

# Tau and Charm Physics @ Belle & Belle II

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile

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(On Behalf of the Belle II Collaboration)

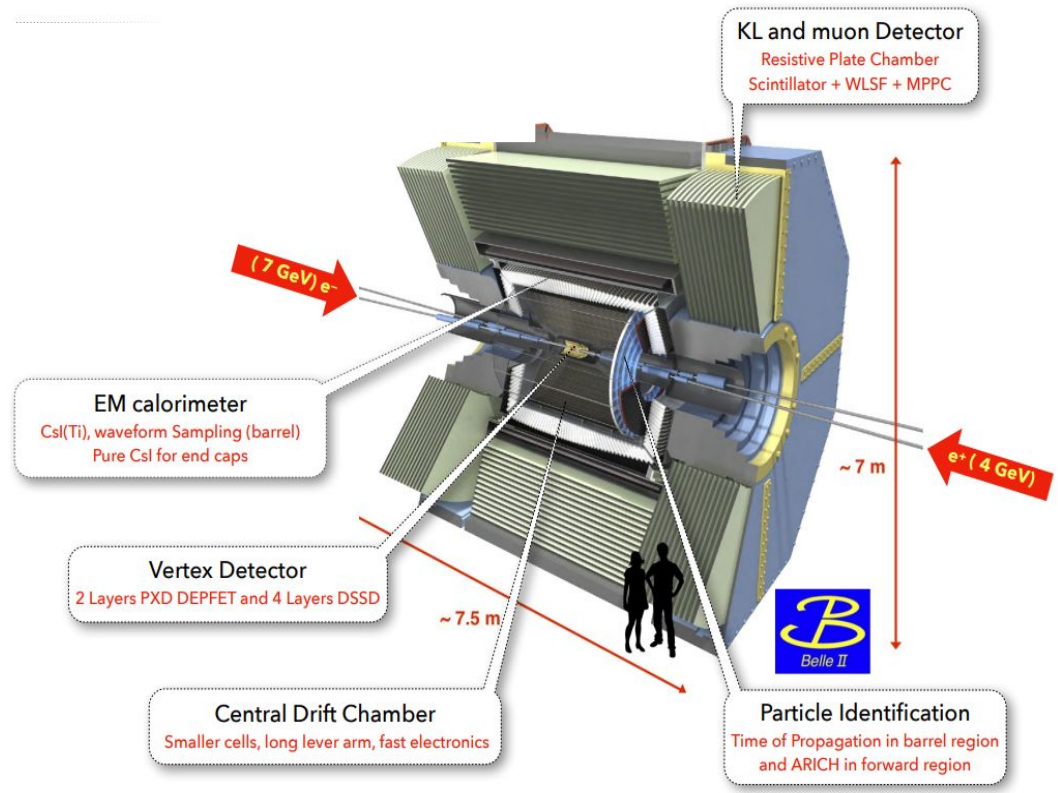
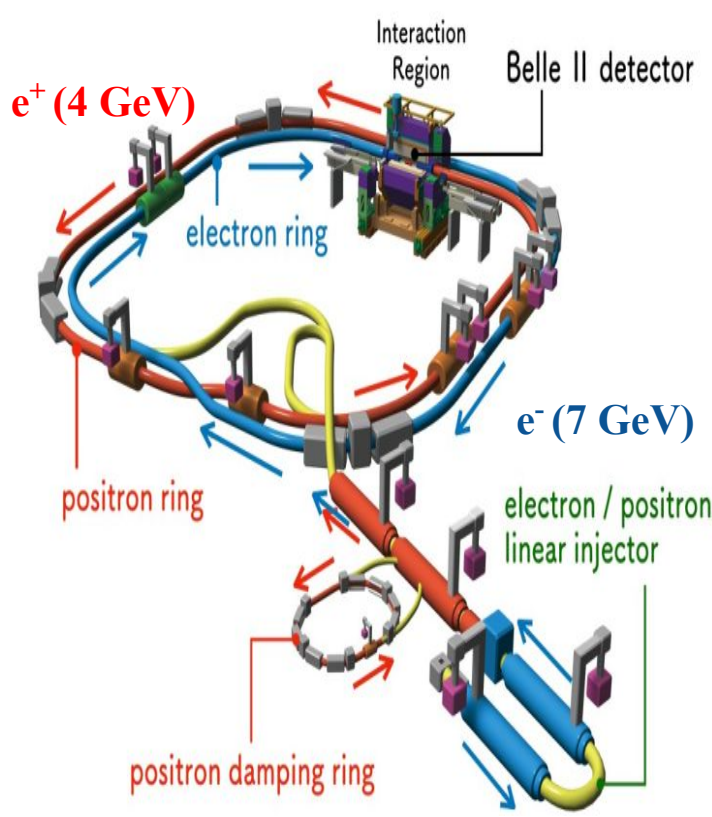
04/03/2026

**Università di Torino, INFN Sezione di Torino**



- *Experimental Facility*
- *Production and reconstruction*
- *Results :*
  - *Precision measurements*
  - *LFV searches*
  - *First observations*
- *Summary*

# SuperKEKB & Belle II Detector




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

$e^+e^- \rightarrow \tau\tau$  (0.92 nb)  
 $e^+e^- \rightarrow c\bar{c}$  (1.3 nb)

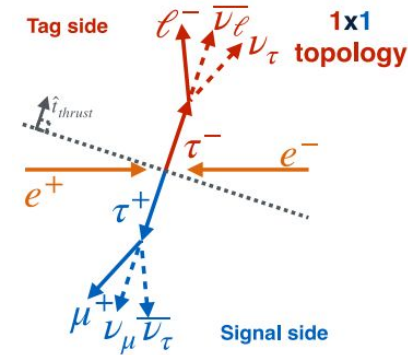
**also a  $\tau$  and charm factory !!**



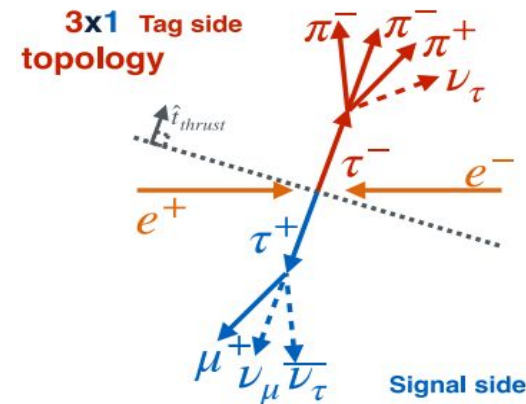
# $\tau$ Physics

# Production and reconstruction of $\tau$ leptons

- $\tau$  pairs are produced back-to-back and boosted in the CM frame
- separation into two hemispheres via plane perpendicular to the thrust axis
- Can reconstruct  $\tau$  either via one charged track (1-prong) or via three charged tracks (3-prong)
- Specific low-multiplicity triggers (not available at Belle)
- Also exploit untagged analyses to boost the signal efficiency



$$T = \max_{\hat{t}} \left( \frac{\sum_i |\rho_i^{CMS} \cdot \hat{t}|}{\sum_i |\rho_i^{CMS}|} \right)$$

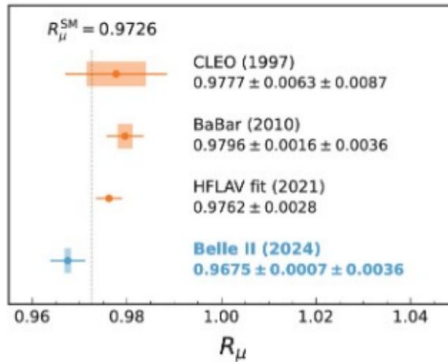
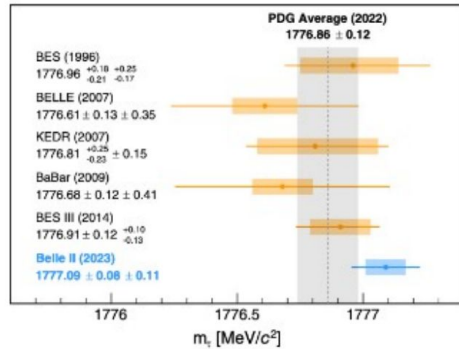


# $\tau$ physics program at Belle II

- **Precision SM measurements:** indirect hints of New Physics (NP) in SM deviations measurements usually dominated by systematic uncertainty.

$\tau$  mass  
PRD 108, 032006 (2023)

e- $\mu$  universality  
JHEP 2024, 205 (2024)



- **Direct search for rare or forbidden processes:**

- charged LFV decays via neutrino oscillation are highly suppressed and immeasurably small (about  $10^{-50}$ ).
- Any observation would be unambiguous sign of NP, need to boost signal efficiencies to reach sensitivities  $< 10^{-8}$

$$\tau \rightarrow 3\mu$$

JHEP 2024, 62 (2024)

$$\tau \rightarrow \Lambda\pi$$

PRD 110, 112003 (2024)

$$\tau \rightarrow \ell\alpha$$

PRL 130, 181803 (2023)

JHEP 2025, 155 (2025)

$$\tau \rightarrow e\ell\ell'$$

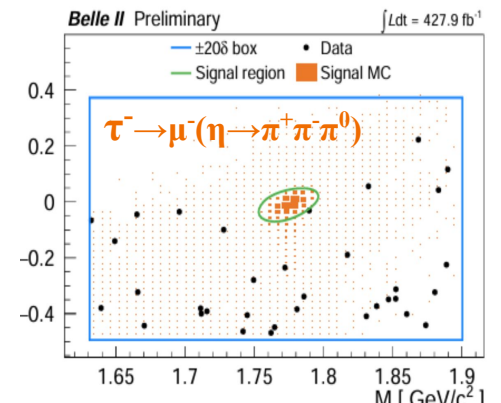
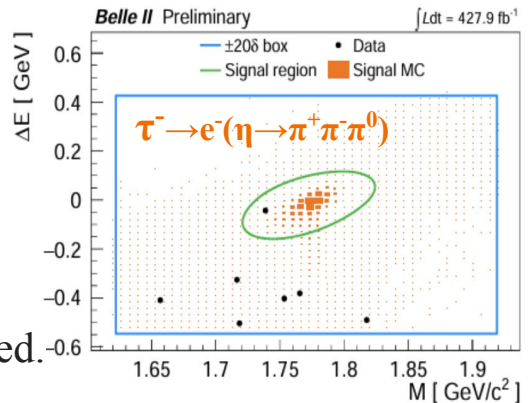
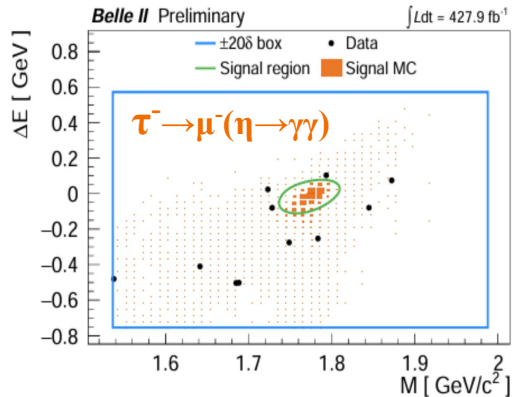
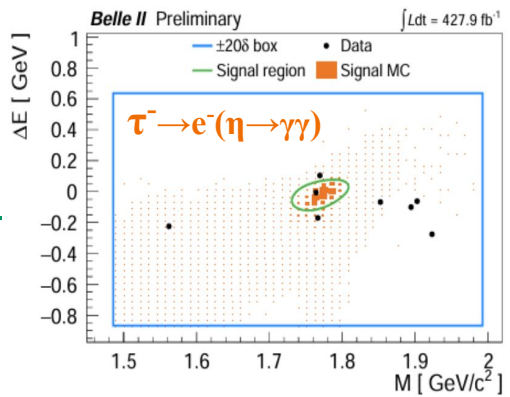
JHEP12(2025)169

$$\tau \rightarrow \ell K_S^0$$

JHEP 2025, 92 (2025)

# $\tau \rightarrow l \eta$

- Enhancement possible in NP scenarios
- Most stringent upper limit set by Belle (401 fb<sup>-1</sup>) at 90% C.L. [PLB 648 \(2007\) 341](#)
- 1x1 (3x1) prong topology
- Search in the 2D plane : (M<sub>τ</sub>, ΔE)
- Background suppression:
  - Cut based selection
  - Residual bkg suppressed using BDT
  - Signal region size are optimized
- no statistically significant excess is observed.
- Current upper limits for (at 90% C.L.)
  - B(τ→eη) < 9.2 x10<sup>-8</sup>
  - B(τ→μη) < 4.2 x10<sup>-8</sup> (*world leading!!*)



$$\Delta E = E_{\tau}^{\text{CM}} - \sqrt{s}/2$$

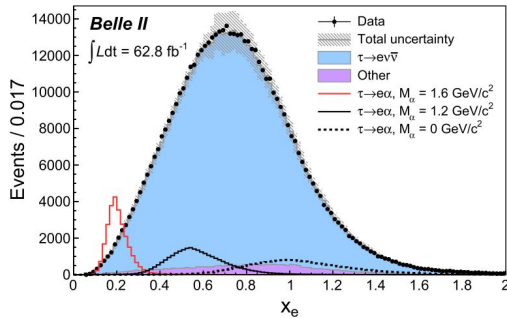
# $\tau \rightarrow l \alpha$

- Light, invisible BSM bosons predicted in models (eg: axion like particles) are collectively called  $\alpha$ .
- Identical visible topology with  $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$  (irreducible bkg), search for 2-body bump on SM 3-body decay spectrum.

- Belle II analysis ( $62.8 \text{ fb}^{-1}$ ): [PRL 130, 181803 \(2023\)](#)
  - look for an excess of events above  $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$  spectrum of normalized lepton energy
  - For  $m_\alpha \in (0, 1.6) \text{ GeV}/c^2$ , 95% CL:

$$\frac{\mathcal{B}(\tau^- \rightarrow e^- \alpha)}{\mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)}$$
 is in  $(1.1-9.7) \times 10^{-3}$  range

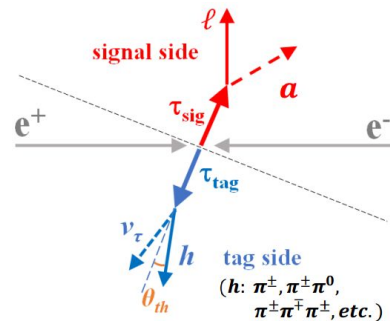
$$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \alpha)}{\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}$$
 is in  $(0.7-12.2) \times 10^{-3}$  range



$$x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2 / 2}$$

$E_\ell^*$  is energy of  $l$  in  $\tau$  rest frame

- Belle analysis ( $800 \text{ fb}^{-1}$ ): [JHEP08\(2025\)155](#)

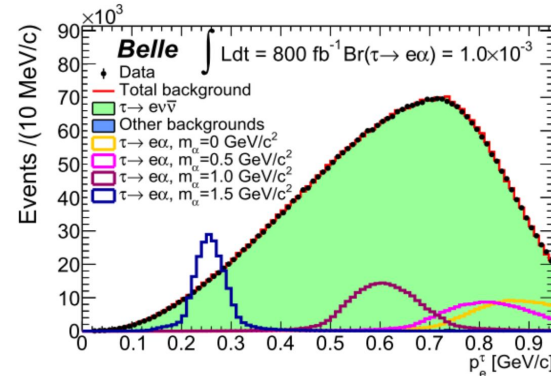


- Selection on  $\theta_{th}$
- look for excess in  $P_\ell^\tau$
- For  $m_\alpha \in (0, 1.6) \text{ GeV}/c^2$

$$B(\tau \rightarrow e \alpha) < (0.4 - 6.4) \times 10^{-4}$$

$$B(\tau \rightarrow \mu \alpha) < (0.2 - 3.5) \times 10^{-4}$$

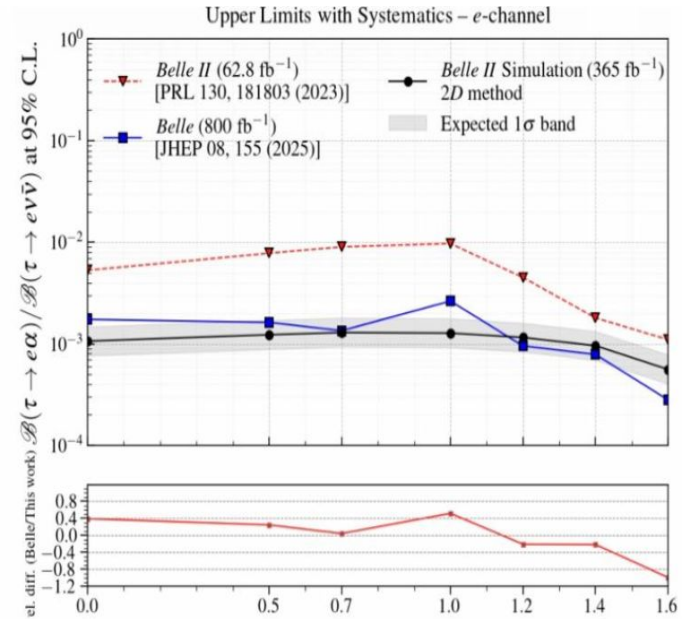
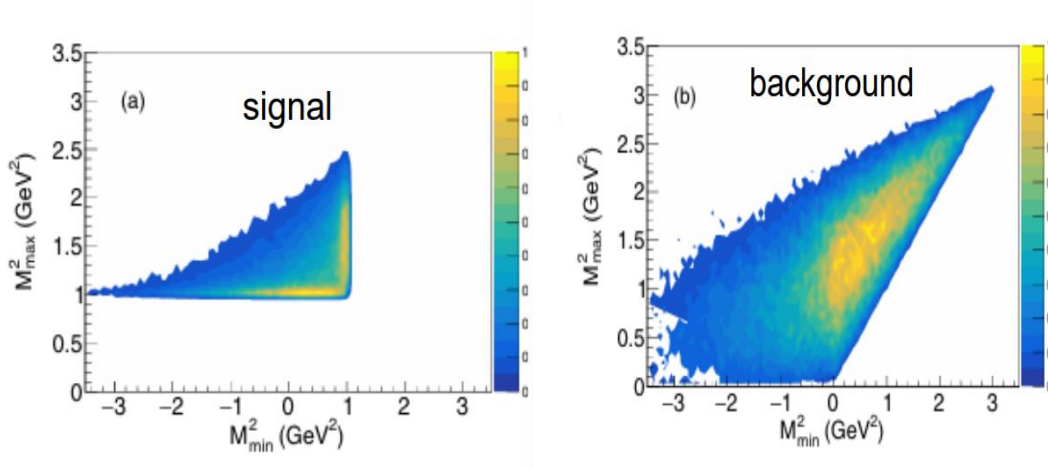
*world's best upper limits*



$P_\ell^\tau$  is lepton momentum in the  $\tau$  rest frame.

# $\tau \rightarrow l \alpha$

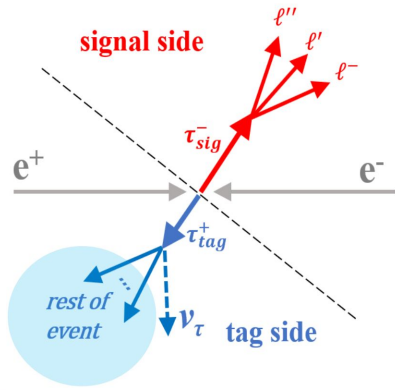
- New, more sensitive method at Belle II (365 fb<sup>-1</sup>)
  - using 2D fit to kinematic constrained  $M_{\min}^2$  and  $M_{\max}^2$  in more abundant 1x1-prong events [\[PRD 102 115001 \(2020\)\]](#)
  - Signal and background occupy different regions in  $(M_{\min}^2, M_{\max}^2)$
  - expected world-leading ULs for < 1.2 GeV!



*Coming soon*

# $\tau \rightarrow e 2 l$

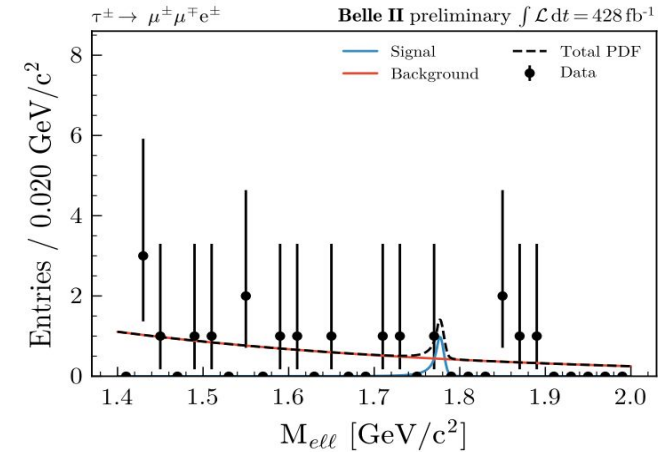
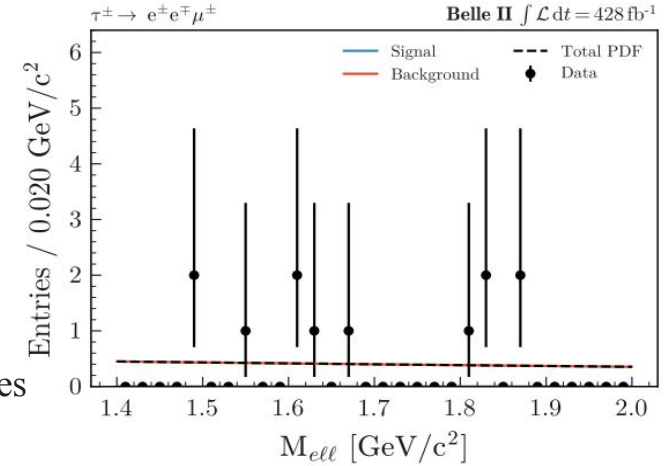
- Extending recent Belle II  $\tau \rightarrow 3\mu$  [JHEP 09 \(2024\) 062](#) to 5 more modes with at least one electron in the final state
- Several NP models could enhance rates up to  $10^{-10} - 10^{-8}$
- Untagged analysis with  $428 \text{ fb}^{-1}$  of Belle II data



- Major bkg: radiative four-lepton final states
  - suppressed by data-driven BDT
- Signal extraction via fit of  $M(e\ell\ell)$

	$\epsilon_{\text{sig}}$	$N_{\text{exp}}$	$N_{\text{obs}}$	$\mathcal{B}_{\text{obs}}^{UL} (10^{-8})$
$e^-e^+e^-$	$(15.0 \pm 0.1)\%$	$6.1^{+4.3}_{-2.9}$	5	2.5★
$e^-e^+\mu^-$	$(20.4 \pm 0.1)\%$	$12.1^{+5.7}_{-4.3}$	12	1.6★
$e^-\mu^+e^-$	$(23.5 \pm 0.1)\%$	$10.5^{+5.3}_{-4.3}$	17	1.6
$\mu^-\mu^+e^-$	$(20.1 \pm 0.1)\%$	$20.7^{+6.6}_{-5.5}$	18	2.4★
$\mu^-e^+\mu^-$	$(24.1 \pm 0.1)\%$	$7.5^{+4.5}_{-3.2}$	9	1.3★

[JHEP12\(2025\)169](#)



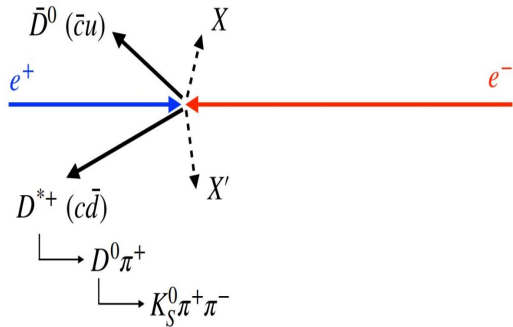
★ *World leading results at 90% CL*



# *Charm Physics*

# Charm production and reconstruction at Belle II

- $e^+e^- \rightarrow c\bar{c} \rightarrow D_{\text{tag}} X_{\text{frag}} D_{\text{sig}}$
- Typically only reconstruct the signal channel

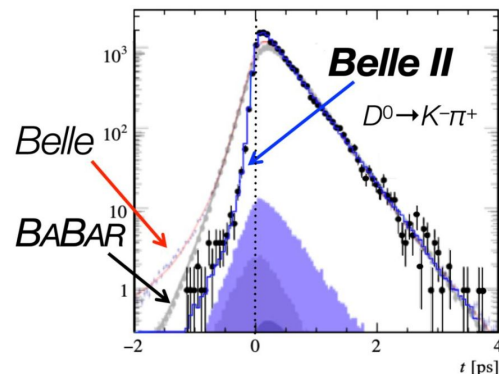


- Flavour tagging using:
  - $D^{*+} \rightarrow D^0\pi^+$
  - Charm Flavour Tagger, *PRD 107, 112010 (2023)*
- Also provides access to charmed baryons

# Charm physics program at Belle II

- **Precision measurements:**

Charm lifetimes:



**World's highest precision:**

$D^0$  : PRL 127, 211801

$D^+$  : PRL 127, 211801

$D_s^+$  : PRL 131, 171803

$A_c^+$  : PRL 130, 071802

$\Omega_c^0$ : PRD 107, L031103

- **Mixing parameters:**

- In  $D^0 \rightarrow K_S \pi^+ \pi^-$  PRD 111, 112011

- **CP Asymmetries:**

- $D^+ \rightarrow \pi^+ \pi^0$ : PRD 112, L031101 (world's best)
- $D^0 \rightarrow \pi^0 \pi^0$ : PRD 112, 012006
- $D^0 \rightarrow K_S K_S$  PRD 111, 012015
- $D^0 \rightarrow K_S K_S$  (with novel flavour tagging technique): PRD 112, 012017
- $D^0 \rightarrow \pi^+ \pi^- \pi^0$  (Accepted in PRD)

- **Charmed Baryons:**

- **CPV:**  $\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-$ ,  $\Lambda_c^+ \rightarrow p h^+ h^-$  PRD 113, 032017

- **First observations and branching fractions:**

- $\Xi_c^0 \rightarrow \Xi^0 h$  ( $h = \pi^0, \eta, \eta'$ ): JHEP 10 (2024) 045
- $\Xi_c^0 \rightarrow \Lambda h$  ( $h^0 = \pi^0, \eta, \eta'$ ): PRD 113, 032015
- $\Xi_c^+ \rightarrow p K_S, \Lambda \pi^+, \Sigma^0 \pi^+$ : JHEP 03 (2025) 061
- $\Xi_c^+ \rightarrow \Sigma^+ K_S, \Xi^0 \pi^+, \Xi^0 K^+$  JHEP 08 (2025) 195

- **Exotic hadrons:**

- $D_{s0}^*(2317)^+$  (Submitted to PRL)

*and many more...*

# Measurements of $\Xi_c^0 \rightarrow \Lambda h$ ( $h = \eta, \eta', \pi^0$ )

[Phys. Rev. D 113, 032015 \(2026\)](#)

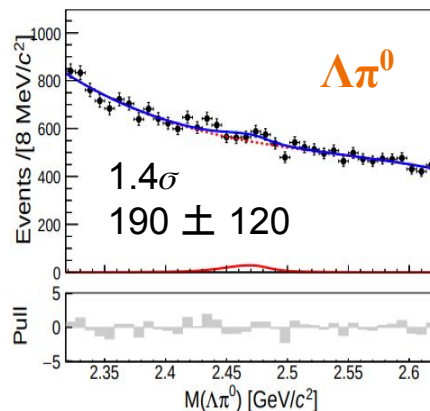
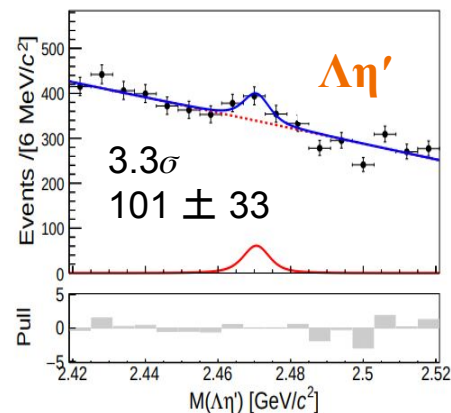
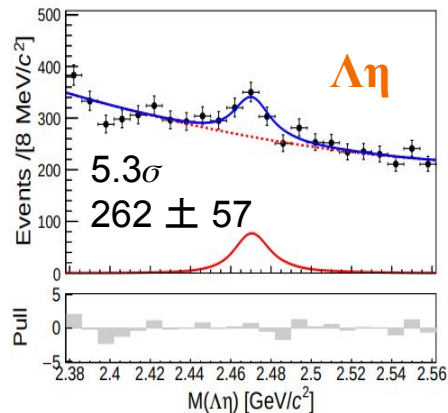
- Probe of non-perturbative QCD
  - Both factorizable and non-factorizable contributions are dominant
  - Important to understand decay dynamics
- Singly Cabibbo-suppressed decays
- Intermediate states :
  - $\Lambda \rightarrow p\pi, \eta' \rightarrow \pi^+\pi^-\eta, \eta' \rightarrow \pi^+\pi^-\gamma, \eta \rightarrow \gamma\gamma,$   
 $\eta \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$
- Control sample:
  - $\Xi_c^0 \rightarrow \Xi^-(\rightarrow \Lambda\pi^-)\pi^+$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Lambda\eta) = (5.95 \pm 1.30 \pm 0.32 \pm 1.13) \times 10^{-4}$$

$$\mathcal{B}(\Xi_c^0 \rightarrow \Lambda\eta') = (3.55 \pm 1.17 \pm 0.17 \pm 0.68) \times 10^{-4}$$

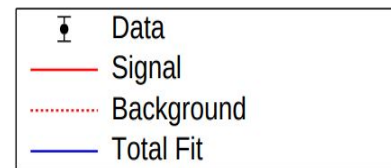
$$\mathcal{B}(\Xi_c^0 \rightarrow \Lambda\pi^0) < 5.2 \times 10^{-4}$$

- First observation of  $\Xi_c^0 \rightarrow \Lambda\eta$
- First evidence for  $\Xi_c^0 \rightarrow \Lambda\eta'$
- Consistent with theoretical predictions



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

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



# CP asymmetry in $\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-$ , $\Lambda_c^+ \rightarrow p h^+ h^-$ ( $h=K, \pi$ )

- No clear explanation of CPV in charm (BSM, non-perturbative QCD...??)
- Separate measurements of  $A_{CP}$  in  $D^0 \rightarrow KK$ ,  $\pi\pi$  indicate large breaking of U spin symmetry [Phys. Rev. Lett. 131, 091802 \(2023\)](#), [JHEP03\(2023\)205](#).
- Look for U spin symmetry in :  $\Lambda_c^+ \rightarrow p h^+ h^-$ ,  $\Xi_c^+ \rightarrow \Sigma^+ h^+ h^-$
- First measurement of  $A_{CP}$  in SCS 3-body charm baryon decays:

$$A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ K^- K^+) = (3.7 \pm 6.6(\text{stat}) \pm 0.6(\text{syst}))\%$$

$$A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ \pi^- \pi^+) = (9.5 \pm 6.8(\text{stat}) \pm 0.5(\text{syst}))\%$$

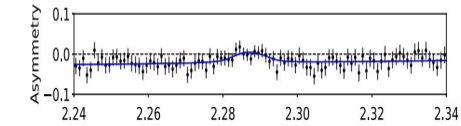
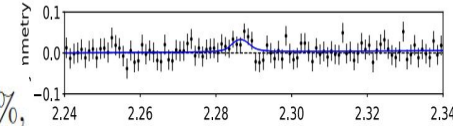
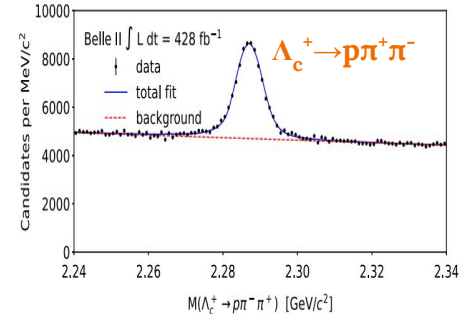
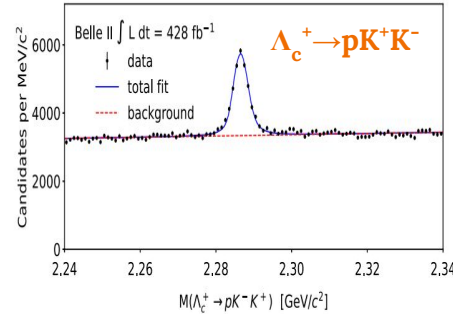
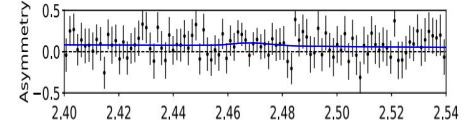
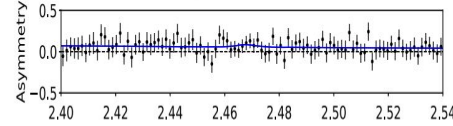
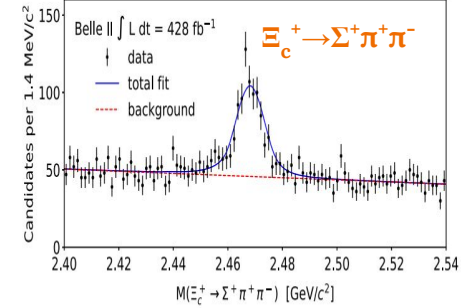
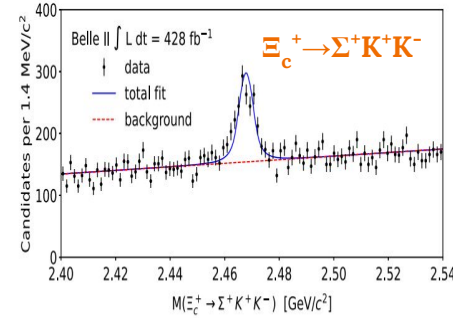
$$A_{CP}(\Lambda_c^+ \rightarrow p K^- K^+) = (3.9 \pm 1.7(\text{stat}) \pm 0.7(\text{syst}))\%$$

$$A_{CP}(\Lambda_c^+ \rightarrow p \pi^- \pi^+) = (0.3 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}))\%$$

- U-spin symmetry with 7% precision:

$$A_{CP}(\Lambda_c^+ \rightarrow p K^+ K^-) + A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-) = (13.4 \pm 7.0(\text{stat}) \pm 0.9(\text{syst}))\%$$

$$A_{CP}(\Lambda_c^+ \rightarrow p \pi^+ \pi^-) + A_{CP}(\Xi_c^+ \rightarrow \Sigma^+ K^+ K^-) = (4.0 \pm 6.6(\text{stat}) \pm 0.7(\text{syst}))\%$$

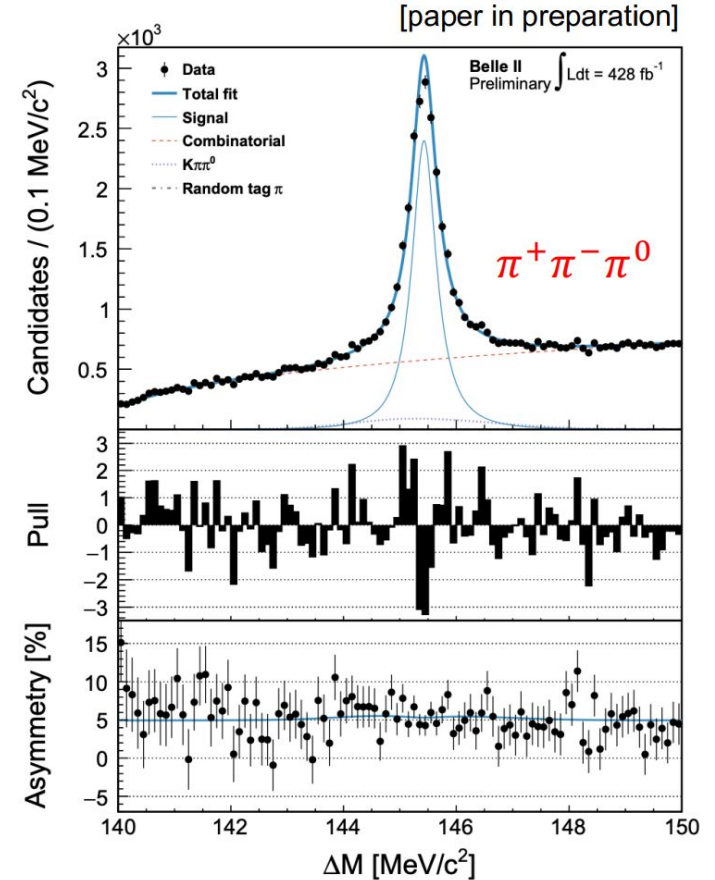


[Phys. Rev. D 113, 032017 \(2026\)](#)

# CP Asymmetry in $D^0 \rightarrow \pi^+ \pi^- \pi^0$

- SCS three-body decay, interference of several amplitudes
- Signal:  $D^{*+}$  tagged sample for  $D^0 \rightarrow \pi^+ \pi^- \pi^0$ .  

$$\mathcal{A}_{\text{raw}}^{\pi\pi\pi^0} \simeq \mathcal{A}_{CP} + \mathcal{A}_{\text{prod}} + \mathcal{A}_{\varepsilon}^{\pi\pi\pi^0} + \mathcal{A}_{\varepsilon}^{\pi\text{tag}}$$
- Control mode: tagged and untagged  $D^0 \rightarrow K^- \pi^+$
- Simultaneous fit to  $(\Delta m, m(\pi^+ \pi^- \pi^0))$  in 8 bins of  $\cos\theta_{\text{CM}}$ , averaged symmetrically around 0 to remove the production asymmetry
- $A_{CP}(D^0 \rightarrow \pi^+ \pi^- \pi^0)$ :  $(0.29 \pm 0.27 \pm 0.13) \%$ 
  - Most precise measurement till date
  - 34% more precise than BABAR with just 10% more statistics



Accepted in PRD [arXiv:2510.21224 \[hep-ex\]](https://arxiv.org/abs/2510.21224)

# Observation of the radiative decay $D_{s0}^*(2317)^+ \rightarrow D_s^{*+} \gamma$

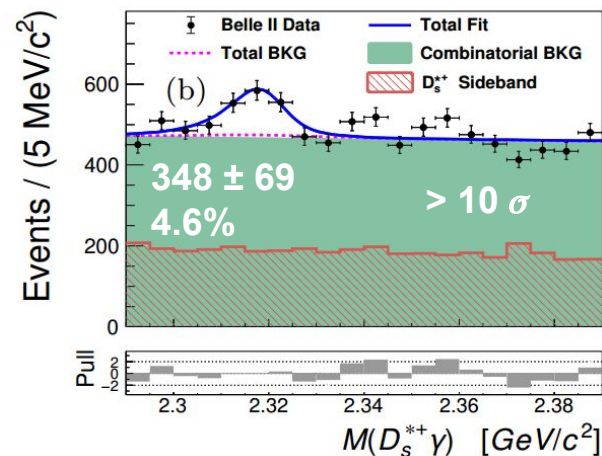
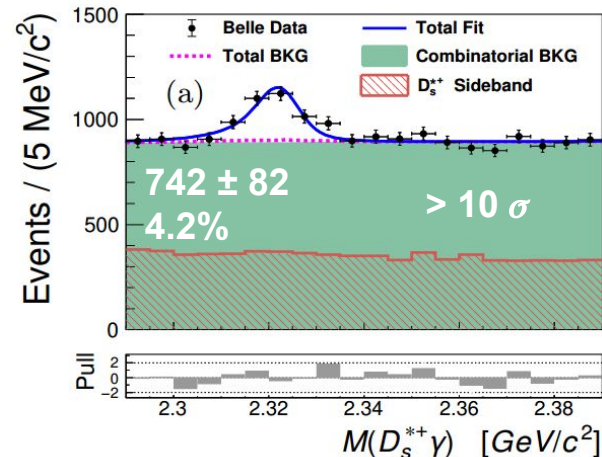
- Exotic hadrons offer insight into nonperturbative QCD.
  - Mass of  $D_{s0}^*(2317)^+$  is much lower than prediction
  - Nature of  $D_{s0}^*(2317)^+$  ??

- Determination of  $R$  can constrain theoretical models

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

- Belle ( $980 \text{ fb}^{-1}$ ) + Belle II ( $428 \text{ fb}^{-1}$ ) analysis:
  - First observation
  - $R = [7.14 \pm 0.70(\text{stat.}) \pm 0.23(\text{syst.})]$ 
    - larger than theoretical predictions suggesting a molecular state
    - Smaller than the  $\bar{c}\bar{s}$  state assumption under the quark model
    - predictions based on the light front quark model and chiral quark model are in agreement (pure  $c\bar{s}$ )
    - could be an admixture of pure  $\bar{c}\bar{s}$  and molecular state*

[arXiv:2510.27174](https://arxiv.org/abs/2510.27174) (Submitted to PRL)



# Summary

- SuperKEKB achieved world record peak luminosity:  $5.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Belle II collected over  $600 \text{ fb}^{-1}$  of data
- World's best sensitivities in LFV searches with taus
- First observations of several charmed baryon decays
- First measurement of  $A_{\text{CP}}$  in SCS three-body charm baryon decays

*Stay tuned for more results!!*



# Backup Slides

