Knut and Alice Wallenberg Foundation

Charm Spectroscopy at Belle II

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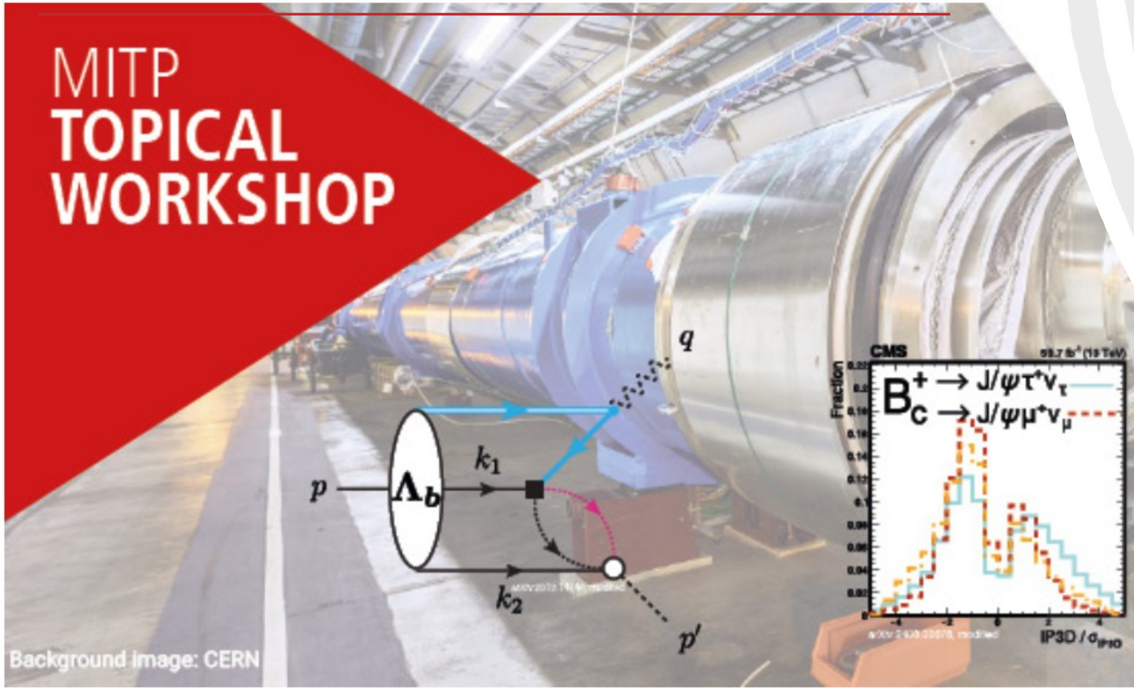


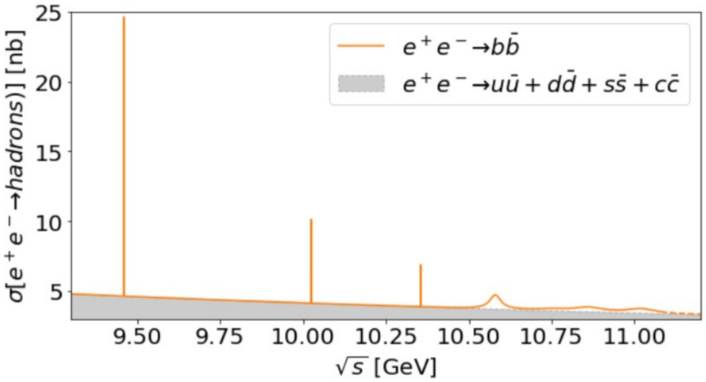
Flavor Physics with b Baryons and B_c Mesons

Mainz, May 26th - 29th, 2026

The (super) *B*-factories

Belle II collects data from e^+e^- collisions between 9 and 11 GeV:

- Mostly at 10.58 GeV, $B\overline{B}$ threshold



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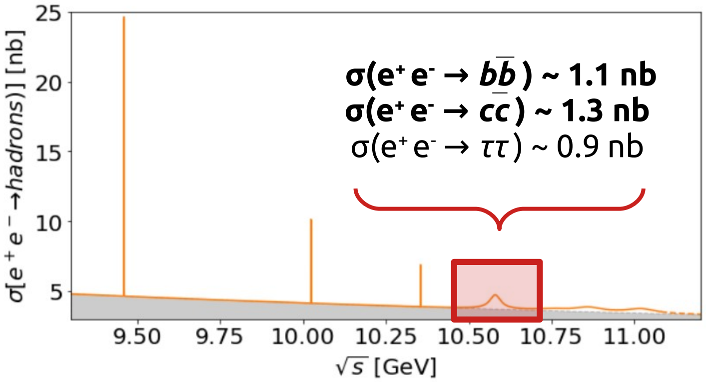

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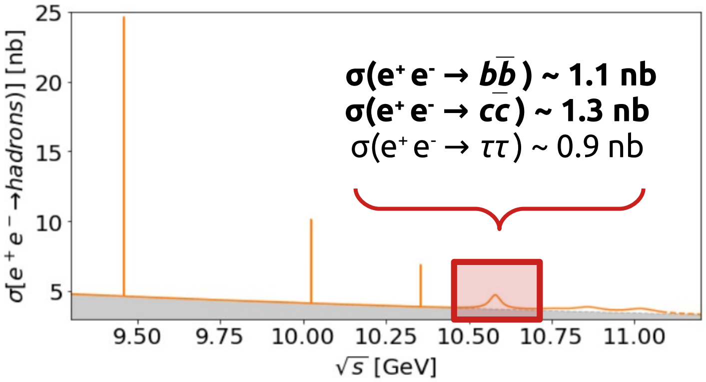
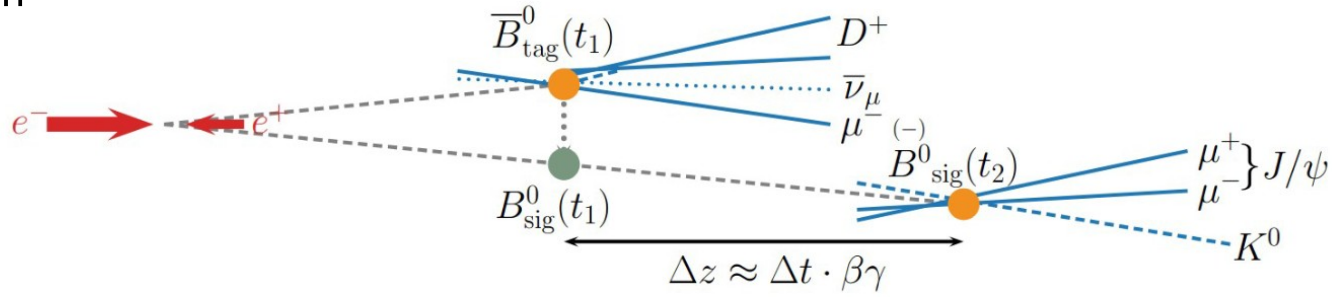


Key features:

- Boosted CM frame
- Micrometric vertex precision
- Hermeticity and PID



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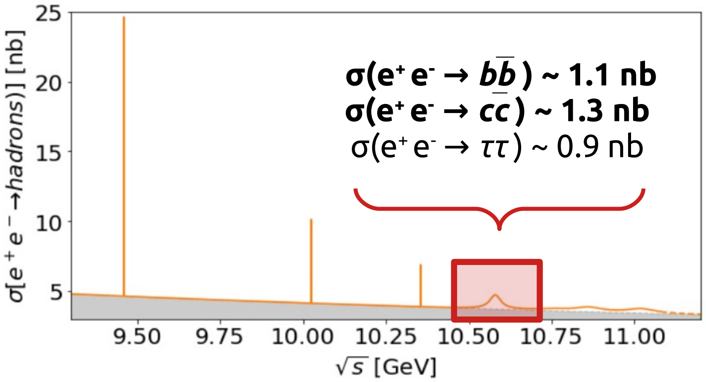

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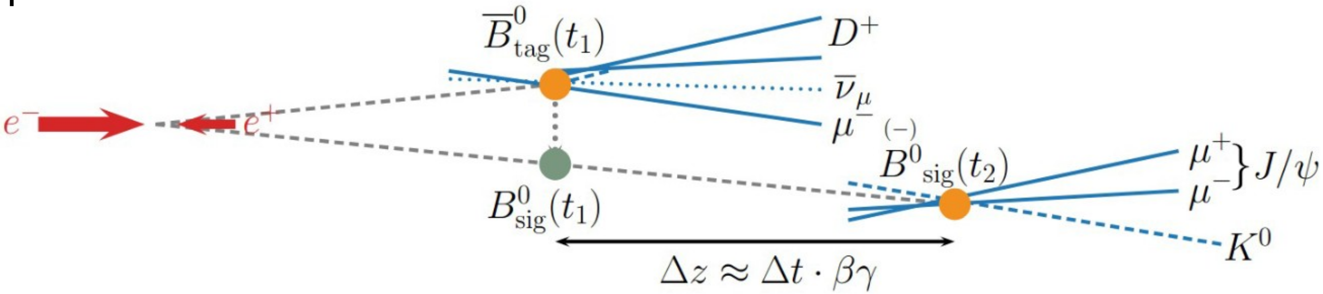

Successor to Belle and BaBar:

- CPV in hadronic decays

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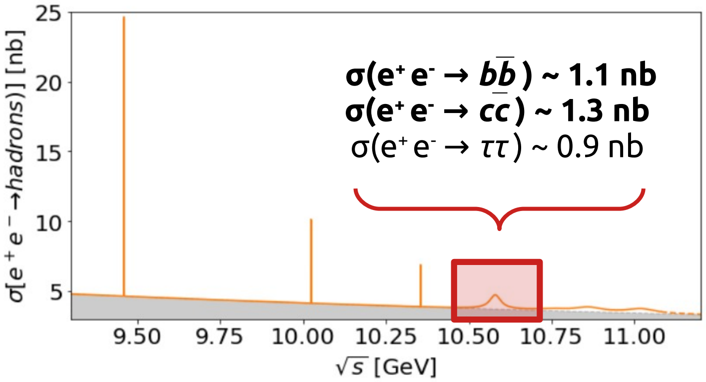
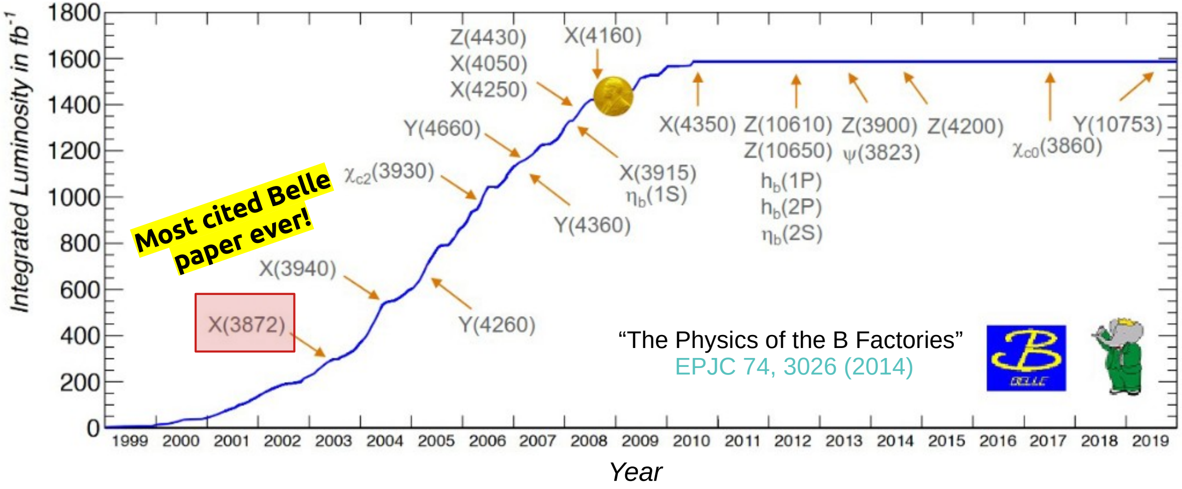
Successor to Belle and BaBar:

- CPV in hadronic decays
- Heavy exotic hadrons





SuperKEKB

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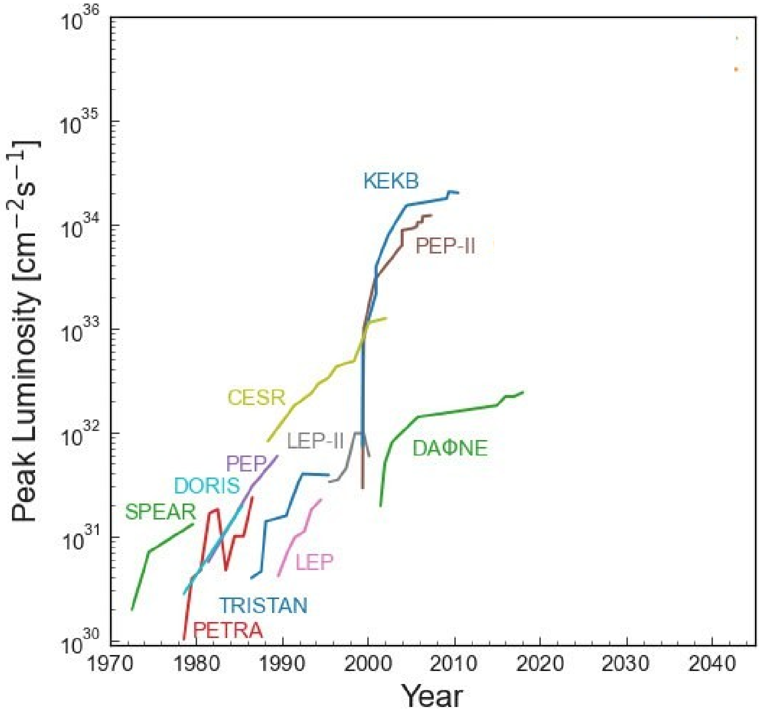
Belle II goal: collect 50 ab^{-1} (~50x Belle data)

SuperKEKB goal: > 30x KEKB luminosity ($6x10^{35}$ cm^{-1} s^{-1})



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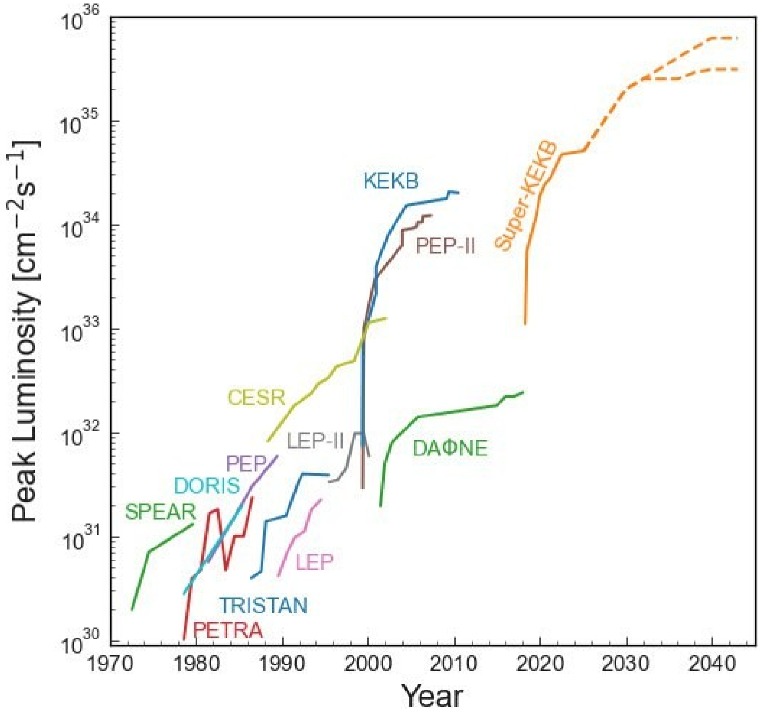

Beam currents

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Beam aspect ratio (flat beam ~1-2%)

Vertical β function at IP

Geometrical corrections

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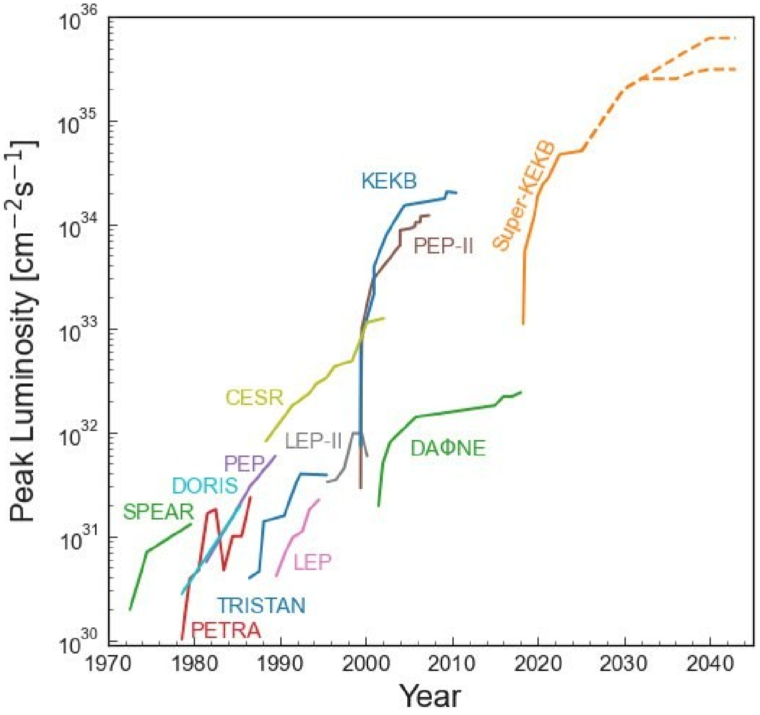

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More intense beams (modest gain):

- **Current 1.5 times larger**

Nanobeam scheme (large gain):

- **β_y* 10-20 times smaller**
- **Vertical beam size ~50 nm**

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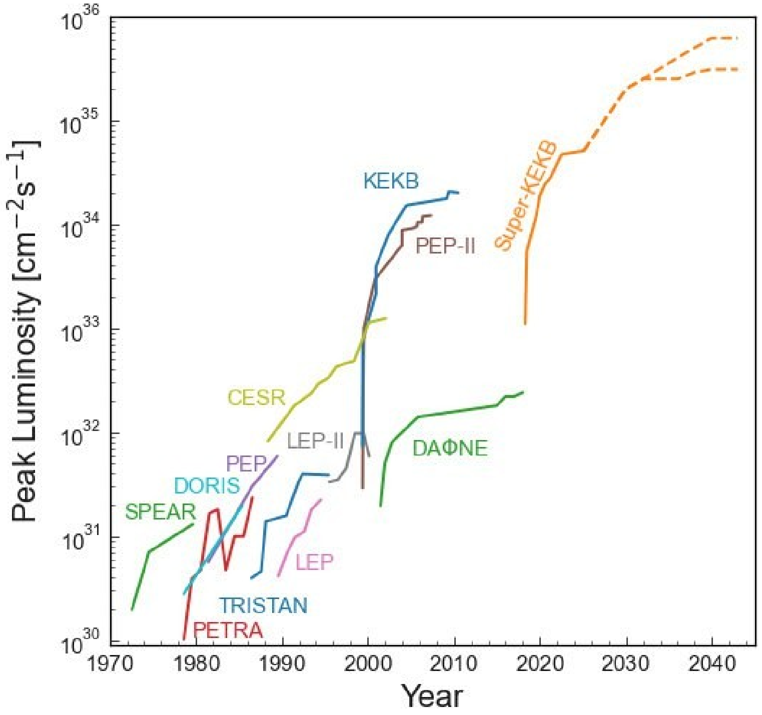

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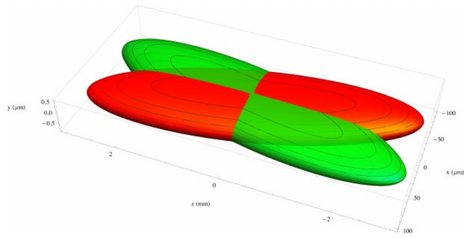

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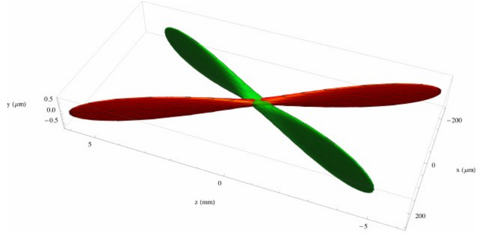


Belle II VS Belle

P. Lewis et al, NIM A 914, 69-144 (2019)

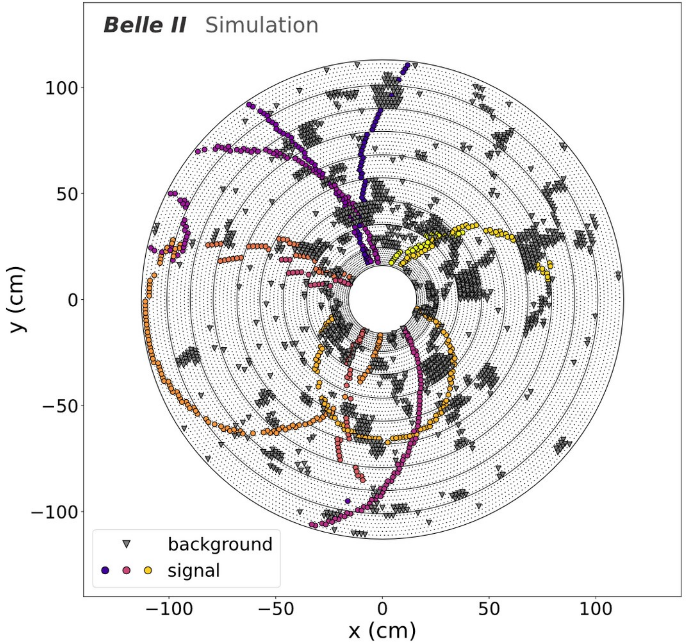
Single beam backgrounds:

- Touschek $\propto I^2 \sigma_y^{-1} n_b^{-1}$
- Beam gas $\propto I$
- Beam gas $\propto I$

Luminosity backgrounds:

- Radiative Bhabha $\propto L$
- Two-photon $\propto L$
- Injection

Belle II is designed to perform as well as or better than Belle with much higher backgrounds!



(a) Event display in the x-y plane.

L. Reuter et al., Comp. Softw. Big Sci 9, 6 (2025)

Belle II performance VS Belle

Comp. Phys. Comm. 259 (2021) 107610

Tracking:

- Better resolution, both low and high p_t
- Better efficiency at low p_t
- 2x better vertexing and decay time resolution

Comput. Softw. Big Sci 3, 6 (2019)

Full event reconstruction:

- Better purity and efficiency

[Paper in preparation]

Neutrals:

- Better algorithms and electronics
- (Currently) only enough to compensate the increased backgrounds

arXiv:2506.04355

PID:

- Better algorithms and new detectors
- (Currently) only enough to compensate the increased backgrounds

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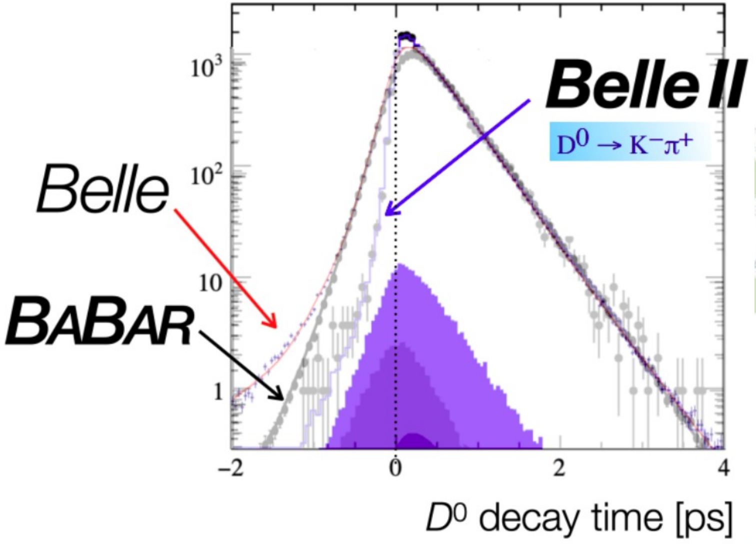

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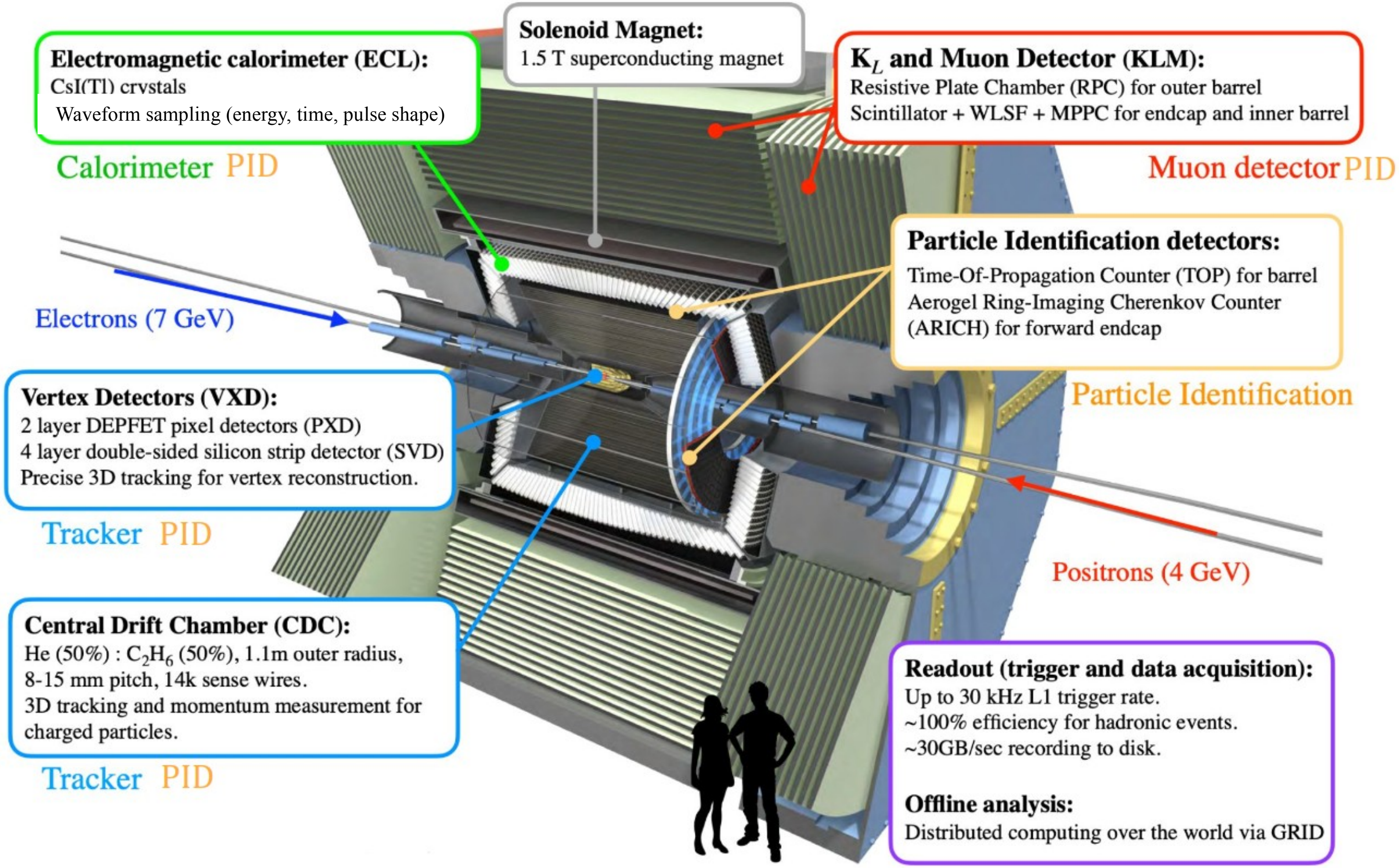
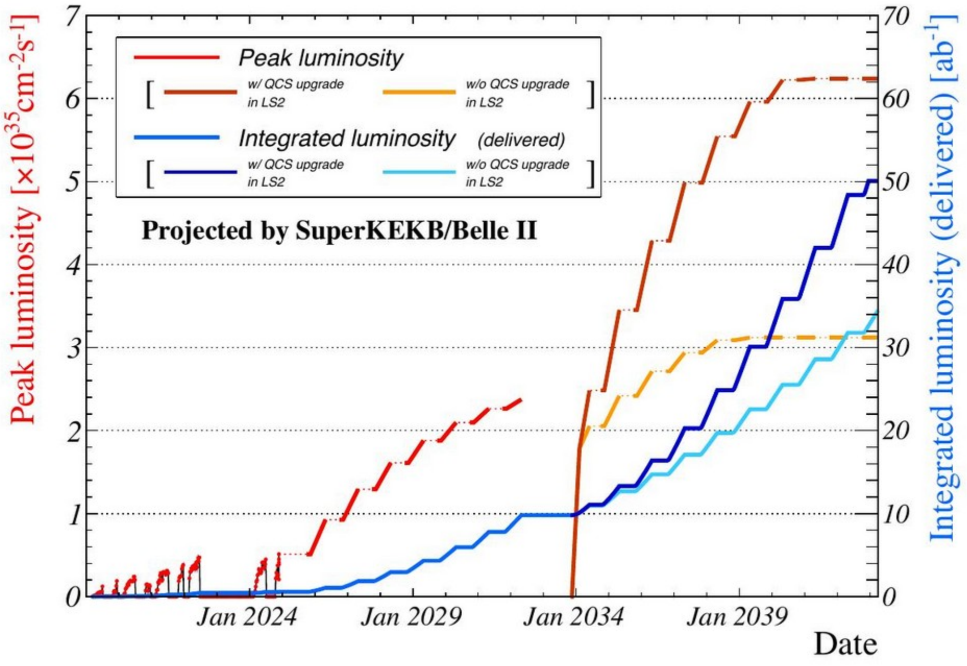
The Belle II detector



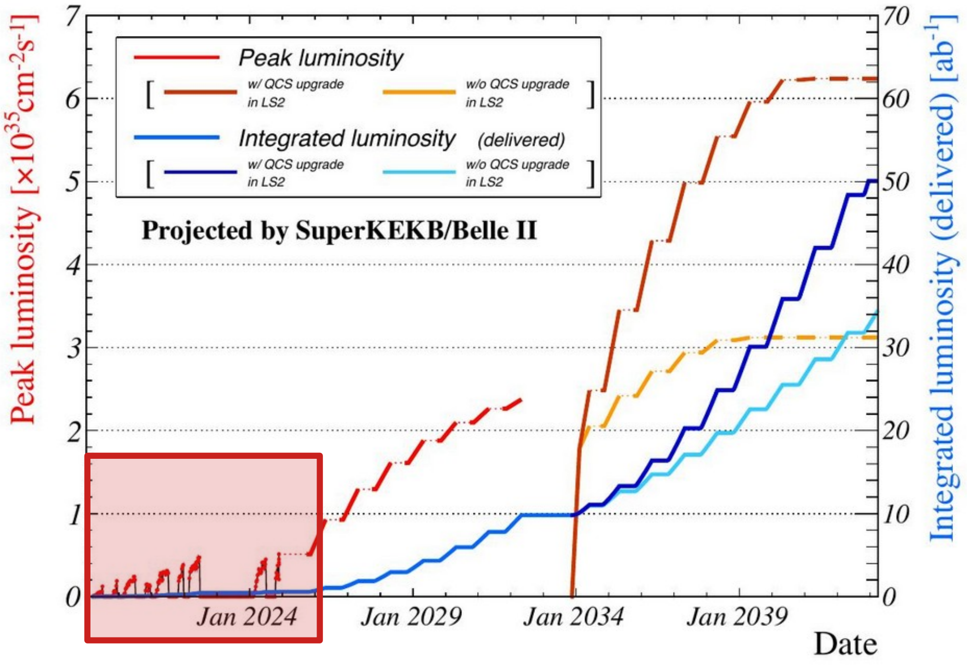
The data taking

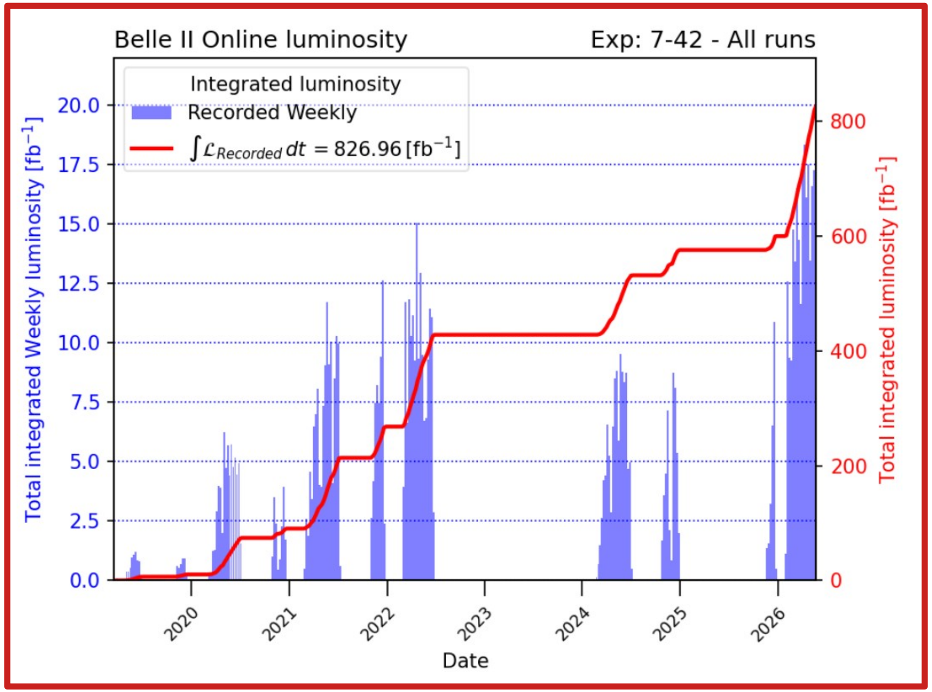


The data taking

On March 19th, 2026 SuperKEKB reached a peak luminosity of 5.244 10^{34} cm^{-2} s^{-1} (world record!)

On May 2026 Belle II surpassed the Υ(4S) luminosity of Belle, with a recorded L_{int} of > 713.7/fb

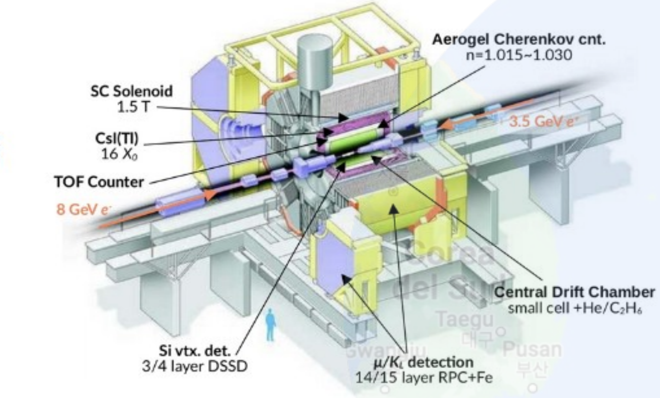




Updated on 2026/05/21 09:28 JST

Belle II + Belle

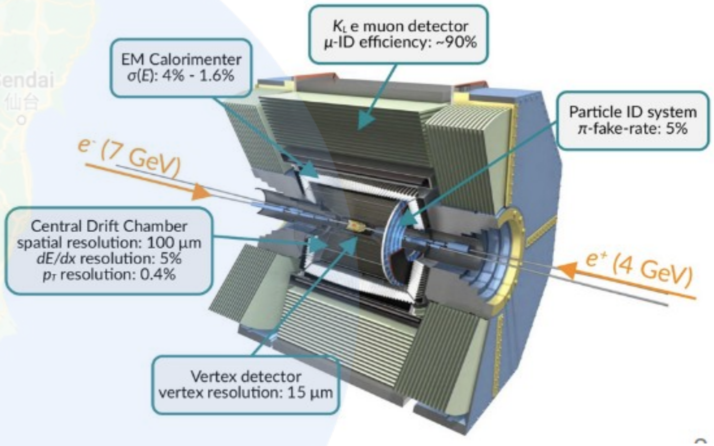
BELLE @ KEKB



BELLE + Belle II

$\int L\, dt$	
1 ab^{-1}	830 fb^{-1} {50 ab^{-1}}
L_{peak} [cm^{-2} s^{-1}]	
2.1 x 10^{34}	5.24 x 10^{34} {60 x 10^{34}} **World record!**

Belle II @ SuperKEKB



Belle & Belle II are now synergic experiments

- Belle data can be analyzed with the Belle II software
- Analyses with combined data samples → Common review procedures in place

The physics of Belle II

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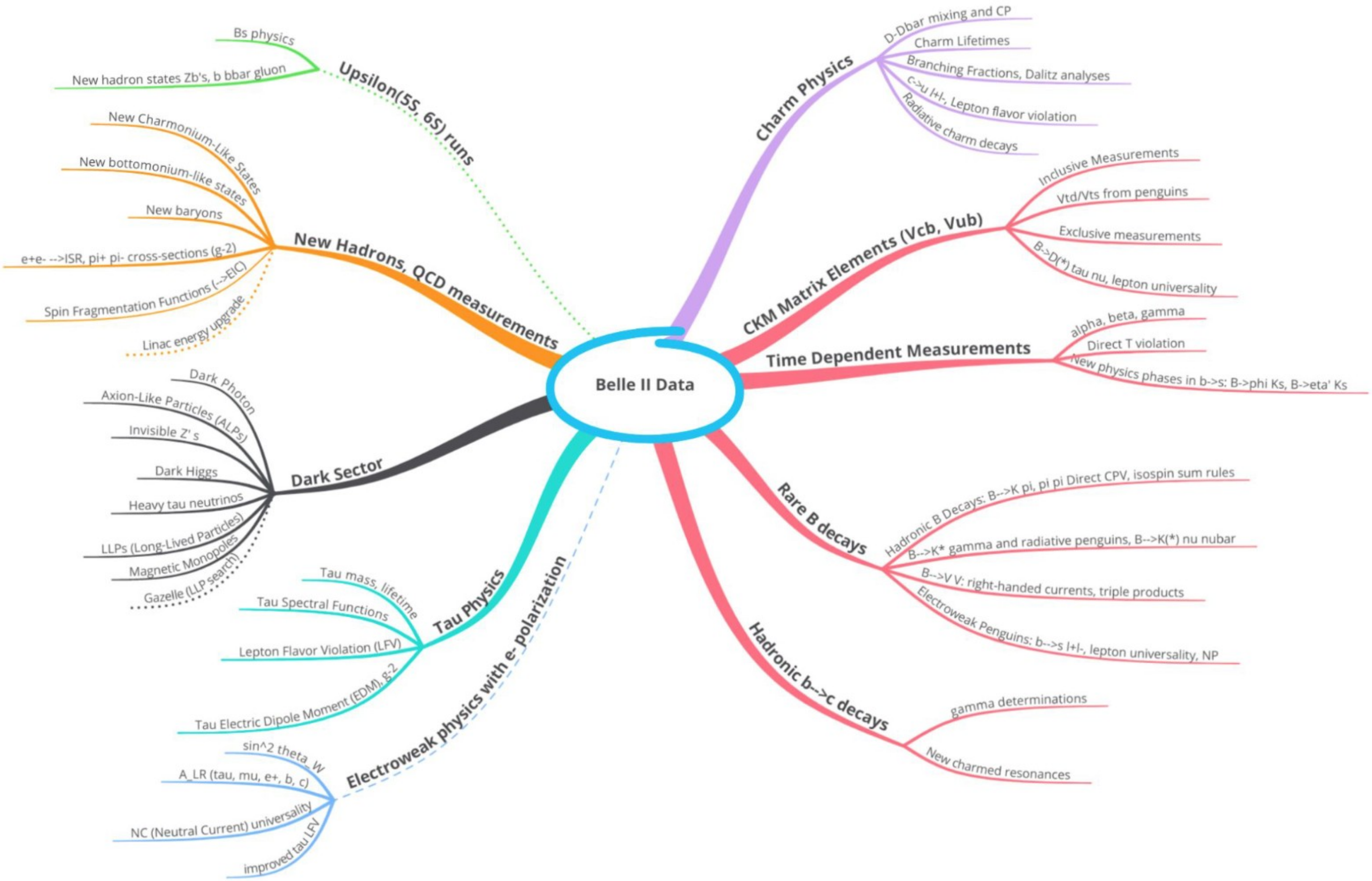
The Belle II Physics Book



Charm production

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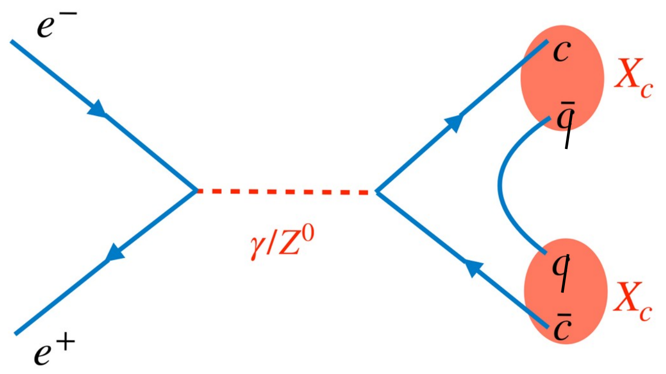
Two ways of producing charm at *B*-Factories

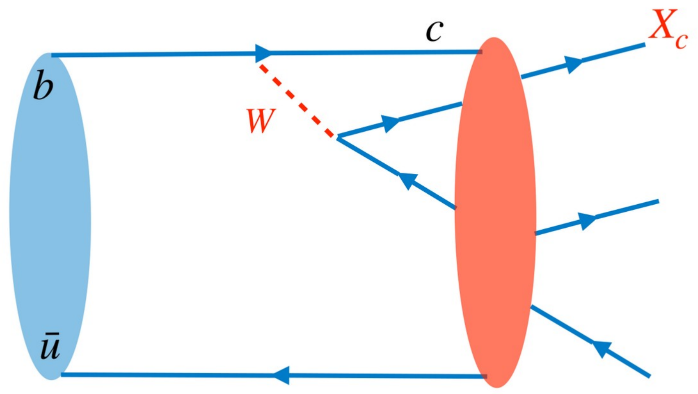
Two charmed hadrons produced from continuum



Large statistics but high level background

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

One or more charmed hadrons produced in *B* decays



Low statistics but very clean sample

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

Charm physics program – Belle II publications (not complete)

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Precision measurements - charm lifetimes:

- D^0, D^+ [PRL 127, 211801 (2021)]
- D^+_s [PRL 131, 171803 (2023)]
- Λ^+_c [PRL 130, 071802 (2023)]
- Ω^0_c [PRD 107, L031103 (2023)]

Charmed mesons, CP asymmetries:

- $D^+ \to \pi^+ \pi^0$ [PRD 112, L031101 (2025)]
- $D^0 \to \pi^0 \pi^0$ [PRD 112, 012006 (2025)]
- $D^0 \to K_s K_s$ [PRD 111, 012015 (2025),PRD 112, 012017 (2025)]

Charmed baryons from B decays:

- $B^{+(0)} \to \Sigma_c(2455)^{++(0)} \bar{\Xi}^{-(0)}_c$ [PRD 112, L051101 (2025)]

Charmed mesons, mixing parameters:

- $D^0 \to K_s \pi^+ \pi^-$ [PRD 111, 112011 (2025)]

Charmed baryons:

First observations and BFs:

- $\Xi^0_c \to \Xi^0 h$ ($h = \pi^0, \eta, \eta'$) [JHEP 10 (2024) 045]
- $\Xi^0_c \to \Lambda h$ ($h = \pi^0, \eta, \eta'$) [PRD 113,032015 (2026)]
- $\Xi^+_c \to p K_s, \Lambda \pi^+, \Sigma^0 \pi^+$ [JHEP 03 (2025) 061]
- $\Xi^+_c \to \Sigma^+ K_s, \Xi^0 \pi^+, \Xi^0 K^+$ [JHEP 08 (2025) 195]

CPV:

- $\Xi^+_c \to \Sigma^+ h^+ h^-$, $\Lambda^+_c \to p h^+ h^-$ [PRD 113, 032017 (2026)]

Exotic hadrons:

- $D_{s0}^*(2317)$ [accepted by PRL, arXiv:2510.27174]

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First measurement of $\mathscr{B}(\Xi^0_c \rightarrow \Lambda h^0)$ at Belle and Belle II

PRD 113,032015 (2026)

Singly Cabibbo-suppressed $\Xi_c^0 \rightarrow \Lambda h^0$ decays ($h^0 = \eta, \eta', \pi^0$)
$\rightarrow$ First measurements of branching fraction relative to $\Xi_c^0 \rightarrow \Xi^- \pi^+$

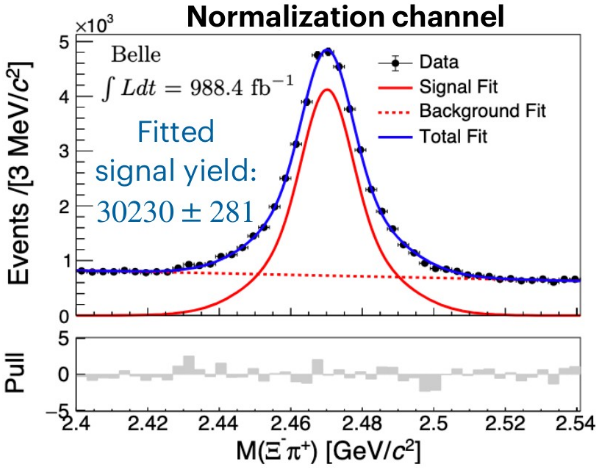
Precise measurements of these modes:

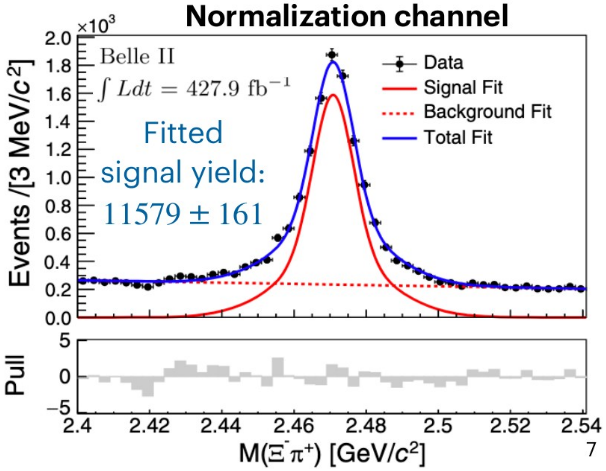
- Improve understanding of decay dynamics
- Clarify the theoretical picture

Reconstruct: $\Lambda \rightarrow p\pi^-$, $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta' \rightarrow \pi^+\pi^-\gamma$,
$\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$

Normalization mode $\Xi_c \rightarrow \Xi^- \pi^+$ cancels common input $\mathscr{B}(\Lambda \rightarrow p\pi^-)$

Normalization yield extracted from an unbinned extended maximum-likelihood fit to $M(\Xi^-\pi^+)$ spectra





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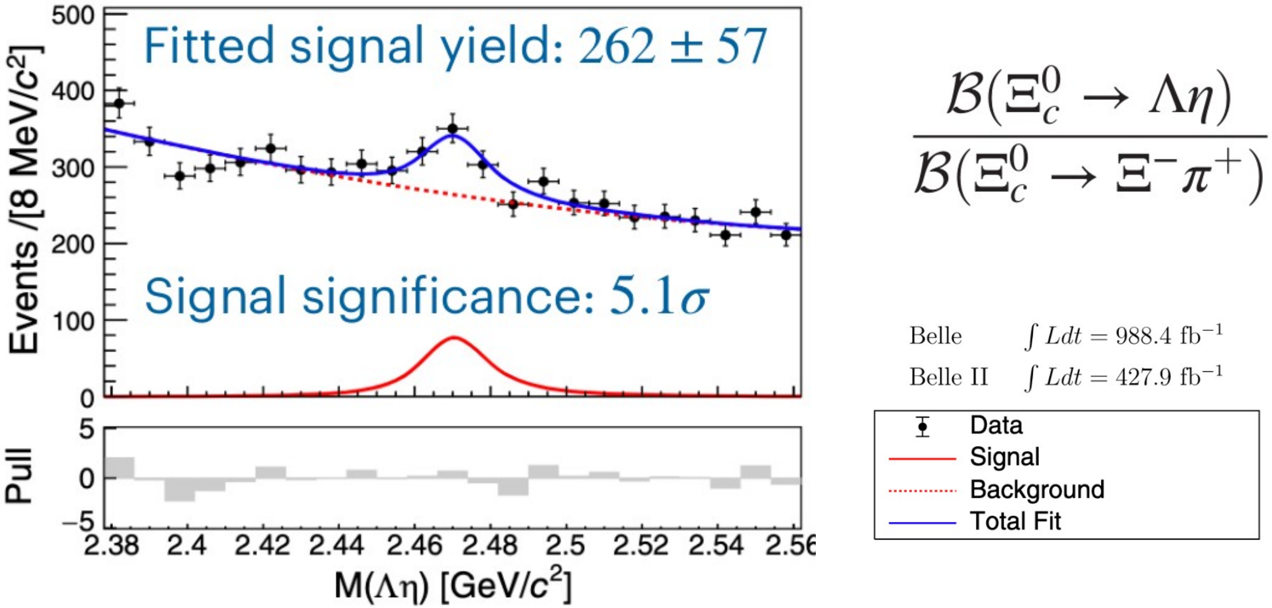
PRD 113,032015 (2026)

$\mathscr{B}(\Xi^0_c \to \Lambda h^0)$ / $\mathscr{B}(\Xi^0_c \to \Xi^- \pi^+)$ simultaneous unbinned extended maximum-likelihood fit to $M(\Lambda h^0)$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda h^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = N_{\Lambda h^0} \cdot \left[\Sigma_i \Sigma_j \left(N^j_{\Xi^-\pi^+} \cdot \frac{\epsilon^j_{i,\Lambda h^0}}{\epsilon^j_{\Xi^-\pi^+}} \cdot \frac{B_i(h^0)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}\right)\right]^{-1}$$



$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda \eta)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = (4.16 \pm 0.91 \pm 0.23)\%$$

Belle $\int L dt = 988.4\ \text{fb}^{-1}$

Belle II $\int L dt = 427.9\ \text{fb}^{-1}$

First measurement of $\mathscr{B}(\Xi^0_c \to \Lambda h^0)$ at Belle and Belle II

PRD 113,032015 (2026)

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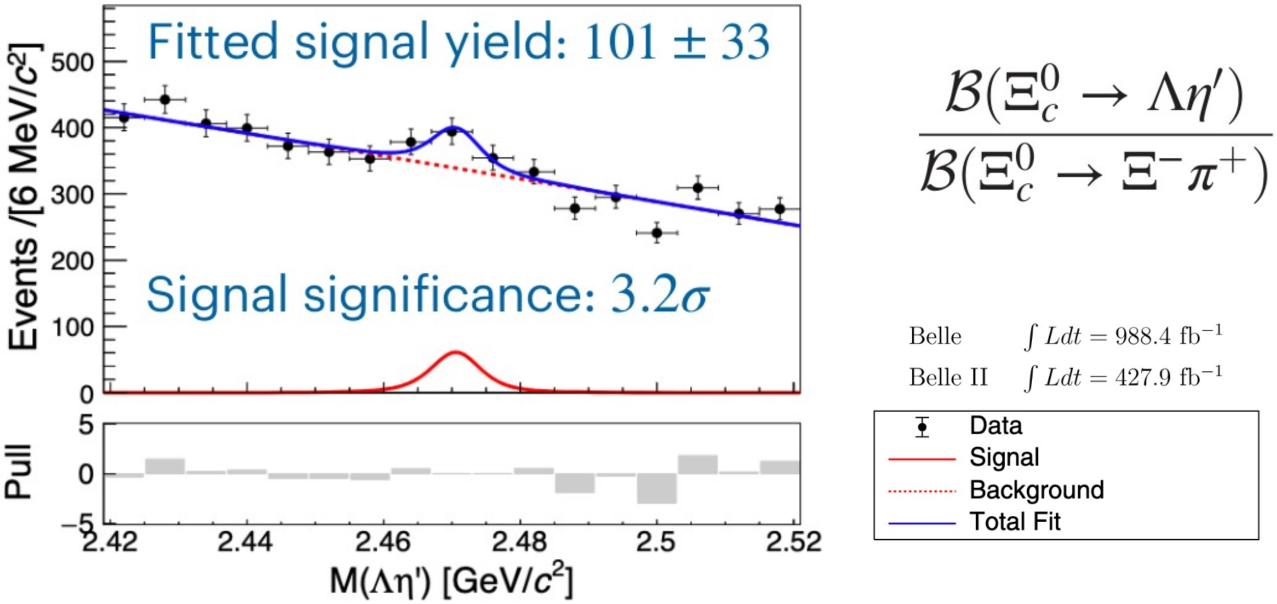

$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda \eta')}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = (2.48 \pm 0.82 \pm 0.12)\%$$

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Belle II $\int L dt = 427.9 \text{ fb}^{-1}$

First measurement of $\mathscr{B}(\Xi^0_c \to \Lambda h^0)$ at Belle and Belle II

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$\mathscr{B}(\Xi^0_c \to \Lambda h^0)$ / $\mathscr{B}(\Xi^0_c \to \Xi^- \pi^+)$
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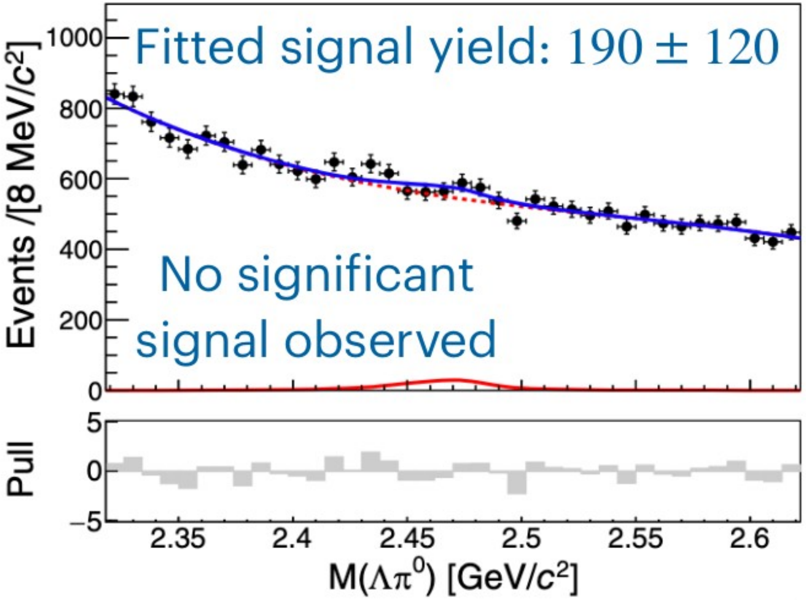
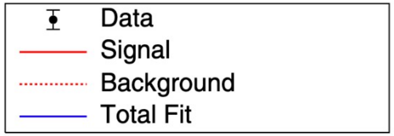


$$\frac{\mathcal{B}(\Xi_c^0 \to \Lambda\pi^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} < 3.5\%$$

Belle $\int L dt = 988.4\ \mathrm{fb}^{-1}$

Belle II $\int L dt = 427.9\ \mathrm{fb}^{-1}$



First measurement of $\mathcal{B}(\Xi^0_c \to \Lambda h^0)$ at Belle and Belle II

PRD 113,032015 (2026)

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$\mathcal{B}(\Xi^0_c \to \Lambda h^0) / \mathcal{B}(\Xi^0_c \to \Xi^- \pi^+)$
simultaneous unbinned extended maximum-likelihood fit to $M(\Lambda h^0)$

Multiplying by the world-average

$$\mathcal{B}(\Xi^0_c \to \Xi^- \pi^+) = (1.43 \pm 0.27)\%$$

$$\mathcal{B}(\Xi^0_c \to \Lambda\eta) = (5.95 \pm 1.30_{stat} \pm 0.32_{syst} \pm 1.13_{th}) \times 10^{-4}$$

$$\mathcal{B}(\Xi^0_c \to \Lambda\eta') = (3.55 \pm 1.17_{stat} \pm 0.17_{syst} \pm 0.68_{th}) \times 10^{-4}$$

$$\mathcal{B}(\Xi^0_c \to \Lambda\pi^0) < 5.2 \times 10^{-4} \text{ at @90\% CL}$$

First-ever measurements, statistically limited

First measurement of $\mathcal{B}(\Xi^0_c \to \Lambda h^0)$ at Belle and Belle II

PRD 113,032015 (2026)

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$\mathcal{B}(\Xi^0_c \to \Lambda h^0) / \mathcal{B}(\Xi^0_c \to \Xi^- \pi^+)$ simultaneous unbinned extended maximum-likelihood fit to $M(\Lambda h^0)$

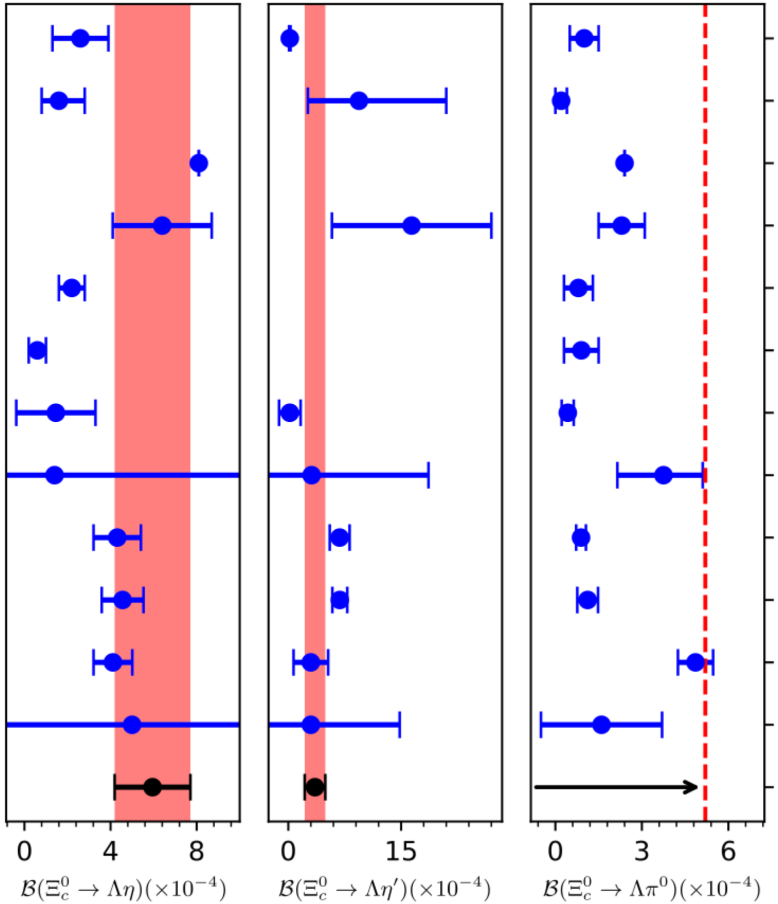
Multiplying by the world-average

$$\mathcal{B}(\Xi^0_c \to \Xi^- \pi^+) = (1.43 \pm 0.27)\%$$

$$\mathcal{B}(\Xi^0_c \to \Lambda\eta) = (5.95 \pm 1.30_{stat} \pm 0.32_{syst} \pm 1.13_{th}) \times 10^{-4}$$

$$\mathcal{B}(\Xi^0_c \to \Lambda\eta') = (3.55 \pm 1.17_{stat} \pm 0.17_{syst} \pm 0.68_{th}) \times 10^{-4}$$

$\mathcal{B}(\Xi^0_c \to \Lambda\pi^0) < 5.2 \times 10^{-4}$ at @90% CL



First-ever measurements, statistically limited

Consistent with theoretical predictions

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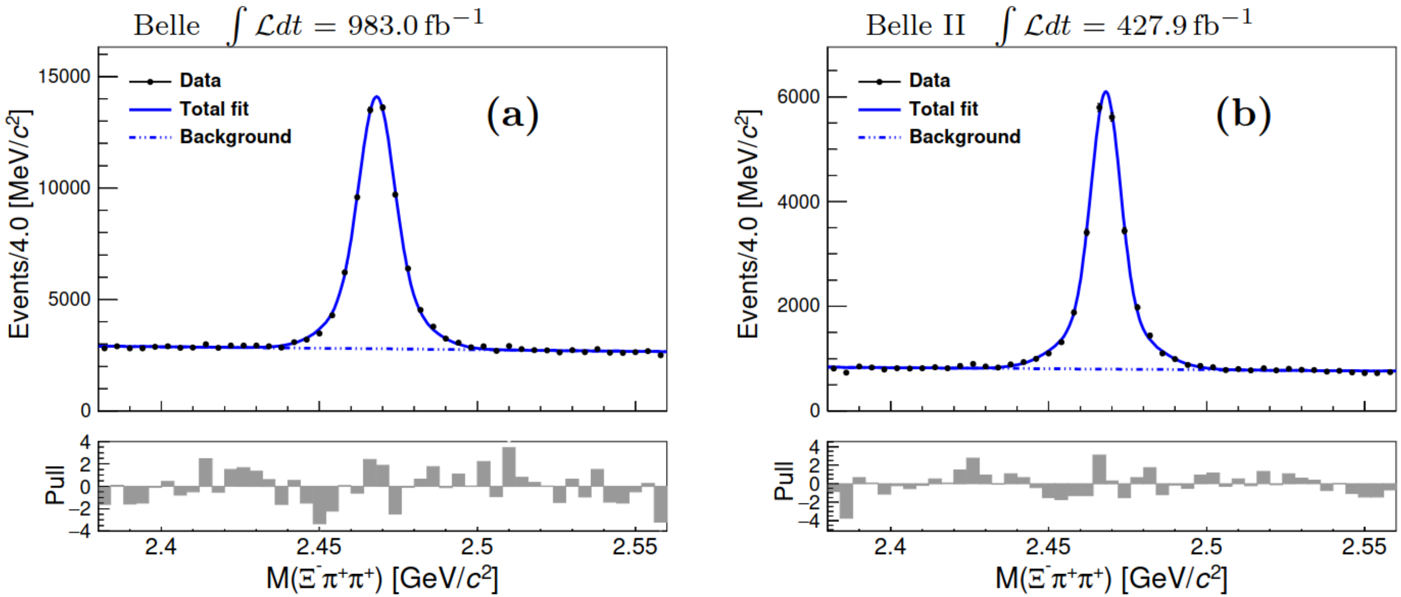
Branching fractions measurements of charmed baryons are indispensable to solve theoretical tensions

Measure the ratio $\mathscr{B}(\Xi^+_c \to \Sigma^+ K_S, \Xi^0 \pi^+, \Xi^0 K^+) / \mathscr{B}(\Xi_c \to \Xi^- \pi^+ \pi^+)$ using an extended maximum-likelihood fit to the invariant masses



Measurements of $\mathscr{B}(\Xi^+_c \to \Sigma^+ K_S, \Xi^0\pi^+, \Xi^0 K^+)$ at Belle and Belle II

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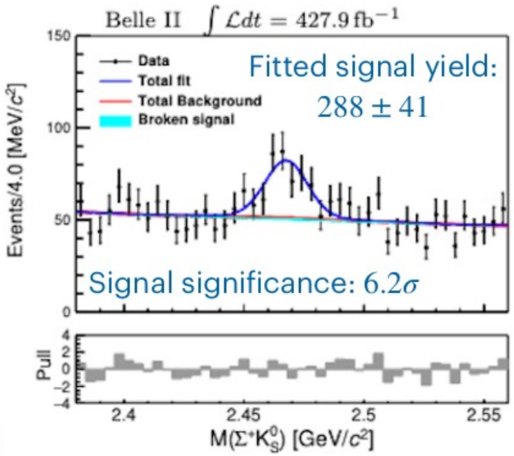
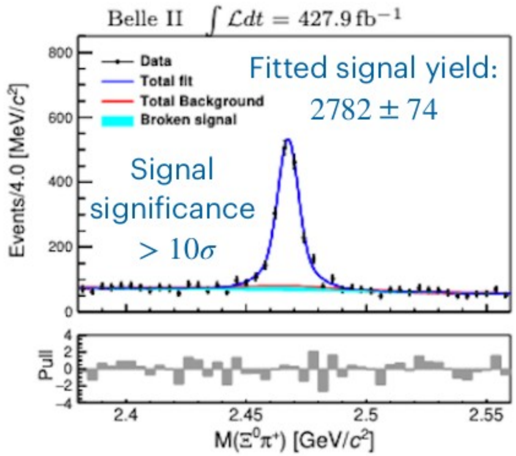
$$\frac{\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0)}{\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)} = 0.067 \pm 0.007 \pm 0.003,$$

$$\frac{\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)} = 0.251 \pm 0.005 \pm 0.010$$

$$\frac{\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)} = 0.017 \pm 0.003 \pm 0.001$$





Measurements of $\mathcal{B}(\Xi^+_c \rightarrow \Sigma^+ K_S, \Xi^0\pi^+, \Xi^0 K^+)$ at Belle and Belle II

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Branching fractions measurements of charmed baryons are indispensable to solve theoretical tensions

Measure the ratio $\mathcal{B}(\Xi^+_c \rightarrow \Sigma^+ K_S, \Xi^0 \pi^+, \Xi^0 K^+) / \mathcal{B}(\Xi_c \rightarrow \Xi^- \pi^+ \pi^+)$ using an extended maximum-likelihood fit to the invariant masses

Multiplying the results by the $\mathcal{B}(\Xi_c \rightarrow \Xi^- \pi^+ \pi^+)_{th} = (2.9 \pm 1.3)\%$:

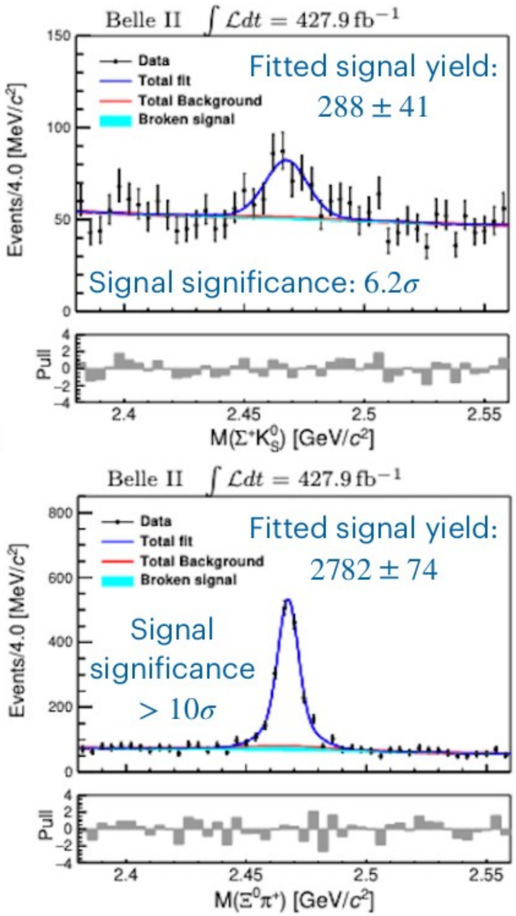
$$\mathcal{B}(\Xi_c^+ \rightarrow \Sigma^+ K_S^0) = (0.194 \pm 0.021_{stat} \pm 0.009_{syst} \pm 0.087_{th})\,\%$$

$$\mathcal{B}(\Xi_c^+ \rightarrow \Xi^0 \pi^+) = (0.728 \pm 0.014_{stat} \pm 0.027_{syst} \pm 0.326_{th})\,\%$$

First measurements of these decays

$$\mathcal{B}(\Xi_c^+ \rightarrow \Xi^0 K^+) = (0.049 \pm 0.007_{stat} \pm 0.003_{syst} \pm 0.022_{th})\,\%$$

World's best measurement



Measurements of $\mathscr{B}(\Xi^+_c \to \Sigma^+ K_S, \Xi^0\pi^+, \Xi^0 K^+)$ at Belle and Belle II

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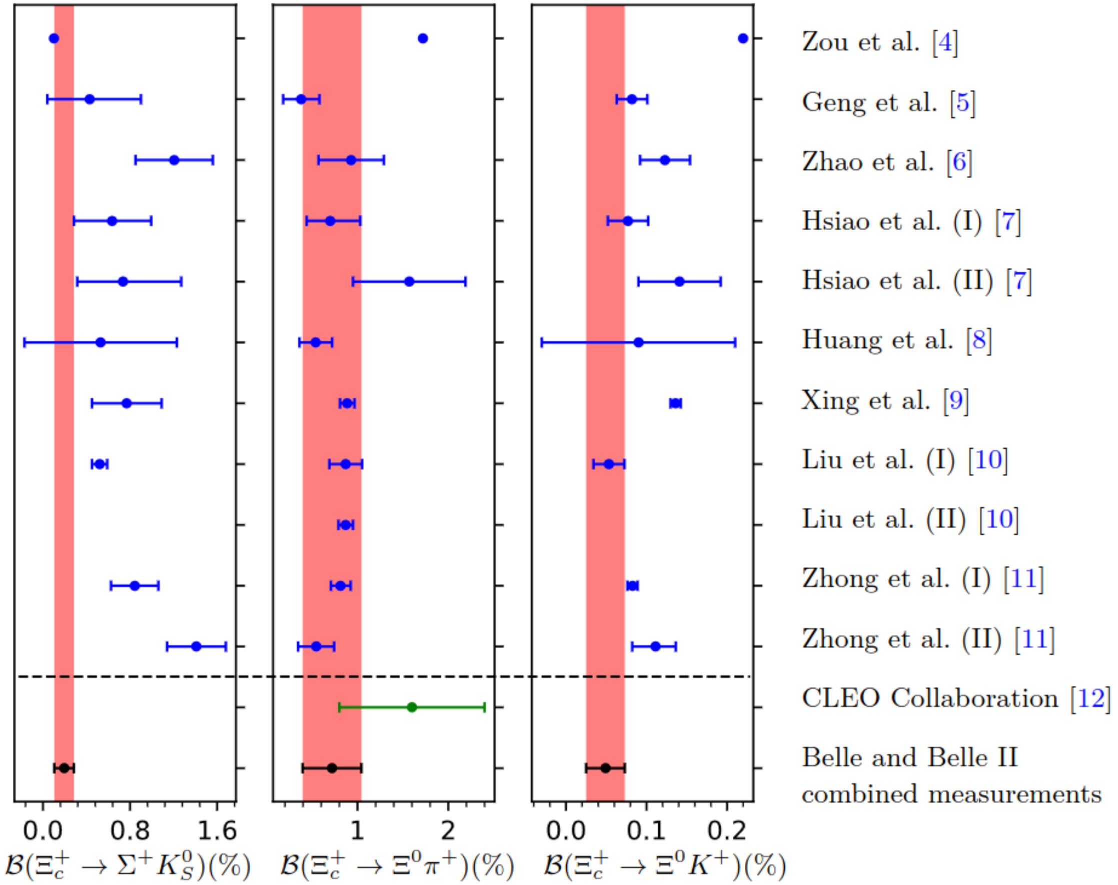

$\mathscr{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.194 \pm 0.021_{stat} \pm 0.009_{syst} \pm 0.087_{th})\,\%$

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First measurements of these decays

$\mathscr{B}(\Xi_c^+ \to \Xi^0 K^+) = (0.049 \pm 0.007_{stat} \pm 0.003_{syst} \pm 0.022_{th})\,\%$

World's best measurement

Results are **independent** of the Ξ^+_c absolute branching fraction scale and may serve as benchmarks for future theoretical works

First observation of the radiative decay $D^*_{s0}(2317)^+ \rightarrow D_s^{*+} \gamma$

arXiv:2510.27174

Nature of $c\bar{s}$ states $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ unclear:
masses significantly below those predicted by the quark model

Several theoretical frameworks: hadronic molecules, mixed configs, tetraquarks
→ motivate further studies

$D^*_{s0}(2317)^+$: mass lies below the DK threshold, restricting its decay to the isospin-violating strong decay channel $D^*_{s0}(2317)^+ \rightarrow D_s^+ \pi^0$

Radiative transitions are particularly sensitive probes of the internal structure
→ Determination of R can constrain theoretical models

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

First observation of the radiative decay $D^*_{s0}(2317)^+ \rightarrow D_s^{*+} \gamma$

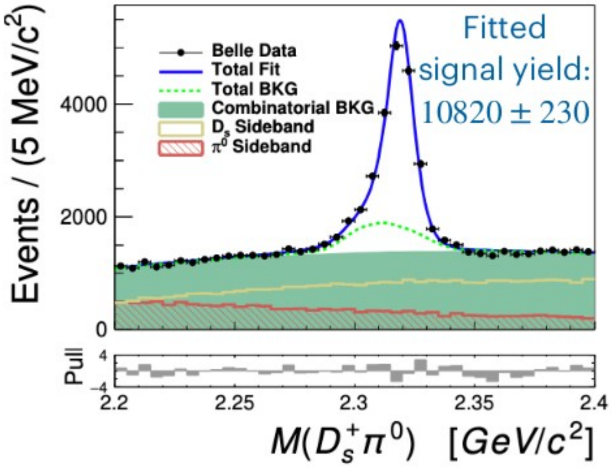
arXiv:2510.27174

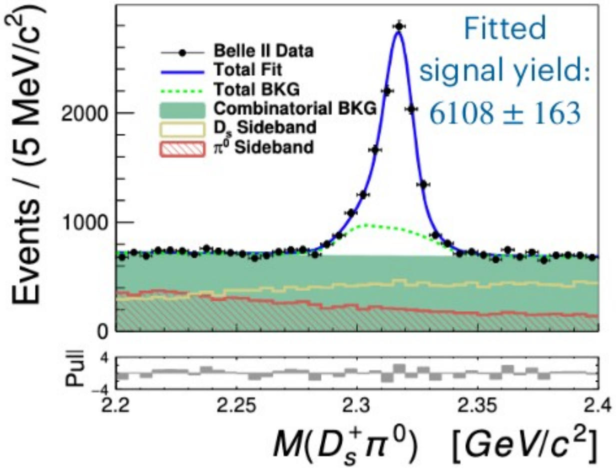
Reconstruct $D_s^+ \rightarrow \phi[\rightarrow K^+K^-]\pi^+$ and $D_s^+ \rightarrow \bar{K}^{*0}[\rightarrow K^- \pi^+] K^+$

- $D^*_{s0}(2317)^+$ from $D_s^{*+}\gamma$ or $D_s^+ \pi^0$ combinations
- $D^*_{s0}(2317)^+ \rightarrow D_s^+ \pi^0$ as a normalization channel: yield obtained from an unbinned maximum-likelihood fit to $M(D_s \pi^0)$ spectra

Detailed study of background sources:

- use D_s and π^0 sidebands
- Peaking background from a missing γ in $D_{s1}(2460)^+ \rightarrow D_s^{*+} \pi^0$ decays
- Shape & yield obtained from fits to signal Monte Carlo samples





First observation of the radiative decay $D^*_{s0}(2317)^+ \to D_s^{*+}\gamma$

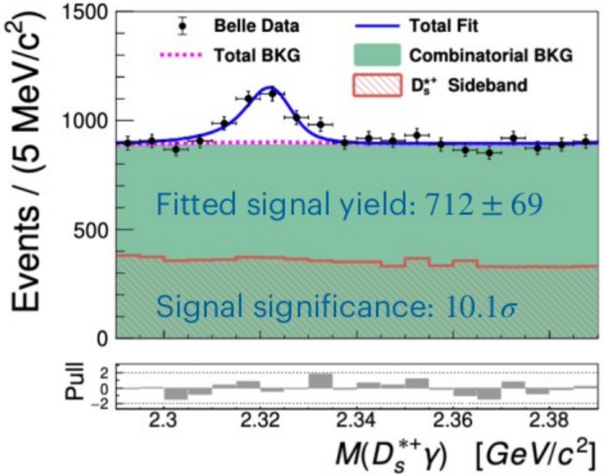
arXiv:2510.27174

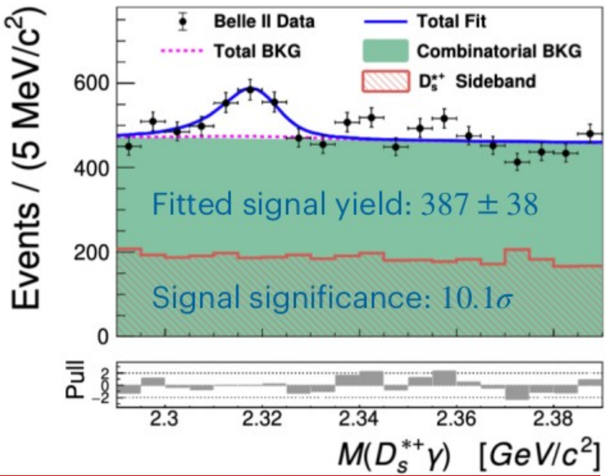
First measurement of R using a simultaneous unbinned maximum-likelihood fit to $M(D_s^{*+}\gamma)$ spectra

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

Statistically limited

$$R = (7.14 \pm 0.70_{stat} \pm 0.23_{syst})\,\%$$





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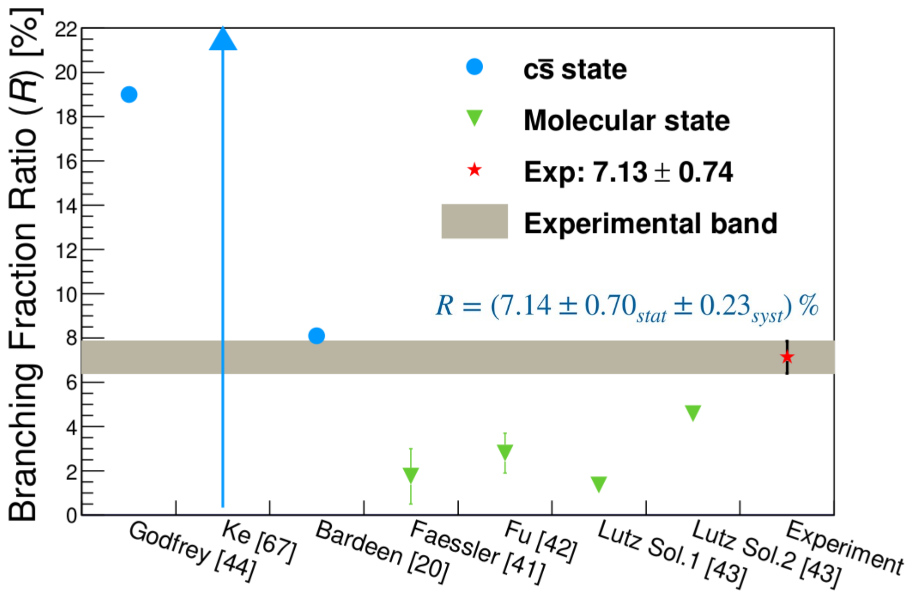

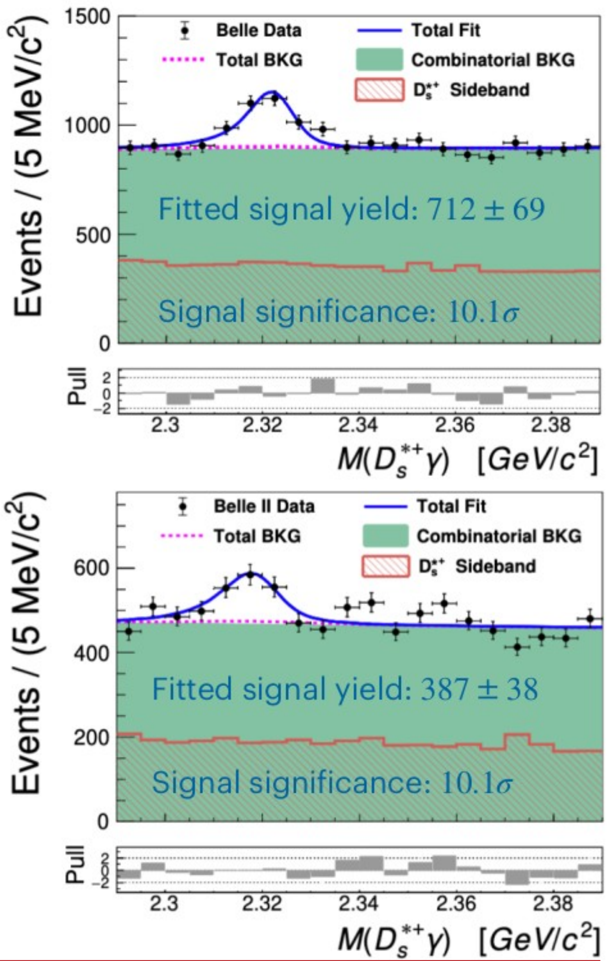

Above molecular predictions, below quark-model expectations: could be a mixed configuration

Summary

Belle and Belle II provide a broad environment for charm-physics studies
→ Datasets can be combined

Presented three recent results on charm spectroscopy

- First measurements of three $\Xi^0 \to \Lambda h^0$ modes
- BF of Cabibbo-favored and singly Cabibbo-suppressed Ξ^+_c decays
- First observation of $D^*_{s0}(2317)^+ \to D_s^{*+}\gamma$

All measurements are statistically limited

All measurements are worlds most precise determinations