delta A_{prod} - \Delta A_{det}$$

CPV in $D^+ \to K^+K^-\pi^+$

Binning inspired by amplitude analysis PRD 78 (2008) 072003



- Run2 dataset ($5.4\mathrm{fb}^{-1}$)
- Choose CF decay $D_s^+ \to K^+K^-\pi^+$ as control mode
- Dalitz plot are divided into bins and ΔA_{CP} for each bin are measured

$$\Delta A_{CP}^i = A_{raw}^{i,S} - A_{raw}^{i,C} - \Delta A_{raw}^{global}$$

- ΔA_{raw}^{global} is the global difference in asymmetries averaged over all bins in the Dalitz plot

$$\Delta A_{raw}^{global} = \frac{\Sigma_i^{N_{bins}} \frac{A_{raw}^{i,S} - A_{raw}^{i,C}}{\sigma^2_{A_{raw}^{i,S}} + \sigma^2_{A_{raw}^{i,C}}}}{\Sigma_i^{N_{bins}} \frac{1}{\sigma^2_{A_{raw}^{i,S}} + \sigma^2_{A_{raw}^{i,C}}}}$$

- In absence of CPV, the significance of ΔA_{CP}^i, defined as $S_{\Delta_{CP}}^i = \frac{\Delta A_{CP}^i}{\sigma_{\Delta A_{CP}^i}}$, follows a normal distribution, with χ^2 statistics given by

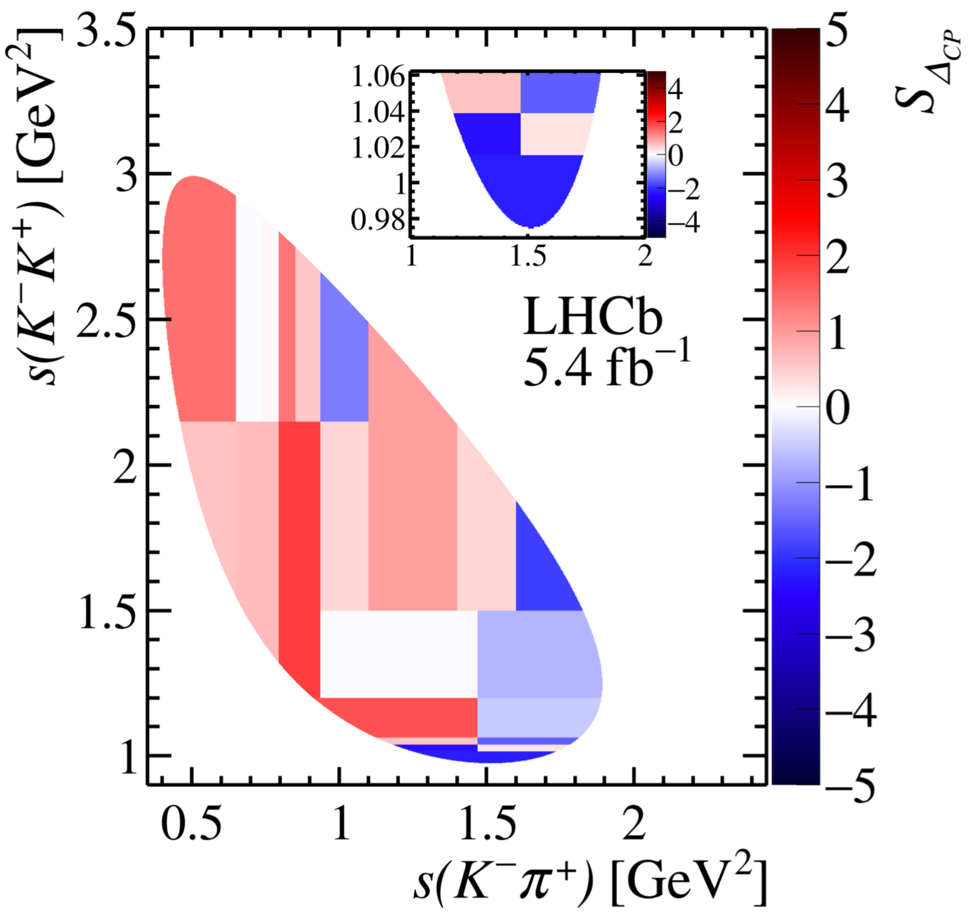
$$\chi^2 = \Sigma_i^{N_{bins}} \left(S_{\Delta_{CP}}^i\right)^2$$

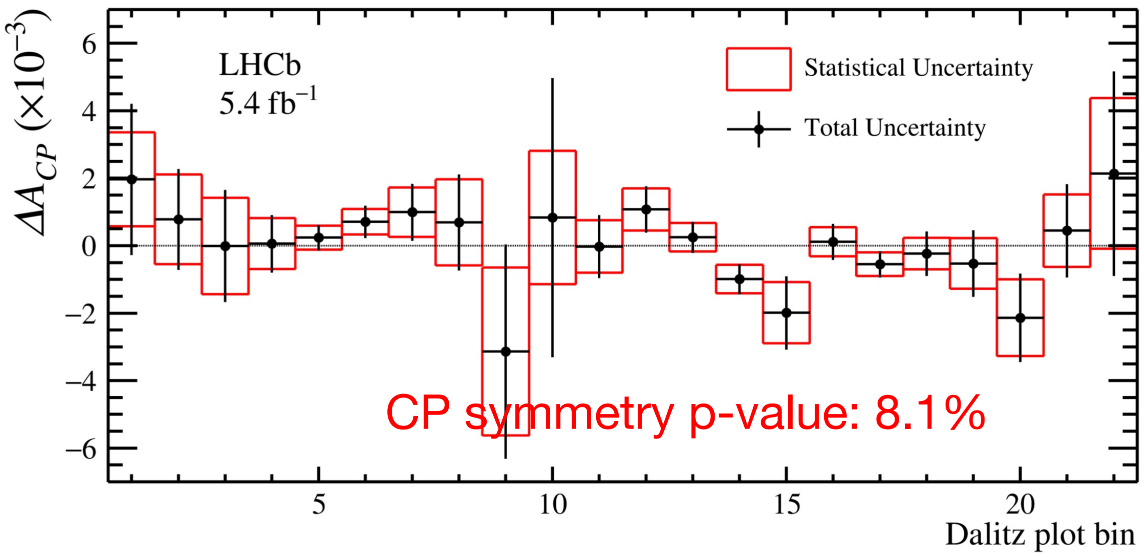
Any difference between the global asymmetries in the two decays is canceled by this term

Cancel the instrumental asymmetry

CPV in $D^+ \to K^+K^-\pi^+$

- Significance variation over Dalitz plot





Asymmetry in ϕ region: $A_{CP}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26)\times 10^{-3}$

Asymmetry in K^{*0} region: $A_{CP}^{K^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18)\times 10^{-3}$

CPV in $D^0 \to K_s^0 K_s^0$

PRD.111.012015(2025)

PRD.112.012017(2025)

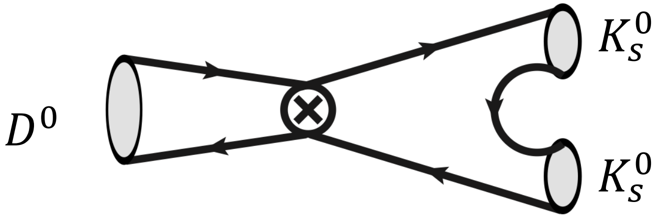
EPJC.84(2024)1264

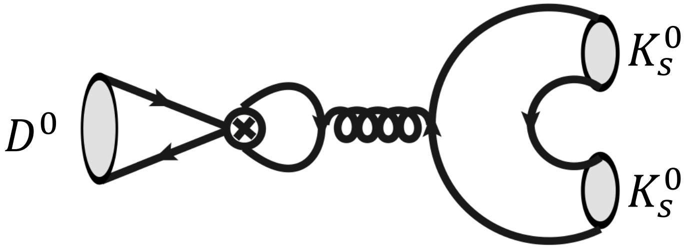
LHCb-PAPER-2025-036 (In preparation)

CPV in $D^0 \to K_S^0 K_S^0$

- Interference between W exchange and penguin annihilation diagram can generate CP asymmetries at 1%

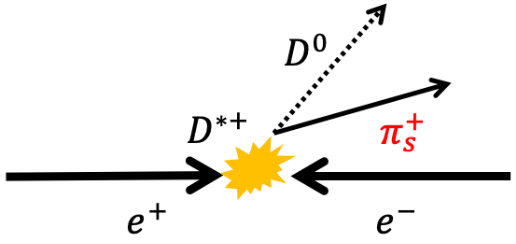
PRD.92.054036 (2015)



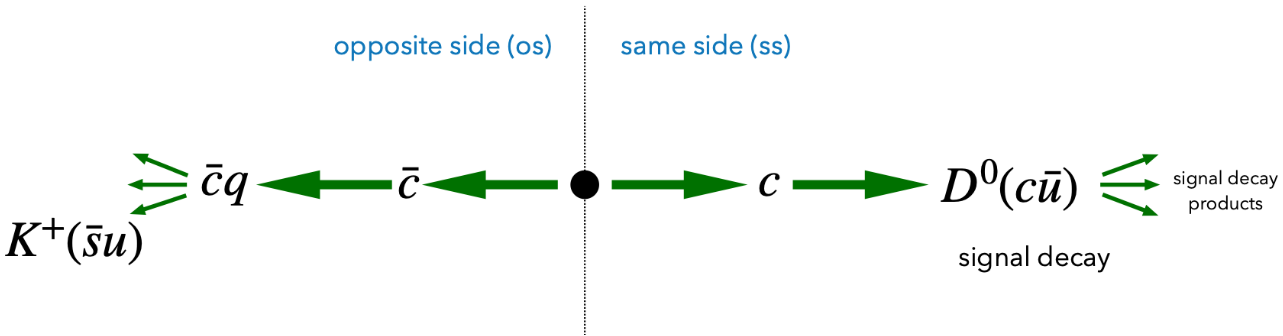


- Two different flavor tagging method

D^* tagger



Charm flavor tagger (CFT)



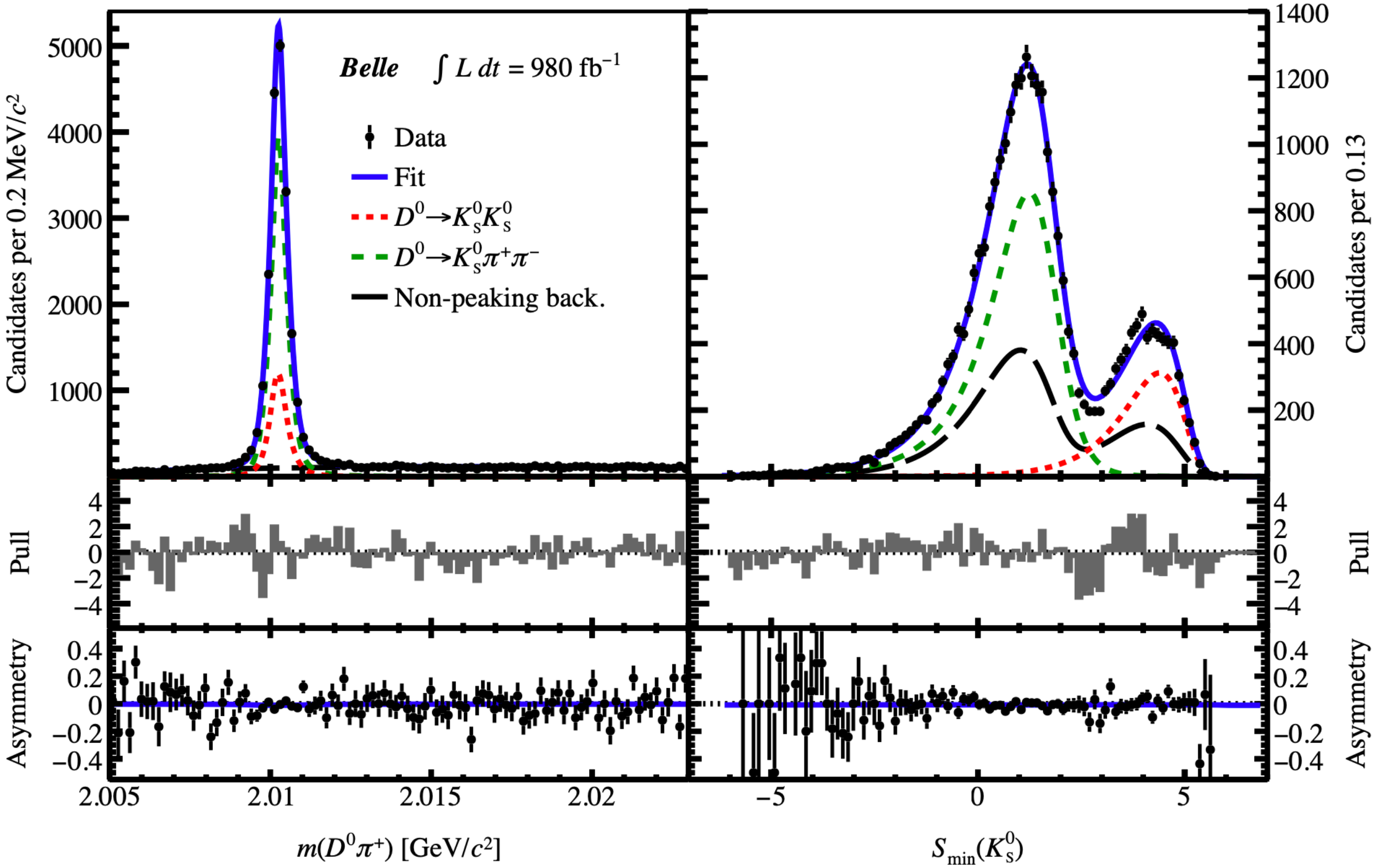
CPV in $D^0 \to K_S^0 K_S^0$

PRD.111.012015(2025)

- With $D^{*+} \to D^0\pi^+$ flavor tagger
- $980\mathrm{fb}^{-1}$ Belle and $428\mathrm{fb}^{-1}$ Belle II data
- Use control channel $D^0 \to K^-K^+$ to correct detection and production asymmetry
- CP observable $A_{CP}(D^0 \to K_S^0 K_S^0) = A_{raw}^{K_S^0 K_S^0} - (A_{raw}^{KK} - A_{CP}(D^0 \to K^-K^+))$
- Main background arises from $D^0 \to K_S^0\pi^+\pi^-$, can be distinguished using K_S^0 flight distance significance $S_{min}(K_S^0)$ defined as
  - $S_{min}(K_S^0) = \log[\min(\frac{L_1}{\sigma_{L_1}}, \frac{L_2}{\sigma_{L_2}})]$

CPV in $D^0 \to K_S^0 K_S^0$

- Signal yields and raw asymmetry extracted by fitting to $m(D^0\pi^+)$ and $S_{min}(K_S^0)$ spectrum, simultaneously for D^{*+} and D^{*-} candidates
- The signal and $D^0 \to K_S^0\pi^+\pi^-$ background peaking at different position in $S_{min}(K_S^0)$ spectrum



Belle: $A\left(D^0 \to K_S^0 K_S^0\right) = (-1.1 \pm 1.6 \pm 0.1)\%$

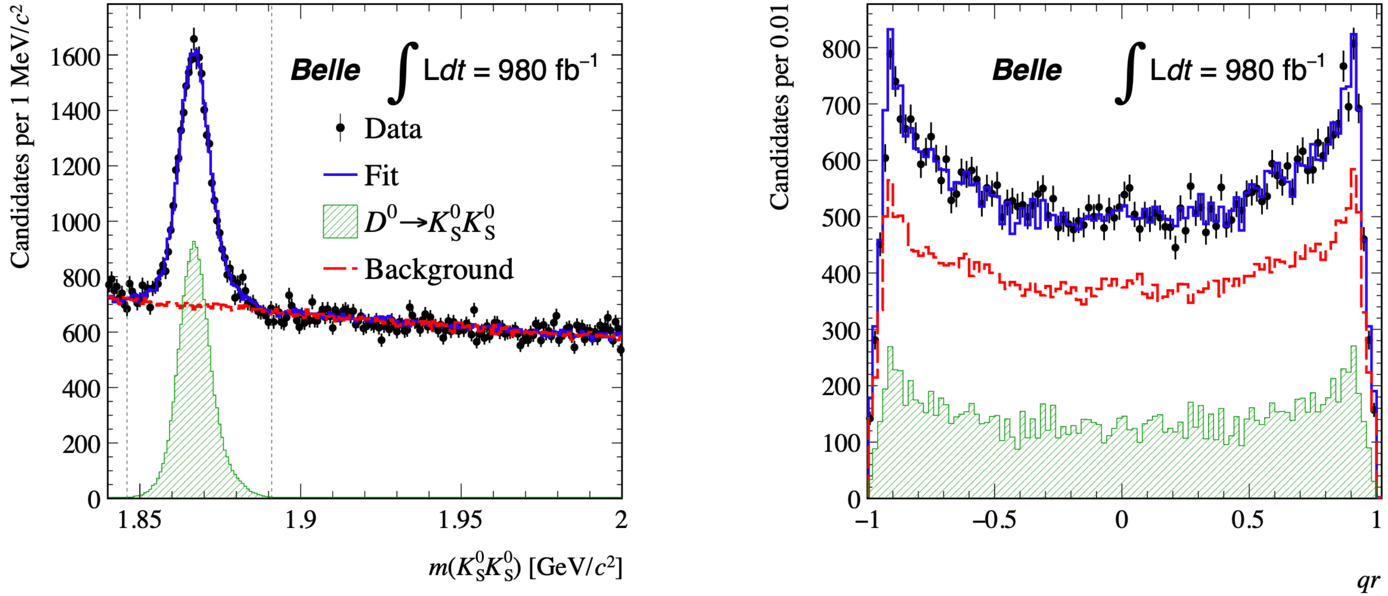
Belle II: $A\left(D^0 \to K_S^0 K_S^0\right) = (-2.2 \pm 2.3 \pm 0.1)\%$

Combined: $A\left(D^0 \to K_S^0 K_S^0\right) = (-1.4 \pm 1.3 \pm 0.1)\%$

CPV in $D^0 \to K_s^0 K_s^0$

PRD.112.012017(2025)

- With charm flavor tagger
- 980fb^{-1} Belle and 428fb^{-1} Belle II data, but all $D^{*+} \to D^0\pi^+$ candidates are removed
- Use BDT and $S_{min}(K_s^0)$ to suppress $D^0 \to K_s^0\pi^+\pi^-$ background
- Signal yields and raw asymmetry extracted by fitting to $m(K_S^0 K_S^0)$ and qr
  - q: flavor tag (± 1)
  - r: dilution factor $r = 1 - 2\omega$, ω is mistag probability for each candidate



Belle: $A(D^0 \to K_S^0 K_S^0) = (2.5 \pm 2.7 \pm 0.4)\%$

Belle II: $A(D^0 \to K_S^0 K_S^0) = (-0.1 \pm 3.0 \pm 0.3)\%$

Combined: $A(D^0 \to K_S^0 K_S^0) = (1.3 \pm 2.0 \pm 0.2)\%$

Combine D^* tagged and CFT tagged:
$A(D^0 \to K_S^0 K_S^0) = (-0.6 \pm 1.1 \pm 0.1)\%$

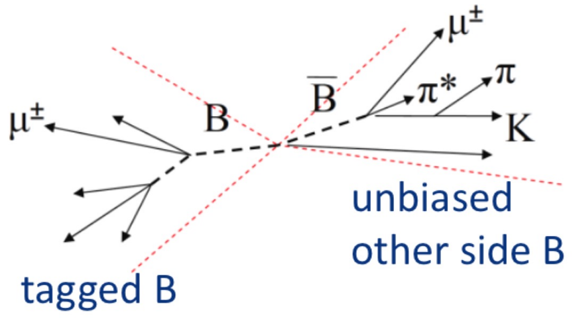
CPV in $D^0 \to K_S^0 K_S^0$ from CMS

EPJC.84(2024)1264

- 41.6fb^{-1} B parking dataset collected with a set of single-muon triggers with different minimum thresholds on the muon p_T and impact parameter

- Triggers require muons inconsistent with being produced in the primary interaction

$b \to \mu X$



- 80% events come from semileptonic decays of b hadron， nearly all of which decay to charm hadrons.

- The flavor of neutral D meson from pion charge from decay $D^{*\pm} \to D^0\pi^\pm$

- A control channel with same final state $D^0 \to K_S^0\pi^+\pi^-$ is introduced to cancel the production and detection asymmetry

$$\Delta A_{CP} = A_{CP}^{raw}(D^0 \to K_S^0 K_S^0) - A_{CP}^{raw}(D^0 \to K_S^0\pi^+\pi^-)$$

CPV in $D^0 \to K_S^0 K_S^0$ from CMS

A 2D fit to the distribution of $m(D\pi^\pm)$ and $m(K_S^0 K_S^0)$ are performed to extract signal yields, simultaneously on D^{*+} and D^{*-} samples

All parameters of pdfs are shared for D^{*+} and D^{*-} samples, except for the yields

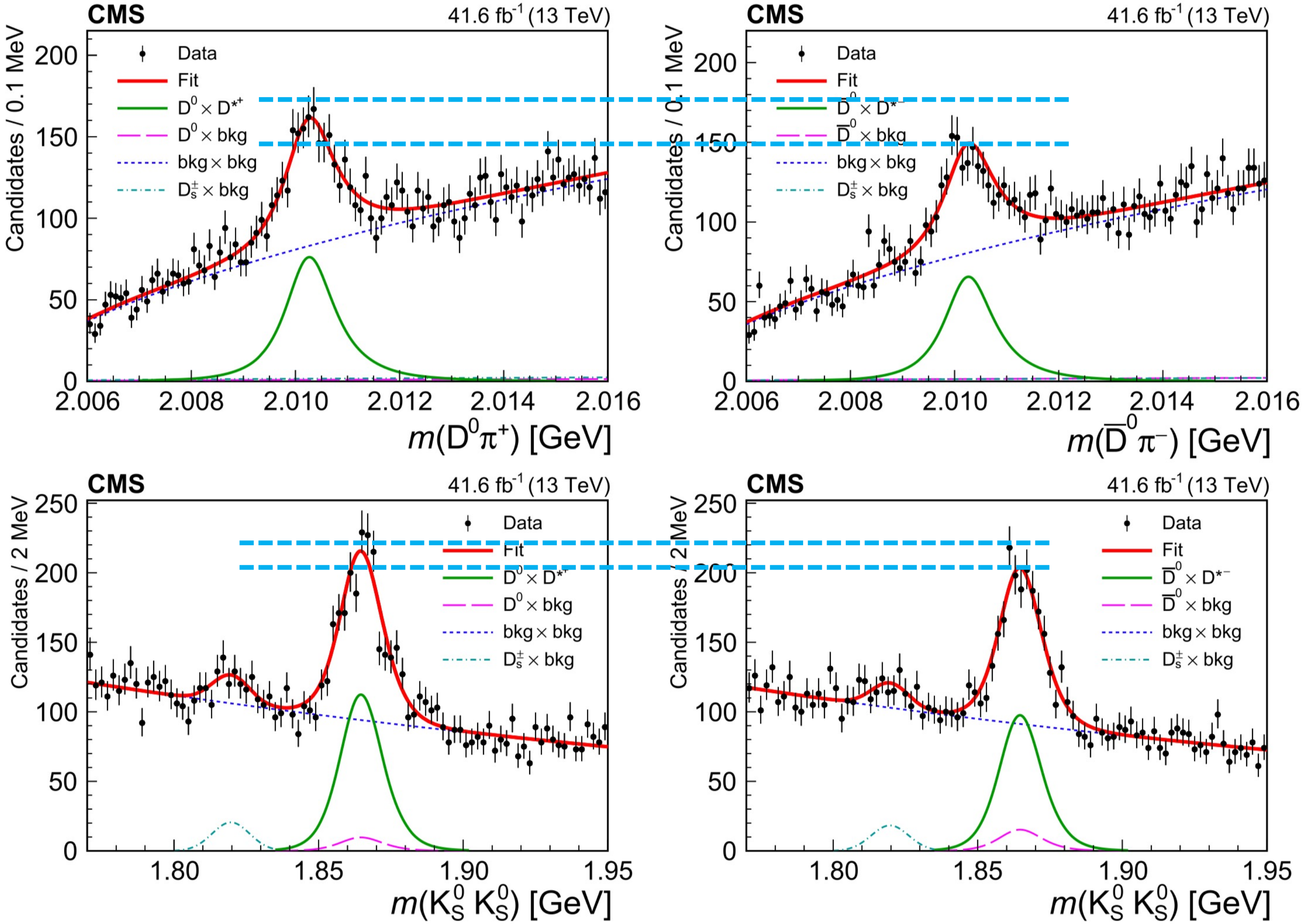
The difference in the CP asymmetries between $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0 \pi^+\pi^-$

$$\Delta A_{CP}(D^0 \to K_S^0 K_S^0) = (6.3 \pm 3.0 \pm 0.2)\%$$

Using the world average value:

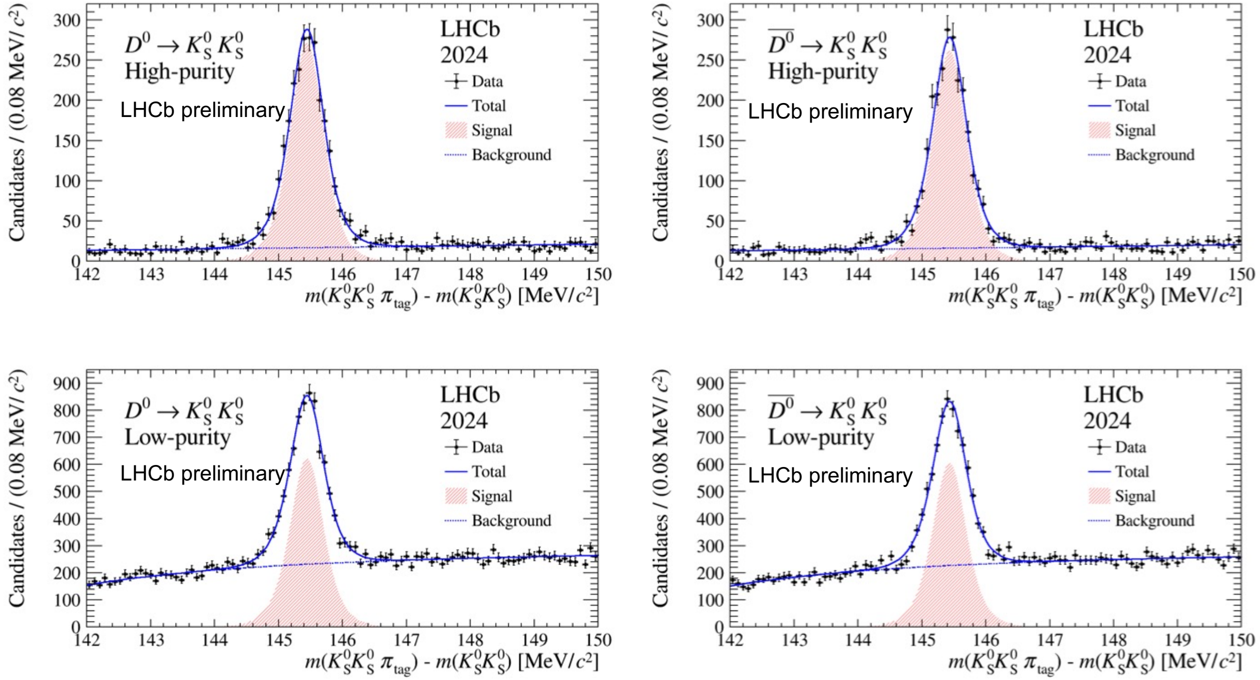
$$A_{CP}(D^0 \to K_S^0 \pi^+\pi^-) = (-0.1 \pm 0.8)\%$$

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%$$



CPV in $D^0 \to K_S^0 K_S^0$ from LHCb

- 6.2fb^{-1} LHCb Run 3 data of best quality, same lumi of the Run 2 analysis
- Data divided into 8 blocks according to data-taking period with different running conditions, and analyzed separately. Each sample further split in two subsamples according to a multivariate classifier (high/low-purity)
- Benefit from new trigger system, events containing K_S^0 are selected at first level trigger for every bunch crossing → 3x higher signal efficiency
- Signal yields and CP asymmetries extracted from 3D fit to $\Delta m \equiv m(D^{*+}) - m(D^0)$ and two $m(K_S^0)$, simultaneously for D^0 and $\overline{D}^0$ samples
- Nuisance asymmetries corrected by reweighting individual candidates with weights extracted from a calibration sample via a kNN algorithm



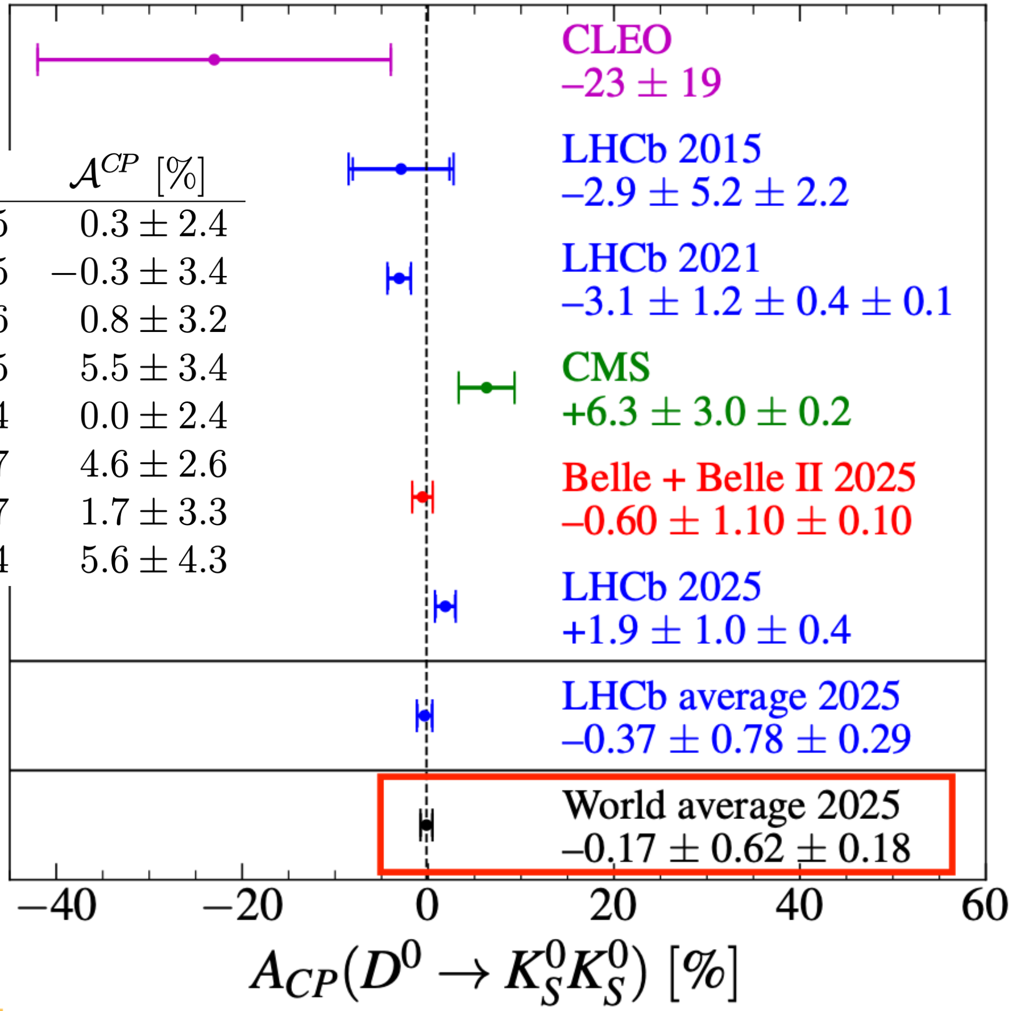
Integrate ALL data blocks

15676 signal candidates, 3x larger than Run2 sample (~5400 candidates for 6/fb)

CPV in $D^0 \to K_S^0 K_S^0$ from LHCb

- The measured CP asymmetries for different data blocks are compatible with each other
- The weighted average is
  $A^{CP} = (1.86 \pm 1.04 \pm 0.38)\%$
- Most precise single measurement of this quantity, compatible with CP symmetry, compatible with world average of previous measurement.
- Combine with LHCb previous measurement:
  $A^{CP} = (-0.37 \pm 0.78 \pm 0.29)\%$

Data block	Yield	$\mathcal{A}^{CP}$ [%]
1	2915 ± 85	0.3 ± 2.4
2	1385 ± 55	-0.3 ± 3.4
3	1639 ± 56	0.8 ± 3.2
4	1534 ± 75	5.5 ± 3.4
5	3149 ± 94	0.0 ± 2.4
6	2544 ± 77	4.6 ± 2.6
7	1599 ± 67	1.7 ± 3.3
8	911 ± 54	5.6 ± 4.3



Expect significant further improvement with complete Run 3 sample

CPV in $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)

PRD 112, 012006 (2025)

CPV in $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$

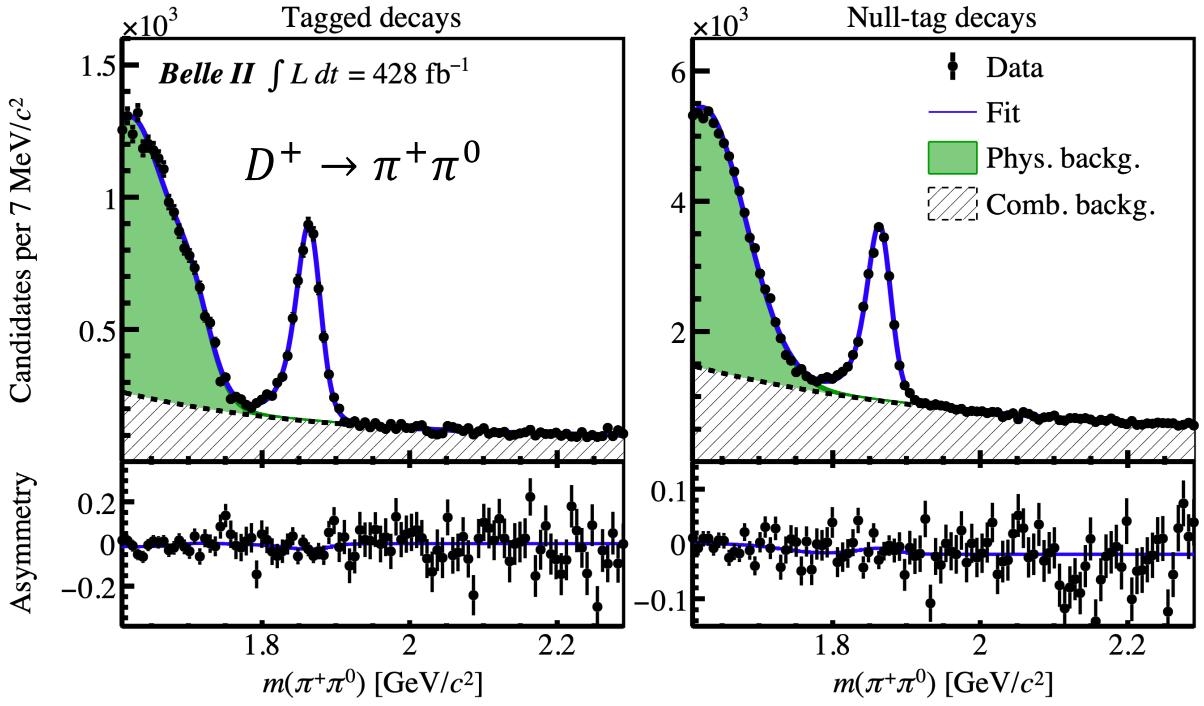
- Direct CP violation in Cabibbo-suppressed charm decays is generated by the interference of a leading tree-level amplitude and a suppressed $\Delta I = 1/2$ QCD penguin diagram
- In SM, $A_{CP}^{dir}(D^+ \to \pi^+\pi^0)_{I=2}$ is expect to be 0 while $A_{CP}^{dir}(D^0 \to \pi^0\pi^0)_{I=0,2}$ or $A_{CP}^{dir}(D^0 \to \pi^+\pi^-)_{I=0,2}$ can have non-zero CPV
- A sum-rule helps determine the source of CP violation PRD85,114036(2012) PRD107,052008(2023)

$$R = \frac{A_{CP}^{dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{B_{\pi^+\pi^-}}\left(\frac{B_{\pi^0\pi^0}}{\tau_{D^0}} - \frac{2B_{\pi^+\pi^0}}{3\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{B_{\pi^0\pi^0}}\left(\frac{B_{\pi^+\pi^-}}{\tau_{D^0}} - \frac{2B_{\pi^+\pi^0}}{3\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3\tau_{D^+}}{2B_{\pi^+\pi^0}}\left(\frac{B_{\pi^0\pi^0}}{\tau_{D^0}} + \frac{B_{\pi^+\pi^-}}{3\tau_{D^0}}\right)}$$

- If $R \neq 0$, CPV arise from $\Delta I = 1/2$ transition. If $R = 0$ and at least one $A_{CP}^{dir} \neq 0$, then CPV arise from BSM $\Delta I = 3/2$ amplitude

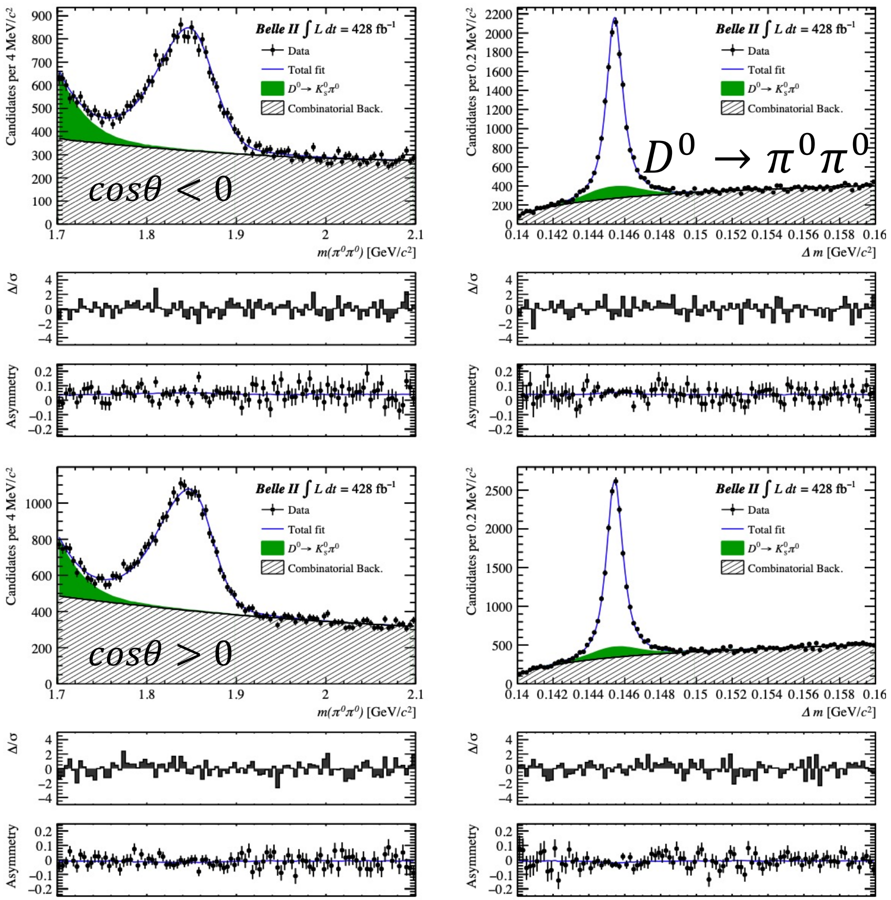
CPV in $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)



$A_{CP}(D^+ \to \pi^+\pi^0) = (-1.8 \pm 0.9 \pm 0.1)\%$

PRD 112, 012006 (2025)



$A_{CP}(D^0 \to \pi^0\pi^0) = (0.30 \pm 0.72 \pm 0.20)\%$

CPV in $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$

$$R = \frac{A_{CP}^{dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{B_{\pi^+\pi^-}}\left(\frac{B_{\pi^0\pi^0}}{\tau_{D^0}} - \frac{2B_{\pi^+\pi^0}}{3\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{B_{\pi^0\pi^0}}\left(\frac{B_{\pi^+\pi^-}}{\tau_{D^0}} - \frac{2B_{\pi^+\pi^0}}{3\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3\tau_{D^+}}{2B_{\pi^+\pi^0}}\left(\frac{B_{\pi^0\pi^0}}{\tau_{D^0}} + \frac{B_{\pi^+\pi^-}}{3\tau_{D^0}}\right)}$$

Before the two measurement: $R = (0.9 \pm 3.1)\times10^{-3}$, limited by $D^0 \to \pi^0\pi^0$

Including $D^0 \to \pi^0\pi^0$: $R = (1.5 \pm 2.5)\times10^{-3}$

Including $D^+ \to \pi^+\pi^0$: $R = (3.1 \pm 2.3)\times10^{-3}$

CPV in $D^+_{(s)} \to K^0_s K^- \pi^+ \pi^+$

JHEP04(2025)036

CPV in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^+$

- Search for CPV with scalar triple-product asymmetries and quadruple-product asymmetry

$$
\begin{aligned}
C_{\mathrm{TP}} &= (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot \vec{p}_{K_S^0}\,, \\
C_{\mathrm{QP}} &= (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot (\vec{p}_{K_S^0} \times \vec{p}_{\pi_l^+})
\end{aligned}
$$

- Data divided into 4 subsamples: $X > 0, X < 0, \bar{X} > 0, \bar{X} < 0$

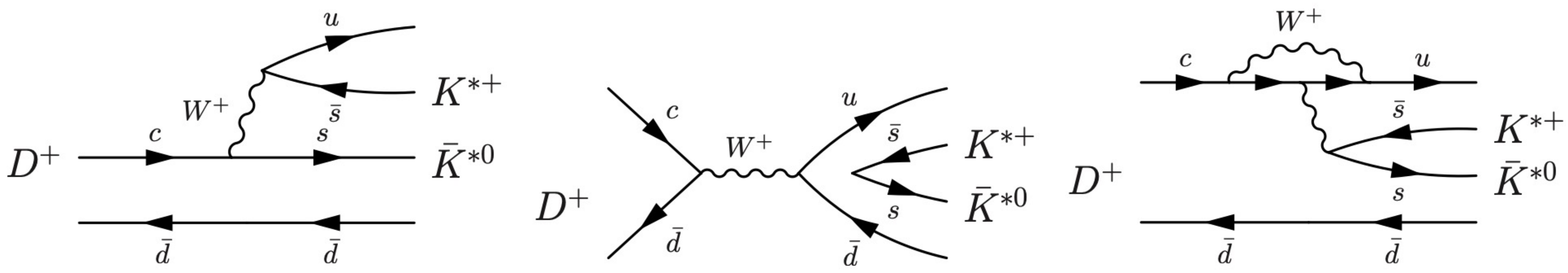
$$
A_X(D_{(s)}^+) = \frac{N(X>0) - N(X<0)}{N(X>0) + N(X<0)} \qquad A_{\bar{X}}(D_{(s)}^-) = \frac{\bar{N}(\bar{X}>0) - \bar{N}(\bar{X}<0)}{\bar{N}(\bar{X}>0) + \bar{N}(\bar{X}<0)}
$$

- Define the clean CP-violating observable :

$$
\mathcal{A}_{CP} = \frac{A_X - A_{\bar{X}}}{2}
$$

CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

- First measurement of CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ JHEP04(2025)036
- The $D^+ \to K^0_S K^- \pi^+ \pi^+$ decay has large BF, multiple diagram contributions, rich intermediate resonance → **promising for CPV study**



- Six observables are studied

$X = C_{TP}$

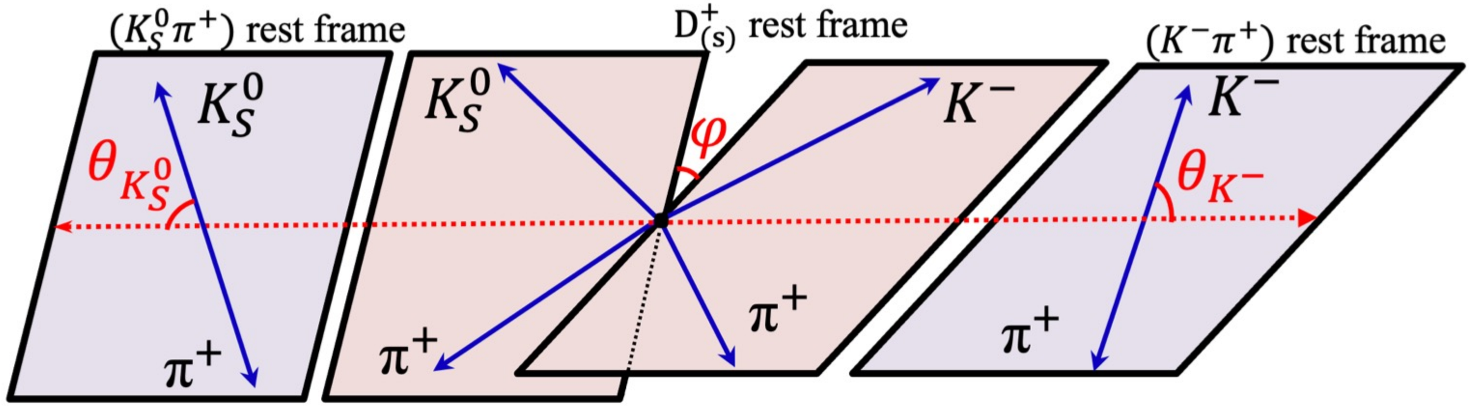
$X = C_{QP}$

$X = C_{TP} \cdot C_{QP}$

$X = cos\theta_{K^0_S} \cdot cos\theta_{K^-}$

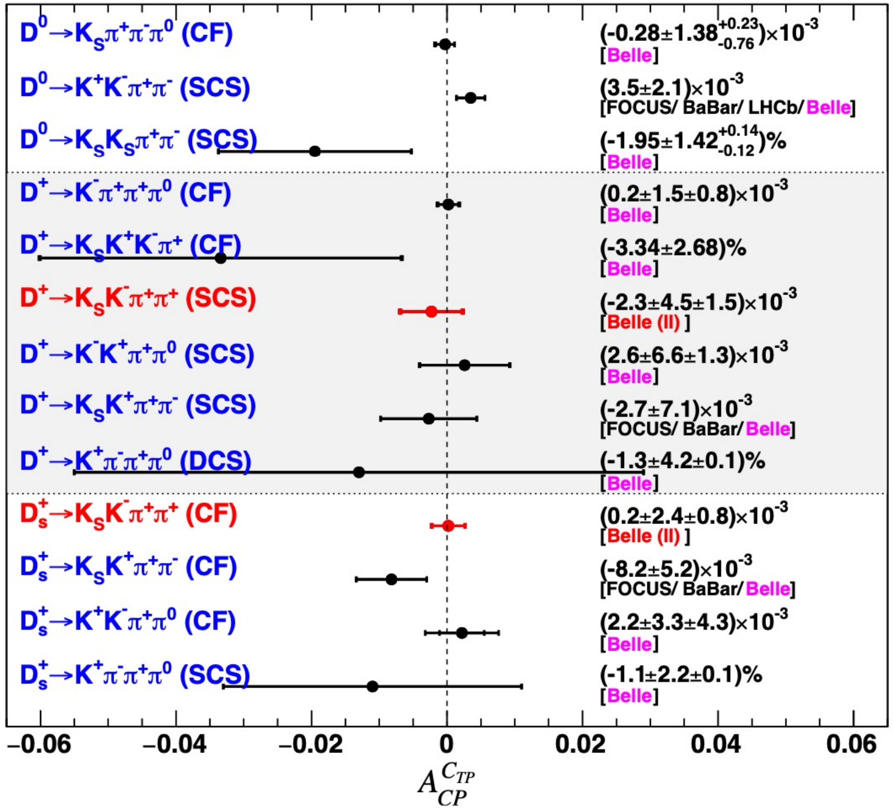
$X = cos\theta_{K^0_S} \cdot cos\theta_{K^-} \cdot C_{TP}$

$X = cos\theta_{K^0_S} \cdot cos\theta_{K^-} \cdot C_{QP}$



CPV in $D_{(s)}^{+} \to K_S^0 K^- \pi^+ \pi^+$

	X	$\mathcal{A}_{CP}^{X}$ Belle	$\mathcal{A}_{CP}^{X}$ Belle II	Combined $\mathcal{A}_{CP}^{X}$	Significance
D^+	$C_{\rm TP}$	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	$C_{\rm QP}$	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	$C_{\rm TP}\, C_{\rm QP}$	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-}$	$-4.7 \pm 5.9 \pm 3.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	$C_{\rm TP} \cos\theta_{K_S^0} \cos\theta_{K^-}$	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	$C_{\rm QP} \cos\theta_{K_S^0} \cos\theta_{K^-}$	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D_s^+	$C_{\rm TP}$	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	$C_{\rm QP}$	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	$C_{\rm TP}\, C_{\rm QP}$	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	$\cos\theta_{K_S^0} \cos\theta_{K^-}$	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	$C_{\rm TP} \cos\theta_{K_S^0} \cos\theta_{K^-}$	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	$C_{\rm QP} \cos\theta_{K_S^0} \cos\theta_{K^-}$	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ



No evidence of CPV found

CPV in $\psi(3686) \to \pi^+\pi^- J/\psi$

BESIII arxiv: 2507.20618

CPV in $\psi(3686) \to \pi^+\pi^- J/\psi$

- Existence of a non-zero EDM implies CPV

- The neutron EDM could be originated from the contribution of quark EDMs and CEDMs

  PLB 245, 640 (1990) PLB 248, 170(1990)

- non-zero CEDMs contribute to the static potential between c and $\bar{c}$, which cause mixing between CP-even and CP-odd bound states, introduce CPV in $\psi(3686) \to \pi^+\pi^- J/\psi$

$$A_{CP} = (9.33 \pm 2.34)\times 10^{-3} d_c' \times m_c \text{ (Chen-Kuang model)}$$

$$A_{CP} = (6.93 \pm 0.97)\times 10^{-3} d_c' \times m_c \text{ (Cornell model)}$$

PRD 85, 114010 (2012)

- CPV effect in $\psi(3686) \to \pi^+\pi^- J/\psi$ is predicted to be $\sim 10^{-5}$ in SM

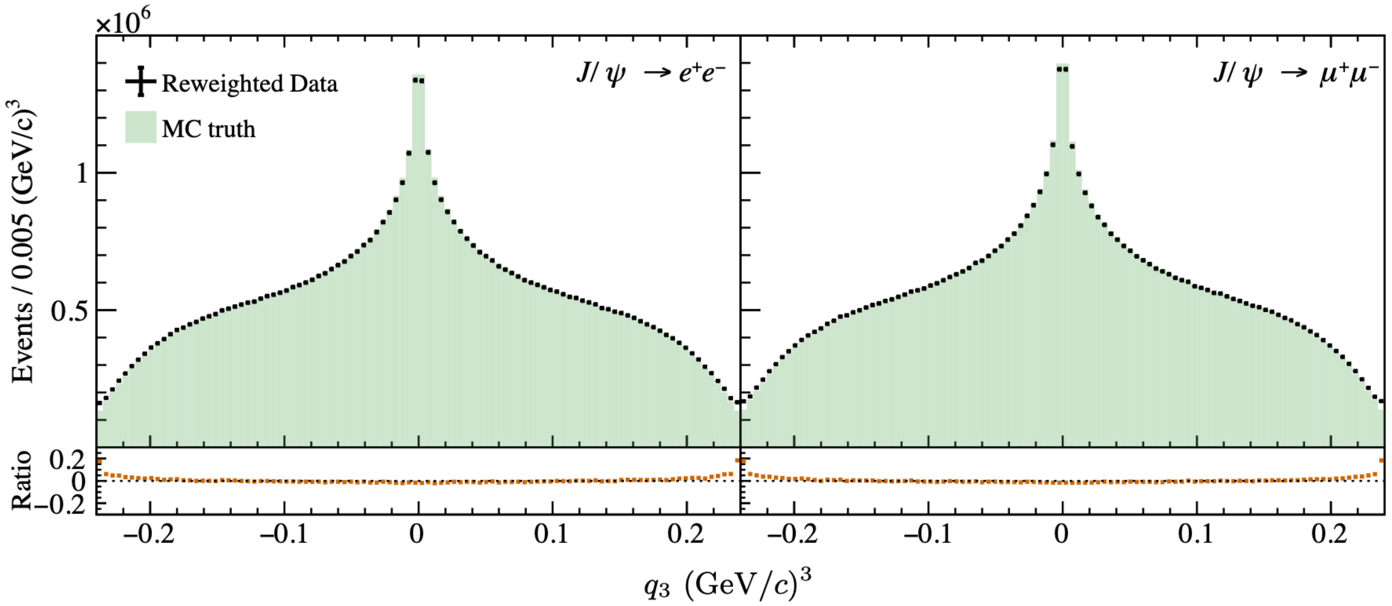
  arXiv:hep-ph/0001314v2

- With largest $\psi(3686)$ dataset, enable a precise measurement for CEDM of charm quark and test of CPV

CPV in $\psi(3686) \to \pi^+\pi^- J/\psi$

arxiv: 2507.20618

- Dataset: 2.7billion $\psi(3686)$
- CP-odd operator is defined: $q_3 = \frac{\vec{p}_{e^+} \cdot (\vec{p}_{\pi^+} - \vec{p}_{\pi^-}) \vec{p}_{e^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})}{|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|}$
- CP observable: $A_{CP} = \frac{N(q_3>0) - N(q_3<0)}{N(q_3>0) + N(q_3<0)}$



Ratio: $1 - \frac{N_{truth}}{N_{data}}$

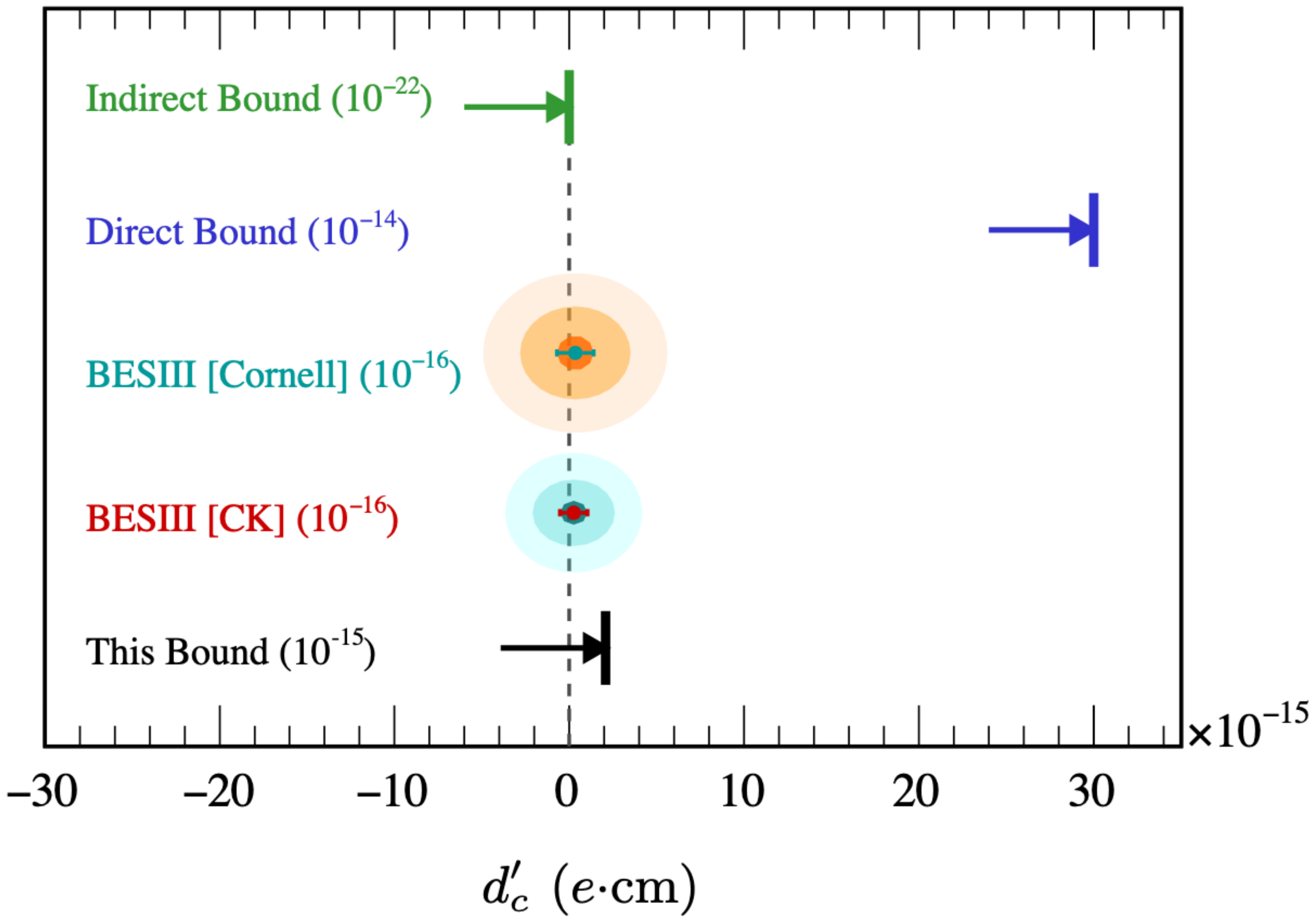
Signal yields and A_{CP} extracted using counting method

Parameter	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$
A_{CP} $(\times 10^{-4})$	$3.3 \pm 2.9 \pm 0.4$	$-1.2 \pm 2.4 \pm 0.1$
$\langle A_{CP} \rangle$ $(\times 10^{-4})$	$0.6 \pm 1.8 \pm 0.1$	
d'_c [CK] $(e\cdot\text{cm})$	$(2.6 \pm 7.8 \pm 0.4 \pm 0.6) \times 10^{-16}$	
d'_c [Cornell] $(e\cdot\text{cm})$	$(3.5 \pm 10.5 \pm 0.6 \pm 0.5) \times 10^{-16}$	
$\lvert d'_c \rvert$ $(e\cdot\text{cm})$	$< 2.1 \times 10^{-15}$	

CPV in $\psi(3686) \to \pi^+\pi^- J/\psi$

- The average CP asymmetry combined from two measurements via e^+e^- and $\mu^+\mu^-$ consistent with CP conservation

- The upper limit of d_c' at a 90% confidence level is proximately one order of magnitude lower than BESII results



Summary

- Charm physics is a highly active research field, important breakthroughs are expected in the coming years.
- Future precise data will be essential to address open questions, such as the origin of CP violation.
- Upgrade of LHCb, Belle II, BESIII and CMS will provide further high-precision measurements.

Thanks for your attention!

Backup

Direct CPV in $D_{(s)}^{+} \rightarrow K^{+}K^{-}K^{+}$

JHEP07(2023)067

CPV in $D_{(s)}^{+} \to K^{+}K^{-}K^{+}$

JHEP07(2023)067

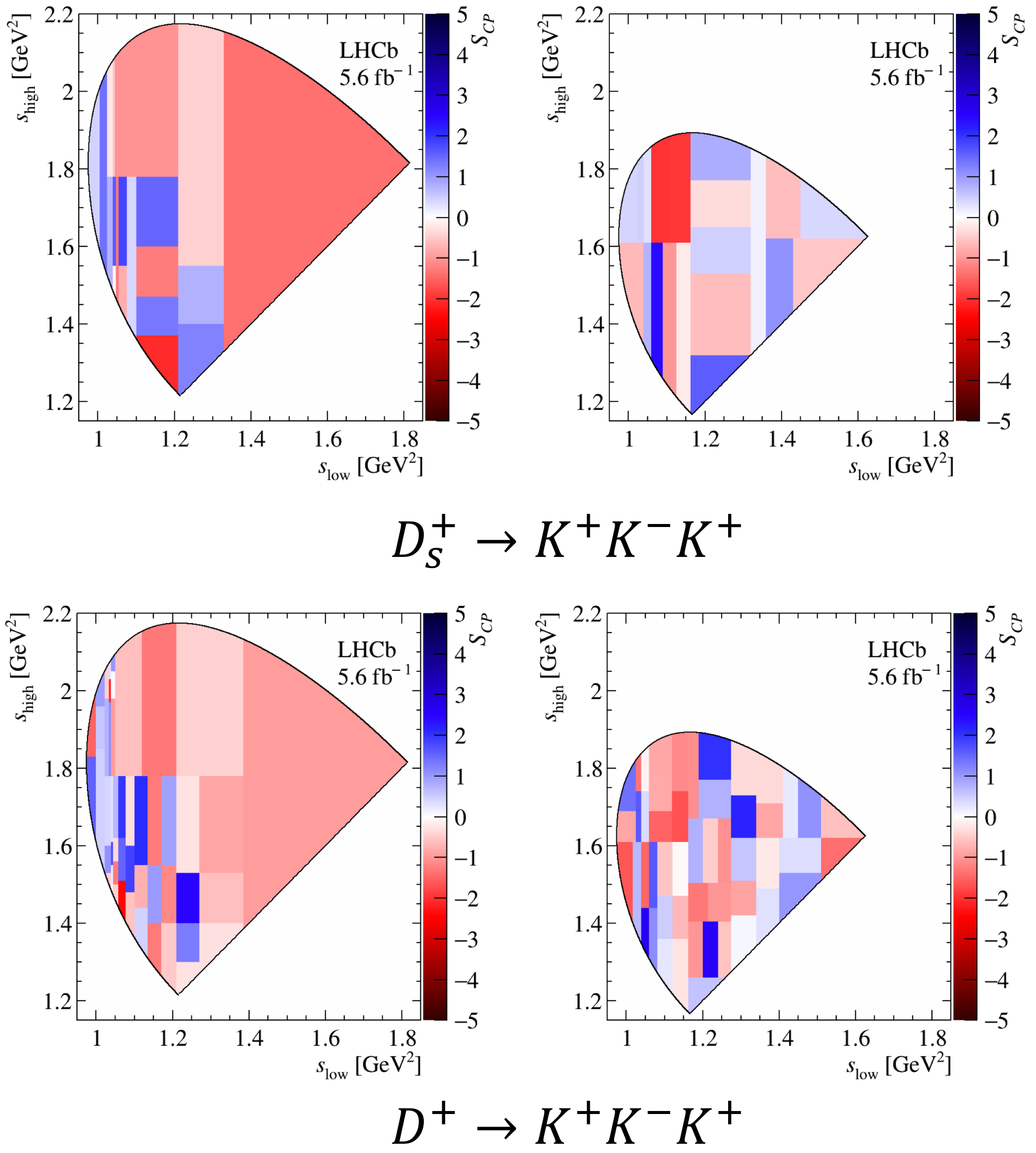
- Run2 dataset (5.6fb^{-1})
- CPV investigated using model independent binned technique
- For each dalitz bin, local CP observable S_{CP} is calculated
- Signal yields in each bin are obtained by fitting to $\mathrm{m}(K^{+}K^{-}K^{+})$ spectrum

$$S_{CP} = \frac{N^{i}(D_{(s)}^{+}) - \alpha N^{i}(D_{(s)}^{-})}{\sqrt{\alpha(\delta^{2}_{N^{i}(D_{(s)}^{+})} + \delta^{2}_{N^{i}(D_{(s)}^{-})})}} \qquad \alpha = \frac{\Sigma_{i} N^{i}(D_{(s)}^{+})}{\Sigma_{i} N^{i}(D_{(s)}^{-})}$$

Only sensitive to local CP asymmetry

P value with respect to the CP conservation hypothesis is:

- $D_{s}^{+} \to K^{+}K^{-}K^{+}$: 13.3%
- $D^{+} \to K^{+}K^{-}K^{+}$: 31.6%



CPV in $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)

CPV in $D^+ \to \pi^+\pi^0$

PRD 112, L031101 (2025)

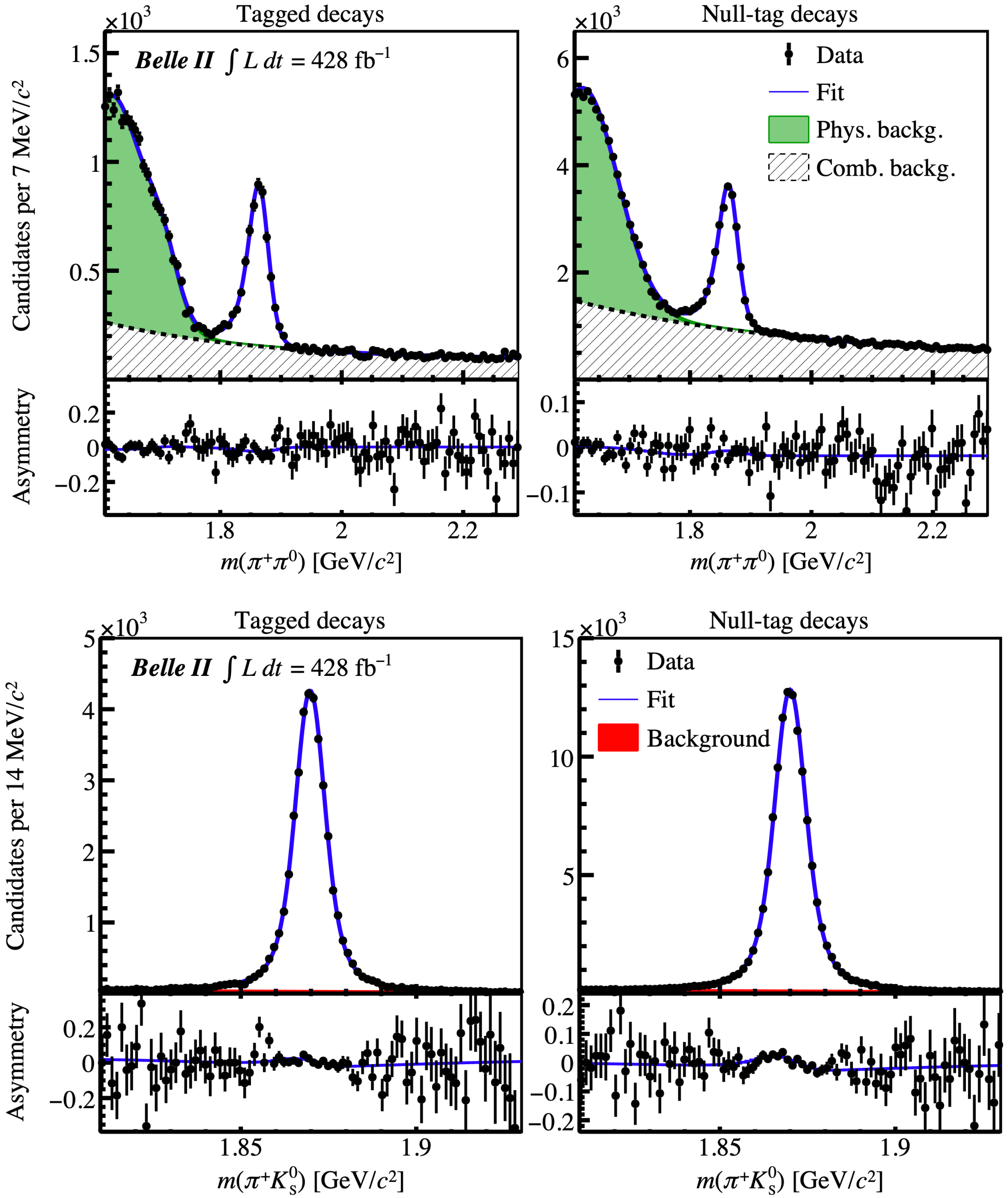
- 428fb^{-1} e^+e^- collision data
- D^+ sample categorized depend on whether or not they originate from $D^{*+} \to D^+\pi^0$(tagged or null-tag)
- CP observable $A_{CP}(D^+ \to \pi^+\pi^0) = A_{raw}^{\pi^+\pi^0} - A_P - A_D^{\pi^+}$
- Nuisance asymmetry estimated by CF control channel $D^+ \to \pi^+K_S^0$
  - $A_P + A_D^{\pi^+} = A_{raw}^{K_S^0\pi^0} - A^{\overline{K}^0}$ → ~0.4%

$$A_{CP}(D^+ \to \pi^+\pi^0) = A_{raw}^{\pi^+\pi^0} - A_{raw}^{\pi^+K_S^0} + A^{\overline{K}^0}$$

Tagged: $(-3.9 \pm 1.8 \pm 0.2)\%$

Null-tag: $(-1.1 \pm 1.0 \pm 0.1)\%$

Combined results: $(-1.8 \pm 0.9 \pm 0.1)\%$,



CPV in $D^0 \to \pi^0\pi^0$

Belle II

PRD 112, 012006 (2025)

CPV in $D^0 \to \pi^0\pi^0$

- 428fb^{-1} data from Belle II

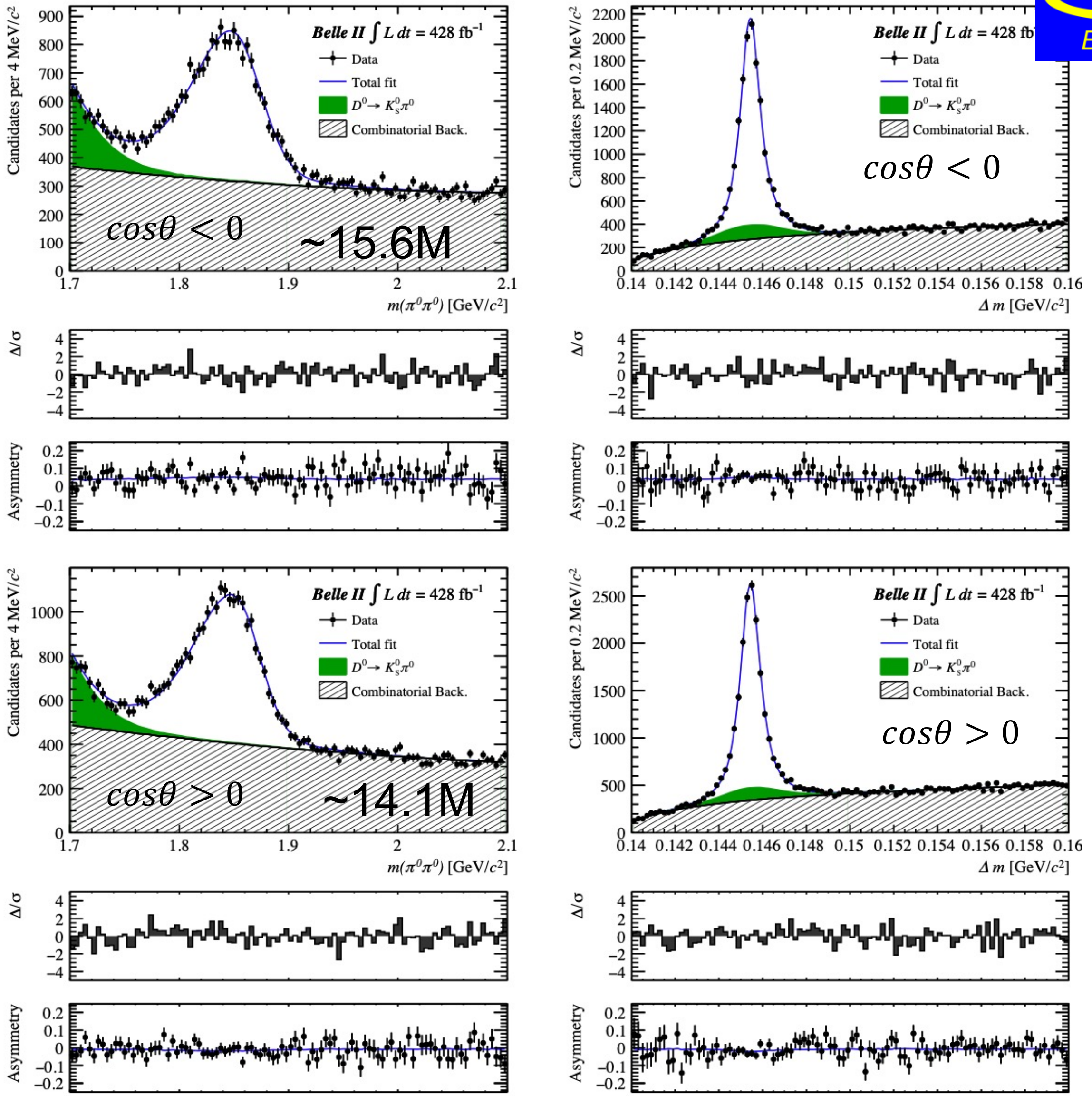
PRD 112, 012006 (2025)

- Flavor of D determined by $D^{*+} \to D^0\pi^+$
- D^* tagged and untagged $D^0 \to K^-\pi^+$ used to estimate instrumental asymmetries
  - $A_{raw}^{K\pi,tag} = A_P^{D^*} + A_\epsilon^{\pi_s} A_\epsilon^{K\pi}$
  - $A_{raw}^{K\pi,untag} = A_P^{D^*} + A_\epsilon^{\pi_s} A_\epsilon^{K\pi}$
- Production asymmetry of D^{*+} and D^0 can be suppressed by averaging raw asymmetries from forward and backward decays:
  - $A'^f = \frac{A^f(cos\theta_{c.m.s}>0)+A^f(cos\theta_{c.m.s}<0)}{2}$
- $A_{CP}(D^0 \to \pi^0\pi^0) = A'^{\pi^0\pi^0} - A'^{K\pi,tag} + A'^{K\pi,untag}$

CPV in $D^0 \to \pi^0\pi^0$

- 2D fit to $m(\pi^0\pi^0)$ and Δm, independently for positive and negative $cos\theta_{c.m.s}$
- Kinematics distributions of control sample are reweighted to match those of signal to ensure the cancellation of detection asymmetry
- Same fit procedure is performed to control sample
- $A_{CP}(D^0 \to \pi^0\pi^0) = (0.30 \pm 0.72 \pm 0.20)\%$

Consistent with CP symmetry. 15% less precise than the Belle measurement, but with less than 50% data



$\Delta m = m(D^{*0}) - m(D^0)$