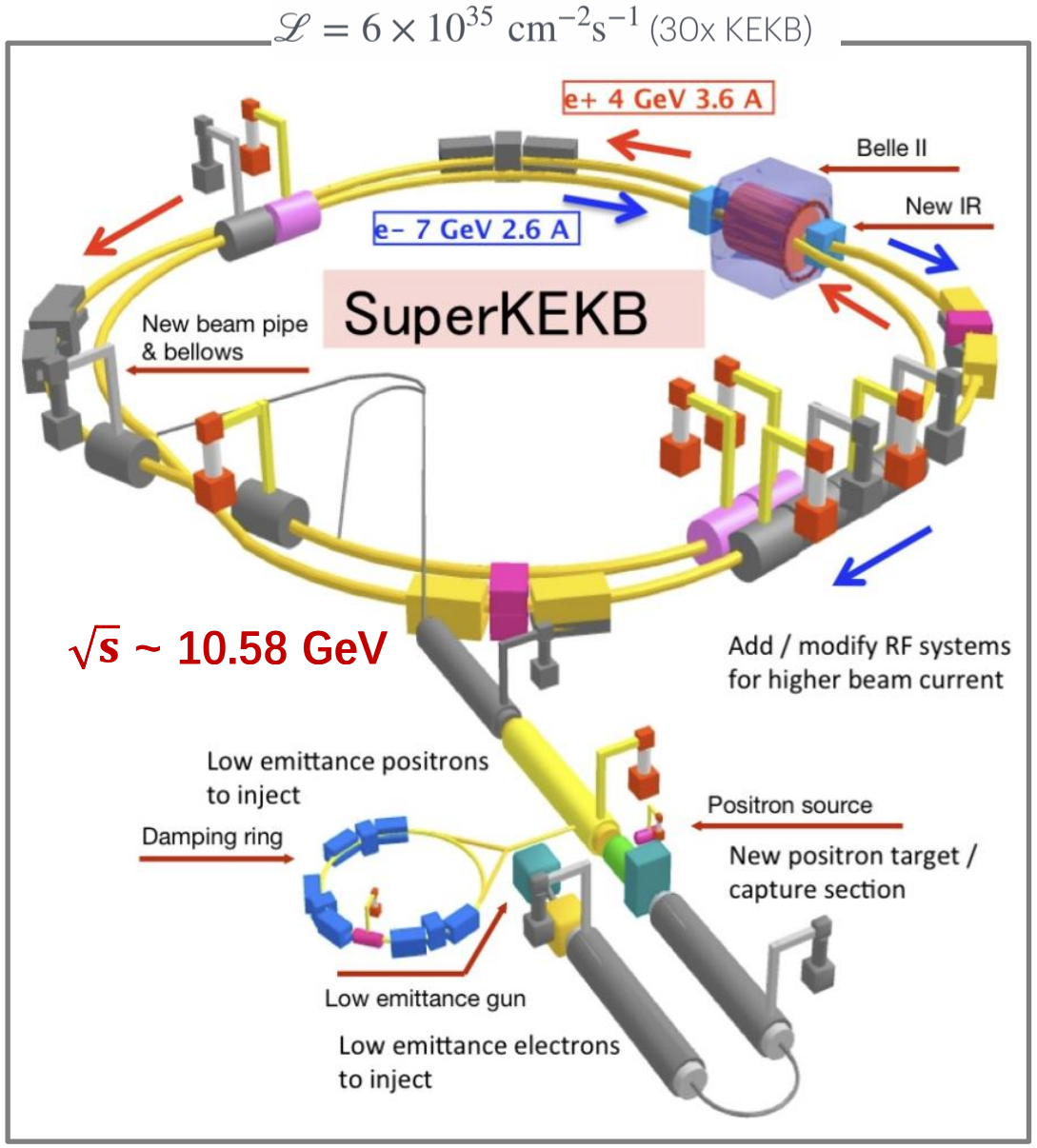
Recent charm results from Belle and Belle II

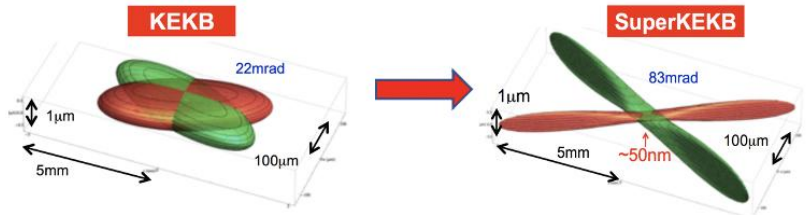
李素娴 (lisuxian@zzu.edu.cn)
郑州大学

2026年BESIII粲强子物理研讨会

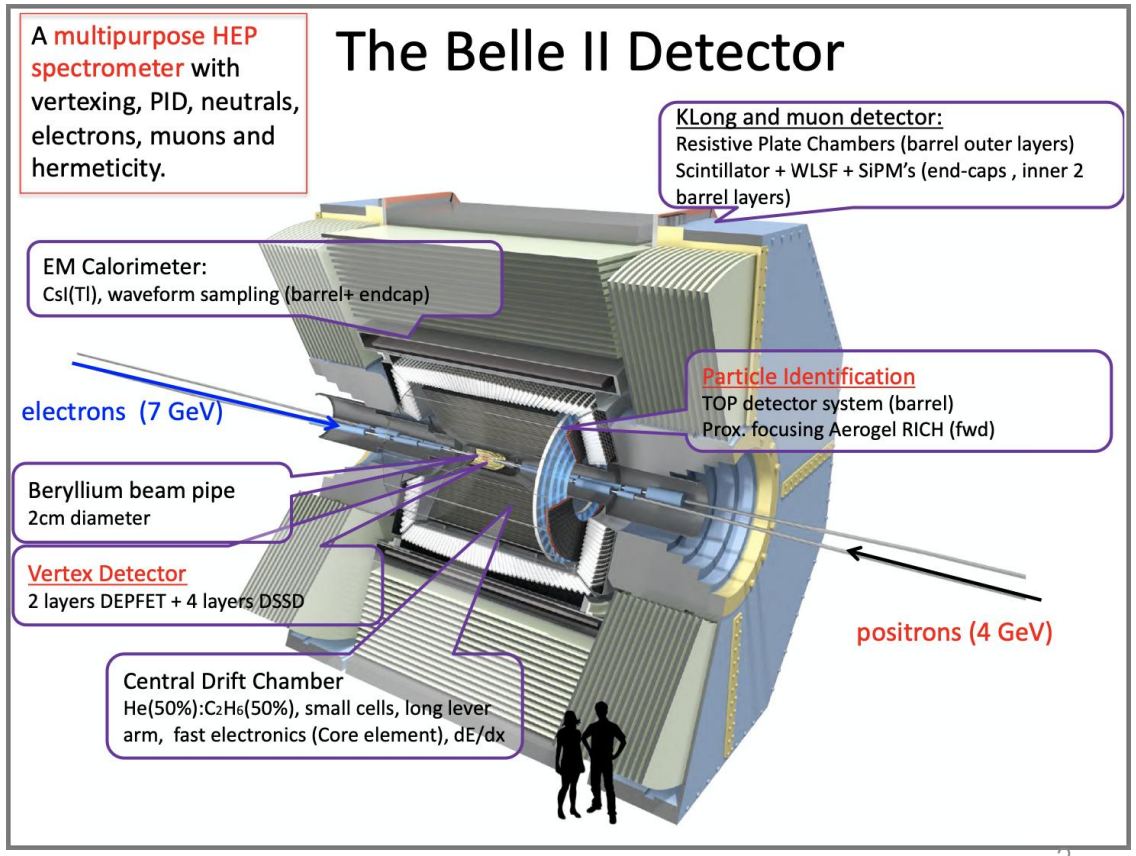
2026年10月16-20日 四川成都

SuperKEKB and Belle II





Nano-beam design:
Beam squeezing: ×20 smaller; Beam current: ×2 larger
Target peak luminosity: KEKB×30

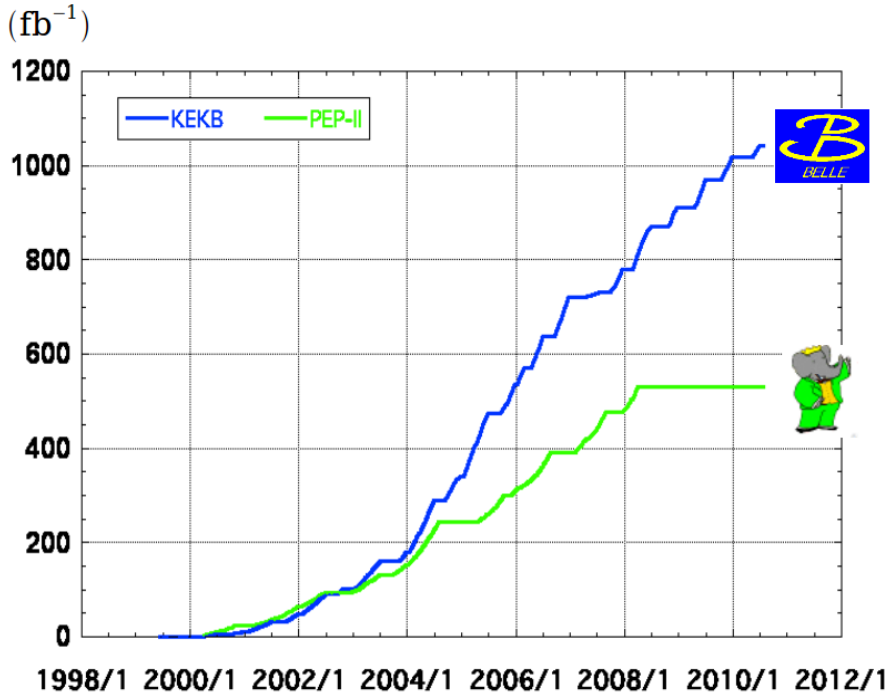


Belle and Belle II Datasets

- Belle (1999 - 2012)
- Belle II RUN-I (2019 - 2023)
- Belle II RUN-II (2024 - 2026)

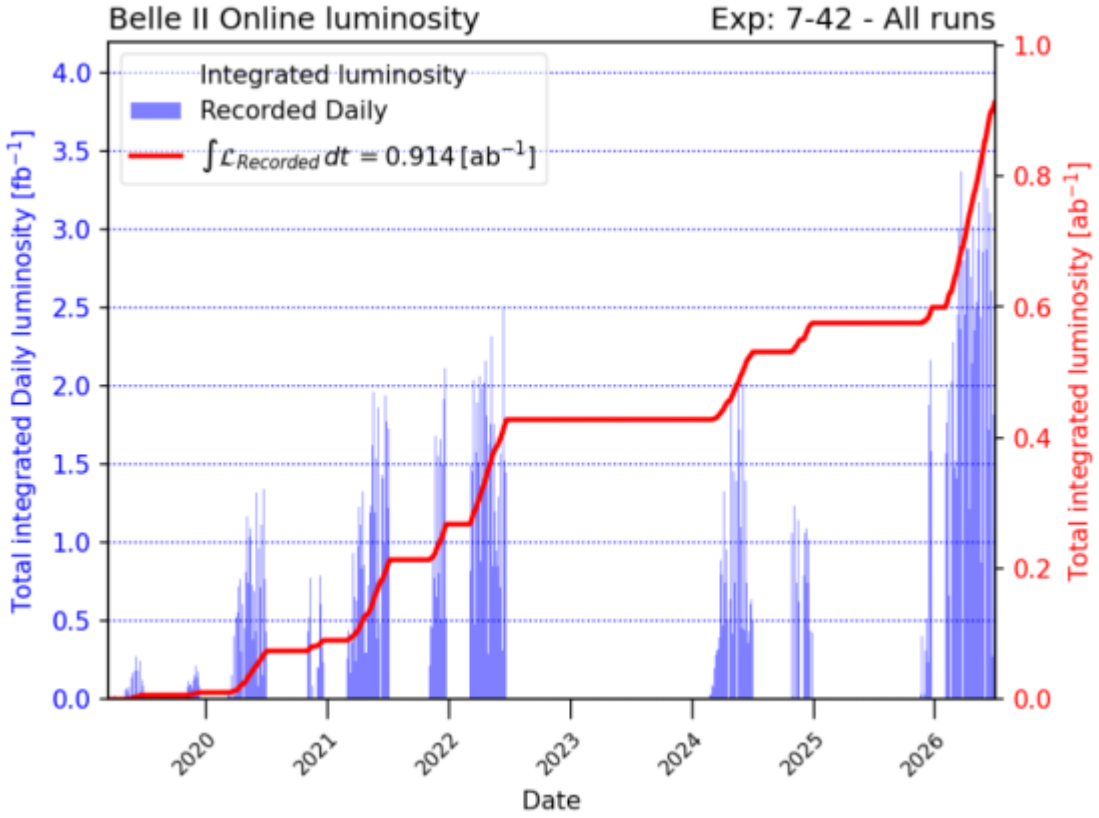
- Asymmetric electron-positron collider at $\Upsilon(4S)$
  - Target instantaneous luminosity: $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (30x KEKB)
  - Max instantaneous luminosity: $\mathscr{L} = 5.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (World record!)

Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}



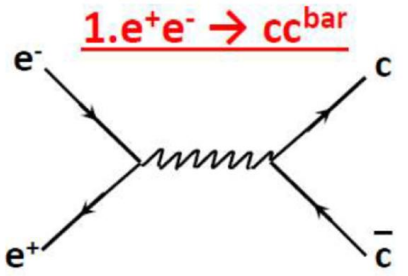
Most data at or near the $\Upsilon(4S)$ resonance, some below/above $\Upsilon(4S)$.

Charm physics at Belle and Belle II

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

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

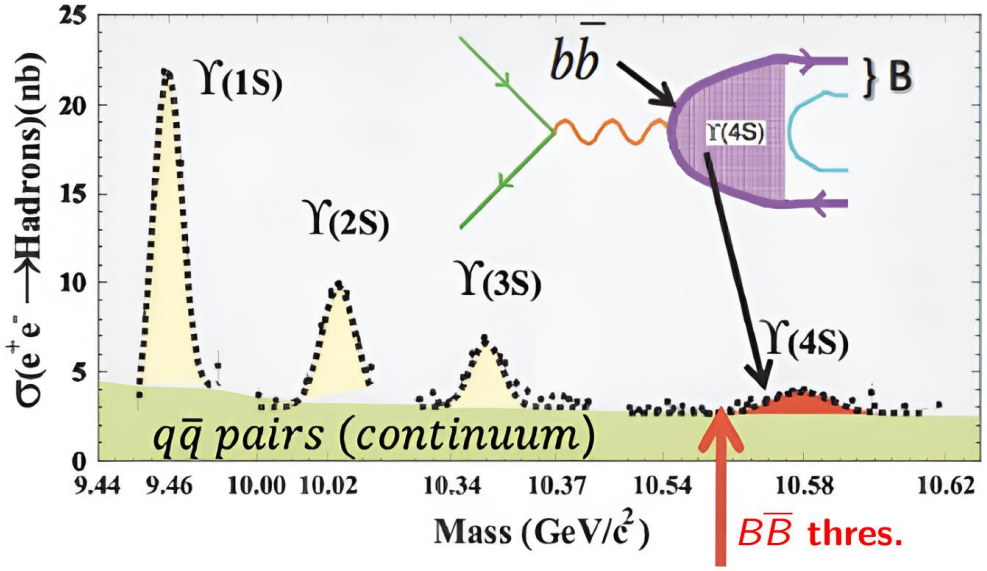
- Absolute measurements not possible without reference
- Used for most analyses due to its simplicity compared to $B\bar{B}$ processes

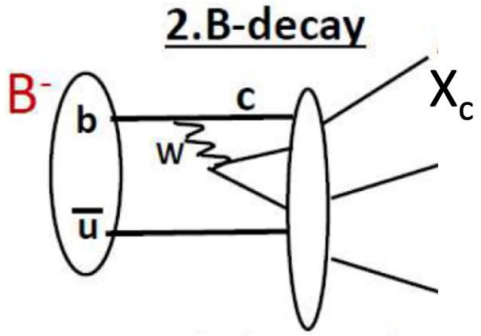


$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

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

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





CPV in Charm

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

PRD 112, L031101 (2025)

- 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 $A_{CP}^{\pi\pi} = A_{raw}^{\pi\pi} - (A_{prod}^{D} + A_{\epsilon}^{\pi})$ → **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.

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

Control mode

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

Signal mode

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

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

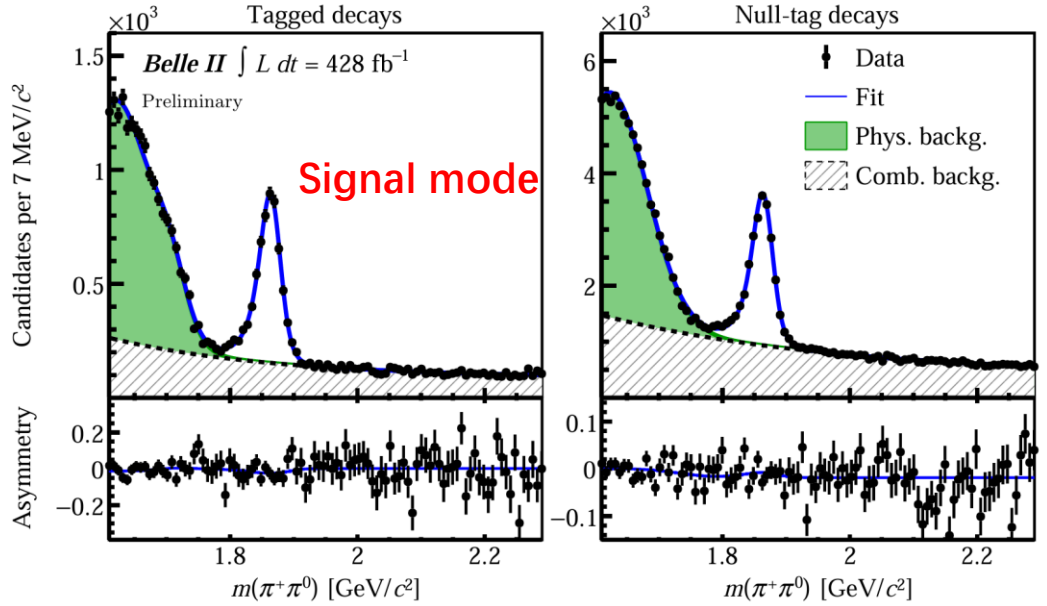
$\sim -0.4\,\%$

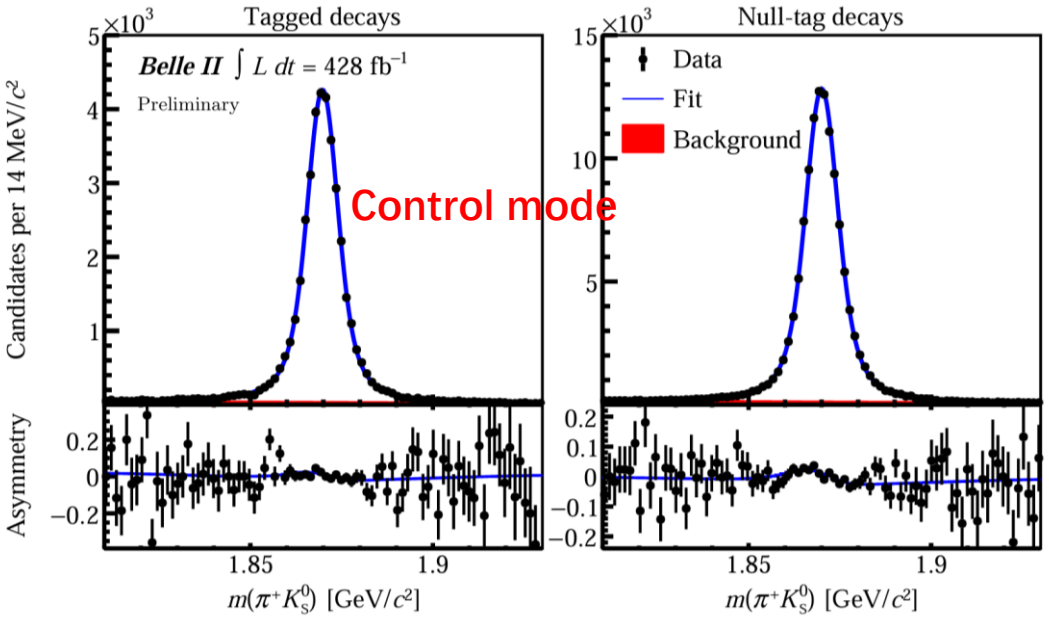
$A_{K_S^0}$: 1, CP-violation in the K^0-$\bar{K}^0$system.

2, different nuclear-interaction cross-sections for K^0 and $\bar{K}^0$ mesons with detector.

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

PRD 112, L031101 (2025)





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:

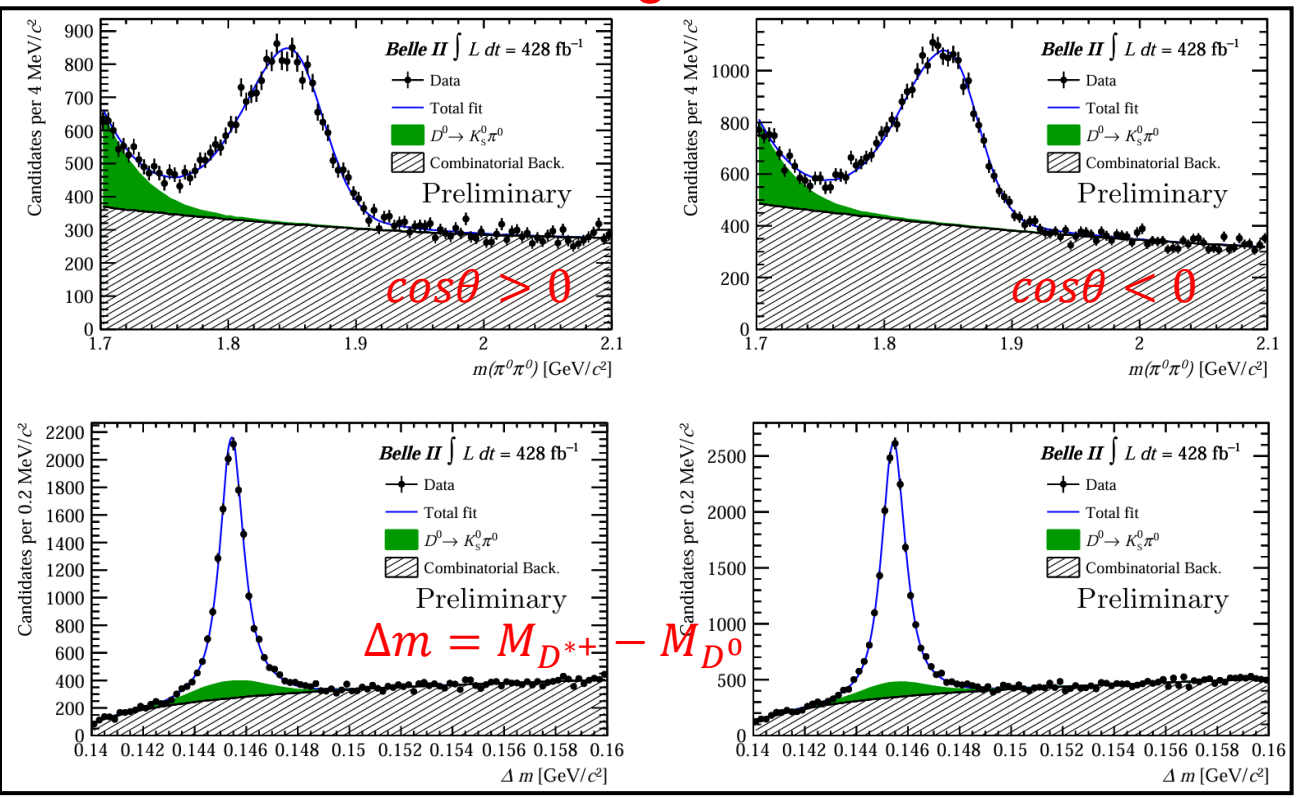
$A_{CP}(D^+ \to \pi^+\pi^0) = [-1.8 \pm 0.9(stat) \pm 0.1(syst)]\,\%$,

  - most precise measurement
  - improved precision compared to Belle's result: $(2.3 \pm 1.3 \pm 0.2)\%$ [*Phys. Rev. D 97, 011101 (2018)*]

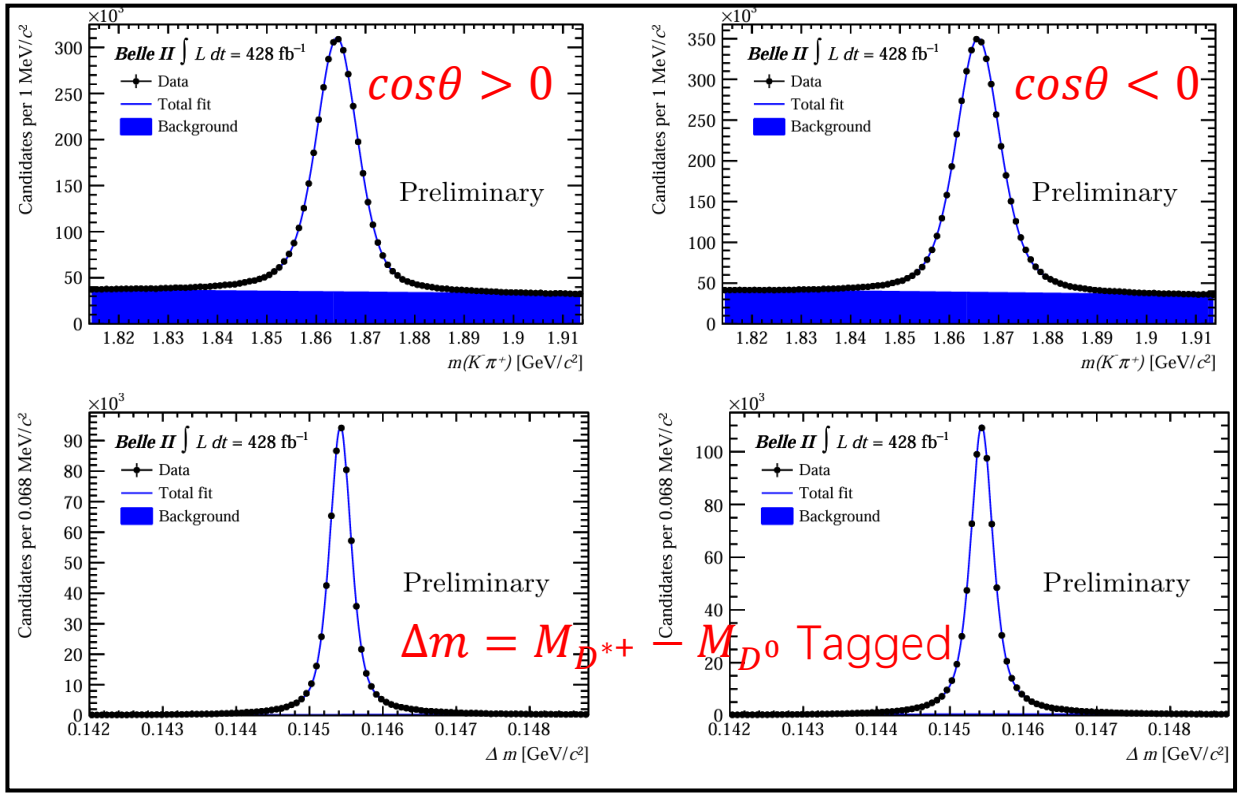
$D^0 \to \pi^0\pi^0$

PRD 112, 012006 (2025)

Signal mode



Control mode



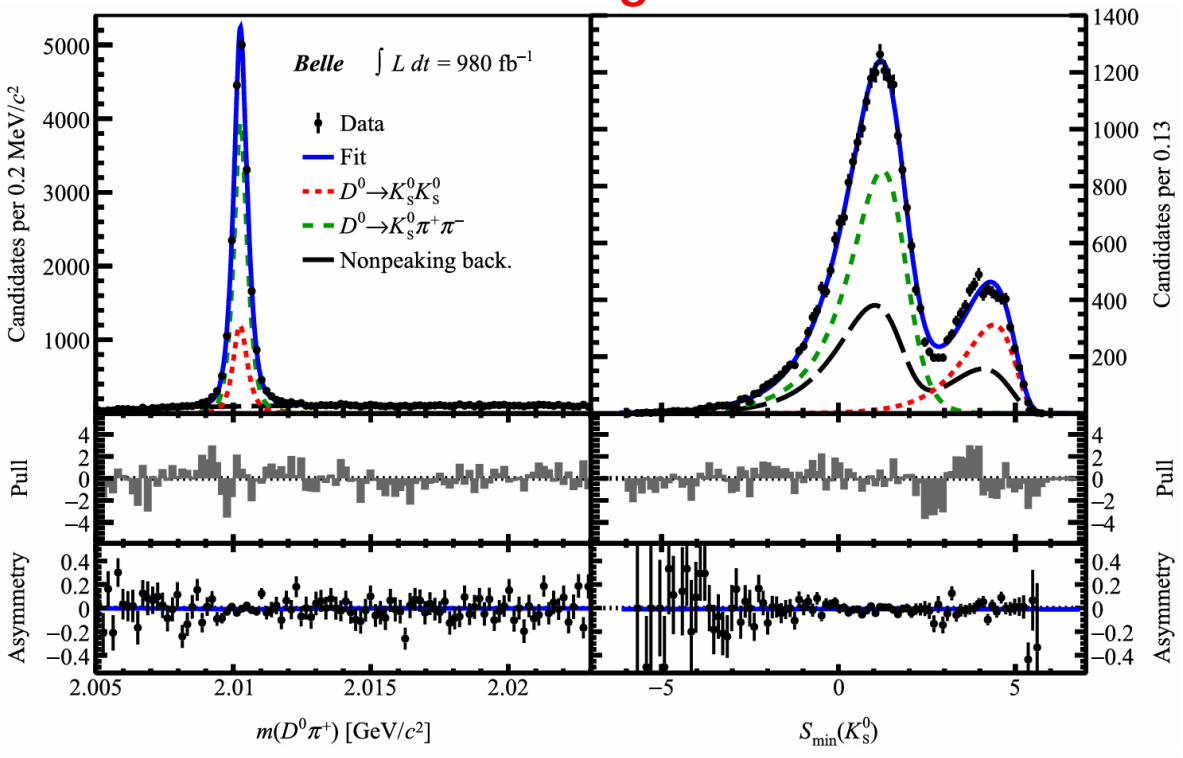
- Using 428 /fb, Belle II obtain:
  - **A_{CP} ($D^0 \to \pi^0\pi^0$): (0.30 ± 0.72 ± 0.20) %**
    - 15% less precise than the Belle measurement: (0.030 ± 0.64 ± 0.10) % [*Phys. Rev. Lett. 112, 211601 (2014)*]
    - The improved precision per luminosity due to Belle II's better reconstruction π^0.

$D^0 \to K^0_S K^0_S$

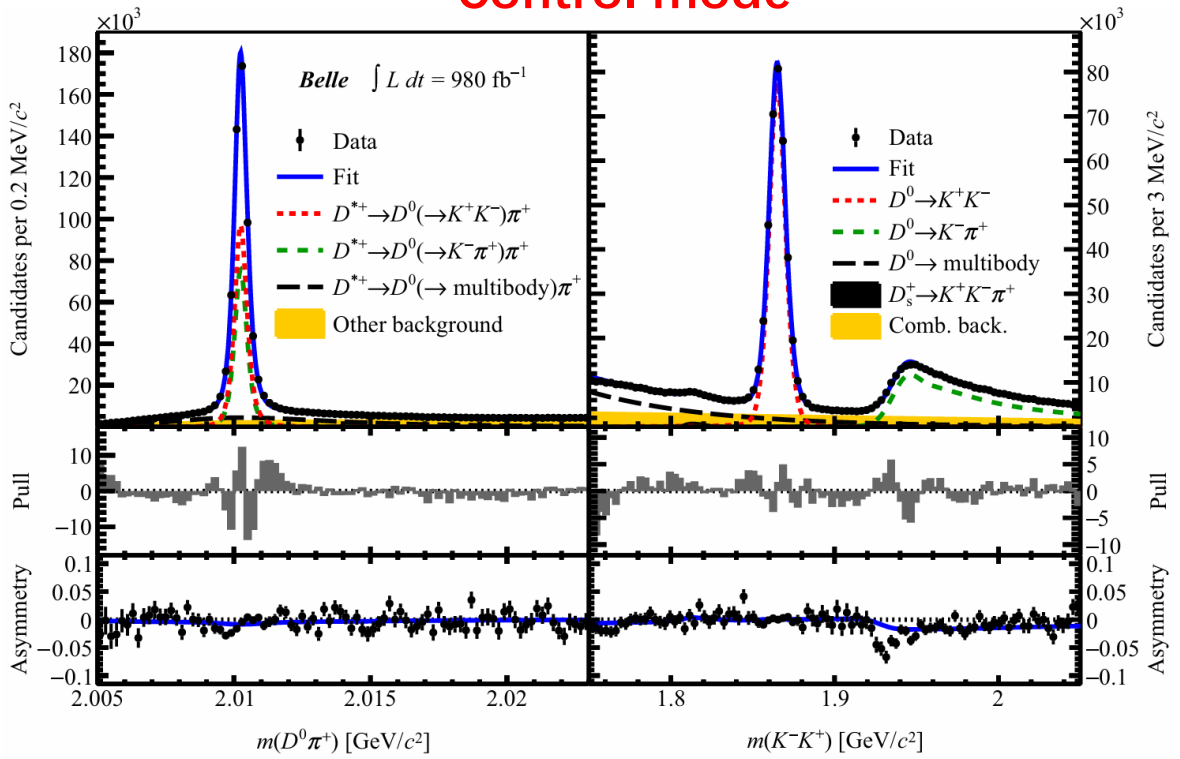
PRD 111, 012015 (2025)

Using D^* tag

Signal mode



Control mode



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

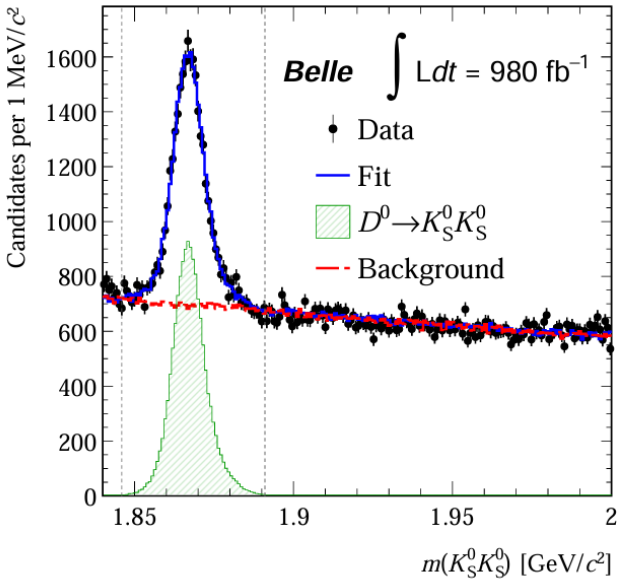
PRD 104, L031102 (2021)

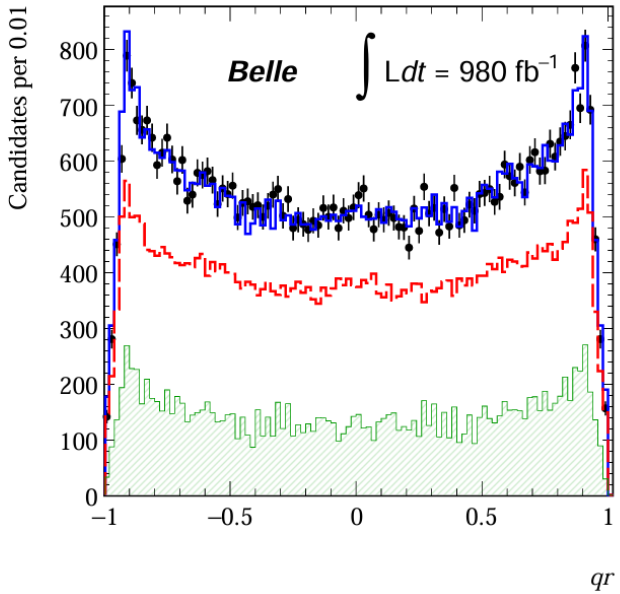
- Factor of two smaller systematic uncertainty as compared to Belle result: (-0.02± 1.53 ± 0.02±0.17) % [*Phys. Rev. Lett. 119, 171801 (2017)*]
- Comparable with world's best measurement by LHCb: (-3.1± 1.2 ± 0.4±0.2) % [*Phys. Rev. D 104, L031102 (2021)*].

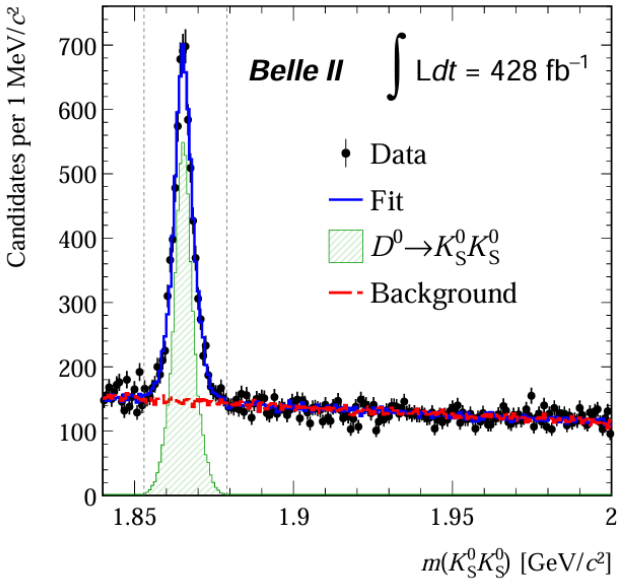
$D^0 \to K^0_S K^0_S$

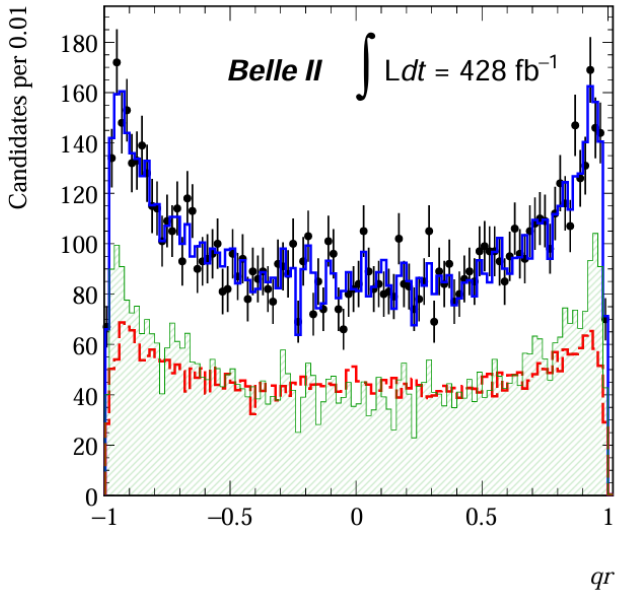
PRD 112, 012017 (2025)

Using charm flavor tagger









- Events used in the previous analysis are removed.
- $D^0 \to K_S \pi^+ \pi^-$ suppressed using $S_{min}(K_S)$.

Combine Belle and Belle II:

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

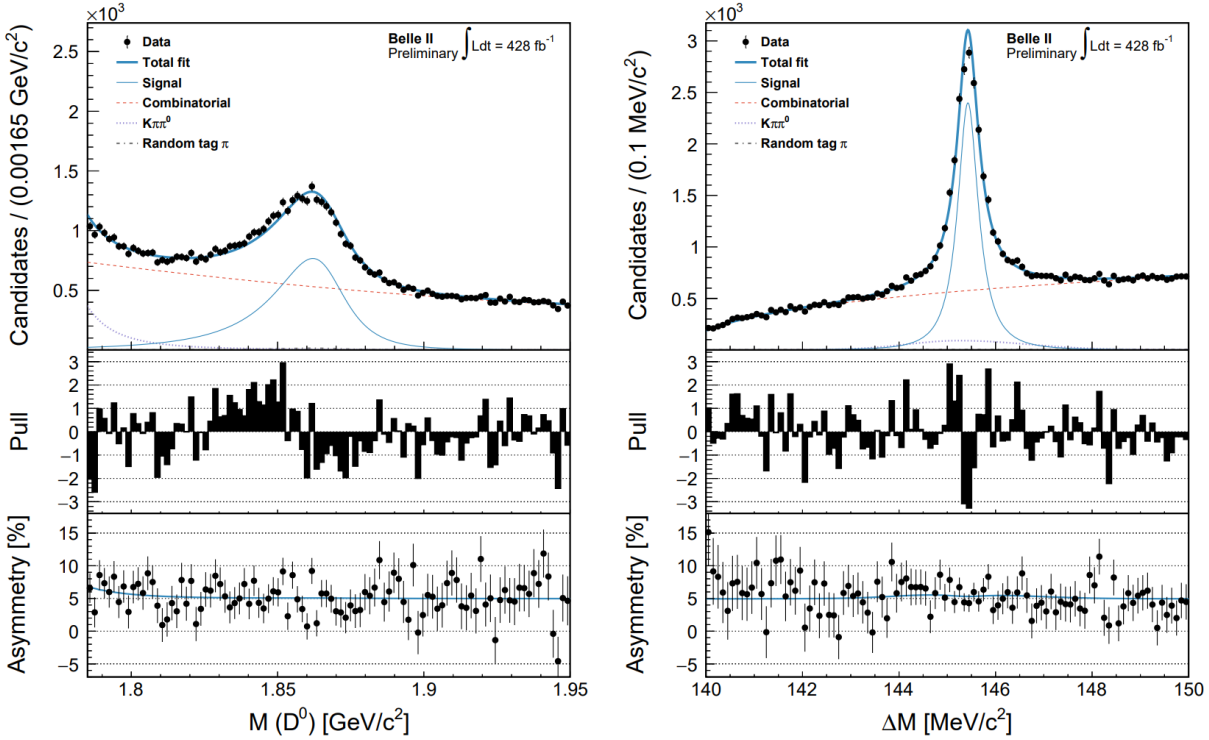
Method	A_{CP} [%]
D^*-tag	-1.4 ± 1.3 ± 0.1
CFT-tag	1.3 ± 2.0 ± 0.3
Combination	**-0.6 ± 1.1 ± 0.1**

- Most precise determination till date.

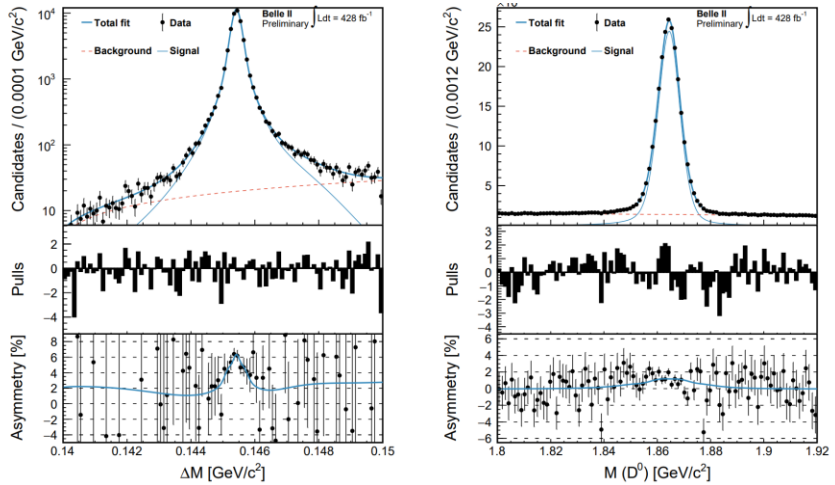
$D^0 \to \pi^+\pi^-\pi^0$

PRD 113, 052006 (2026)

- SCS three-body decay, interference of several amplitudes
- Signal: D^{*+} tagged sample for $D^0 \to \pi^+\pi^-\pi^0$.
- Control mode: tagged and untagged $D^0 \to K^-\pi^+$
- Simultaneous fit to (Δm, $m(\pi^+\pi^-\pi^0)$) in 8 bins of $\cos\theta_{CM}$, averaged symmetrically around 0 to remove the production asymmetry

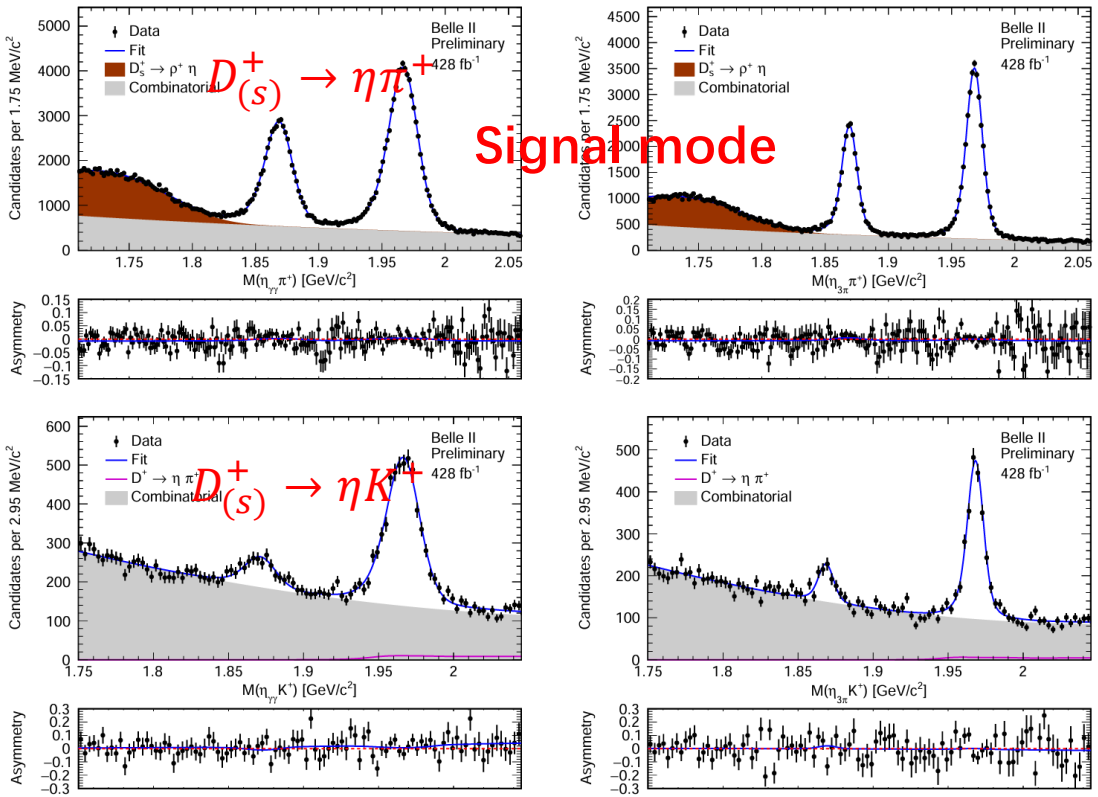


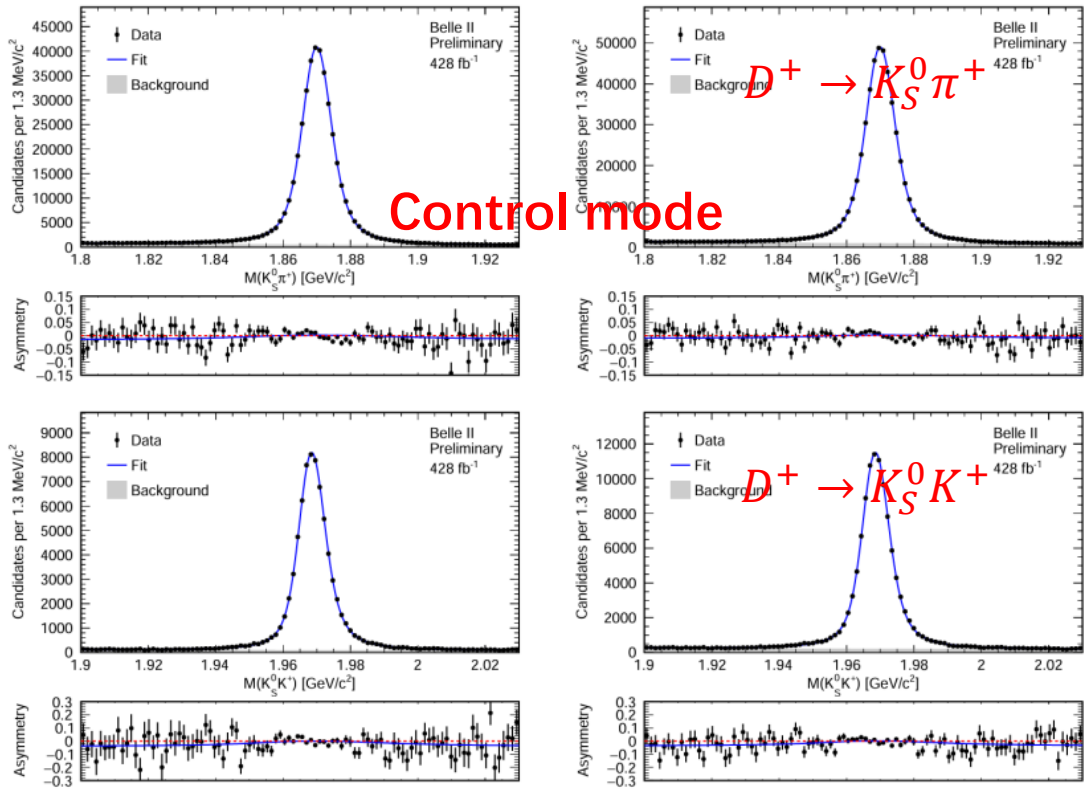
- Using 428 /fb, Belle II obtain:
  - **A_{CP} ($D^0 \to \pi^+\pi^-\pi^0$): (0.29 ± 0.27 ± 0.13) %**
    - Most precise measurement till date
    - 34% more precise than BABAR with just 10% more statistics



$D^+_{(s)} \to \eta h^+$

Preliminary result





- Using 428 /fb, Belle II obtain:

$$A_{CP}(D^+ \to \eta\pi^+) = (-0.70 \pm 5.15 \pm 0.18) \times 10^{-3},$$
$$A_{CP}(D_s^+ \to \eta\pi^+) = (-3.23 \pm 3.80 \pm 0.18) \times 10^{-3},$$
$$A_{CP}(D^+ \to \eta K^+) = (-1.63 \pm 6.51 \pm 0.26) \times 10^{-2},$$
$$A_{CP}(D_s^+ \to \eta K^+) = (-0.37 \pm 1.85 \pm 0.10) \times 10^{-2}.$$

- Agree with previous measurements
- Most precise determination till data
- Consistent with zero, with no evidence of CPV

$\Xi_c^+ \to \Sigma^+ h^+ h^-$, $\Lambda_c^+ \to p h^+ h^-$

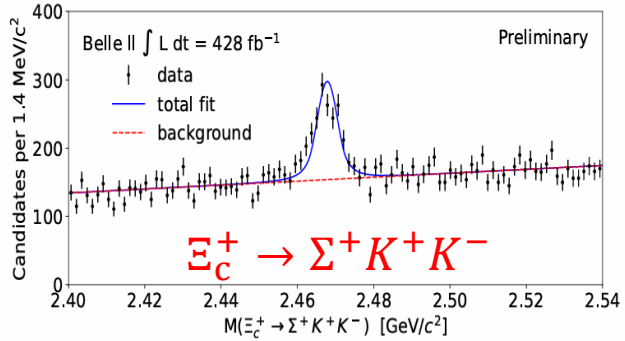
PRD 113, 032017 (2026)

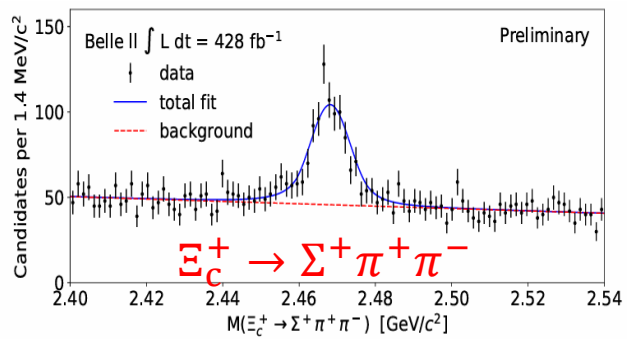
First measurement of A_{CP} in SCS three-body charm baryon decays.

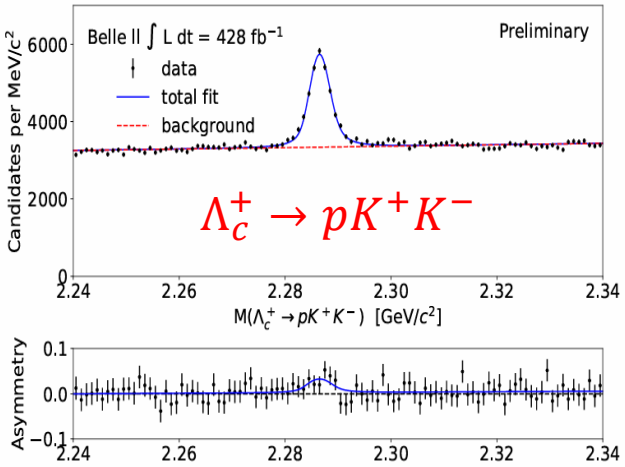
$$A_{CP}(X_c^+ \to f^+) \equiv \frac{\Gamma(X_c^+ \to f^+) - \Gamma(\bar{X}_c^- \to \bar{f}^-)}{\Gamma(X_c^+ \to f^+) + \Gamma(\bar{X}_c^- \to \bar{f}^-)}.$$

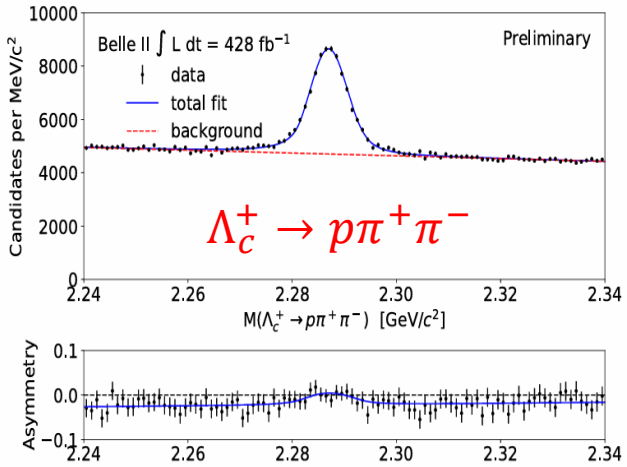
- Using 428 /fb, Belle II obtain:

$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) = (3.7 \pm 6.6 \pm 0.6)\%,$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) = (9.5 \pm 6.8 \pm 0.5)\%,$$
$$A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (3.9 \pm 1.7 \pm 0.7)\%,$$
$$A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (0.3 \pm 1.0 \pm 0.2)\%,$$









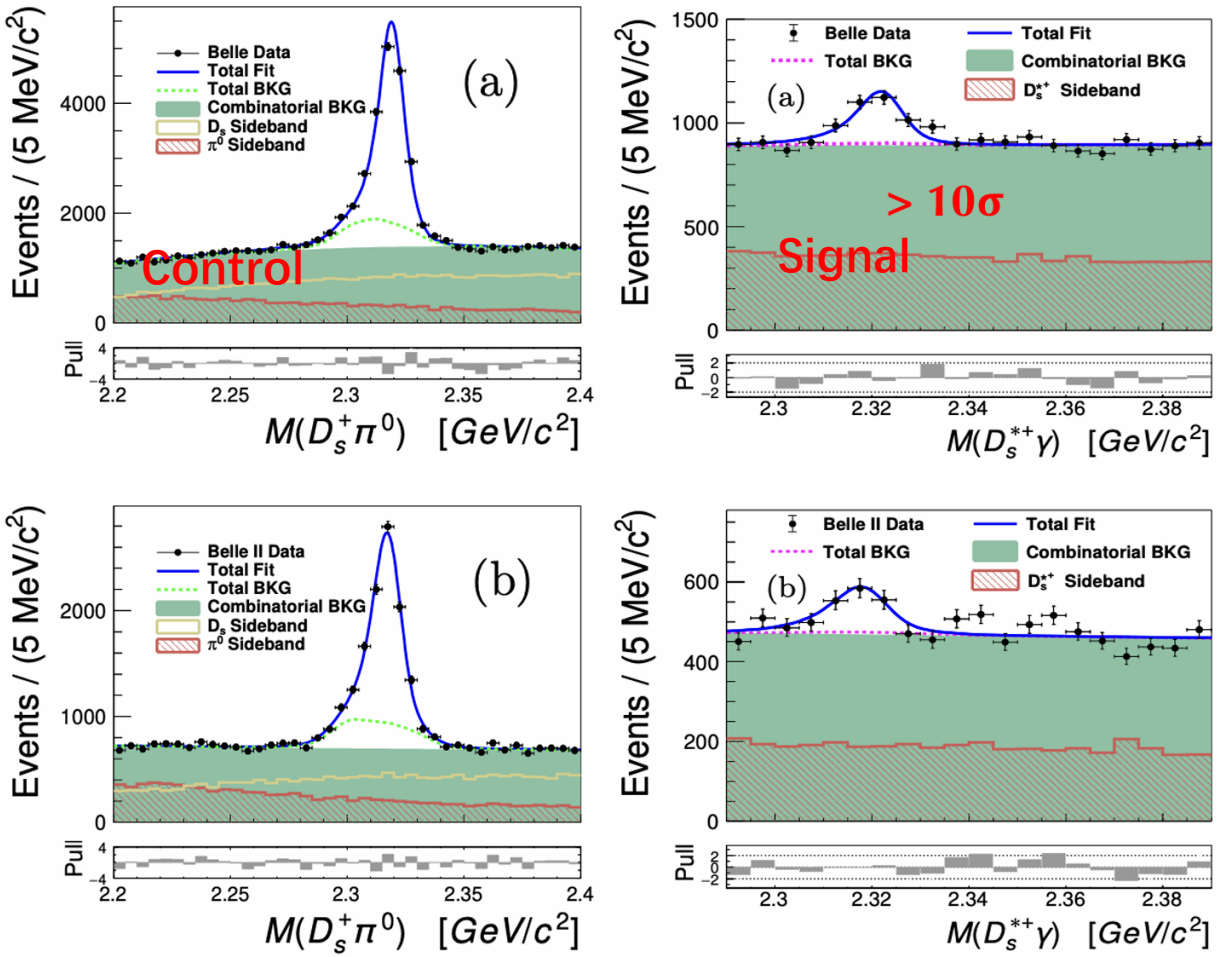
- First measurements
- Statistical uncertainty dominant
- Future measurements with more data are expected.

Radiative decay

Fisrt Observation of $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$

PRL 136, 241901 (2026)

- Nature of $D_{s0}^{*}(2317)^{+}$ uncertain: lower than expected mass according to quark model
  - $c\bar{s}$, molecule, tetraquark, mixed state
- Sensitive probe of internal structure of potential exotic state

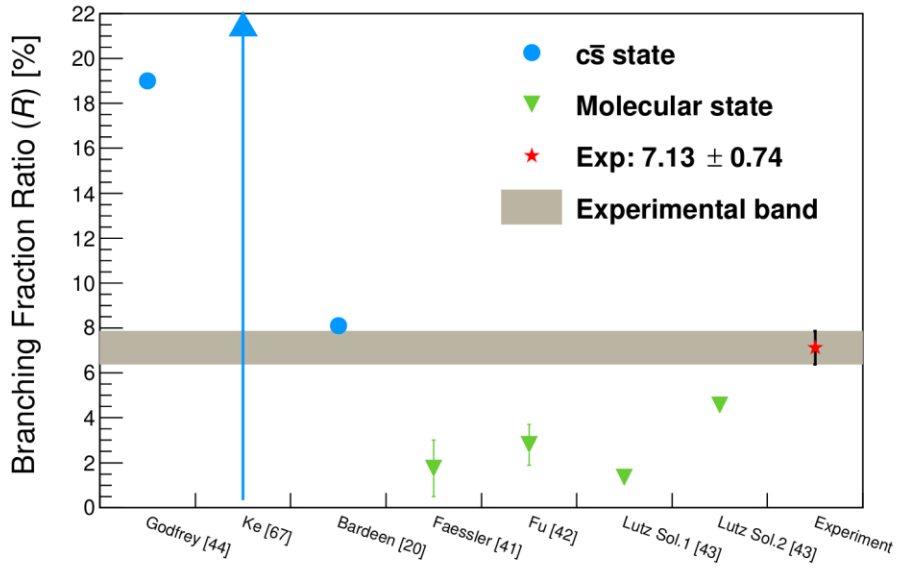


- Combined Belle and Belle II (1.4 /ab)

Partial decay widths:
unique in discriminating between various models

$$\mathcal{R} = \frac{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma)}{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0})}$$

$$= [7.14 \pm 0.70(\text{stat.}) \pm 0.23(\text{syst.})]\%$$

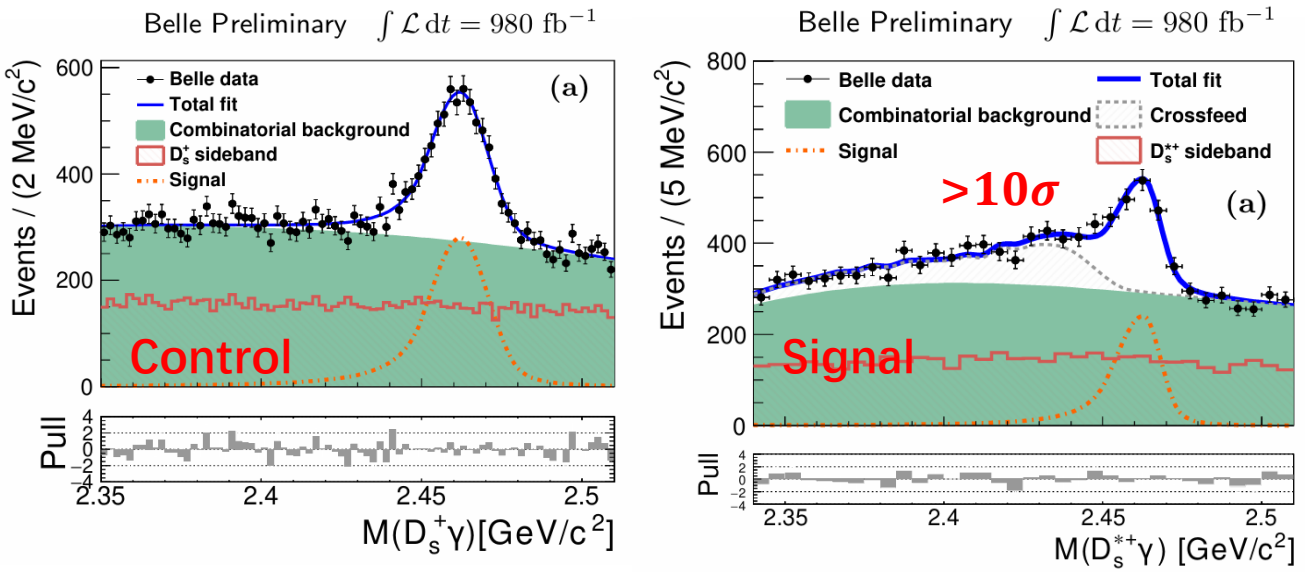


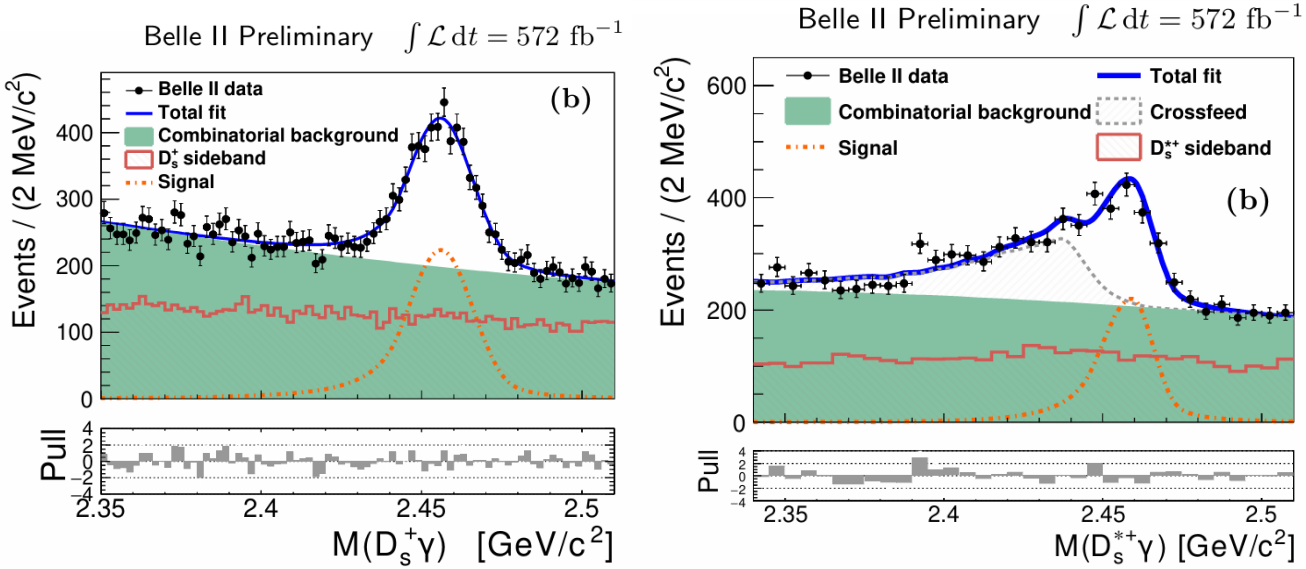
$D_{s0}(2317)^{+}$ could be the mixture state of pure $c\bar{s}$ state and molecular state.

First Observation of $D_s(2460)^+ \to D_s^{*+}\gamma$

Preliminary result

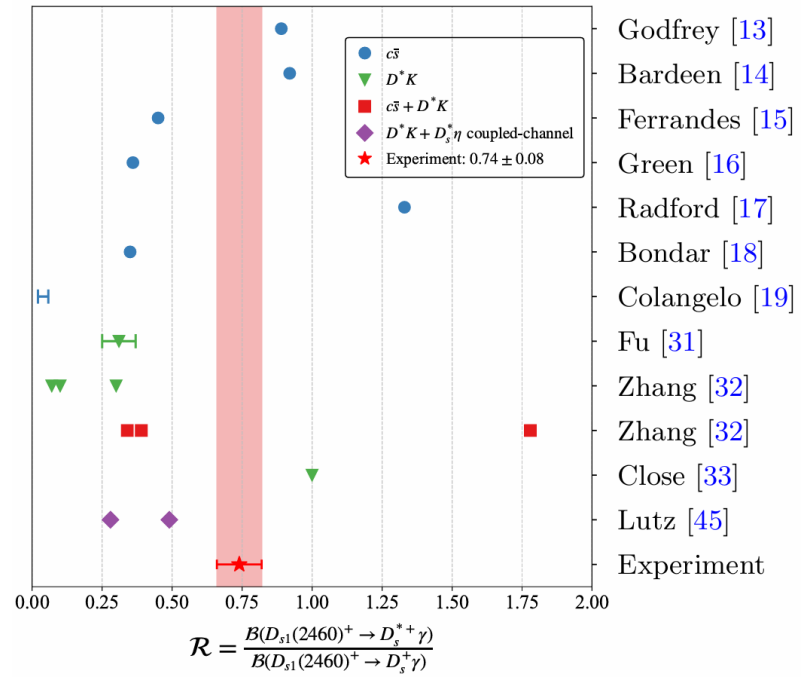
- Combined Belle and Belle II (1.4 /ab)





Partial decay widths:
unique in discriminating between various models

$$\mathcal{R} = \frac{\mathcal{B}[D_{s1}(2460)^+ \to D_s^{*+}\gamma]}{\mathcal{B}[D_{s1}(2460)^+ \to D_s^{+}\gamma]}$$
$$= 0.74 \pm 0.05\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

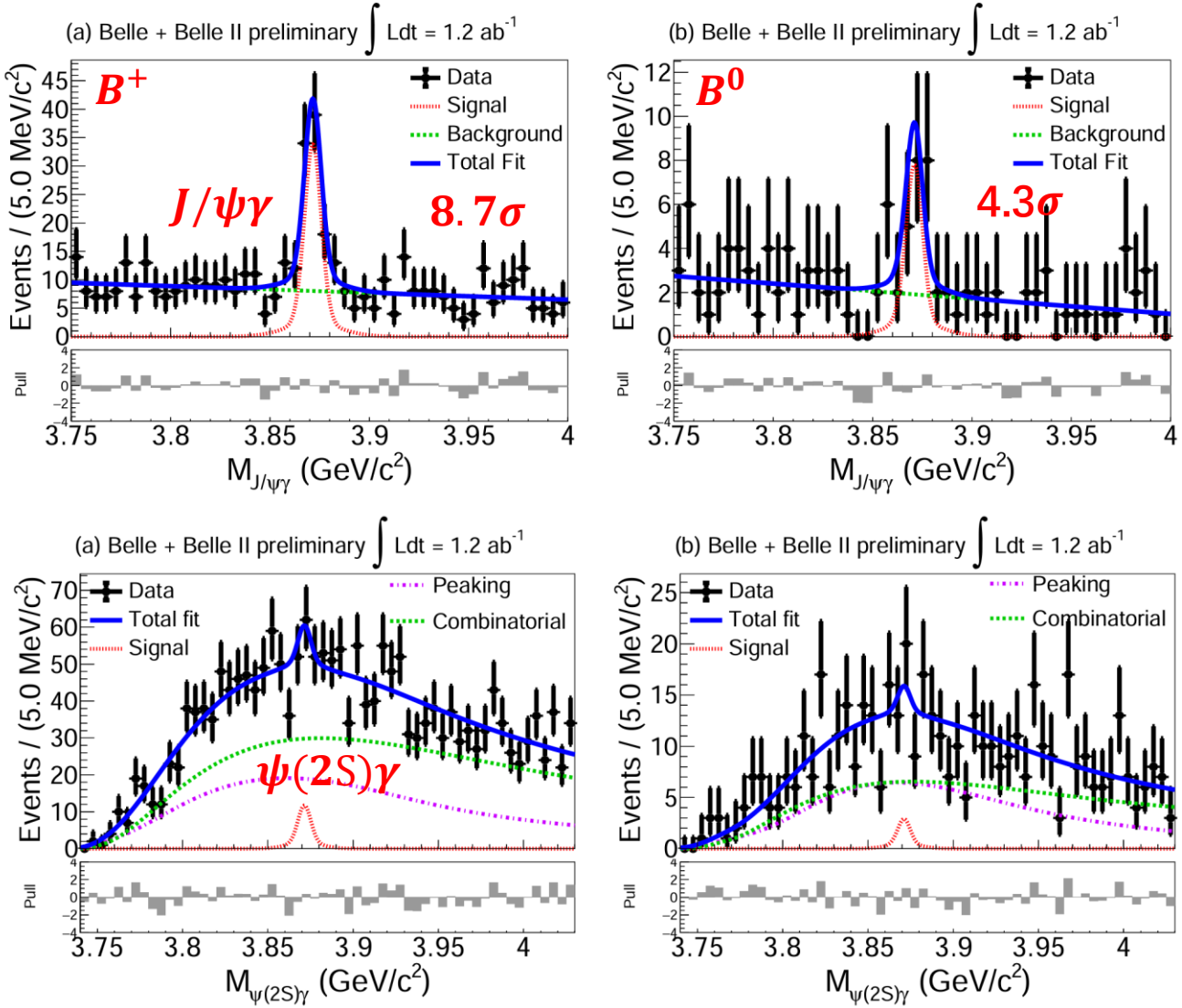


provide constraints on theoretical descriptions and experimental input for understanding the internal structure of the $D_s(2460)^+$

$\chi_{c1}(3872) \to \psi(2S)\gamma$

Preliminary result

Decay $\chi_{c1}(3872) \to \gamma\psi(2S)$ is sensitive to its internal structure



- **Combined Belle and Belle II (1.2 /ab) at Y(4S)**
  - 8.7σ for $B^+ \to \chi_{c1}(3872)(\to J/\psi\gamma)K^+$
  - 4.3σ for $B^0 \to \chi_{c1}(3872)(\to J/\psi\gamma)K^0$
  - No significant signal for $\chi_{c1}(3872) \to \psi(2S)\gamma$

$$\frac{\boldsymbol{B[\chi_{c1}(3872) \to \psi(2S)\gamma]}}{\boldsymbol{B[\chi_{c1}(3872) \to J/\psi\gamma]}}$$

$$\boldsymbol{= 0.95 \pm 0.45 \pm 0.20 < 1.7(90\%\ C.L.)}$$

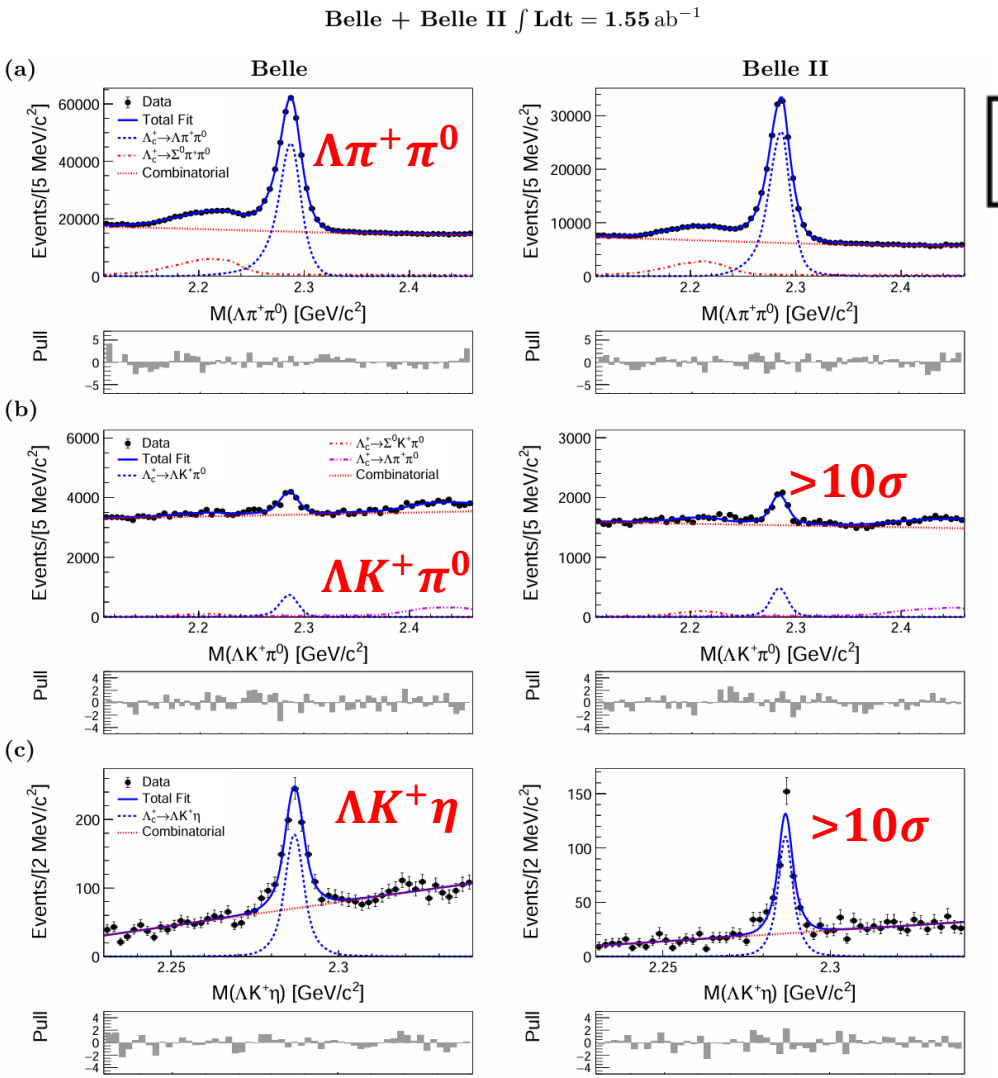
- Consistent with the Belle/LHCb results
- Favor a compact charmonium- D^0D^{*0} molecular mixture for $\chi_{c1}(3872)$
- Disfavor a mostly compact charmonium scenario.

Hadronic decay

$\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\eta$

Preliminary result

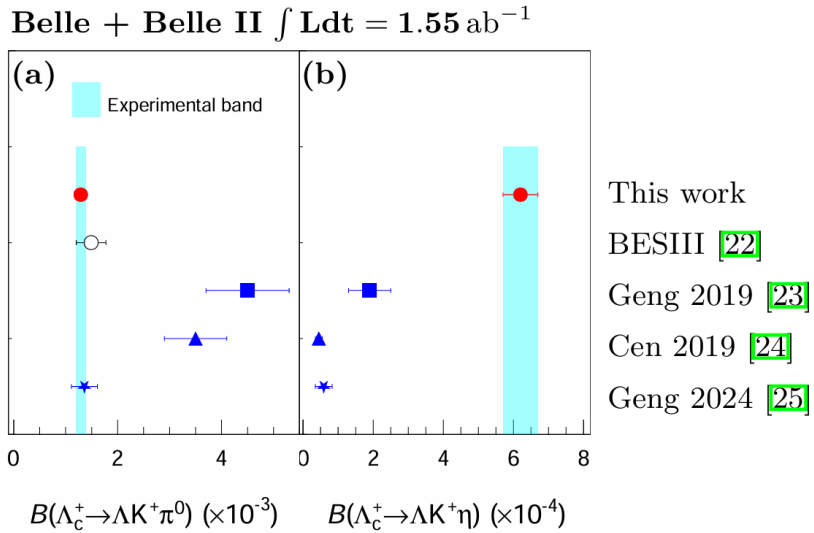
- Singly Cabibbo-Suppressed (SCS) decays are still poorly explored
- Nonfactorizable contributions play an essential role in this case



- Combined Belle and Belle II (1.4 /ab)

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\pi^0)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (1.82 \pm 0.07 \pm 0.07)\%$$

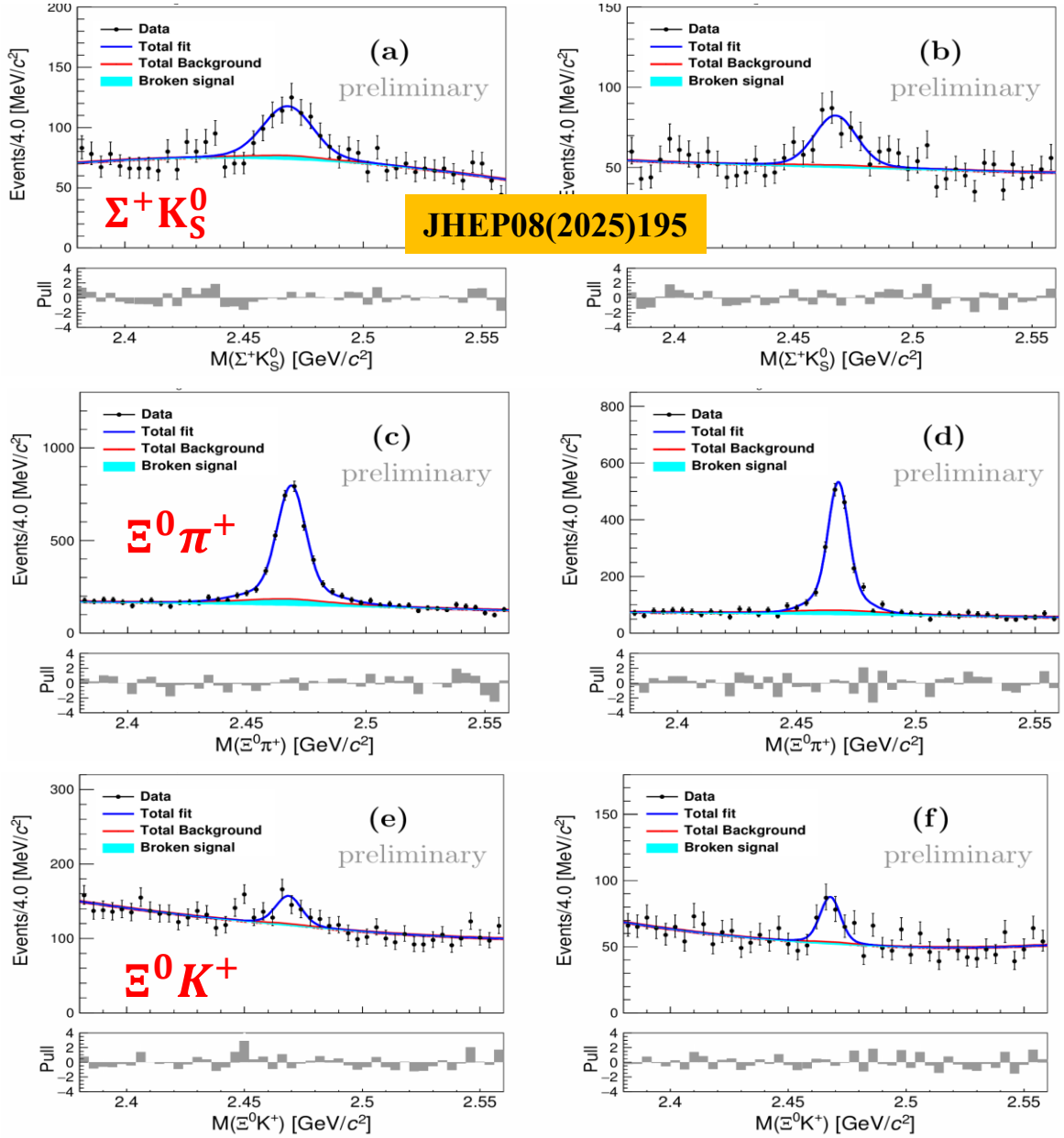
$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+\eta)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (8.73 \pm 0.35 \pm 0.43) \times 10^{-3}$$

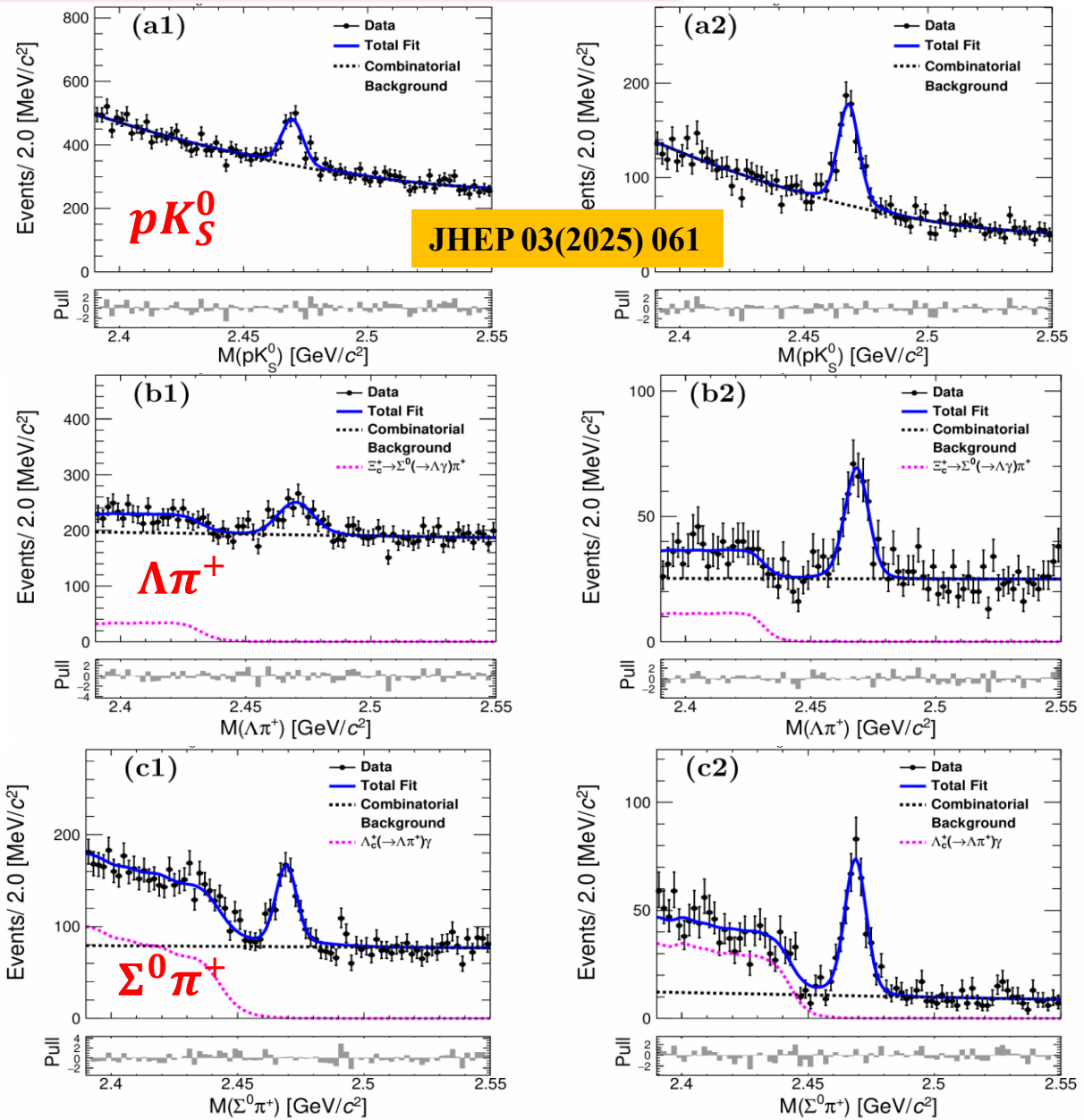


- **First observation of $\Lambda_c^+ \to \Lambda K^+\eta$, an excess of $> 5\sigma$ from theo.**
- **Most precise determination for $\Lambda_c^+ \to \Lambda K^+\pi^0$**

Two-body decay of Ξ_c^+

- Combined Belle and Belle II (1.4 /ab)



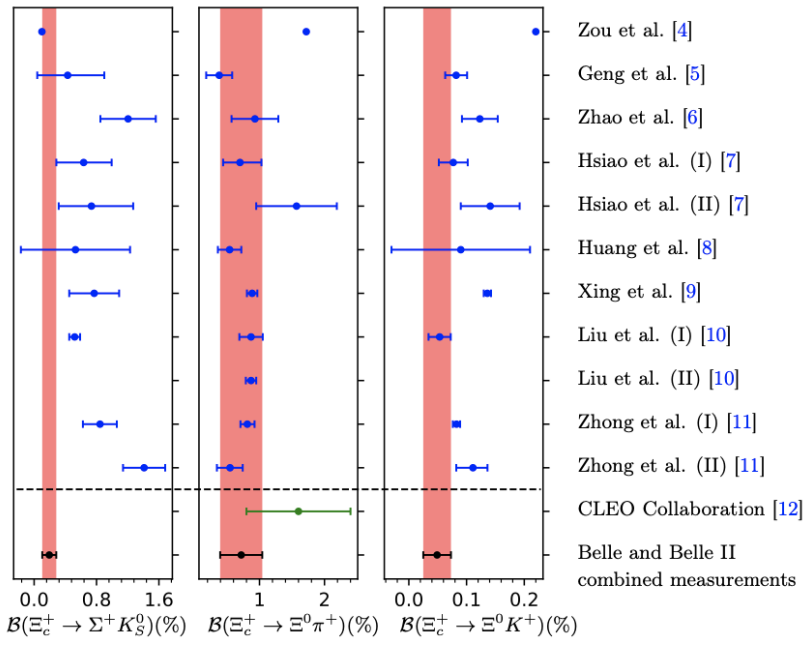


Two-body decay of Ξ_c^+

First or most precise measurements! Consistent with different predictions.

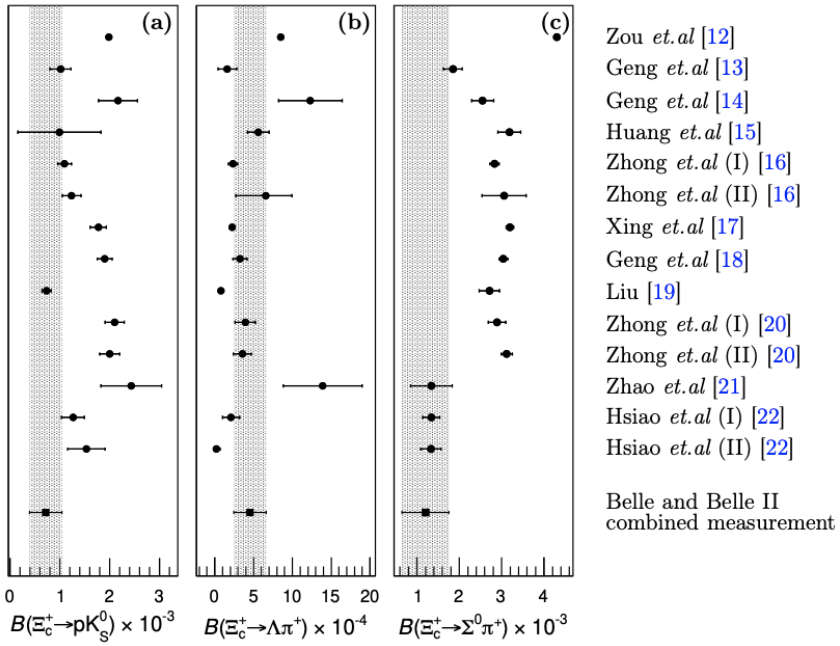
First BR* measurement of CF decay $\Xi_c^+ \to \Sigma^+ K_S$ and CS decay $\Xi_c^+ \to \Xi^0 K^+$.
Most precise BR* measurement of CF decay $\Xi_c^+ \to \Xi^0 \pi^+$.

JHEP08(2025)195



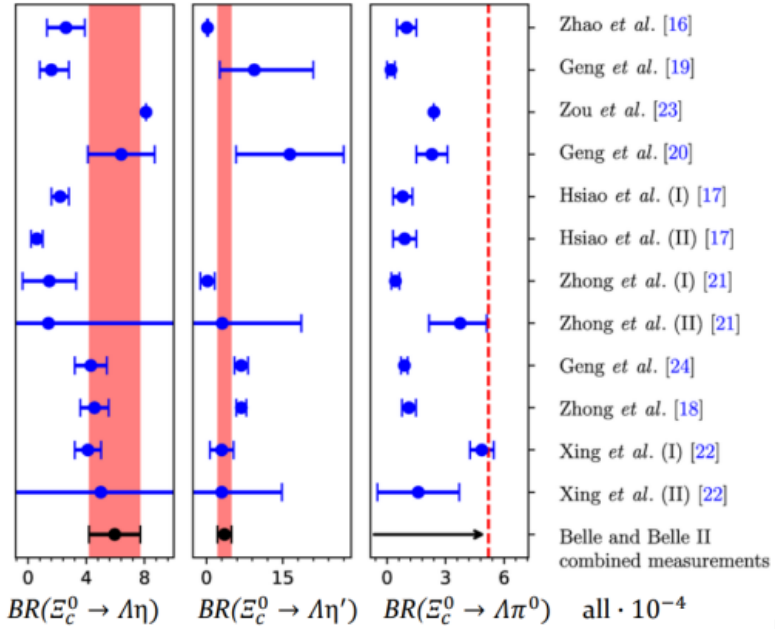
First BR* measurements of CS decays $\Xi_c^+ \to p K_S$, $\Xi_c^+ \to \Lambda \pi^+$ and $\Xi_c^+ \to \Sigma^0 \pi^+$.

JHEP 03(2025) 061



First BR* measurement of CS decays $\Xi_c^0 \to \Lambda\eta, \Lambda\eta'$
Upper limit *of* $\Xi_c^0 \to \Lambda\pi^0$.

PRD 113, 032015 (2026)

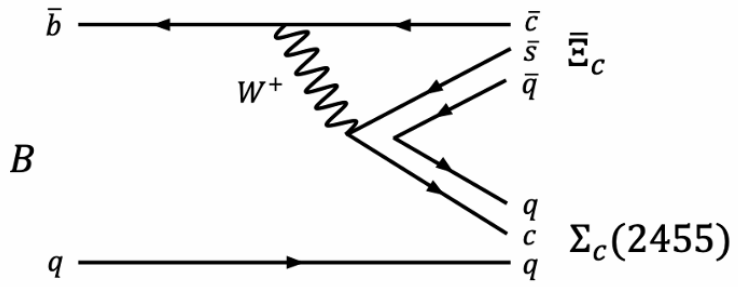


$B^{+,0} \to \Sigma_c(2455)^{++,0}\bar{\Xi}_c^{-,0}$

PRD 112 L051101 (2025)

- BF predicted to be 4×10^{-3} (sum rule) [NPB 345, 137 (1990)] or of the order 10^{-4} (di-quark model) [ZPC 51, 445 (1991)].

These two decays proceed through a purely internal W-emission:



$$\mathcal{B}(B^+ \to \Sigma_c^{++}\bar{\Xi}_c^-) = (5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}) \times 10^{-4}$$

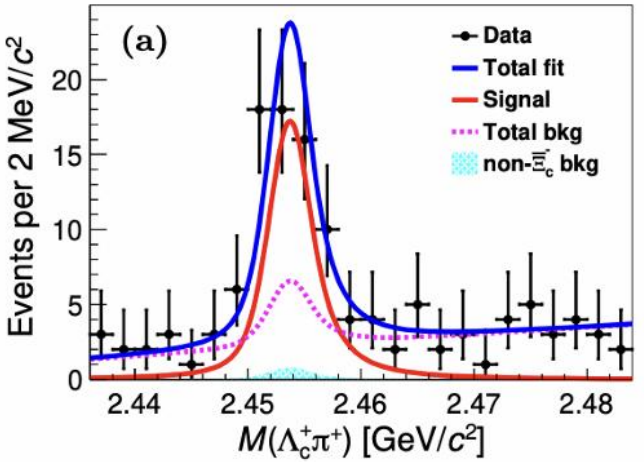
$$\mathcal{B}(B^0 \to \Sigma_c^0\bar{\Xi}_c^0) = (4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}) \times 10^{-4}$$

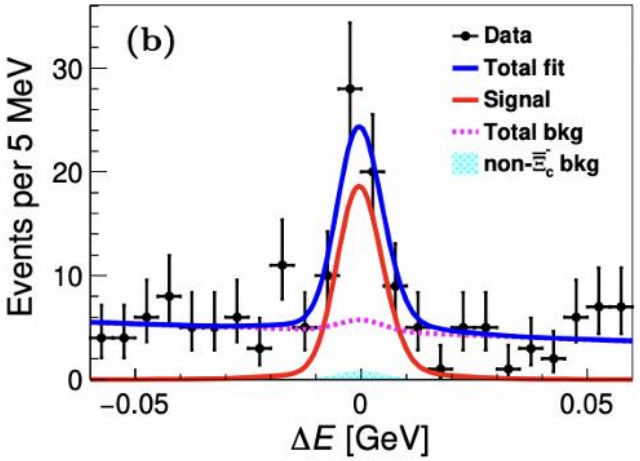
First observations!

- Significance $> 6\sigma$
- Consistent with diquark model
- BFs larger than single-charm $B \to p\bar{\Sigma}_c(2455)$

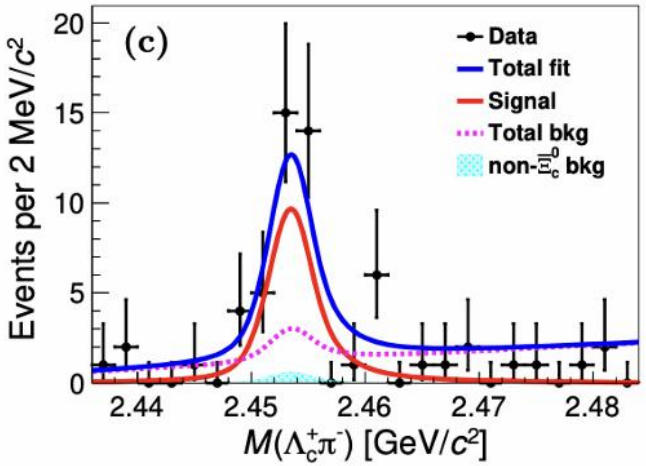
- **Combined Belle and Belle II (1.2 /ab) at Y(4S)**

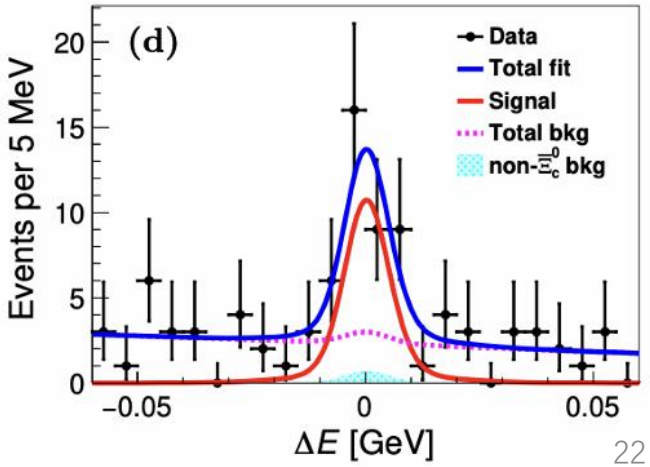
$B^+ \to \Sigma_c^{++}\bar{\Xi}_c^-$





$B^0 \to \Sigma_c^0\bar{\Xi}_c^0$





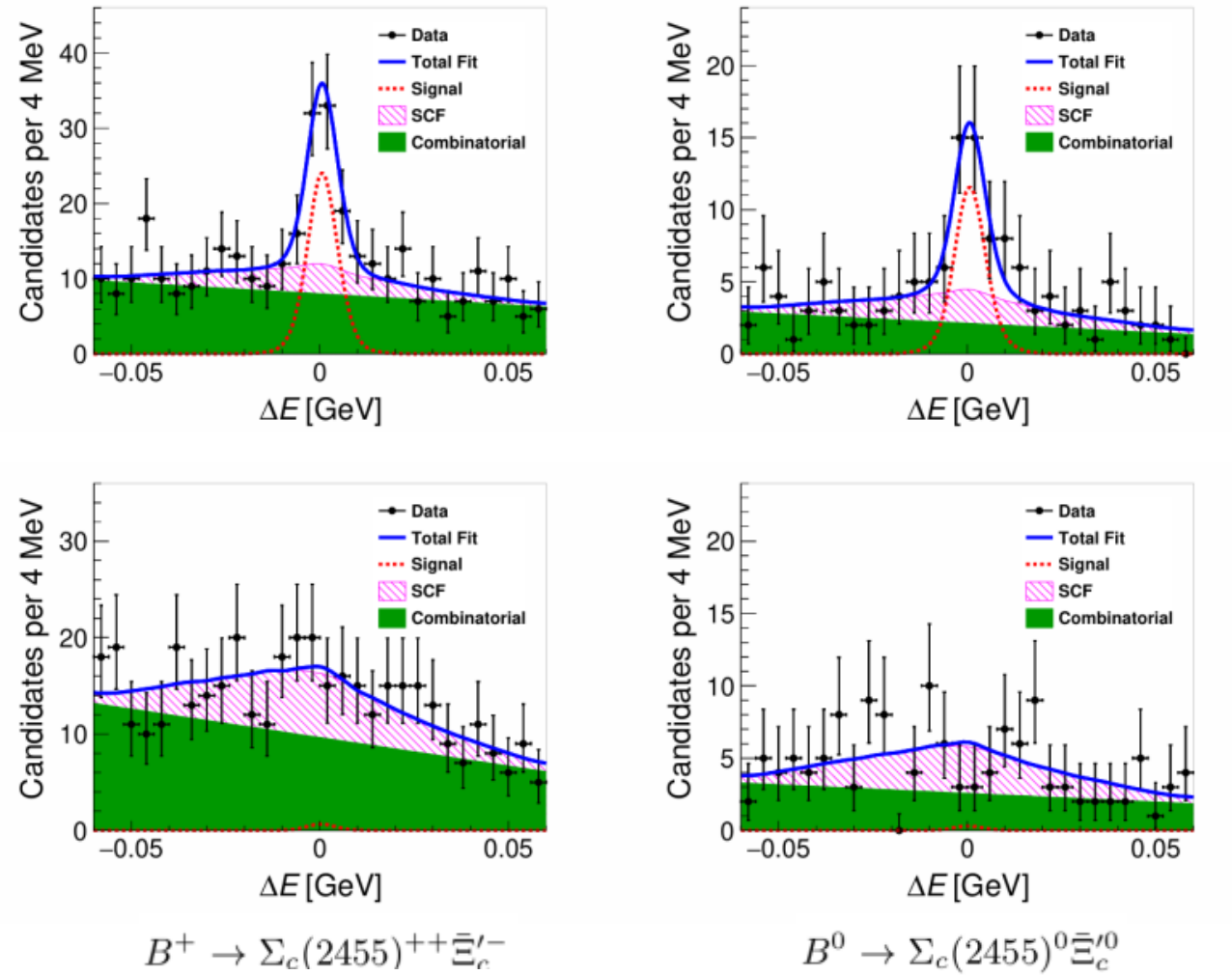
$B^{+,0} \to \Sigma_c(2455)^{++,0}\bar{\Xi}_c'^{-,0}$

arXiv: 2606.12905
Acc. by PRD

Same diagrams, but an extra γ from $\bar{\Xi}_c' \to \bar{\Xi}_c\gamma$

- **Combined Belle and Belle II (1.3 /ab) at Y(4S)**

$\int \mathcal{L}dt = 711\,\text{fb}^{-1}$ (Belle) + $492\,\text{fb}^{-1}$ (Belle II)



Decay	BR ($\cdot 10^{-4}$) $\pm$ stat. $\pm$syst. $\pm$syst. from BR(Ξ_c)
$B^+ \to \bar{\Xi}_c^- \Sigma_c^{++}(2455)$ [1]	$5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}$
$B^0 \to \bar{\Xi}_c^0 \Sigma_c^0(2455)$ [1]	$4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.6}$
$B^+ \to \bar{\Xi}_c'^- \Sigma_c^{++}(2455)$ [2]	$16.8 \pm 3.1 \pm 1.2^{+14.9}_{-5.4}$
$B^0 \to \bar{\Xi}_c'^0 \Sigma_c^0(2455)$ [2]	$12.8 \pm 3.2 \pm 1.0^{+3.0}_{-2.1}$

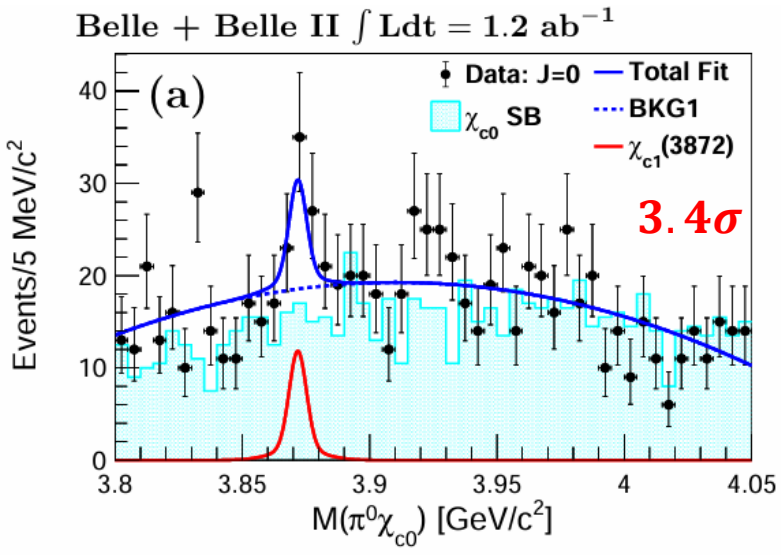
First observation

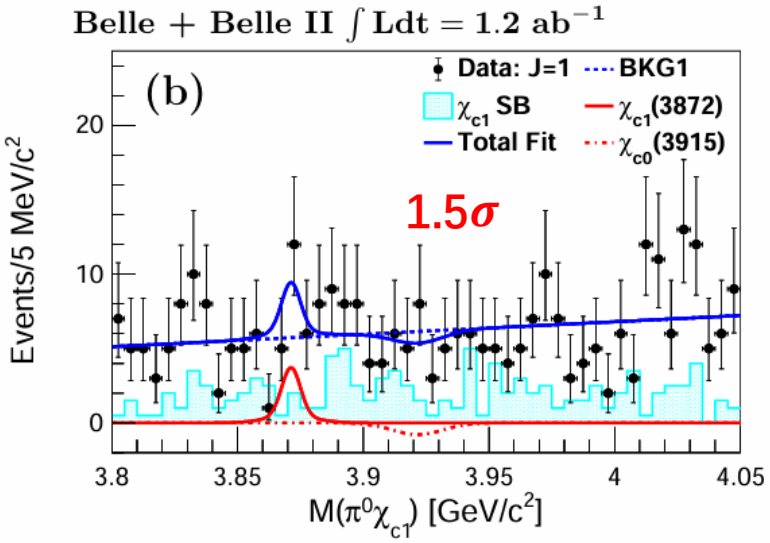
- **BFs 2-3 times larger for $\bar{\Xi}_c'$ than for $\bar{\Xi}_c$, despite smaller available phase space**
- **May indicate nontrivial dynamical effects in baryonic B decays**

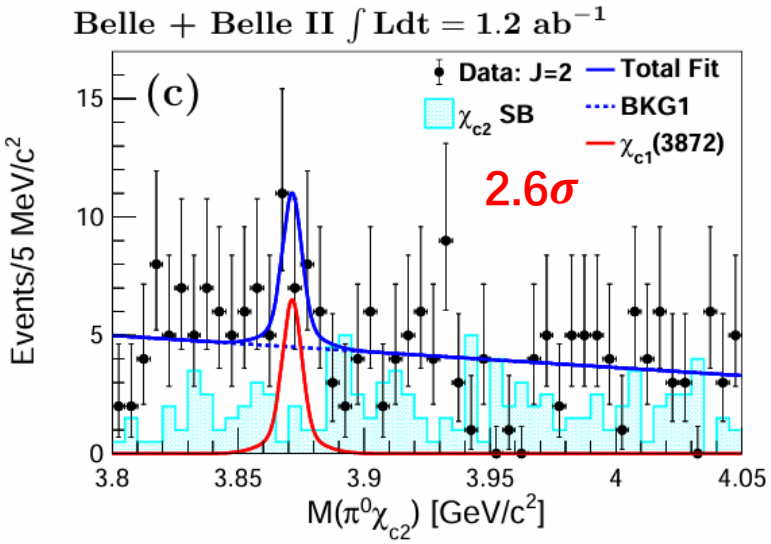
$\chi_{c1}(3872) \to \pi^0\chi_{cJ}$

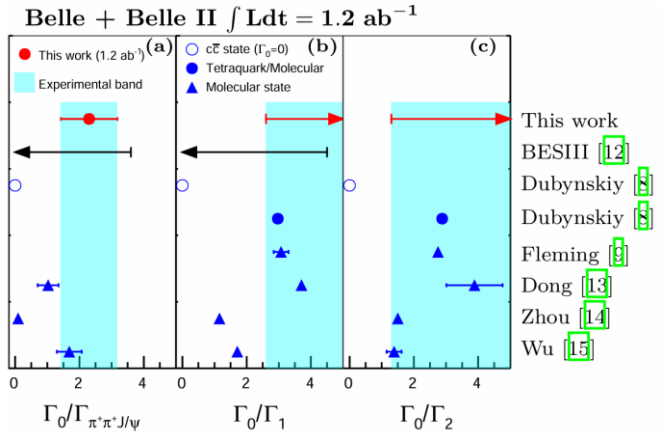
arXiv:2606.24578

- **Decay $\chi_{c1}(3872) \to \pi^0\chi_{cJ}$ is sensitive to its internal structure**
  - Expect small rate for a charmonium state – Enhanced for tetraquark or molecular state









Belle + Belle II analysis of $B^+ \to (\pi^0\chi_{cJ})K^+$

- *First evidence for $X(3872) \to \pi^0\chi_{c0}$ (3.4σ)*
- *BF disfavors pure charmonium interpretation, consistent with most predictions for four-quark state*

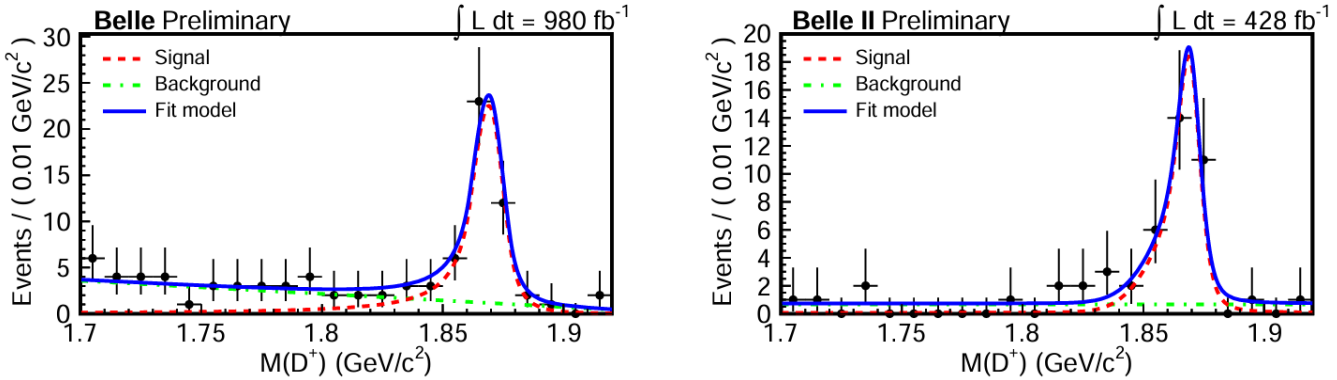
Rare decay

$D^+ \to \pi^+ e^+ e^-$

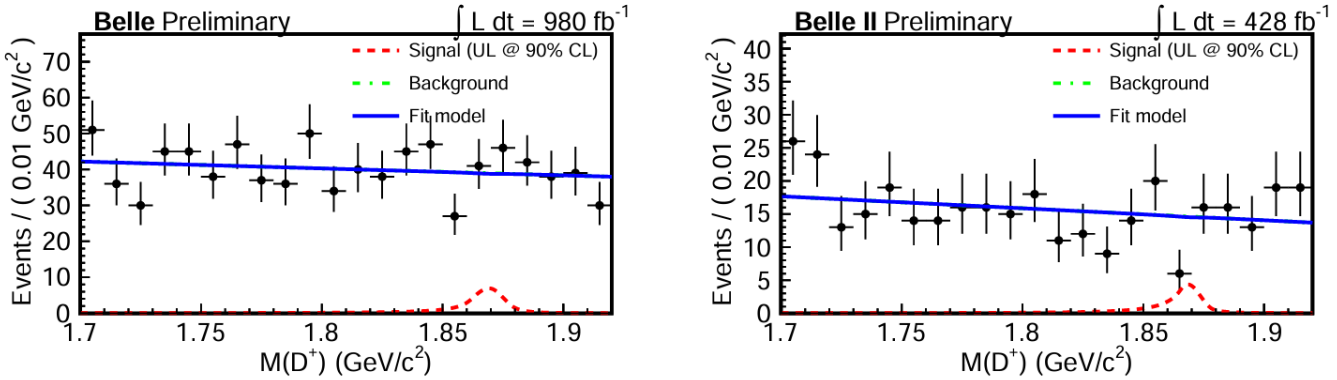
Preliminary result

- FCNC decay $c \to u\ell^+\ell^-$ suppressed in SM; proceeds via loop or box diagrams
  - SM long-distance contributions dominate near resonances: $\mathcal{B}(SM) \sim \mathcal{O}(10^{-6})$
  - BSM contributions may be comparable far from resonances: $\mathcal{B}(SM) \sim \mathcal{O}(10^{-12})$

$D^+ \to \pi^+ \phi(\to e^+ e^-)$



$D^+ \to \pi^+ e^+ e^-$



- Combined Belle and Belle II (1.4 /ab)

$$\mathcal{B}[D^+ \to \pi^+ \phi(\to e^+ e^-)] = (1.75 \pm 0.22 \pm 0.12) \times 10^{-6}$$

- Consistent with previous measurements
- Improved precision

$$\mathcal{B}(D^+ \to \pi^+ e^+ e^-) < 4.7 \times 10^{-7}\ (90\%\ C.L.)$$

- No significant signal obs.
- Comparable with babar UL.

Summary

- Belle II collected 575 fb^{-1} of data + Belle 1 ab^{-1}
- Belle (II) is a charm factory, allowing for unique studies for charm physics.
  - Spectroscopy, charmed baryons, charmonium,…
- So far only analyses included only up to about half of the Belle II dataset
  - Many more studies in the pipeline
  - Much more data to come
- Belle II will continue to produce exciting charm results in the future!

Thanks for your attention!

Backup

Comparison of available charm samples

Experiment	Machine	C.M.	Luminosity	$N_{\rm prod}$	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 ($8 \to 20$) fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7(\to 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	0.4 ($\to 50$) ab^{-1}	D^0: 6×10^8 ($\to 10^{11}$) $D^+_{(s)}$: 10^8 ($\to 10^{10}$) Λ_c^+: 10^7 ($\to 10^9$)		☺ high-efficiency detection of neutrals ☺ good trigger efficiency ☺ time-dependent analysis ☹ smaller cross-section than LHCb
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$D^{0,+}, D_s^+$: 10^9 Λ_c^+: 10^8 ★★☆	$\mathcal{O}$(1-10%) ★★	
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} ($\to 23 \to 50$) fb^{-1}	5×10^{12} 10^{13} ★★★★	★	☺ very large production cross-section ☺ large boost, excellent time resolution ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0@3.77\,\text{GeV})$=3.61 nb, $\sigma(D^+D^-@3.77\,\text{GeV})$=2.88 nb, $\sigma(D_s^*D_s@4.17\,\text{GeV})$=0.967 nb; $\sigma(c\bar{c}@10.58\,\text{GeV})$=1.3 nb where each $c\bar{c}$ event averagely has 1.1/0.6/0.3 $D^0/D^+/D_s^+$ yields; $\sigma(D^0@CDF)$=13.3 μb, and $\sigma(D^0@LHCb)$=1661 μb, mainly from *Int. J. Mod. Phys. A* **29***(2014)24,14300518*.

- BESIII, Belle II, and LHCb experiments have their advantages for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.

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

PRD 112, L031101 (2025)

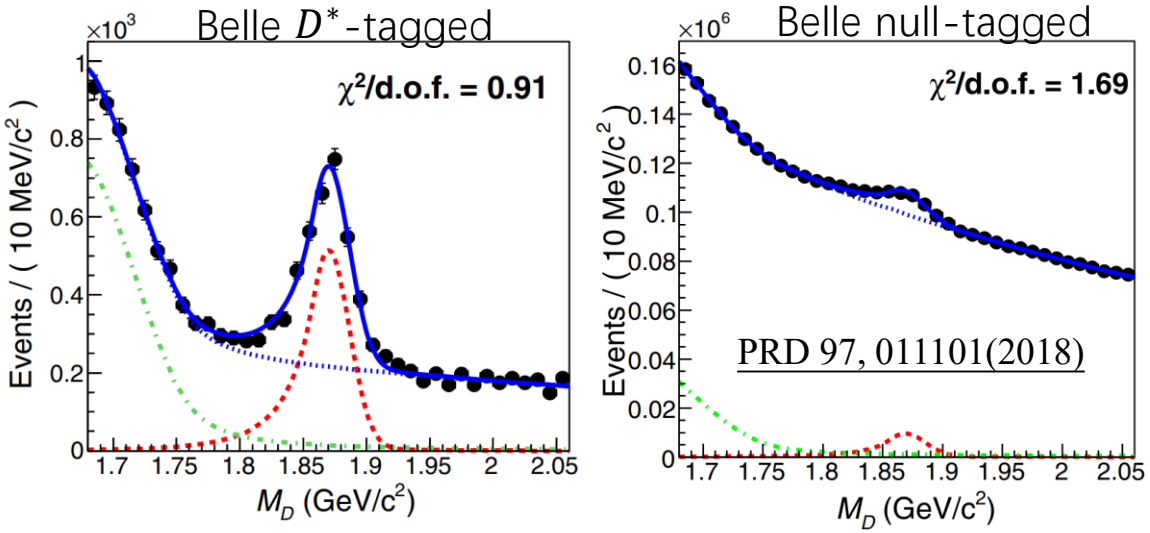
- A 3.8σ CPV in the pionic mode $D^0 \to \pi^+\pi^-$.
  - Unclear if observed CP violation can be described by the SM or not, due to large hadronic uncertainties

PRL 131, 051802 (2023) PRD 108, 036026 (2023) PRD 109, 033011 (2024)

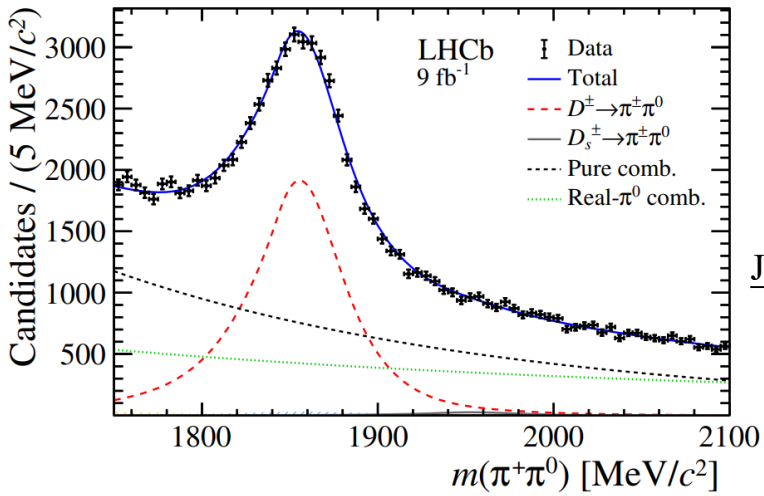
- Isospin-related modes $D^+ \to \pi^+\pi^0$ can reduce hadronic uncertainty.
- In addition, $D^+ \to \pi^+\pi^0$ $(I = 2)$ is expected to have no CPV in SM
  - since it does not receive QCD penguin $(\Delta I = 1/2)$ contribution and has suppressed electroweak penguin contribution.

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

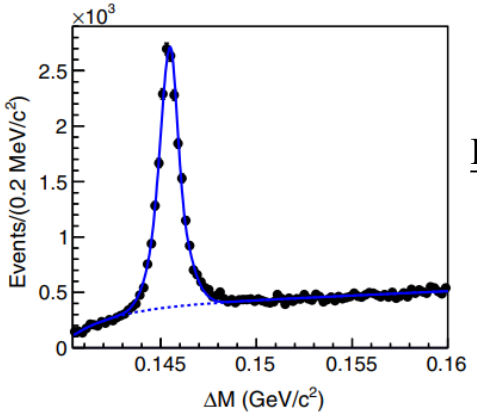


JHEP 06, 019 (2021)

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

PRD 112, 012006 (2025)

- 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 $D^0 \to K^0_S K^0_S$

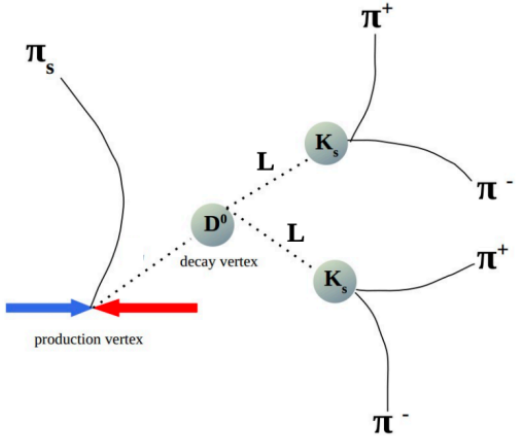
PRD 111, 012015 (2025)

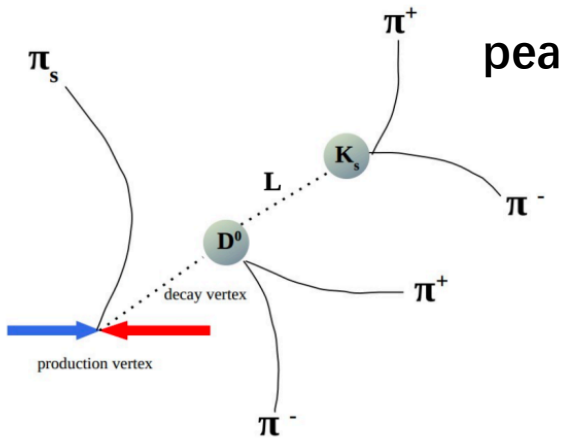
$A_{CP}(D^0 \to K^0_S K^0_S)$ using D^*-tagged sample

- Measure $A_{CP}(D^0 \to K^0_S K^0_S)$ based on $D^{*+} \to D^0 \pi^+_s$ sample at Belle + Belle II (1.4 /ab).

- $A_{CP}^{K^0_S K^0_S} = (A_{raw}^{K^0_S K^0_S} - A_{raw}^{K^+K^-}) + A_{CP}^{K^+K^-}$ assuming nuisance asymmetries are made identical by kinematics weighting.

- Main background from same-final-state $D^0 \to K^0_S \pi^+ \pi^-$ decays. Separate with K^0_S flight distance significance L/σ: $S_{min}(K^0_S)$ = log[min(L1/σ1, L2/σ2)].





peaking background

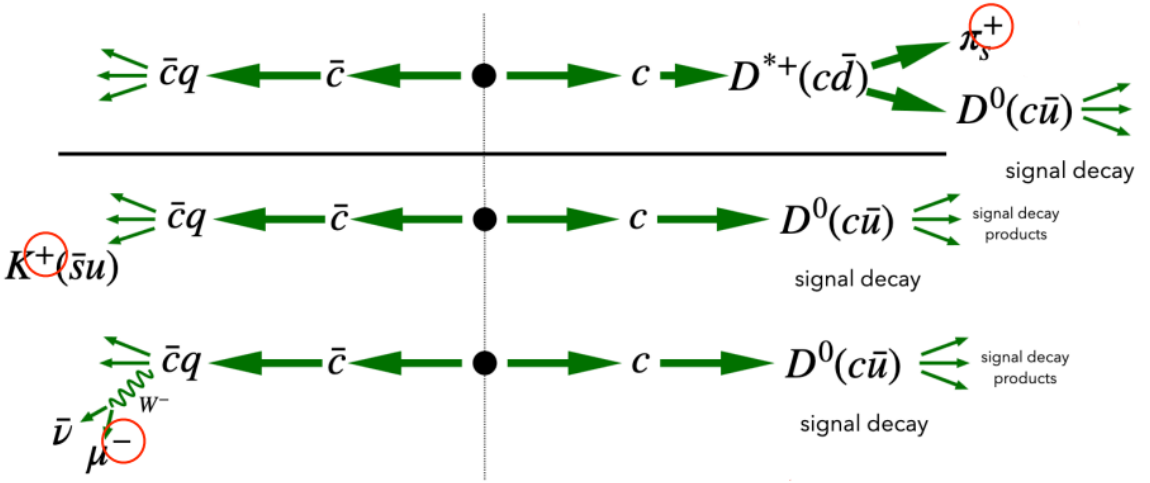
CP asymmetry in $D^0 \to K^0_S K^0_S$

PRD 112, 012017 (2025)

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

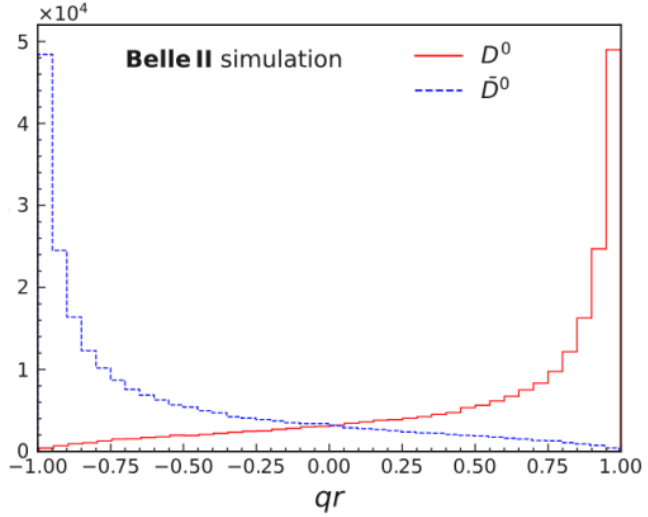
PRD 107, 112010 (2023)

- 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 $r = 1\text{-}2\omega$. 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 $D^0 \to K^0_S\pi^+\pi^-$ significantly.



CPV in $D \to \pi\pi$

- $D^0 \to \pi^+\pi^-$:
  - the only channel with > 3σ evidence of CPV in charm.
  - The SM generates CPV through interference of a tree-level and suppressed QCD loop amplitude ΔI = 1/2 (I = isospin) [*Pys. Rev.D 85, 114036 (2012)*].

- $D^+ \to \pi^+\pi^0$:
  - I= 2 and can be reached from the I= 1/2 initial state only via a ΔI = 3/2 transition.
  - Therefore, any observation will confirm New Physics.

- $D^0 \to \pi^0\pi^0$:
  - Can have I=0 or I=2 and hence can have nonzero direct CP asymmetries in SM.
  - Isospin sum rule:

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

  - $a_{CP} \neq 0$, $R=0$: CP violation from the ΔI= 3/2 amplitude (New Physics!!)
  - $R = (0.93 \pm 3.1) \times 10^{-3}$, uncertainty is dominated by the $\pi^0\pi^0$ mode *HFLAV*

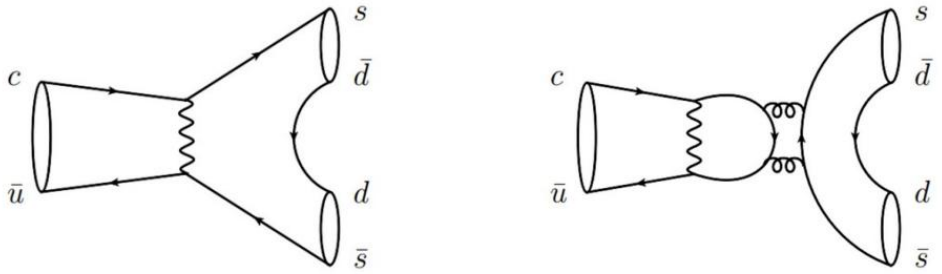
$D^0 \to K_S^0 K_S^0$

PRD 111, 012015 (2025)
PRD 112, 012017 (2025)

- The CP asymmetry (SCS)

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

- 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)