Belle II粲物理近期成果亮点

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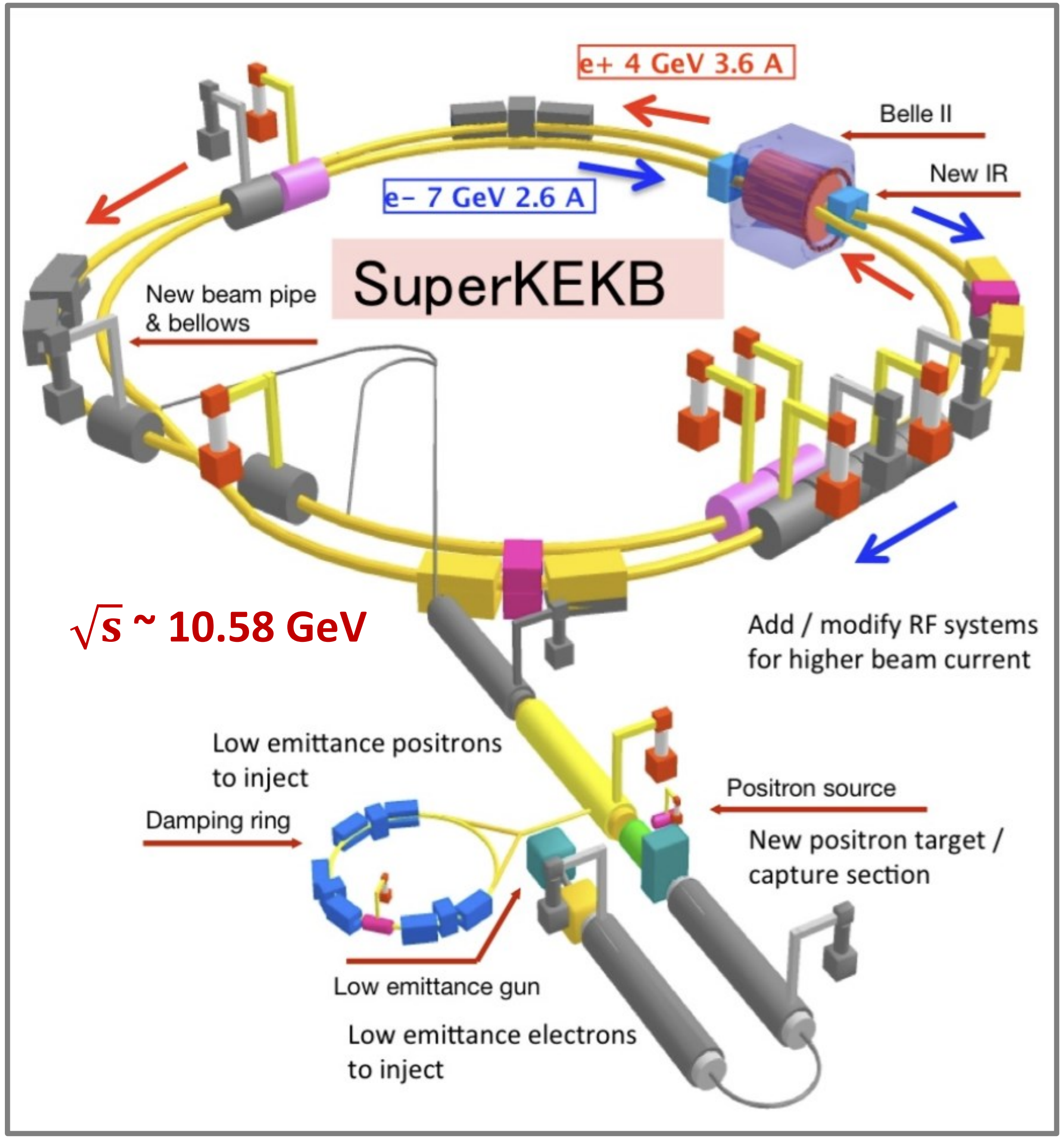
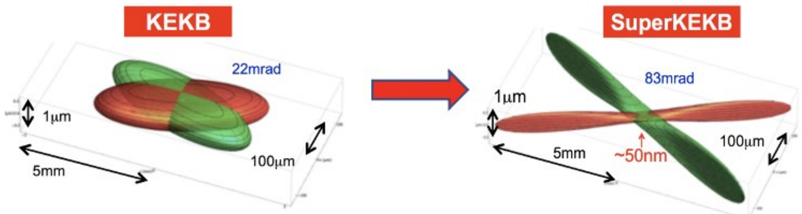
第三届BESIII-Belle II-LHCb粲强子物理联合研讨会
2025/6/27-7/1 长沙

SuperKEKB and Belle II

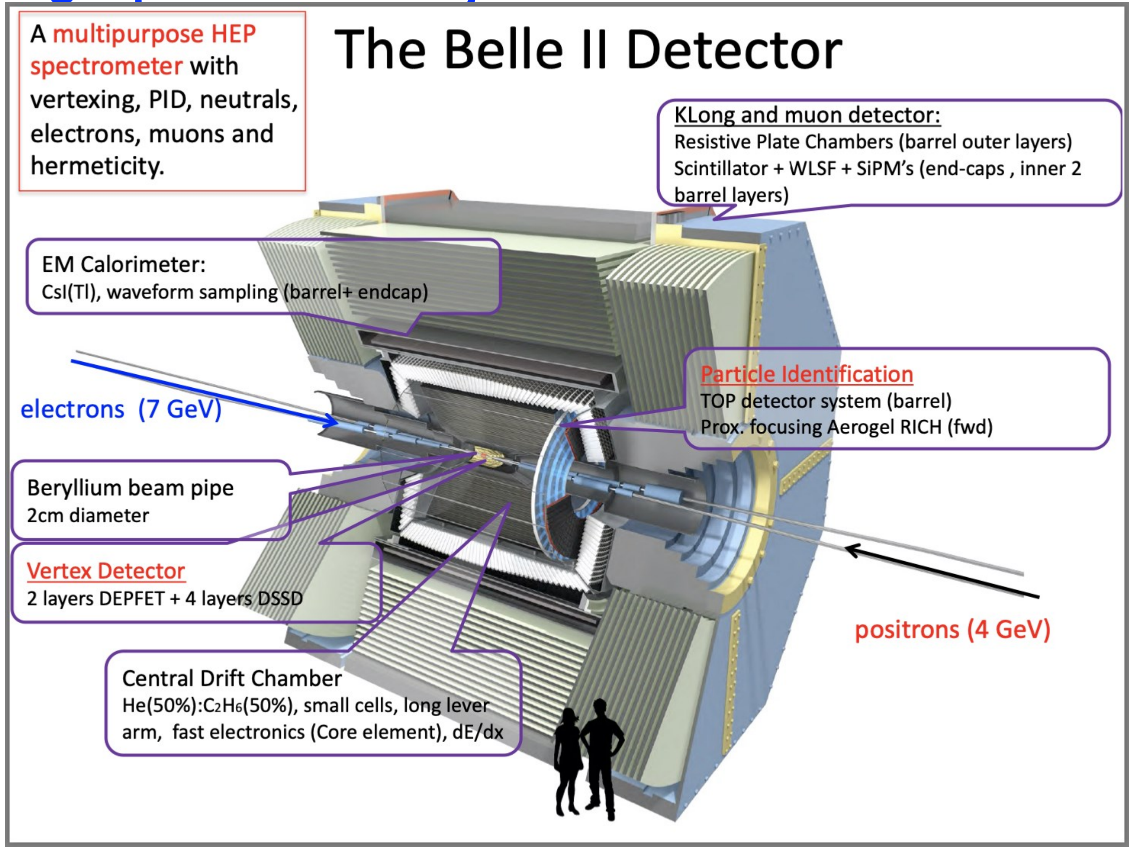




Nano-beam design:

Beam squeezing: ×20 smaller; Beam current: ×2 larger

Target peak luminosity: KEKB×30



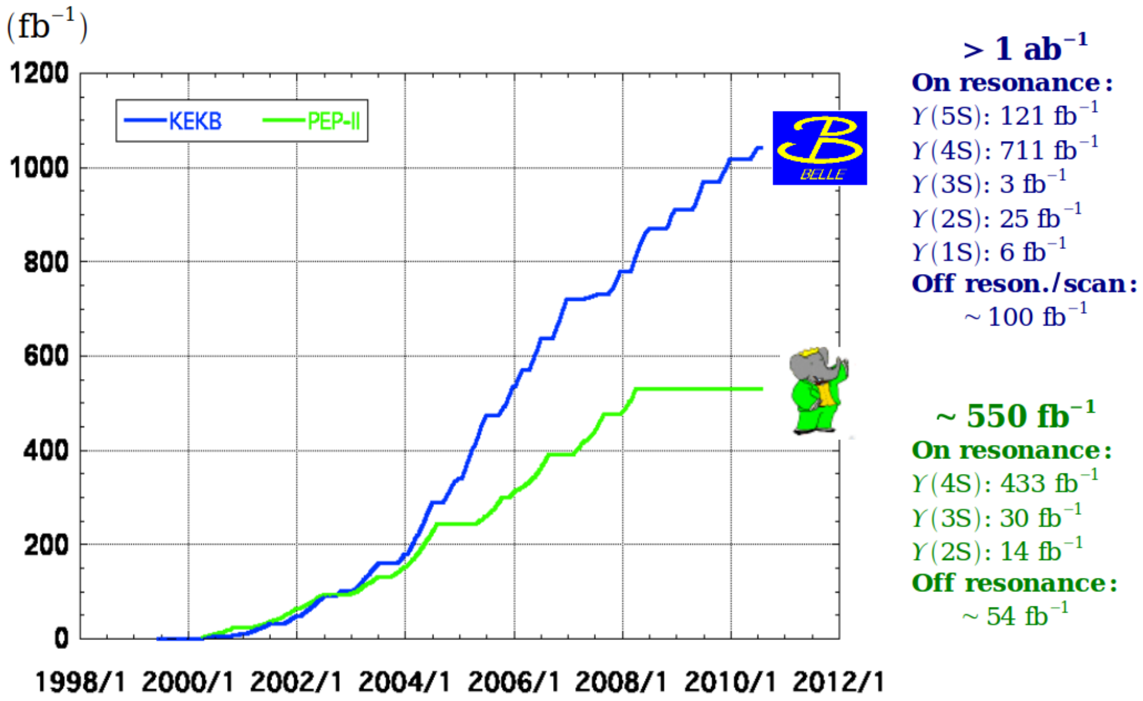
Belle and Belle II Datasets

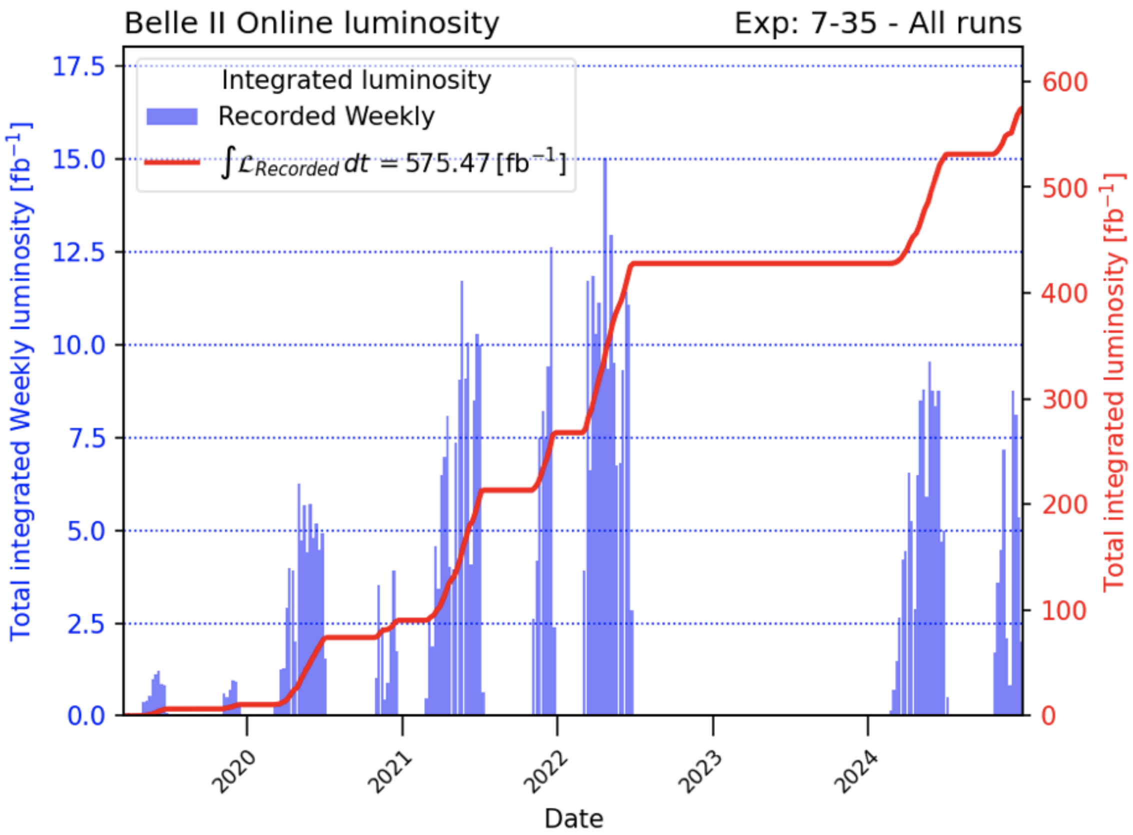
- **Belle (1999 - 2012)**
- **Belle II RUN-I (2019 - 2022)**
- **Belle II RUN-II (2024 - 2025)**

In December 2024

WORLD RECORD: $5.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Integrated luminosity of B factories



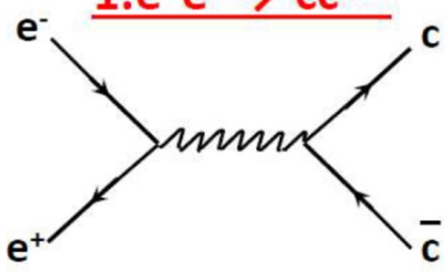


Most data at or near the $\Upsilon(4S)$ resonance, and 19.6 fb^{-1} near $\Upsilon(10753)$.

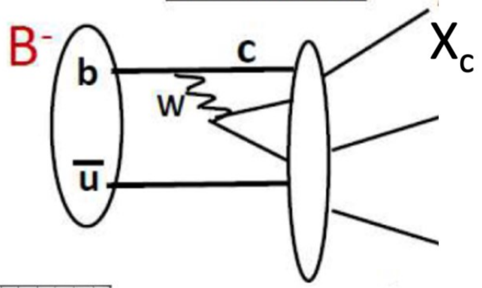
Charm physics at Belle (II)

Two primary mechanisms for charm production at Belle/Belle II:

1.e$^+$e$^-$ → cc^{bar}



2.B-decay



1. $e^+e^- \rightarrow c\bar{c} \rightarrow X_c$

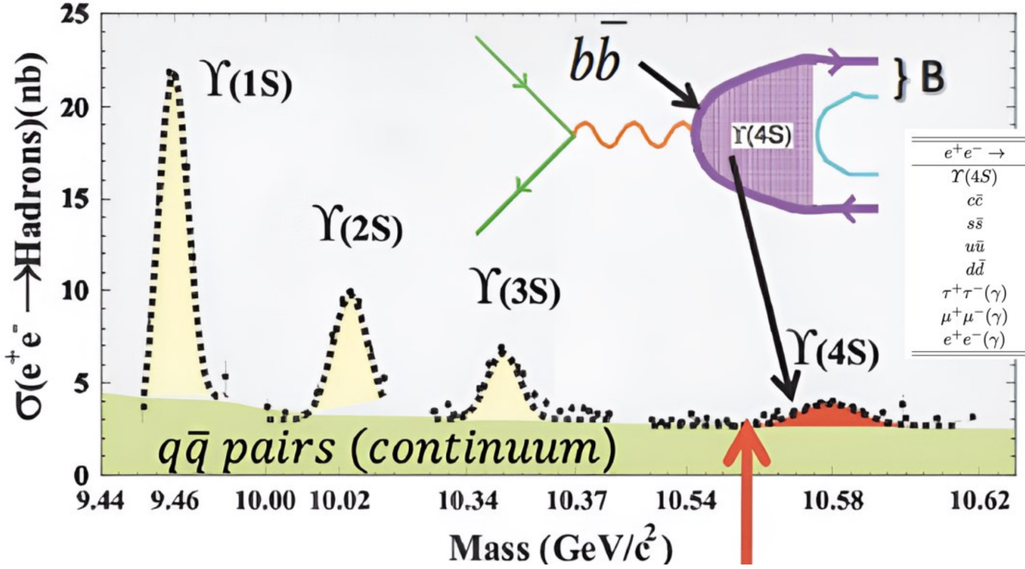
- Absolute measurements not possible without reference
- Used for most analyses due to its simplicity compared to $B\bar{B}$ processes

2. $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \rightarrow X_c$

- Precise $B\bar{B}$ cross section allows for absolute measurements

Full topics for charm physics:

- ➢ **CP violation** ✓
- ➢ **$D^0 - \bar{D}^0$ mixing** ✓
- ➢ **Charmed baryon** ✓
- ➢ Amplitude analysis
- ➢ Lifetime
- ➢ Rare decay



$e^+e^- \rightarrow$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

CPV in Charm

CP asymmetry in $D^+ \to \pi^+\pi^0$

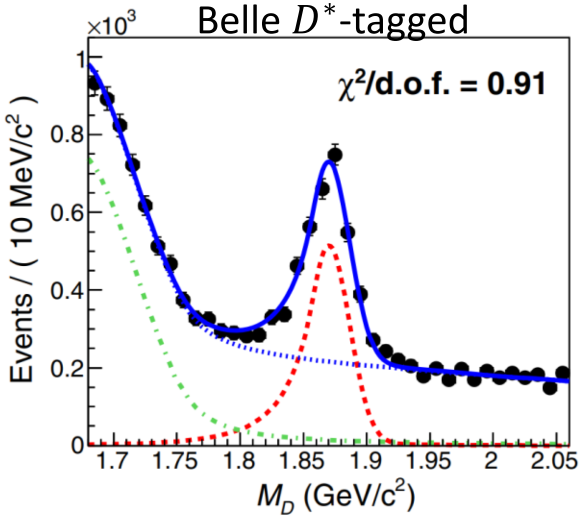
arXiv: 2506.07879

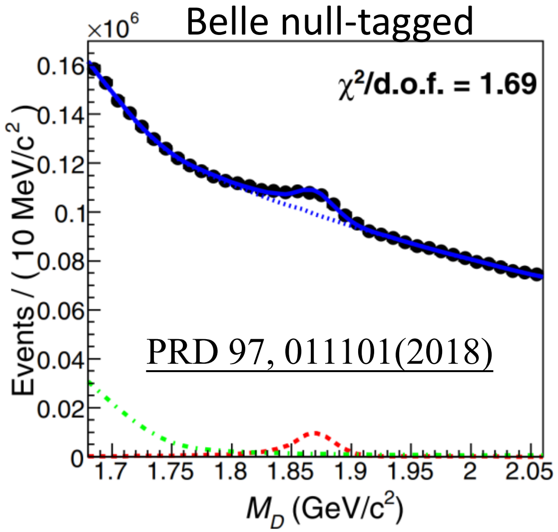
- A 3.8σ CPV in the pionic mode $D^0 \to \pi^+\pi^-$.
  - ➢ Unclear if observed CP violation can be described by the SM or not, due to large hadronic uncertainties
    PRL 131, 051802 (2023) PRD 108, 036026 (2023) PRD 109, 033011 (2024)
- Isospin-related modes $D^+ \to \pi^+\pi^0$ can reduce hadronic uncertainty.
- In addition, $D^+ \to \pi^+\pi^0$ $(I = 2)$ is expected to have no CPV in SM
  - ➢ since it does not receive QCD penguin $(\Delta I = 1/2)$ contribution and has suppressed electroweak penguin contribution.

History of $A_{cp}(D^+ \to \pi^+\pi^0)$:

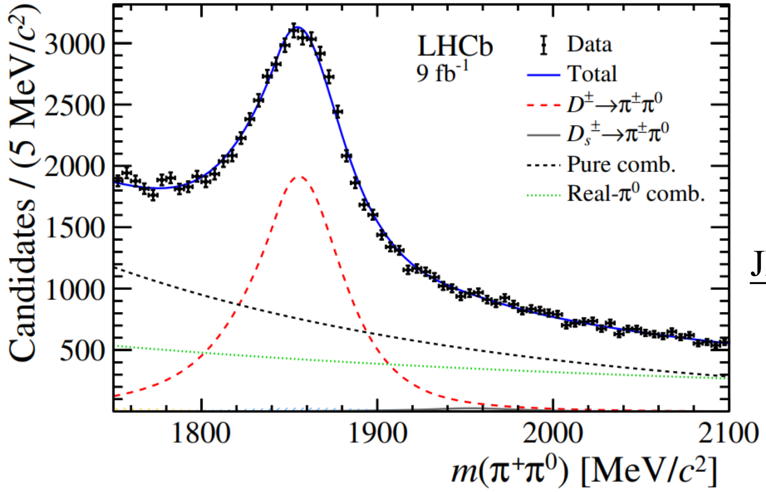
Belle: $A_{cp}(D^+ \to \pi^+\pi^0) = (2.31 \pm 1.24 \pm 0.23)\%$

LHCb: $A_{cp}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$





PRD 97, 011101(2018)



JHEP 06, 019 (2021)

CP asymmetry in $D^+ \to \pi^+\pi^0$

arXiv: 2506.07879

- The physics variable that we are interested is $A_{CP}(D^+ \to \pi^+\pi^0) = \frac{\Gamma(D^+\to\pi^+\pi^0)-\Gamma(D^-\to\pi^-\pi^0)}{\Gamma(D^+\to\pi^+\pi^0)+\Gamma(D^-\to\pi^-\pi^0)}$

- But the variable easily accessed in exp is $A_{raw}^{\pi\pi} = \frac{N(D^+\to\pi^+\pi^0)-N(D^-\to\pi^-\pi^0)}{N(D^+\to\pi^+\pi^0)+N(D^-\to\pi^-\pi^0)}$

- $A_{raw}^{\pi\pi}$ is related by $A_{raw}^{\pi\pi} = A_{CP}^{\pi\pi} + \boxed{A_{prod}^{D} + A_{\epsilon}^{\pi}}$ $\rightarrow$ **nuisance asymmetries**

A_{prod}^{D}: forward-backward asymmetric production in e^+e^- collisions of charm hadrons, due to $\gamma^* - Z^0$ interference and higher-order QED effects, is an odd function of $\cos\theta_{CM}(D^{\pm})$.

$A_{\epsilon}^{\pi^{\pm}}$: detection asymmetry of the low-momentum tagging pions.

$\downarrow$

use $D^+ \to \pi^+ K_S^0$ as a control mode to estimate this

$D^+ \to \pi^+ K_S^0$ $(Br = (1.562 \pm 0.031)\,\%$, Cabibbo-favored)

$$A_{raw}^{\pi K_S} = A_{K_S} + \boxed{A_{prod}^{D} + A_{\epsilon}^{\pi^{\pm}}}$$

$A_{K_S} \sim -0.4\,\%$

Control mode $\uparrow$

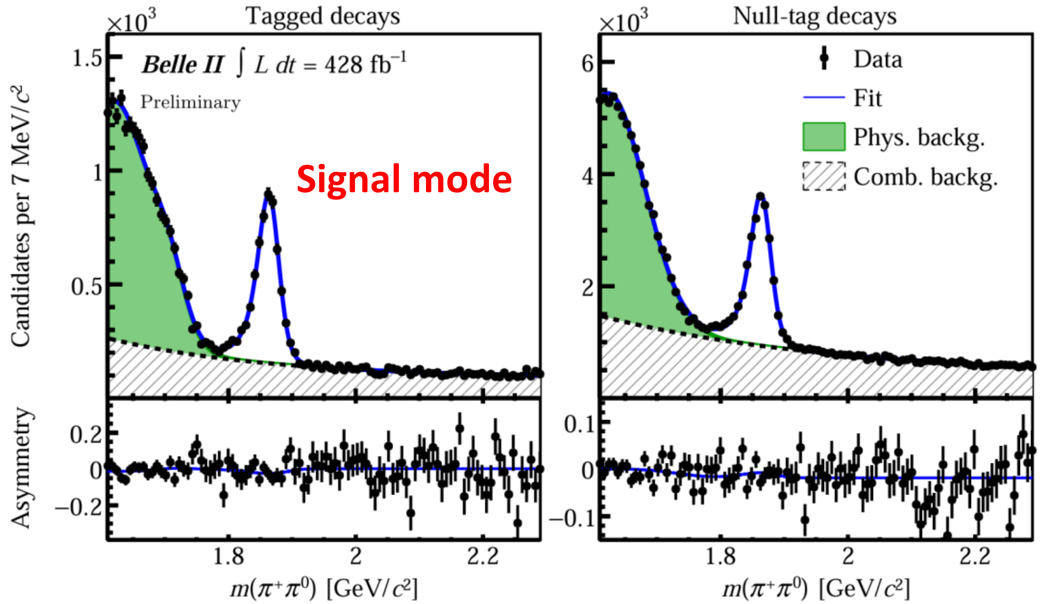
$$\boxed{A_{CP}^{\pi\pi} = A_{raw}^{\pi\pi} - A_{raw}^{\pi K_S} + A_{K_S}}$$

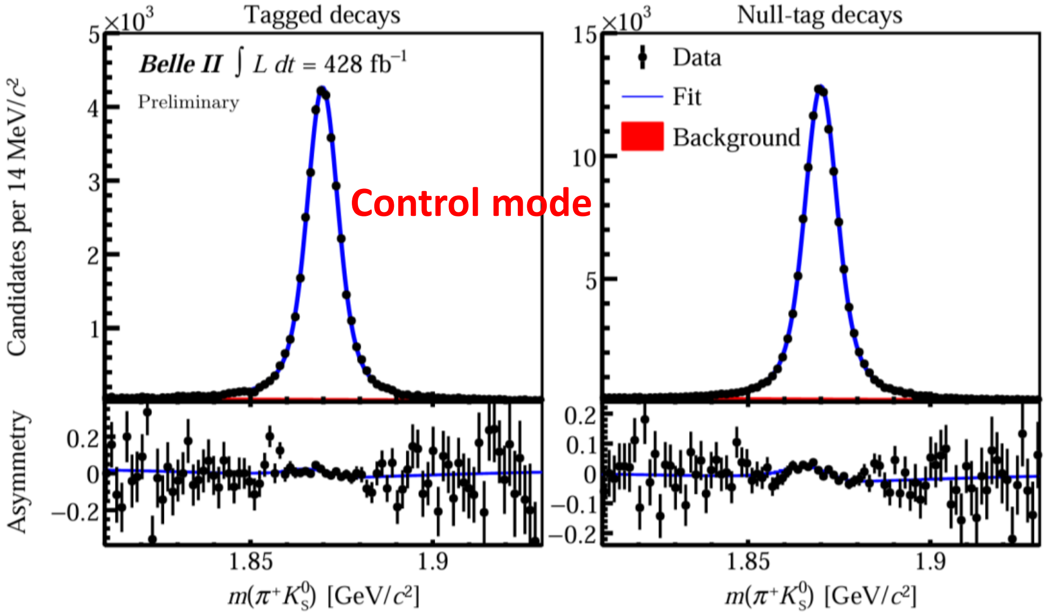
$\downarrow$ Signal mode

$A_{K_S^0}$: 1, CP-violation in the K^0-$\bar{K}^0$ system.
2, different nuclear-interaction cross-sections for K^0 and $\bar{K}^0$ mesons with detector.

CP asymmetry in $D^+ \to \pi^+\pi^0$

arXiv: 2506.07879





Signal mode

	Tagged	Null-tag
Yield	5130±110	18510±240
A_{raw}	(-2.9±1.8)%	(-0.4±1.0)%

Control mode

	Tagged	Null-tag
Yield	39630±300	123560±500
A_{raw}	(0.54±0.53)%	(0.33±0.30)%

- Using 428 /fb, Belle II obtain:

1. $A_{CP}(D^+ \to \pi^+\pi^0) = [-3.9 \pm 1.8(stat) \pm 0.2(syst)]\,\%$ for D^*-tagged sample;
2. $A_{CP}(D^+ \to \pi^+\pi^0) = [-1.1 \pm 1.0(stat) \pm 0.1(syst)]\,\%$ for null-tag sample.

- Combined:

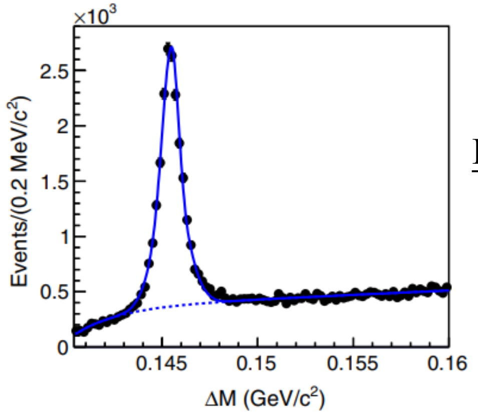
$A_{CP}(D^+ \to \pi^+\pi^0) = [-1.8 \pm 0.9(stat) \pm 0.1(syst)]\,\%$, **most precise!**

- **Agree with previous measurements**
- **Agree with CP symmetry**

CP asymmetry in $D^0 \to \pi^0\pi^0$

arXiv:2505.02912

- Belle reported $A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$ using 980 fb^{-1} datasets.



PRL 112, 211601 (2014)

- Signal mode: $A_{raw}^{\pi^0\pi^0} = A_{CP}^{\pi^0\pi^0} + A_{prod}^{D^*} + A_{\epsilon}^{\pi_s}$; control modes: D^*-tagged $D^0 \to K^-\pi^+$, untagged $D^0 \to K^-\pi^+$.
- $A_{raw}^{K\pi,tag} = A_{prod}^{D^{*+}}(D^0 \to K^-\pi^+) + A_{\epsilon}^{\pi_s}(D^0 \to K^-\pi^+) + A_{\epsilon}^{K\pi}(D^0 \to K^-\pi^+)$
- $A_{raw}^{K\pi,untag} = A_{prod}^{D^0}(D^0 \to K^-\pi^+) + A_{\epsilon}^{K\pi}(D^0 \to K^-\pi^+)$
- Using $A'_{raw} = \dfrac{A_{raw}(cos\theta_{CM} < 0) + A_{raw}(cos\theta_{CM} > 0)}{2}$, the Production Asymmetry is averaged out.

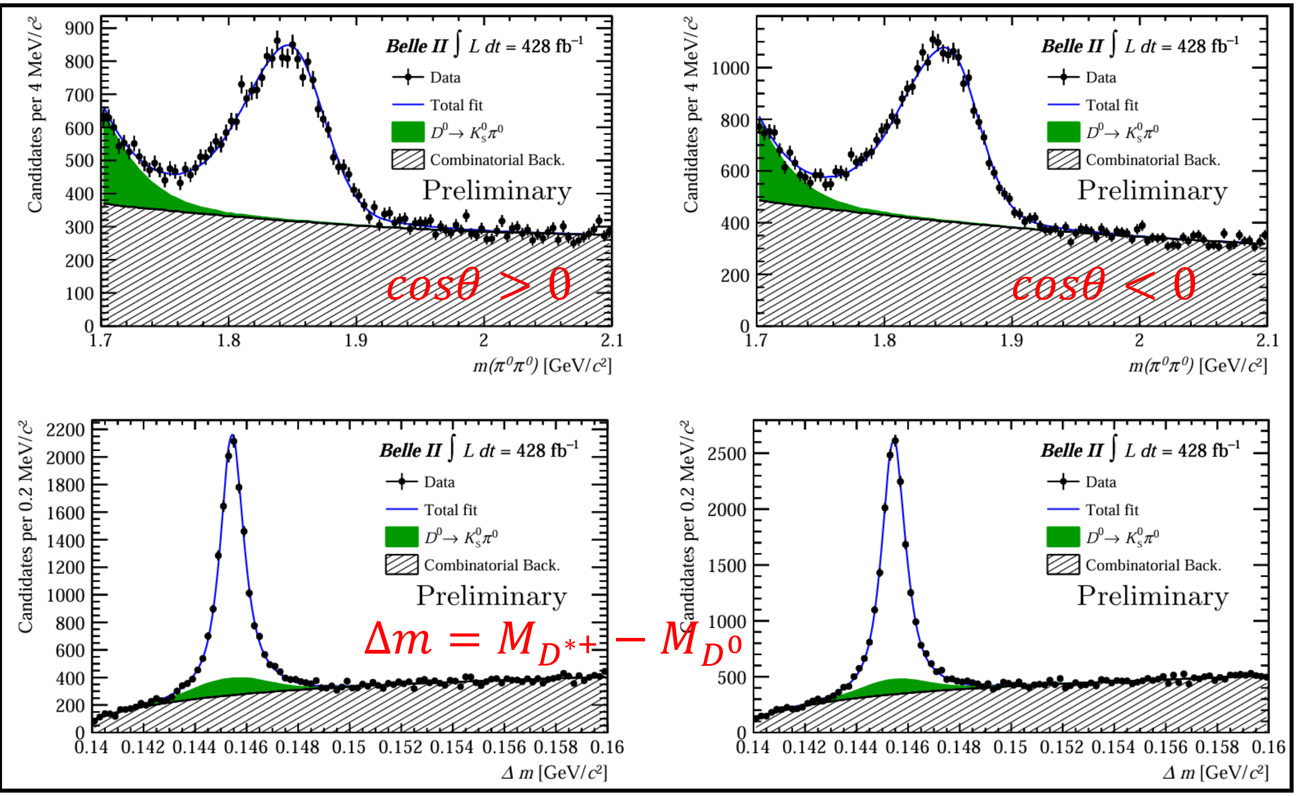
(odd function of $cos\theta_{CM}$)

- $A_{CP}(D^0 \to \pi^0\pi^0) = A'^{\pi^0\pi^0}_{raw} - (A'^{K\pi,tag}_{raw} - A'^{K\pi,untag}_{raw})$

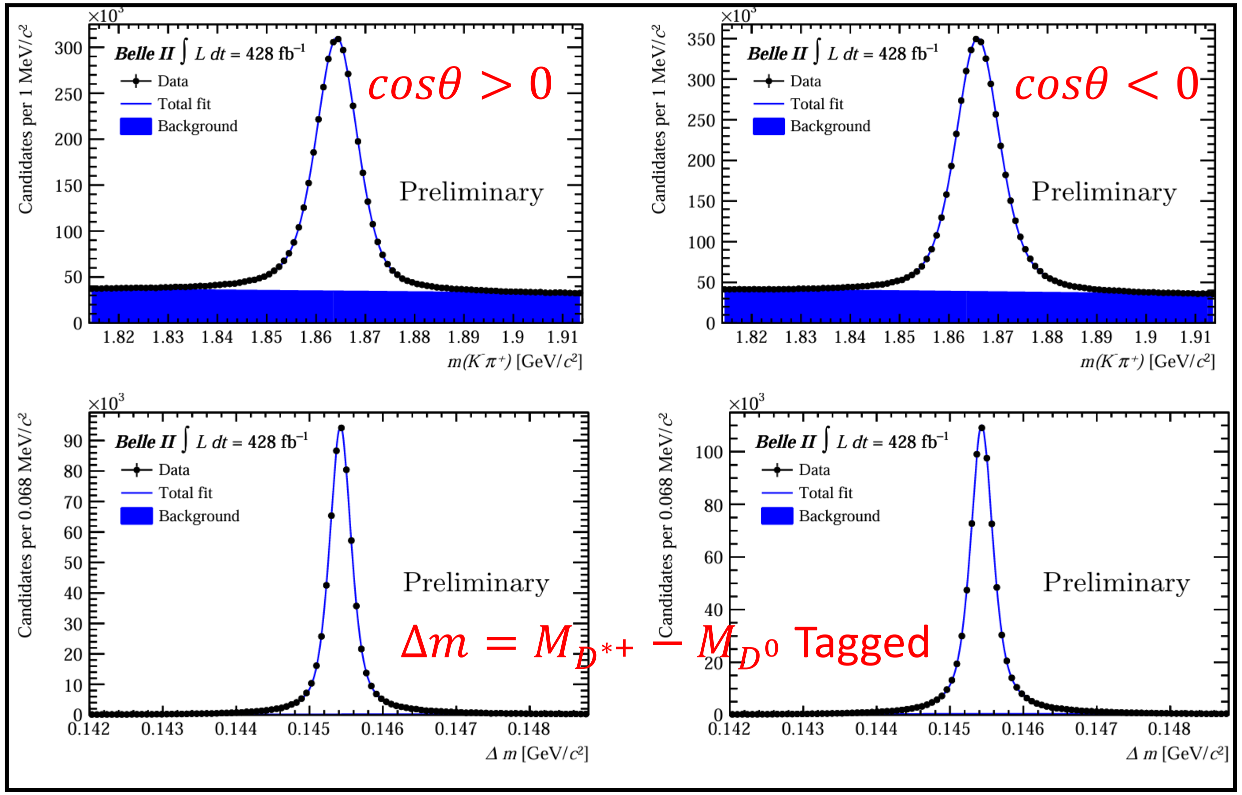
CP asymmetry in $D^0 \to \pi^0\pi^0$

arXiv:2505.02912

Signal mode



Control mode



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

- 15% less precise than Belle, but with < 50% data sets.
- Consistent with CP symmetry and the best existing measurement, from Belle

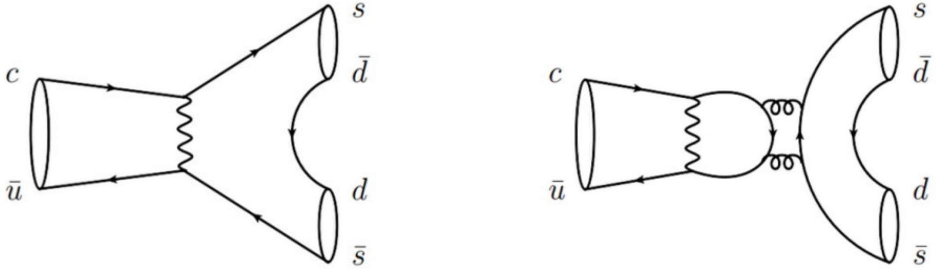
CP asymmetry in $D^0 \to K_S^0 K_S^0$

PRD 111, 012015 (2025)
arXiv: 2504.15881

- The CP asymmetry

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

- It may be enhanced to be an observable level (~1%) within the Standard Model, due to the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes. [PRD 99, 113001 (2019), PRD 86, 014023 (2012), PRD 92, 054036 (2015)]



- World average: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\,\%$ is dominated by

Belle (921 /fb): $A_{CP} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\,\%$, using $D^0 \to K_S^0 \pi^0$ as control mode. PRL 119, 171801 (2017)

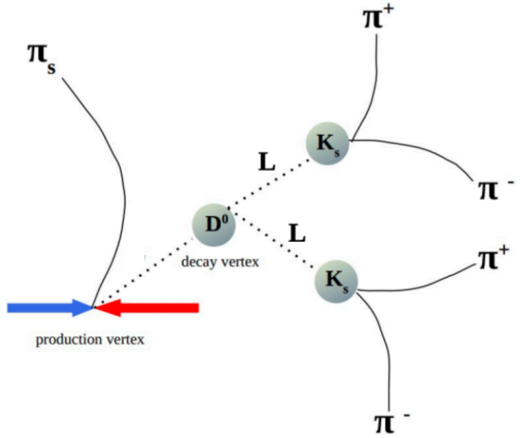
LHCb (6 /fb): $A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$, using $D^0 \to K^+ K^-$ as control mode. PRD 104, L031102 (2021)

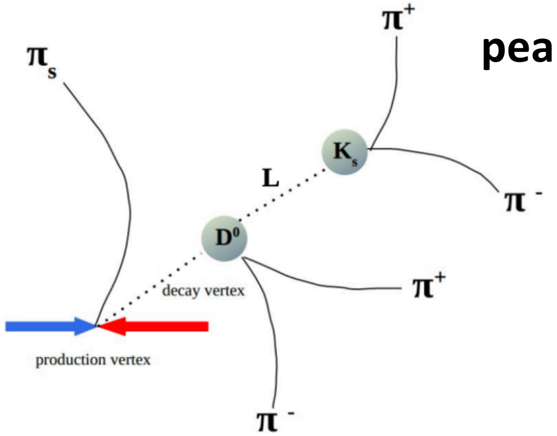
CP asymmetry in $D^0 \to K_S^0 K_S^0$

PRD 111, 012015 (2025)

$A_{CP}(D^0 \to K_S^0 K_S^0)$ using D^*-tagged sample

- Measure $A_{CP}(D^0 \to K_S^0 K_S^0)$ based on $D^{*+} \to D^0 \pi_s^+$ sample at Belle + Belle II (1.4 /ab).
- $A_{CP}^{K_S^0 K_S^0} = (A_{raw}^{K_S^0 K_S^0} - A_{raw}^{K^+K^-}) + A_{CP}^{K^+K^-}$ assuming nuisance asymmetries are made identical by kinematics weighting.
- Main background from same-final-state $D^0 \to K_S^0 \pi^+ \pi^-$ decays. Separate with K_S^0 flight distance significance L/σ: $S_{min}(K_S^0) = \log[\min(L1/\sigma1, L2/\sigma2)]$.



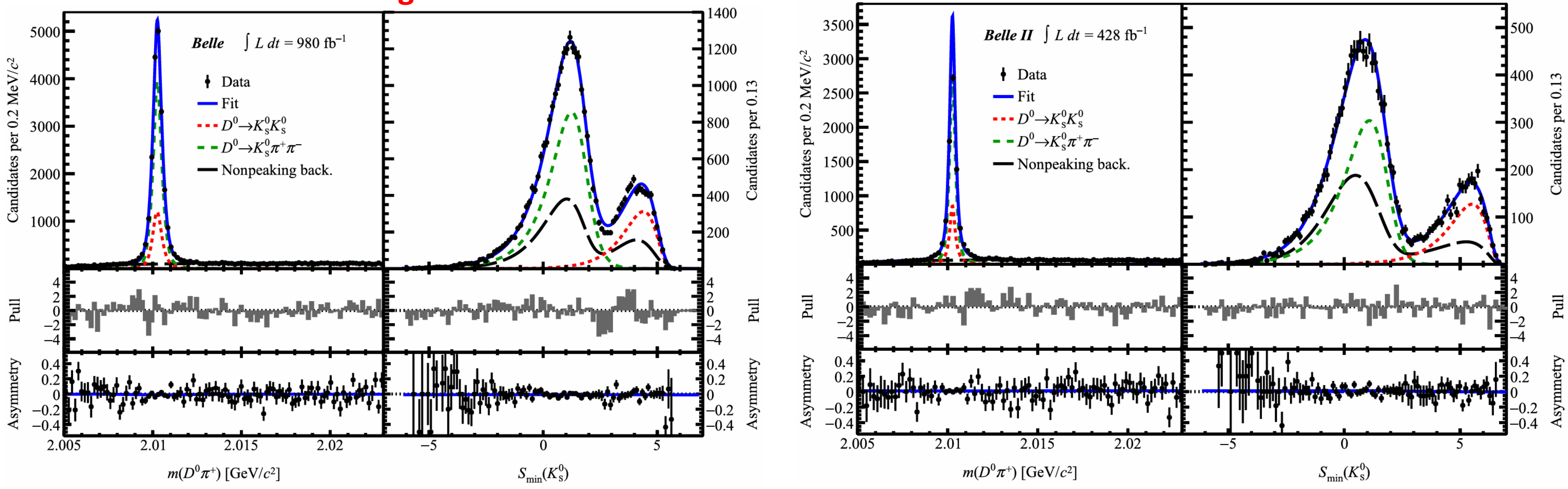


peaking background

CP asymmetry in $D^0 \to K_S^0 K_S^0$

PRD 111, 012015 (2025)

Signal mode



- Simultaneous 2D fit to $m(D^0\pi^+)$ and $S_{min}(K_S^0)$.

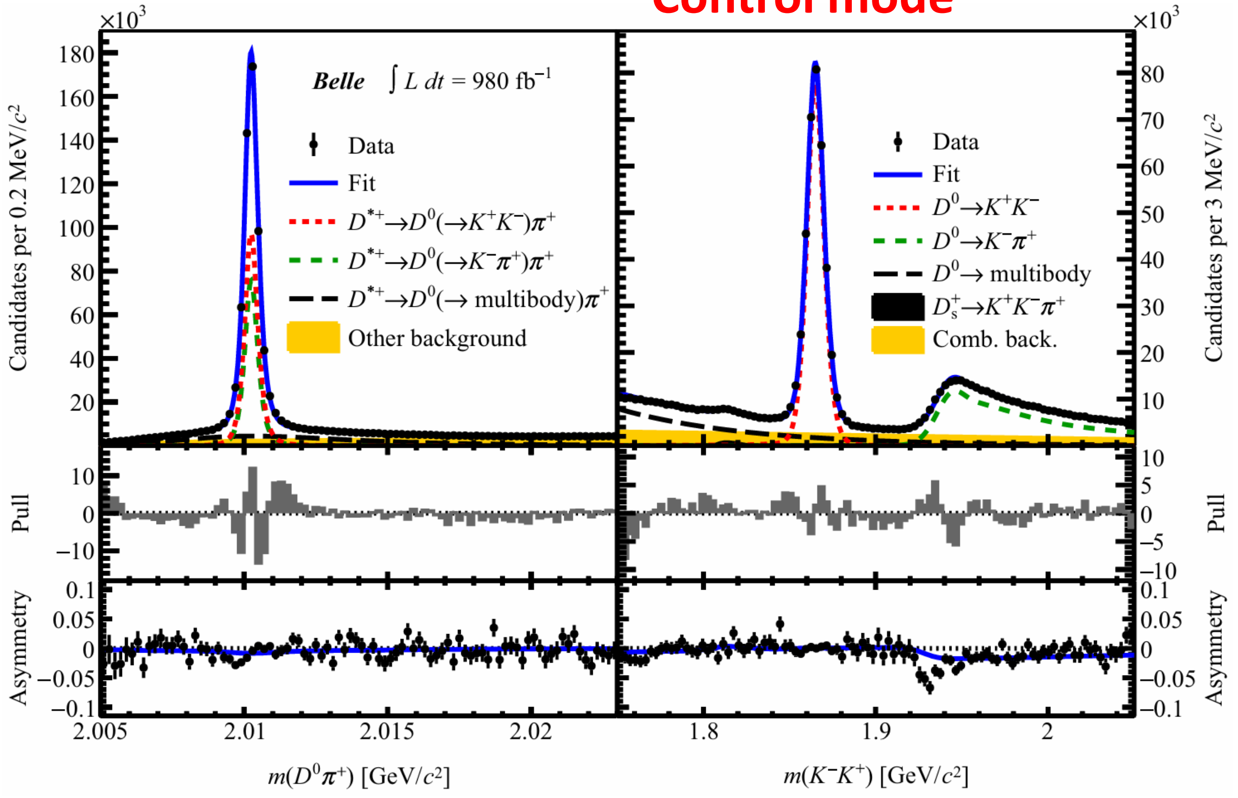
- Signal and Physics background ($D^0 \to K_S^0\pi^+\pi^-$) peak at the same position in $m(D^0\pi^+)$ but different in $S_{min}(K_S^0)$.

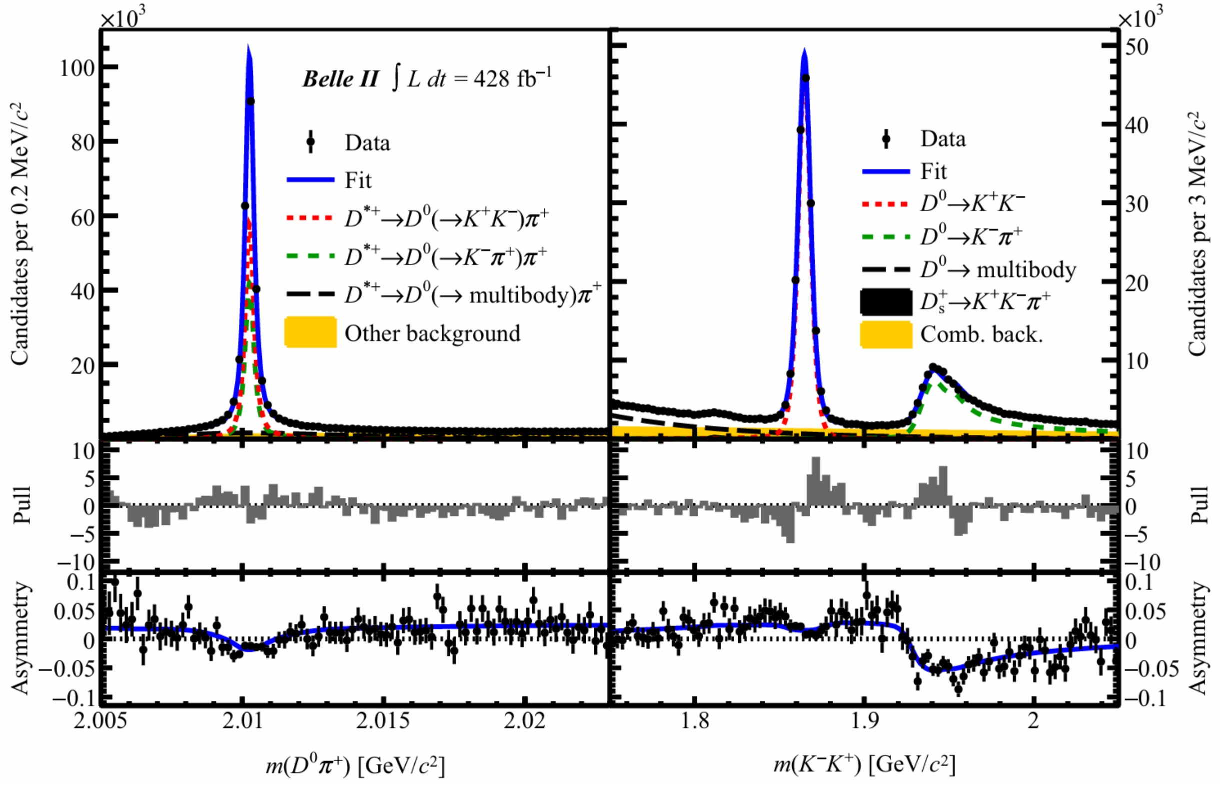
$$A_{raw}^{K_S^0K_S^0} = (-1.0 \pm 1.6)\,\% \text{ in Belle; } A_{raw}^{K_S^0K_S^0} = (-0.6 \pm 2.3)\,\% \text{ in Belle II.}$$

CP asymmetry in $D^0 \to K_S^0 K_S^0$

PRD 111, 012015 (2025)

Control mode





$A_{raw}^{K^+K^-} = (0.17 \pm 0.19)\,\%$ in Belle; $A_{raw}^{K^+K^-} = (1.61 \pm 0.27)\,\%$ in Belle II.

- Combined Belle and Belle II (1.4 /ab), $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\,\%$, comparable to the best existing measurement (LHCb).

PRD 104, L031102 (2021)

- **Agree with CP symmetry**

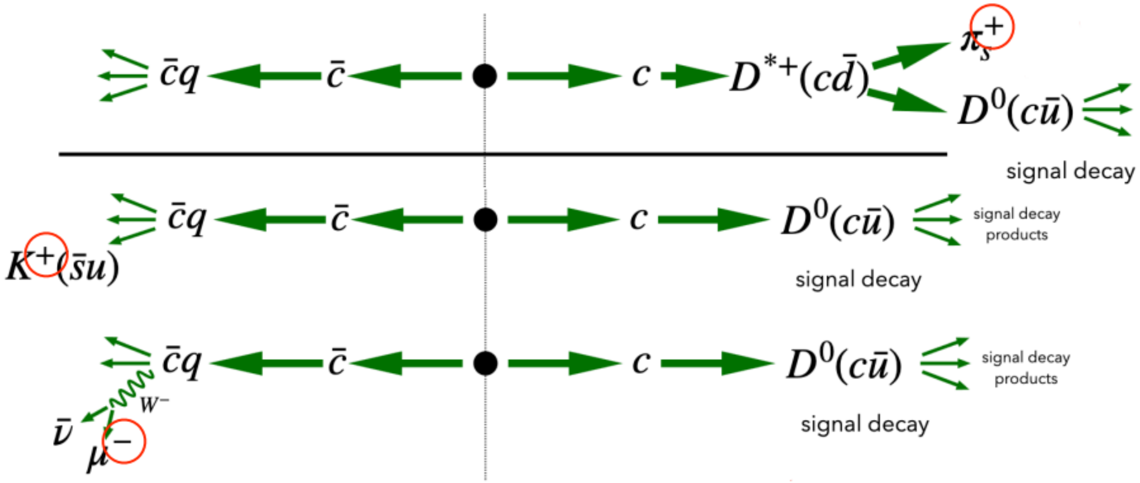
CP asymmetry in $D^0 \to K_S^0 K_S^0$

arXiv: 2504.15881

$A_{CP}(D^0 \to K_S^0 K_S^0)$ using opposite side charm-flavor tagger

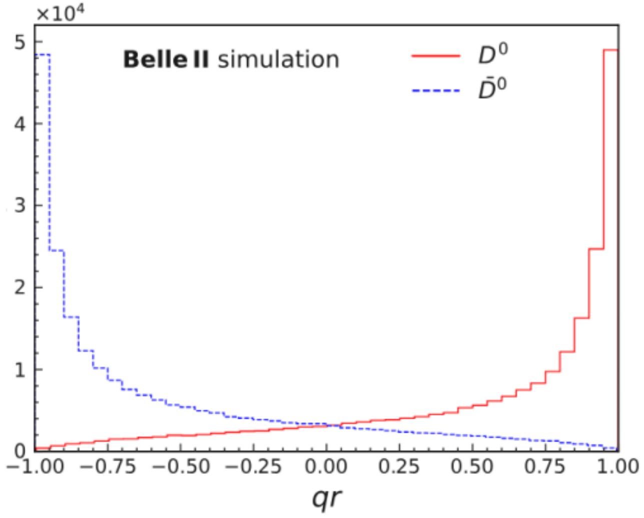
PRD 107, 112010 (2023)

- Charm flavor tagger: novel method to tag flavor of D^0 meson from other collision products ($K^\pm/\mu^\pm$ from other charm hadron) → new CFT-tag independent sample.



- $q = \pm 1$, the predicted flavor
- ω, per-event wrong-tag probability

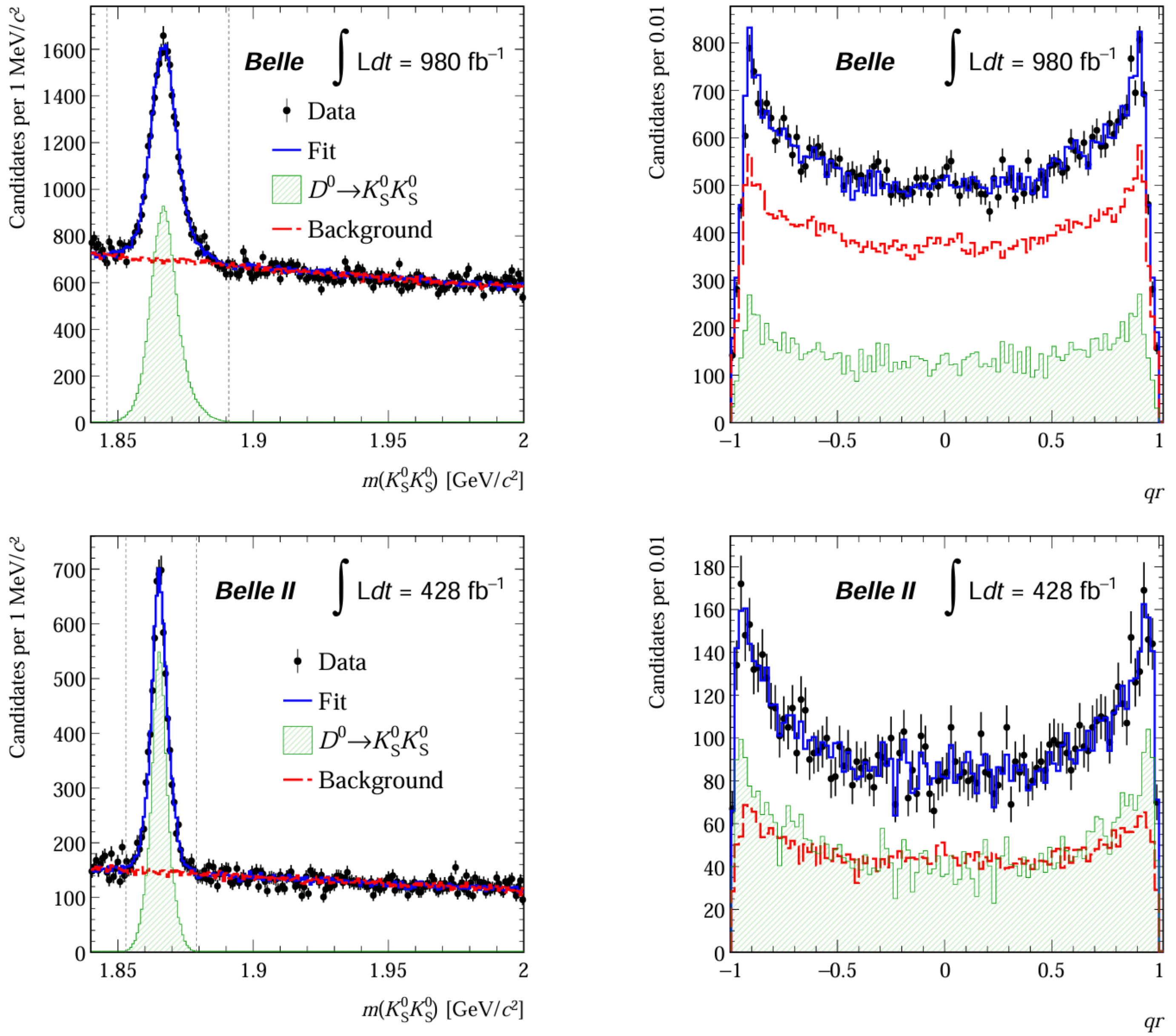
- Define dilution r = 1-2ω. Use product qr to measure A_{CP}.
- Calibrate r value using self-tagged decays ($D^0 \to K^-\pi^+$) in data.



- Use Belle + Belle II data sets (1.4 /ab), excluding D^*-tagged sample.
- Larger background wrt D^*-tag: train BDT with kinematic information.
- Cut on BDT output and S_{min} reduce $D^0 \to K_S^0\pi^+\pi^-$ significantly.

CP asymmetry in $D^0 \to K_S^0 K_S^0$

arXiv: 2504.15881



No nuisance asymmetry!

- No π_s^+ from D^{*+}
- Negligible production asymmetry

Combine Belle and Belle II:

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (1.3 \pm 2.0 \pm 0.3)\%$$

Method	A_{CP} [%]
D^*-tag	-1.4 ± 1.3 ± 0.1
CFT-tag	1.3 ± 2.0 ± 0.3
Combination	**-0.6 ± 1.1 ± 0.1**

Most precise!

It agrees with CP symmetry and with results from other experiments!

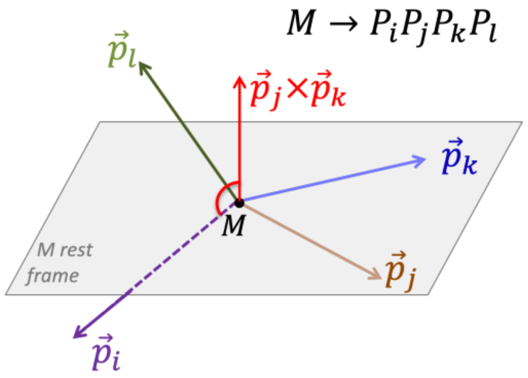
Search for CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

JHEP 04 (2025) 036

- $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$ has a dominant intermediate process: $D^+_{(s)} \to \bar{K}^{*0} K^{*+}$ (tree, annihilation, penguin.)

  These amplitudes interfere with one another, potentially giving rise to CPV

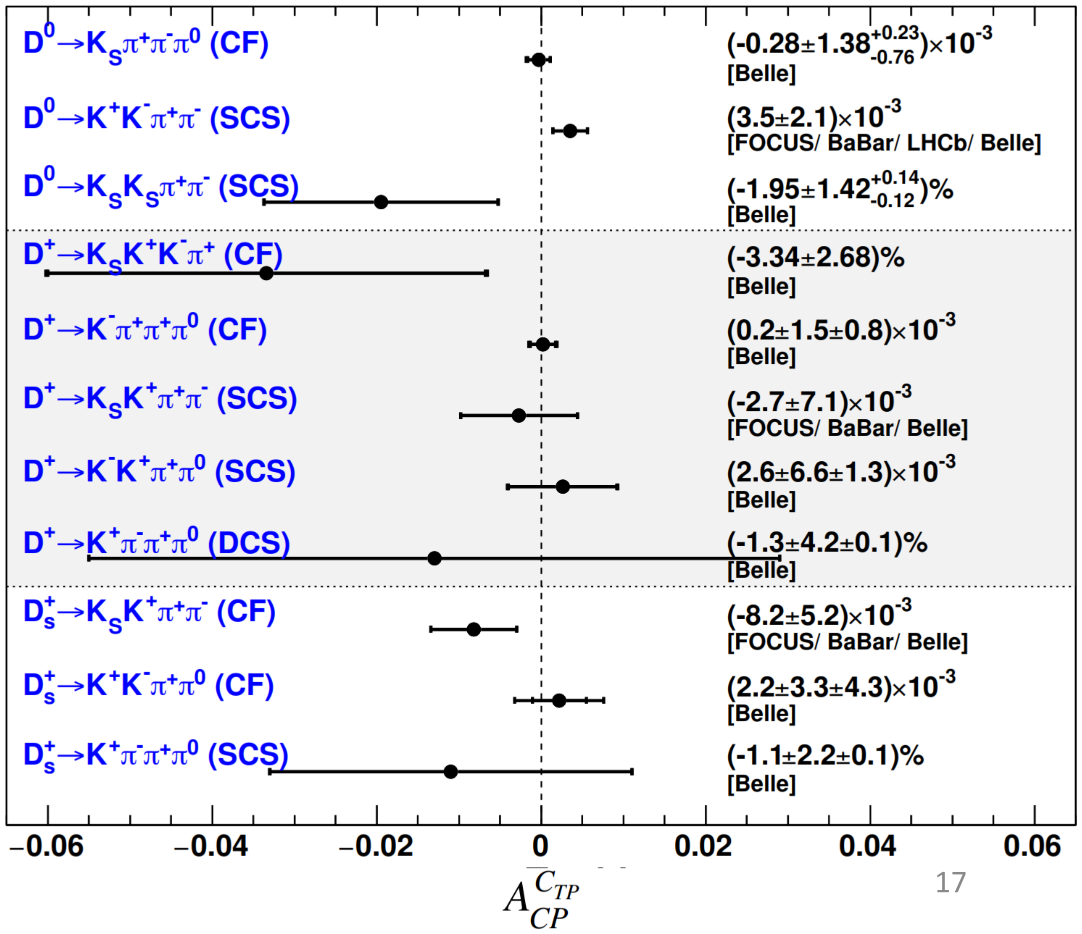
- Unlike time-integrated CPV, which is proportional to $sin\delta \cdot sin\phi$, CPV via kinematic observables (e.g. triple-product) is proportional to $cos\delta \cdot sin\phi$. (δ strong phase difference, ϕ weak phase difference)



$$X = C_{TP} \equiv (\vec{p}_j \times \vec{p}_k) \cdot \vec{p}_i$$

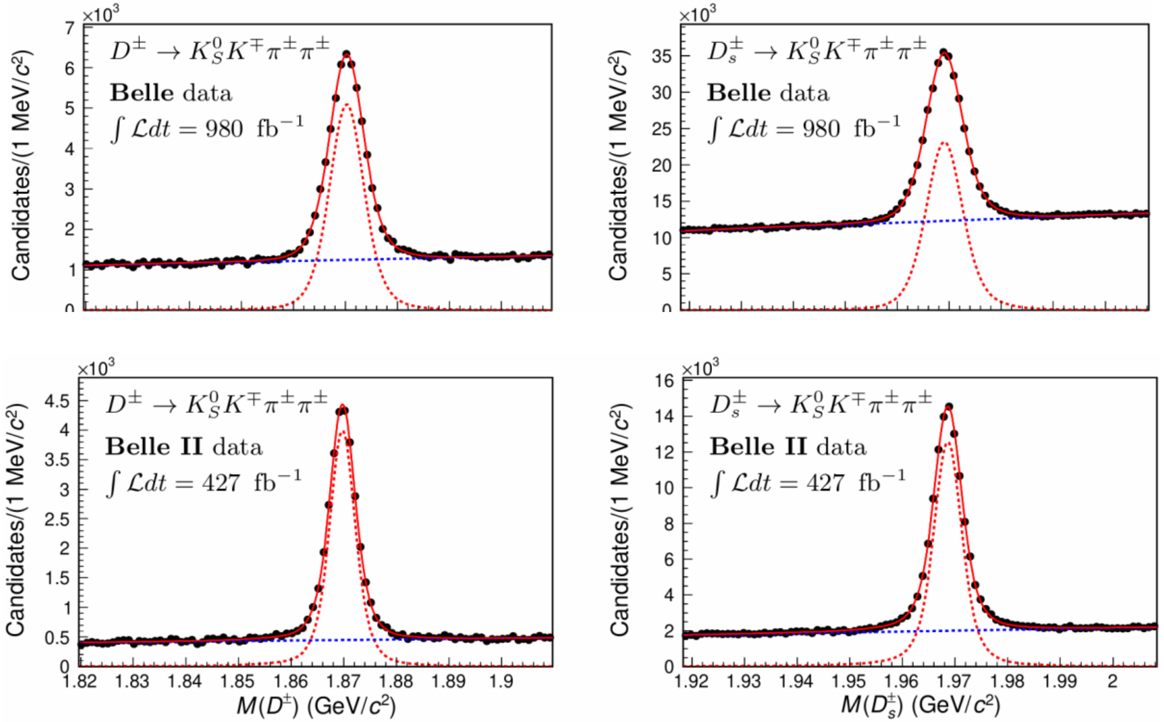
- $A_X(D^+_{(s)}) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)}$; $A_{\bar{X}}(D^-_{(s)}) = \frac{N_-(\bar{X}>0) - N_-(\bar{X}<0)}{N_-(\bar{X}>0) + N_-(\bar{X}<0)}$
- N is obtained from fit. $\bar{X}$ is CP-conjugate of X
- $A^X_{CP} = \frac{1}{2}(A_X(D^+_{(s)}) - A_{\bar{X}}(D^-_{(s)}))$

- A couple of 4-body decays searched using this technique.
- First time on $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$, whose $\mathscr{B} = 0.23\,\%\ (1.53\%)$.



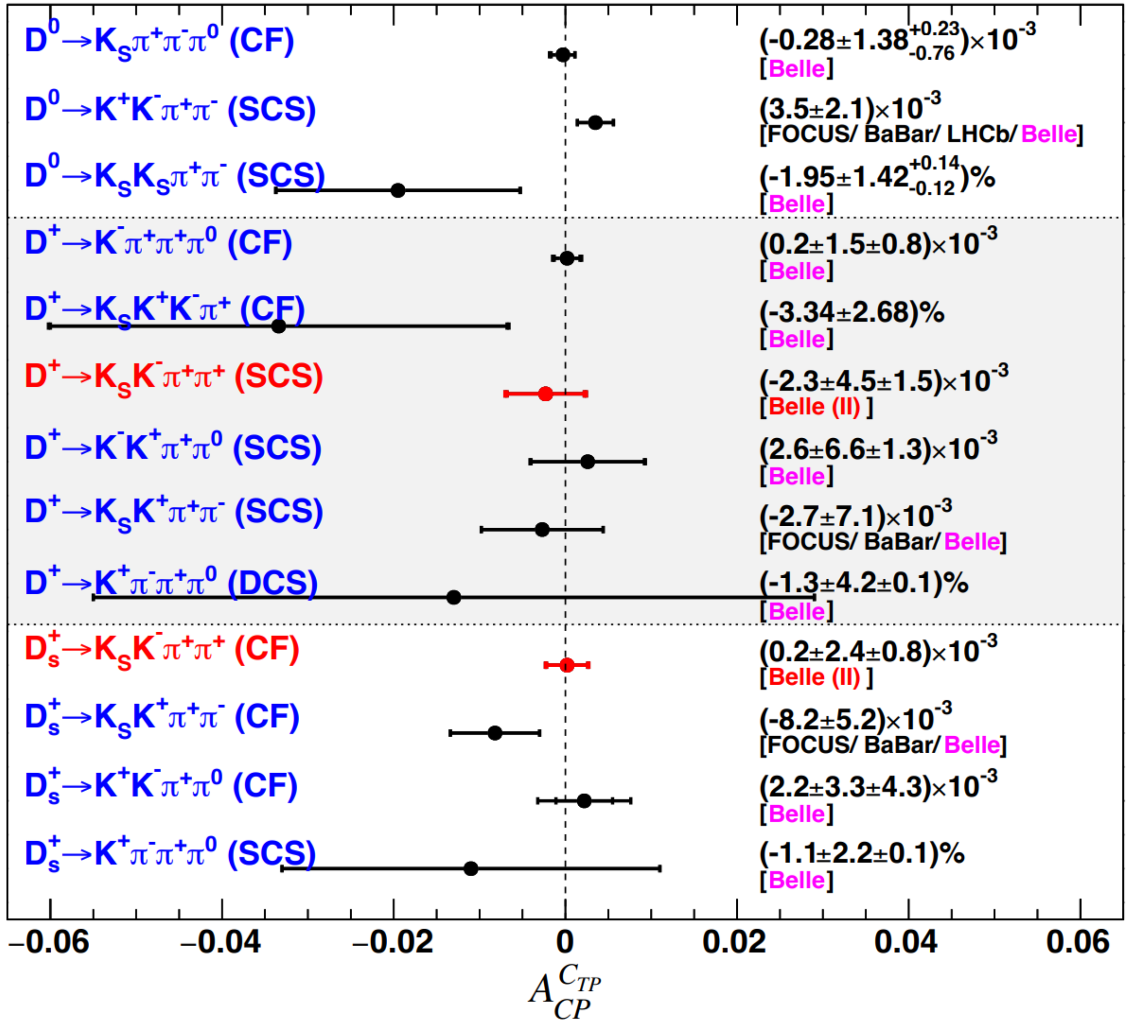
Search for CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

JHEP 04 (2025) 036



$$A_{cp}^{C_{TP}}(D^+) = (-2.3 \pm 4.5 \pm 1.5) \times 10^{-3}$$

$$A_{cp}^{C_{TP}}(D_s^+) = (0.2 \pm 2.4 \pm 0.8) \times 10^{-3}$$



No evidence for CPV found!

$\boldsymbol{D^0}$- $\boldsymbol{\bar{D}^0}$ *Mixing*

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

arXiv:2410.22961

- In SM, the $D^0-\bar{D}^0$ mixing in charm is small ($x\approx y\approx 10^{-3}$).
- Some New Physics effects beyond the SM can enhance the mixing.
- Hence, precise measurements of charm mixing can serve as tools to probe NP.

The mass eigenstates of neutral D can be expressed in terms of flavor eigenstates as:

$$|D_{1,2}> = p|D^0> \pm q|\bar{D}^0>, \qquad |p|^2+|q|^2=1$$

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

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

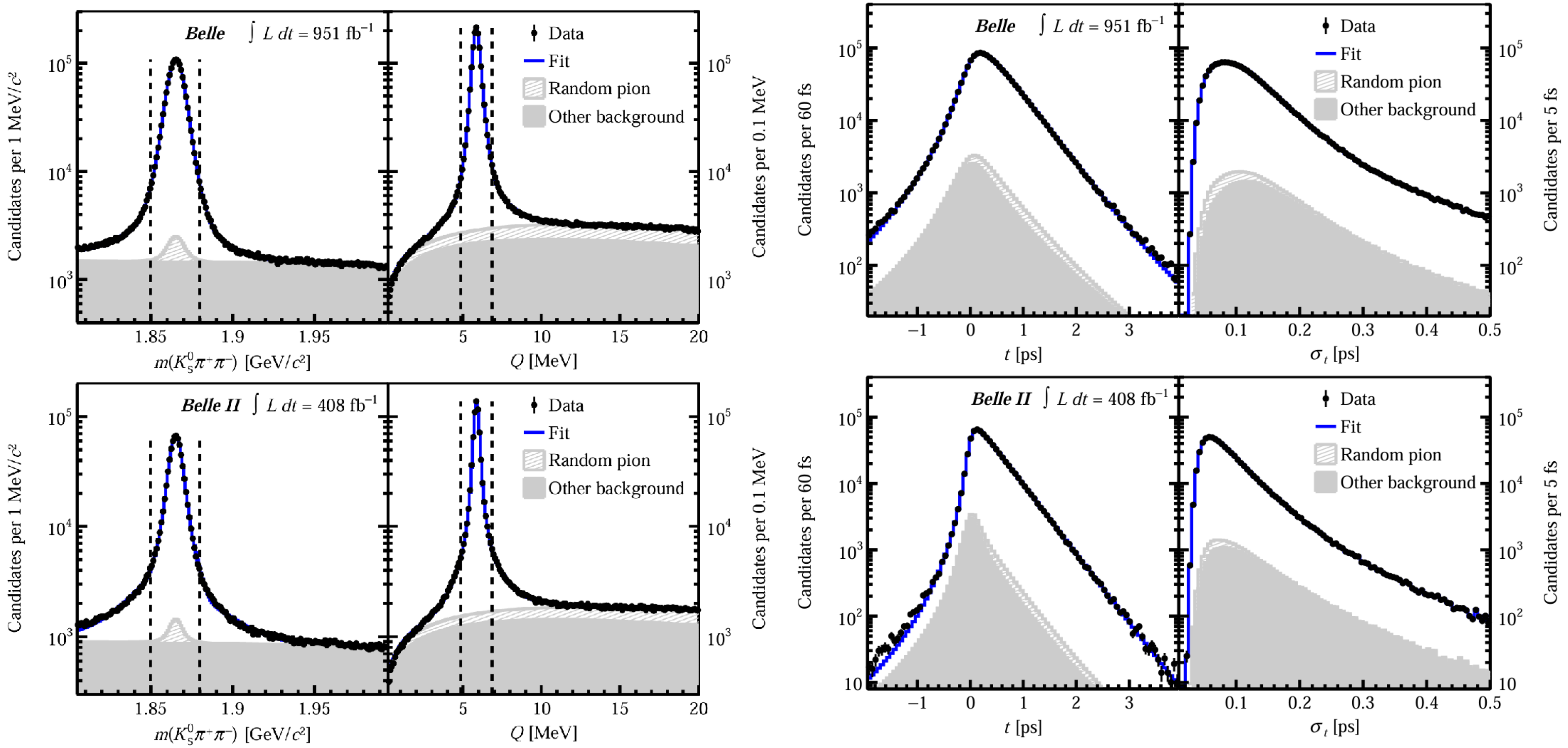
Mass of $D_{1,2}$ Width of $D_{1,2}$

Parameters	Word-averaged value
x	$(4.07\pm0.44)\times10^{-3}$
y	$(6.45^{+0.24}_{-0.23})\times10^{-3}$

➢ Using combined Belle and Belle II datasets, we perform the measurement of the $D^0-\bar{D}^0$ mixing parameters using **D^{*+}-tagged $D^0\to K_S^0\pi^+\pi^-$** decay.

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

arXiv:2410.22961



- 2D fit of m and Q to subtract signal events
- Fit to (t, σ_t) distributions to obtain mixing parameters.

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

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

Charm baryons

Topics

- Hadronic decay:
  - $\Xi_c^0 \to \Sigma^+ K_S^0, \Xi^0 \pi^+, \ldots$
  - $\Lambda_c^+ \to p K_s^0 \pi^0$
- Rare decays:
  - $\Xi_c^0 \to \Xi^0 l^+ l^-$
- Charmed Baryon Spectroscopy:
  - Search for excited charmed baryons

Branching fractions of $\Xi_c^0 \to \Xi^0 h^0$

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- ✓ First measurements of the branching fractions

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3(\text{stat.}) \pm 0.5(\text{syst.}) \pm 1.5(\text{norm.})) \times 10^{-3}$$

$$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2(\text{stat.}) \pm 0.2(\text{syst.}) \pm 0.4(\text{norm.})) \times 10^{-3}$$

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

- taking $\Xi_c^0 \to \Xi^-\pi^+$ as reference mode
- favoring predictions in SU(3) flavor symmetry [JHEP 02, 235 (2023)]

- ✓ First asymmetry parameter $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ measurement

$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\text{stat.}) \pm 0.23(\text{syst.})$$

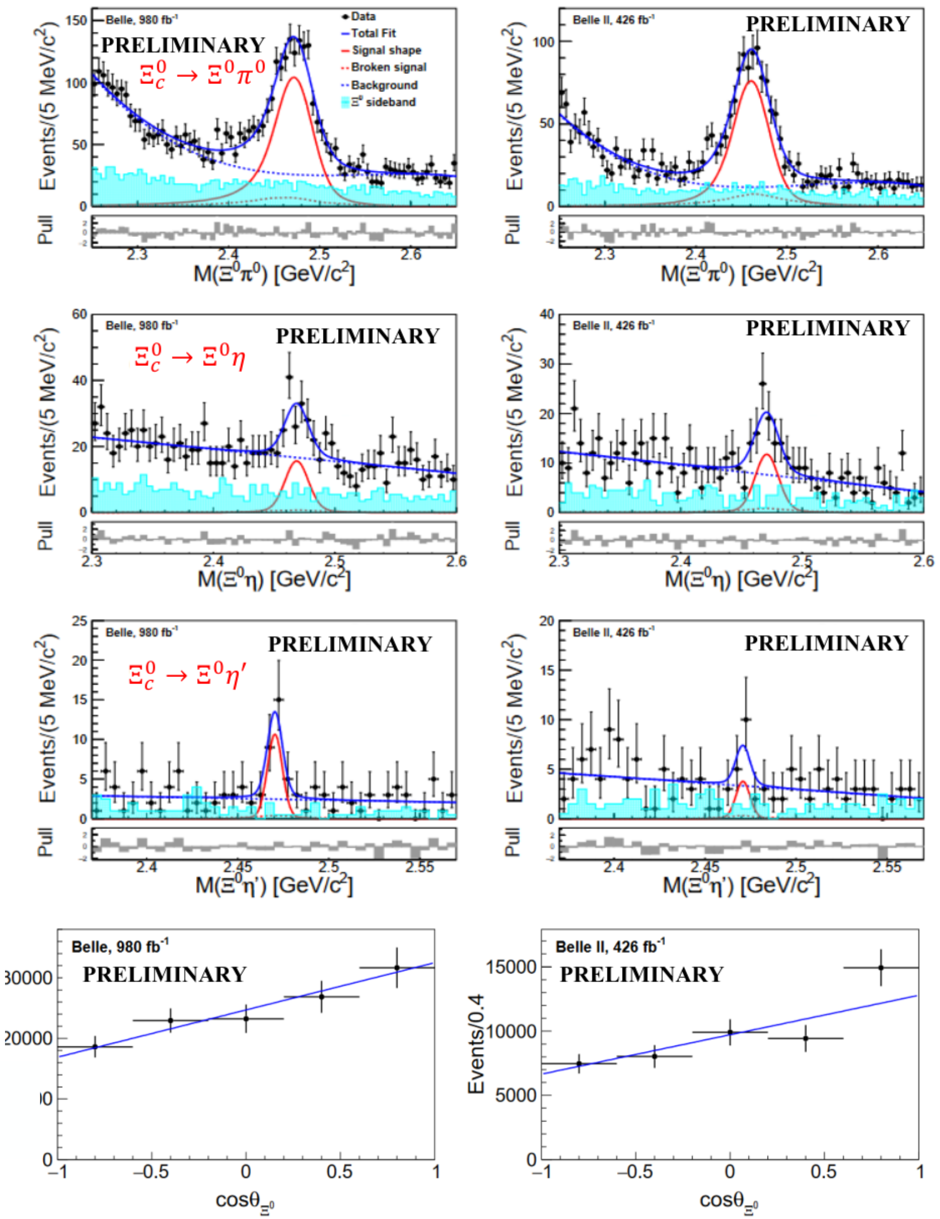
- through a simultaneous fit depending on differential decay rate

$$\frac{dN}{dcos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)cos\theta_{\Xi^0}$$

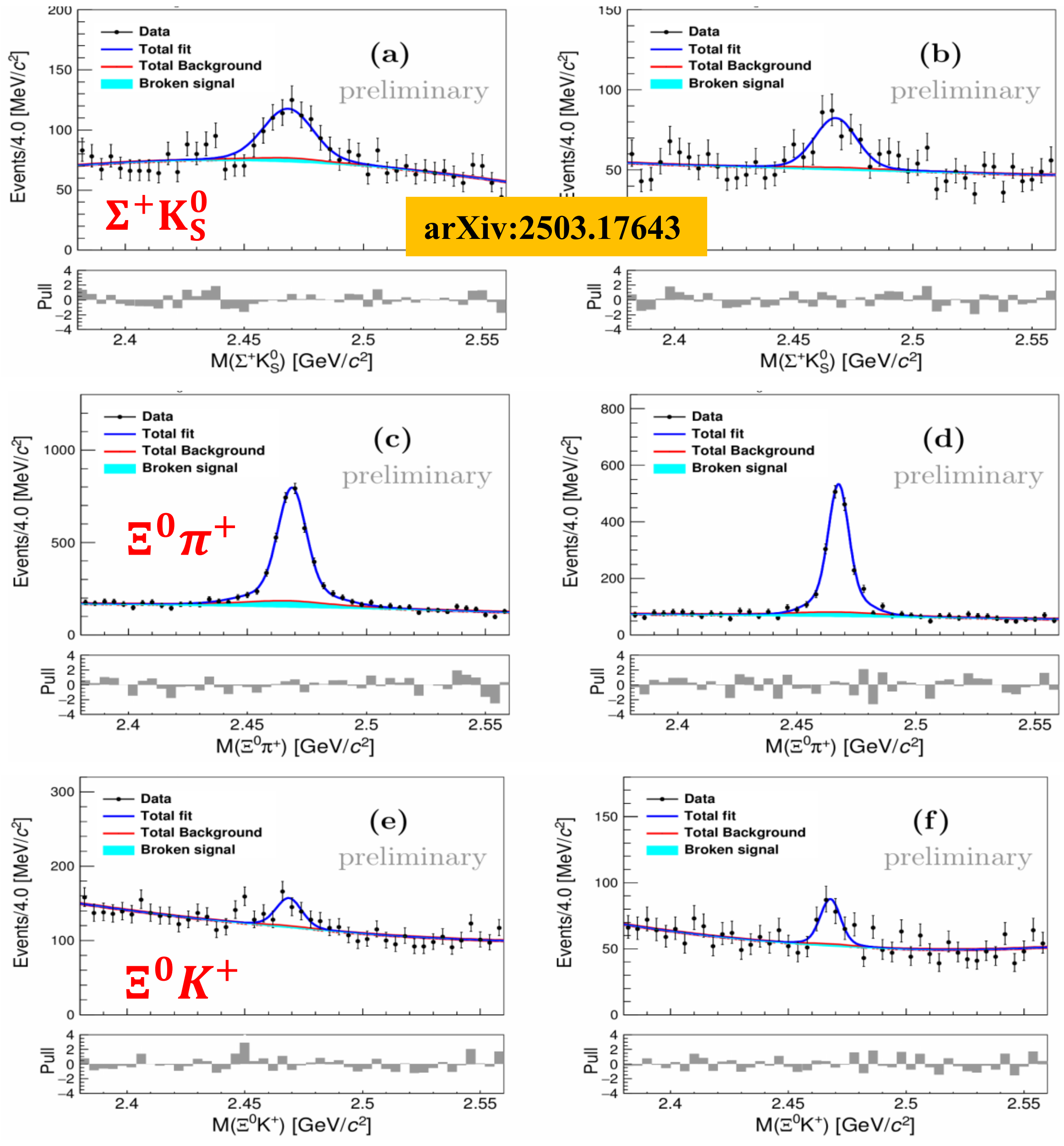
- consistent with predictions[1-4]

[1]PRD 48, 4188 (1993) [2] PRD 101, 014011 (2020) [3] EPJC 7, 217 (1999) [4]PLB 794, 19 (2019)

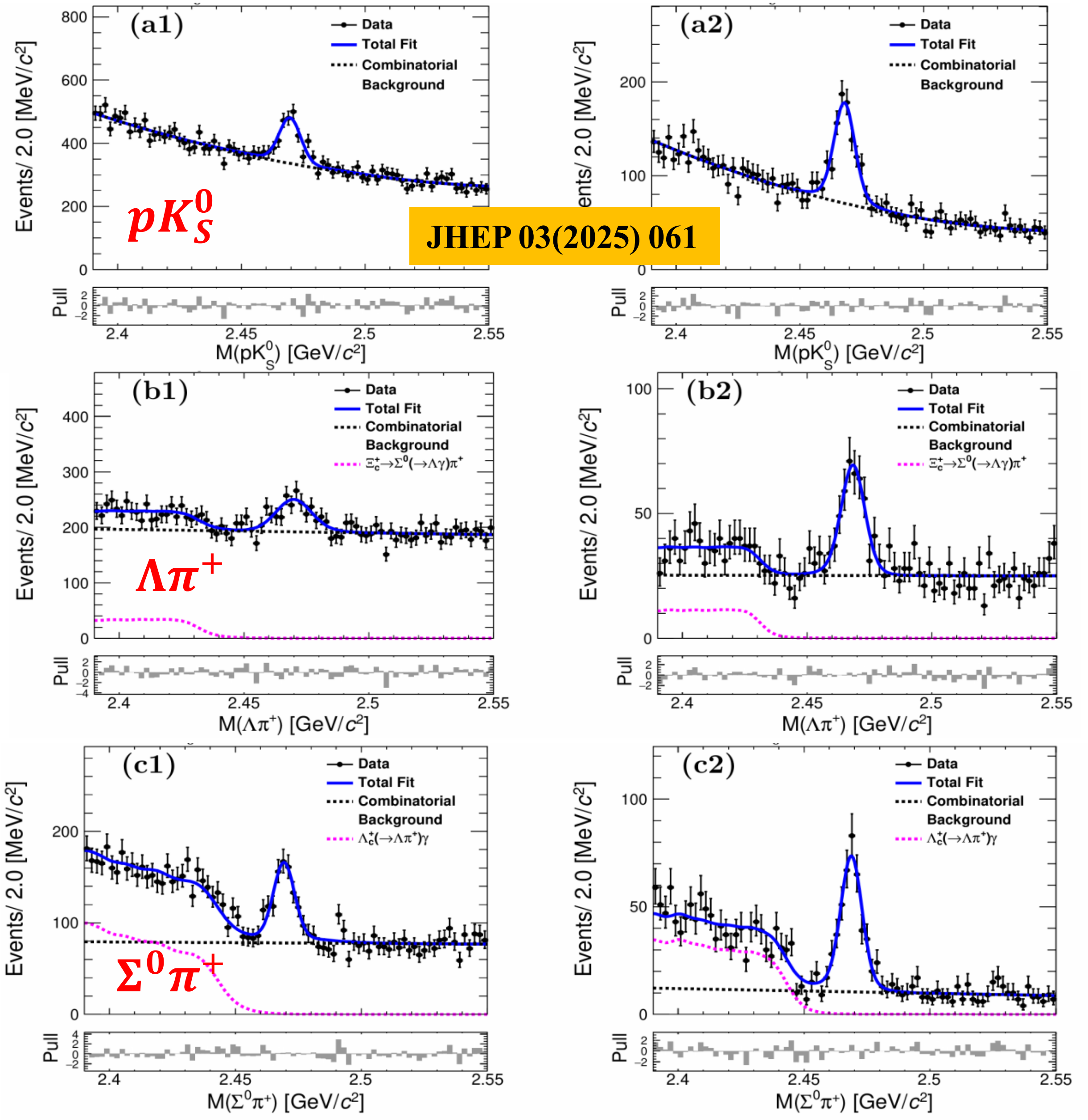
First Belle + Belle II combined charm measurement



$\Xi_c^+ \to \Sigma^+ K_S^0, \Xi^0\pi^+, \Xi^0 K^+, pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$



arXiv:2503.17643



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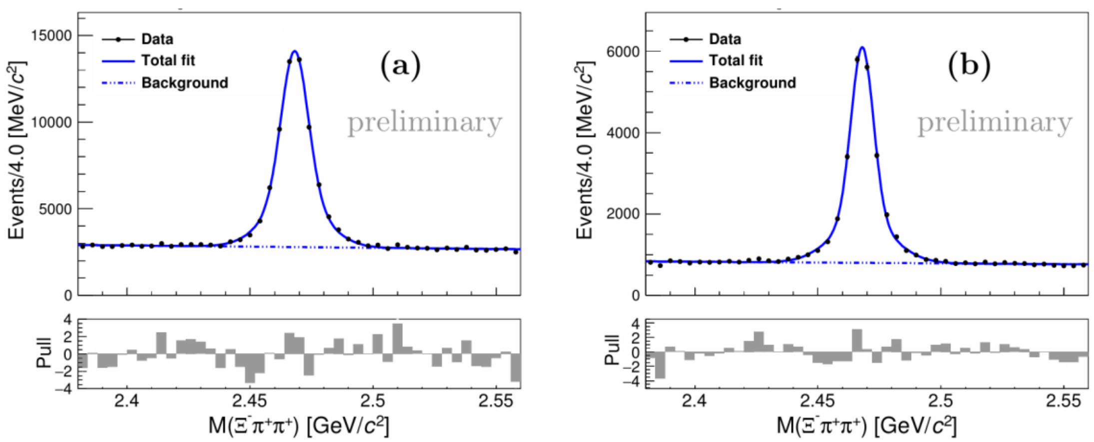
$\Xi_c^+ \rightarrow \Sigma^+ K_S^0, \Xi^0\pi^+, \Xi^0 K^+, pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$

Ratio of BF between signal and reference mode: $\frac{B_{sig}}{B_{ref}} = \frac{y_{sig} \times B'_{sig}}{y_{ref} \times B'_{ref}}$

arXiv:2503.17643



$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.194 \pm 0.021 \pm 0.009 \pm 0.087)\%,$$

$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+) = (0.719 \pm 0.014 \pm 0.024 \pm 0.322)\%,$$

$$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+) = (0.049 \pm 0.007 \pm 0.002 \pm 0.022)\%,$$

Improved precision

For the first time

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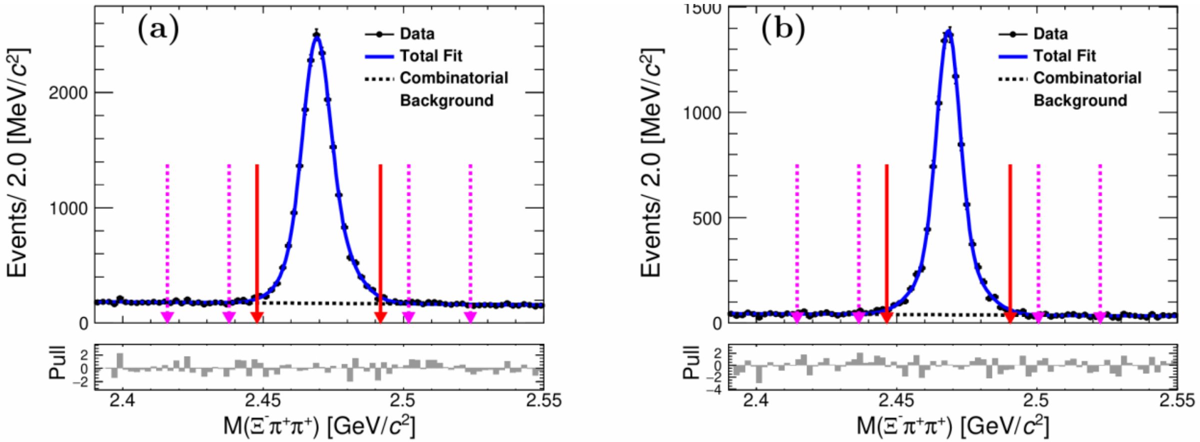


$$\mathcal{B}(\Xi_c^+ \to pK_S^0) = (7.16 \pm 0.46 \pm 0.20 \pm 3.21) \times 10^{-4}$$

$$\mathcal{B}(\Xi_c^+ \to \Lambda\pi^+) = (4.52 \pm 0.41 \pm 0.26 \pm 2.03) \times 10^{-4}$$

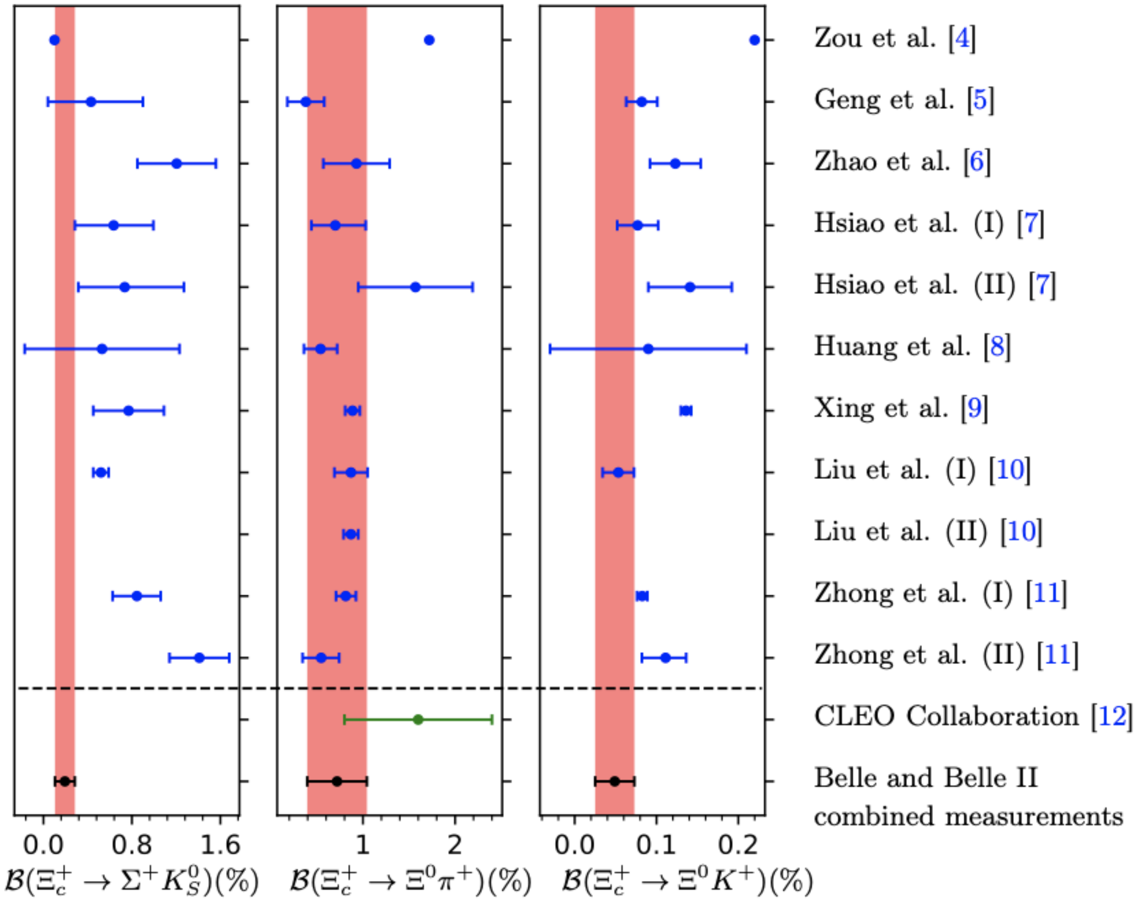
$$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+) = (1.20 \pm 0.08 \pm 0.07 \pm 0.54) \times 10^{-3}$$

For the first time

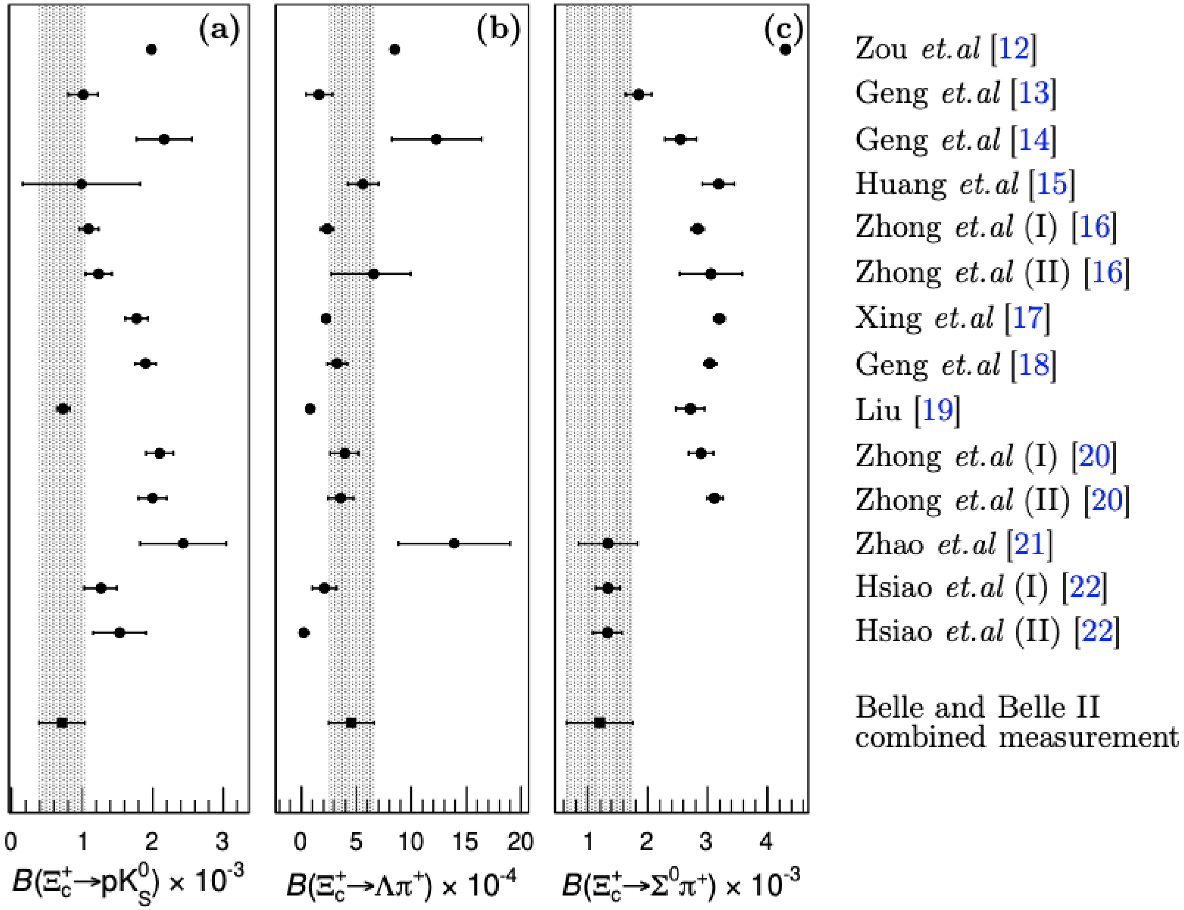
$\Xi_c^+ \to \Sigma^+ K_S^0, \Xi^0\pi^+, \Xi^0 K^+, pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$

First or most precise measurements!

arXiv:2503.17643



JHEP 03(2025) 061

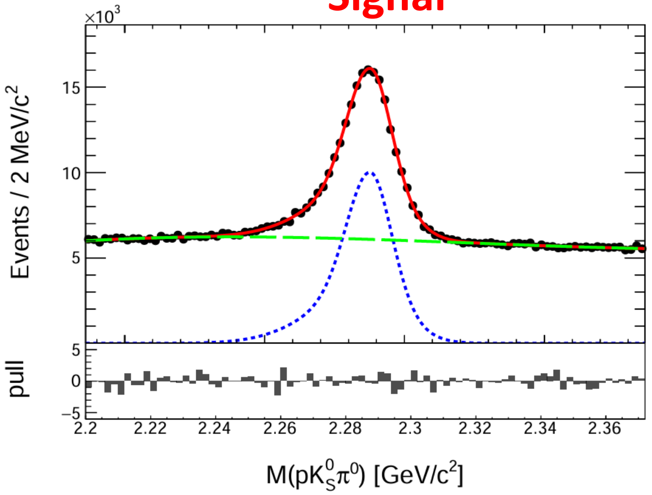


$\Lambda_c^+ \to p K_S^0 \pi^0$

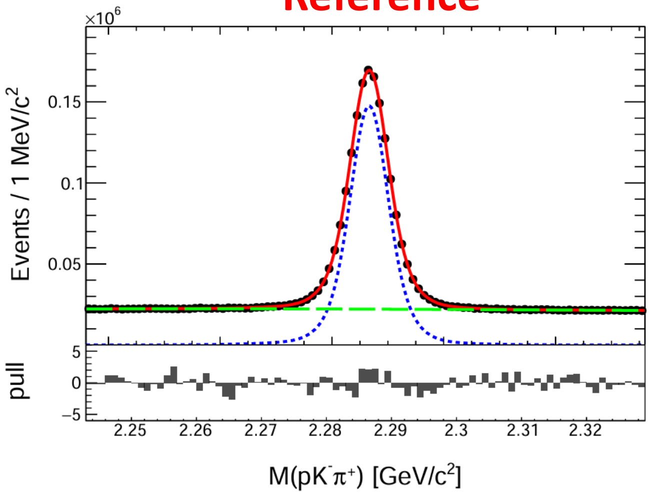
arXiv:2503.04371

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = \frac{y^{corr}(\Lambda_c^+ \to pK_S^0\pi^0)}{y^{corr}(\Lambda_c^+ \to pK^-\pi^+)\times\mathcal{B}(\pi^0 \to \gamma\gamma)\times\mathcal{B}(K_S^0 \to \pi^+\pi^-)}$$

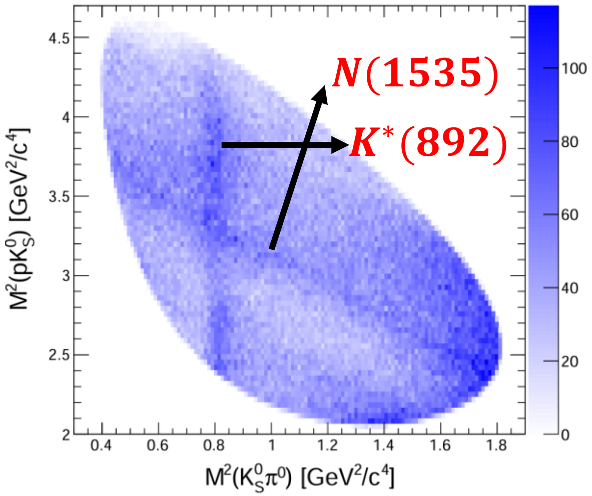
Signal



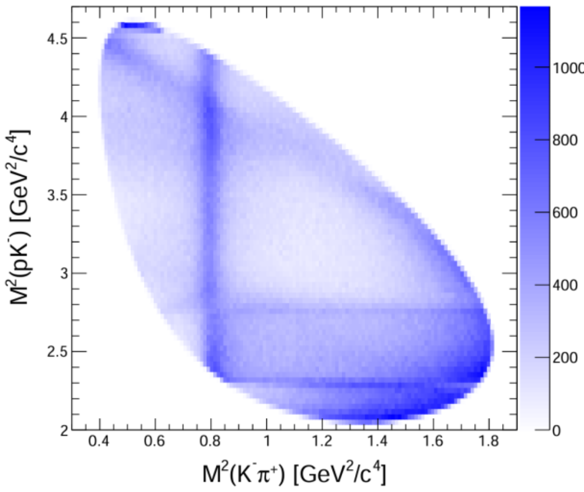
Reference



Signal



Reference



$$\frac{\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.339 \pm 0.002 \pm 0.009, \quad \longrightarrow \quad \mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^0) = (2.12 \pm 0.01 \pm 0.05 \pm 0.10)\%,$$

Consistent with the previous measurement by CLEO and has a fivefold improvement in precision!

PWA or amplitude analysis in the future.

First search for $\Xi_c^0 \to \Xi^0 l^+ l^-$

Belle 980/fb [PRD 109, 052003 (2024)]

✓ No neutrino-less semileptonic decays of charmed baryons observed yet.

- Only upper limits of $\Lambda_c \to p\ell^+\ell^-$ decays were set for charmed baryons[1,2], which receive both W-exchange and FCNC process contributions.

[1] PRD 84, 072006(2011)
[2] PRD 97, 091101(2018)

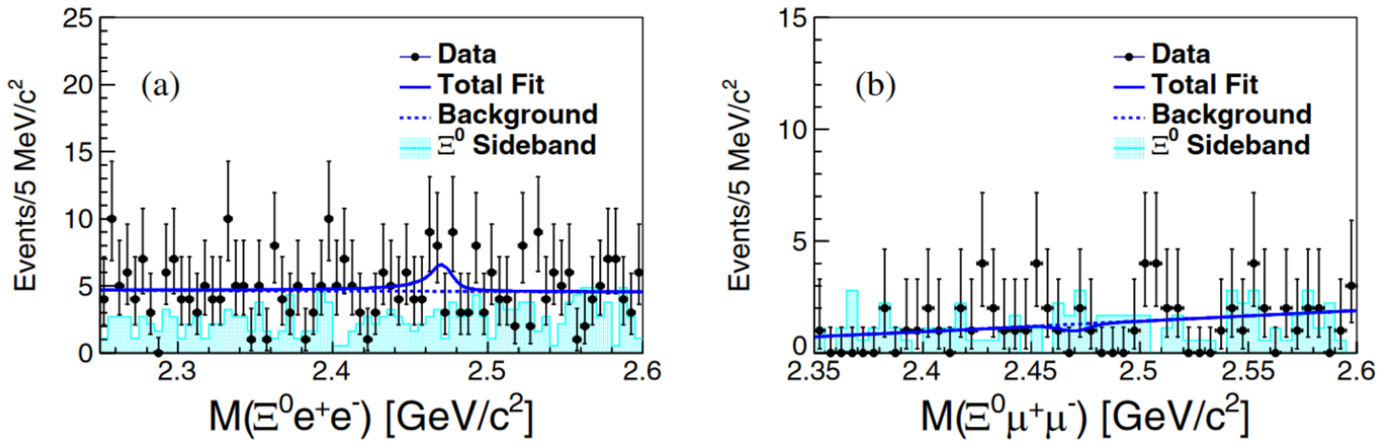
- If observed, the signal channels would allow to test LFU

- **Belle Result**: No significant signal was observed but consistent with SM

➡ First set upper limits set at 90% CL:

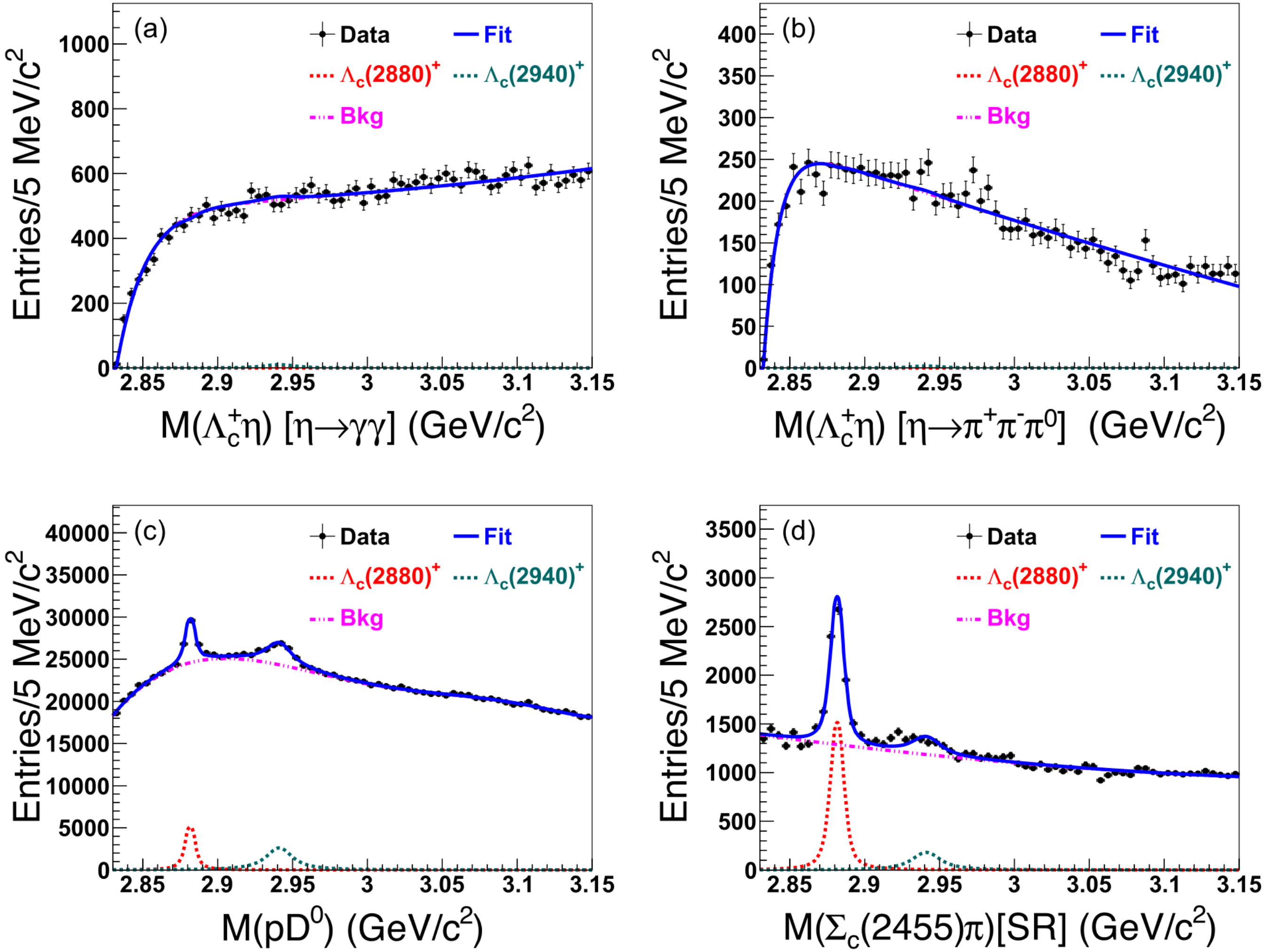
	Measured	SM prediction
$\mathscr{B}(\Xi_c^0 \to \Xi^0 e^+ e^-)$	$< 9.9 \times 10^{-5}$	$< 2.35 \times 10^{-6}$
$\mathscr{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-)$	$< 6.5 \times 10^{-5}$	$< 2.25 \times 10^{-6}$

SM prediction: PRD **103**, 013007 (2021)



Search for excited charmed baryons in $\Lambda_c^+\eta$ system

Belle 980/fb PRD 110, 032021 (2024)



- No significant excess is found in the $M(\Lambda_c\eta)$ spectrum. This is in contrast to excited hyperons, where resonances decaying into $\Lambda\eta$ have been observed.
- Clear $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signals are observed in the pD^0 mass spectrum.
- Ratio to $\Sigma_c(2455)\pi$:

$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07,$$
$$R_{pD^0}(2940) = 3.59 \pm 0.21 \pm 0.56,$$

First measurement

Summary

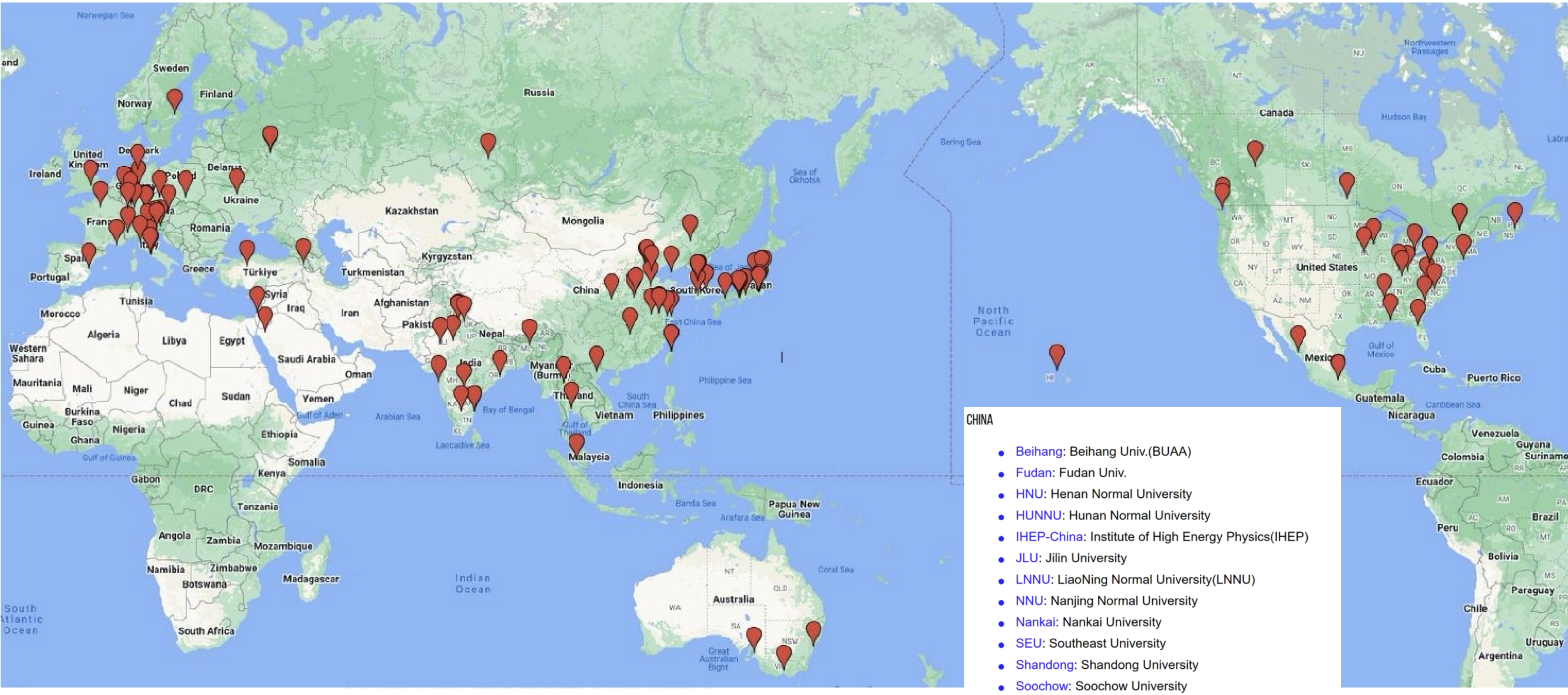
- Belle II and Belle hold a unique data sample. A number of interesting measurement has been already performed in charm sector, such as
  - Measurement of CP asymmetry in $D^{0,+} \to \pi^{0,+}\pi^0$ and $D^0 \to K_S^0 K_S^0$
  - Search for CPV in $D^0 \to K_S^0 K\pi\pi$, no CPV found.
  - Measurement of the D^0- $\overline{D}^0$ mixing parameters
  - Charm baryon decays and spectroscopy.

- Only 1% of target luminosity collected so far. Stay tuned for more exciting results from Belle & Belle II.

Thanks for your attention!

Backup slides

International Belle II collaboration



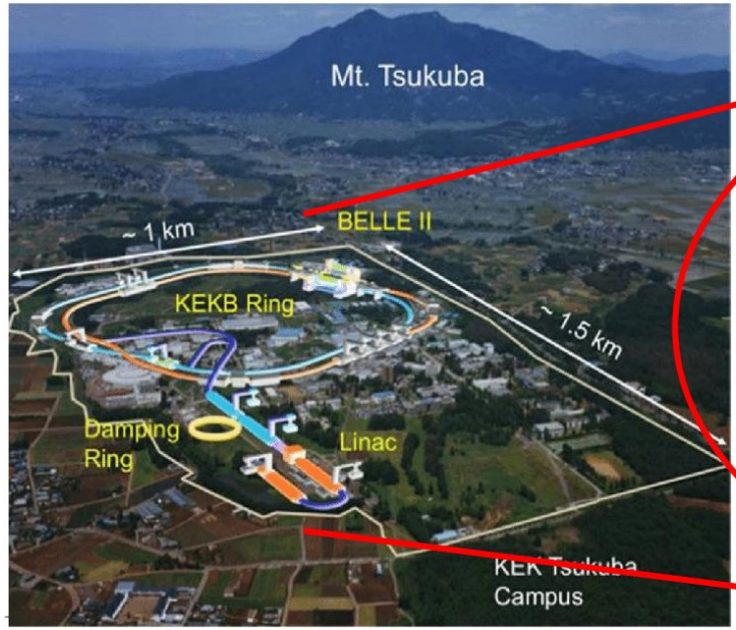
CHINA

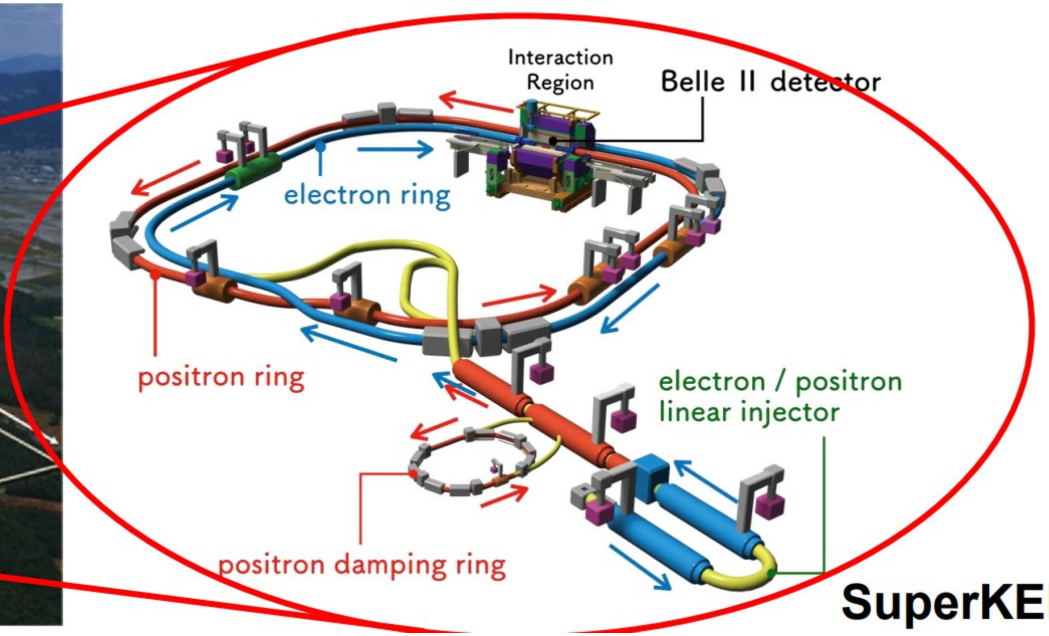
- Beihang: Beihang Univ.(BUAA)
- Fudan: Fudan Univ.
- HNU: Henan Normal University
- HUNNU: Hunan Normal University
- IHEP-China: Institute of High Energy Physics(IHEP)
- JLU: Jilin University
- LNNU: LiaoNing Normal University(LNNU)
- NNU: Nanjing Normal University
- Nankai: Nankai University
- SEU: Southeast University
- Shandong: Shandong University
- Soochow: Soochow University
- USTC: Univ. of Science and Technology of China(USTC)
- XJTU: Xi'an Jiaotong University
- ZZU: Zhengzhou University

Belle II now has grown to 1229 researchers from 28 countries/regions.

What is Belle II?

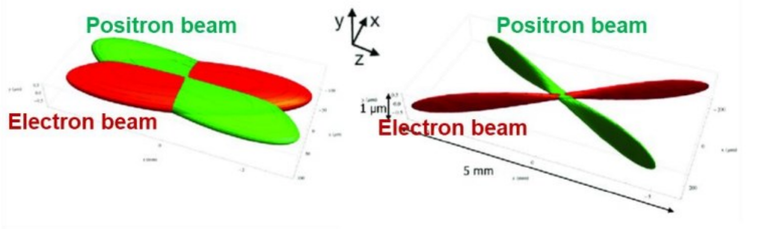
- Multipurpose experiment for the SM and BSM.
  B physics, tau physics, dark sector physics
- SuperKEKB (e^-e^+ collider) + Belle II detector
  Typical $\sqrt{s} = 10.58$ GeV ($\Upsilon(4S)$ resonance)
- World's highest luminosity with "Nano-beam scheme"
  Design peak luminosity: 6×10^{35} cm^{-2}s^{-1}
  (30 times higher than predecessor KEKB)





SuperKEKB

Nano-beam scheme



$\sigma_x \sim 100\ \mu m$
$\sigma_y \sim 2\ \mu m$

$\sigma_x \sim 10\ \mu m$
$\sigma_y \sim 0.06\ \mu m$

What is Belle II?

- Multipurpose experiment for the SM and BSM.
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- SuperKEKB (e^-e^+ collider) + Belle II detector
  Typical $\sqrt{s} = 10.58$ GeV ($\Upsilon(4S)$ resonance)
- World's highest luminosity with "Nano-beam scheme"
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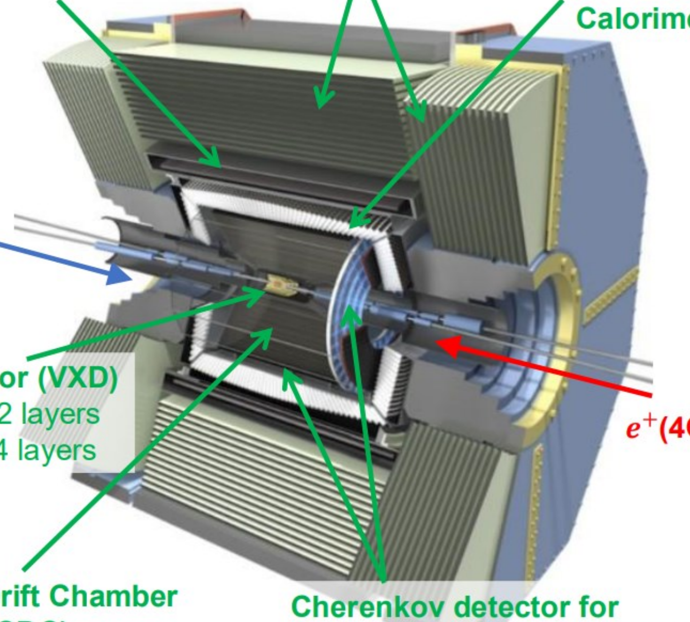
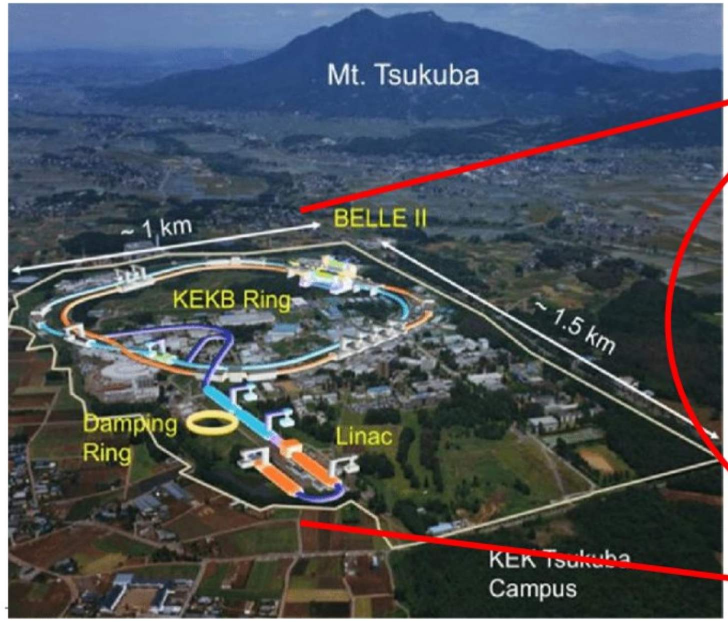
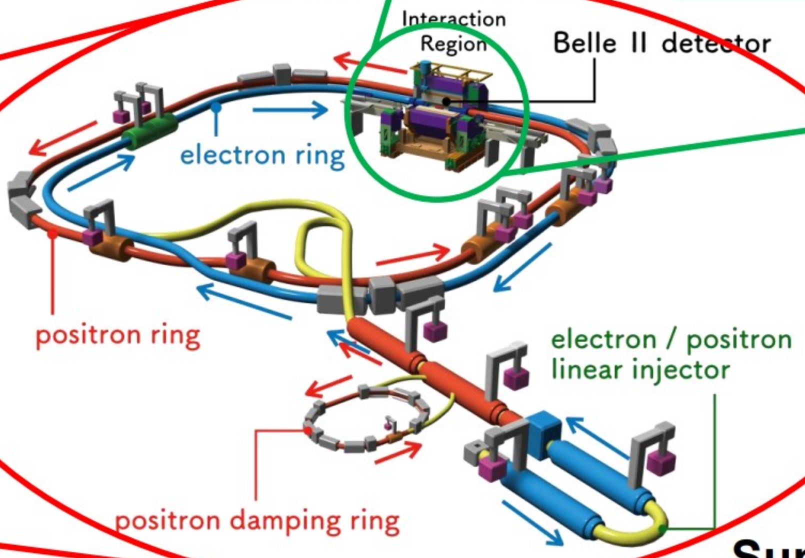
  (30 times higher than predecessor KEKB)

Belle II detector



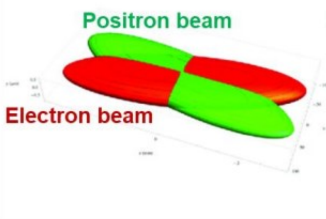




SuperKEKB

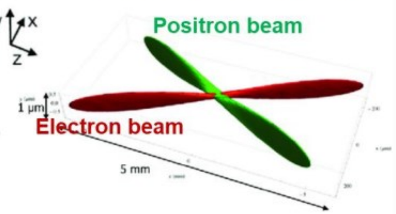
Nano-beam scheme

KEKB(Belle)



$\sigma_x \sim 100\ \mu m$
$\sigma_y \sim 2\ \mu m$

SuperKEKB(Belle II)



$\sigma_x \sim 10\ \mu m$
$\sigma_y \sim 0.06 \mu m$

Overview of the run schedule

Run 1 was from March 2019 to June 2022.

- Total integrated luminosity: 426 fb^{-1}

Long Shutdown (LS) 1 to upgrade both SuperKEKB and the detector.

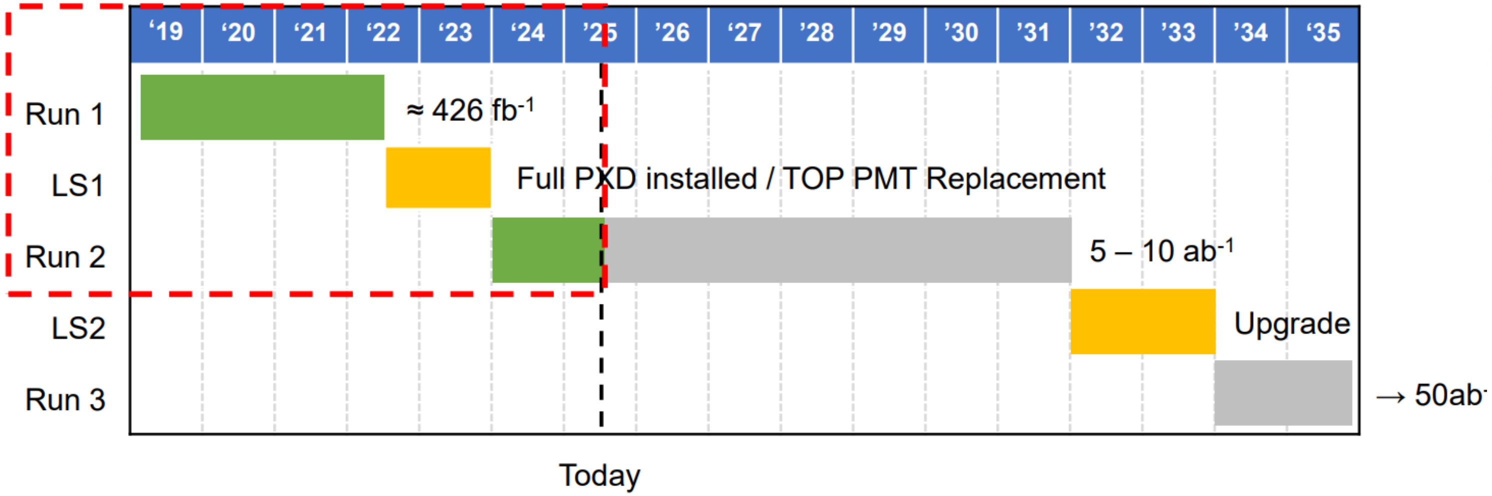
Run 2 started in January 2024 with efforts to maximize the performance

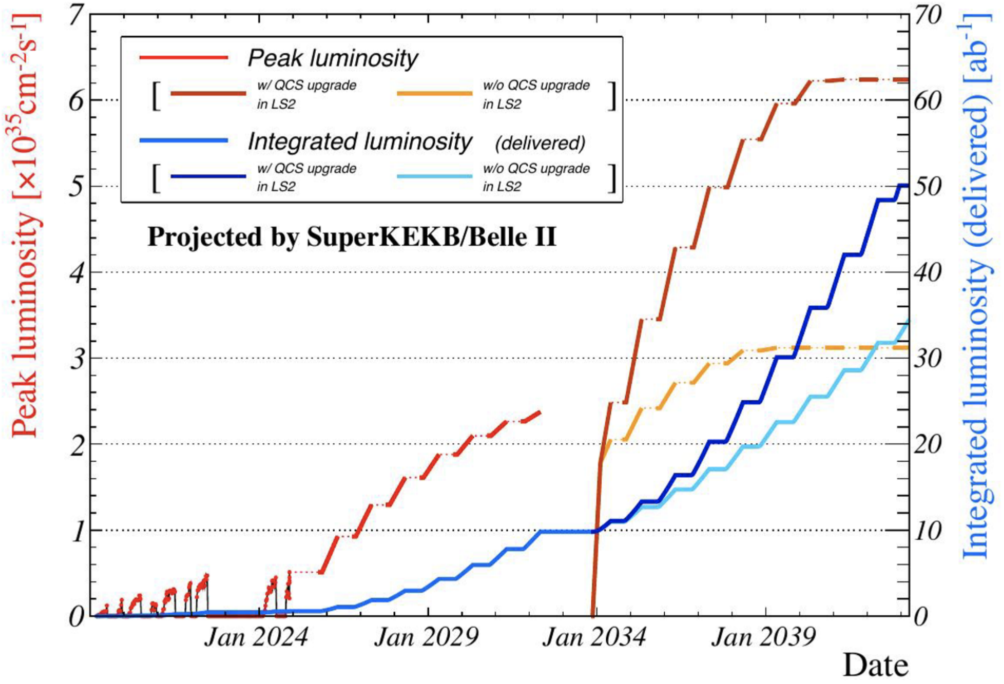
- The peak luminosity: $5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ World record

(KEKB: $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)

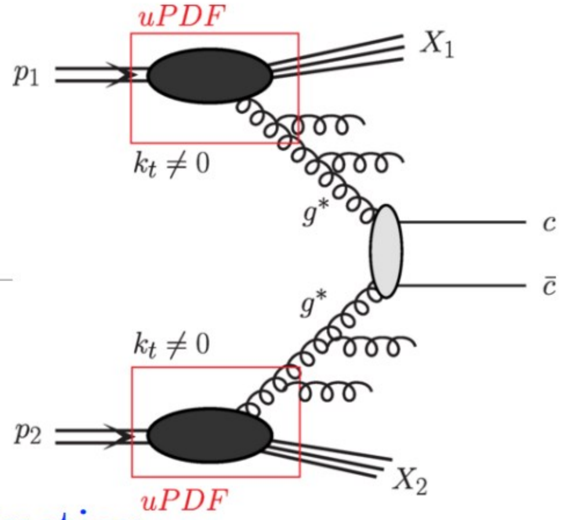
- Total integrated luminosity: 573 fb^{-1} so far

- *Until 2026, about 1 ab^{-1} data, comparable to Belle*
- *Until 2029, about 4 ab^{-1} data.*





Two different charm factories

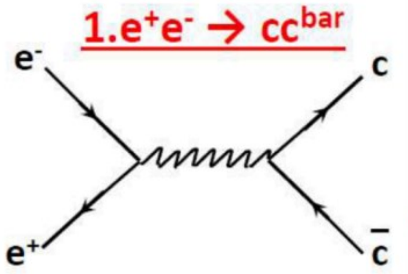


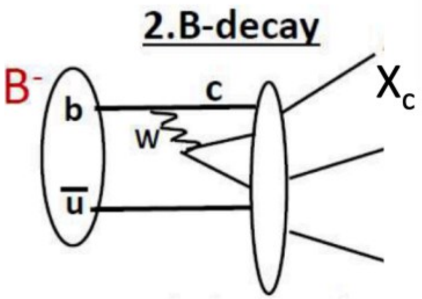
Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Better reconstruction of neutrals and unique access to final states with invisible particles
- Much easier separation between promptly produced charm and secondary (from-B) decays

LHCb

- Huge advantage in production rate, but also large backgrounds — stringent online selections
- Superior decay-time resolution and access to longer decay times (boost)
- …but tricky efficiency effects (*e.g.* decay-time acceptance)





CPV in Charm

- Unlike in Beauty sector, Charm sector has rather small CPV in standard model:

  1. GIM mechanism
  2. small size of $|V_{cb}|$
  3. dominance of tree-level (lack of **interference**)

  $\rightarrow$ $\boldsymbol{CP}$ **violation** $\sim 10^{-3}$

- Dominance of matter in the Universe indicates Charge-Parity (CP) Violation. KM is not sufficient. There should be additional source of CPV.

- Observation of “sizable” CPV in charm could be a hint to physics beyond standard model.

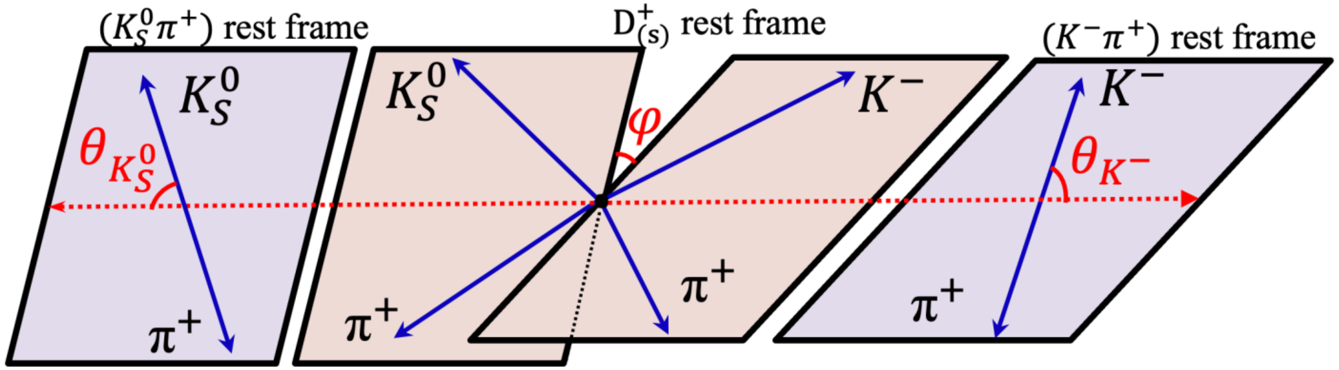
Search for CPV in $D^0_{(s)} \to K^0_S K^- \pi^+ \pi^+$

JHEP 04 (2025) 036

Kinematic observables (X) A^X_{CP}

- In addition to triple-product $C_{TP} = \vec{p}_{K^-} \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$, first time use quadruple product $C_{QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot (\vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l})$
- Six variables for CPV search:

1. $X = C_{TP}$
2. $X = C_{QP}$
3. $X = C_{TP} \cdot C_{QP}$
4. $X = cos\theta_{K^0_S} \cdot cos\theta_{K^-}$
5. $X = cos\theta_{K^0_S} \cdot cos\theta_{K^-} \cdot C_{TP}$
6. $X = cos\theta_{K^0_S} \cdot cos\theta_{K^-} \cdot C_{QP}$



- Asymmetry defined first by signs of X then charm flavor:
- $A_X(D^+_{(s)}) = \frac{N_+(X>0) - N_+(X<0)}{N_+(X>0) + N_+(X<0)}$; $A_{\bar{X}}(D^-_{(s)}) = \frac{N_-(\bar{X}>0) - N_-(\bar{X}<0)}{N_-(\bar{X}>0) + N_-(\bar{X}<0)}$
- N is obtained from fit.

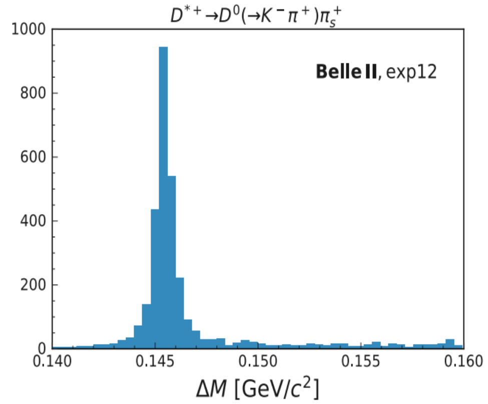
$\bar{X}$ is CP-conjugate of X

- $A^X_{CP} = \frac{1}{2}(A_X(D^+_{(s)}) - A_{\bar{X}}(D^-_{(s)}))$

D* Tagging

slow pion: $M(D^{*+}) - M(D^0) \approx 145\,\mathrm{MeV}/c^2$

- main ingredient is to determine the D^0 flavor at time of production
- standard approach: reconstruct strong decay $D^{*+} \to D^0 \pi_s^+$, where charge of "slow" pion determines flavor
- major drawbacks:
  - inefficient reconstruction of slow=low momentum pion
  - loss in statistics (only ~25% of all charm quarks hadronize into D^*)



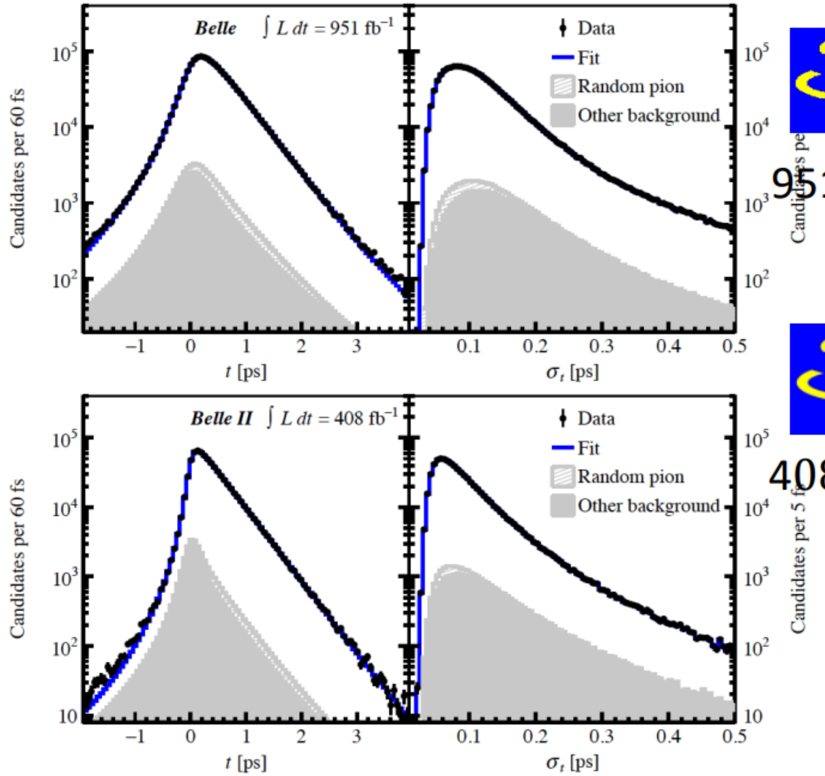
The ROE Flavor Tag

- perform flavor tag with information from the rest of the event (ROE)
- ROE : every track and cluster not related to signal decay
- inclusive approach in which single tracks are reconstructed in the ROE and their charge provides the tag
- this approach could
  - compensate loss in statistics of D* tag,
  - reduce combinatorial background (charged mesons)
- inspired by:
  - ROE method for flavor tagging (by Giulia and Giacomo, link)
  - B-flavor tagging algorithms at Belle II (category-based and deep-learning tagger, link)

$D^0 \to K_S^0\pi^+\pi^-$ Time-dependent Fit

- Fit decay time t and per-candidate uncertainty $\sigma(t)$ simultaneously in Dalitz bins
- Shapes: directly determined from the fit or the $M(K_S^0\pi^+\pi^-)$ sideband. Independent parameters in different Dalitz bins

arxiv:2410.22961 submitted to JHEP



signal PDF = D^0 decay rate ⊗ time resolution

$$P(t,\sigma_t|b) = \mathcal{C}_b\left\{ f^b_{\rm sig} P_{\rm sig}(t,\sigma_t|b) + f^b_{\rm rnd} P_{\rm rnd}(t,\sigma_t|b) + \left[1 - f^b_{\rm sig} - f^b_{\rm rnd}\right] P_{\rm oth}(t,\sigma_t|b) \right\}$$

Fractions are from the MQ fit

PDF for Random soft pions bkg. is defined by the signal PDF and mist-tag rate (measured with Q sideband)

PDF for other background is decided by the sideband