Charm Physics at Belle II

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第五届强子与重味物理理论与实验联合研讨会
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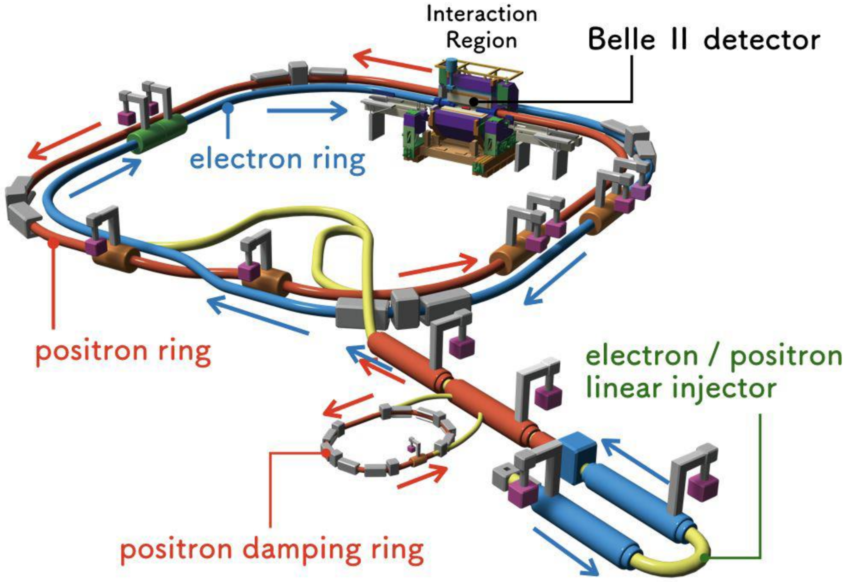
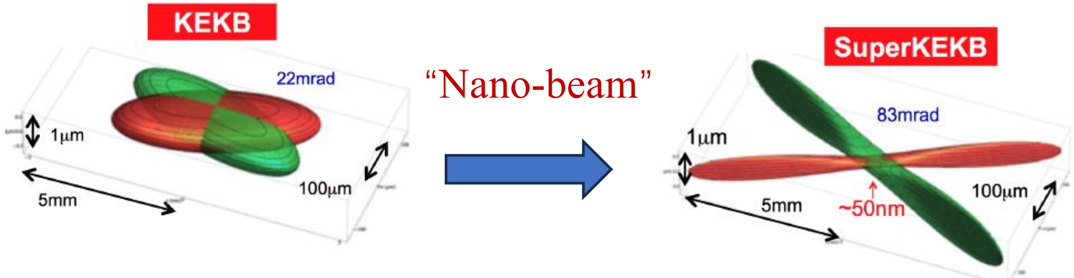
SuperKEKB and Belle II

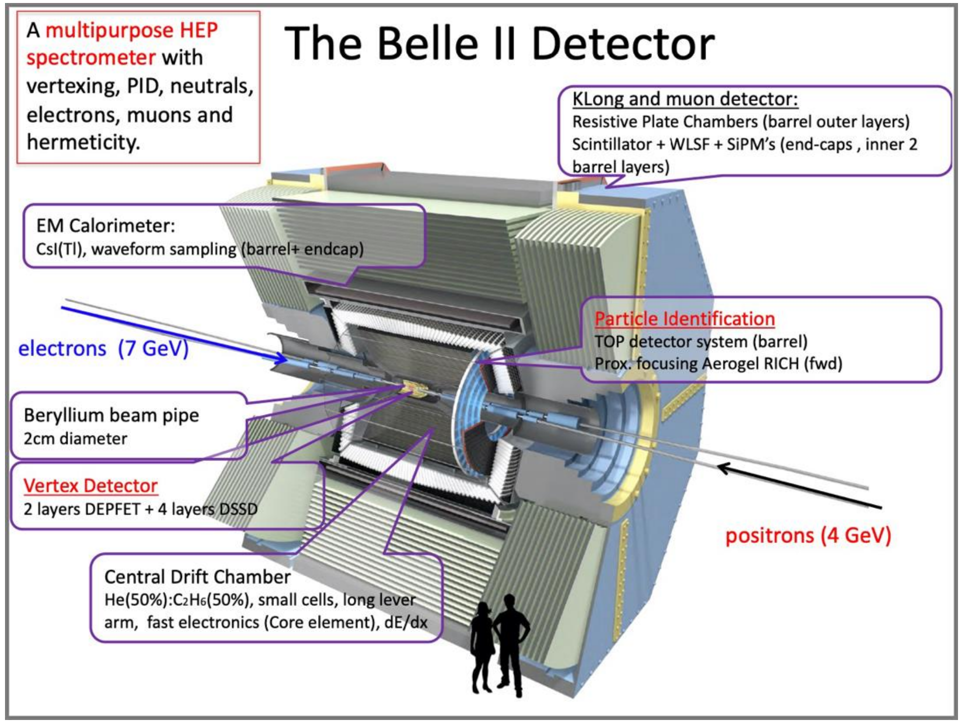
- SuperKEKB: upgrade of asymmetric e^+e^- collider KEKB with e^+ (e^-) beam energy at 4.0 (7.0) GeV.

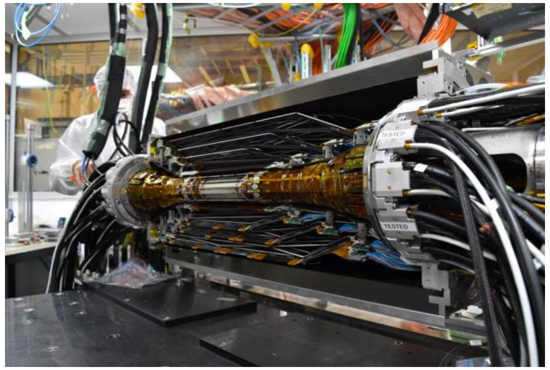




Nano-beam design:
Beam squeezing: ×20 smaller; Beam current: ×2 larger
Target peak luminosity: **KEKB ×30**

- Belle II: upgrade of Belle detector at the IP of SuperKEKB.

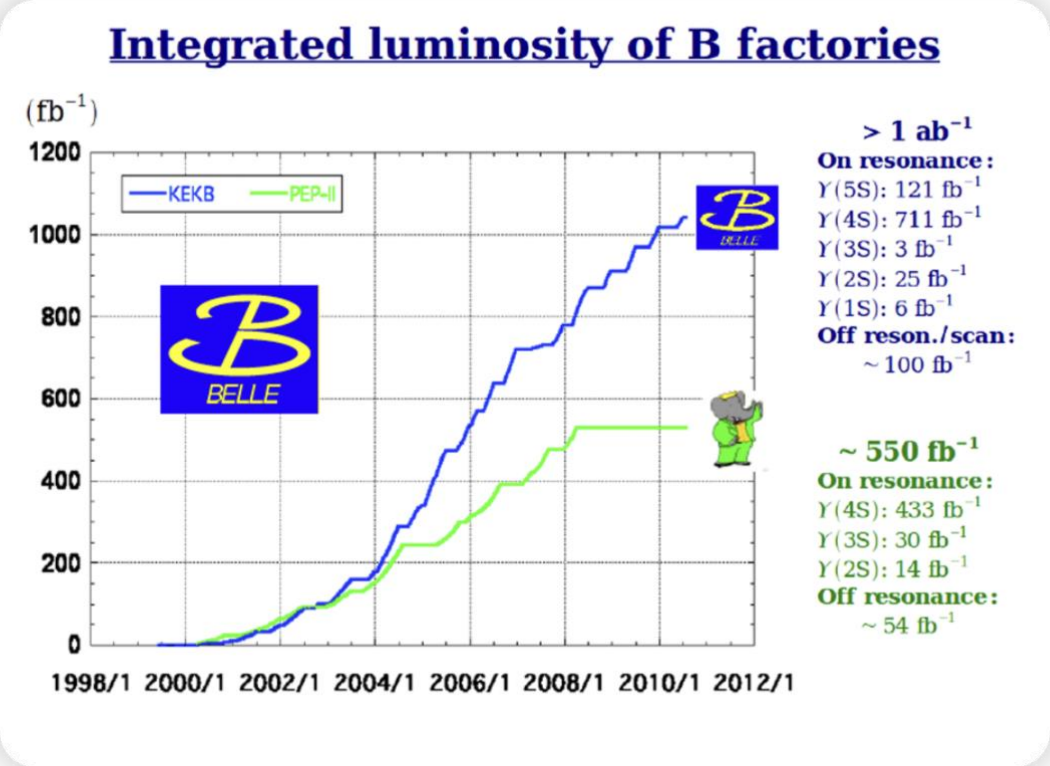




New detectors: vertexing detectors (PXD, SVD), tracking and PID systems (CDC, TOP, ARICH)

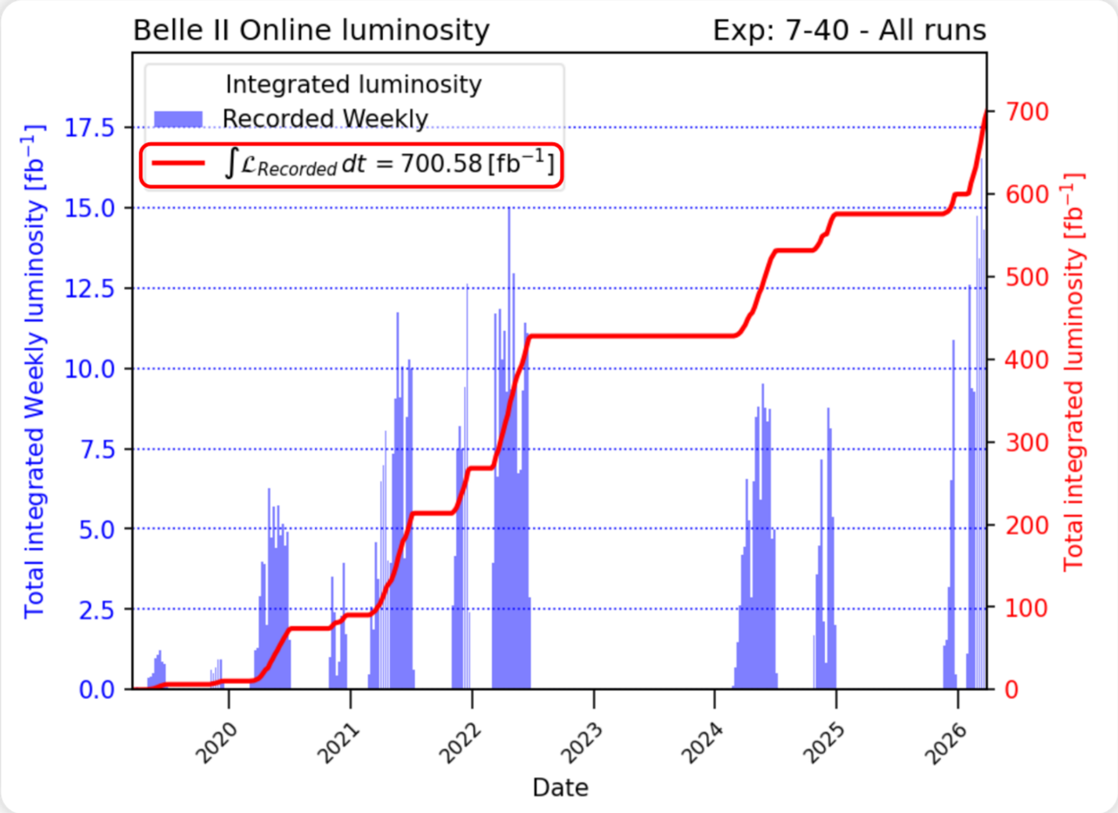
Belle and Belle II datasets

Belle (1999 - 2010)



Belle II: RUN-I (2019 - 2022); RUN-II (2024 - now)

New peak luminosity :
$\mathcal{L} = 5.24 \times 10^{34} cm^{-2} s^{-1}$ (March 19, 2026)

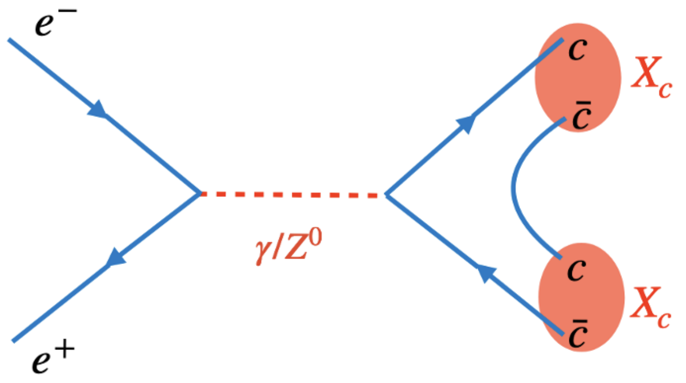


From Feb. 2026 to the present, a total of >100 fb^{-1} of data has been accumulated.

Charm production at Belle II

Two ways of producing charm at B-factories.

Two charmed hadrons produced from continuum

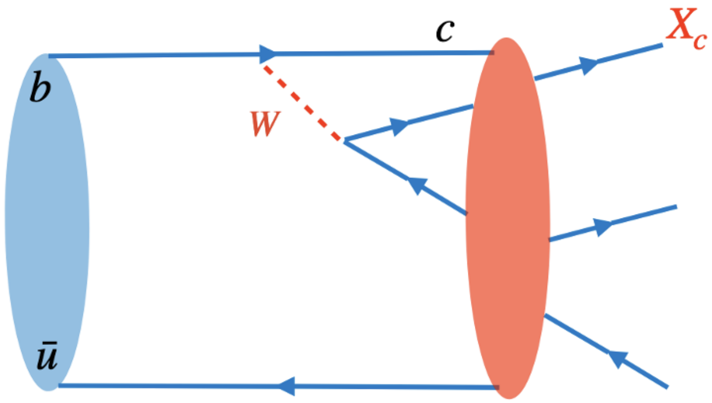


Large statistics but high level background

Only relative branching fractions can be measured
Absolute values obtained using external inputs

$$\sigma(e^+e^- \to c\bar{c}) \sim 1.3\text{nb}$$

One or more charmed hadrons produced in B decays



Low statistics but very clean sample

Absolute branching fractions can be obtained:
cross section of $B\bar{B}$ precisely measured

$$\sigma(e^+e^- \to \Upsilon(4S)) \sim 1.05\text{nb}$$

$$\mathcal{B}(B \to \Lambda_c^+ + X) \sim 10^{-2}$$

All the results presented today are derived from continuum processes.

CPV in Charm

How do we measure A_{CP}?

We want

$$A_{CP}(D \to f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

We measure

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

related by

$$A_{raw}^{sig} = A_{CP}^{sig} + A^{det} + A^{prod}$$

To subtract these effects, we measure A_{CP} in another control channel (*cc*) where it's either known or expected to be zero

$$A_{raw}^{cc} = A_{CP}^{cc} + A^{det} + A^{prod}$$

→ known or null

→ can also remove averaging on D production angle θ^*

and measure the signal A_{CP} as

$$A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{cc} + A_{CP}^{cc}$$

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

- $D^0 \to \pi^+\pi^-$
  - The only channel with $> 3\sigma$ evidence of *CPV* in charm [PRL 131, 091802 (2023)].
  - The SM generates *CPV* through interference of a tree-level and suppressed QCD loop amplitude $\Delta I = 1/2$ (I=isospin) [PRD 85, 114036 (2012)].
- $D^+ \to \pi^+\pi^0$
  - $I = 2$ and can be reached from the $I = 1/2$ initial state only via a $\Delta I = 3/2$ transition.
  - In SM, no direct *CPV* is expected.
- $D^0 \to \pi^0\pi^0$
  - Can have $I = 0$ or $I = 2$ and hence can have nonzero direct *CP* asymmetries in SM.

✓ The following sum-rule for *CPV* in $D \to \pi\pi$ decays; it helps to determine the source of *CPV:*

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

- ✓ if $R \neq 0$, *CPV* from $\Delta I = 1/2$ amplitude.
- ✓ If $R = 0$ and at least one $A_{CP}^{dir} \neq 0$, *CPV* from a beyond-SM $\Delta I = 3/2$ amplitude.
- ✓ $R = (0.9 \pm 3.1) \times 10^{-3}$, uncertainty is dominated by $D^0 \to \pi^0\pi^0$ mode.

[EPJC 83, 279 (2023); PRD 107, 052008 (2023)]

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

- In SM, the no *CPV* is expected in $D^+ \to \pi^+\pi^0$ decay.
- Utilizing split sample: D^+ from $D^{*+} \to D^+\pi^0$ decay or not.

[PRD 112, L031101 (2025)]

Signal mode

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

Control mode: $D^+ \to \pi^+ K_S^0$

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

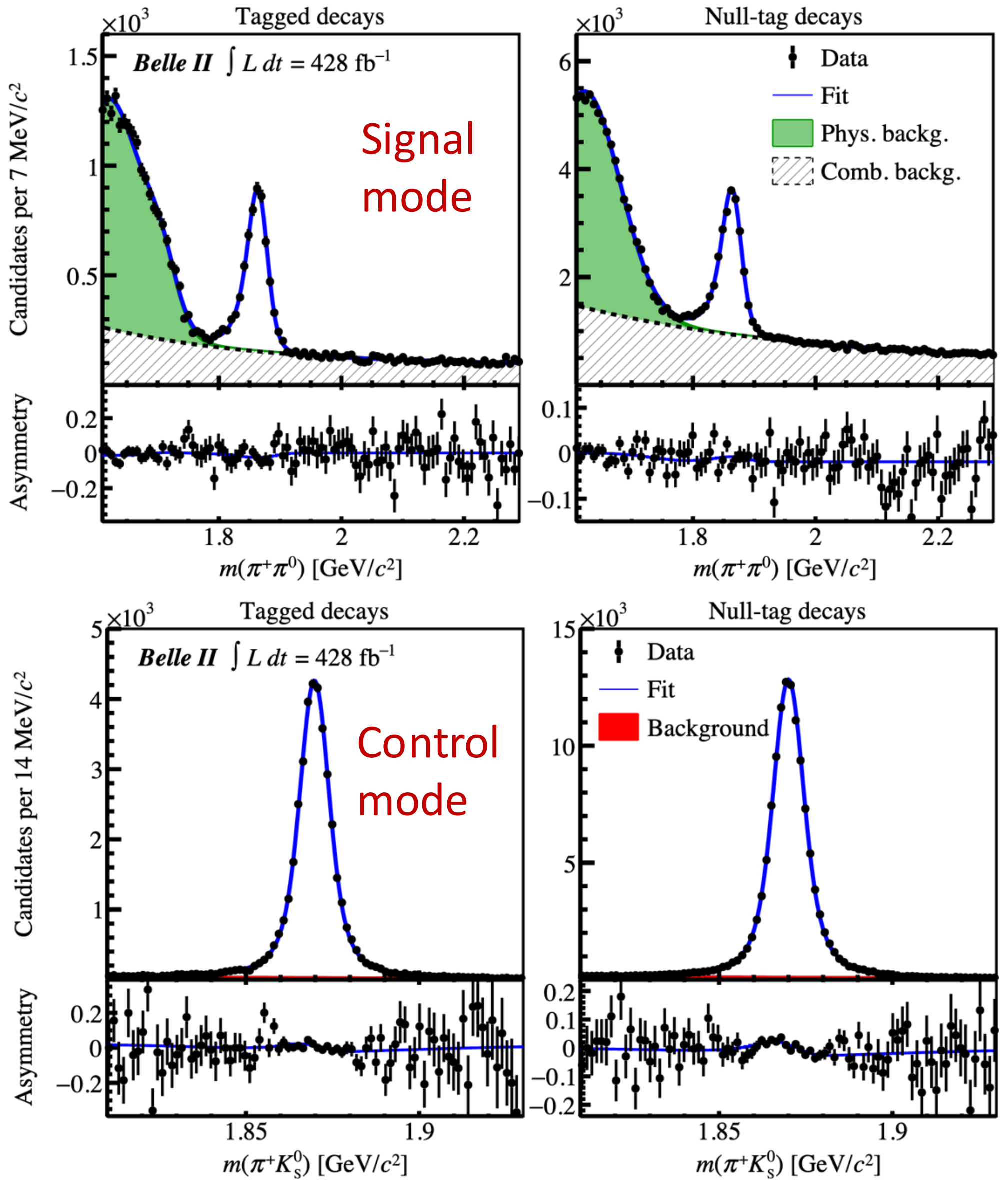
- Using 428 fb^{-1} data, Belle II obtains

$A_{CP} = (-3.9 \pm 1.8 \pm 0.2)\%$ For D^{*+} − tagged sample

$A_{CP} = (-1.1 \pm 1.0 \pm 0.1)\%$ For null−tag sample

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

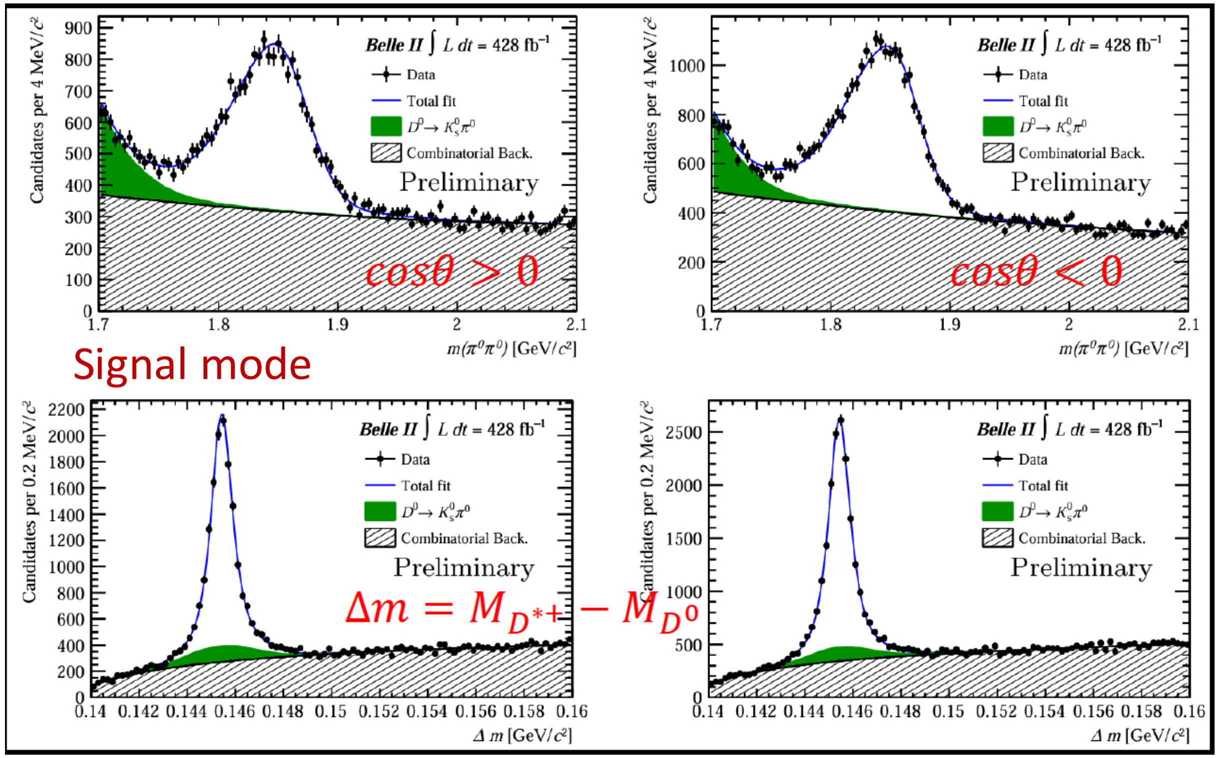
30% improved precision compared to Belle (921 fb^{-1}): $(+2.31 \pm 1.24 \pm 0.23)\%$ [PRD 97, 011101 (2018)].

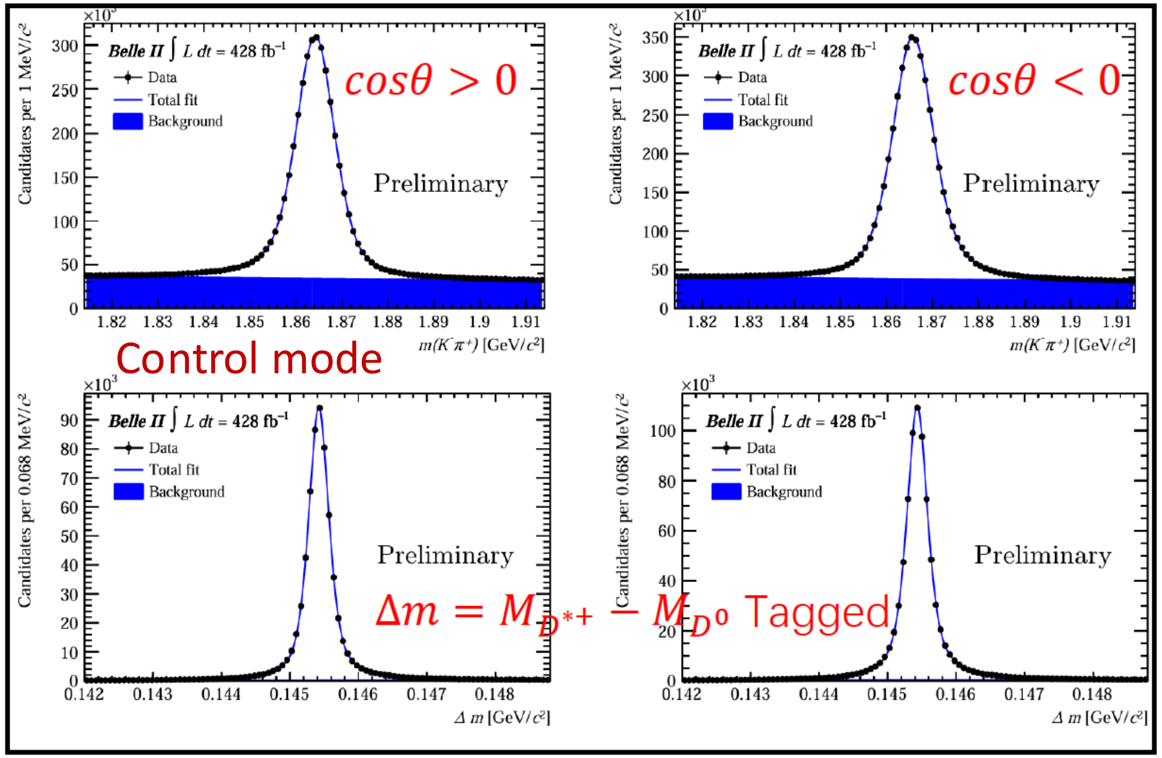


$A_{CP}(D^0 \to \pi^0\pi^0)$

- The D^0 decays are required to originate from the flavor-conserving $D^{*+} \to D^0\pi^+$ decay.
- Taking $D^0 \to K^-\pi^+$ samples as control channel.

[PRD 112, 012006 (2025)]





- Result at Belle II (428 fb^{-1}):

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

➢ Consistent with *CP* symmetry and with Belle (980 fb^{-1}): $(-0.03 \pm 0.64 \pm 0.10)\%$ [PRL 112, 211601 (2014)].

➢ 15% less precise than Belle, but with < 50% datasets.

- Using our result, $A_{CP}^{\pi^+\pi^-}$(LHCb), W.A. $A_{CP}^{\pi^+\pi^0}$, ΔY(LHCb), W.A. $\mathcal{B}$ and D lifetimes,

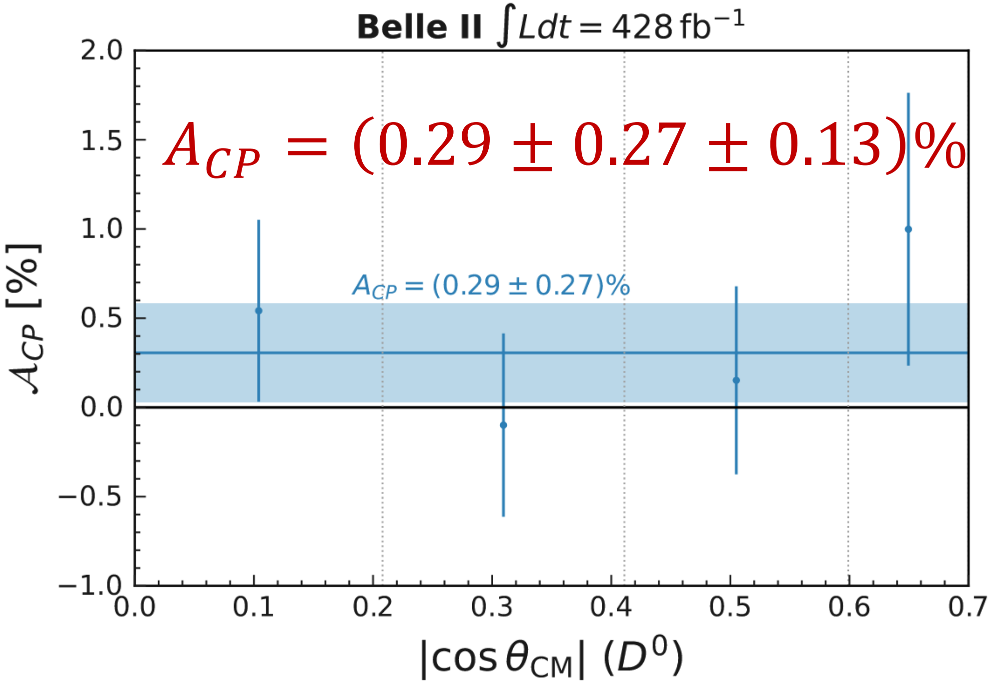
  $R = (1.5 \pm 2.5) \times 10^{-3}$

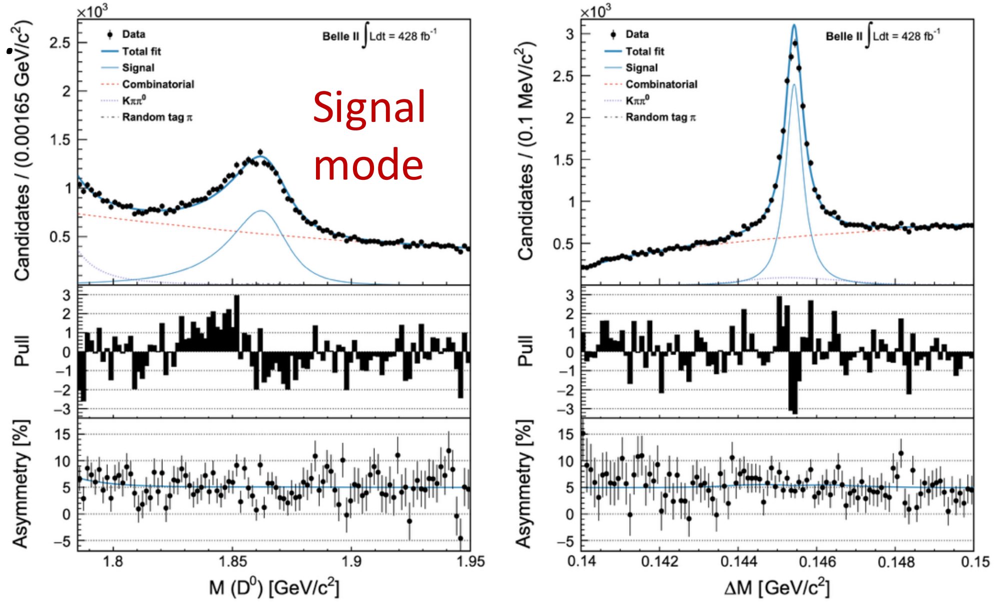
  20% improved precision

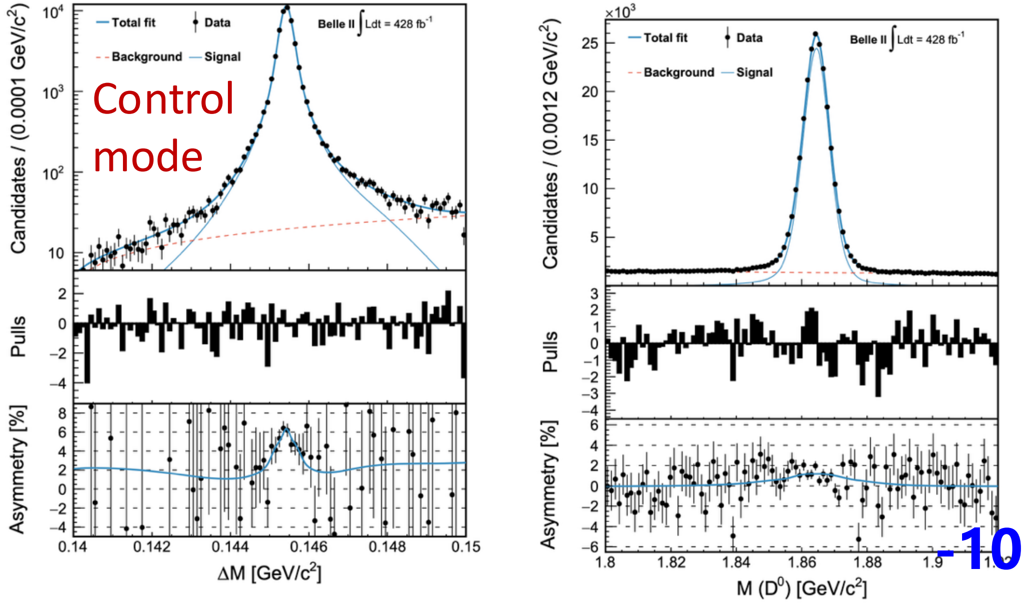
$A_{CP}(D^0 \to \pi^+\pi^-\pi^0)$

- The D^0 mesons are required to originate from the $D^{*+} \to D^0\pi^+_{tag}$.
- Using tagged and untagged $D^0 \to K^-\pi^+$ to eliminate common asymmetry sources.
- The data are divided into eight $\cos\theta_{CM}$ bins to cancel the production asymmetry.

[PRD 113, 052006 (2026)]





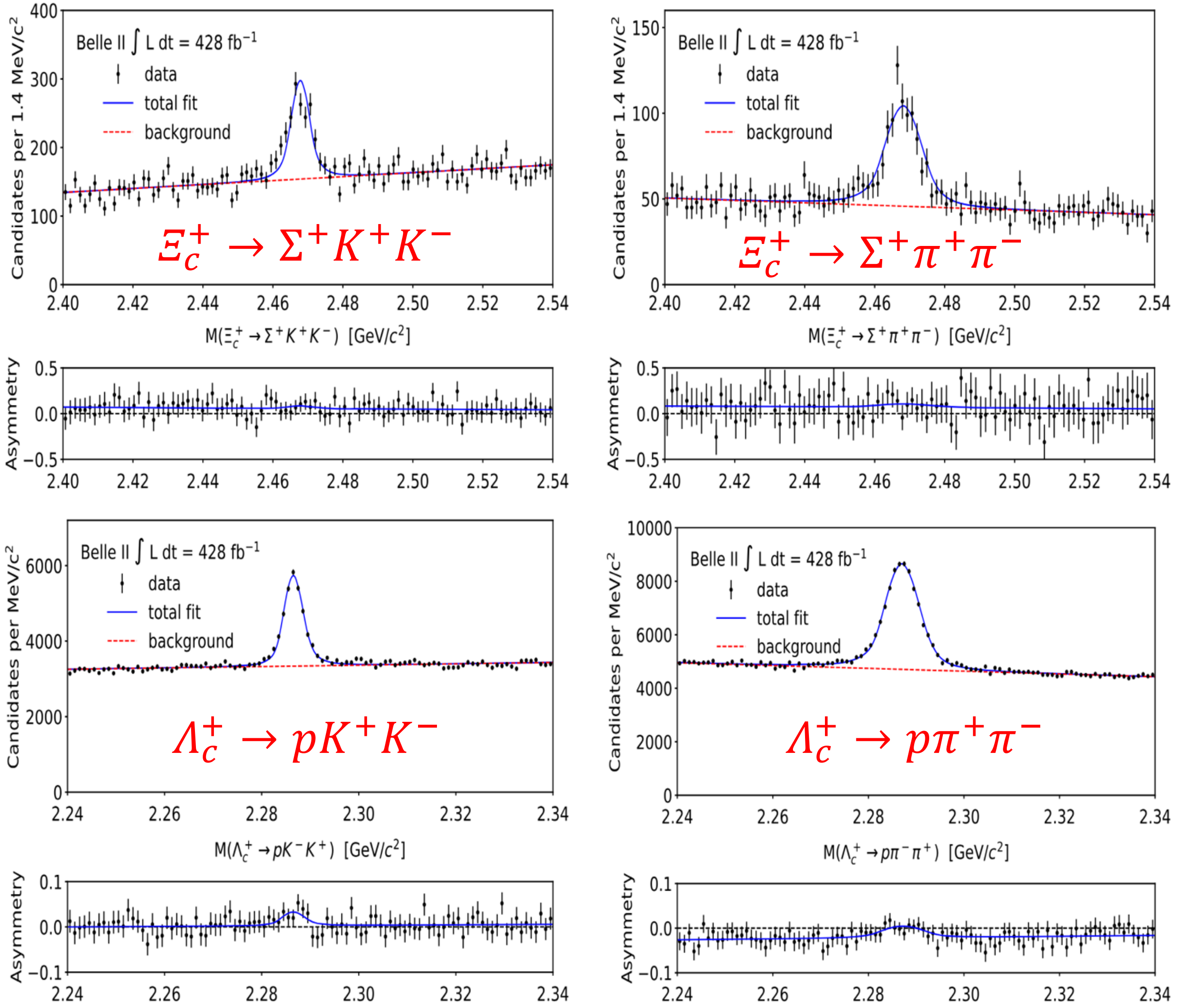


34% improved precision compared to Babar (385 fb^{-1}): $(0.31 \pm 0.41 \pm 0.17)\%$[PRD 78, 051102 (2008)].

$A_{CP}(\Xi_c^+ \to \Sigma^+ h^+ h^-, \Lambda_c^+ \to p h^+ h^-)$

- First measurement of A_{CP} in singly-Cabibbo-suppressed three-body charmed baryon decays.
- Taking $\Lambda_c^+ \to \Sigma^+ h^+ h^-$, $\Lambda_c^+ \to p\pi^+ K^-$, and $D^0 \to K^-\pi^+\pi^+\pi^-$ as control channels.
- Using 428 fb^{-1} data, Belle II obtains

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



- Test U-spin sum rules:

$$A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) + A_{CP}(\Lambda_c^+ \to p K^+ K^-) = (13.4 \pm 7.0 \pm 0.9)\%$$
$$A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) + A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) = (4.0 \pm 6.6 \pm 0.7)\%$$

[PRD 113, 032017 (2026)]

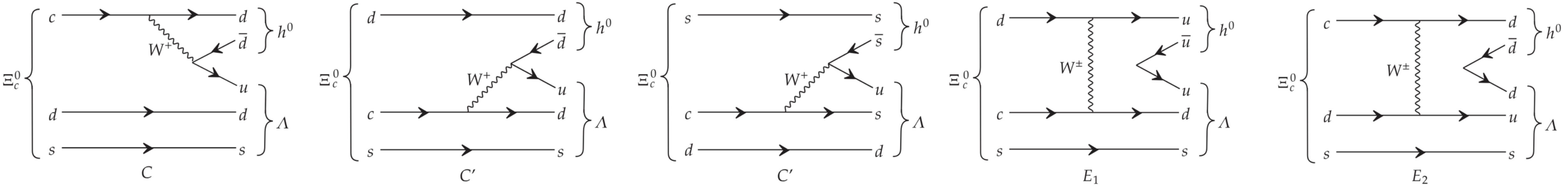
Summary of *CPV* in charm

Channel	A_{CP}	References
$D^+ \to \pi^+\pi^0$	$(-1.8 \pm 0.9 \pm 0.1)\%$	PRD 112, 012006 (2025)
$D^0 \to \pi^0\pi^0$	$(+0.30 \pm 0.72 \pm 0.20)\%$	PRD 97, L031101 (2025)
$D^0 \to \pi^+\pi^-\pi^0$	$(+0.29 \pm 0.27 \pm 0.13)\%$	PRD 113, 052006 (2026)
$D^0 \to K_S^0 K_S^0$	$(-0.6 \pm 1.1 \pm 0.1)\%$	PRD 111, 012015 (2025) PRD 112, 012017 (2025)
$D^+, D_s^+ \to K_S^0 K^-\pi^+\pi^+$	$(+3.9 \pm 4.5 \pm 1.1)\%$, $(-0.2 \pm 2.5 \pm 1.1)\%$	JHEP 04 (2025) 036
$\Lambda_c^+ \to \Lambda K^+$, $\Sigma^0 K^+$	$(+2.1 \pm 2.6 \pm 0.1)\%$, $(+2.5 \pm 5.4 \pm 0.4)\%$	Sci. Bull. 68 (2023) 583
$\Lambda_c^+ \to pK^+K^-$, $\Lambda_c^+ \to p\pi^+\pi^-$	$(+3.9 \pm 1.7 \pm 0.7)\%$, $(+0.3 \pm 1.0 \pm 0.2)\%$	PRD 113, 032017 (2026)
$\Xi_c^+ \to \Sigma^+K^+K^-$, $\Xi_c^+ \to \Sigma^+\pi^+\pi^-$	$(+3.7 \pm 6.6 \pm 0.6)\%$, $(+9.5 \pm 6.8 \pm 0.5)\%$	PRD 113, 032017 (2026)

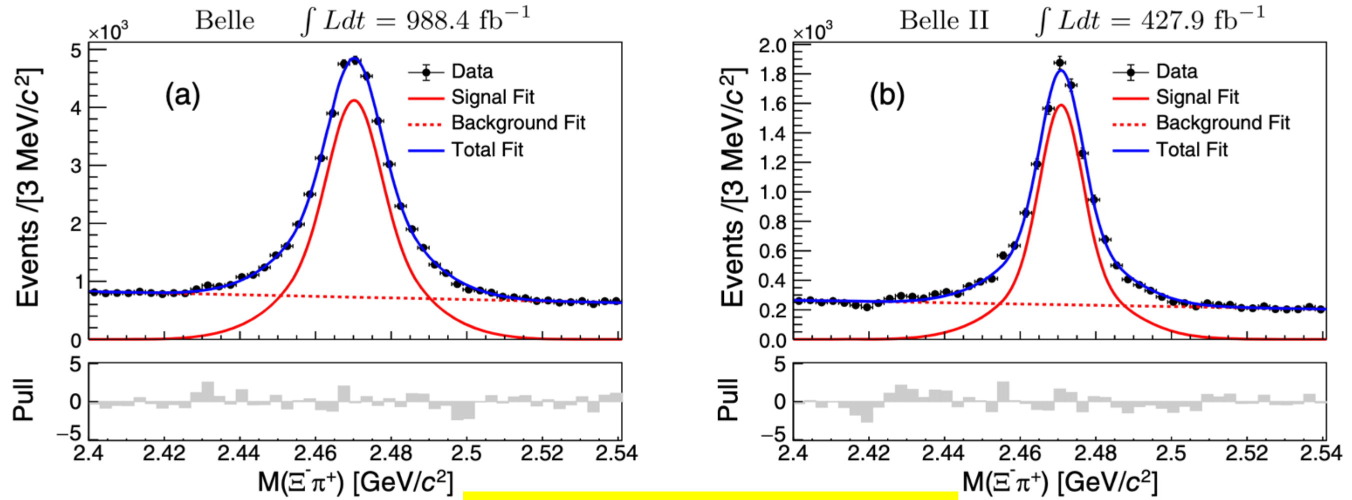
Charm hadron decays

Ξ_c^0 and Ξ_c^+ decays

- Decay amplitudes of charmed baryons receive contribution from factorizable and non-factorizable terms,
  - e.g. *W*-emission and *W*-exchange that indroduce significant challenges in theoretical calculation



- The absolute $\Xi_c^{0,+}$ yields are not well known, relative branching fractions are measured using $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ as reference channels.



[PRD 113, 032015 (2026)]

$$\frac{\mathcal{B}_{\mathrm{sig}}}{\mathcal{B}_{\mathrm{ref}}} = \frac{\mathrm{N_{sig}} \times \epsilon_{\mathrm{ref}}}{\mathrm{N_{ref}} \times \epsilon_{\mathrm{sig}}}$$

$$\mathcal{B}_{\mathrm{ref}}(\Xi_c^0 \to \Xi^-\pi^+) = (1.80 \pm 0.52)\%$$

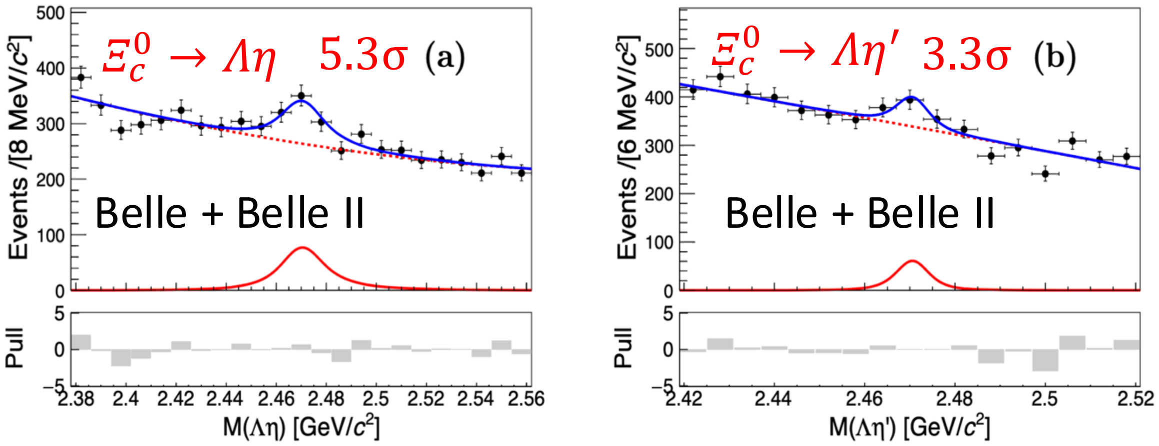
$$\mathcal{B}_{\mathrm{ref}}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (2.9 \pm 1.3)\%$$

[PRL 122, 082001 (2019); PRD 100, 031101 (2019)]

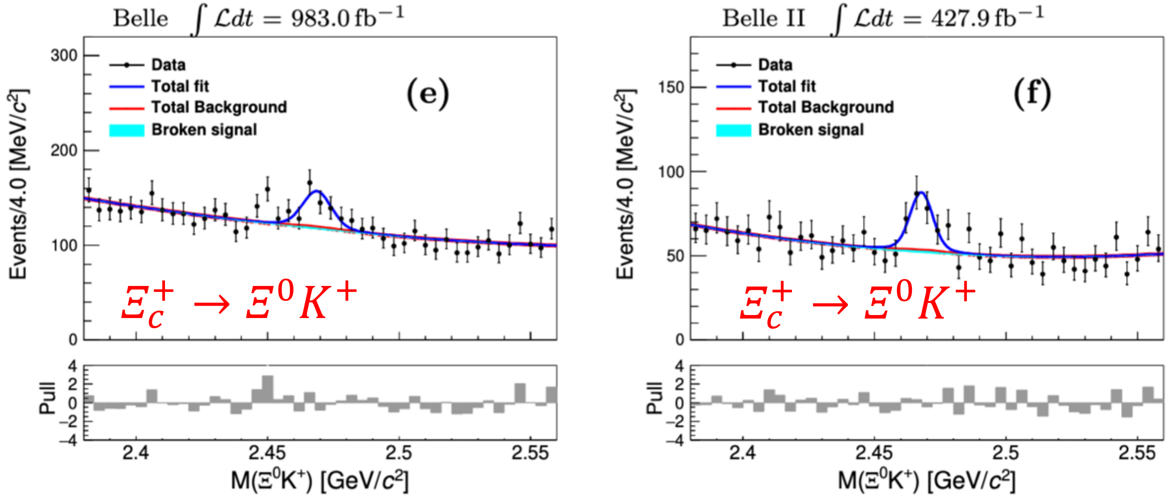
Ξ_c^0 and Ξ_c^+ decays

- Using combined Belle and Belle II data ($1.4\ \mathrm{ab}^{-1}$), many two-body hadronic decays of Ξ_c^0 and Ξ_c^+ are measured.

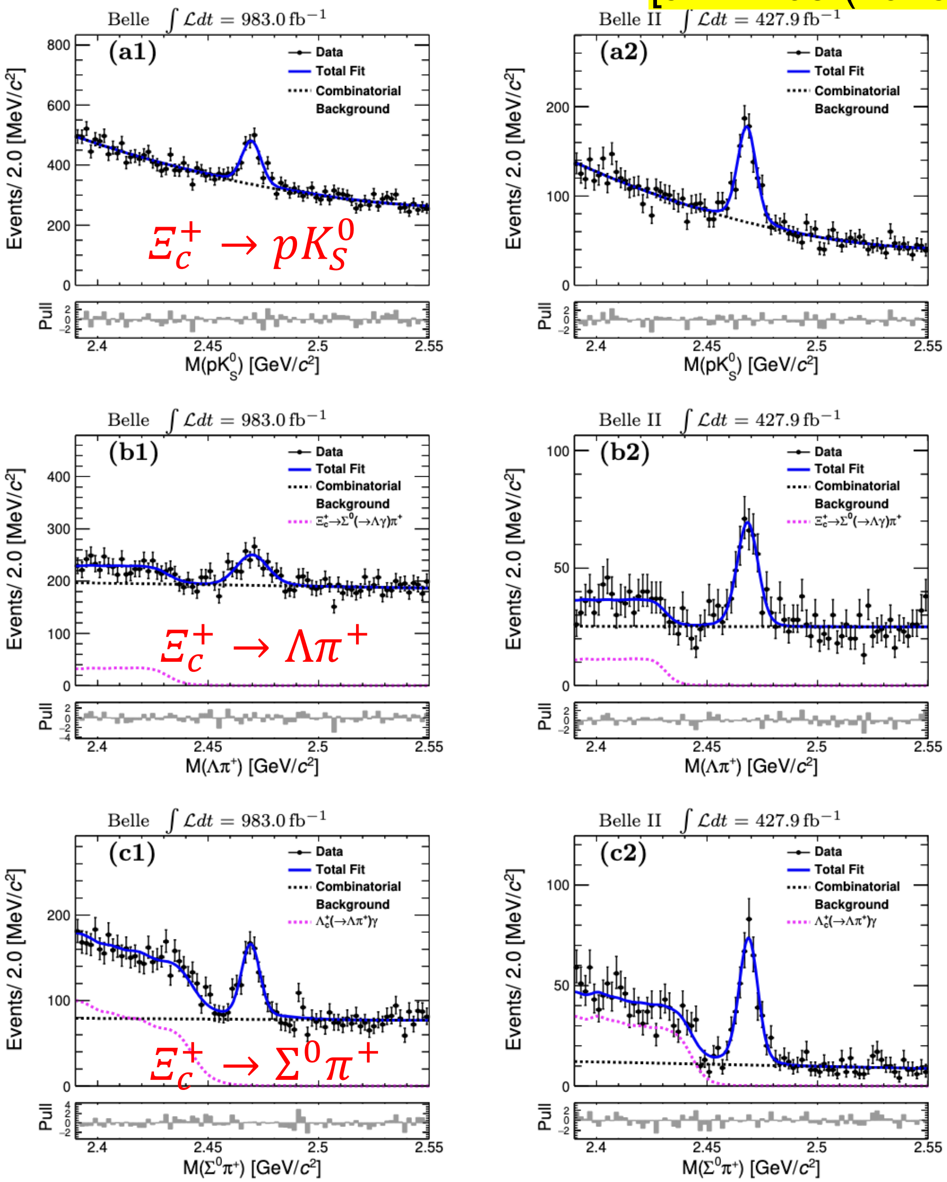
[PRD 113, 032015 (2026)]



[JHEP 08 (2025) 195]



[JHEP 03 (2025) 061]

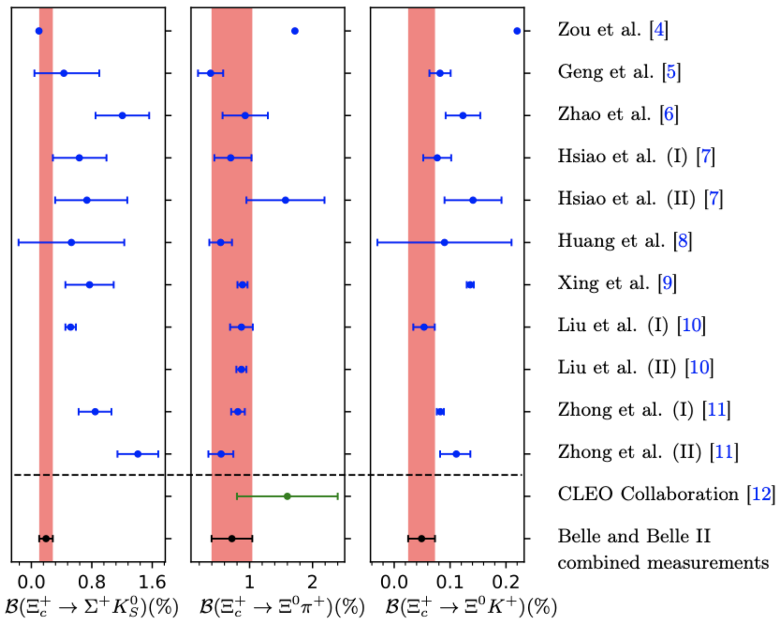


Ξ_c^0 and Ξ_c^+ decays

First or most precise measurements of branching fractions!

- These measurements serve as experimental inputs to constrain and test the quark model, the pole model (Pole), current algebra (CA), and SU(3) flavor symmetry.

JHEP 08 (2025) 195



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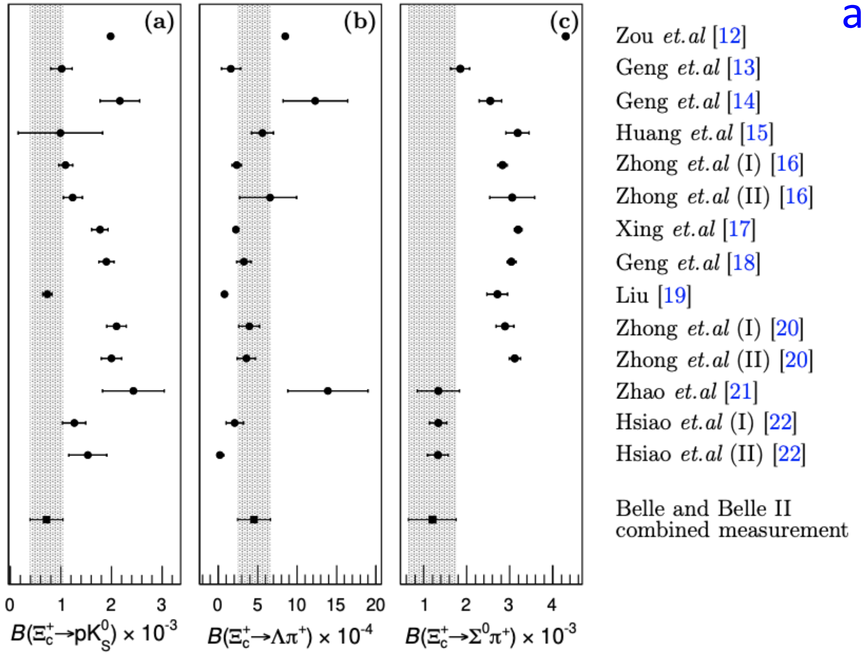
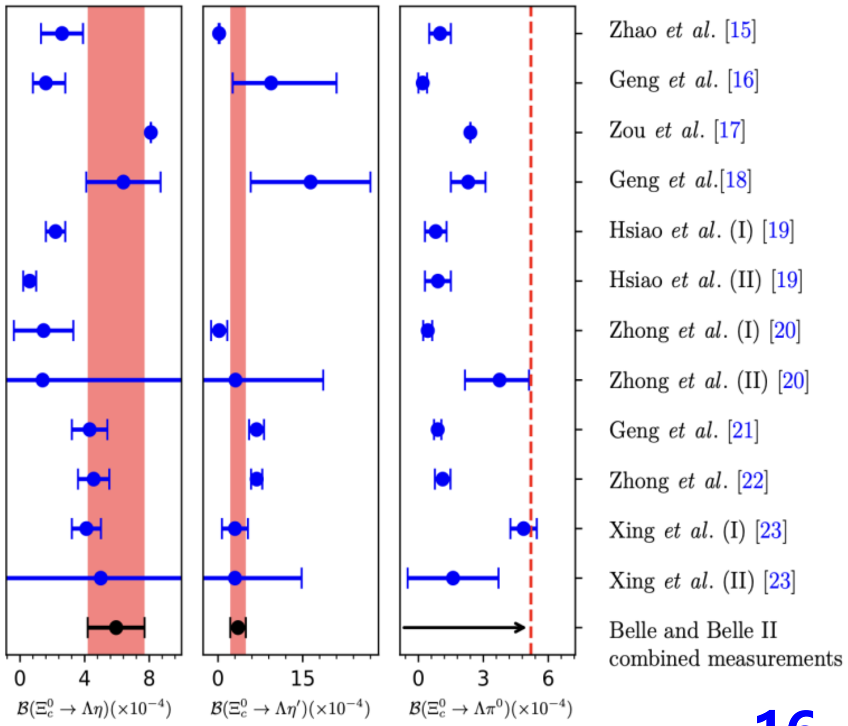


[PRD 113, 032015 (2026)]



Next steps:

1. Explore three-body decays;
2. Amplitude analyses to search for new intermediate states and identify J^P.

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

- The $D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0}$ was first observed by Babar in 2003 [PRL 90, 242001 (2003)].

$D_{s0}^{*}(2317)^{\pm}$ **DECAY MODES**

$D_{s0}^{*}(2317)^{-}$ modes are charge conjugates of modes below.

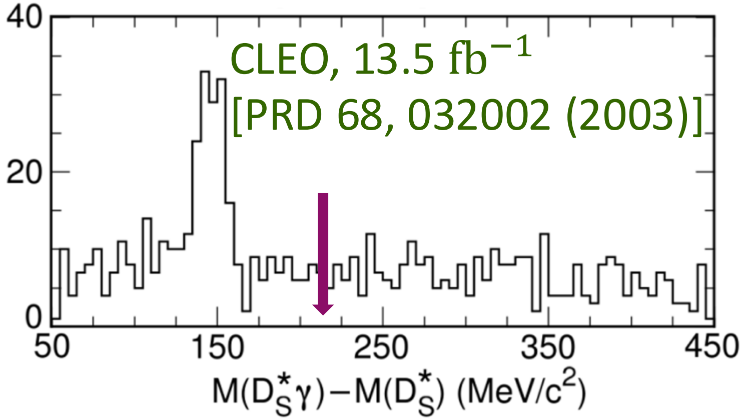
	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	(100^{+0}_{-20}) %		298
Γ_2	$D_s^+\gamma$	<5 %	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	<6 %	CL=90%	
Γ_4	$D_s^+\gamma\gamma$	<18 %	CL=95%	323
Γ_5	$D_s^*(2112)^+\pi^0$	<11 %	CL=90%	
Γ_6	$D_s^+\pi^+\pi^-$	$< 4 \times 10^{-3}$	CL=90%	194
Γ_7	$D_s^+\pi^0\pi^0$	not seen		205

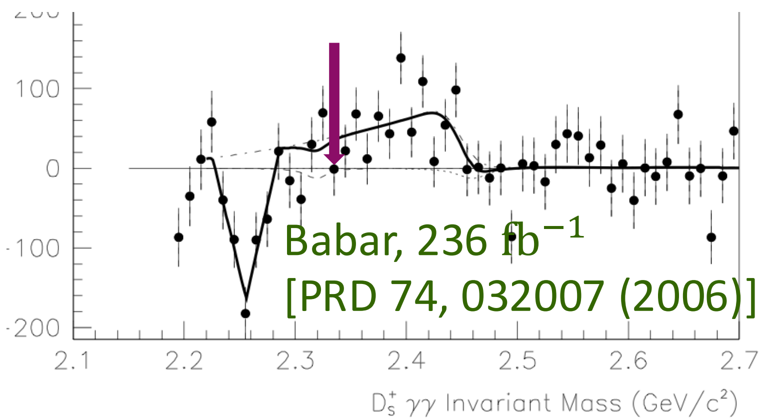
Mass of $D_{s0}^{*}(2317)^{+}$ is much lower than the quark model predictions of the lowest $c\bar{s}$ mesons with $J^P = 0^+$

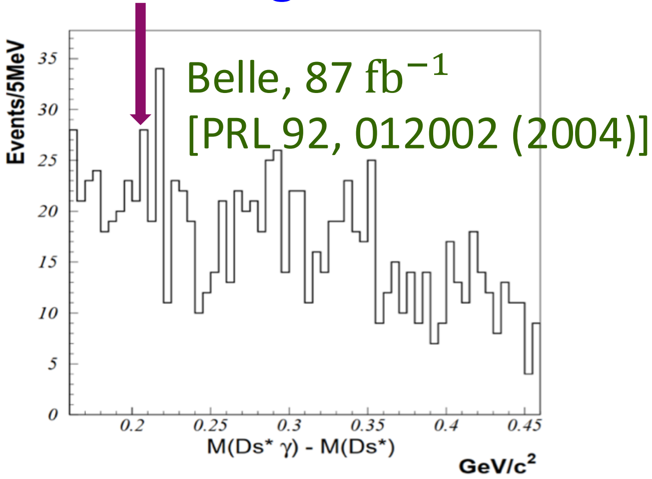
- Modifying the $c\bar{s}$ quark model
- D^*K hadronic molecule
- Compact tetraquarks
- Chiral partners of the ground states D_s^*

Partial decay widths:
unique in discriminating between various models

- The $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$ was searched from by CLEO, Belle, and Babar , but no signals were found.





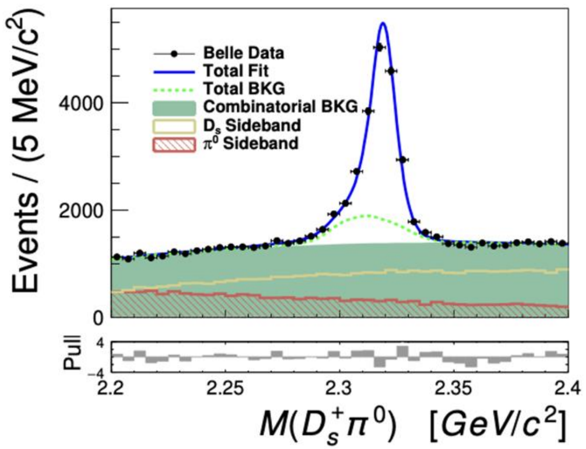


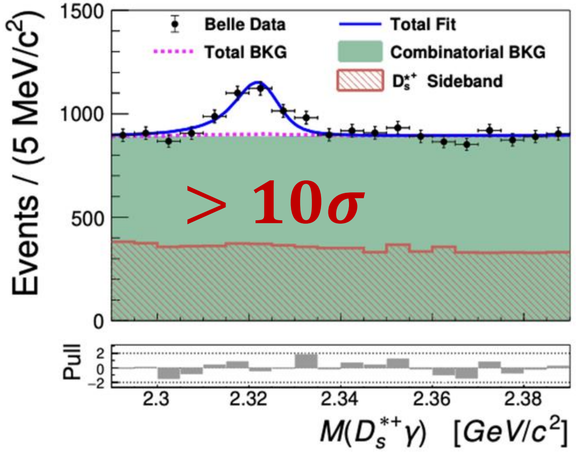
First observation of $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$

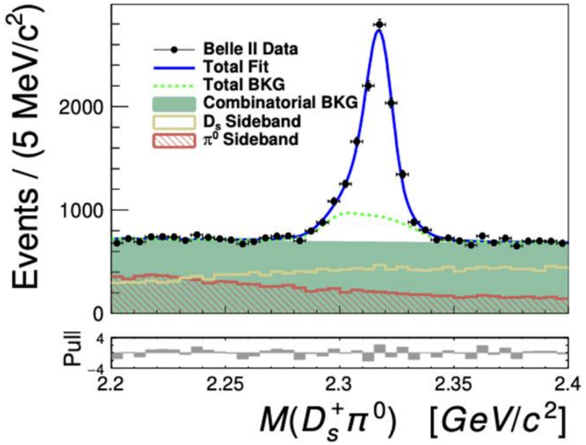
[arXiv: 2510.27174]

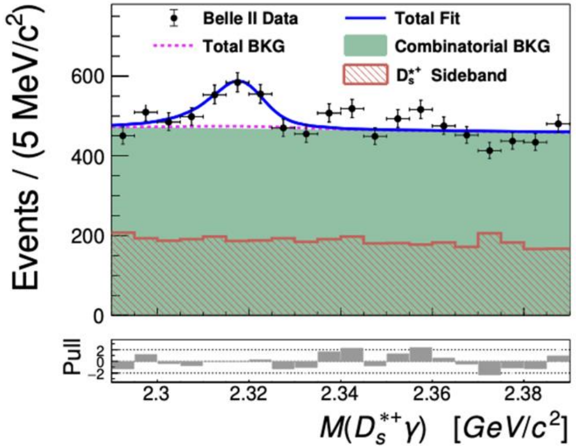
Using all Belle data (983 fb^{-1}) and Belle II data (428 fb^{-1})

- Target: $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$
- Control channel: $D_{s0}^*(2317)^+ \to D_s^+\pi^0$ [$\mathcal{B} = (100^{+0}_{-20})\%$]



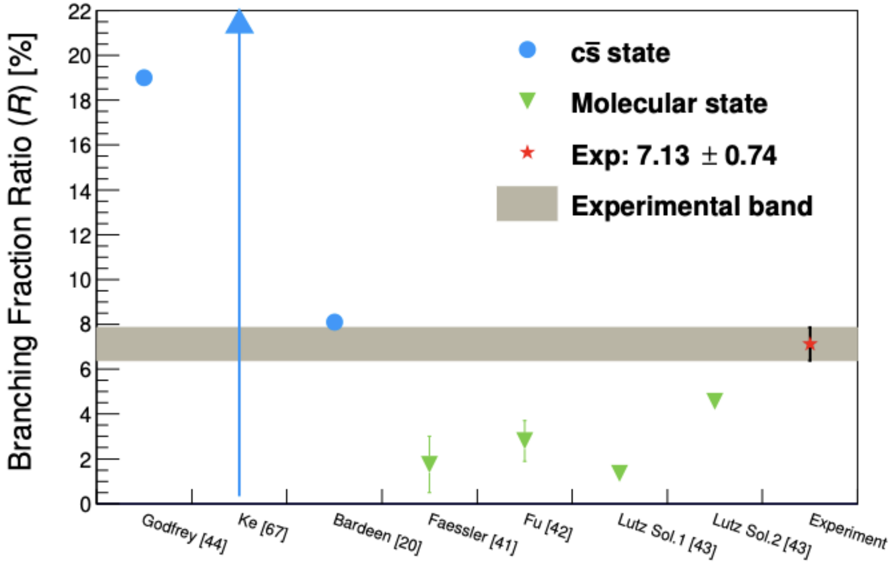






$$\mathcal{R} = \frac{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)}$$

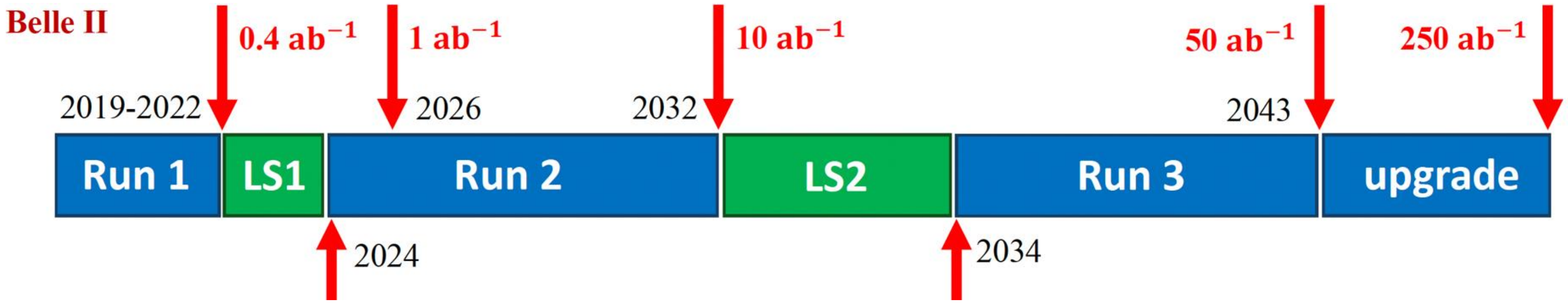
$$= [7.14 \pm 0.70(\mathrm{stat.}) \pm 0.23(\mathrm{syst.})]\%$$



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

Summary

- The Belle II physics program has strong potential for charm physics, especially in measurements of *CPV* in meson and baryon decays.
  —Belle and Belle II are actively producing and analyzing data jointly.
- The SuperKEKB accelerator continues to break world records for instantaneous luminosity. On Mar. 19, it achieved a peak luminosity of $5.24 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Belle II: new data + new vertex detectors + new software tools.
- Only 2% of target luminosity collected so far. Stay tuned for more exciting results from Belle II.



Thanks for your attention!

Backup

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**)

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

- 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.

Comparison of available charm samples

From Prof. Longke LI

Experiment	Machine	C.M.	Luminosity(fb^{-1})	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	20 7.3 4.5	$D^{0,+}$: 10^8 D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	$\sim$ 10-30% ★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	600 ($\rightarrow$ 50000)	D^0: 10^9 ($\rightarrow 10^{11}$) $D^+_{(s)}$: 10^8 ($\rightarrow 10^{10}$) Λ_c^+: 10^7 ($\rightarrow 10^9$)	$\mathcal{O}$(1-10%) ★★	☺ high-efficiency detection of neutrals ☺ good trigger efficiency ☺ time-dependent analysis ☹ smaller cross-section than LHCb
Belle	KEKB (e^+e^-)	10.58 GeV	1000	$D^{0,+}$, D_s^+: 10^9 Λ_c^+: 10^8 ★★☆		
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 6+9 ($\rightarrow$ 23 $\rightarrow$ 50)	5×10^{12} 10^{13} ★★★★	$\mathcal{O}$(0.1%) ★	☺ 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, with their advantages, are all ideal platforms for charm studies.
- They all are continuously collecting more datasets with increased luminosity in the foreseeable future.