Heavy QCD bound states at Belle and Belle II

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Representing the collaboration

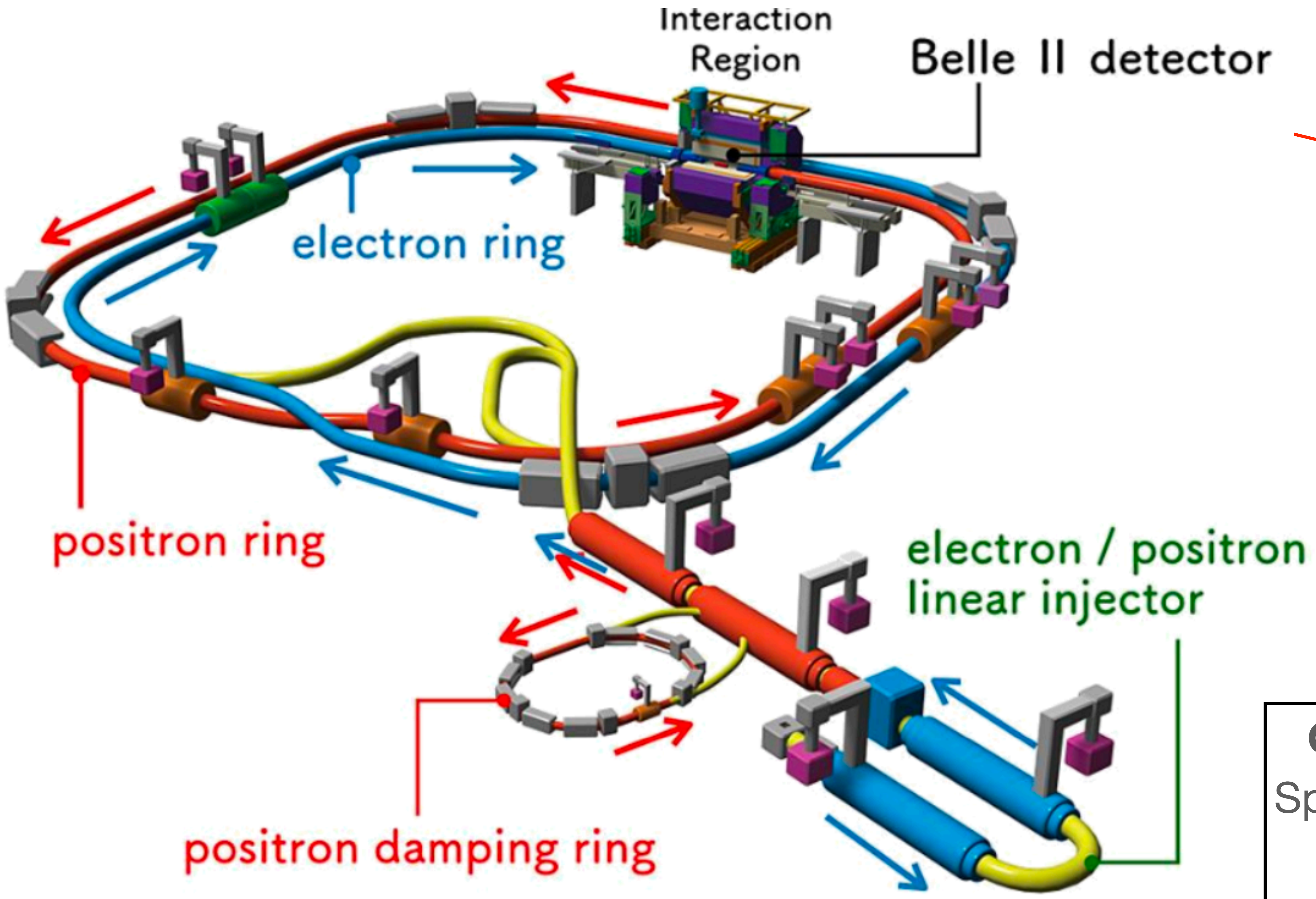
Excited QCD 2026, University of Granda, Carmen de la Victoria, Jan 8-14, 2026

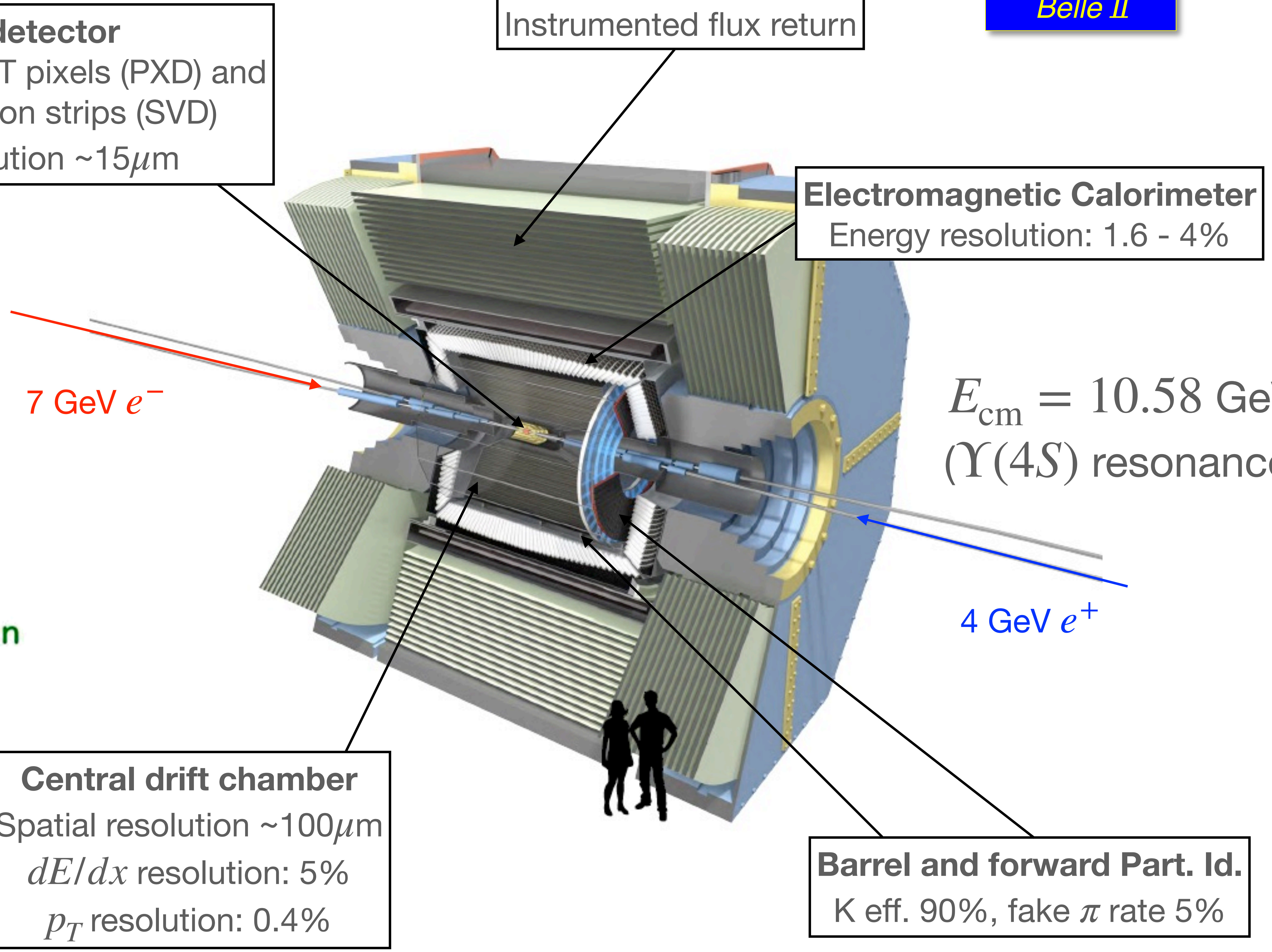
Belle II @ SuperKEKB

- Luminosity frontier experiment located in KEK (Japan) to search for Physics beyond the Standard Model but also a great laboratory to study QCD bound states — both conventional and exotic
    - e^+e^- asymmetric collision at 10.58 GeV ($\Upsilon(4S)$ resonance)
    - High current / nano-beams, challenging background conditions
- Luminosity targets to achieve physics goals:
    - $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, $\int \mathscr{L} dt = 50/\mathrm{ab}$

KEK
Tsukuba, Japan

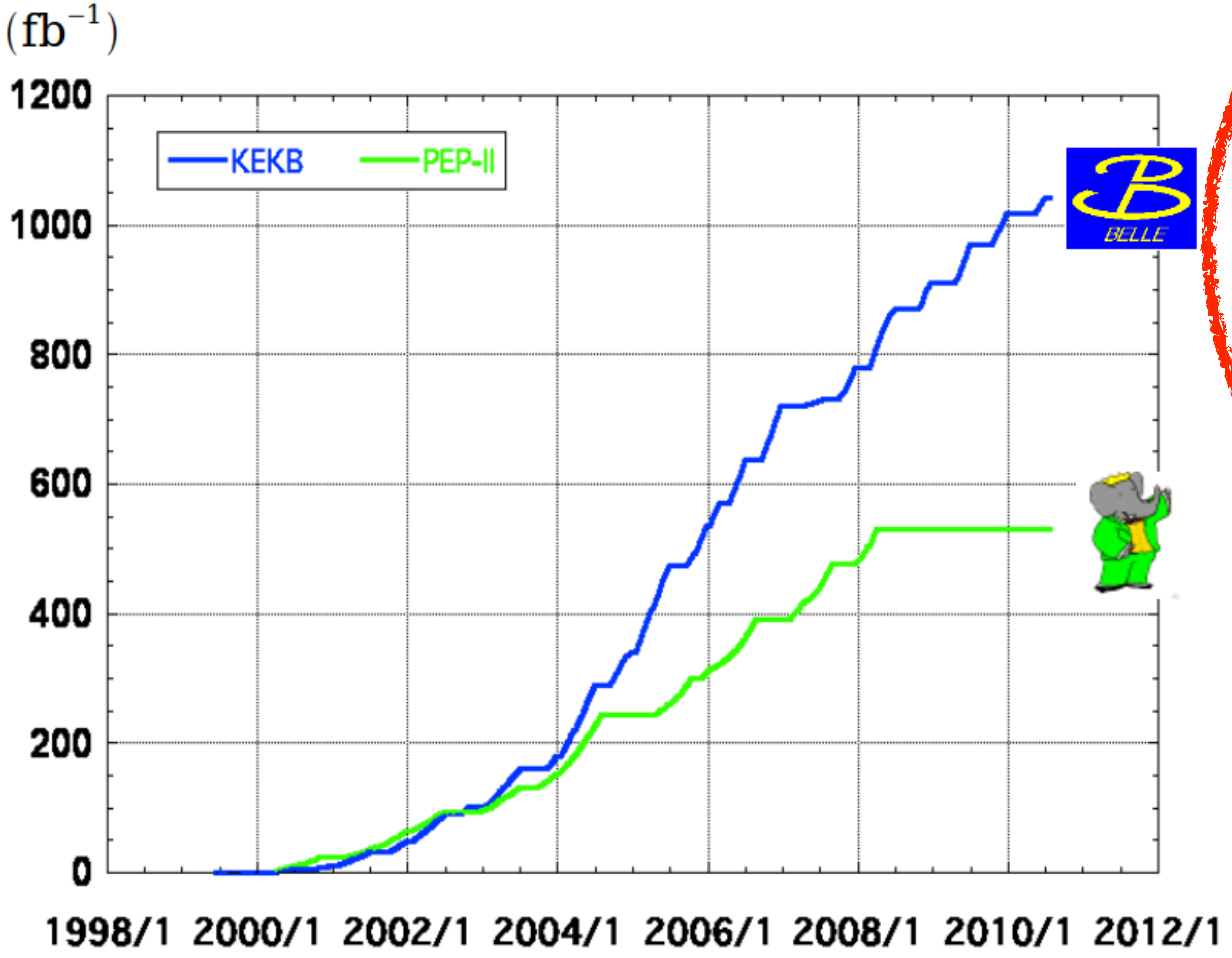
Belle II @ SuperKEKB (2)





$E_{\rm cm} = 10.58$ GeV
($\Upsilon(4S)$ resonance)

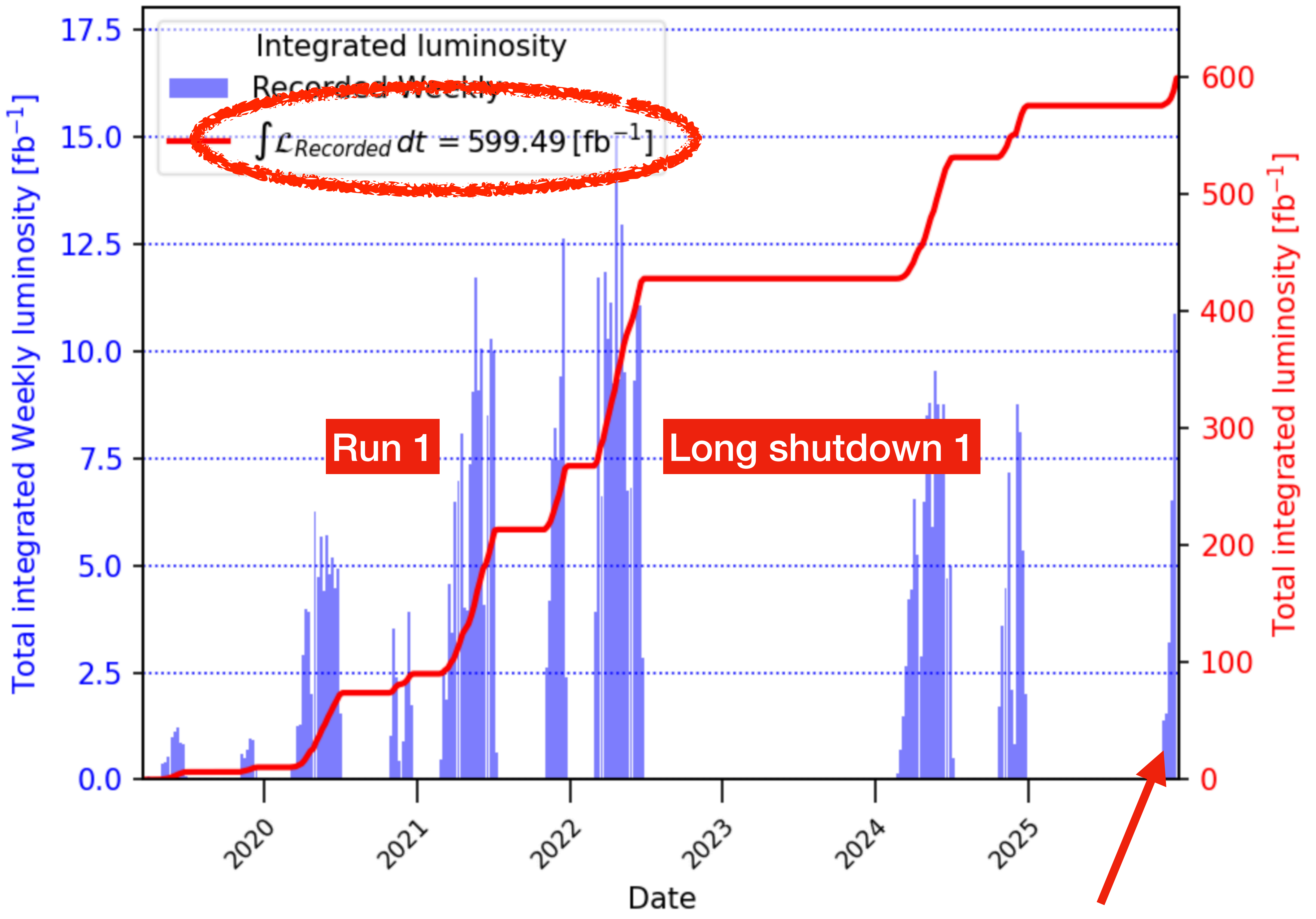
Belle luminosity (1999-2010)



> 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}

Belle II luminosity (from 2019)



Run resumed in Nov 2025 and is expected to continue until ~May 2026

Outline of this talk

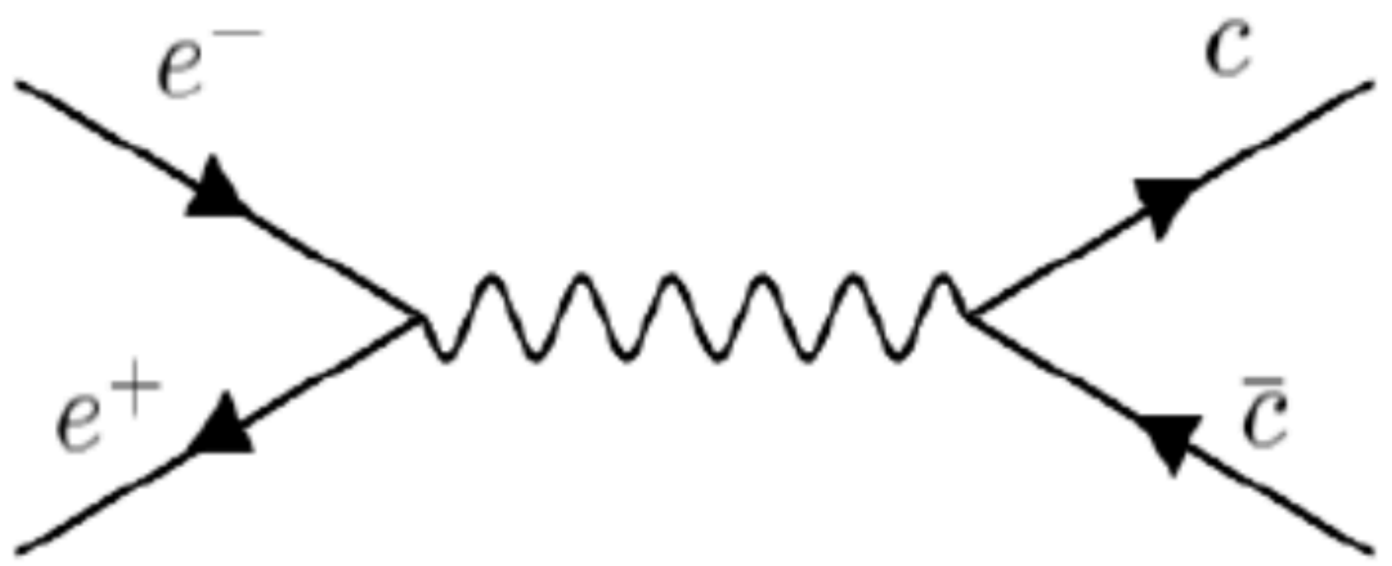
1. Precise charm lifetime measurements
   [Phys. Rev. Lett. 127, 211801 (2021), Phys. Rev. Lett. 131, 171803 (2023), Phys. Rev. Lett. 130, 071802 (2023), Phys. Rev. D 107, L031103 (2023)]

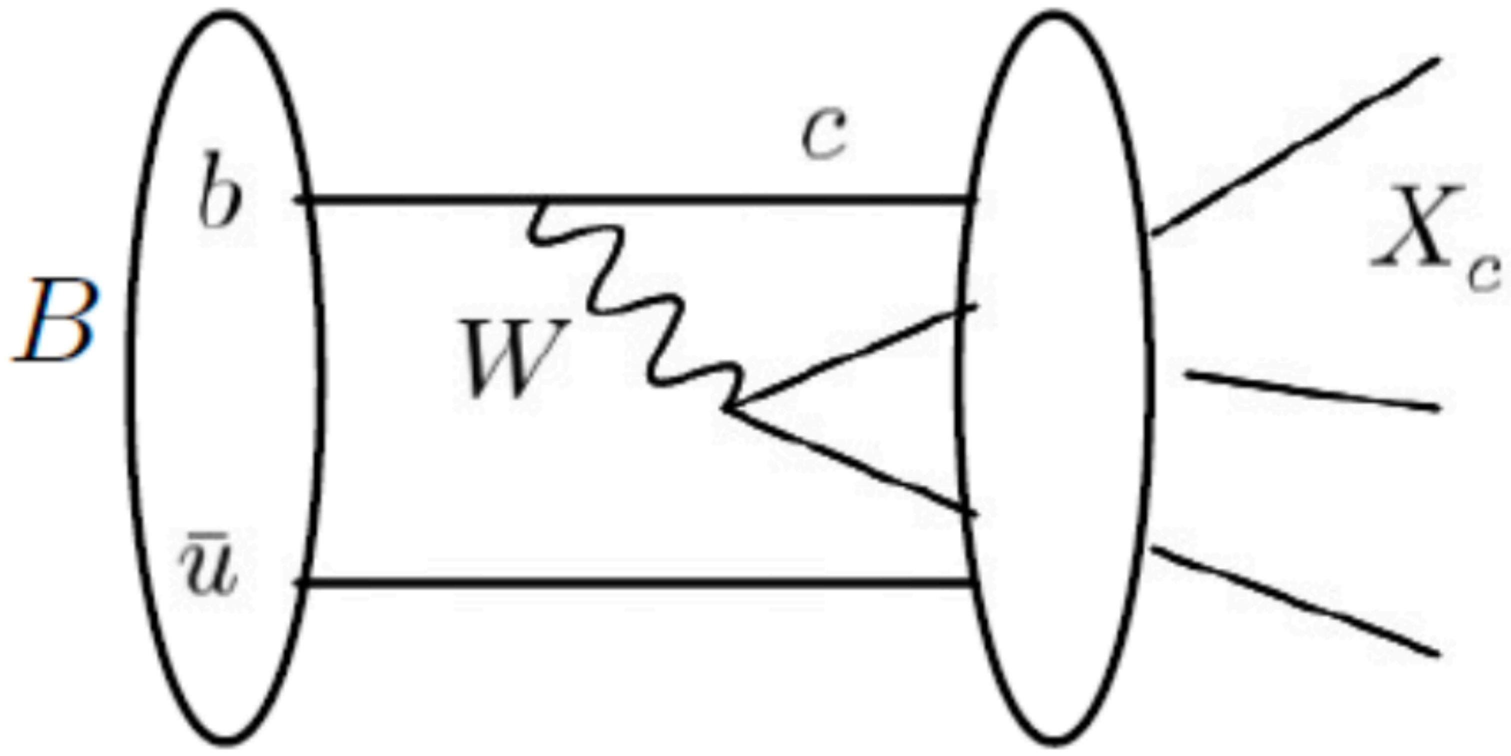
2. CP asymmetry in $D^0 \to K_S K_S$, search for CPV in $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^-$
   [Phys. Rev. D 111, 012015 (2025), Phys. Rev. D 112, 012017 (2025), arXiv:2509.25765]

3. Observation of new two body charm baryon modes
   [JHEP 10 (2024) 045, JHEP 08 (2025) 195, JHEP03(2025) 061, arXiv:2510.20882]

Charm production at Belle II

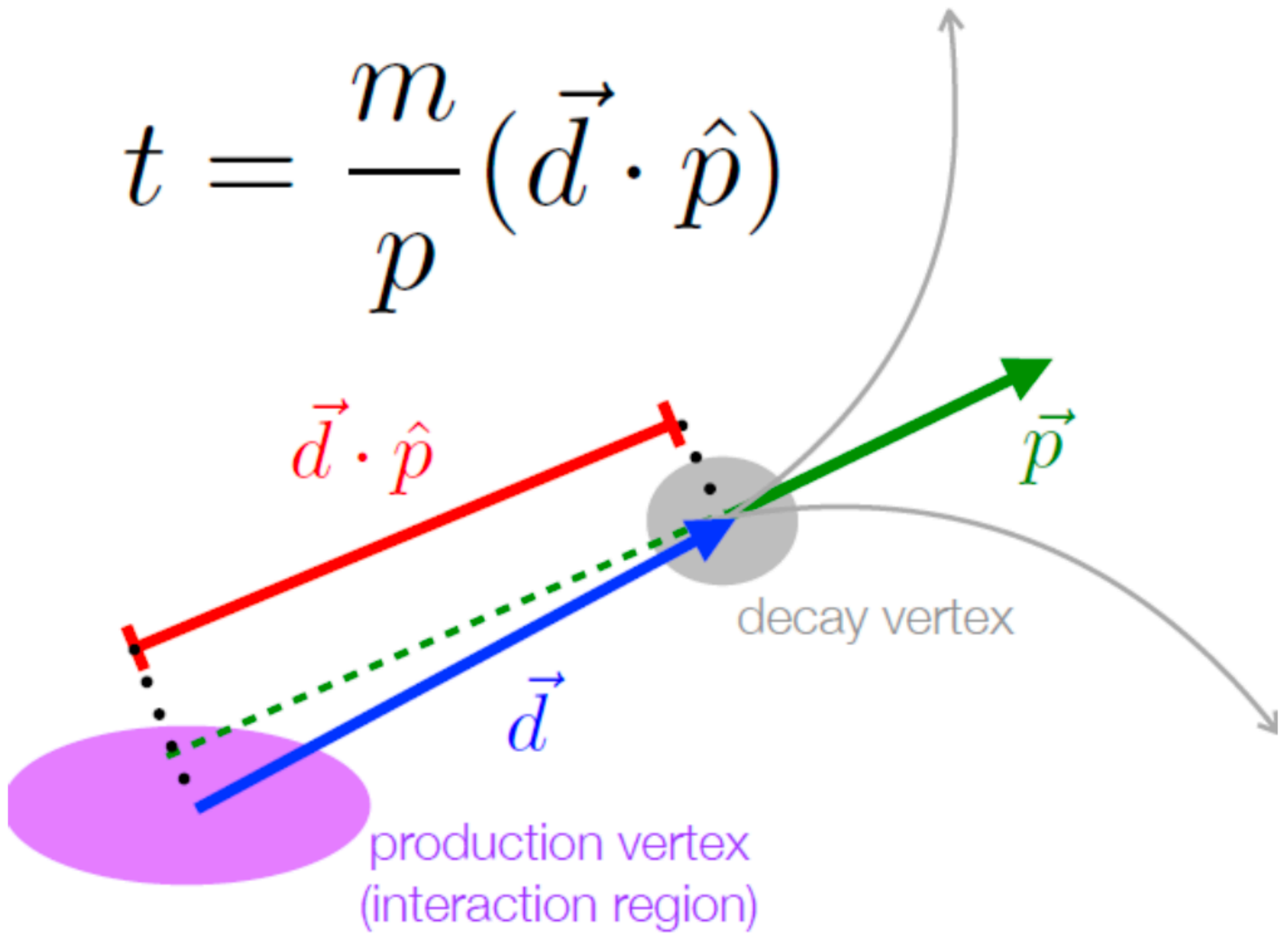
- Two production mechanism for charmed hadrons
  - Charm fragmentation $e^+e^- \to c\bar{c}$
  - In decays of B mesons produced at the $\Upsilon(4S)$
- Large datasets
  - $e^+e^- \to c\bar{c}$ ~1.3×10^9 at Belle + ~0.75×10^9 at Belle II
  - $B\bar{B}$ pairs from $\Upsilon(4S)$ 772×10^6 at Belle + 483×10^6 at Belle II



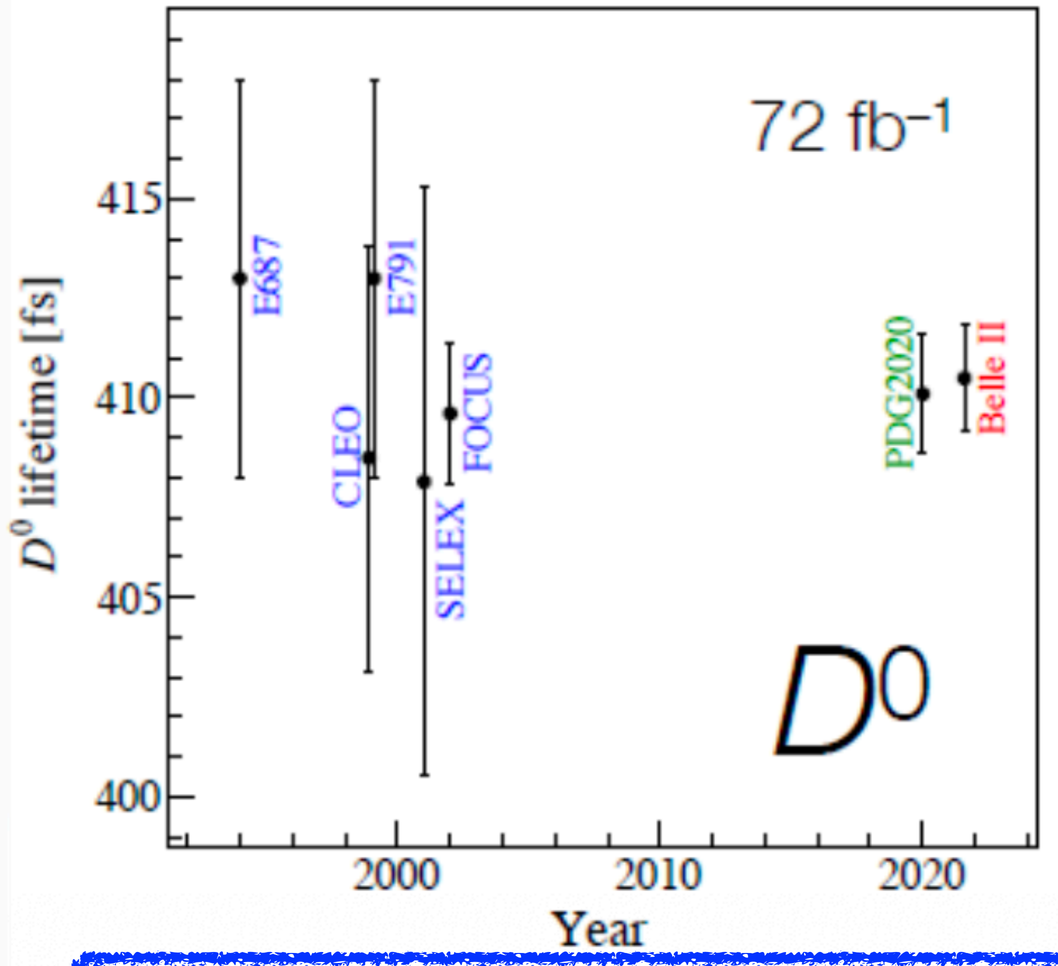


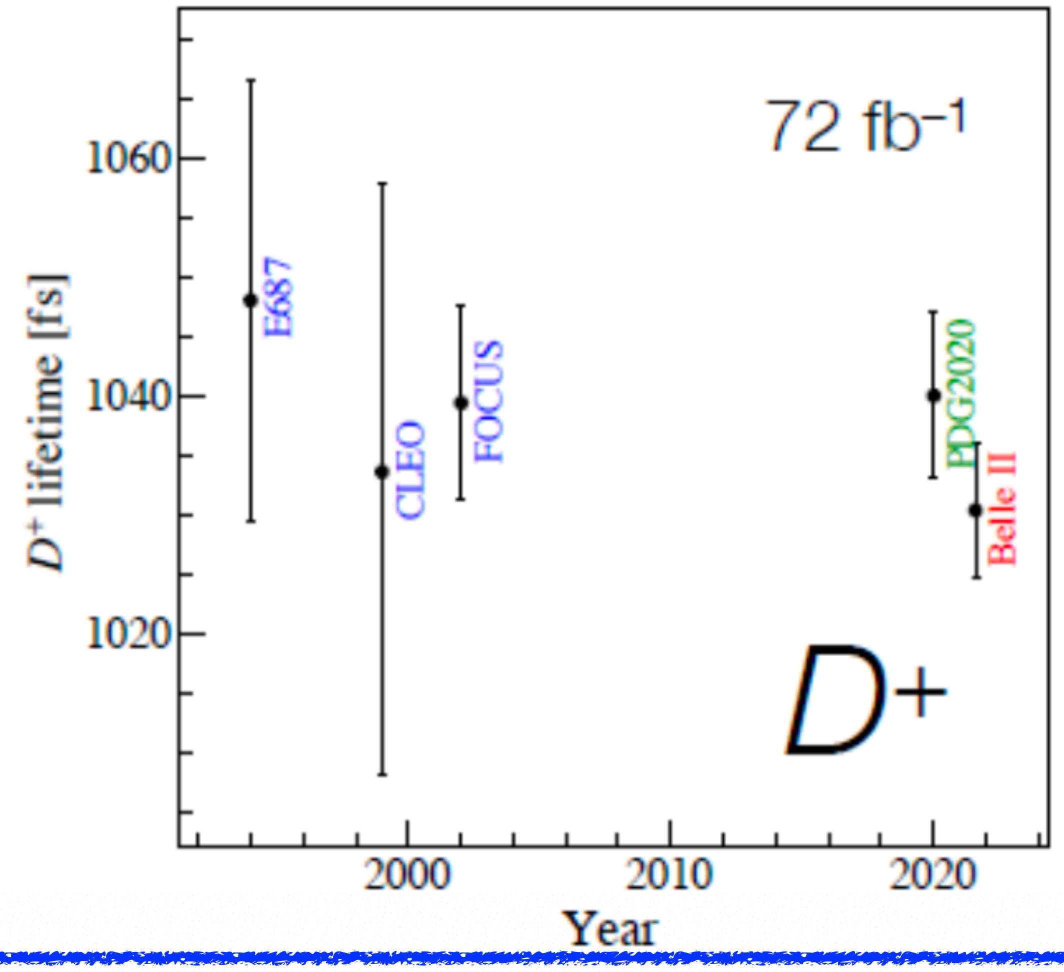
Precise charm lifetimes

- Uses charm hadrons produced in fragmentation $e^+e^- \to c\bar{c}$
- Boosted charm hadrons are displaced by about 200 to 500 μm from the interaction region (IR)
- Measurement thus relies on precise vertexing and detector alignment



Precise charm lifetimes (2)

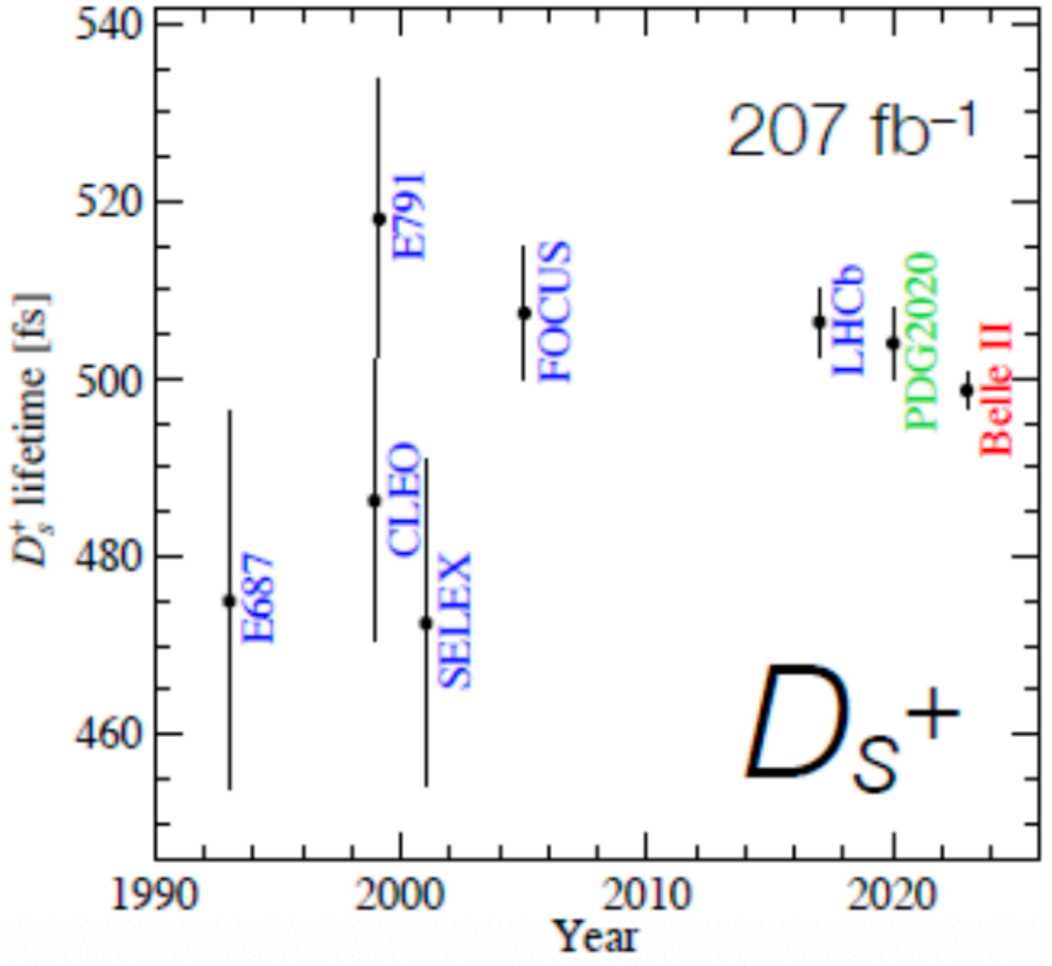


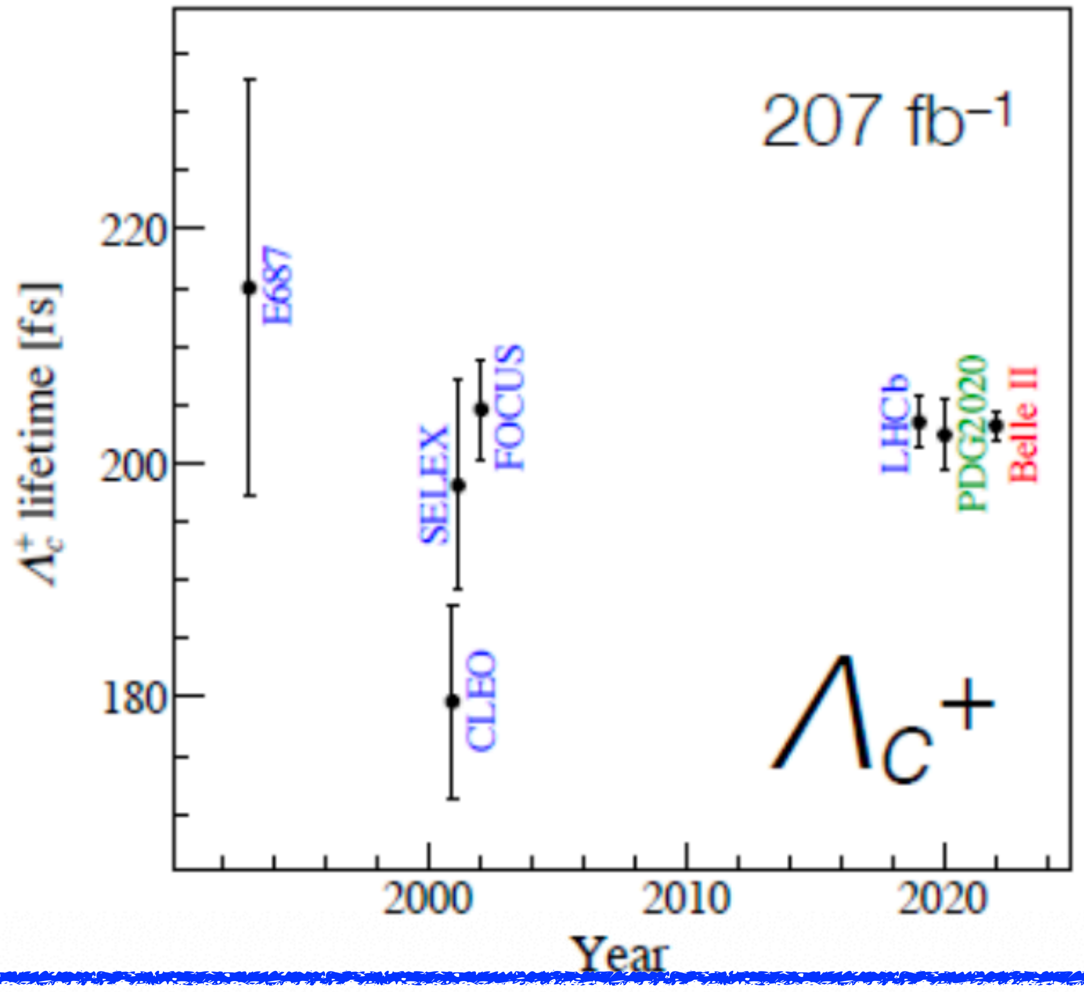


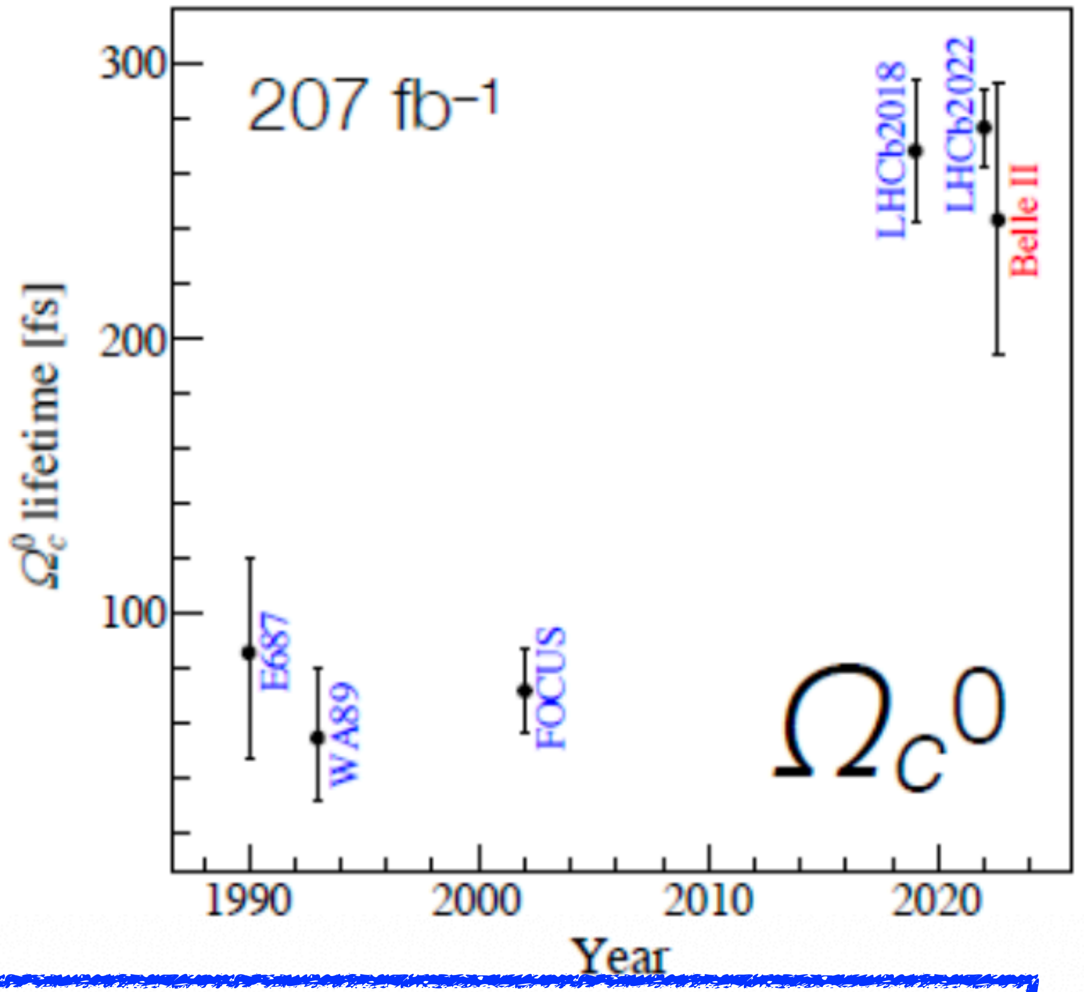
Phys. Rev. Lett. 127, 211801 (2021)

$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})$ fs

$\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})$ fs







Phys. Rev. Lett. 131, 171803 (2023)
Phys. Rev. Lett. 130, 071802 (2023)
Phys. Rev. D 107, L031103 (2023)

$\tau(D_s^+) = 498.7 \pm 1.7(\text{stat.})^{+1.1}_{-0.8}(\text{syst.})$ fs

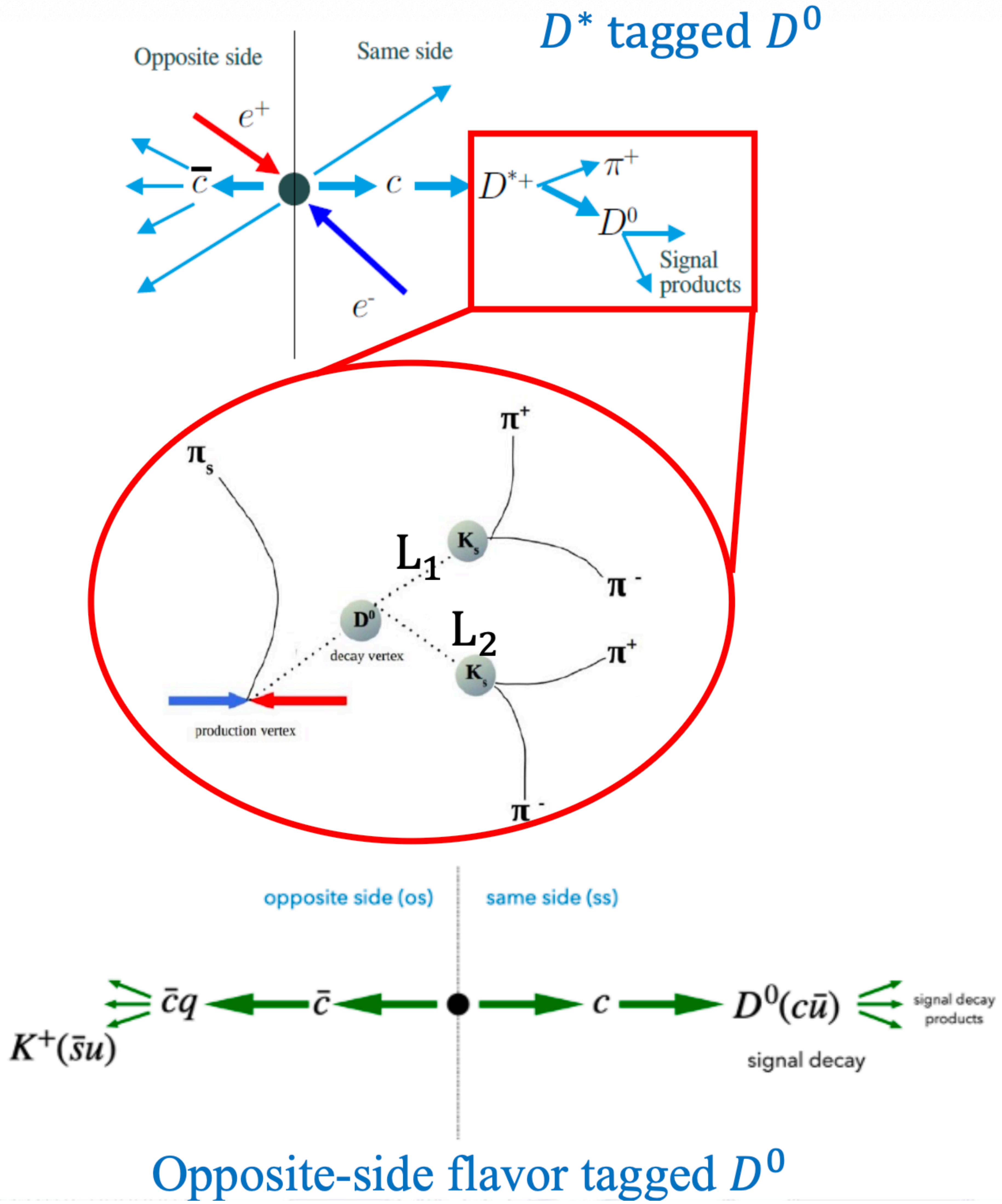
$\tau(\Lambda_c^+) = 203.20 \pm 0.89(\text{stat.}) \pm 0.77(\text{syst.})$ fs

$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})$ fs

Time-integrated CP asymmetry in $D^0 \to K_S K_S$

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

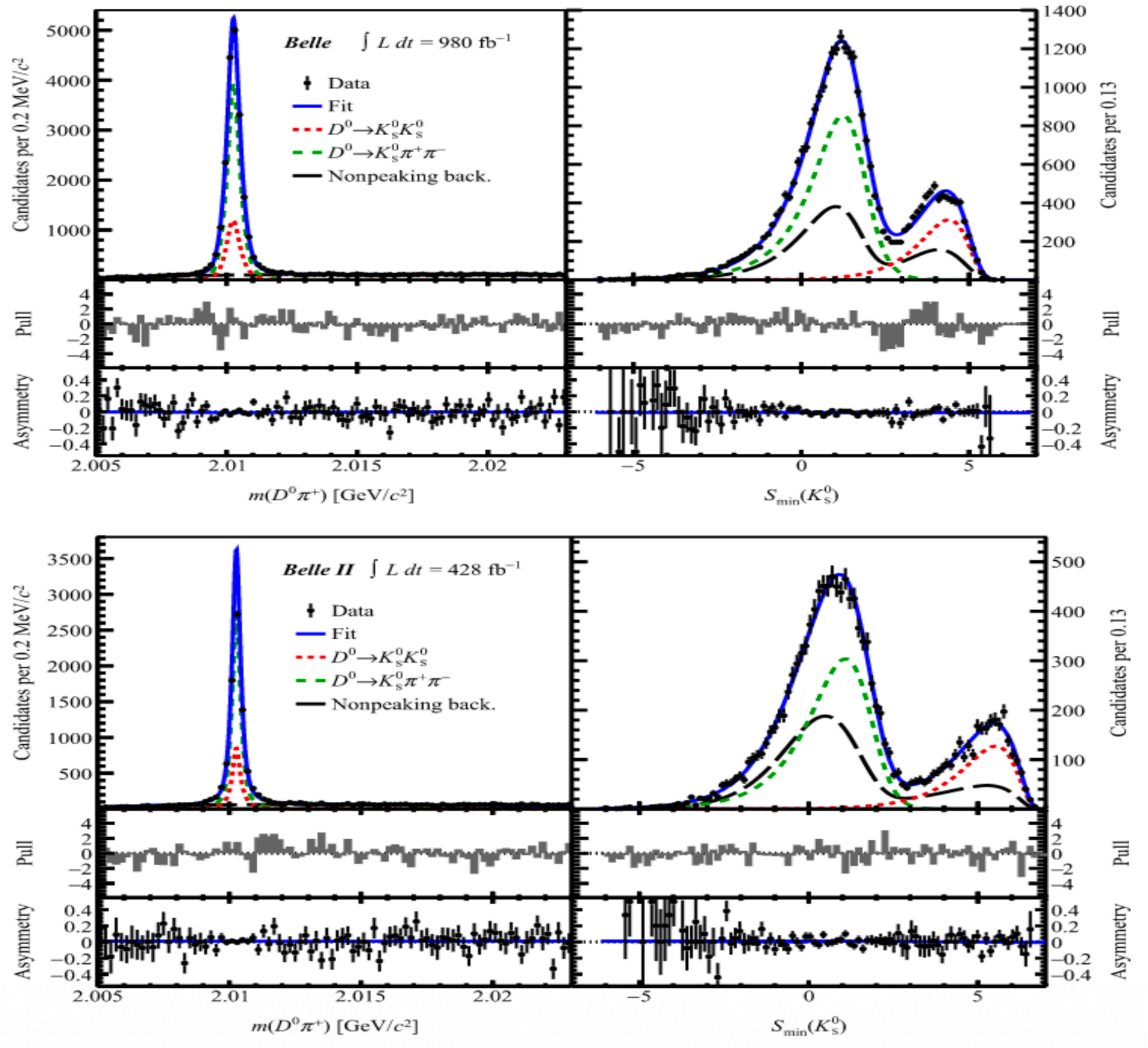
- Arises from the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes but precise prediction requires understanding of hadronic physics
- Expected to be at the level of ~1%
- Belle+Belle II data sets combined
- Two independent methods
  - Same side tagging through $D^{*+} \to D^0 \pi_s^+$
  - Slow D^0 oscillation also allows opposite side tagging using the charm flavor tagger [Phys.Rev.D 107 (2023) 11, 112010]



Same side tagging

Phys.Rev.D 111 (2025) 1, 012015

- Flavor tag through $D^{*+} \to D^0 \pi_s^+$
- Main background from $D^0 \to K_S \pi^+ \pi^-$
  - Separated using $S_{\min} = \log[\min(L_1/\sigma_1, L_2/\sigma_2)]$
- Production/detection asymmetry corrected using $D^0 \to K^+ K^-$
- 2d extended maximum likelihood fit to $m(D^0\pi^+)$ and $S_{\min}$



Belle: $A_{CP} = (-1.1 \pm 1.6(\text{stat.}) \pm 0.1(\text{syst.}))\%$

Belle II: $A_{CP} = (-2.2 \pm 2.3(\text{stat.}) \pm 0.1(\text{syst.}))\%$

Belle + Belle II: $A_{CP} = (-1.4 \pm 1.3(\text{stat.}) \pm 0.1(\text{syst.}))\%$

Opposite side flavor tag

Phys.Rev.D 112 (2025) 1, 012017

- Other tracks in the event are used to infer the flavor of the other c-quark
- Statistical overlap with the other analysis is removed
- 2d extended maximum likelihood fit to $m(K_S K_S)$ and qr
  - Flavor tag $q = 1$ for D^0 and -1 for $\bar{D}^0$
  - Dilution factor $r = 1 - 2\omega$ (ω is the mistag probability)

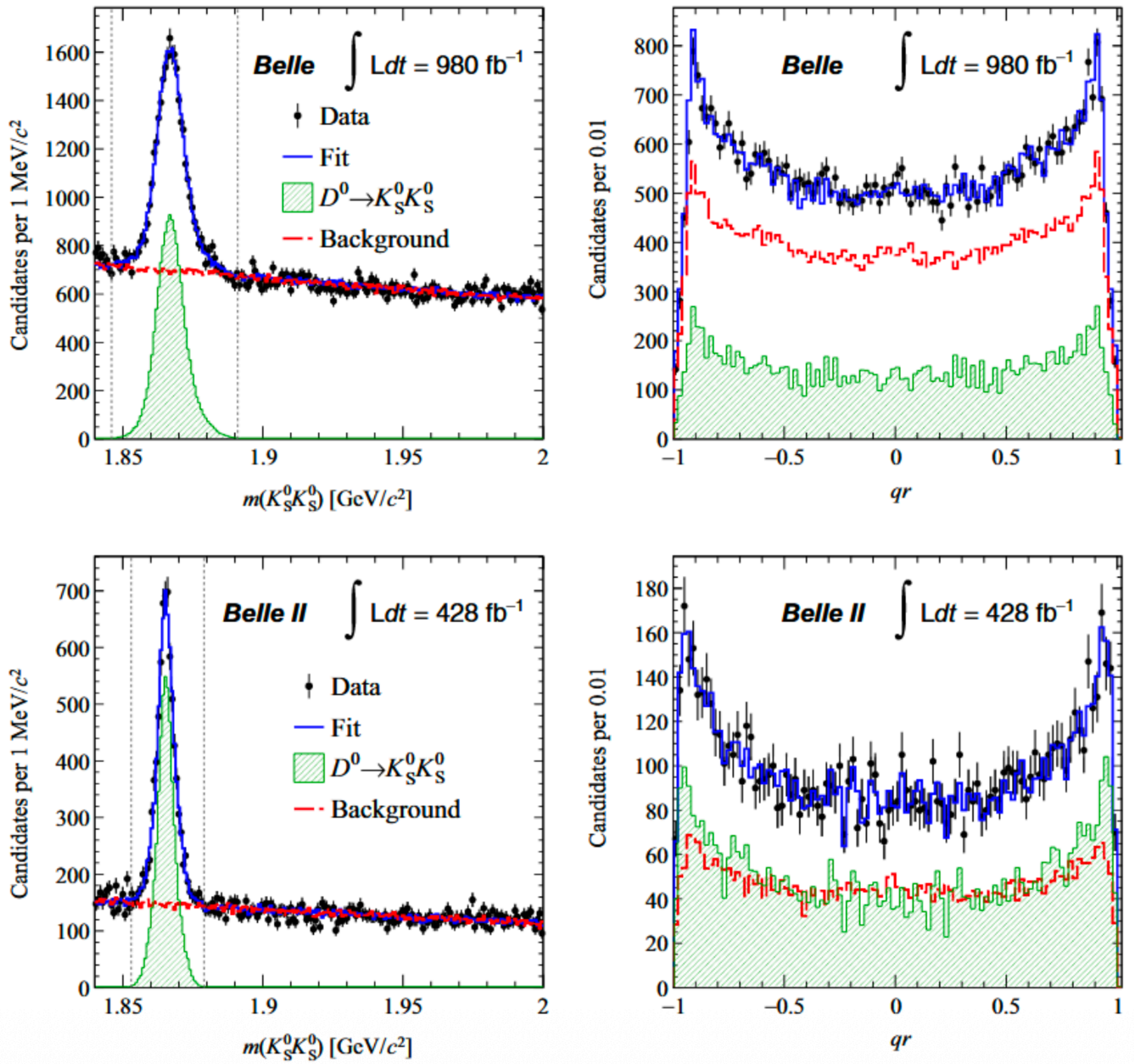
Belle: $A_{CP} = (2.5 \pm 2.7(\text{stat.}) \pm 0.4(\text{syst.}))\%$

Belle II: $A_{CP} = (-0.1 \pm 3.0(\text{stat.}) \pm 0.3(\text{syst.}))\%$

Belle + Belle II: $A_{CP} = (1.3 \pm 2.0(\text{stat.}) \pm 0.2(\text{syst.}))\%$

- Combination of the two methods (most precise result to date)

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



CP asymmetry in $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^-$

arXiv:2509.25765, submitted to PRD

- First search for CP asymmetries in individual hadronic three-body charm baryon modes
- Control channels: $\Lambda_c^+ \to p\pi^+K^-$ and $D^0 \to \pi^+K^-\pi^-\pi^+$

Preliminary

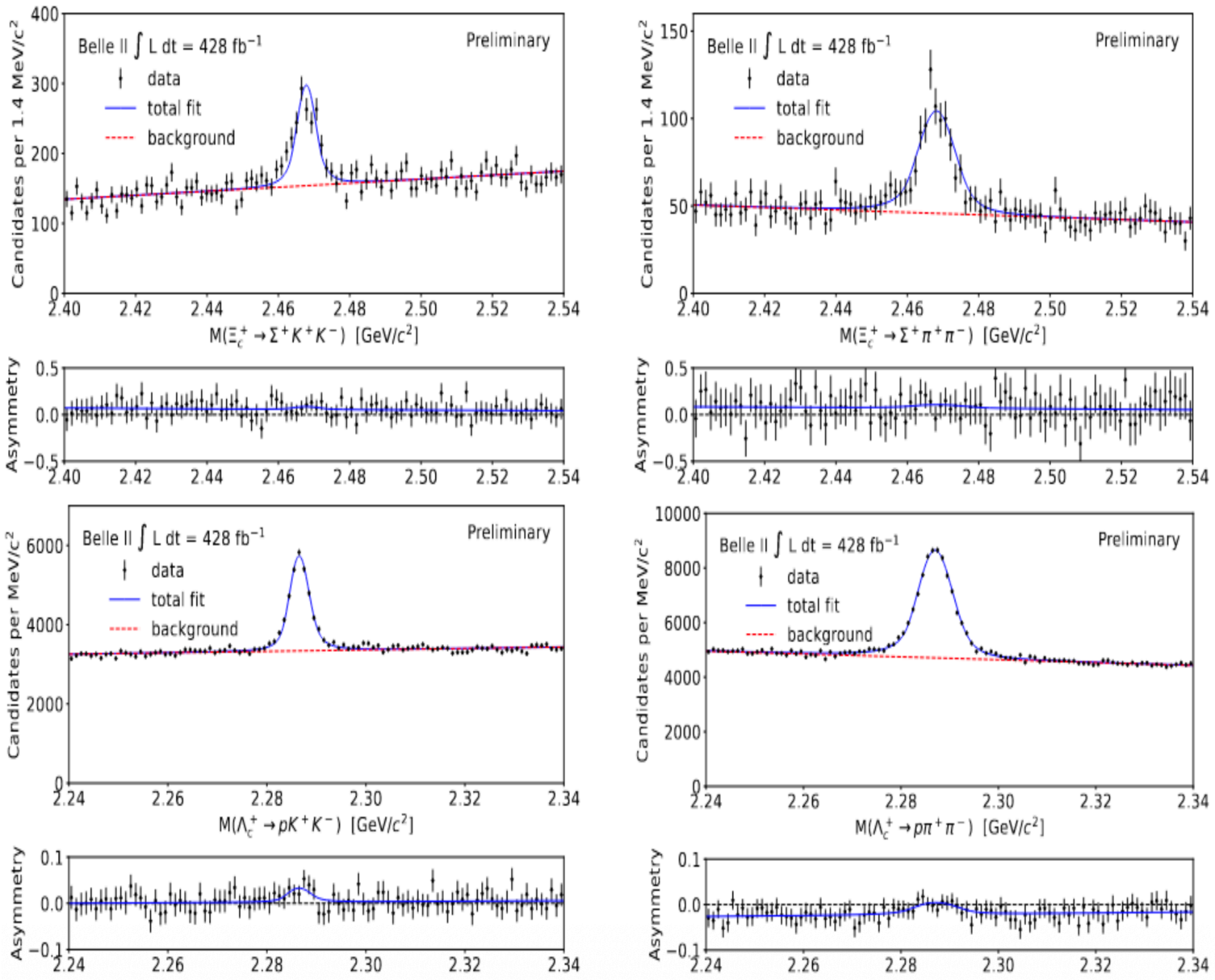
$$A_{CP}(\Xi_c^+ \to \Sigma^+K^+K^-) = (3.7 \pm 6.6 \pm 0.6)\%$$

$$A_{CP}(\Xi_c^+ \to \Sigma^+\pi^+\pi^+) = (9.5 \pm 6.8 \pm 0.5)\%$$

$$A_{CP}(\Lambda_c^+ \to pK^+K^-) = (3.9 \pm 1.7 \pm 0.7)\%$$

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

- First uncertainties are statistical, second are systematic

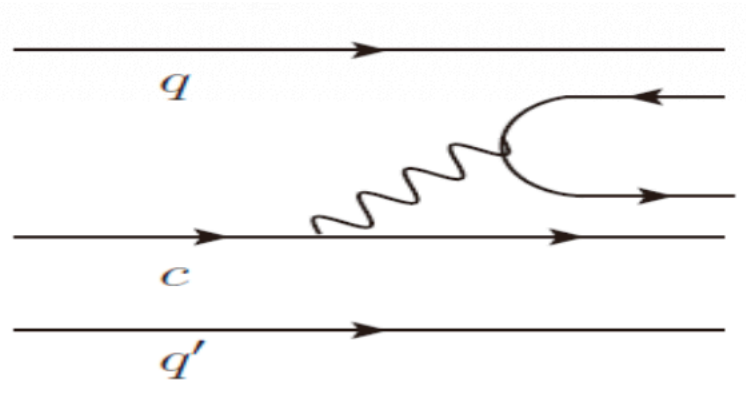


Two body charm baryon modes

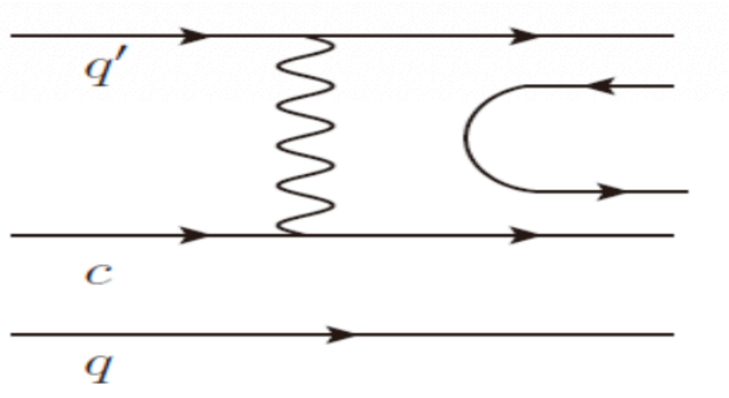
Preliminary

- Both Cabibbo-favored and Cabibbo-suppressed modes have been investigated with the Belle+Belle II data

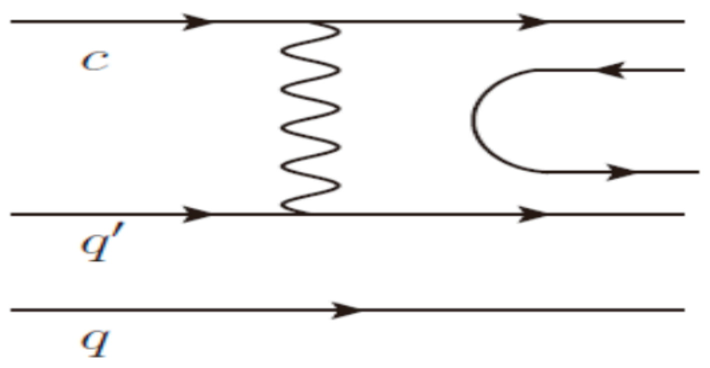
- Large nonfactorizable contributions pose challenges for theoretical calculations



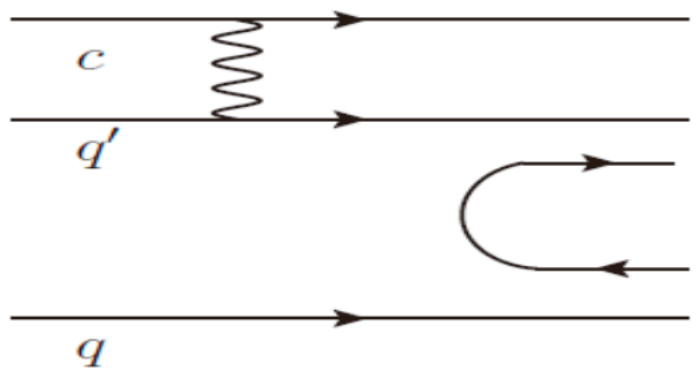
Inner W-emission C'



W-emission E_1



W-emission E_2



W-emission E_3

[JHEP 10 (2024) 045, JHEP 08 (2025) 195, JHEP03(2025) 061, arXiv:2510.20882]

Decay channel	Normalization mode ratio	Branching fraction
$\Xi_c^0 \to \Xi^0\pi^0$	$0.48 \pm 0.02 \pm 0.03$	$(6.9 \pm 0.3 \pm 0.5 \pm 1.3) \times 10^{-3}$
$\Xi_c^0 \to \Xi^0\eta$	$0.11 \pm 0.01 \pm 0.01$	$(1.6 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-3}$
$\Xi_c^0 \to \Xi^0\eta'$	$0.08 \pm 0.02 \pm 0.01$	$(1.2 \pm 0.3 \pm 0.1 \pm 0.2) \times 10^{-3}$
$\Xi_c^0 \to \Lambda\pi^0$	$< 3.5\%$ @ 90% C.L.	$< 5.2 \times 10^{-4}$ @ 90% C.L.
$\Xi_c^0 \to \Lambda\eta$	$(4.16 \pm 0.91 \pm 0.23)\%$	$(5.95 \pm 1.30 \pm 0.32 \pm 1.13) \times 10^{-4}$
$\Xi_c^0 \to \Lambda\eta'$	$(2.48 \pm 0.82 \pm 0.21)\%$	$(3.55 \pm 1.17 \pm 0.17 \pm 0.68) \times 10^{-4}$
$\Xi_c^+ \to pK_S^0$	$(2.47 \pm 0.16 \pm 0.07)\%$	$(7.16 \pm 0.46 \pm 0.20 \pm 3.21) \times 10^{-4}$
$\Xi_c^+ \to \Lambda\pi^+$	$(1.56 \pm 0.14 \pm 0.09)\%$	$(4.52 \pm 0.41 \pm 0.26 \pm 2.03) \times 10^{-4}$
$\Xi_c^+ \to \Sigma^0\pi^+$	$(4.13 \pm 0.26 \pm 0.22)\%$	$(1.20 \pm 0.08 \pm 0.07 \pm 0.54) \times 10^{-4}$
$\Xi_c^+ \to \Sigma^+K_s^0$	$0.067 \pm 0.007 \pm 0.003$	$(0.194 \pm 0.021 \pm 0.009 \pm 0.087)\%$
$\Xi_c^+ \to \Xi^0\pi^+$	$0.251 \pm 0.005 \pm 0.010$	$(0.728 \pm 0.014 \pm 0.027 \pm 0.326)\%$
$\Xi_c^+ \to \Xi^0K^+$	$0.017 \pm 0.003 \pm 0.001$	$(0.049 \pm 0.007 \pm 0.003 \pm 0.022)\%$

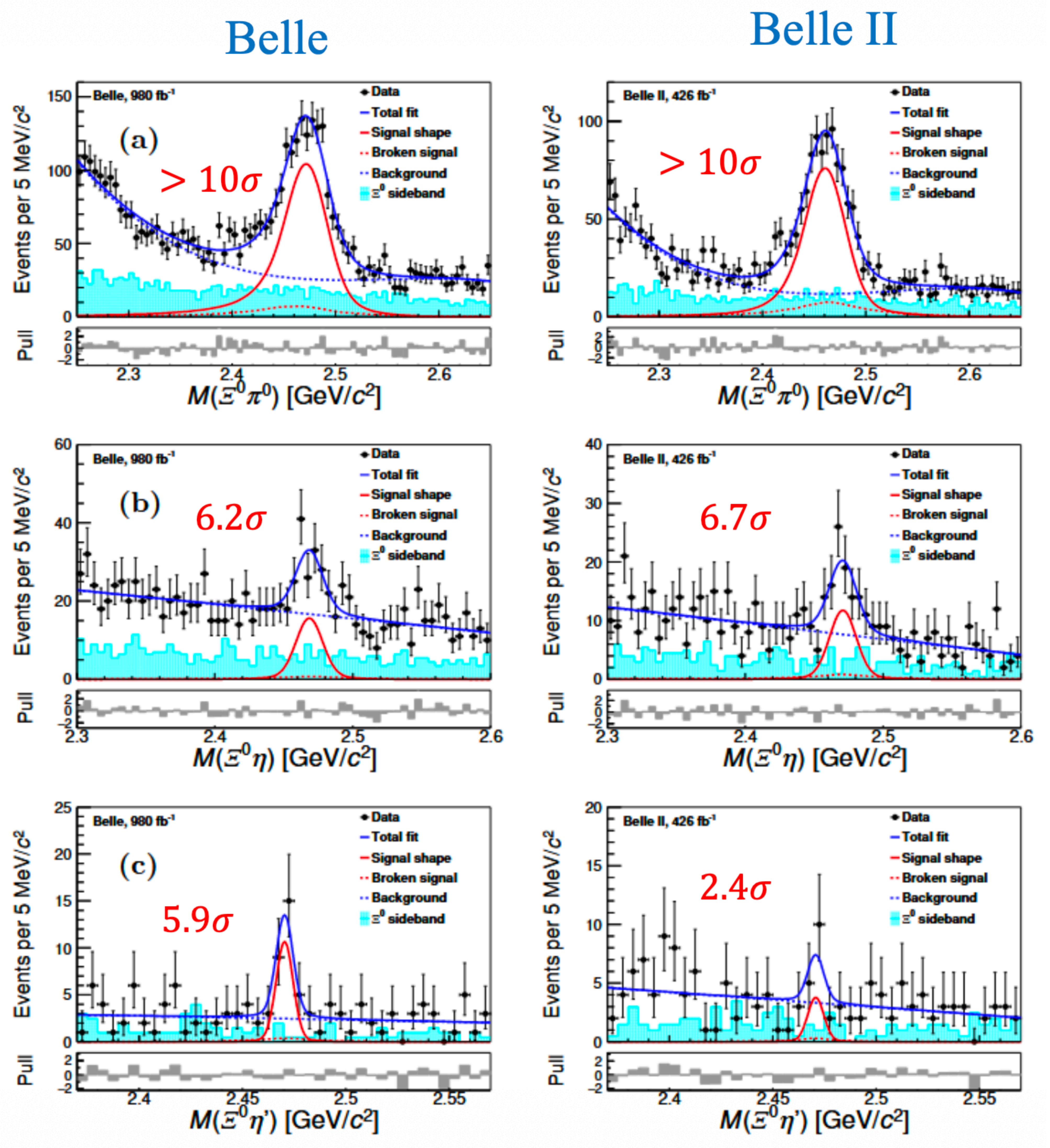
The third column assumes the following normalization mode branching fractions:

$\mathscr{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.43 \pm 0.27)\,\%$

$\mathscr{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^-) = (2.9 \pm 1.3)\,\%$

First observation of $\Xi_c^0 \to \Xi^0 h^0, h^0 = \pi^0, \eta, \eta'$

JHEP 10 (2024) 045



- All three Cabibbo-favored modes are observed for the first time in the Belle+Belle II data

- Results relative to the $\Xi_c^0 \to \Xi^- \pi^+$ normalization mode

$$B(\Xi_c^0 \to \Xi^0 \pi^0)/B(\Xi_c^0 \to \Xi^- \pi^+) = (0.48 \pm 0.02 \pm 0.03)$$
$$B(\Xi_c^0 \to \Xi^0 \eta)/B(\Xi_c^0 \to \Xi^- \pi^+) = (0.11 \pm 0.01 \pm 0.01)$$
$$B(\Xi_c^0 \to \Xi^0 \eta')/B(\Xi_c^0 \to \Xi^- \pi^+) = (0.08 \pm 0.02 \pm 0.01)$$

- Absolute BRs assuming $\mathscr{B}(\Xi_c^0 \to \Xi^- \pi^+) = (1.43 \pm 0.27)\,\%$

$$B(\Xi_c^0 \to \Xi^0 \pi^0) = (6.9 \pm 0.3 \pm 0.5 \pm 1.3) \times 10^{-3}$$
$$B(\Xi_c^0 \to \Xi^0 \eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-3}$$
$$B(\Xi_c^0 \to \Xi^0 \eta') = (1.2 \pm 0.3 \pm 0.1 \pm 0.2) \times 10^{-3}$$

Observation of $\Xi_c^+ \to \Sigma^+ K_S$, $\Xi^0\pi^+$ and $\Xi^0 K^+$

JHEP 08 (2025) 195

- Similarly, the Cabibbo-favored modes $\Xi_c^+ \to \Sigma^+ K_S, \Xi^0\pi^+$ and the singly Cabibbo-suppresed mode $\Xi_c^+ \to \Xi^0 K^+$ are observed in the Belle + Belle II data

- Results relative to $\Xi_c^+ \to \Xi^-\pi^+\pi^-$

$B(\Xi_c^+ \to \Sigma^+ K_S^0)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (0.067 \pm 0.007 \pm 0.003)$

$B(\Xi_c^0 \to \Xi^0\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (0.11 \pm 0.01 \pm 0.01)$

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- Absolute BRs assuming $\mathscr{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^-) = (2.9 \pm 1.3)\,\%$

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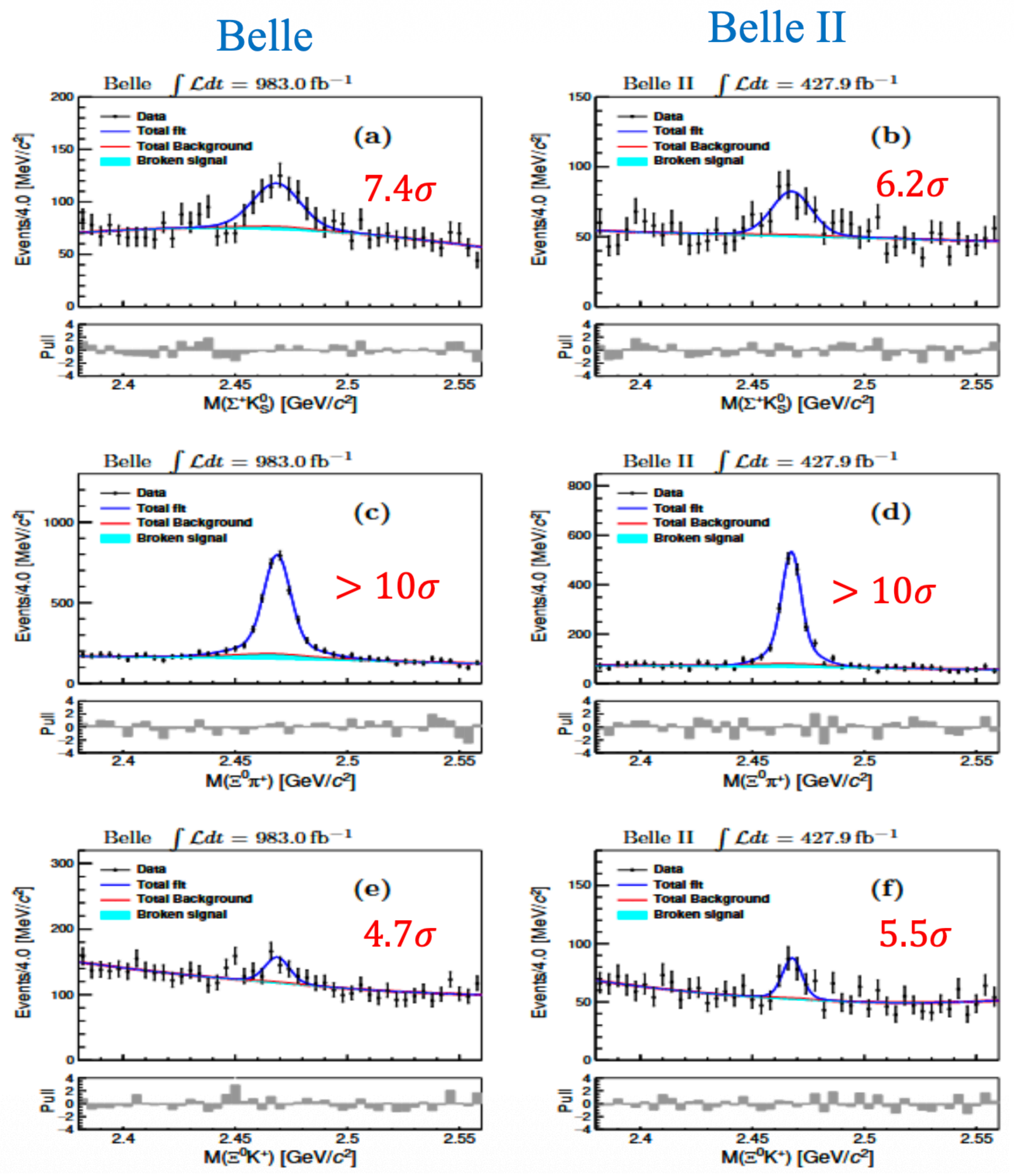

Summary

- The Belle/Belle II data set allows to make numerous contributions to the study of heavy QCD bound states (lifetimes, CP asymmetries, decay modes, excited states)

- Measurement of the D^0, D^+, D_s^+, Λ_c^+, Ω_c^+ lifetimes

$$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})\ \text{fs}$$
$$\tau(D_s^+) = 498.7 \pm 1.7(\text{stat.})^{+1.1}_{-0.8}(\text{syst.})\ \text{fs}$$
$$\tau(\Lambda_c^+) = 203.20 \pm 0.89(\text{stat.}) \pm 0.77(\text{syst.})\ \text{fs}$$
$$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})\ \text{fs}$$

- CP asymmetry in $D^0 \to K_S K_S$

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

- Measurement of numerous two body charm baryon modes

$\Xi_c^0 \to \Xi^0\pi^0$	$\Xi_c^+ \to pK_S^0$
$\Xi_c^0 \to \Xi^0\eta$	$\Xi_c^+ \to \Lambda\pi^+$
$\Xi_c^0 \to \Xi^0\eta'$	$\Xi_c^+ \to \Sigma^0\pi^+$
$\Xi_c^0 \to \Lambda\pi^0$	$\Xi_c^+ \to \Sigma^+K_s^0$
$\Xi_c^0 \to \Lambda\eta$	$\Xi_c^+ \to \Xi^0\pi^+$
$\Xi_c^0 \to \Lambda\eta'$	$\Xi_c^+ \to \Xi^0K^+$

Backup