Charm Physics and Hadron Spectroscopy at Belle and Belle II

Vietnam Flavour Physics Conference 2025

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On Behalf of Belle and Belle II Collaboration

2025-08-20

The Belle → Belle II experiments

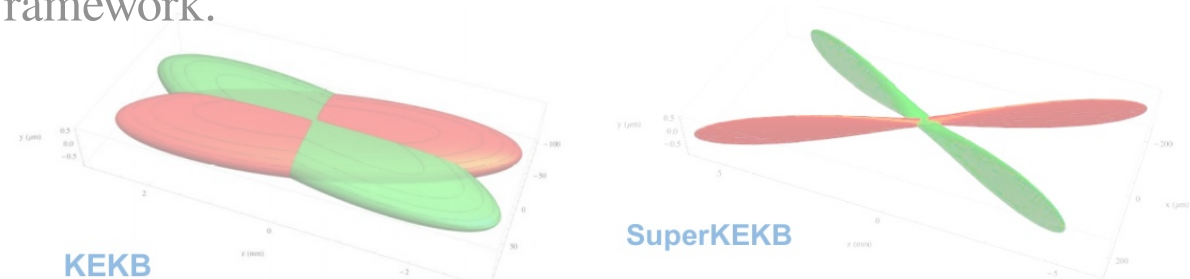
Belle:

- Operated from 1999-2010 at KEKb e^+e^- asymmetric collider.
- 1 ab^{-1} data sample, most of it at $\Upsilon(4S)$.
- Peak luminosity: 2.1×10^{-34} cm^{-2}s^{-1}.

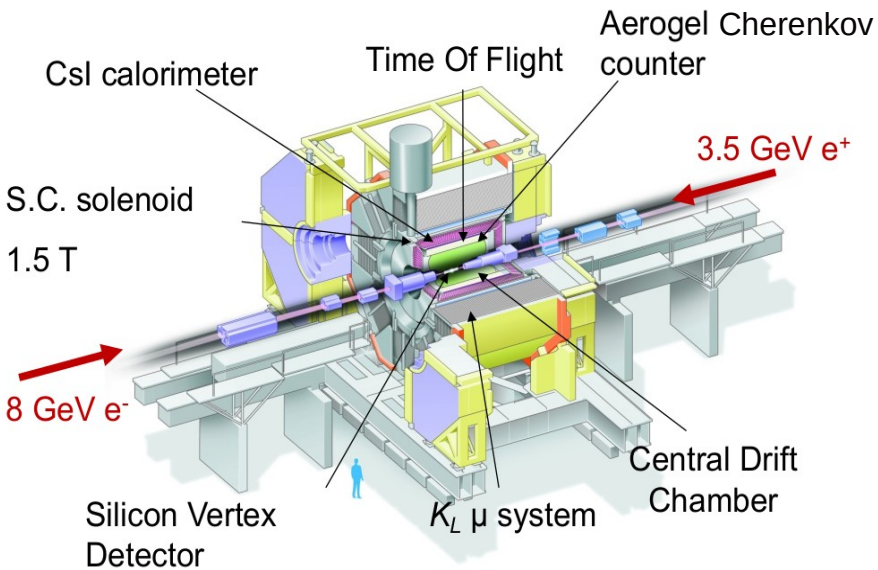
Belle II:

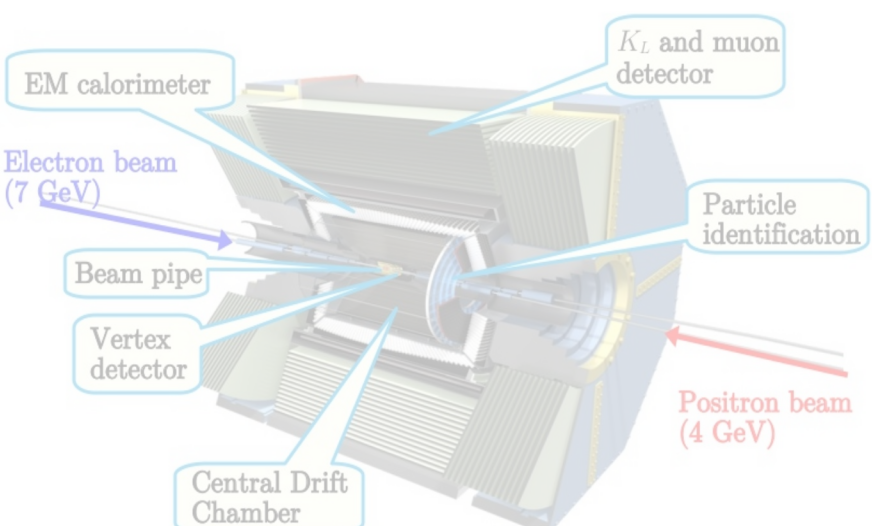
- Successor of Belle.
- Improved tracking, vertexing, PID, neutral reconstruction.
- **World record luminosity: 5.1×10^{-34} cm^{-2}s^{-1} (December 2024).**
- Target is to achieve 30x higher than Belle peak luminosity.
- Aims to accumulate 50 ab^{-1} data to study rare decays and precision measurements.

Both Belle and Belle II datasets are analyzable with Belle II Software Framework.



Shape of colliding beam at IP.





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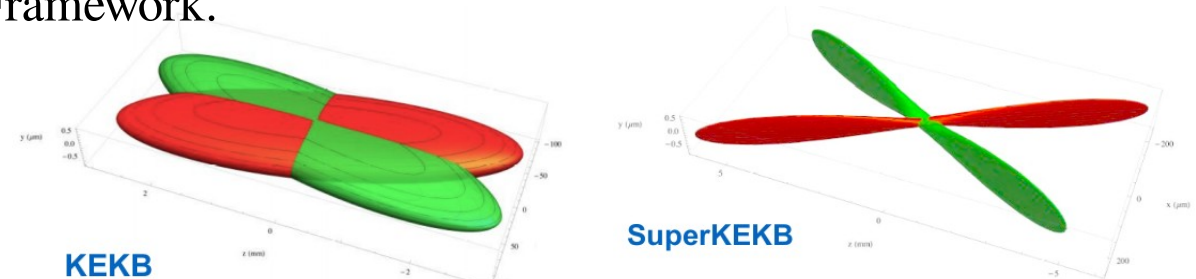

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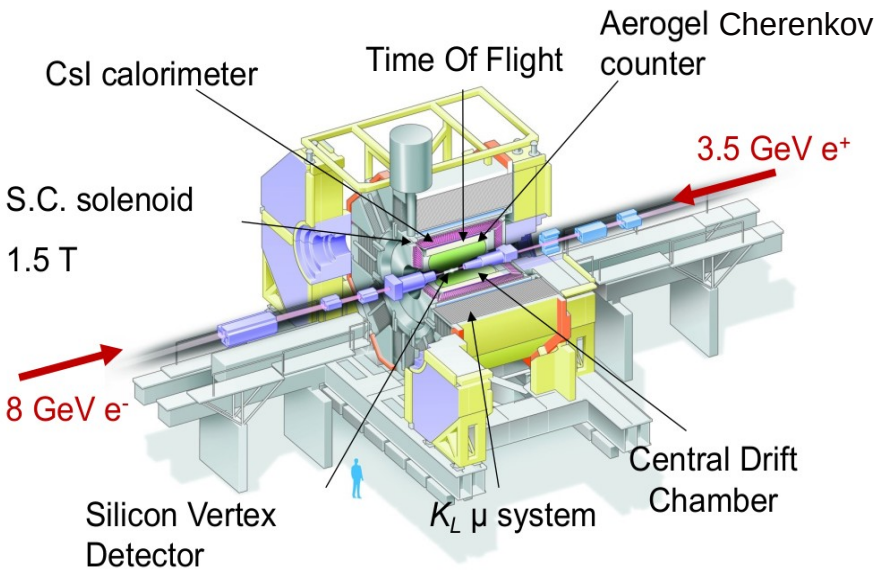
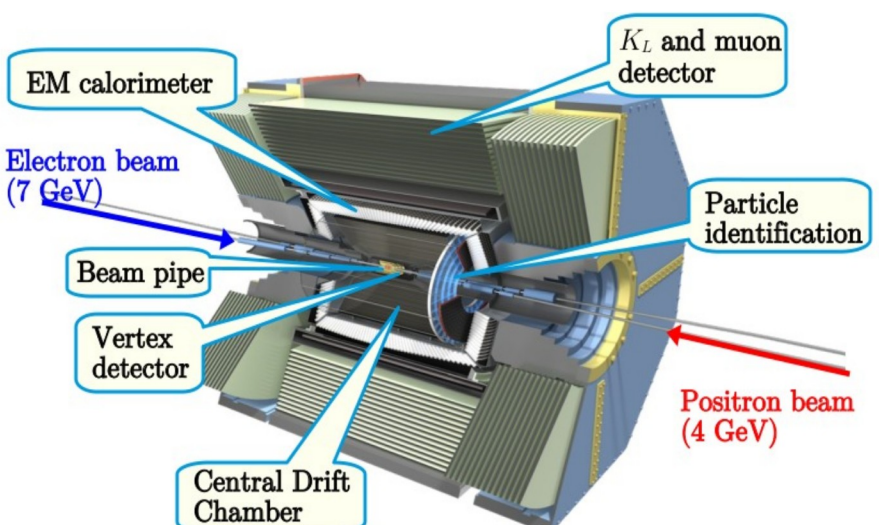




Outline

Charm physics:

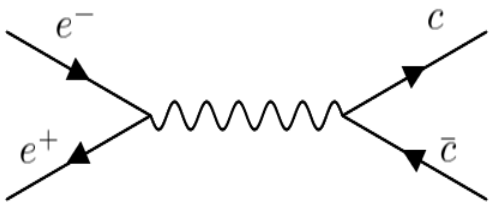
1) Measurement of $D^0-\bar{D}^0$-mixing parameters in $D^0\to K^0_S\pi^+\pi^-$ decays at Belle and Belle II.
2) CP asymmetry measurement in
   (a) $D^0\to K^0_SK^0_S$ decays using Belle and Belle II data.
   (b) $D^+\to \pi^+\pi^0$ decays at Belle II.
3) Measurements of the branching fractions of Ξ^+_c decays at Belle and Belle II.

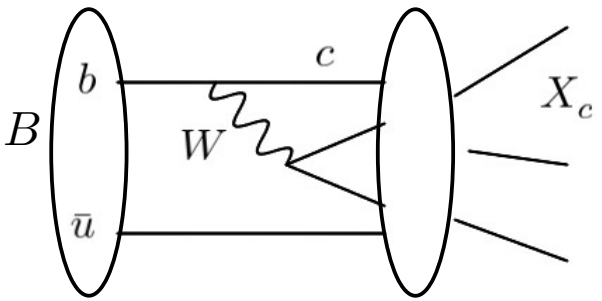
Hadron spectroscopy:

1) Evidence of $P_{c\bar{c}s}(4459)^0$ the in $\Upsilon(1S,2S)$ inclusive decays at Belle.
2) Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II.

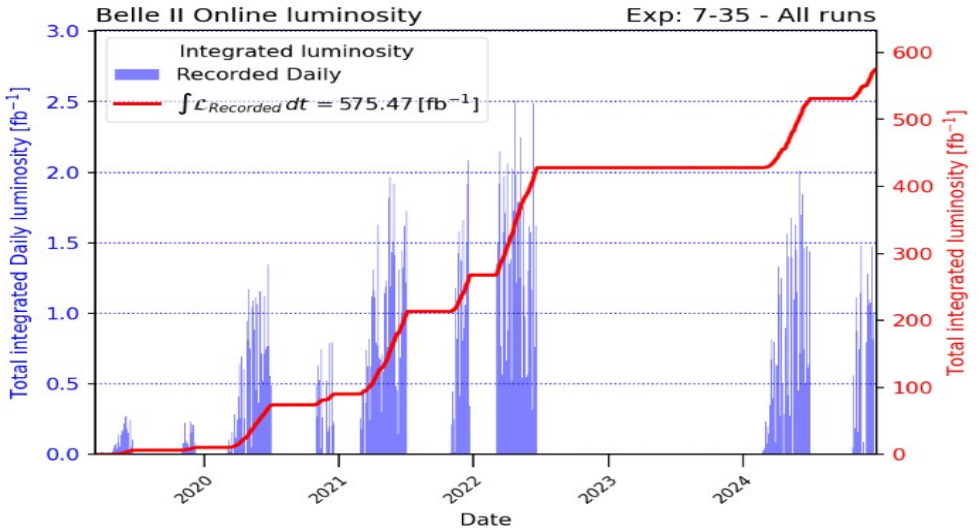
Charm physics at Belle (II)

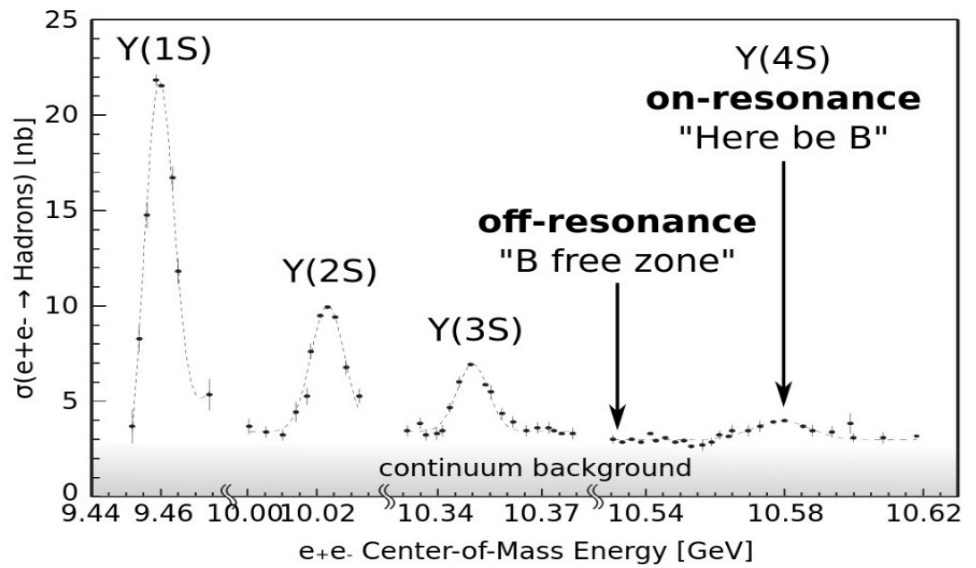
- Two production mechanism:
  - $e^+e^- \to c\bar{c}$ with large production cross section.
  - Decay of B meson produced from $\Upsilon(4S)$.
- Clean environment.
- Large dataset.





Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40





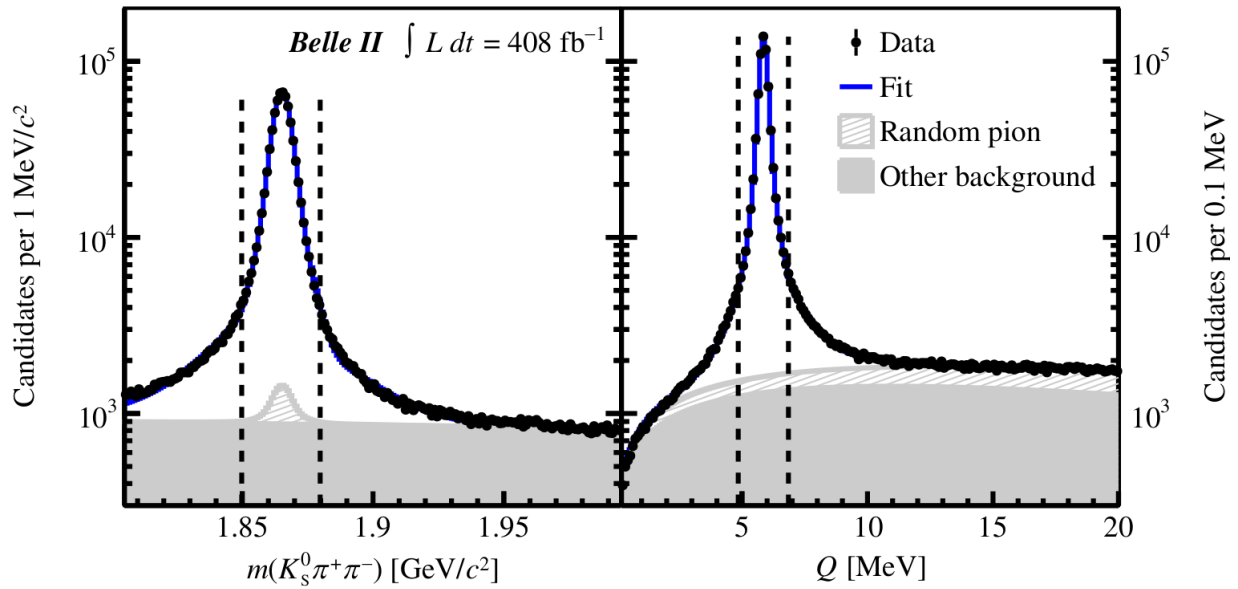
$D^0-\bar{D}^0$ mixing parameters in $D^0\to K^0_S\pi^+\pi^-$

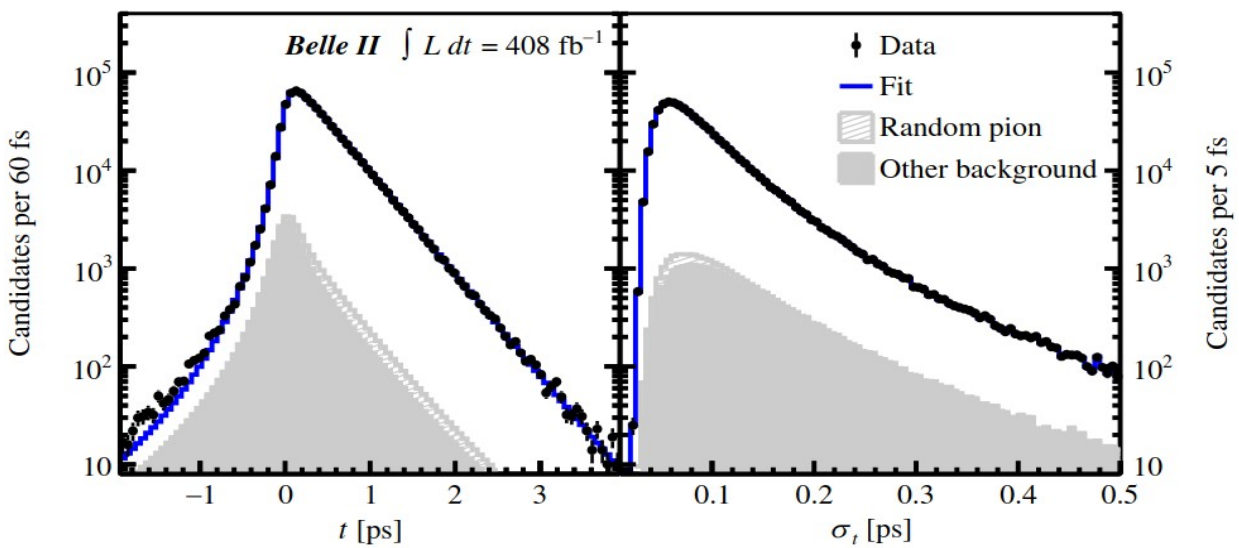
World average:

$$x = \frac{m_1 - m_2}{\Gamma} = (4.07\pm0.44)\times10^{-3}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = (6.45^{+24}_{-23})\times10^{-3}$$

- Split Dalitz plot in symmetric bin pairs, for model independent measurement.
- Separate signal and background using 2D fit to $m(K^0_S\pi^+\pi^-)$ and the energy released Q in D^{*+} decay.
- Fit (t,σ_t) in Dalitz bins.
- Belle (951 fb^{-1}) + Belle II (408 fb^{-1}) data are used.





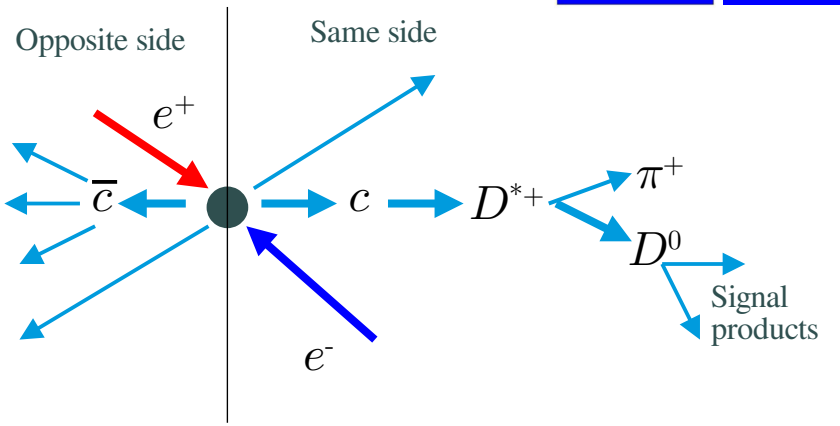
Phys. Rev. D 111, 112011 (2025)

$x=(4.0\pm1.7\pm0.4)\times10^{-3}$

$y=(2.9\pm1.4\pm0.3)\times10^{-3}$

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

- Proceeds through color- and Cabibbo-suppressed transition.
- Involves $c \to u s \bar{s}$ and $c \to u d \bar{d}$.
- Expected CP asymmetry of 1%.



World average:

$A_{CP}(D^0 \to K^0_S K^0_S) = (-1.9 \pm 1.0)\%$ **limited by statistics**.

- Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) data are used.

Two independent measurements:

D^* tagged D^0

- Use $D^{*+} \to \pi^+ D^0$ to tag flavor.
- Calibrate detection asymmetries using $D^0 \to K^+ K^-$.
- Main background: $D^0 \to K^0_S \pi^+ \pi^-$.
- 2D extended UML fit to $m(D^0\pi^+)$, and $S_{min}(K^0_S) = log[min(L_1/\sigma_1, L_2/\sigma_2)]$ based of KS flight significance.

Charm-flavor-tag D^0

- Use information from the other tracks in the event to tag flavor.
- Remove all events containing $D^{*+} \to \pi^+ D^0 (K^0_S K^0_S)$
- Background from partially reconstructed D_s^+ decays in addition.
- 2D extended UML fit to $m(K^0_S K^0_S)$ and qr, q is flavor of the signal candidate and r is the corresponding dilution factor.

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

Phys. Rev. D 111, 012015 (2025)

D^* tagged D^0

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

Phys. Rev. D 112, 012017 (2025)

Charm-flavor-tag D^0

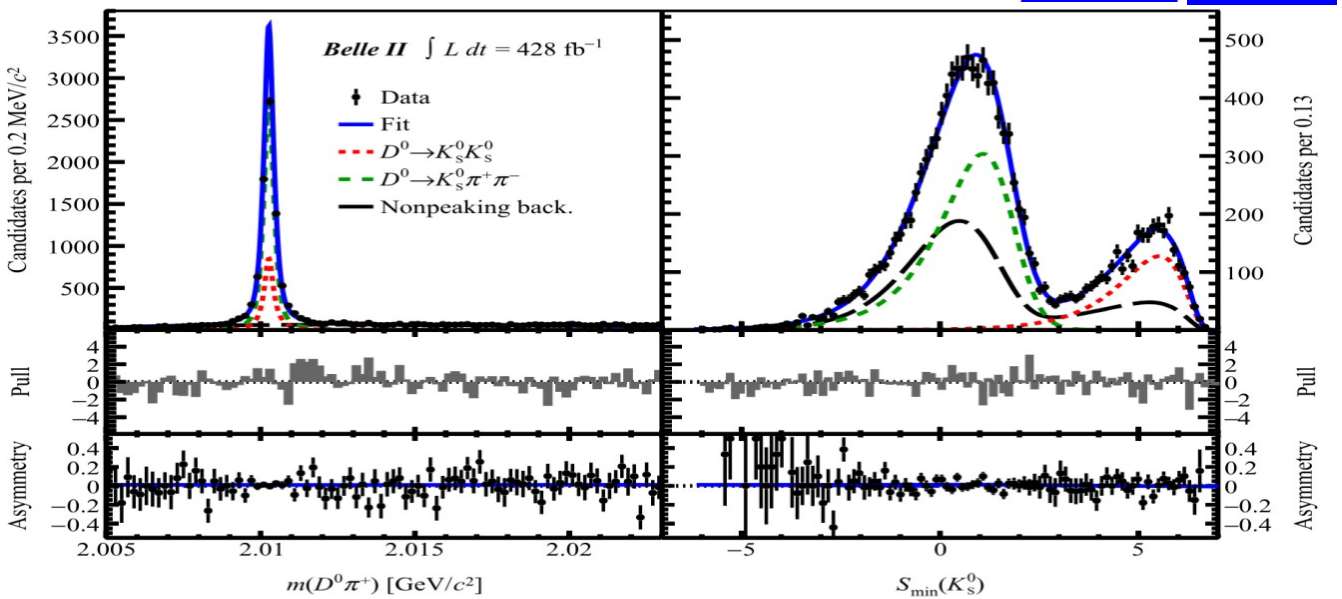
$A_{CP} = (1.3 \pm 2.0(stat) \pm 0.2(syst))\%$

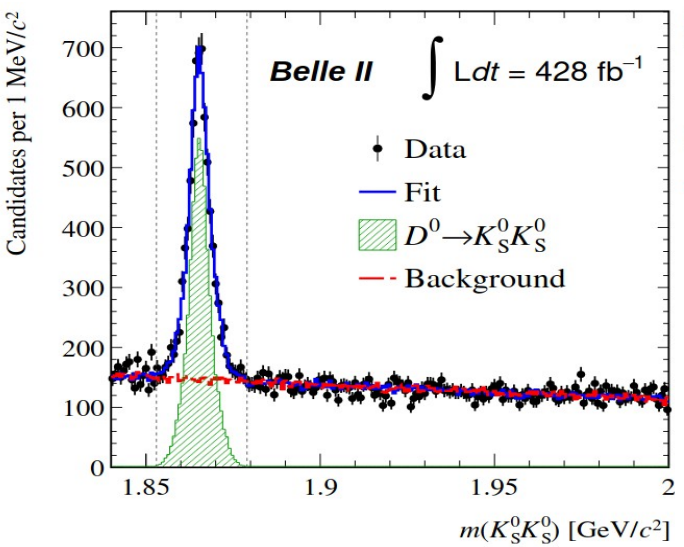
Combination

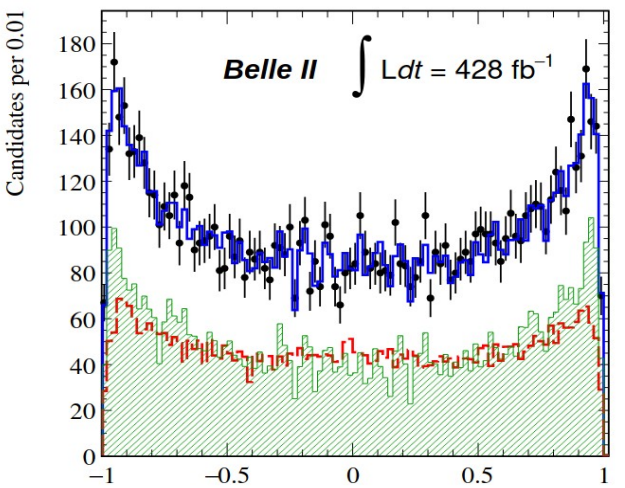
$A_{CP} = (-0.6 \pm 1.1(stat) \pm 0.1(syst))\%$

World's most precise determination!

Agreement with CP asymmetry and results from other experiments.

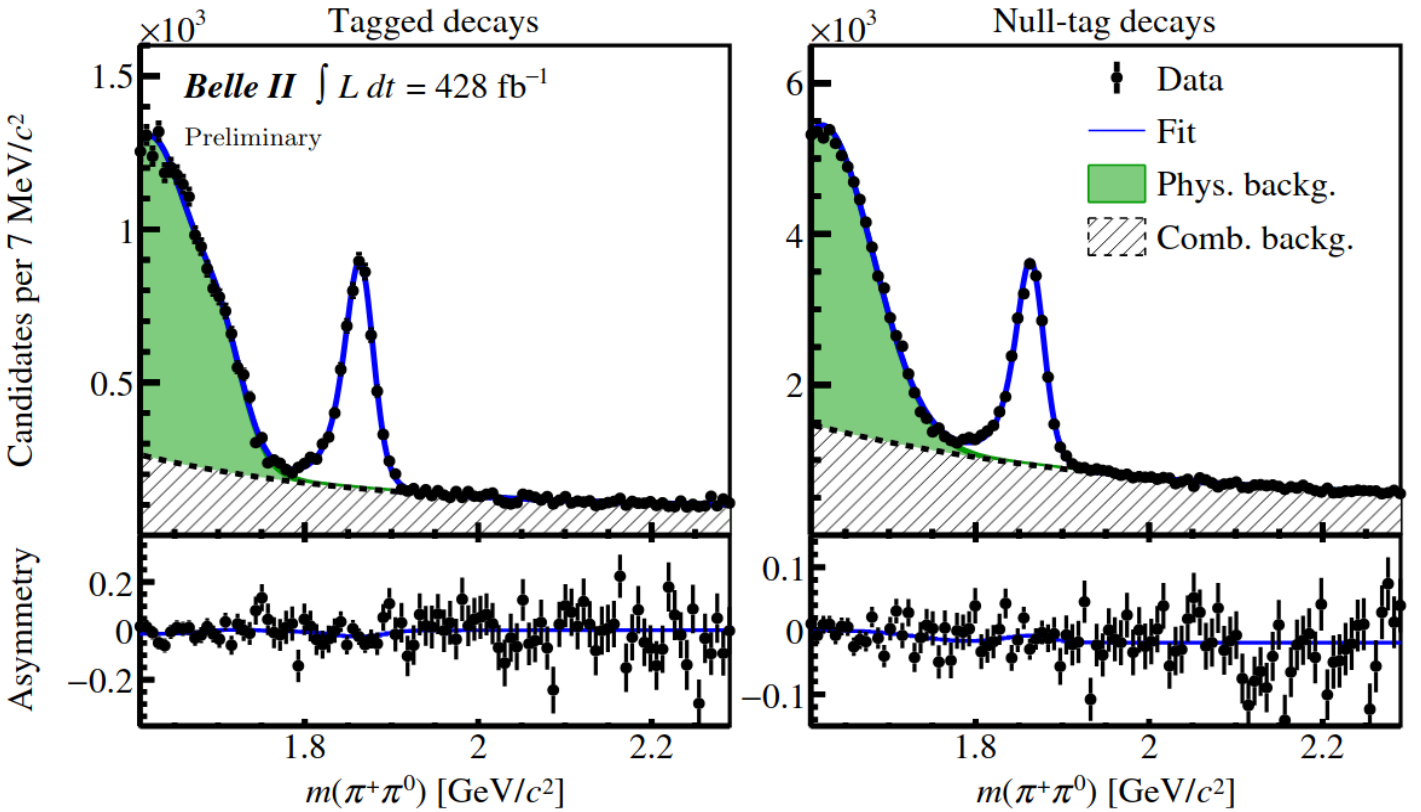






CP asymmetry in $D^+ \to \pi^+\pi^0$ decays

- $\Delta I = 3/2$ transition, absence of second amplitude. No CP violation expected in standard model.
- Correct for the production and detection asymmetries using abundant Cabibbo favored control sample $D^+ \to \pi^+ K^0_S$.
- Separate samples to increase purity:
  - Tagged decays originating form $D^{*+} \to D^+\pi^0$
  - Null-tag decays.
- **30% improvement compared to previous Belle measurement** due to better signal purity through improved event selection.
- Agrees with CP asymmetry and previous measurements.



arXiv:2506.07879

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

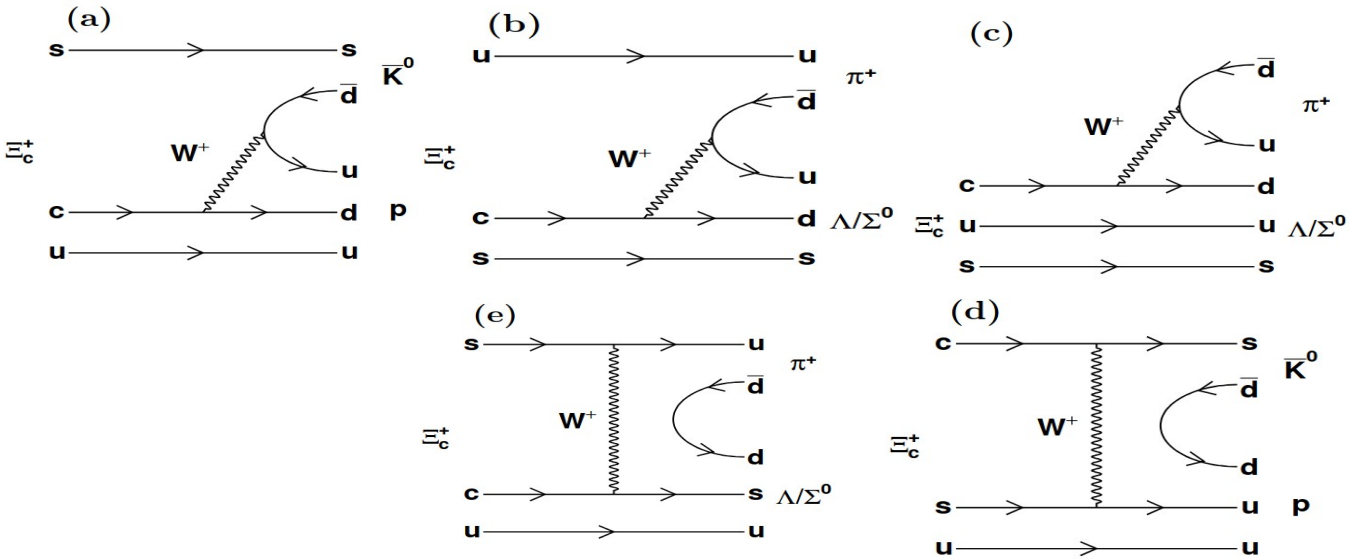
Branching Fractions of Ξ_c^+ decays

Measurement for the first time:

- Cabibbo-favored: $\Xi_c^+ \to \Sigma^+ K_S^0$
- Singly Cabibbo-suppressed: $\Xi_c^+ \to \Xi^0 K^+$, pK_S^0 , $\Lambda\pi^+$, $\Sigma^0\pi^+$

Many theoretical predictions, need experimental measurement to constraint them.

- Belle (983 fb^{-1}) + Belle II (427 fb^{-1}) data are used.



arXiv:2503.17643

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

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

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

$stat.$ $syst.$ $BFratio.$

JHEP03(2025)061

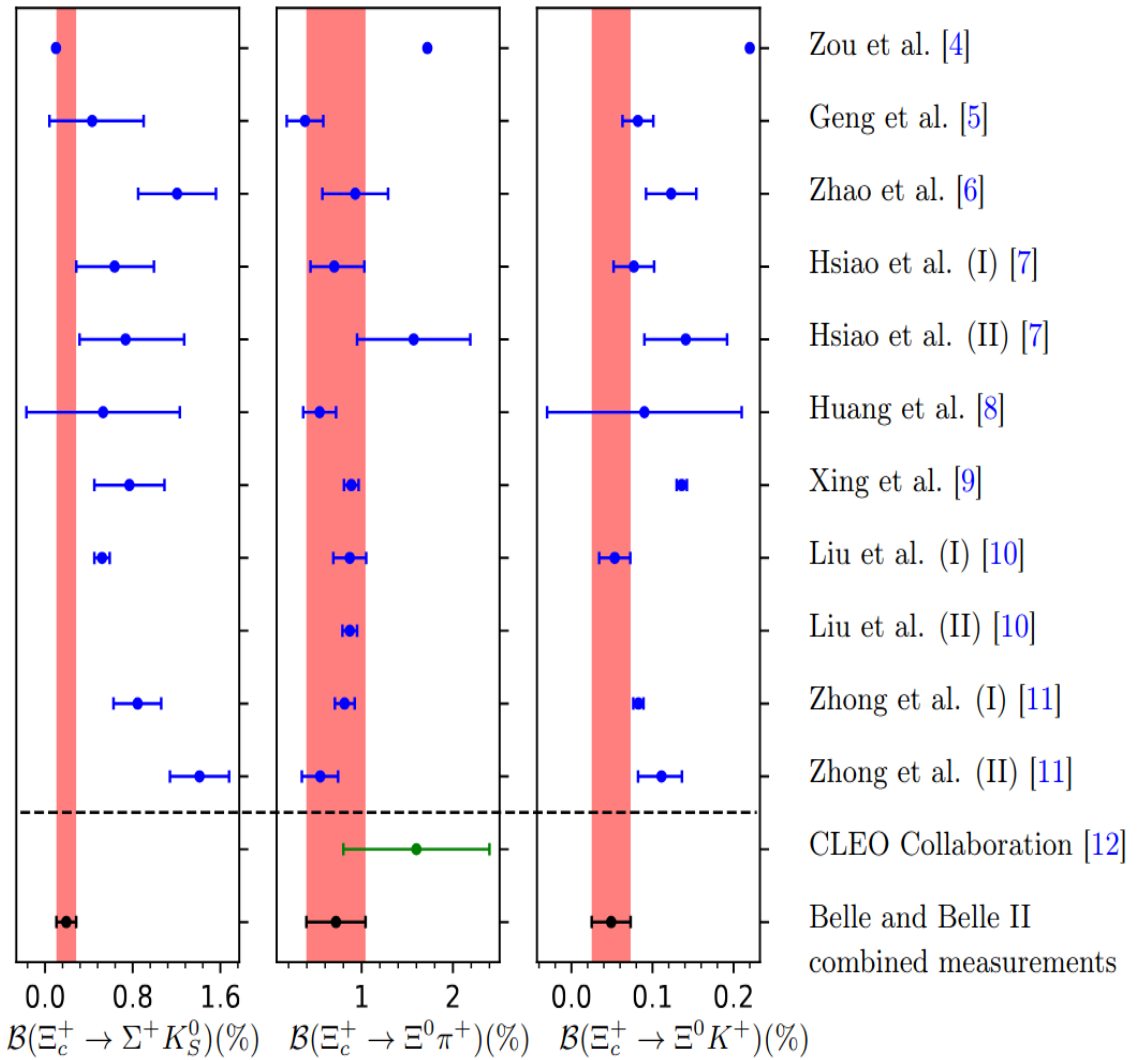
$$\mathcal{B}(\Xi_c^+ \to pK_S^0) = (7.16 \pm 0.46 \pm 0.20 \pm 3.21) \times 10^{-4},$$

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

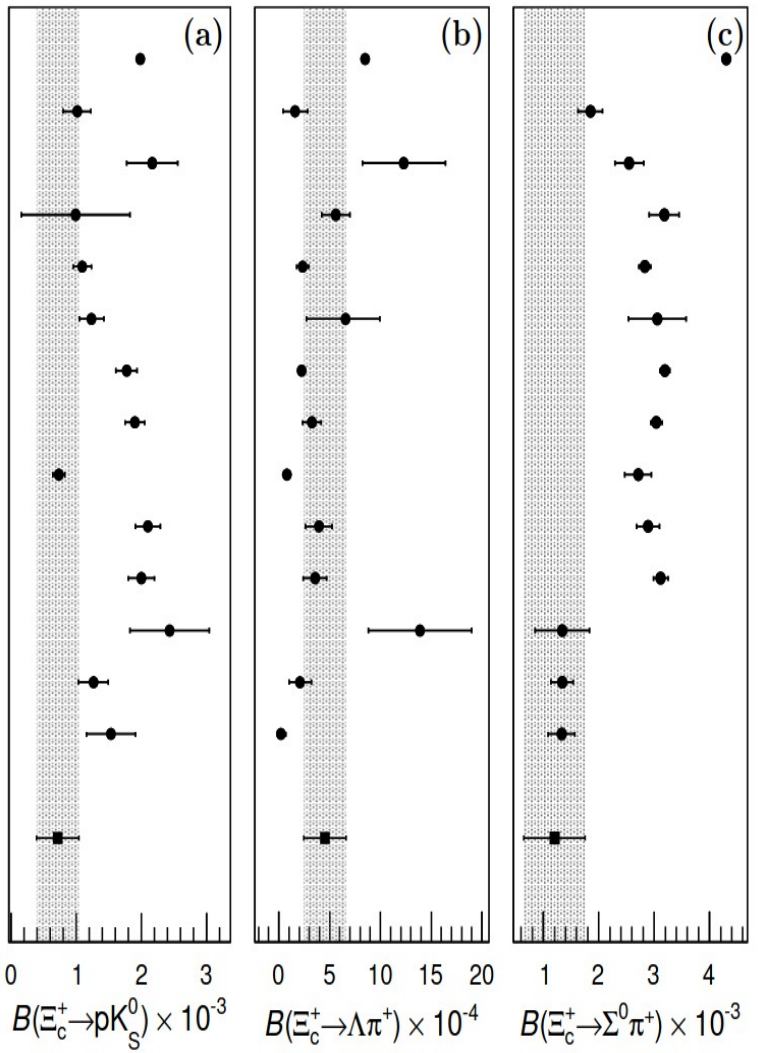
$$\mathcal{B}(\Xi_c^+ \to \Sigma^0\pi^+) = (1.20 \pm 0.08 \pm 0.07 \pm 0.54) \times 10^{-3}.$$

$stat.$ $syst.$ $BFratio.$

Branching Fractions of Ξ_c^+ decays



Zou et al. [4]
Geng et al. [5]
Zhao et al. [6]
Hsiao et al. (I) [7]
Hsiao et al. (II) [7]
Huang et al. [8]
Xing et al. [9]
Liu et al. (I) [10]
Liu et al. (II) [10]
Zhong et al. (I) [11]
Zhong et al. (II) [11]
CLEO Collaboration [12]
Belle and Belle II combined measurements



Zou *et.al* [12]
Geng *et.al* [13]
Geng *et.al* [14]
Huang *et.al* [15]
Zhong *et.al* (I) [16]
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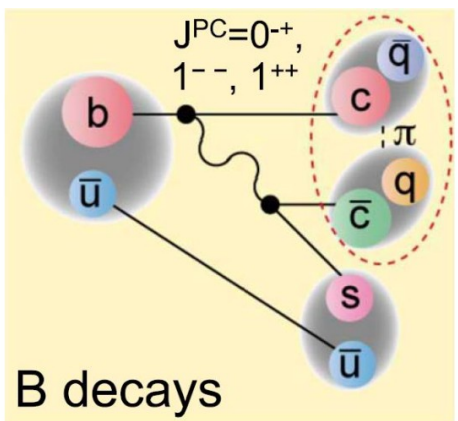
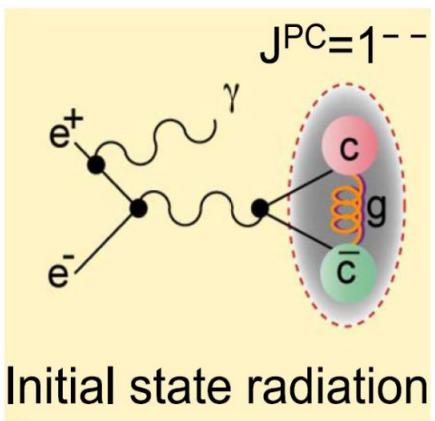
Xing *et.al* [17]
Geng *et.al* [18]
Liu [19]
Zhong *et.al* (I) [20]
Zhong *et.al* (II) [20]
Zhao *et.al* [21]
Hsiao *et.al* (I) [22]
Hsiao *et.al* (II) [22]

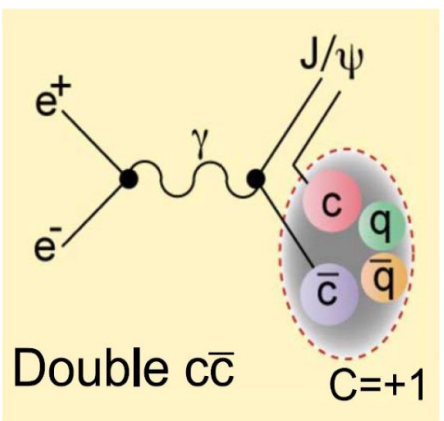
Belle and Belle II combined measurement

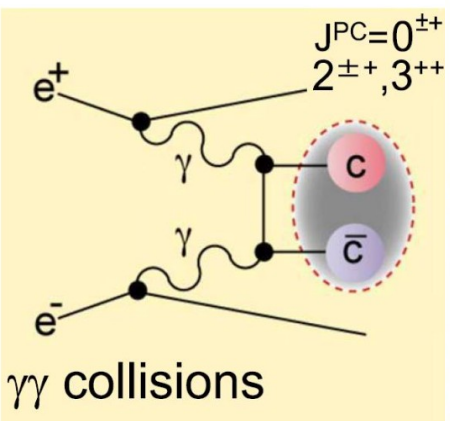
Hadron spectroscopy at Belle (II)

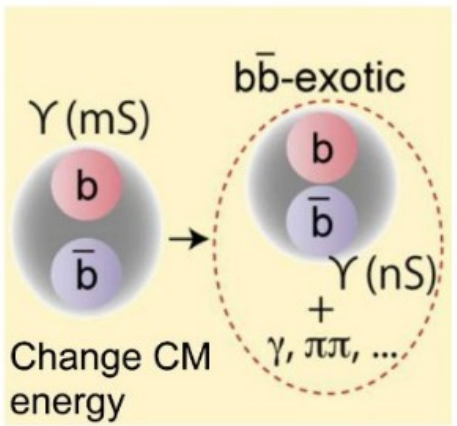
- Multiple production mechanisms









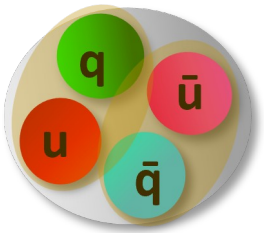


- Full event reconstruction, excellent capability of detection and reconstruction of neutrals.
- Wide range of physics goals with energy reach upto 11.24 GeV.

Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S,2S)$ inclusive decays

- Gell-Mann mentioned the possibility of four and five quark exotic states in his first paper of quark model.
- Pentaquark states seen by LHCb
  - Evidence of $P_{c\bar{c}s}(4459)^0$ with 3.1σ significance.
  - Observation of $P_{c\bar{c}s}(4338)^0$ with 15σ significance.
  - Both in $P_{c\bar{c}s} \to J/\psi\,\Lambda$ decays.
  - Nature of the states still largely unknown. Only reported by LHCb.
  - Need more study to confirm existance and internal structure.
- $\Upsilon(1S,2S)$ decays suitable for study exotic quark configutaion.
- Largest data sample collected by Belle:
  - **5.8 fb^{-1} at $\Upsilon(1S)$ [102M]**
  - **24.5 fb^{-1} at $\Upsilon(2S)$ [158M]**

Tetraquak



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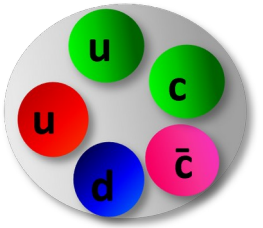
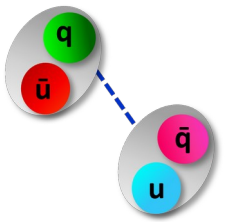
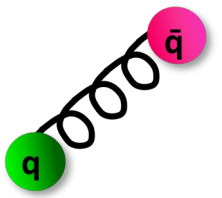


Molecule

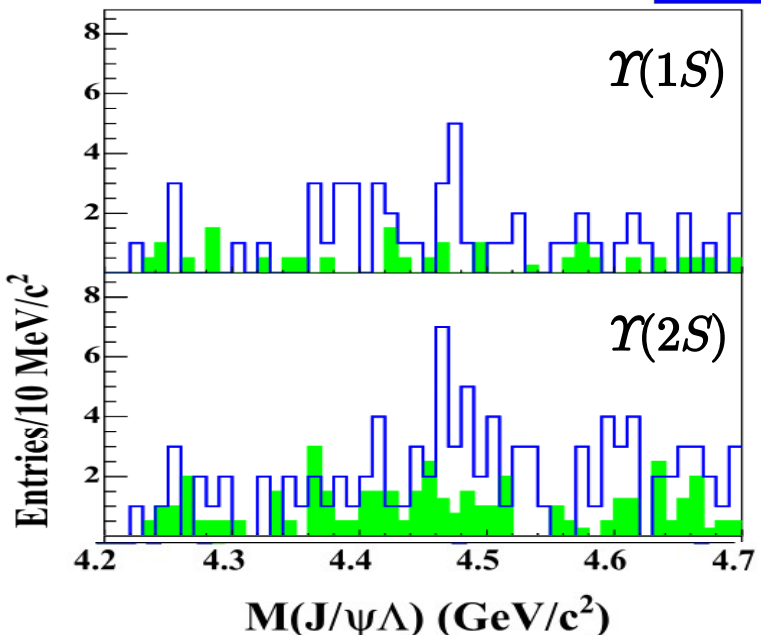


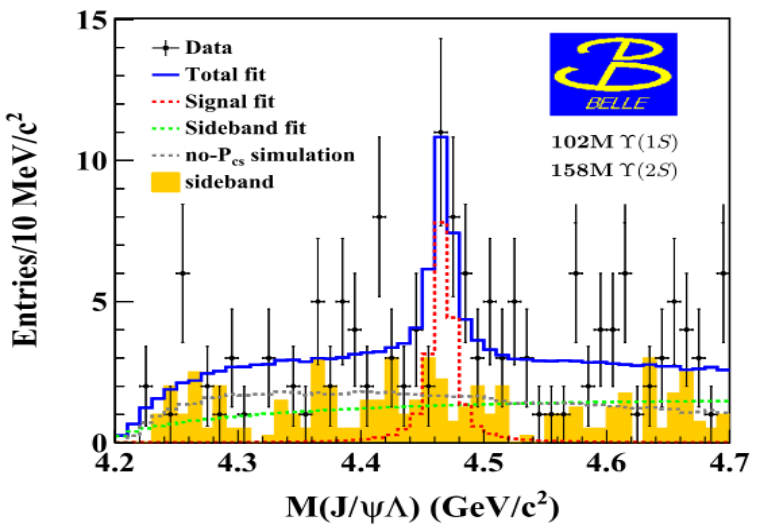
Hybrid meson



Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S,2S)$ inclusive decays

- Event accumulation seen near the mass of $P_{c\bar{c}s}(4459)^0$ in $M(J/\psi\Lambda)$ distribution, but none in $P_{c\bar{c}s}(4338)^0$.
- Assuming it is the same particle, significance of 3.3σ .
  - **First evidence in the decays of $\Upsilon(1S,2S)$.**
  - Significantly different production mechanism than that of LHCb evidence found in Ξ_b^-.
  - $\mathcal{B}\,(\Upsilon(1S)\to P_{c\bar{c}s}(4459)^0X)=(3.5\pm2.0\pm0.2)\times10^{-6}$
  - $\mathcal{B}\,(\Upsilon(2S)\to P_{c\bar{c}s}(4459)^0X)=(2.9\pm1.7\pm0.4)\times10^{-6}$
- Assuming it is not same, mass and width are found to be $M=(4471.7\pm4.8\pm0.6)$ MeV/c^2 and $\Gamma=(22\pm13\pm3)$ MeV.
- No $P_{c\bar{c}s}(4338)^0$ signal. Upper limits at 90% CL:
  - $\mathcal{B}\,(\Upsilon(1S)\to P_{c\bar{c}s}(4338)^0X)<1.8\times10^{-6}$
  - $\mathcal{B}\,(\Upsilon(2S)\to P_{c\bar{c}s}(4338)^0X)<1.6\times10^{-6}$



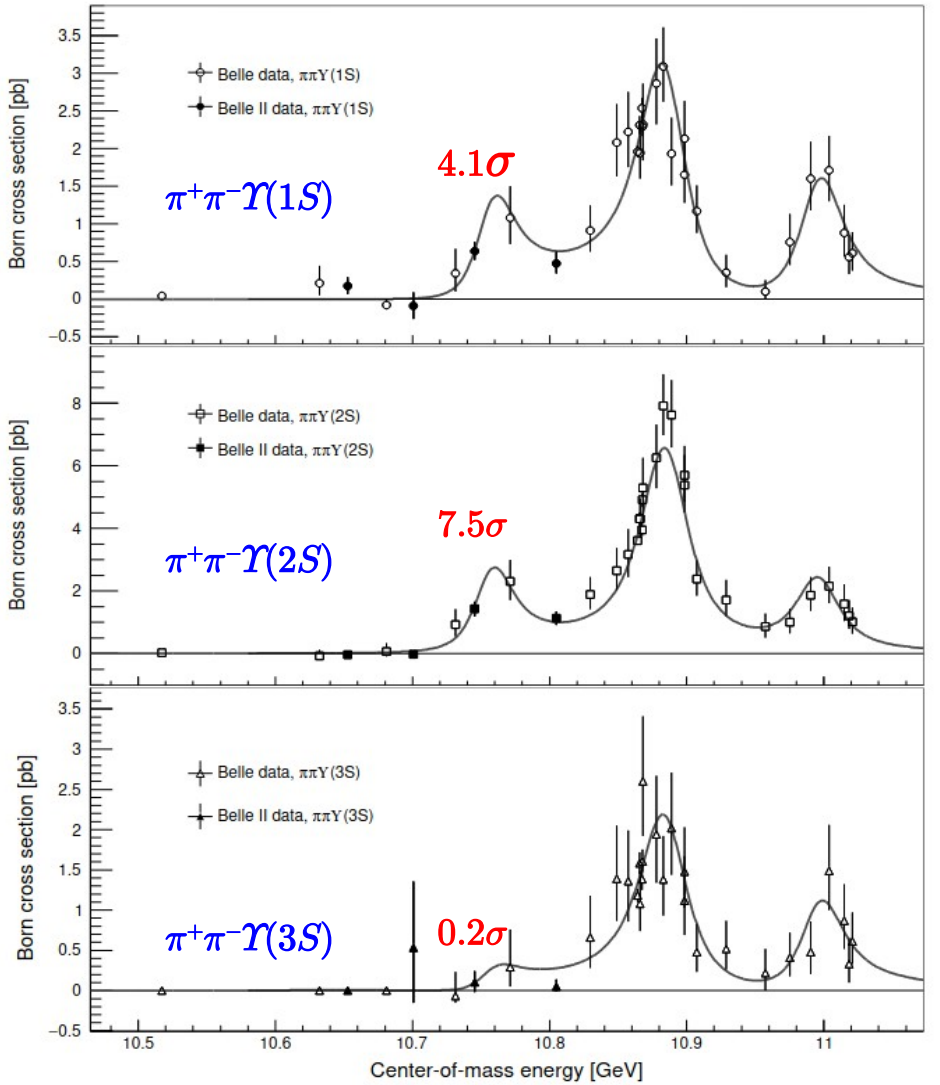


Phys. Rev. Lett. 135, 041901(2025)

Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$

JHEP 07 (2024) 116

- **First observation of $\Upsilon(10753)$ by Belle in $e^+e^- \to \pi^+\pi^-\Upsilon(nS), (n=1,2,3)$.**
- Global significance is 5.2σ .
- Several competing interpretations:
  - Conventional bottomonium, hybrid or tetraquark.
  - Previous Belle studies consistent with **4S-3D mixing model**.
- Belle II collected special sets of data (19.6 fb^{-1}) in November, 2021 for $\Upsilon(10753)$ studies.
- **Excellent confirmation.**
  - $M=(10756.6\pm2.7\pm0.9)$ MeV/c^2
  - $\Gamma=(29.0\pm8.8\pm1.2)$ MeV

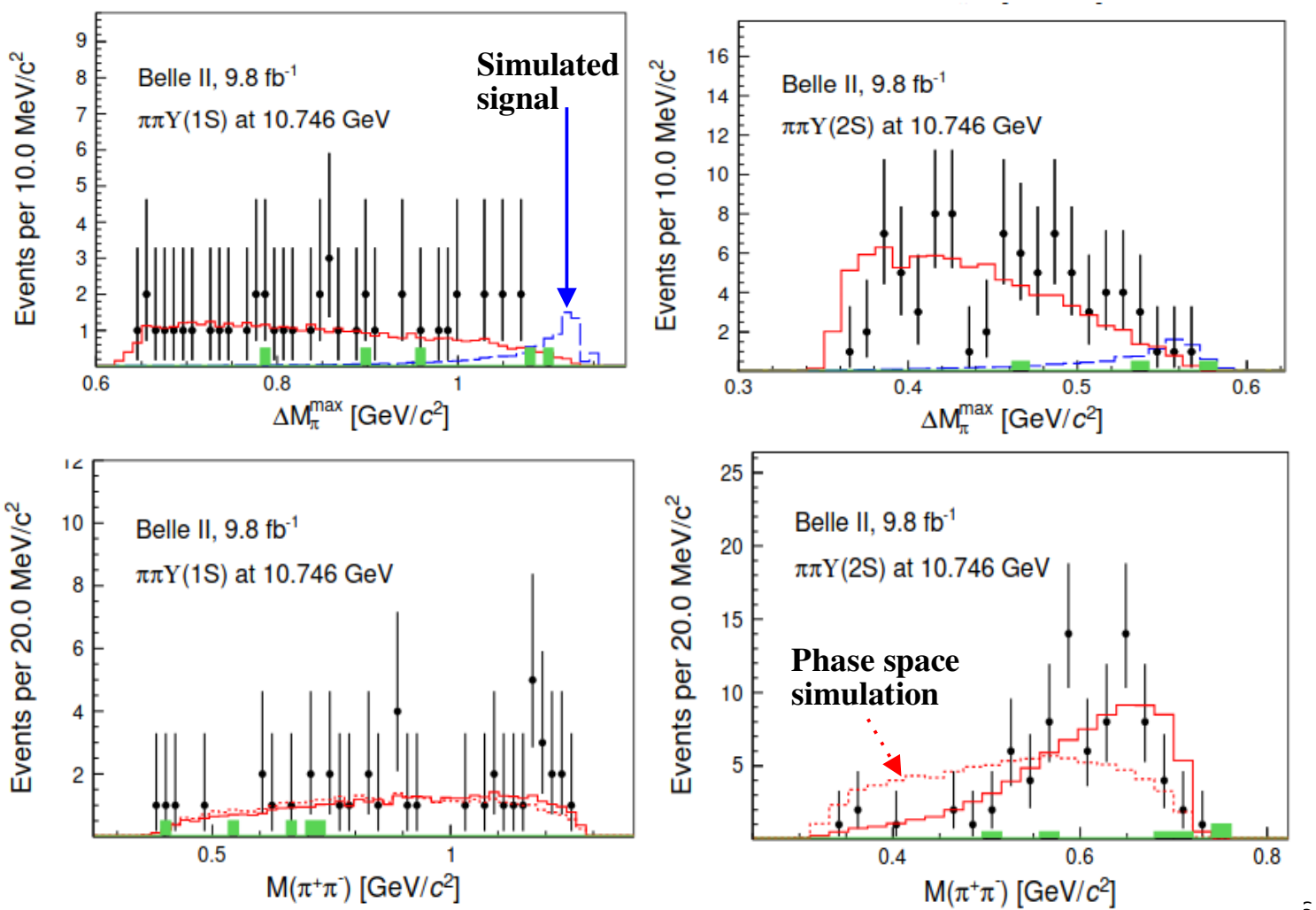


Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$

- Search for $f_0(980)[\rightarrow \pi^+\pi^-]$ and $Z_b(10610,10650)^{\pm}[\rightarrow\pi^{\pm}\Upsilon(nS)]$ which may provide deeper understanding.

$$\Delta M^{max}{}_{\pi} = max(M(\mu\mu\pi) - M(\mu\mu))$$

- No evidence for decays proceeding through $\pi^{\mp}$ $Z_b^{\pm}$ or $f_0(980)\Upsilon(nS)$ found.



Summary

- Belle II offers unique capabilities and advantages in study of charm physics and hadron spectroscopy.
- Today showed:
  - Measurement of model independent D^0-$\bar{D}^0$ mixing parameters.
  - A_{CP} measurement of in two different decay channels. World's best measurement on $K^0_S K^0_S$ final states.
  - Evidence of $P_{c\bar{c}s}(4459)^0$ pentaquark state.
  - Confirmation of $\Upsilon(10753)$ decays.
- More data is coming.
  - Improved uncertainty and significance.
  - Crucial for constraining values.

Back Up

Mixing and asymmetry parameters

Mixing

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

World average:

$x=(4.07\pm0.44)\times10^{-3}$, $y=(6.45^{+24}_{-23})\times10^{3}$

Might be enhanced by particles beyond standard model!

CP asymmetry

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

What we measure:

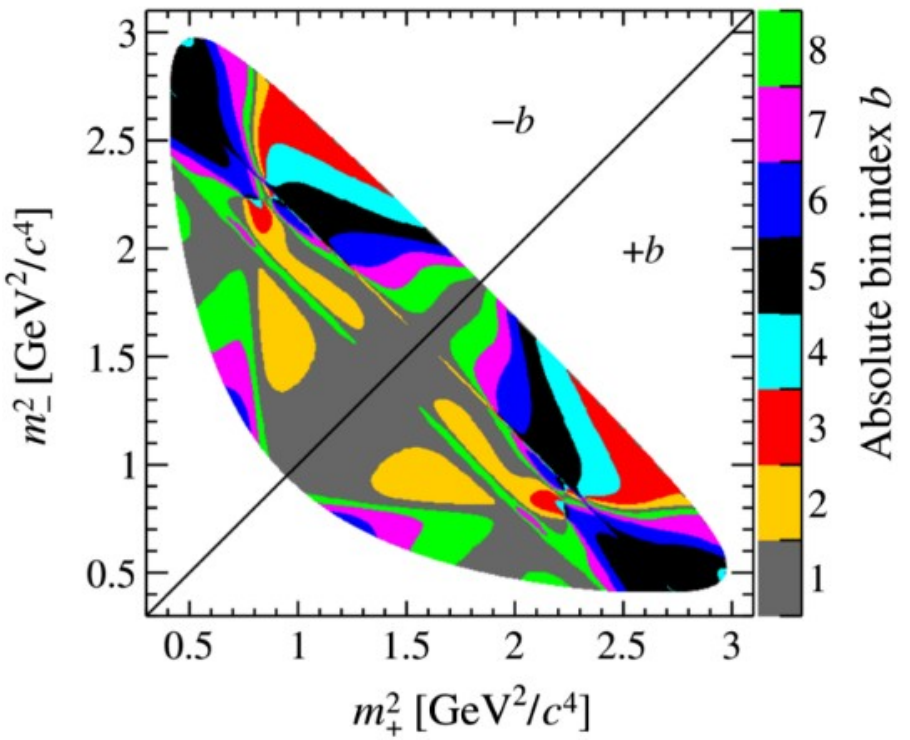
$$A^{f}_{raw} = \frac{N(D\to f)-N(\bar{D}\to\bar{f})}{N(D\to f)+N(\bar{D}\to\bar{f})} \simeq A^{f}_{CP} + A^{D}_{production} + A^{\pi}_{detection}$$

Detection asymmetry of π from D^+, D^{*+} decays due to detector.

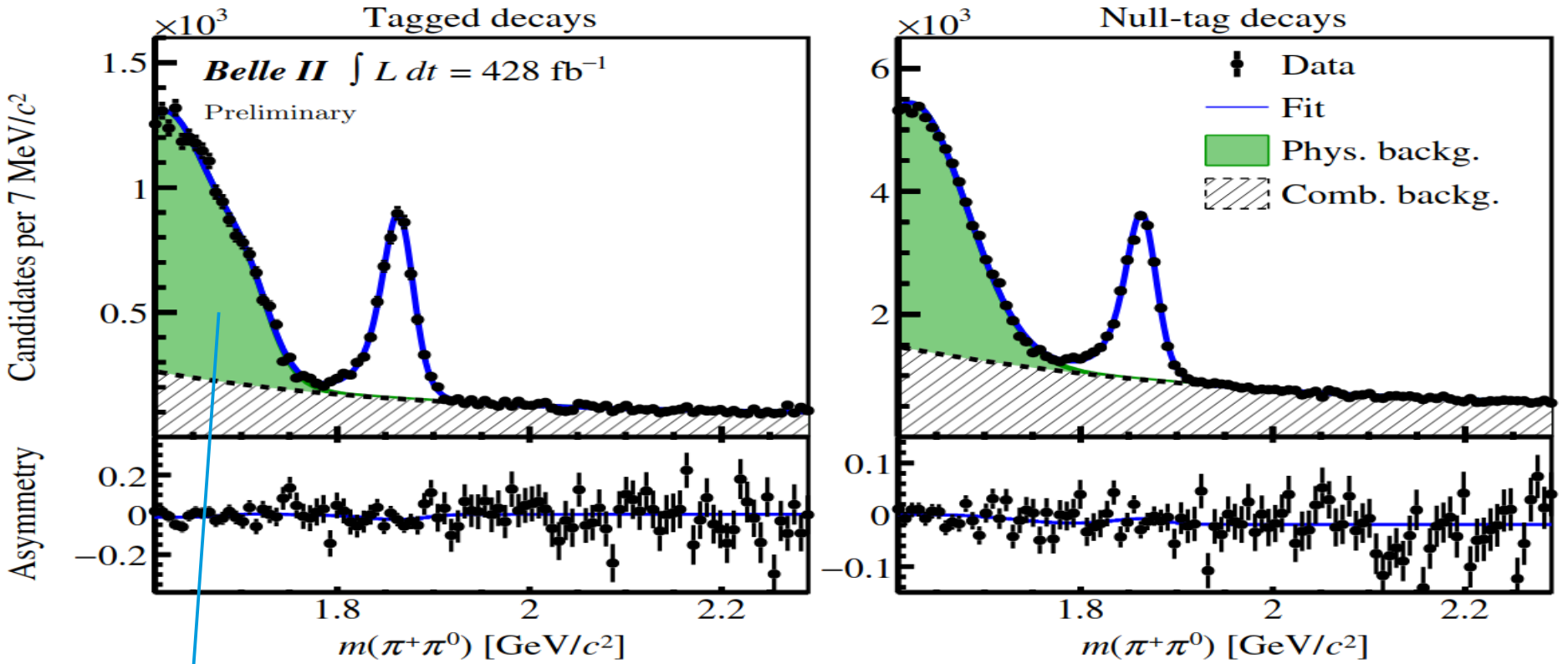
Forward backward asymmetry of D^+, D^{*+} production due to γ^*-Z^0 interference.

D^0-D^0 mixing parameters in $D^0\to K^0_S\pi^+\pi^-$

- "iso $\Delta\delta$" binning
- Hadronic parameters determined by BESIII https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.112002



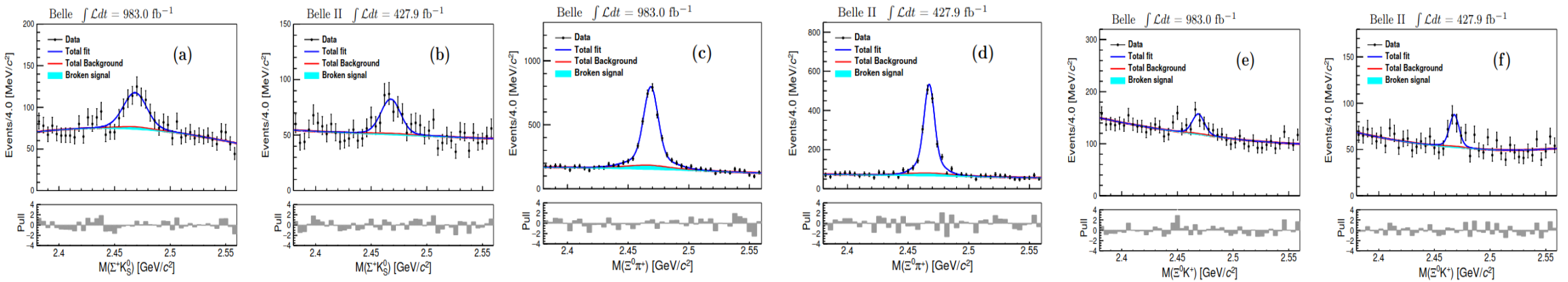
CP asymmetry in $D^+ \to \pi^+\pi^0$ decays

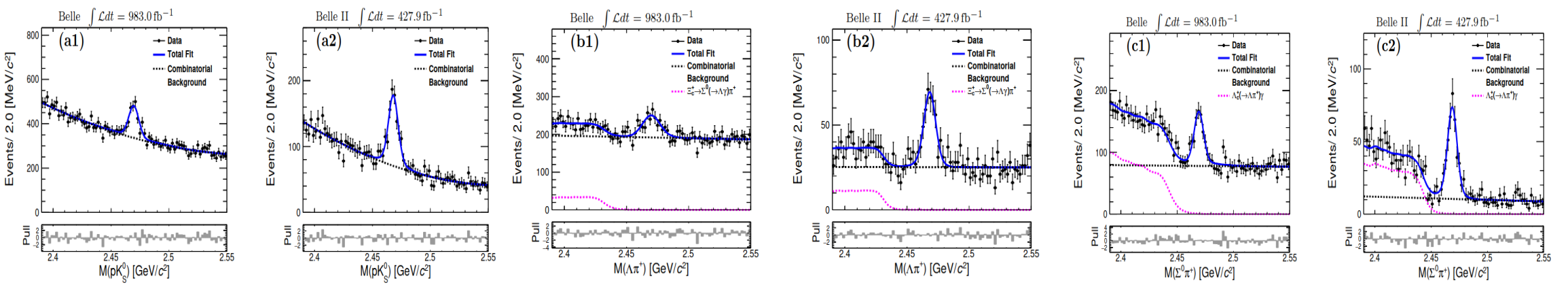


$D^0 \to \pi^+\pi^-\pi^0$, $D^+ \to \pi^+\pi^0\pi^0$, $D^+ \to \pi^0\mu^+\nu$, $D^+ \to K^0_S(\to \pi^0\pi^0)\pi^+$

Branching Fractions of Ξ_c^+ decays

Reconstruct: $\Sigma^0 \to \Lambda\gamma$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$, $\Xi^0 \to \Lambda\pi^0$, $\Sigma^+ \to p\pi^0$





Search for $P_{c\bar{c}s}(4459)^0$ and $P_{c\bar{c}s}(4338)^0$ in $\Upsilon(1S,2S)$ inclusive decays

- Assuming it is not same, mass and width are found to be $M=(4471.7\pm4.8\pm0.6)$ MeV/c^2 and $\Gamma=(22\pm13\pm3)$ MeV.
- LHCb found it

  $M=(4458.8\pm2.9^{+4.7}_{-1.1})$MeV/c^2 and $\Gamma=(17.3\pm6.5^{+8.0}_{-4.7})$ MeV