The 7th International Workshop on Tau Charm Facilities

November, 23-27, 2025

FTCF2025, Huangshan

Overview of Charm Physics at Belle and Belle II

Murad Yasaveev

Higher School of Economics

on behalf of Belle II collaboration

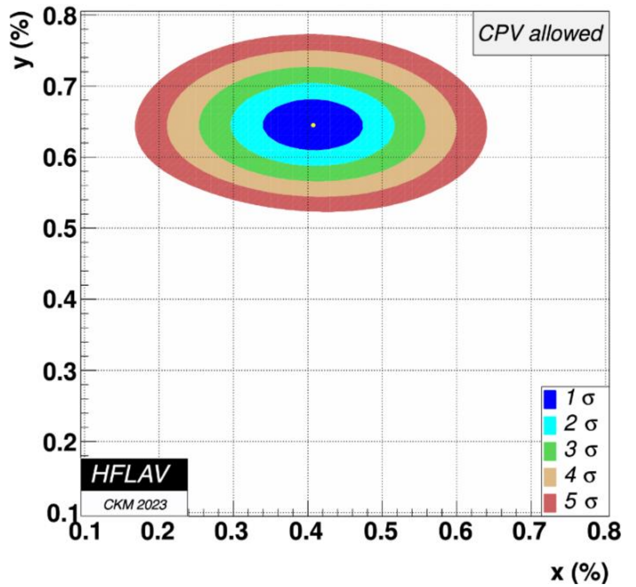
Topics for charm physics

- $D^0 - \bar{D}^0$ mixing

$$x = \frac{m_1 - m_2}{\Gamma}, \; y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

World average values: $x = (4.07 \pm 0.44) \times 10^{-3}$

$$y = (6.45^{+0.24}_{-0.23}) \times 10^{-3}$$



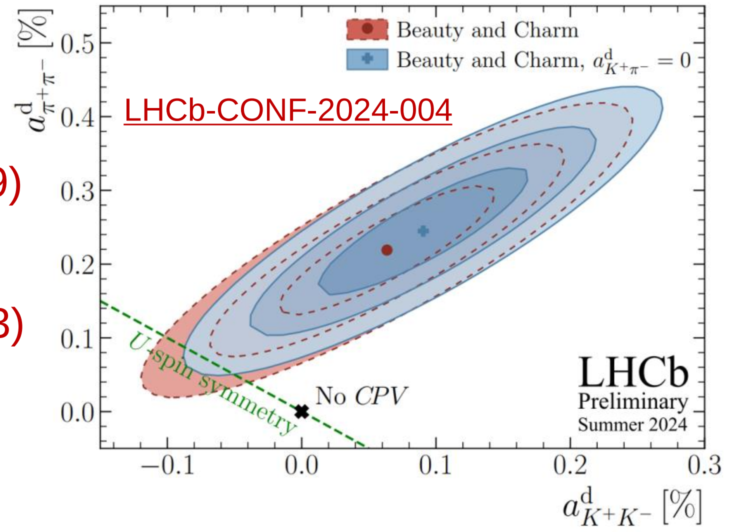
- CP violation

$$\Delta A(D \to KK, \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4} \quad [5.3\sigma]$$

PRL **122, 211803** (2019)

3.8σ evidence of direct CPV in $D^0 \to \pi^+\pi^-$

PRL **131, 091802** (2023)



- Charmed baryons
- Lifetimes of charm hadrons

Belle and Belle II experiments

Operation at asymmetric e^+e^- colliders at or near the $\Upsilon(4S)$

- KEKB (1999-2010), $\mathcal{L}_{peak}$= $2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathcal{L}_{int}$= 1/ab
- SuperKEKB, $\mathcal{L}_{peak}$= $5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathcal{L}_{int}$= 0.57/ab

world record!

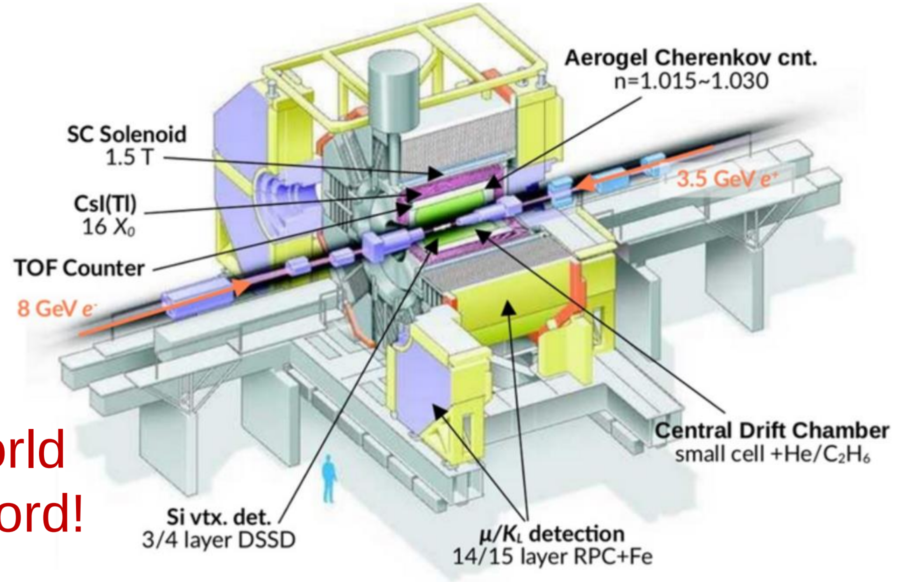
Two ways to produce the charm hadrons in e^+e^- at $\Upsilon(4S)$:

- $e^+e^- \to c\bar{c} \to X_c$, $\sigma(e^+e^- \to\ c\bar{c})$ ~ 1.3 nb at $\sqrt{s} = 10.58$ GeV
- $e^+e^- \to \Upsilon(4S) \to X_c$, $\sigma(e^+e^- \to\ \Upsilon(4S))$ ~ 1.1 nb

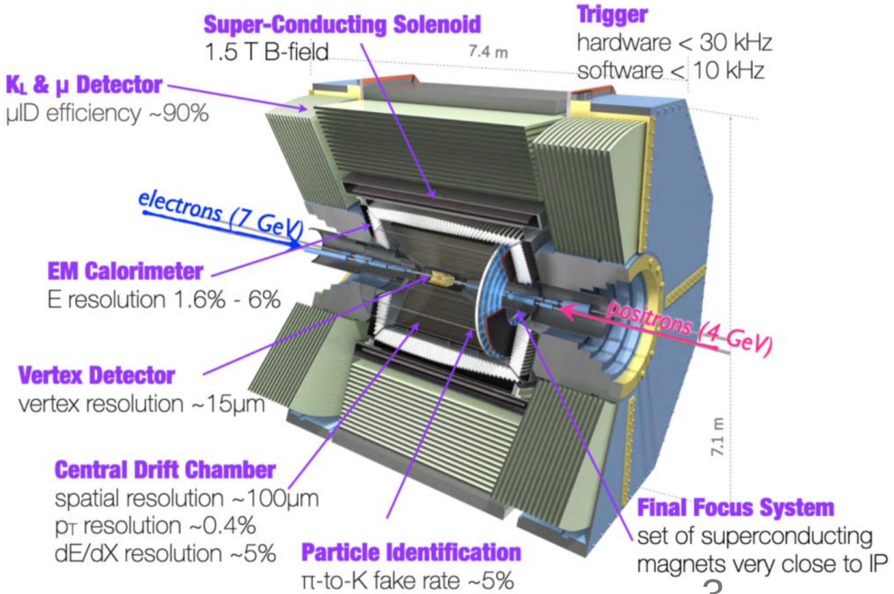
Belle and Belle II are synergistic experiments

- combined analysis, especially important for charm, where large statistics is crucial to improve the precision
- statistical power of Belle II data is larger than that of Belle data:
  - improved detector and reconstruction algorithms
  - improved impact parameter resolution

Belle



Belle II

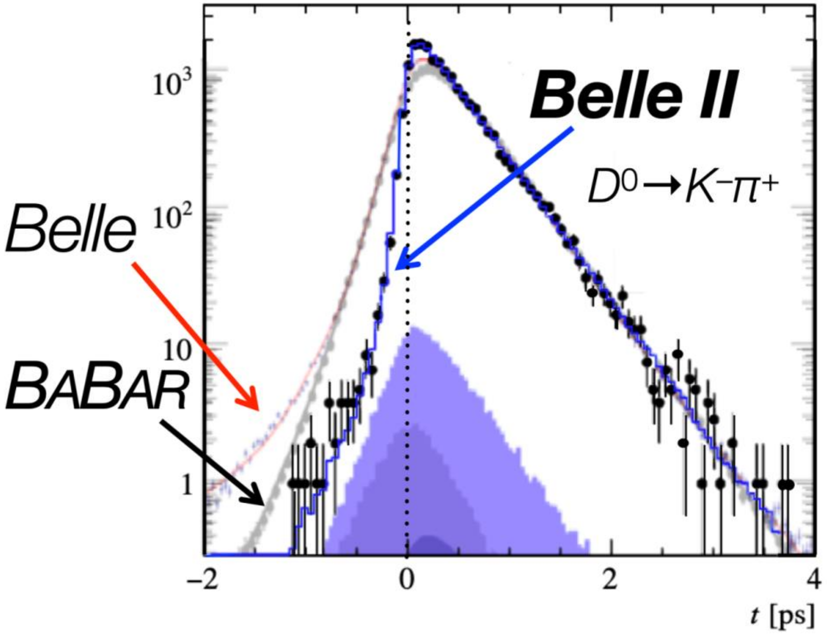


Charm lifetimes at Belle II

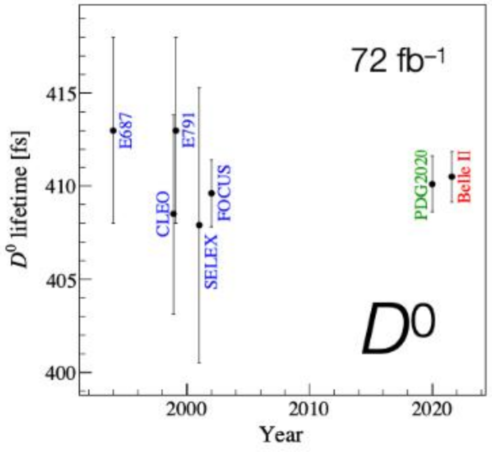
Belle II data allows to precisely measure absolute lifetimes

- not done at Belle/BaBar, ×2 better decay resolution at Belle II
- the world's highest precision in $D^0, D^+,\ D_s^+$ and Λ_c^+ lifetimes
- confirmation of the longer Ω_c lifetime

Excellent performance and understanding of the Belle II detector

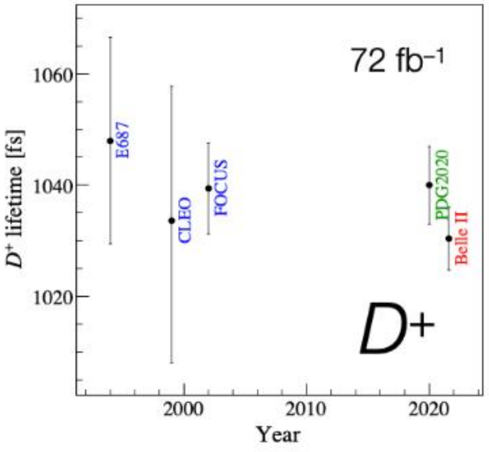


PRL **127**, 211801



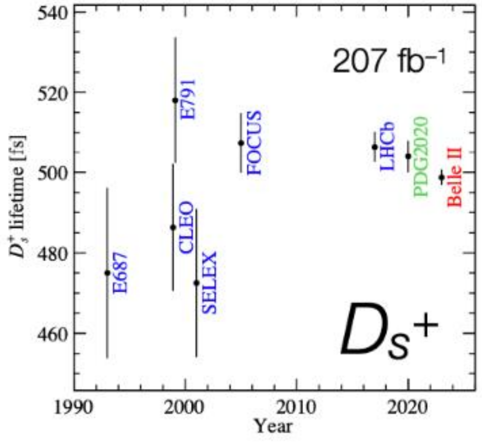
$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs

PRL **127**, 211801



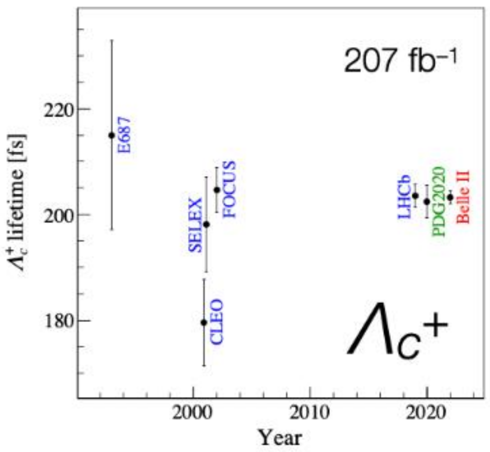
$\tau(D^+) = 1030 \pm 5 \pm 4$ fs

PRL **131, 171803**



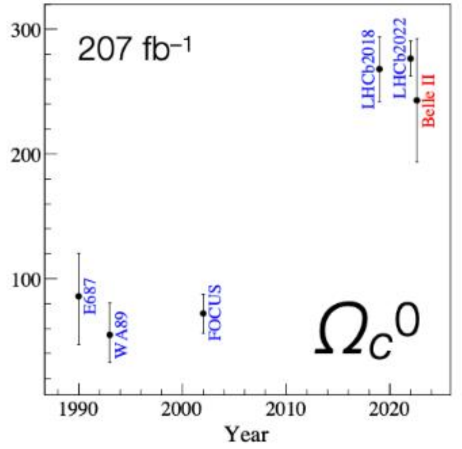
$\tau(D_s^+) = 499.5 \pm 1.7 \pm 0.9$ fs

PRL **130, 071802**



$\tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.8$ fs

PRD **107, L031103**

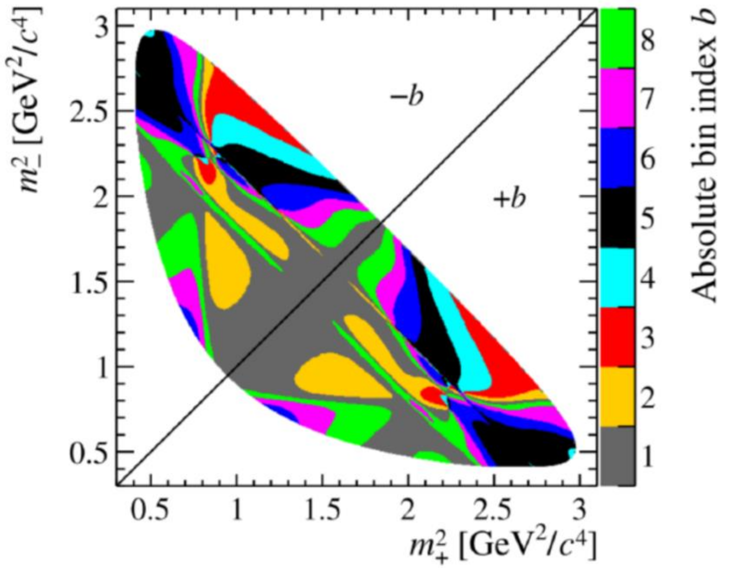


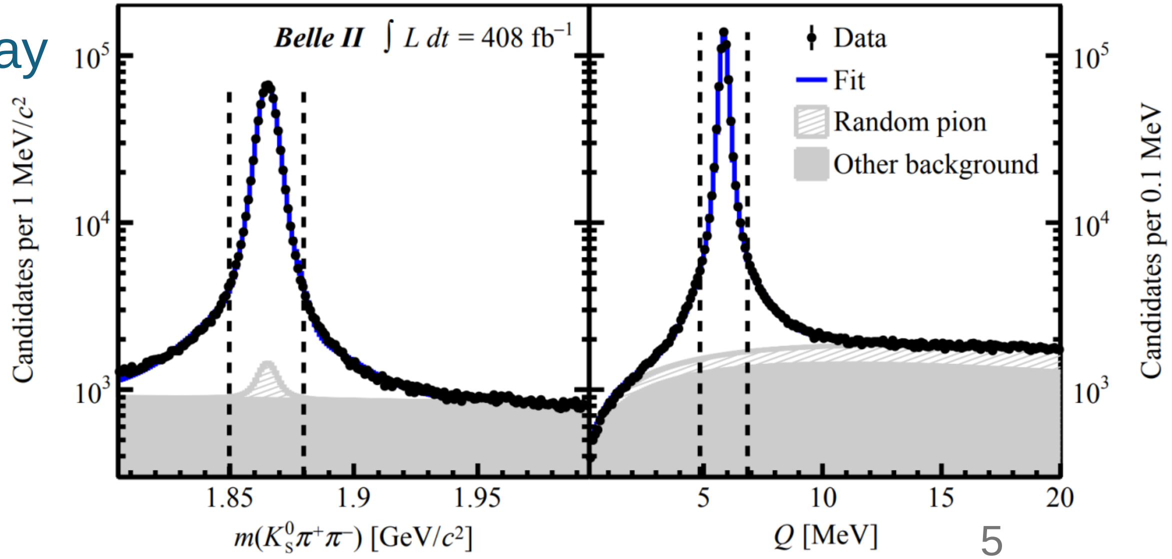
$\tau(\Omega_c^+) = 243 \pm 48 \pm 11$ fs

$D^0 - \overline{D}^0$ mixing parameters in $D^0 \to K_S^0\pi^+\pi^-$

PRD **111, 112011** (2025)

- Model-independent measurement
- Splitting of the Dalitz plot $[M^2(K_S^0\pi^+)\ vs.\ M^2(K_S^0\pi^-)]$ into 16 bins with constant δ (strong phase between D^0 and $\overline{D}^0$) determined by BESIII [PRL **124, 241802** (2020)]
- Using combined Belle and Belle II datasets, the model-independent measurement of the $D^0 - \overline{D}^0$ mixing parameters using D^{*+}-tagged $D^0 \to K_S^0\pi^+\pi^-$ decay
- Fit to distribution in D^0 mass and energy released Q in the $D^{*+} \to D^0\pi^+$





$D^0 - \bar{D}^0$ mixing parameters in $D^0 \to K_S^0 \pi^+ \pi^-$

PRD **111, 112011** (2025)

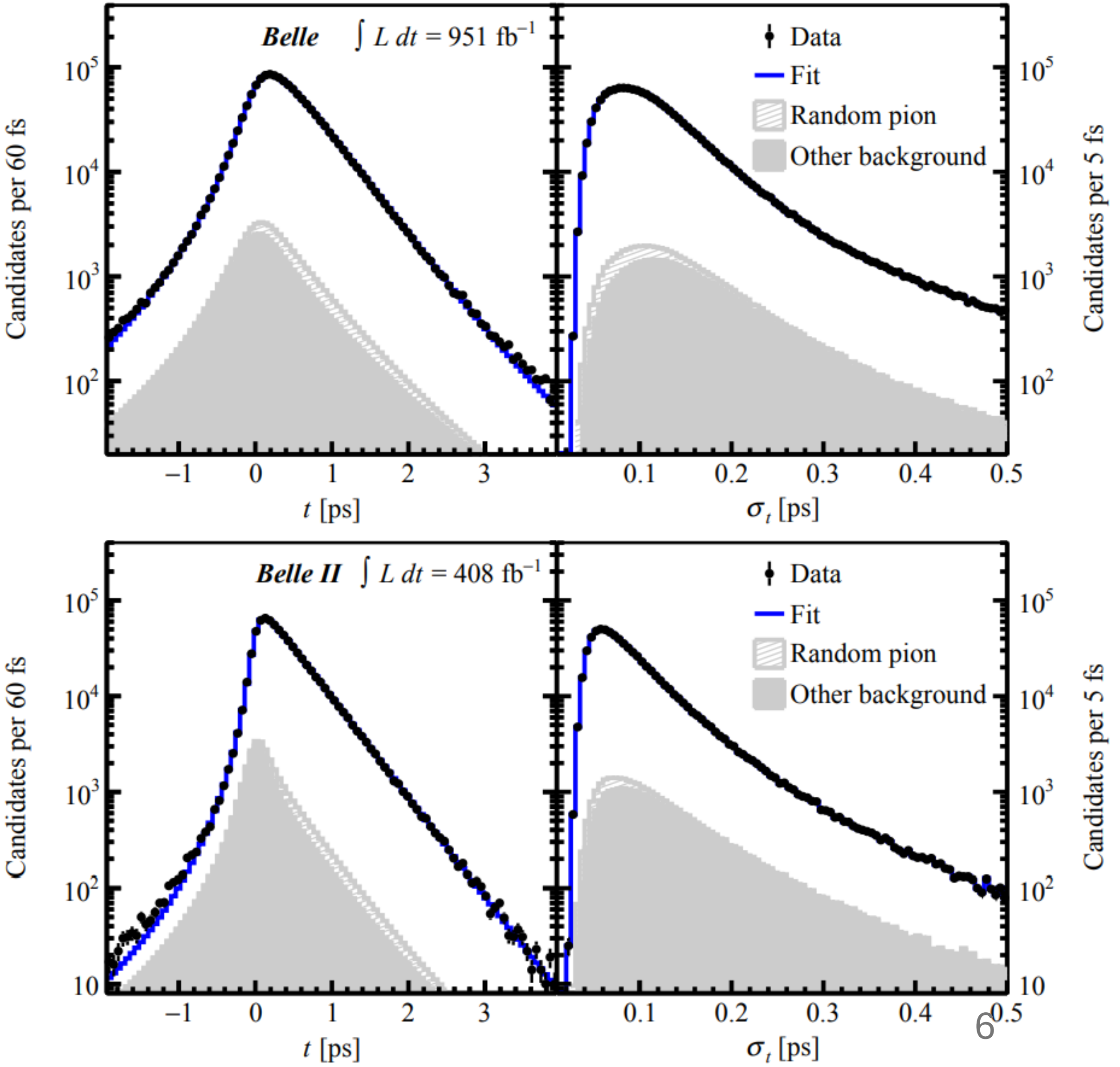
Mixing parameters obtained from a fit to the (t, σ_t) distributions in each of 16 Dalitz plot bins

Sample average purity 96%

$$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$$
$$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$$

These results are about 20% and 14% more precise than the model-dependent Belle measurement!

PRD 89, 091103 (2014)



Measurement of CP asymmetry at Belle (II)

- The only evidence for direct CPV in $D^0 \rightarrow \pi^+\pi^-$ by LHCb
- It is essential to continue searching for CPV in charm sector to understand its origin
- Belle and Belle II mainly contribute with decays with neutral particles in the final state

$$A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} \simeq A_{CP} + A_{production} + A^{D^0}_{detection} + A^{tag}_{detection}$$

Measured value

Observed yields

Detector-induced asymmetries
Measured on control channel

Real goal of the measurement
Time-integrated asymmetry

$$A_{CP} = \frac{\Gamma(D^0) - \Gamma(\bar{D}^0)}{\Gamma(D^0) + \Gamma(\bar{D}^0)}$$

Γ - decay-time integrated rate

Forward-backward $e^+e^- \rightarrow c\bar{c}$ asymmetry due to $\gamma - Z^0$ interference
(odd in $\cos\theta_{CM}$ of D mesons, independent on the final state)
Asymmetry from $B \rightarrow DX$ decays

A_{CP} in $D^0 \to K_S^0 K_S^0$ with D^{*+} flavor tagging

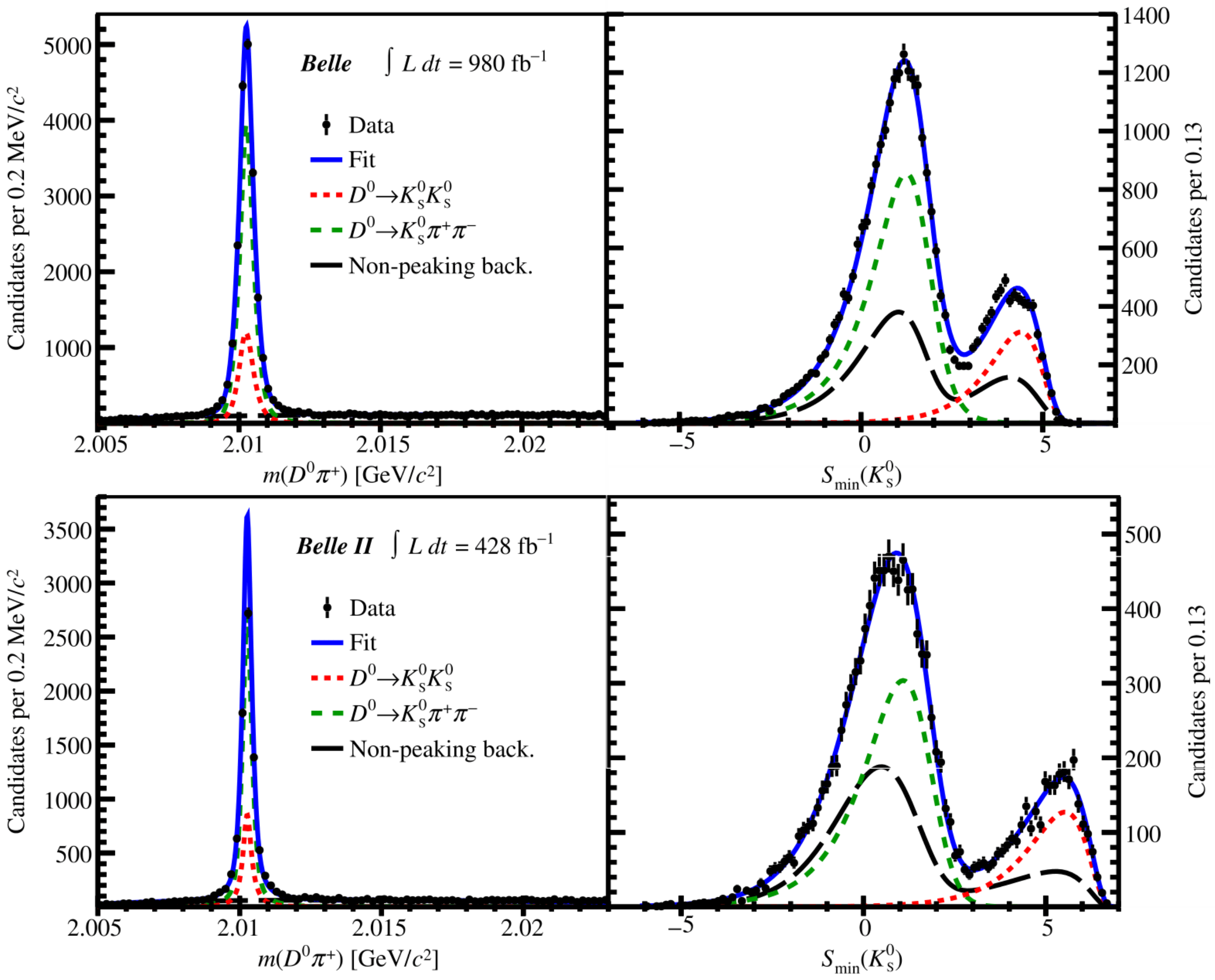
PRD **111, 012015** (2025)

- Main background from $D^0 \to K_S^0 \pi^+ \pi^-$
- K_S^0 flight significance to discriminate background:

$$S_{\min} = \log\left(\min\left(\frac{L_1}{\sigma_1}, \frac{L_2}{\sigma_2}\right)\right)$$

- 2D fit to $M(D^{*+})$ and $S_{\min}$
- Control channel: $D^0 \to K^+K^-$
- About 7 000 tagged D^0

$$A_{CP} = (-1.4 \pm 1.3 \pm 0.1)\%$$



A_{CP} in $D^0 \to K_S^0 K_S^0$ with Charm Flavor Tagger

PRD **112, 012017** (2025)

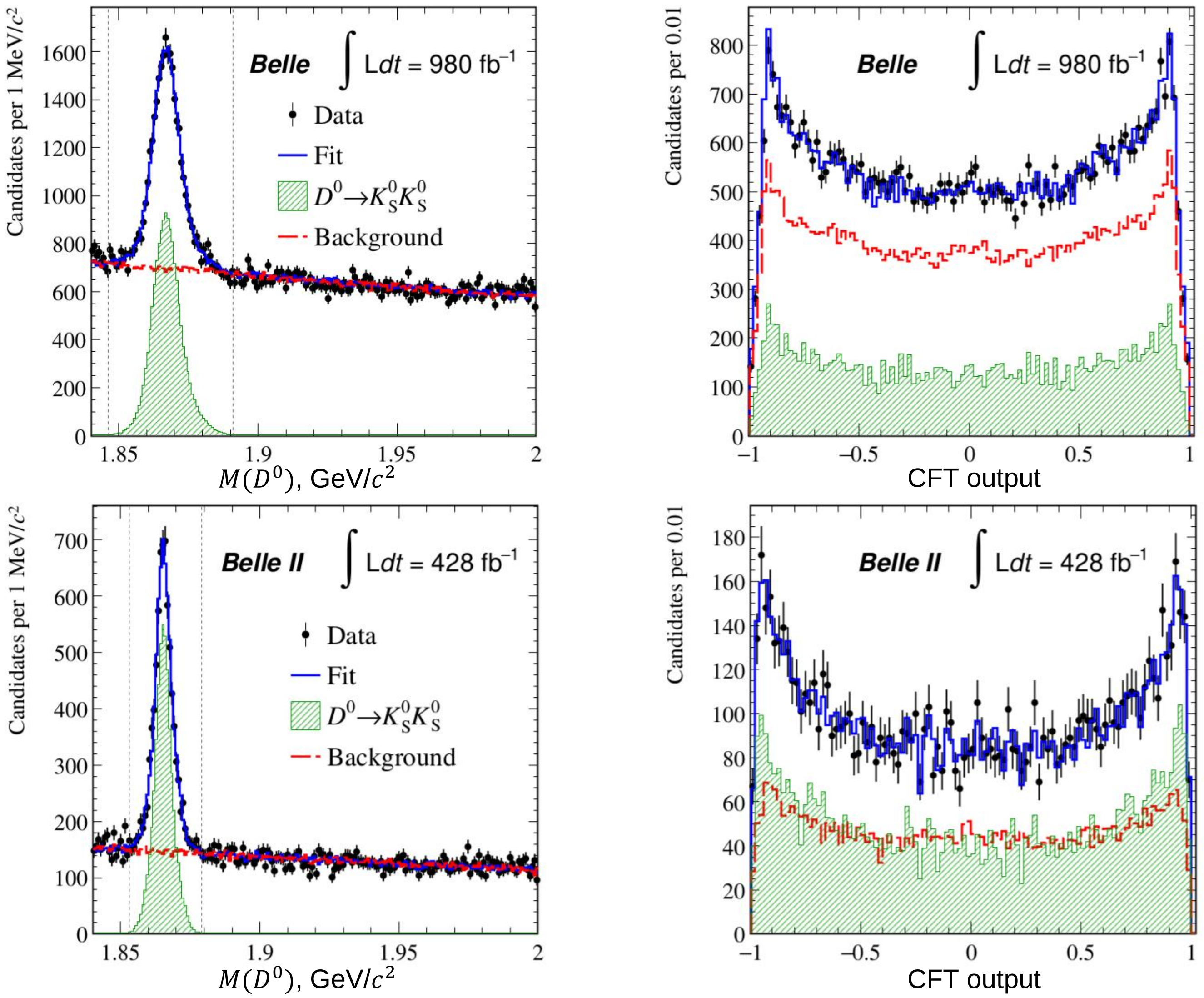
- Tagging method based on rest-of-event
- BDT+$S_{\min}$ to suppress background from $D^0 \to K_S^0\,\pi^+\,\pi^-$
- 2D fit to $M(D^0)$ and CFT output
- Independent sample: events from D^{*+}-tagged analysis are removed
- About 20 000 tagged D^0

$$A_{CP} = (1.3 \pm 2.0 \pm 0.2)\%$$

Combined result:

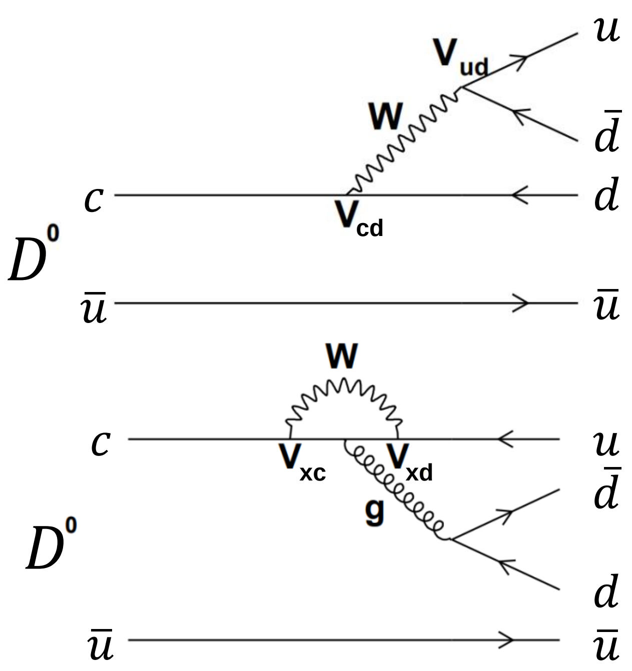
$$A_{CP} = (-0.6 \pm 1.1 \pm 0.1)\%$$

World's best determination



A_{CP} in $D \to \pi\,\pi$

- CP violation in Cabibbo-suppressed decays arises from tree-level and $\Delta I = 1/2$ penguin amplitudes interference
- Measurement of A_{CP} in $D^+ \to \pi^+\pi^0$ and $D^0 \to \pi^0\pi^0$ can help to identify the reason for large CP violation in $D^0 \to \pi^+\pi^-$
- Isospin sum rule R:



$$R = \frac{A_{CP}^{dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

HFLAV: $R = (0.9 \pm 3.1) \times 10^{-3}$

τ – lifetime
$\mathcal{B}$ – branching fraction

A_{CP} in $D^0 \to \pi^0\pi^0$

PRD **112, 012006** (2025)

- Flavor tagging by $D^{*+} \to D^0\pi^+$
- Fit to $M(D^0)$ and $\Delta M = M(D^{*+}) - M(D^0)$
- Production asymmetry : A_{raw} is measured for forward ($\cos\theta_{CM} > 0$) and backward decays
- Detection asymmetry: $D^0 \to K^-\pi^+$ ($A^{tag\ \pi}_{detection}$)

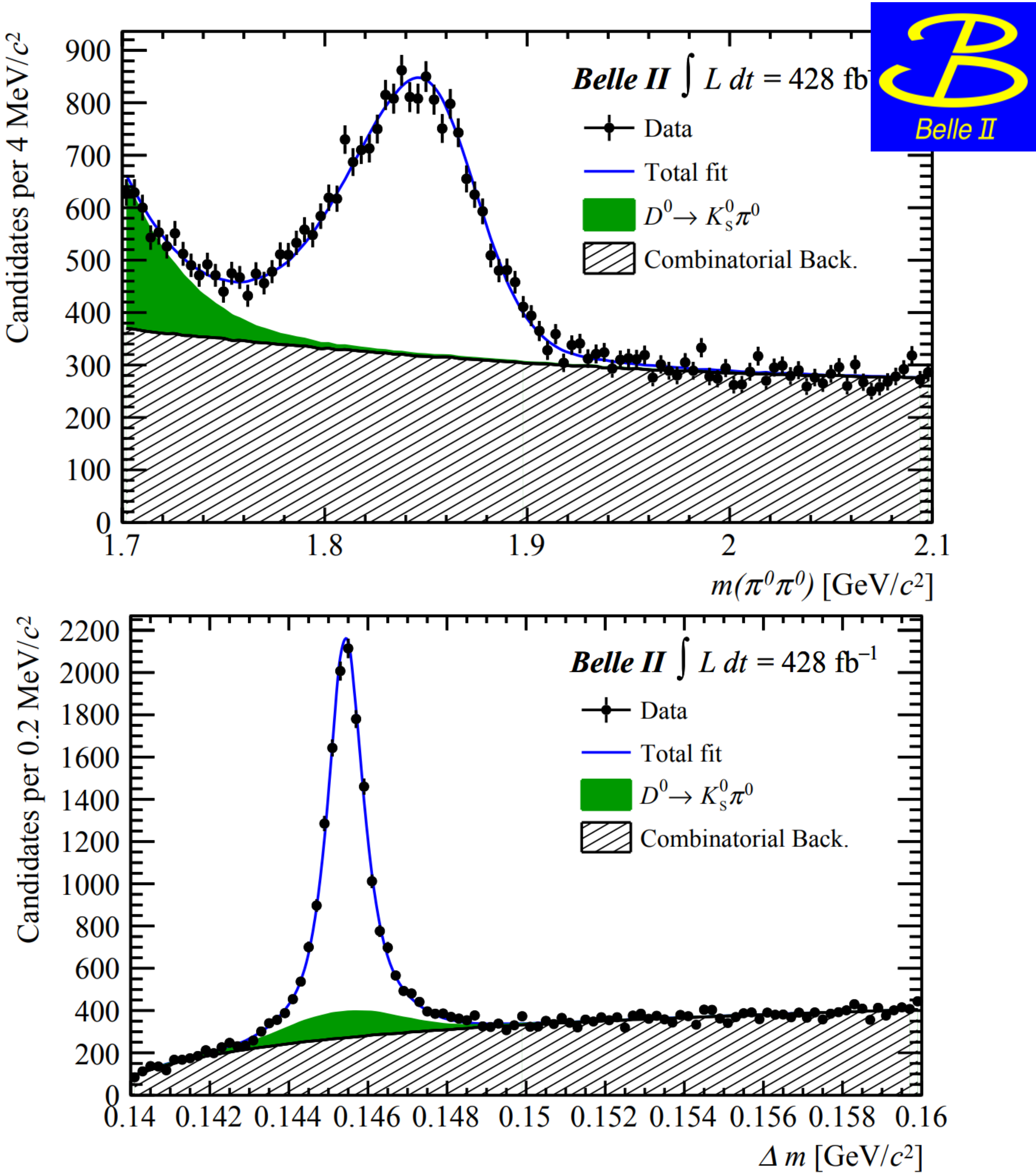
tagged D^0: $A_{production} + A^{tag\ \pi}_{detection} + A^{D^0\to K\pi}_{detection}$

untagged D^0: $A_{production} + A^{D^0\to K\pi}_{detection}$

$$A^{tag\ \pi}_{detection} = A_{tagged} - A_{untagged}$$

$$A_{CP} = (0.30 \pm 0.72 \pm 0.20)\%$$

only ~15% less precise than Belle PRL **112, 211606** (2014)



A_{CP} in $D^+ \to \pi^+\pi^0$

PRD **112, L031101** (2025)

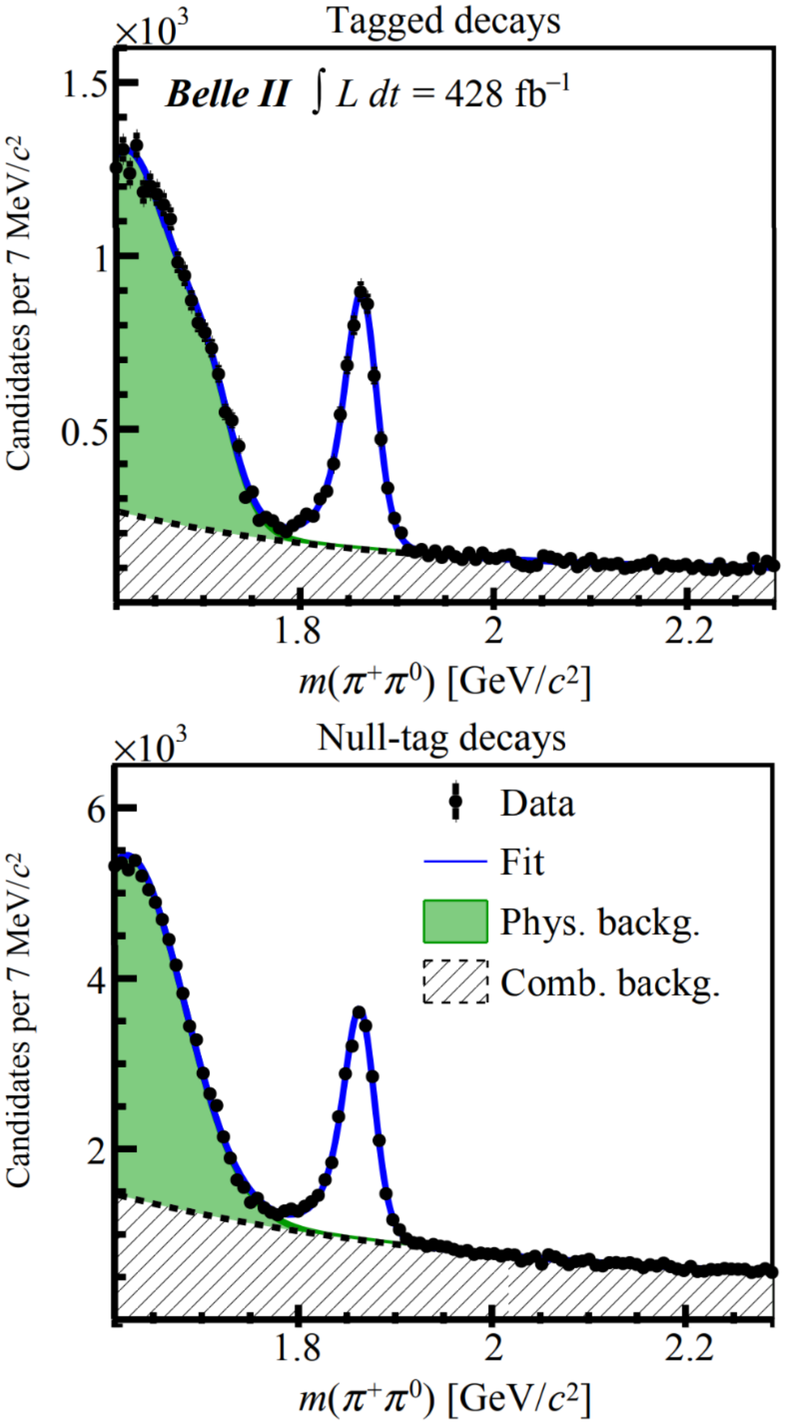
- No CPV is expected in SM: $\Delta I = 3/2$ transition
- Fit to $M(D^+)$ is performed to measure asymmetry
- Fit to D^+ from D^{*+} separately (different backgrounds and purity)
- Production and detection asymmetries $D^+ \to \pi^+ K_S^0$ (with $K^0 - \overline{K}^0$ mixing and regeneration effects correction)

$$A_{CP} = (-1.8 \pm 0.9 \pm 0.1)\%$$

30% improvement in statistics and 50% in systematics wrt Belle: $A_{CP} = (2.31 \pm 1.24 \pm 0.23)\%$ PRD **97, 011101** (2018)

more precise than LHCb (9/fb): $A_{CP} = (-1.3 \pm 0.9 \pm 0.6)\%$ JHEP **06, 019** (2021)

$R = (3.1 \pm 2.3) \times 10^{-3}$, precision improved by 25%



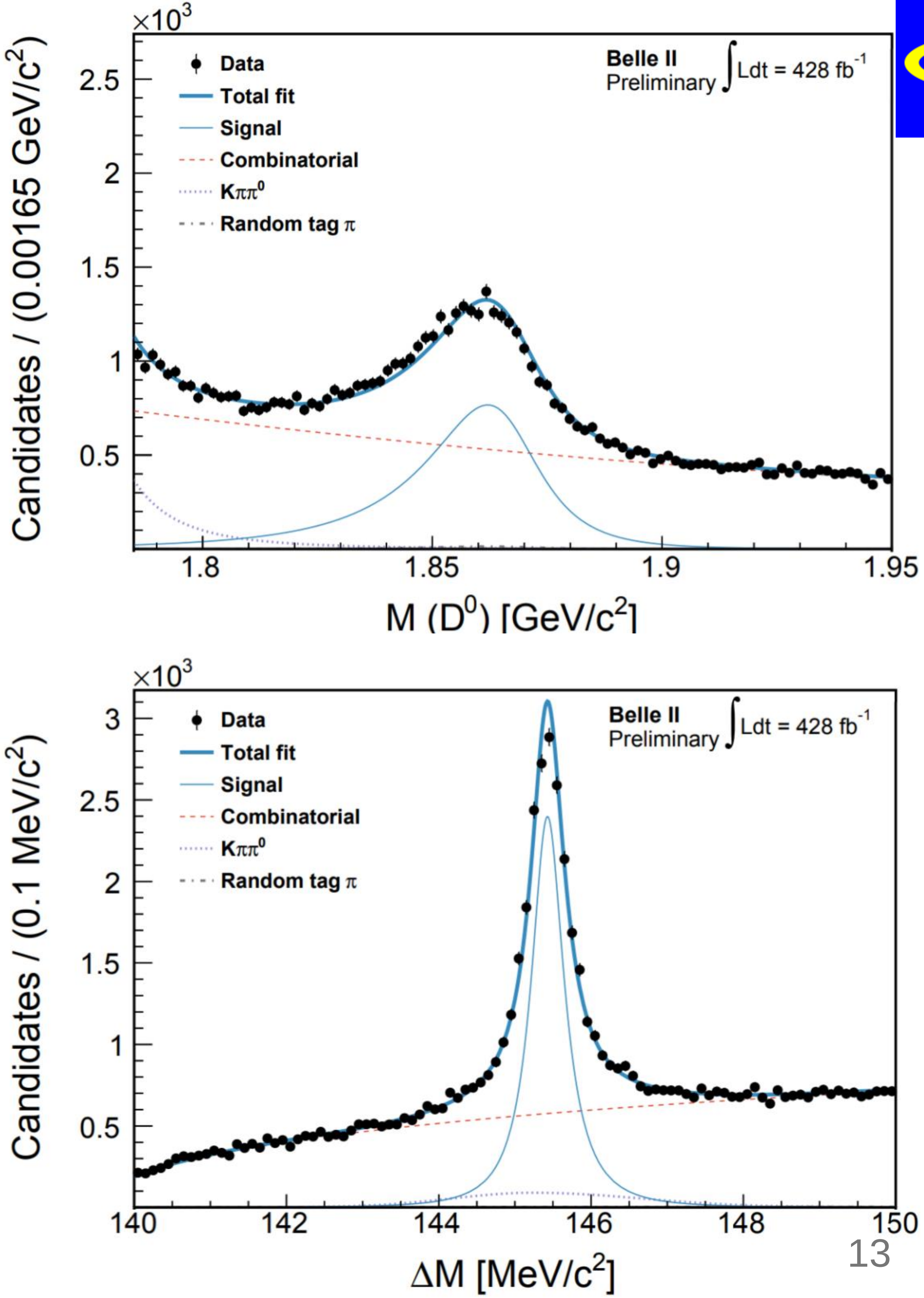
A_{CP} in $D^0 \to \pi^+\pi^-\pi^0$

Submitted to PRD

- SCS three-body decay, interference of several amplitudes: $\rho^0\pi^0, \rho^\pm\pi^\mp$
- Flavor of D^0 is tagged by $D^{*+} \to D^0\pi^+$
- Fit to $M(D^0)$ and $\Delta M = M(D^{*+}) - M(D^0)$
- Production asymmetry: A_{raw} is averaged over 8 bins in $\cos\theta_{CM}$
- Tag detection asymmetry: with tagged and untagged $D^0 \to K^-\pi^+$

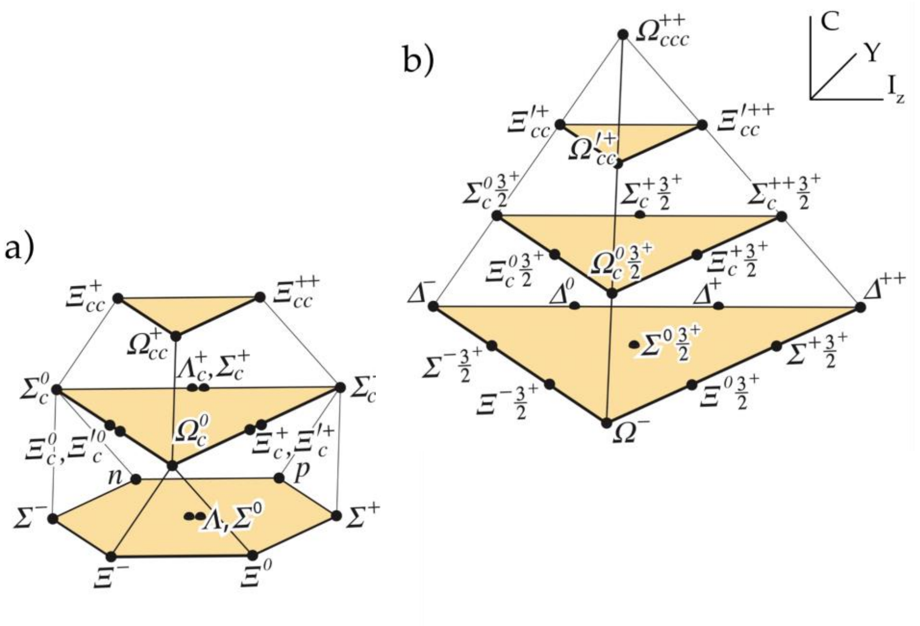
$$A_{CP} = (0.29 \pm 0.27 \pm 0.13)\%$$

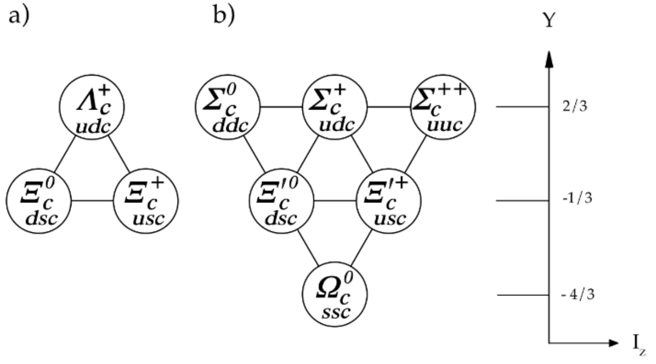
34% more precise than BABAR with just 10% more statistics PRD **78, 051102** (2008)



Charmed baryons

- Baryon physics is rich and provides complementary information to that of meson physics
- A lot of topics to improve our knowledge:
  - branching ratios: difficult for theoretical predictions due to W-exchange and internal W-emission interference
  - Dalitz structure of multi-body decays, hadronic form factors
  - important for experimental study of CPV, search for NP, search for rare or forbidden processes
- Recent LHCb observation [Nature **643, 8074** (2025)] of CPV in $\Lambda_b \to pK^-\pi^+\pi^-$ represents a milestone for flavor physics, need to search for CP violations in charm.





Observations $\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$

JHEP **03, 061** (2025)

- Singly Cabibbo-suppressed decays
- Intermediate states reconstructed in

$$\Sigma^0 \to \Lambda\gamma, \qquad \Xi^- \to \Lambda\pi^-, \qquad \Lambda \to p\pi^-$$

- Normalization mode: $\Xi_c^+ \to \Xi^-\pi^+\pi^+$,
  $\mathcal{B} = (2.9 \pm 1.3)\%$ [PDG]

- Significant signals observed

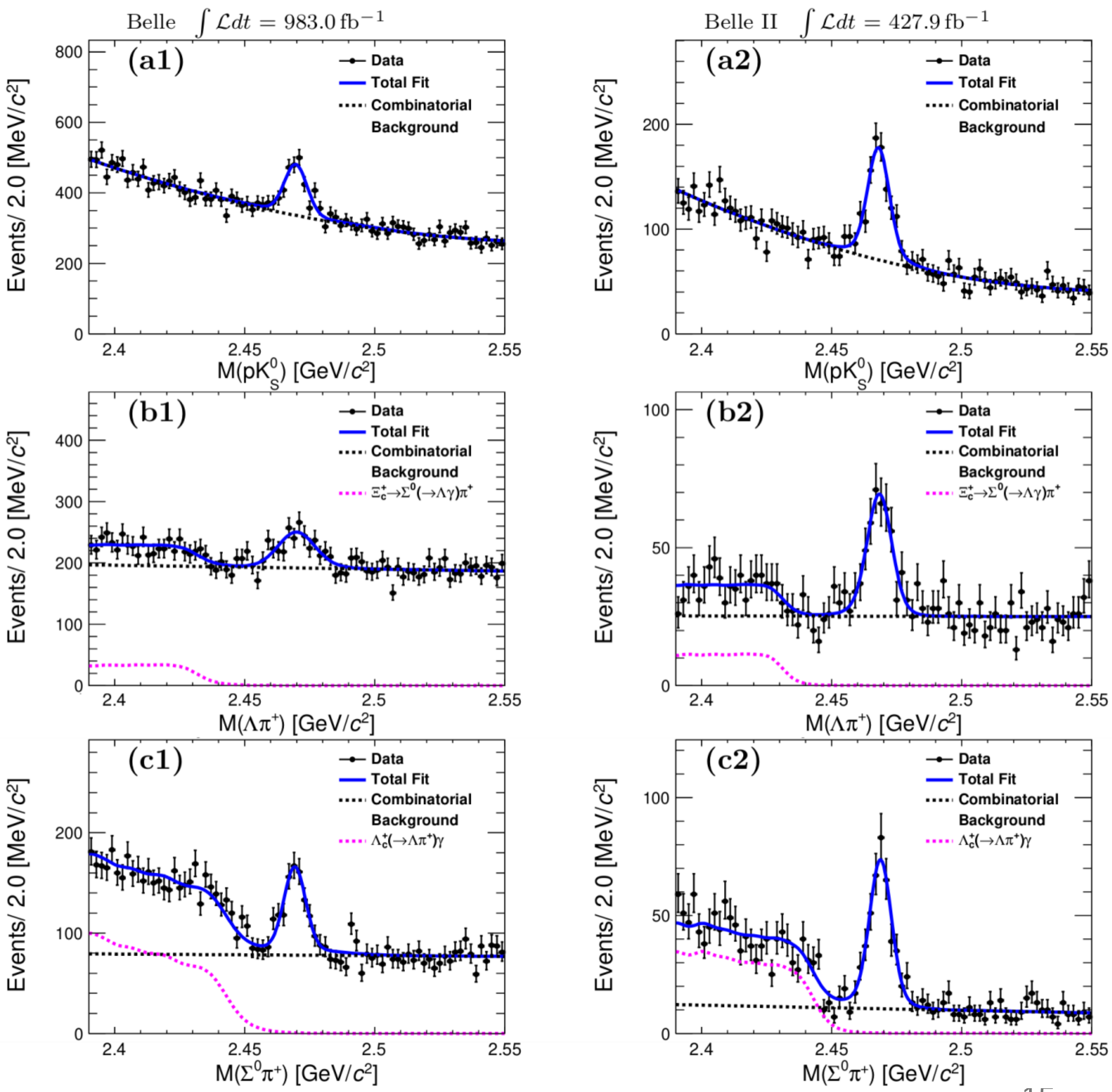
stat syst norm

$$\mathcal{B}(\Xi_c^+ \to pK_S^0) = (7.2 \pm 0.5 \pm 0.2 \pm 3.2) \times 10^{-4}$$

$$\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+) = (4.5 \pm 0.4 \pm 0.3 \pm 2.0) \times 10^{-4}$$

$$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+) = (12.0 \pm 0.2 \pm 0.4 \pm 5.4) \times 10^{-4}$$

first observations of these decays (each one > 10σ)



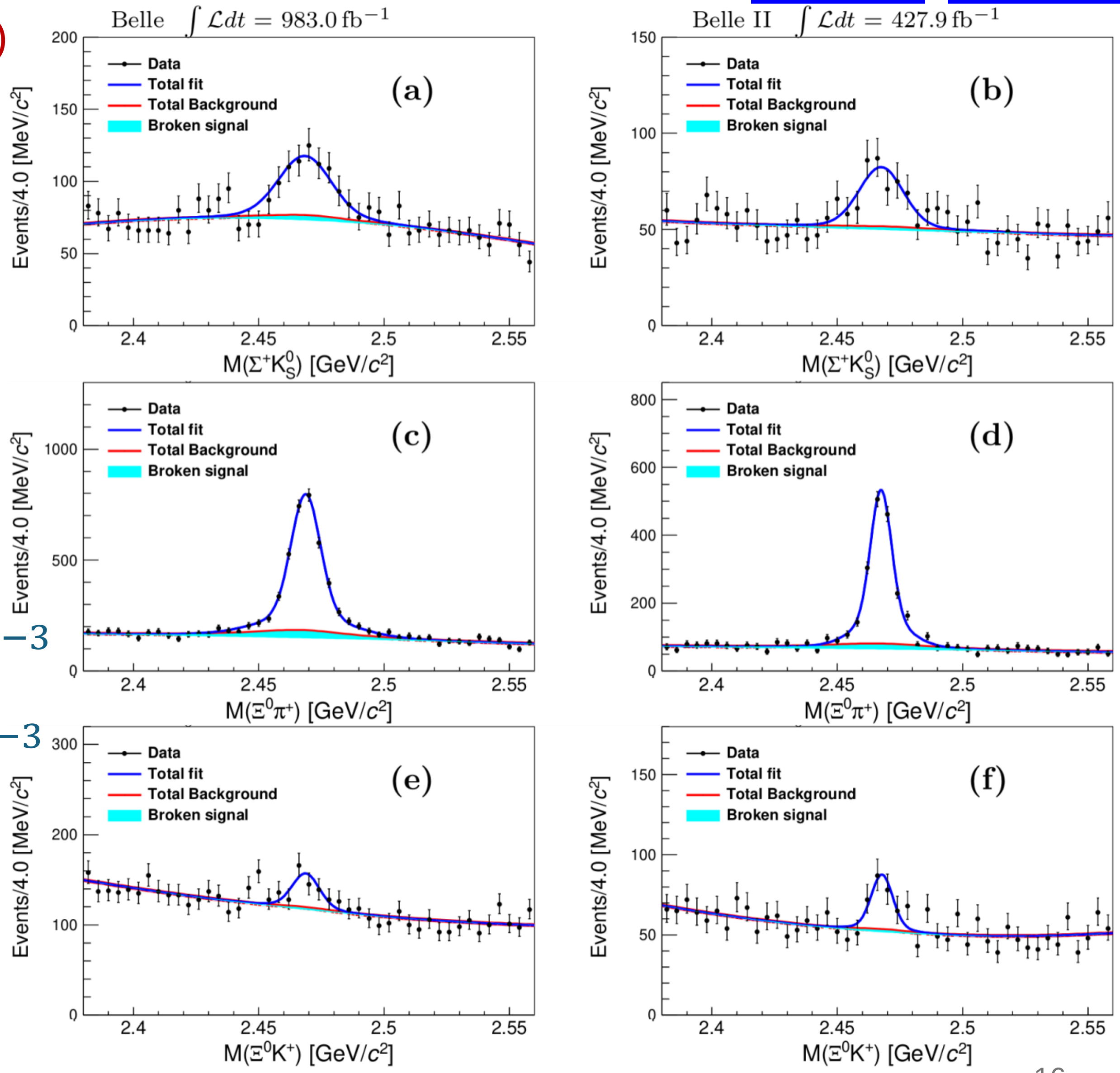
Measurements of $\Xi_c^+ \to \Sigma^+ K_S^0$, $\Xi^0\pi^+$, and $\Xi^0 K^+$

JHEP **08, 195** (2025)

- Cabibbo-favored and SCS decays
- Intermediate states reconstructed in

$$\Sigma^+ \to p\pi^0,\ \Xi^{0/-} \to \Lambda\pi^{0/-},\ \Lambda \to p\pi^-$$

- Normalization mode: $\Xi_c^+ \to \Xi^- \pi^+\pi^+$
- Significant signals observed



stat syst norm

$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (1.94 \pm 0.21 \pm 0.09 \pm 0.87) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+) = (7.19 \pm 0.14 \pm 0.24 \pm 3.22) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+) = (4.9 \pm 0.7 \pm 0.2 \pm 2.2) \times 10^{-4}$$

first measurements of $\Sigma^+ K_S^0$ and $\Xi^0 K^+$,

most precise $\Xi^0 \pi^+$

Measurements of $\Xi_c^0 \to \Lambda\eta$, $\Lambda\eta'$, and $\Lambda\pi^0$

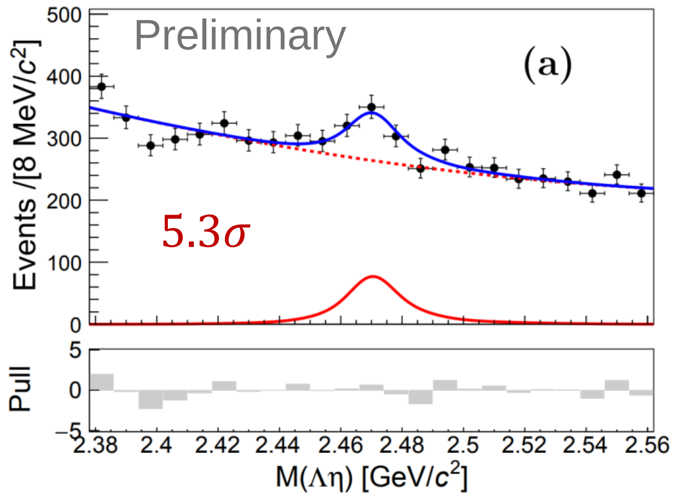
Submitted to PRD

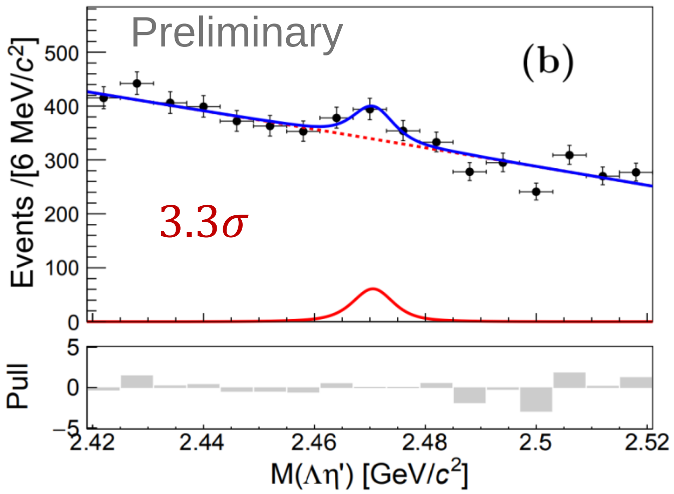
- Cabibbo-suppressed decays
- Intermediate states reconstructed in

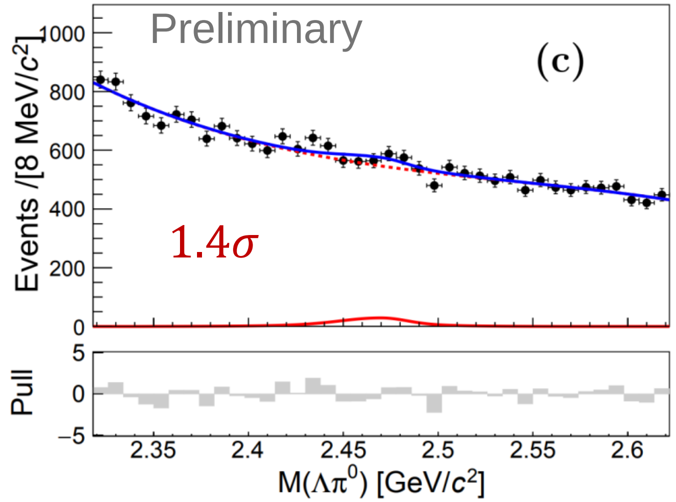
$\eta' \to \pi^+\pi^-\eta/\gamma\,, \eta \to \pi^+\pi^-\pi^0, \eta \to \gamma\gamma$

- Normalization mode: $\Xi_c^0 \to \Xi^-(\to \Lambda\pi^-)\pi^+$

$\mathcal{B} = (1.43 \pm 0.27)\%$ [PDG]







stat syst norm

$\mathcal{B}(\Xi_c^0 \to \Lambda\eta) = (5.95 \pm 1.30 \pm 0.32 \pm 1.13) \times 10^{-4}$

$\mathcal{B}(\Xi_c^0 \to \Lambda\eta') = (3.55 \pm 1.17 \pm 0.17 \pm 0.68) \times 10^{-4}$

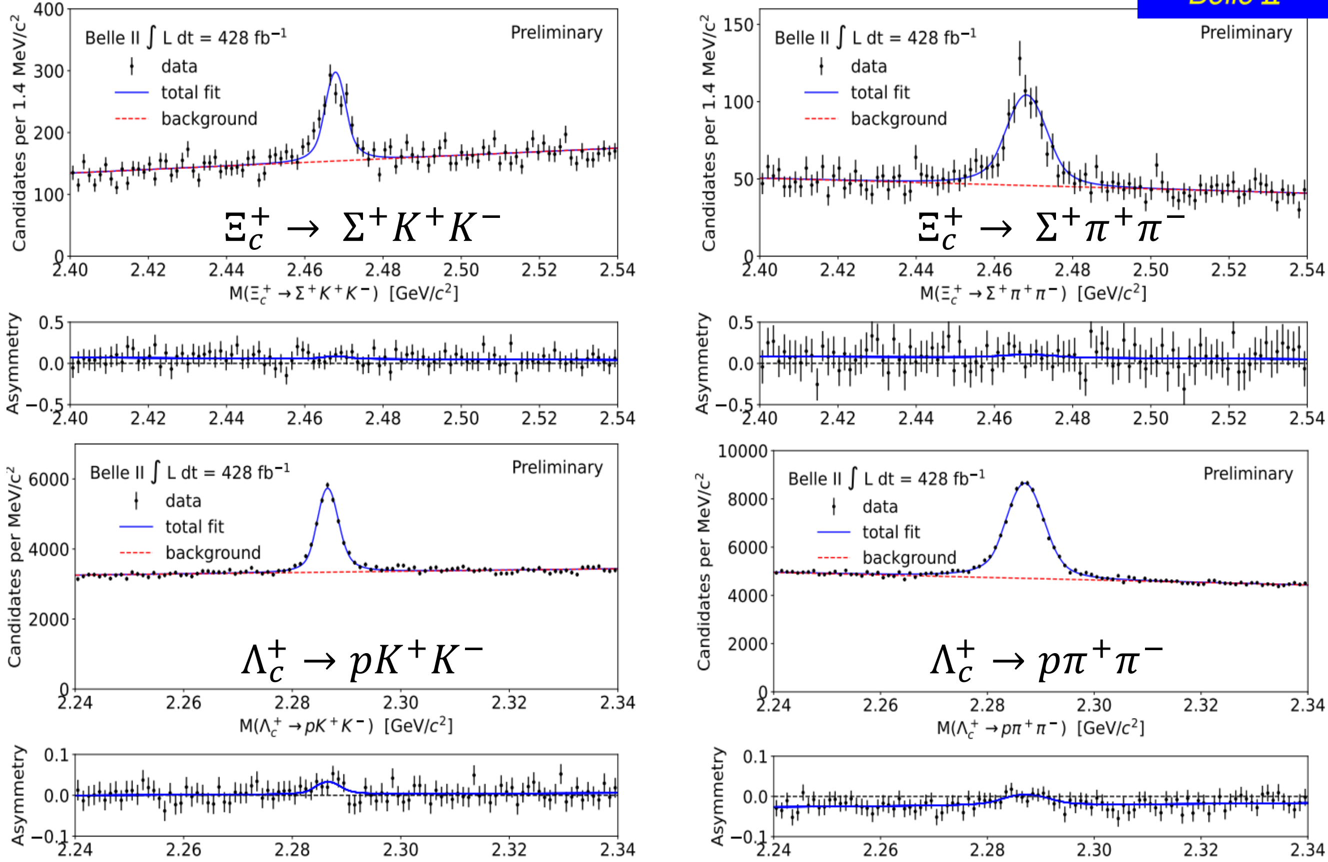
$\mathcal{B}(\Xi_c^0 \to \Lambda\pi^0) < 5.2 \times 10^{-4}$

first observation of $\Lambda\eta$, first evidence for $\Lambda\eta'$

A_{CP} in baryon decays

Submitted to PRD

- $\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-, \Lambda_c^+ \rightarrow p h^+ h^-$, $h = K, \pi$
- Intermediate state $\Sigma^+ \rightarrow p\pi^0$
- Production asymmetry: A_{raw} averaged for forward ($\cos\theta_{CM} > 0$) and backward
- Detection asymmetry: Cabibbo-favored decays



$$A_{CP}^{\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-} = A_{raw}^{\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-} - A_{detection}^{\Lambda_c^+ \rightarrow \Sigma^+ h^+ h^-}$$

$$A_{CP}^{\Lambda_c^+ \rightarrow p h^+ h^-} = A_{raw}^{\Lambda_c^+ \rightarrow p h^+ h^-} - A_{detection}^{\Lambda_c^+ \rightarrow p \pi^+ K^-} + A_{detection}^{D^0 \rightarrow \pi^+ K^- \pi^+ \pi^-}$$

$$A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ K^+ K^-) = (3.7 \pm 6.6 \pm 0.6)\%$$

$$A_{CP}(\Lambda_c^+ \rightarrow p K^+ K^-) = (3.9 \pm 1.7 \pm 0.7)\%$$

$$A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-) = (9.5 \pm 6.8 \pm 0.5)\%$$

$$A_{CP}(\Lambda_c^+ \rightarrow p \pi^+ \pi^-) = (0.3 \pm 1.0 \pm 0.2)\%$$

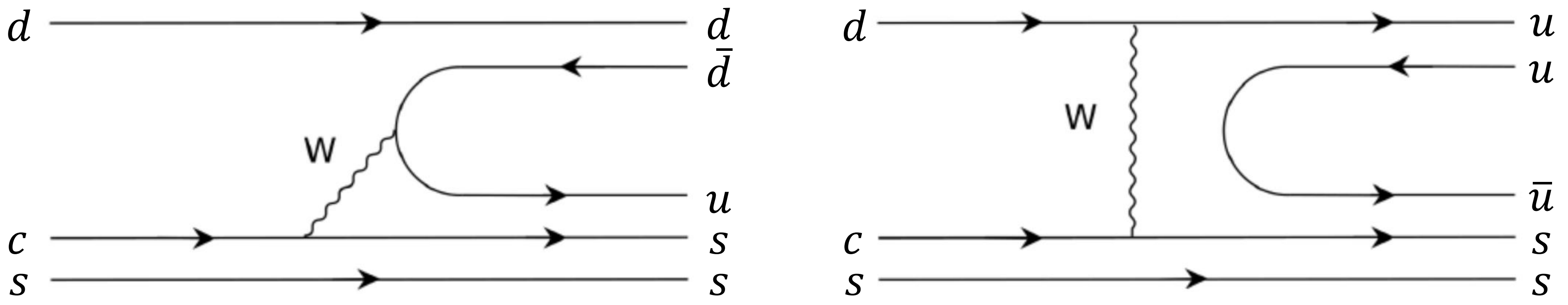
Summary and conclusions

- Belle and Belle II provide a unique environment and unique sensitivity for SM measurements as well as for the search for physics beyond the SM in the charm sector both in meson and baryon decays
- A_{CP} measurements of $D^0 \to K_S^0 K_S^0$ and $D^0 \to \pi^+\pi^-\pi^0$ with world's best precisions
- Measurements of CP asymmetries and related sum rules of $D \to \pi\pi$ have been presented, no evidence of CPV was observed
- First observations and measurements of branching ratios for baryon decays and search for CP asymmetries in baryon decays have been shown
- New data taking started in November 2025

Branching fractions of charmed baryons

- Nonfactorizable amplitudes arising from internal W-emission and W-exchange lead to difficulties for theoretical predictions

  $\Xi_c^0 \to \Xi^0 h^0$:



- Measurements of branching fractions will help to clarify the theoretical picture
- Data analysis is pretty much similar among different decay modes:
  - momentum cut to suppress background (mostly from B decays)
  - particle identification
  - vertex fits (mass constrained for intermediate states, IP constrained for final state)
  - best candidate selection (usually based on vertex fit quality)

Measurements of the BF of $\Xi_c^0 \to \Xi^0\pi^0$, $\Xi^0\eta$, and $\Xi^0\eta'$

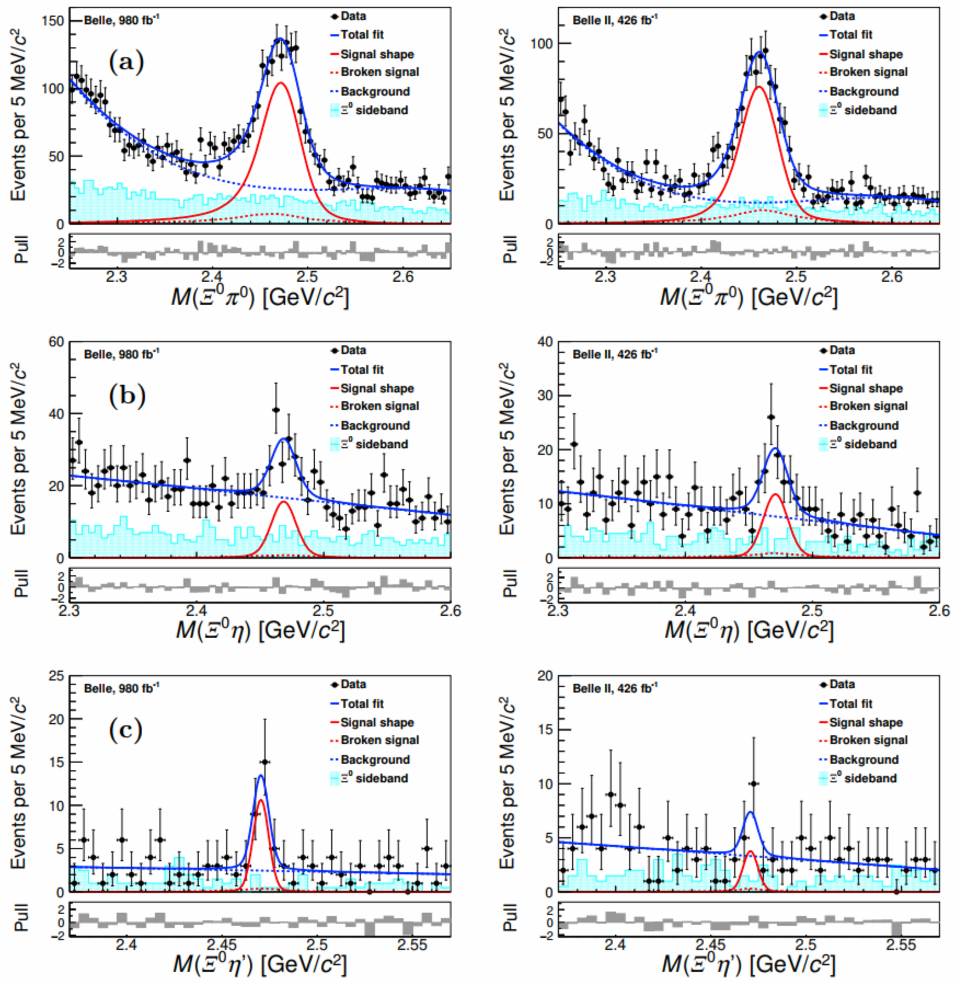
JHEP 10 (2024) 045

- Intermediate states reconstructed in
  $\Xi^{0/-} \to \Lambda\pi^{0/-}$, $\Lambda \to p\pi^-$, $\eta' \to \pi^+\pi^-\eta$, $\eta/\pi^0 \to \gamma\gamma$
- Normalization mode: $\Xi_c^0 \to \Xi^-\pi^+$,
  $\mathcal{B} = (1.43 \pm 0.27)\%$ [PDG2024]
- Significant signals observed
- Branching fractions

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm \underset{\text{stat}}{0.3} \pm \underset{\text{syst}}{0.5} \pm \underset{\text{norm}}{1.3}) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3 \pm 0.1 \pm 0.2) \times 10^{-3}$$



first measurement of these decays

Comparison with theory predictions

- Theory predictions mostly not far from measurements
- The obtained results cannot rule-out any models