Charm Results at Belle and Belle II

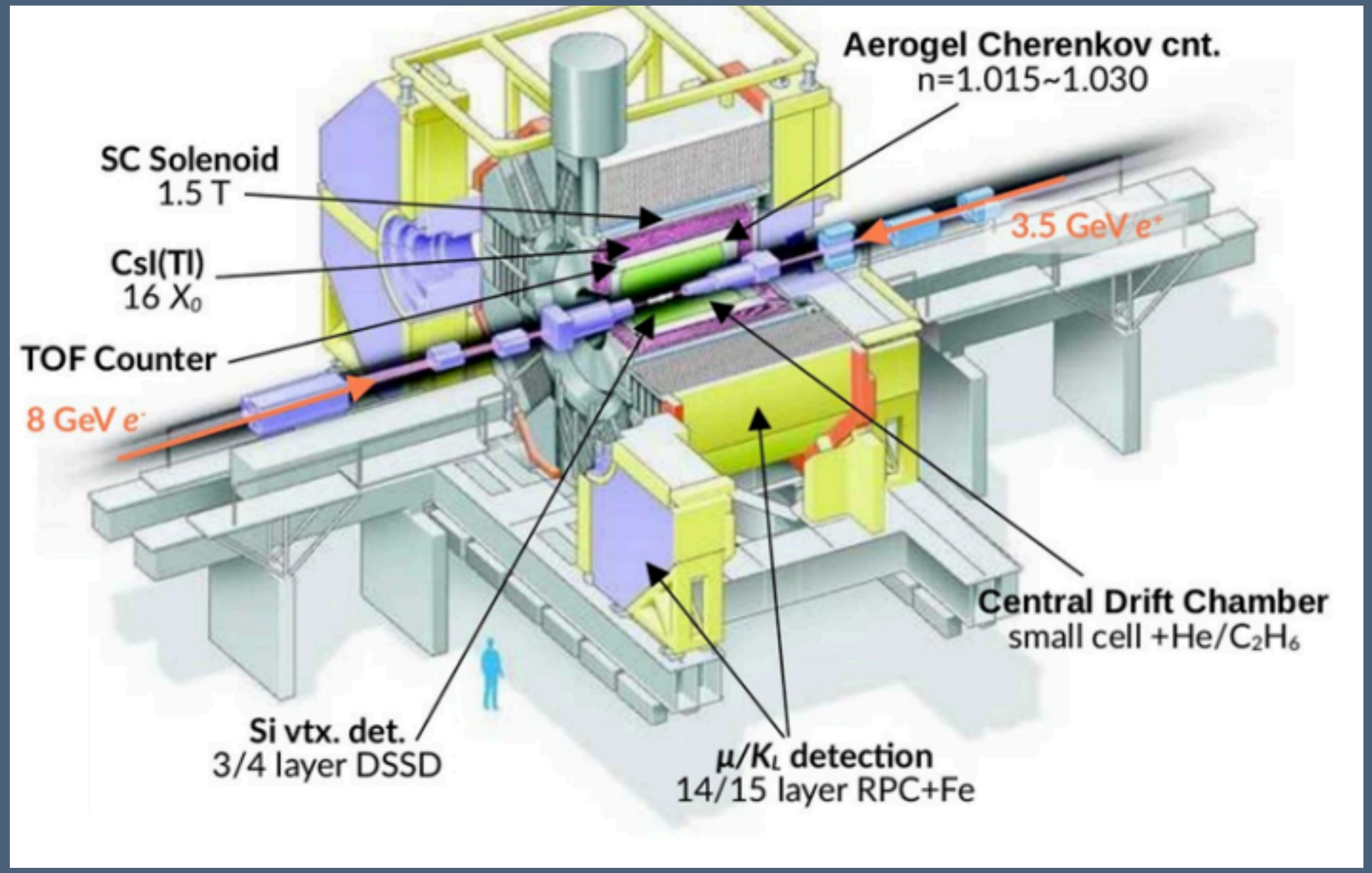
On Behalf of the Belle and Belle II collaborations

Paul Gebeline | June 5, 2024

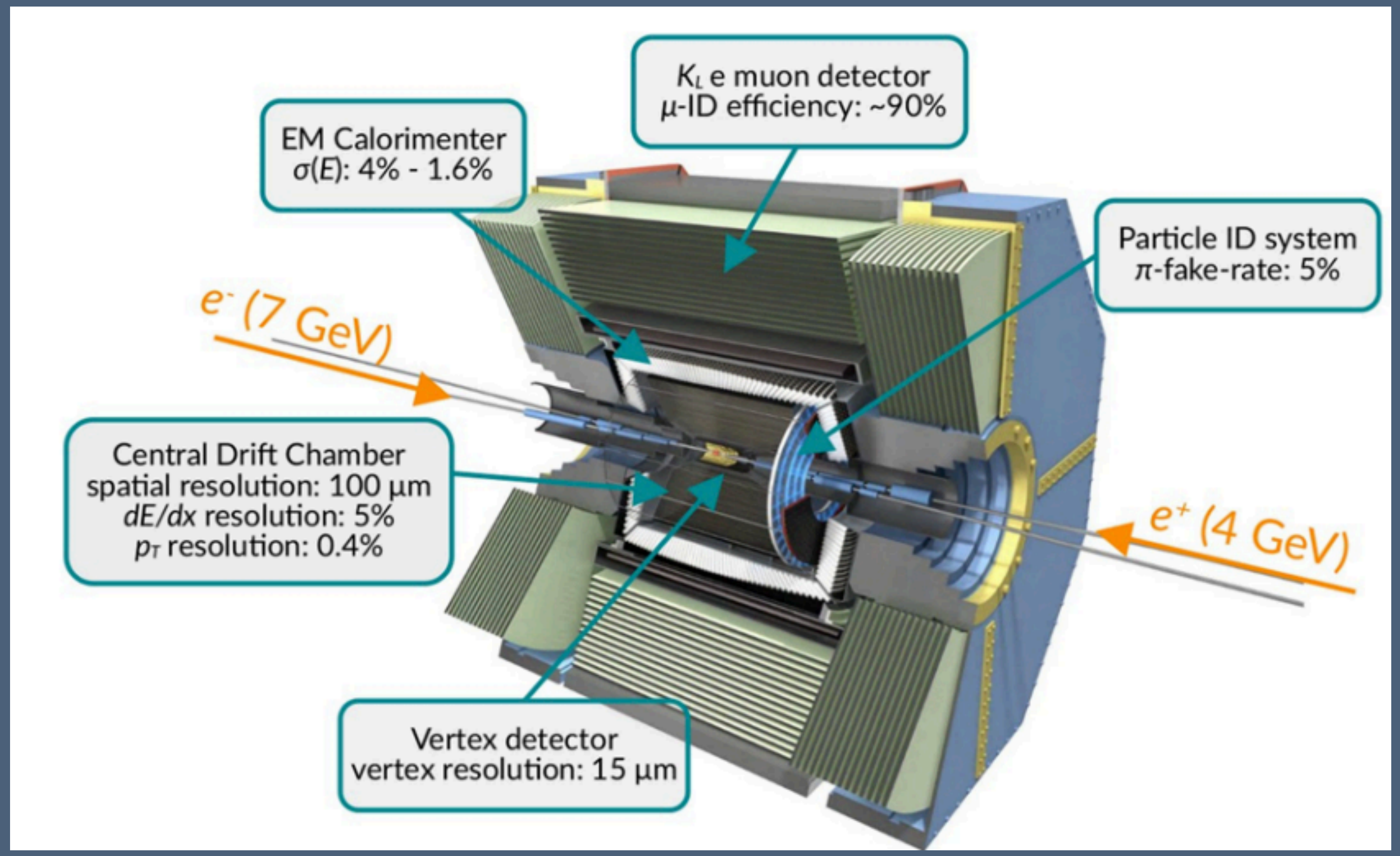
Experiments

- Asymmetric e^+e^- colliders near $\Upsilon(4S)$ resonance
  - Belle @ KEKB (1999-2010)
    $\mathscr{L}_{peak} = 2 \times 10^{34}\ cm^{-2}s^{-1}$, $\mathscr{L}_{int} = 1\ ab^{-1}$
  - Belle II @ SuperKEKB (2019-current)
    $\mathscr{L}_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$, $\mathscr{L}_{int} = 0.42\ ab^{-1}$
- "Synergic" experiments
  - Belle data can be analyzed with the **Belle II Analysis Software Framework** (basf2)
    - Analyses can be performed with a combination of Belle and Belle II data!

Belle @ KEKB



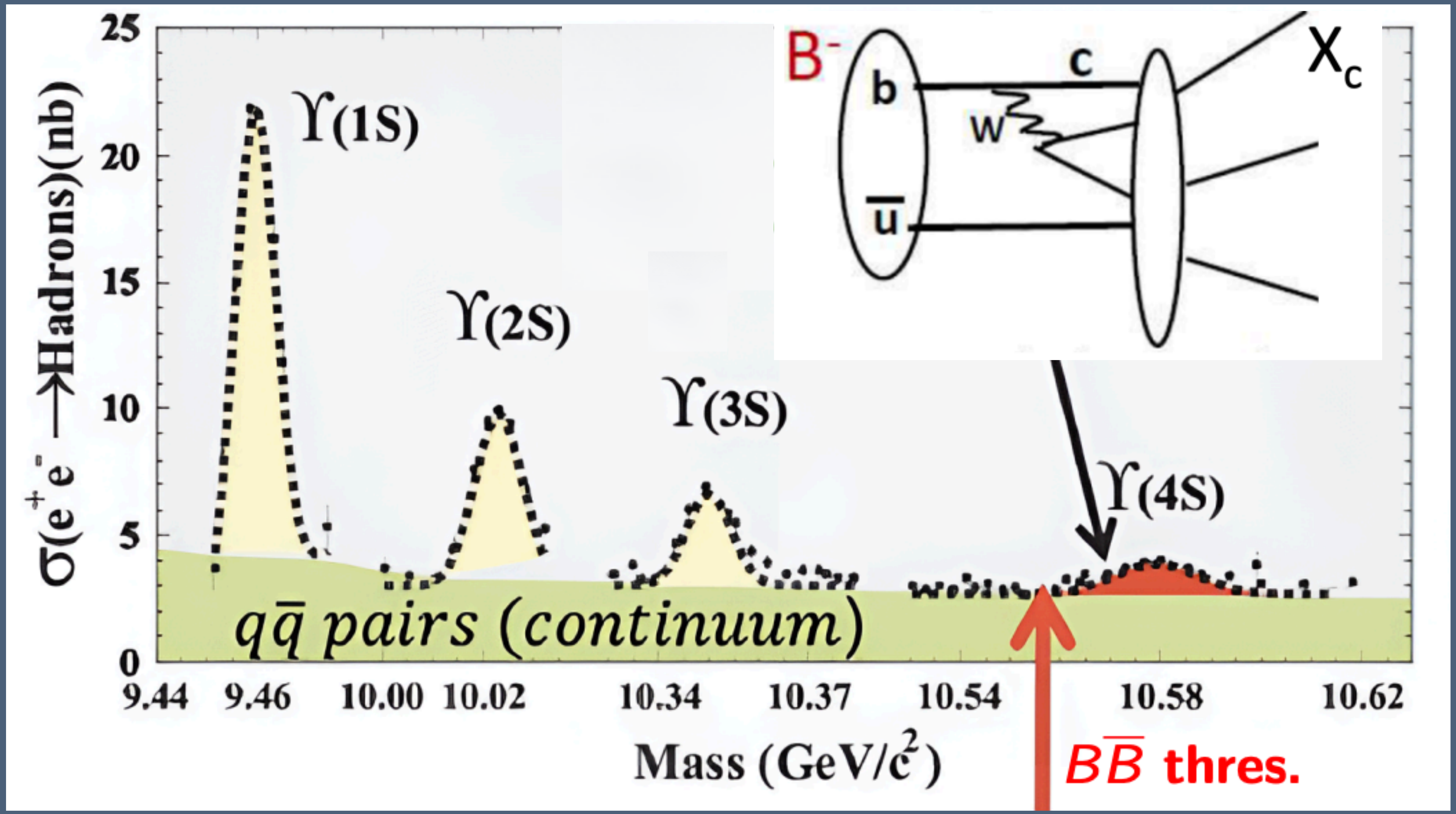
Belle II @ SuperKEKB



Charm Production

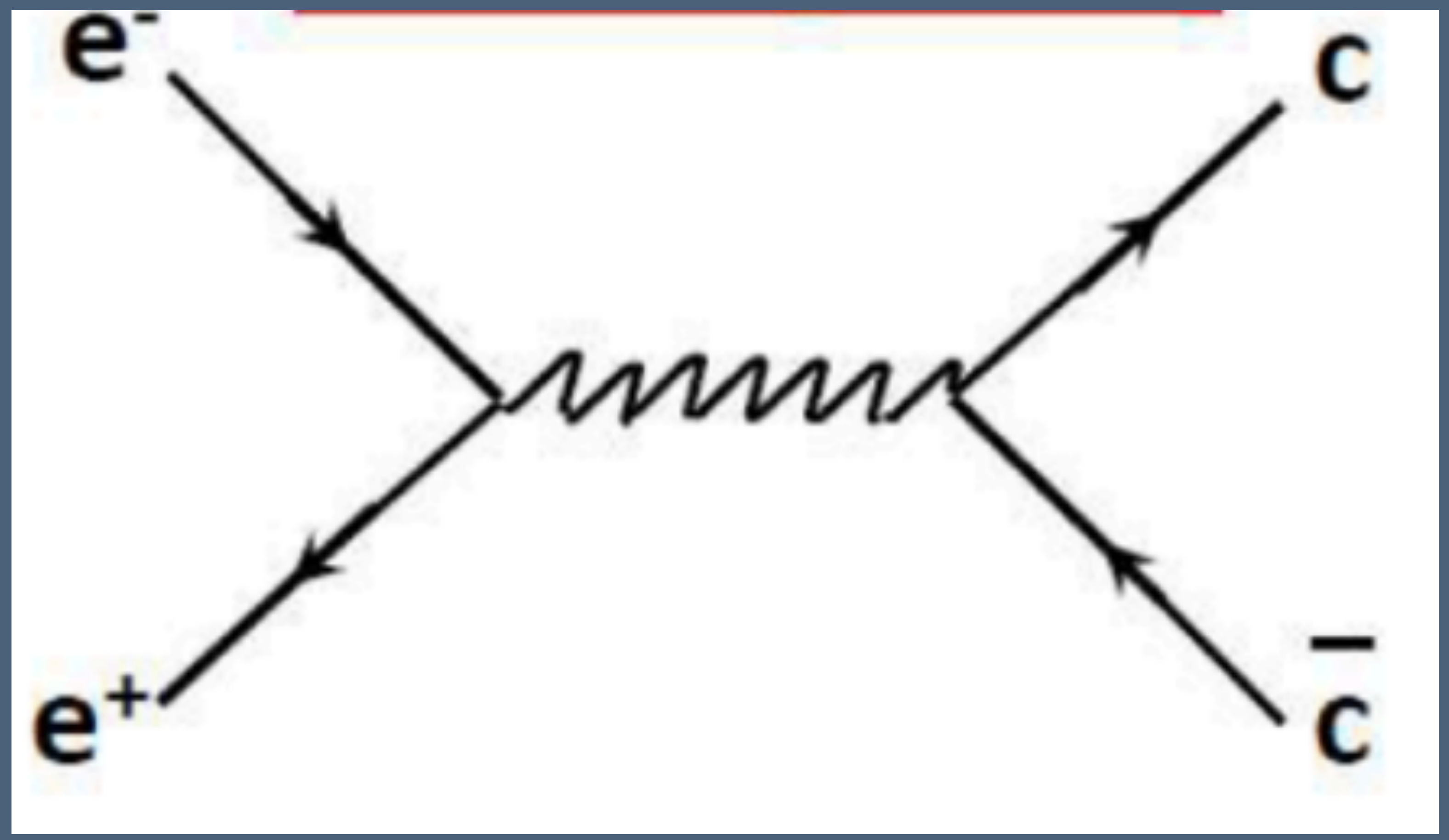
- Two primary mechanisms for charm production at Belle/Belle II:

1. $e^+e^- \to \Upsilon(4S) \to B\bar{B} \to X_c$
   Precise $B\bar{B}$ cross section allows for absolute measurements



2. $e^+e^- \to c\bar{c} \to X_c$
   Absolute measurements not possible without reference

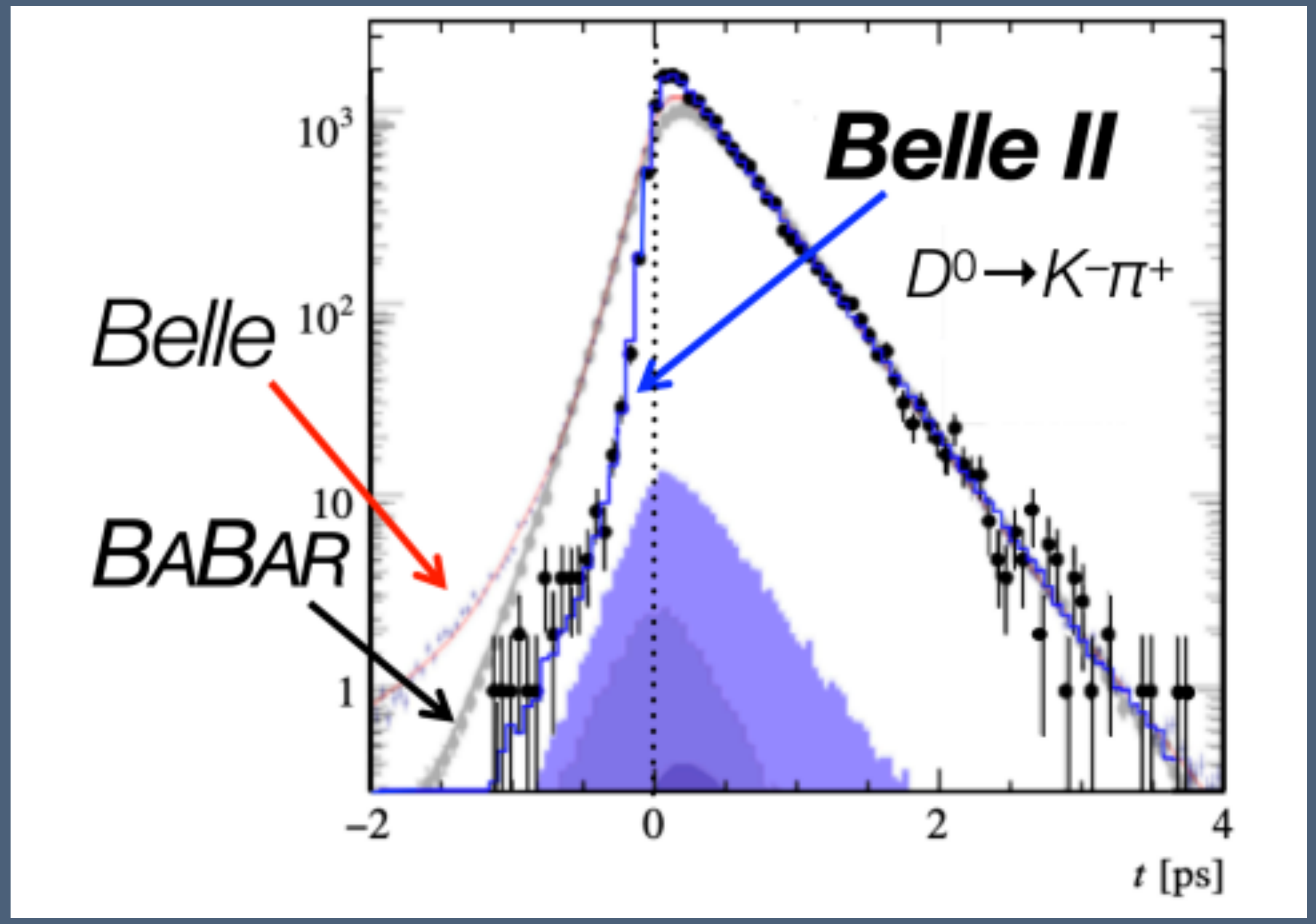
   - Used for most analyses due to its **simplicity** compared to $B\bar{B}$ processes

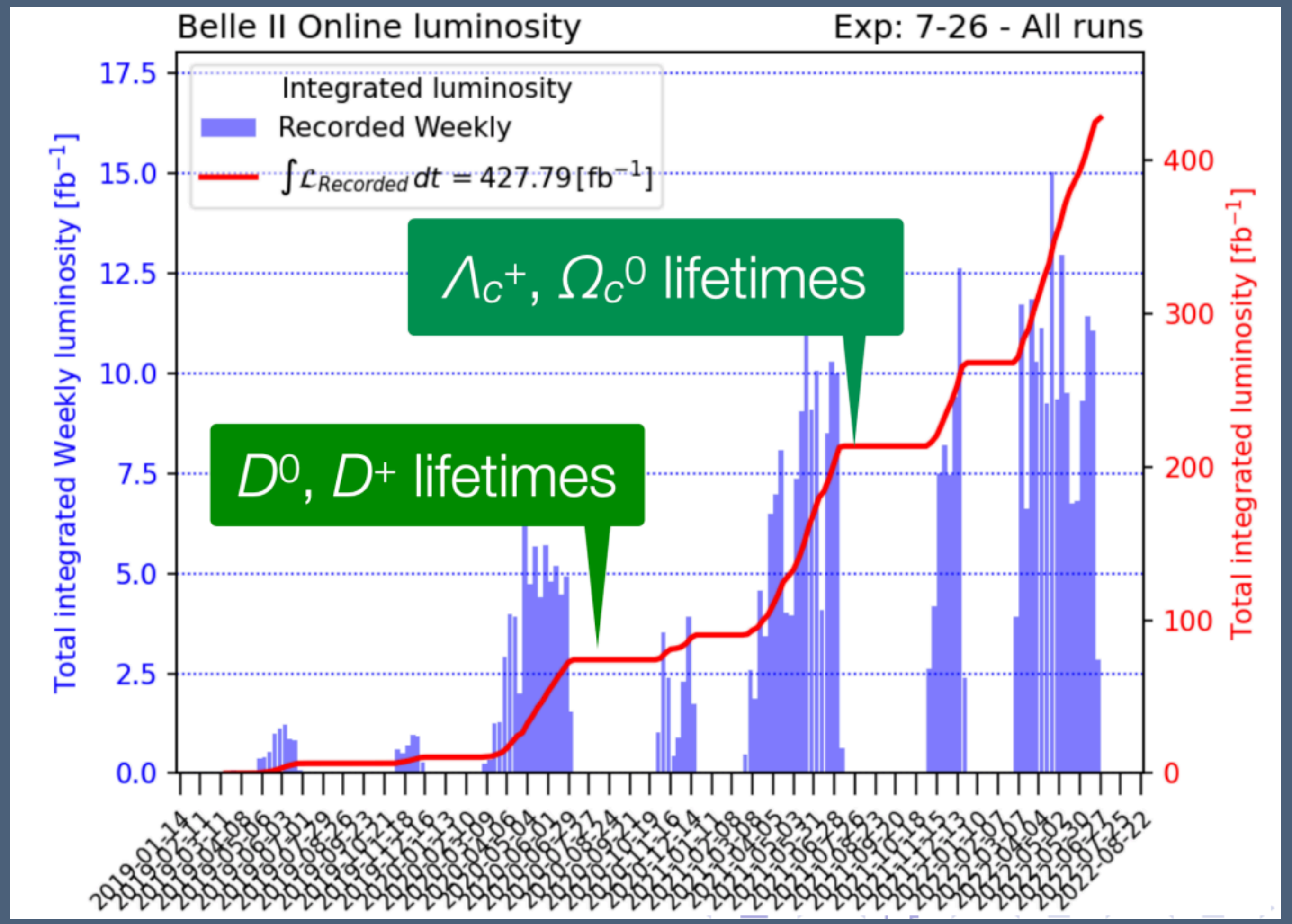


Charm Lifetimes

Charm Lifetimes

Strengthen existing theory





- Theoretically difficult to calculate due to non-perturbative effects from QCD
  - Can improve theoretical understanding of QCD and provide stringent tests of the Heavy Quark Expansion (used to predict decay-widths of heavy hadrons):

$$\Gamma(H_Q \to X) = \Gamma_3 + \Gamma_5 \frac{\langle \widetilde{\mathcal{O}}_5 \rangle}{m_Q^2} + \Gamma_6 \frac{\langle \widetilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \ldots + 16\pi^2 \left(\widetilde{\Gamma}_6 \frac{\langle \widetilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \Gamma_7 \frac{\langle \widetilde{\mathcal{O}}_7 \rangle}{m_Q^4} + \ldots \right)$$

- Belle II has precise vertexing and decay-time resolution, allowing for precise lifetime measurements
- Early dataset alone has produced **four world-leading** charm lifetime measurements and one **strong confirmation** of an LHCb result

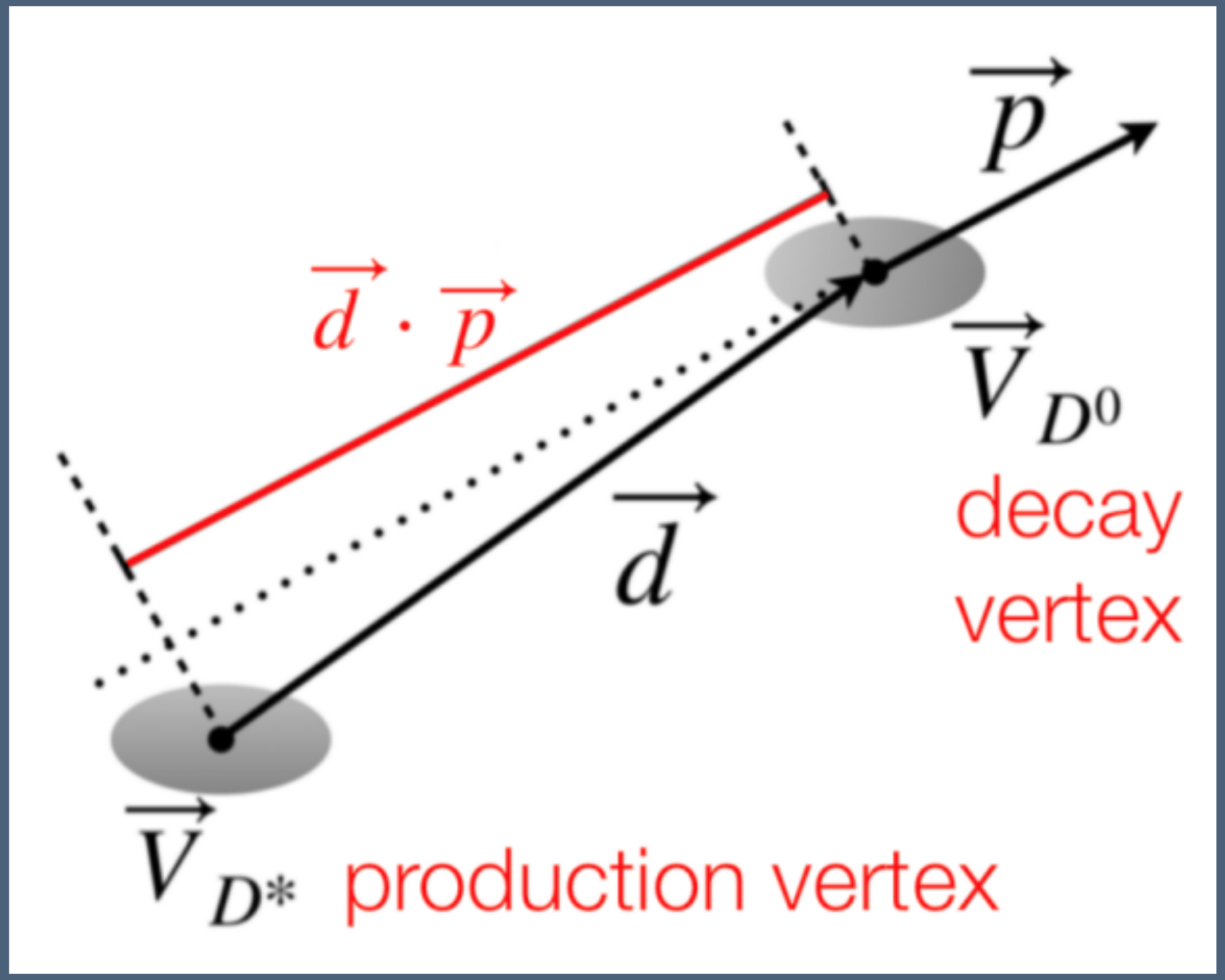
Charm Lifetimes

Strengthen existing theory

- Obtained from unbinned maximum-likelihood fits to the decay-time t and the decay-time uncertainty σ_t

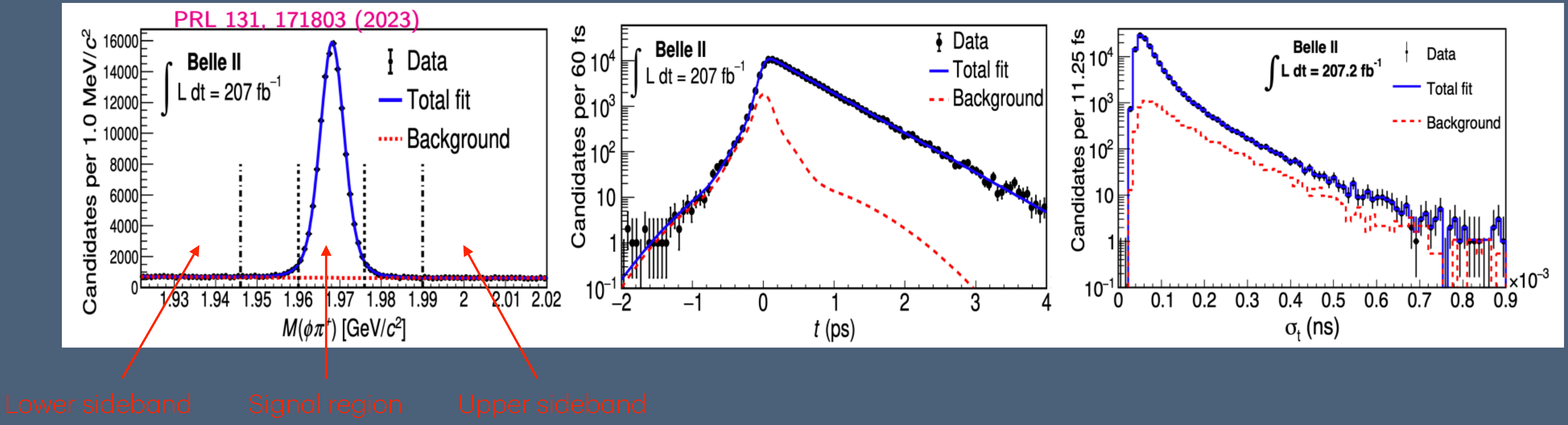
$$pdf(t, \sigma_t | \tau, f, b, s_1, s_2) = pdf(t | \sigma_t, \tau, f, b, s_1, s_2)\ pdf(\sigma_t)$$
$$\propto \int_0^\infty e^{-t_{true}/\tau} R(t - t_{true} | \sigma_t, f, b, s_1, s_2) dt_{true}\ pdf(\sigma_t),$$

Signal pdf for Λ_c^+ lifetime measurement

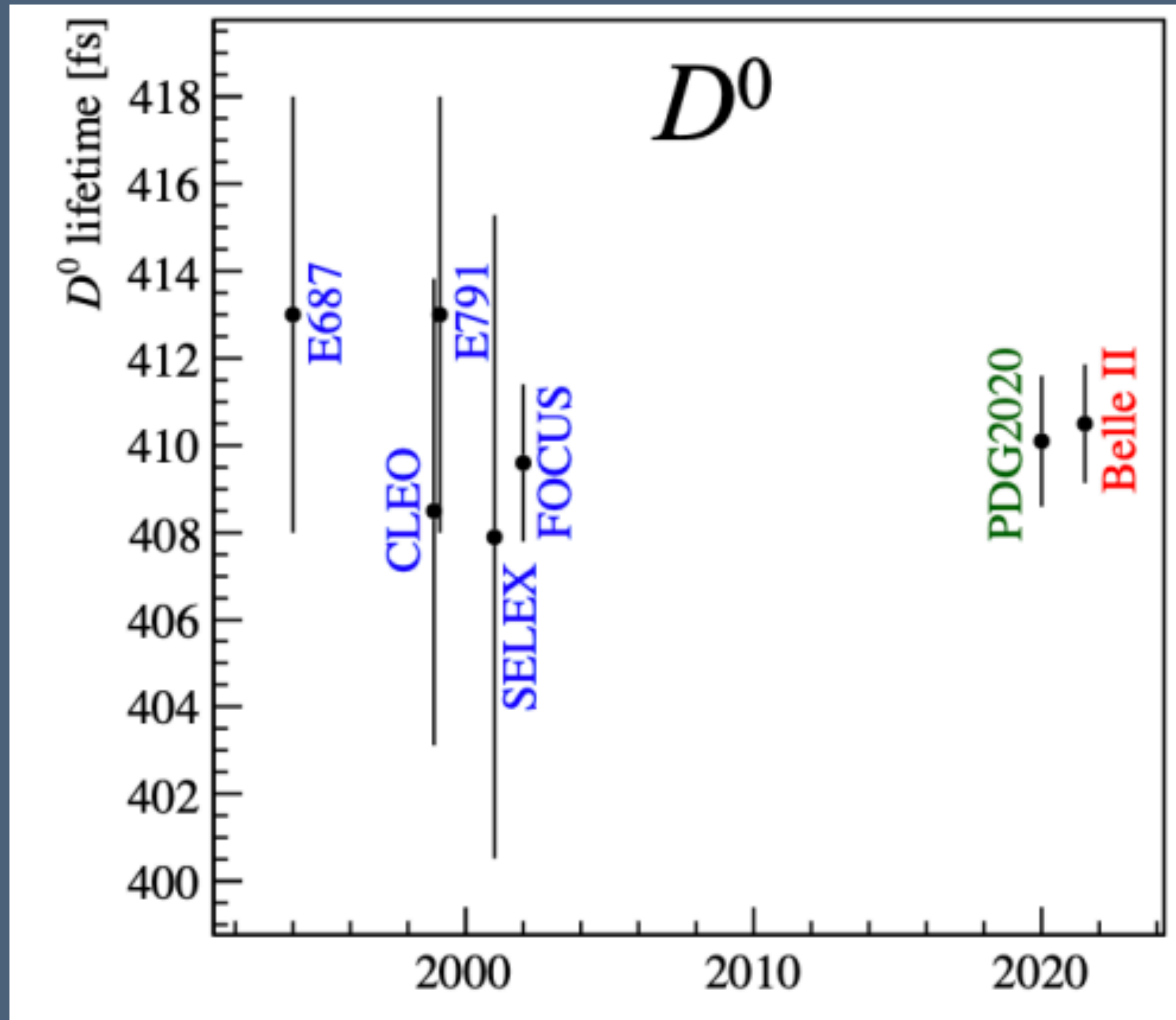


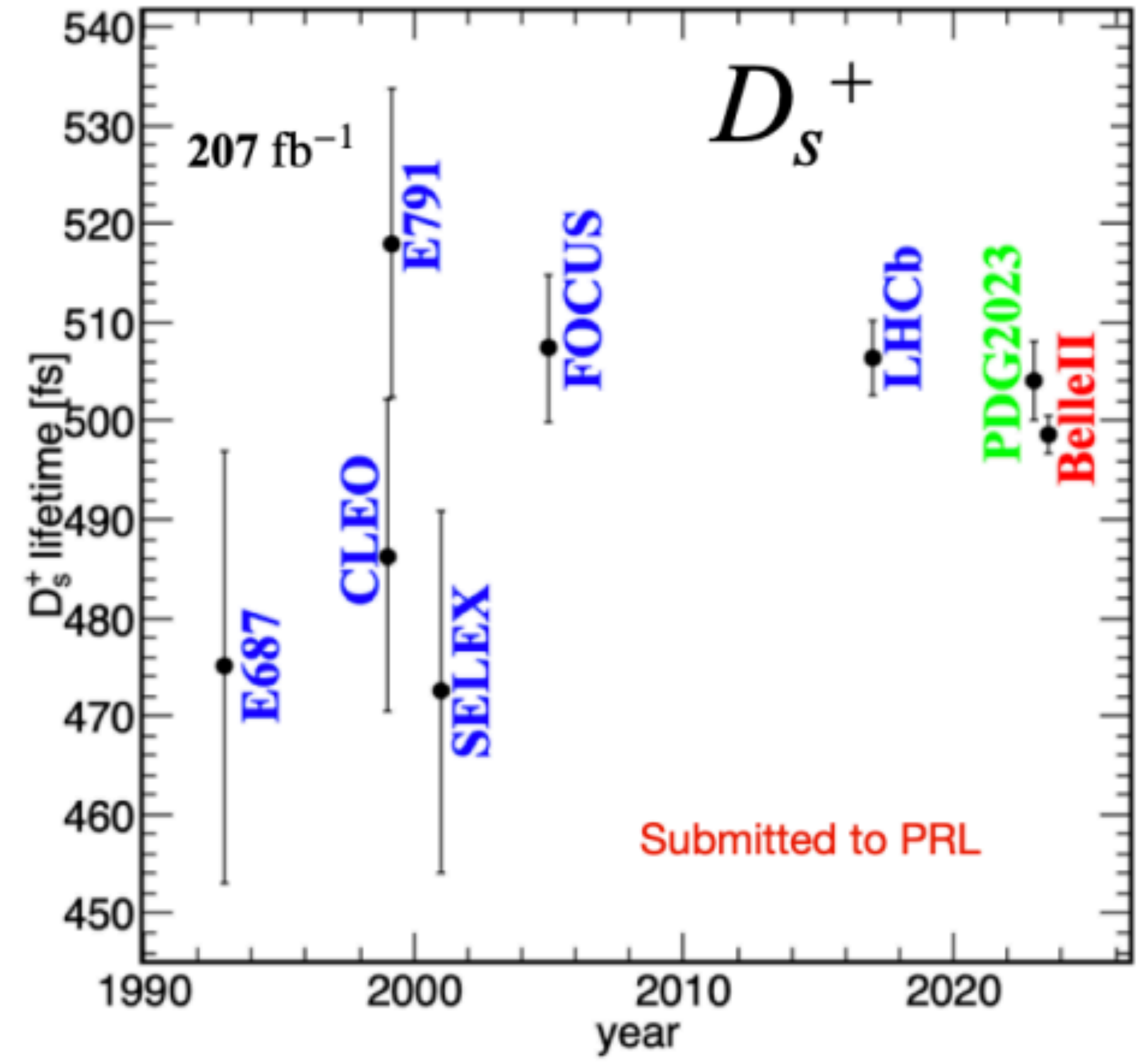
$$t = \frac{m_D}{p} \left(\vec{d} \cdot \hat{p} \right)$$

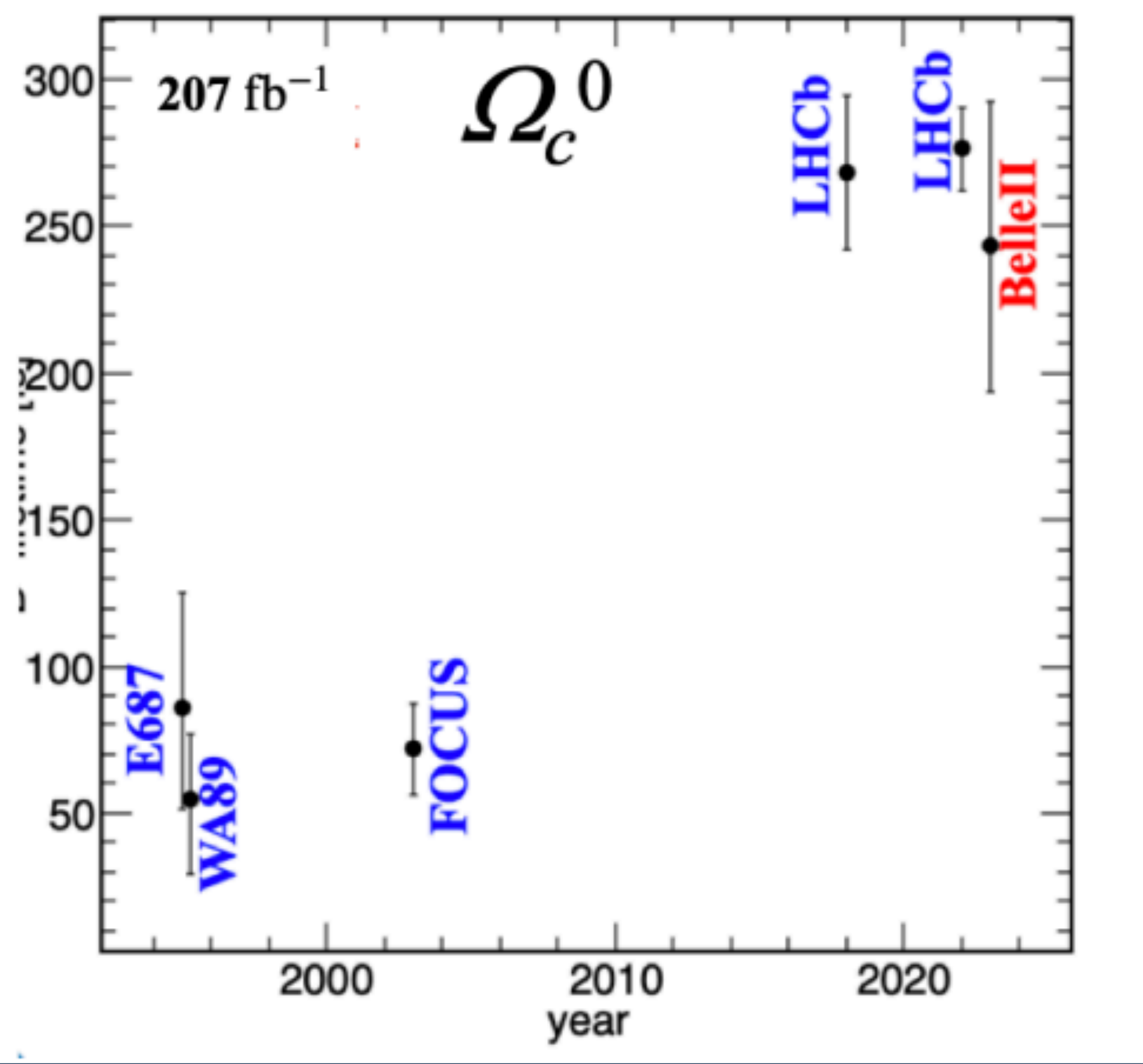
D_s^+

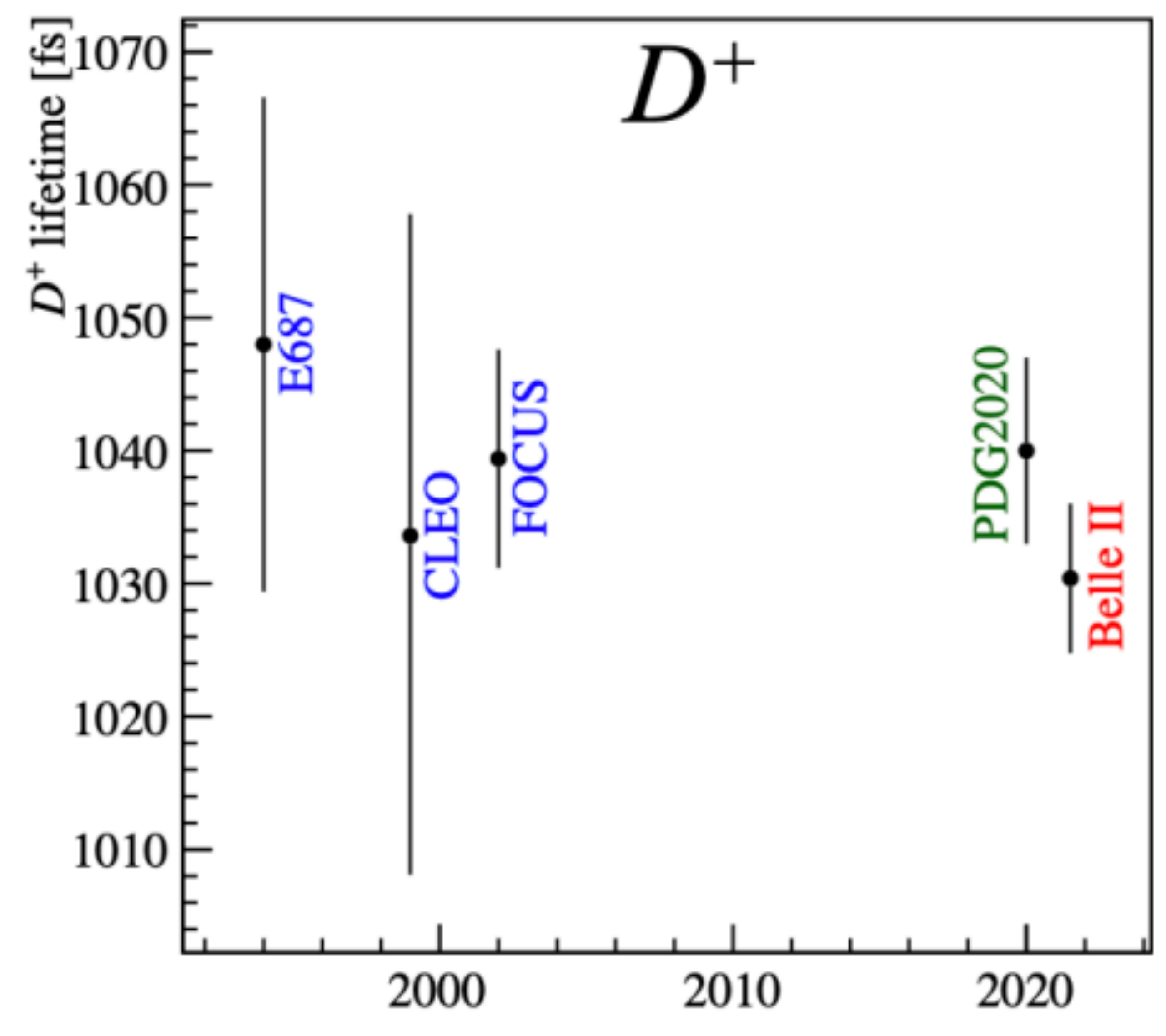


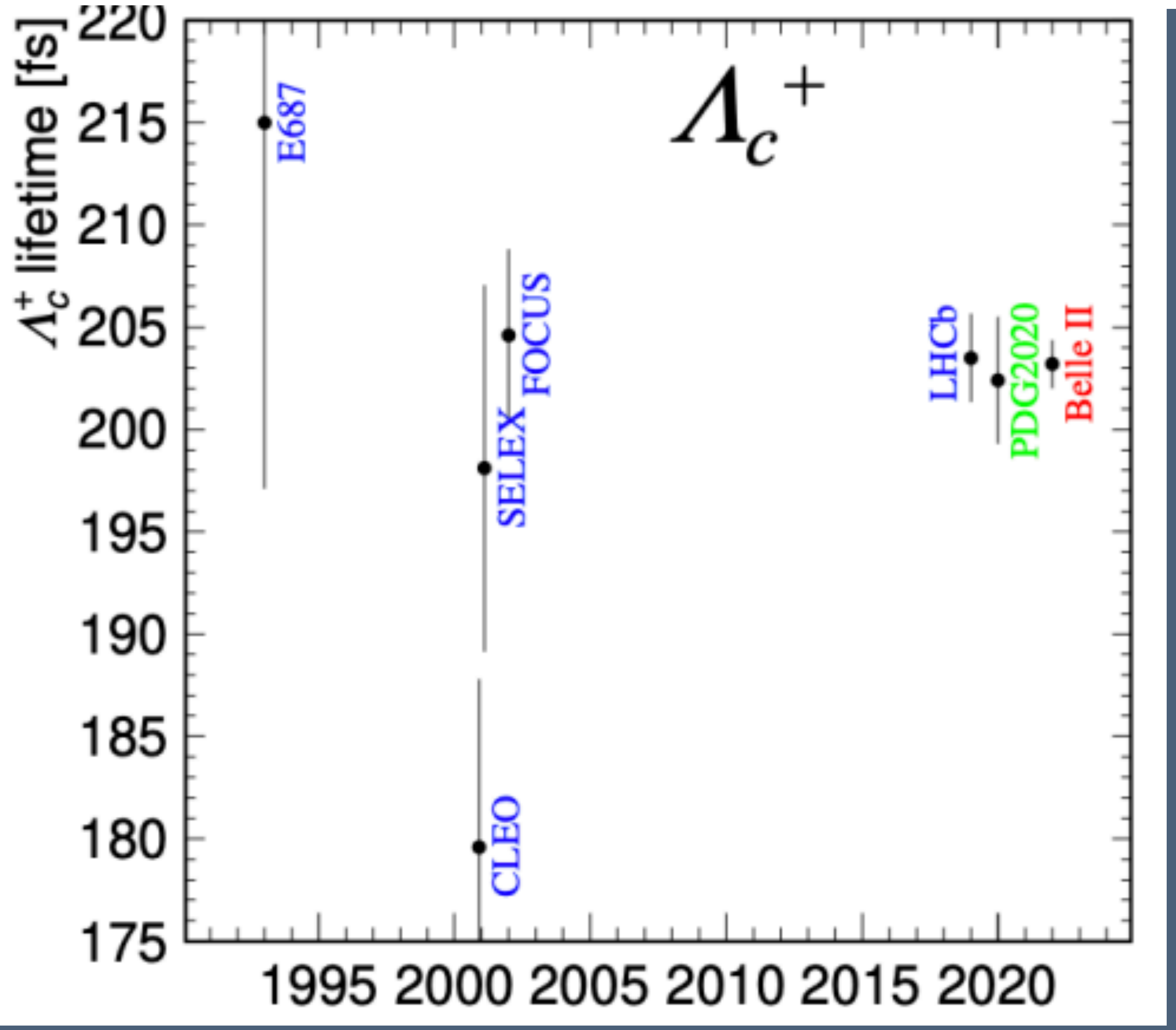
Charm Lifetime Results at Belle II









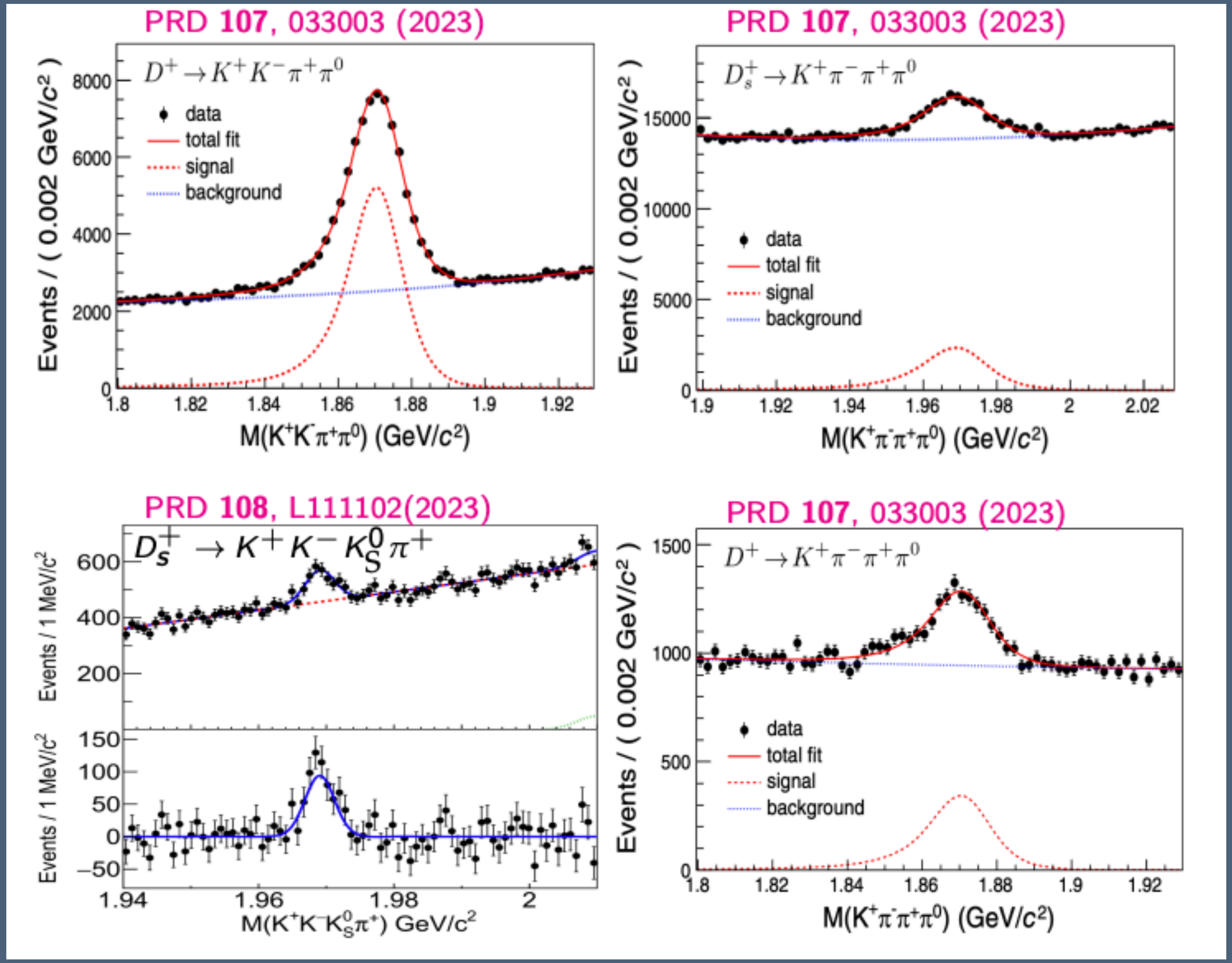


- $D^0, D_s^+, D^+, \Lambda_c^+$ more precise than world average
- Ω_c^0 measurement confirms hierarchy adjustment
  - Was believed to be the shortest lived weakly decaying charm baryon

Branching Fractions

Branching Fraction of Charm Mesons

- Cabbibo-suppressed (CS) decays provide a **strong probe for NP and CP Violation**



Belle (2023)

stat syst norm

$$\mathcal{B}(D^+ \to K^+K^-\pi^+\pi^0) = (7.08 \pm 0.08 \pm 0.16 \pm 0.2) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to K^+\pi^-\pi^+\pi^0) = (9.44 \pm 0.34 \pm 0.28 \pm 0.32) \times 10^{-3}$$
$$\mathcal{B}(D^+ \to K^+\pi^-\pi^+\pi^0) = (1.05 \pm 0.07 \pm 0.02 \pm 0.03) \times 10^{-3}$$
$$\mathcal{B}(D^0 \to K_s^0K_s^0\pi^+\pi^-) = (4.79 \pm 0.08 \pm 0.10 \pm 0.31) \times 10^{-4}$$

Consistent with prior results but with greater precision

Phys. Rev. D 107, 052001

$$\mathcal{B}(D_s^+ \to K^+K^-K_s^0\pi^+) = (1.29 \pm 0.14 \pm 0.04 \pm 0.11) \times 10^{-4}$$

First measurement; 9.2σ signal significance

Branching Fraction of Charm Baryons

$\mathscr{B}(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.17 \pm 0.25) \times 10^{-3}$

$\mathscr{B}(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.17 \pm 0.25) \times 10^{-3}$

$\mathscr{B}(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$

$\mathscr{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 + 0.19 + 0.06 + 0.19) \times 10^{-4}$

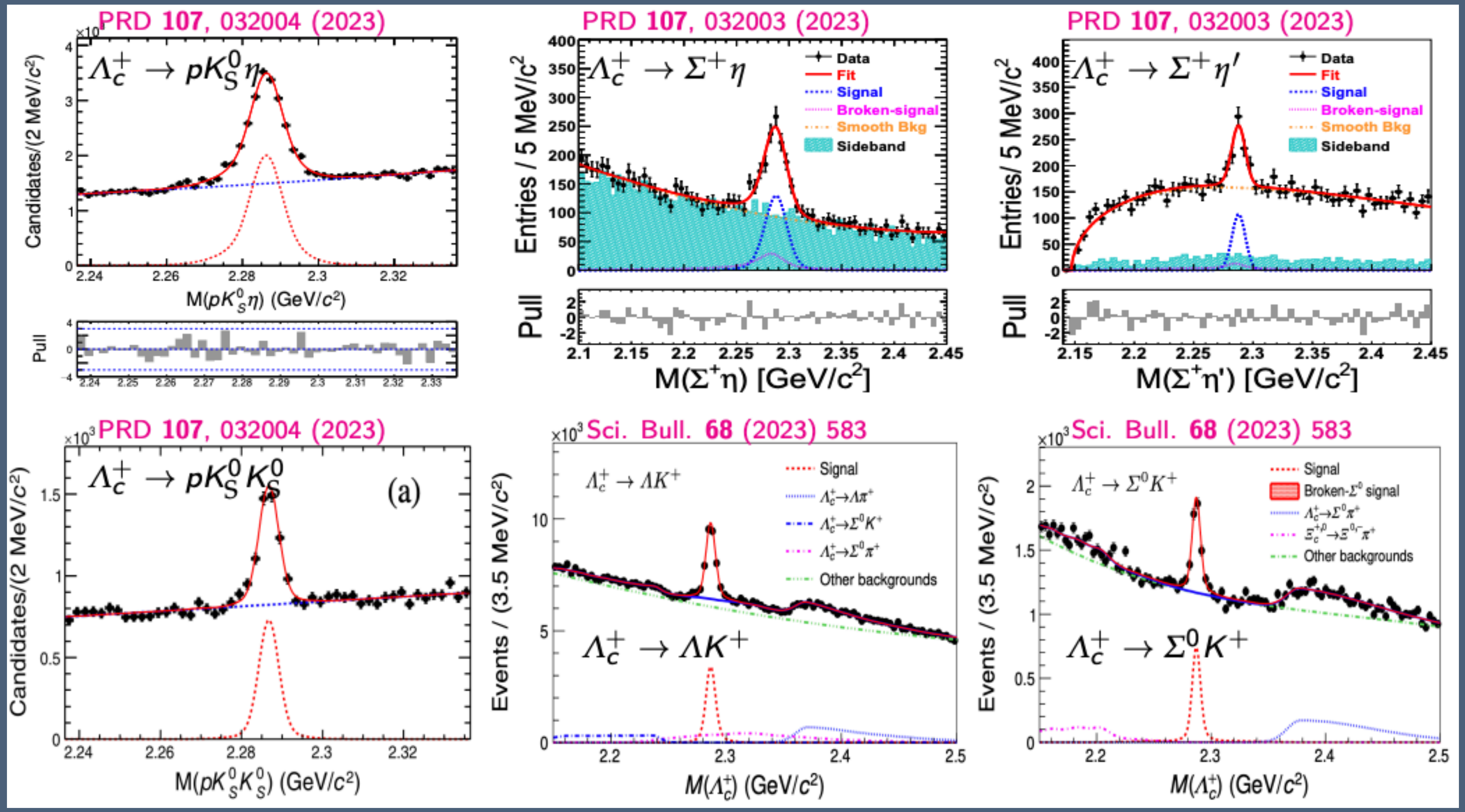
Agrees with prior results within 2σ, but with best precision

$\mathscr{B}(\Lambda_c^+ \to pK_s^0K_s^0) = (2.35 \pm 0.12 \pm 0.07 \pm 0.12) \times 10^{-4}$

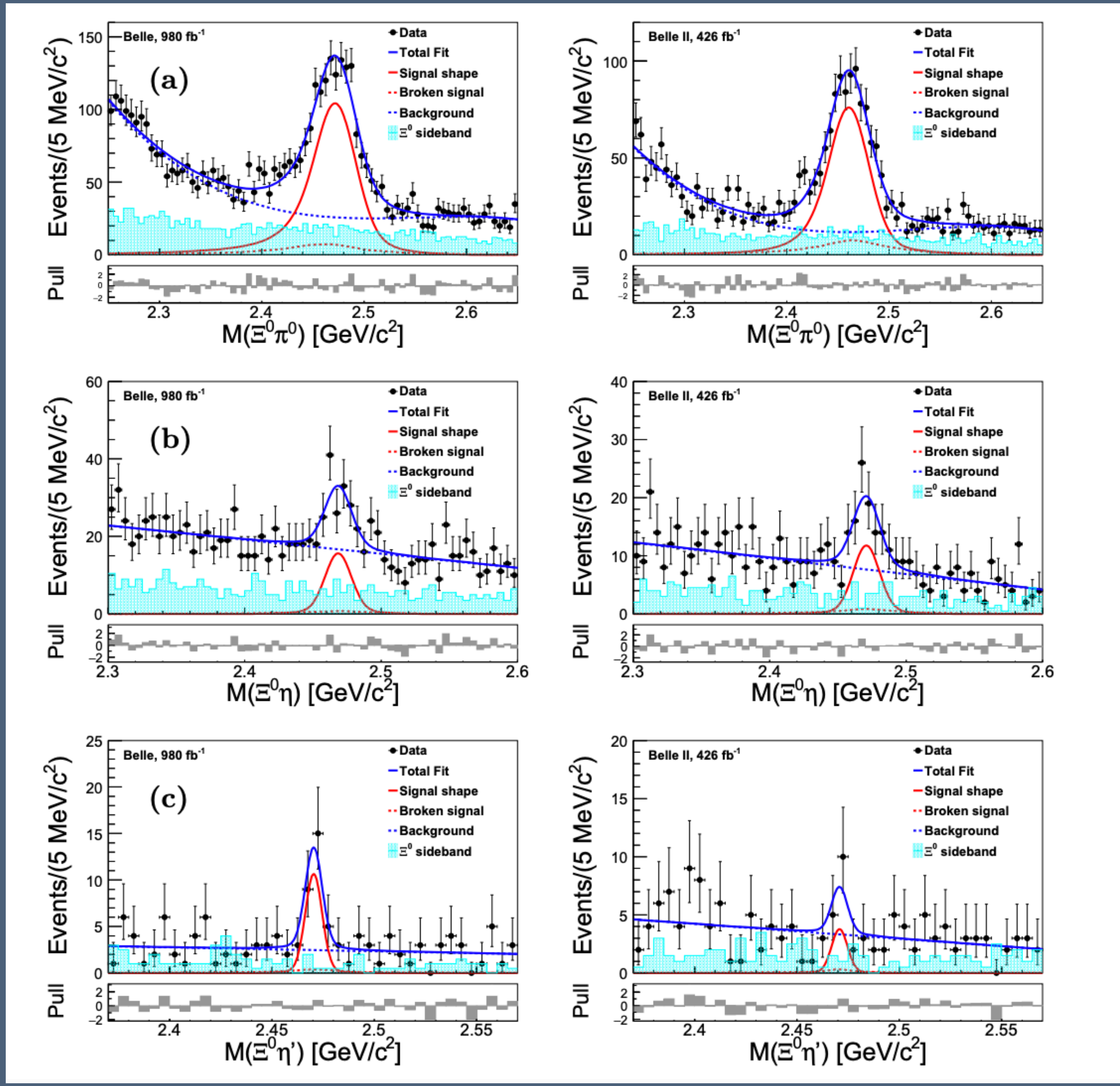
Agrees with prior results; threefold improvement in precision

$\mathscr{B}(\Lambda_c^+ \to pK_s^0\eta) = (4.35 \pm 0.10 \pm 0.20 \pm 0.22) \times 10^{-3}$

First measurement; $> 10\sigma$ statistical significance



Branching Fraction of Charm Baryons



BELLE2-NOTE-PH-2023-054

Belle 2024

$$\mathscr{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3 \pm 0.5 \pm 1.5) \times 10^{-3}$$

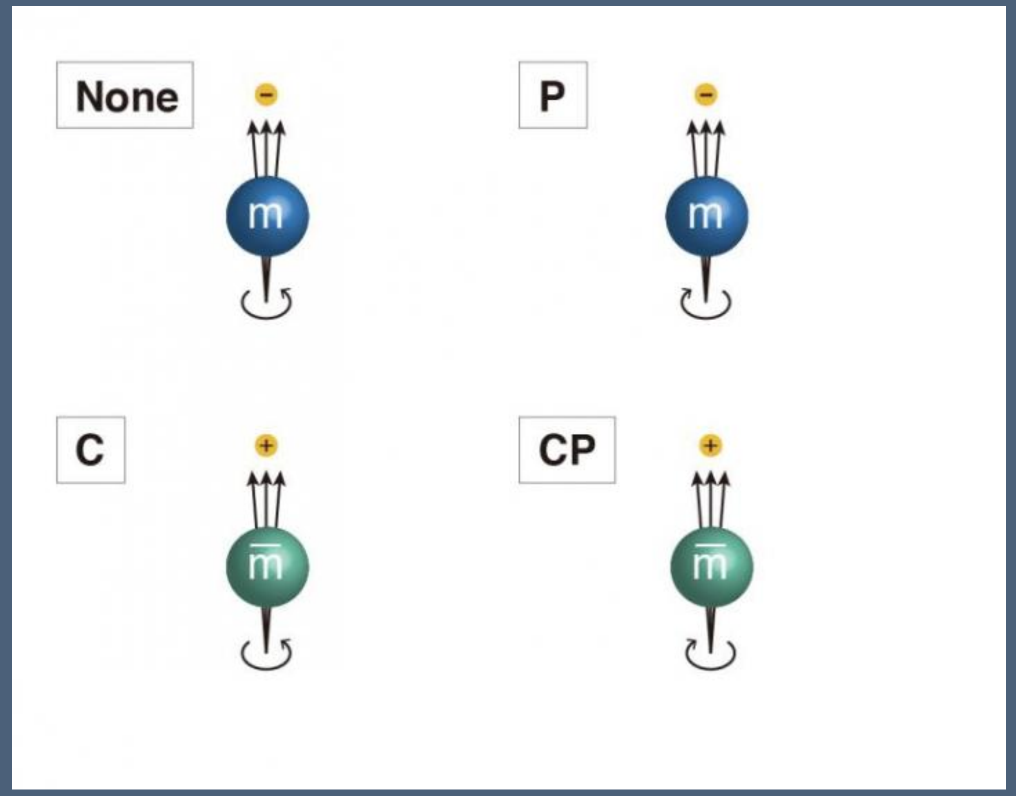
$$\mathscr{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-3}$$

$$\mathscr{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-3}$$

First synergic measurement; rules out various models and favors $SU(3)_F$ – breaking models

Search for CPV in the Charm Sector

Introduction to CP Violation



- SM —> Violated via complex phase in **Cabbibo-Kobayashi-Maskawa (CKM)** matrix
  - Strength characterized by the **Jarlskog invariant:**

    $$\mathcal{J} = Im[V_{us}V_{cb}V^*_{ub}V^*_{cs}] = A^2\lambda^6\eta(1-\lambda^2/2) + \mathcal{O}(\lambda^{10}) \approx 10^{-5}$$

  - Insufficient to produce large-scale matter-antimatter asymmetry
- CPV observed in all meson flavor sectors, but not baryon sector
  - Charm baryons —> sensitive probe for NP

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(4)$$

Wolfenstein Parameterization to $\mathcal{O}(4)$

CPV in the Charm Sector

- ΔA_{CP} first observed between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays (LHCb 2019, arXiv:1903.08726)
    - Combining this with time-integrated CP asymmetry $\mathscr{A}^{CP}(K^-K^+)$ yields
        - $a_{CP}^{dir}(K^-K^+) = (7.7 \pm 5.7) \times 10^{-4}$
        - $a_{CP}^{dir}(\pi^-\pi^+) = (23.2 \pm 6.1) \times 10^{-4}$

(LHCb 2022, arXiv:2209.03179)

- Effect due to charm hadrons is $\approx \mathcal{O}(10^{-3})$ or less (PRD 86, 036012; PRD 104, 073003)
- Searches for other sources of CPV in the charm sector are ongoing via **complementary** observables

1. T-odd asymmetry (a_{CP}^{T-odd}) measurements
2. Asymmetry (A_{CP}) measurements

T-odd asymmetries in four-body decays

- Define a **T-odd observable** $C_T = \vec{p_1} \cdot \left(\vec{p_2} \times \vec{p_3}\right)$ where 1,2,3 correspond to three of the four final state particles in a four-body decay
    - C_T should be symmetric about zero; otherwise indicates T violation (TV)
    - Quantify asymmetry via

Implies CPV via CPT Theorem!

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

Can be nonzero due to T violation **or** strong phases — take difference to remove phase effects

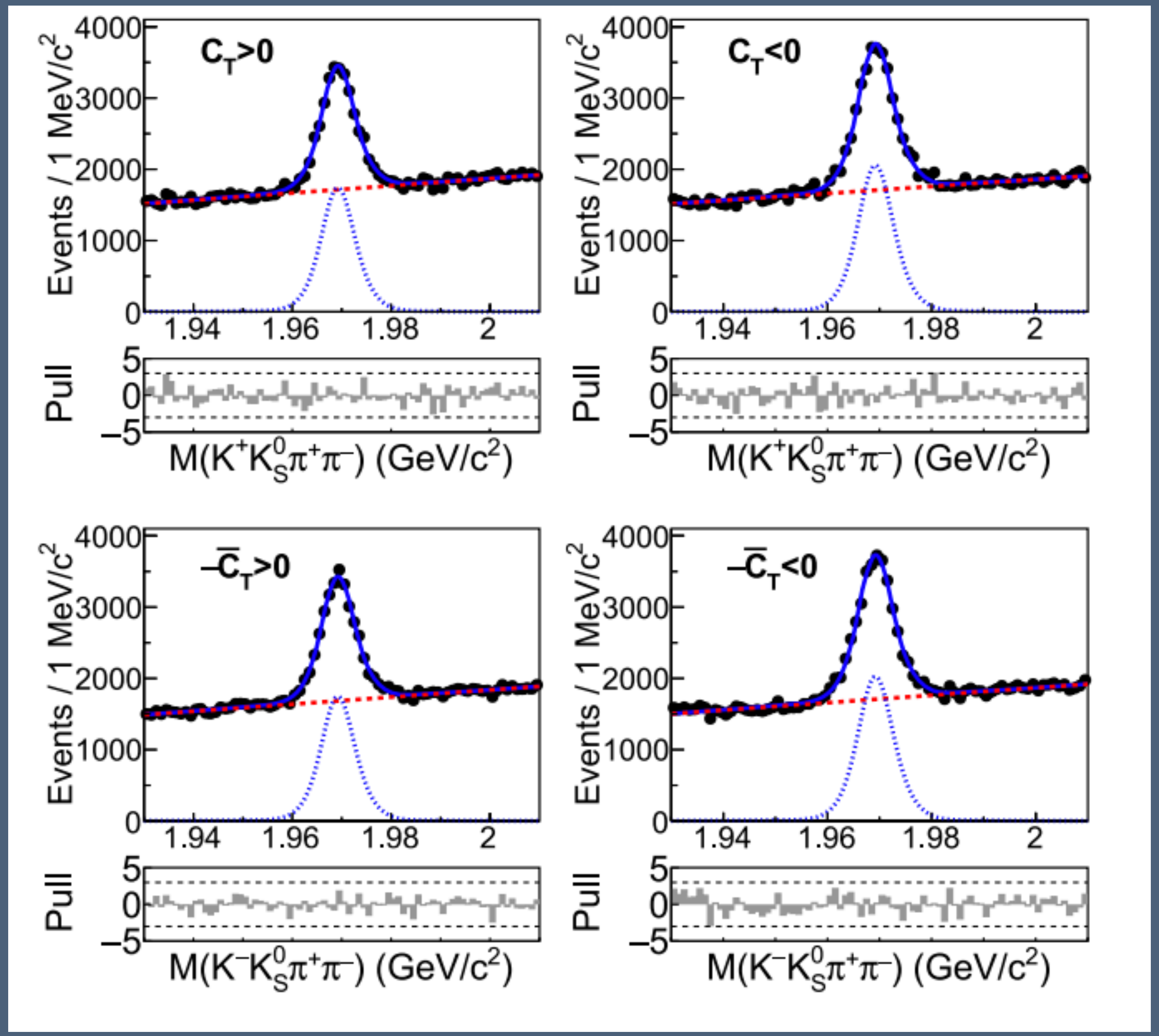
$$a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)$$

T-odd asymmetries in $D^+_{(s)} \to K^+ K^0_s h^+ h^-$

-World leading precision

-Dominated by statistical uncertainty

-No direct CPV evidence

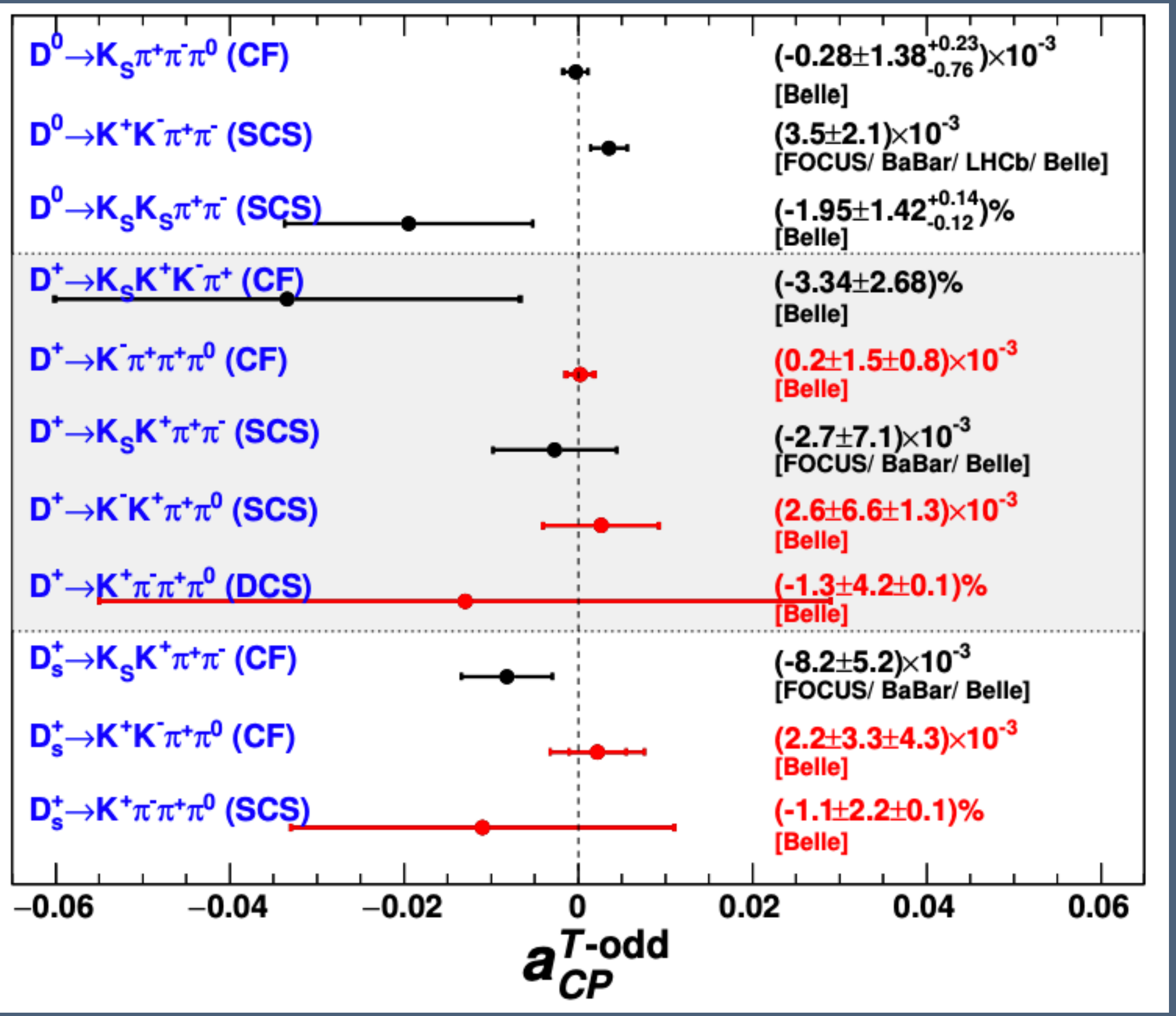


Mode	A_T (%)	$a_{CP}^{T\text{-odd}}$ (%)
$D^+ \to K^+ K^0_S \pi^+ \pi^-$	(3.67 ± 1.23)	(0.34 ± 0.87)
$D^+_s \to K^+ K^0_S \pi^+ \pi^-$	(-8.31 ± 8.89)	(-0.46 ± 0.63)
$D^+ \to K^+ K^- K^0_S \pi^+$	(-1.40 ± 4.23)	(-3.34 ± 2.66)

Sys ~ 0.35%

Phys.Rev.D108, L111102 (2023)

T-odd asymmetries in $D^+_{(s)} \to Kh\pi^+\pi^0$



- -First measurements
- -Strong precision
- -No direct CPV evidence

Decay	$D^+ \to f$			$D_s^+ \to f$	
Final state (f)	$K^+K^-\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^+K^-\pi^+\pi^0$
N_D	27284 ± 254	2062 ± 127	438432 ± 947	15197 ± 484	167357 ± 786
$N_{\bar{D}}$	27177 ± 255	2044 ± 125	450667 ± 961	14945 ± 479	167064 ± 788
A_T (%)	$+3.63 \pm 0.93$	-0.4 ± 6.0	-0.76 ± 0.22	$+1.4 \pm 3.2$	$+2.96 \pm 0.47$
$a_{CP}^{T\text{-odd}}$ (%)	$+0.26 \pm 0.66$	-1.3 ± 4.2	$+0.02 \pm 0.15$	-1.1 ± 2.2	$+0.22 \pm 0.33$

Submitted to PRD, arXiv:2305.12806

Direct CPV via Raw Asymmetry Measurements

- The raw asymmetry for $\Lambda_c^+ \to \Lambda K^+$ is given by

$$A_{raw}(\Lambda_c^+ \to \Lambda K^+) \approx A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) + A_{CP}^{dir}(\Lambda \to p\pi^-) + A_\epsilon^{\Lambda} + A_\epsilon^{K^+} + A_{FB}^{\Lambda_c^+}$$

production forward-backward asymmetry ($\gamma - Z^0$ interference/higher order QED)

CP Asymmetry

Detection Asymmetry (efficiency differences between charge conjugates)

- $A_\epsilon^{K^+}$ contribution is reduced by weighting $w_{\Lambda_c,\bar{\Lambda}_c} = 1 \mp A_\epsilon^{K^+}[cos\theta, p_T]$

- Use a control mode, $\Lambda_c^+ \to \Lambda\pi^+$, to cancel out terms

  - $\Delta A_{raw} = A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{dir}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+)$ (measuring ΔA_{raw} is sufficient!)

Direct CPV via Raw Asymmetry Measurements

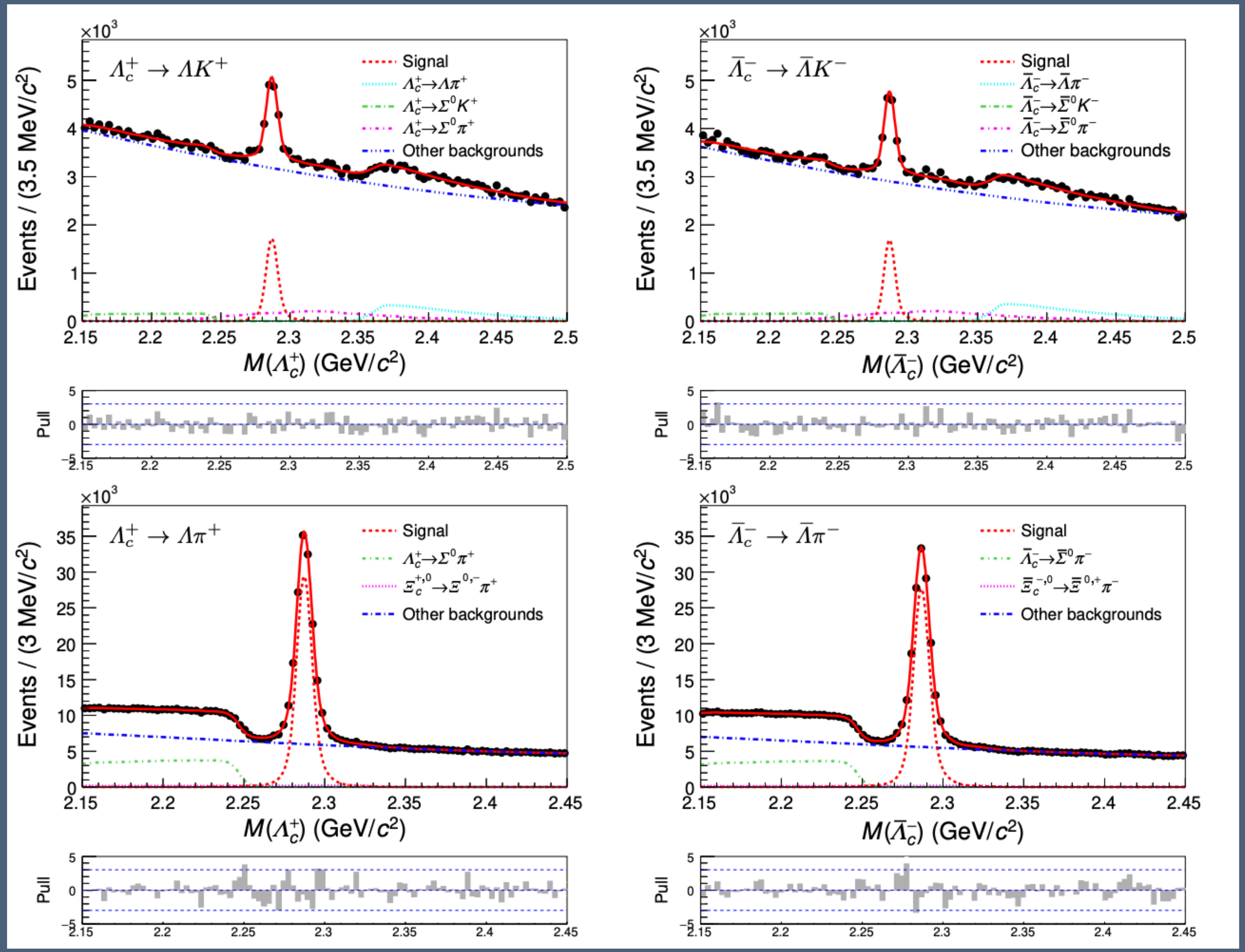
- Measure

$$A_{raw}(\Lambda_c^+ \to \Lambda K^+) = \frac{N(\Lambda_c^+ \to \Lambda K^+) - N(\bar{\Lambda}_c^- \to \bar{\Lambda} K^-)}{N(\Lambda_c^+ \to \Lambda K^+) + N(\bar{\Lambda}_c^- \to \bar{\Lambda} K^-)}$$

(similarly for control mode and $\Lambda_c^+ \to \Sigma^0 K^+$ with $\Lambda_c^+ \to \Sigma^0 \pi^+$ control)

- **Results from Belle, 2023**
  - first measurements of 2-body SCS charm decays, dominated by statistical uncertainty) — no evidence of CPV
    - $A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) = (2.1 \pm 2.6 \pm 0.1)\,\%$
    - $A_{CP}^{dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (2.5 \pm 5.4 \pm 0.4)\,\%$
  - $A_{CP}^{dir}(D^0 \to K_s^0 K_s^0 \pi^+ \pi^-) = [-2.51 \pm 1.44(\text{stat})^{+0.11}_{-0.10}(\text{syst})]\,\%$
    - Same paper measured $a_{CP}^{T-odd} = [-1.95 \pm 1.42(\text{stat})^{+0.14}_{-0.12}(\text{syst})]\,\%$

Science Bulletin 68 (2023) 583



Phys. Rev. D 107, 052001

Exotic Searches

Search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ at Belle

Lepton Flavor Universality (LFU)

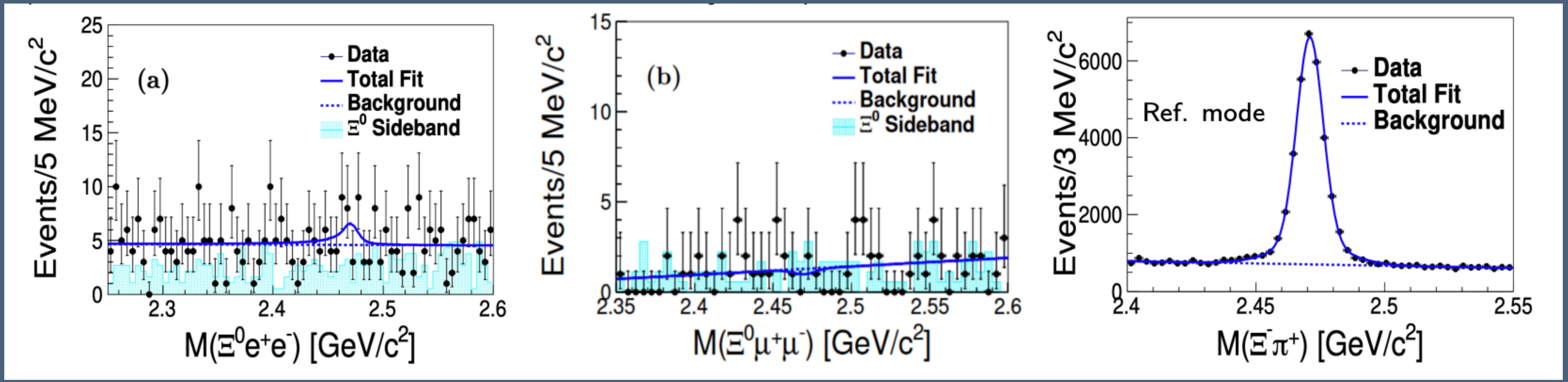
- SM —> each lepton flavor equally likely to interact with the weak force
- Search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$, where $\ell = e, \mu$, occurred in Dec 2023 (90% CL)
  - First search for a FCNC semi-leptonic decay without neutrinos (sensitive to hamiltonian helicity structure through W-exchange diagrams)

Results:

$$\mathscr{B}(\Xi_c^0 \to \Xi^0 e^+ e^-) < 9.9 \times 10^{-5}$$

$$\mathscr{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-) < 6.5 \times 10^{-5}$$

arXiv:2312.02580



No signal observed but consistent with SM:

$$\mathscr{B}_{SM}(\Xi_c \to \Xi^0 e^+ e^-) < 2.35 \times 10^{-6}$$

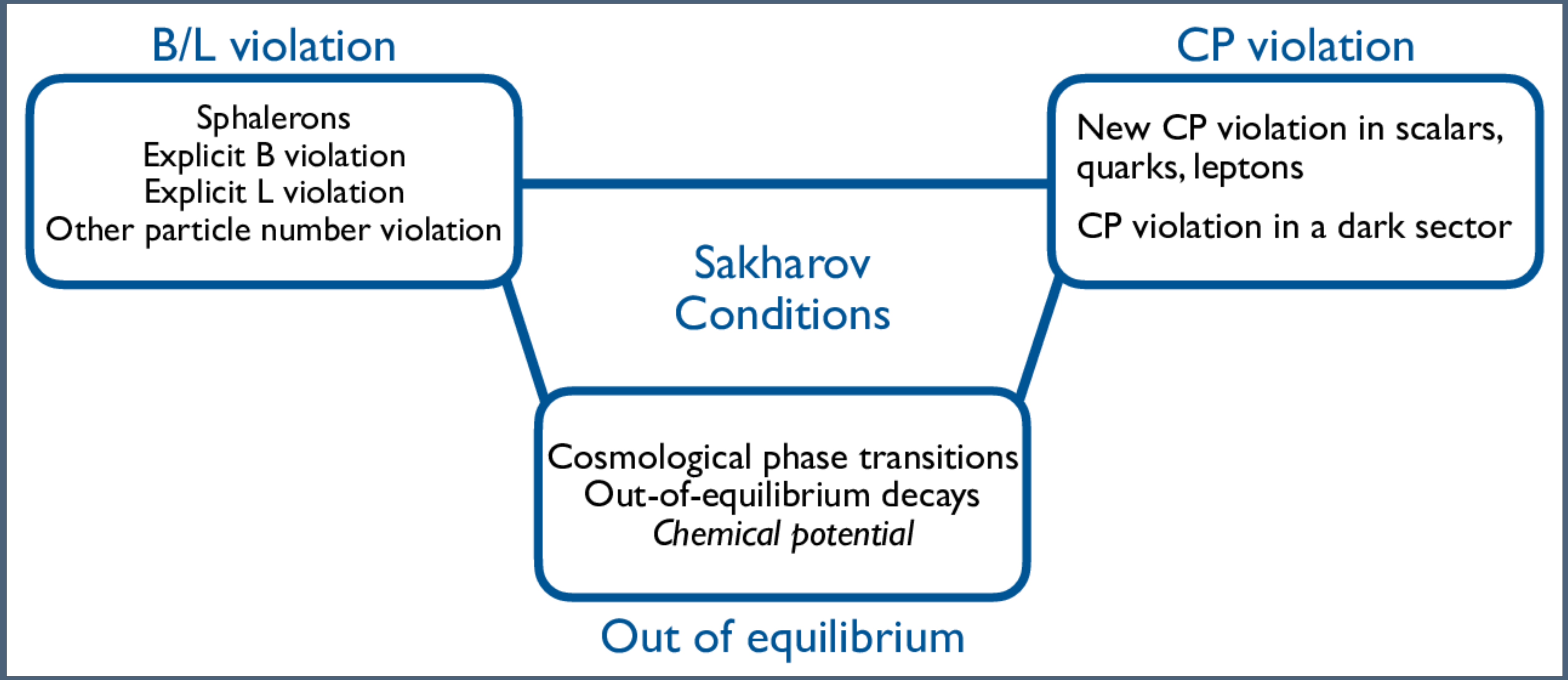
$$\mathscr{B}_{SM}(\Xi_c \to \Xi^0 \mu^+ \mu^-) < 2.25 \times 10^{-6}$$

PRD103(2021):013007

Search for $D \to p\ell^-$ at Belle

Test of Baryon Number Violation (BNV)

- BNV: One of Sakharov's conditions for a matter-dominated universe
- BESIII (2022, 90% Confidence Level (CL)) 10.1103/PhysRevD.105.032006
  - $\mathscr{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^{-6}$
  - $\mathscr{B}(D^0 \to pe^-) < 2.2 \times 10^{-6}$



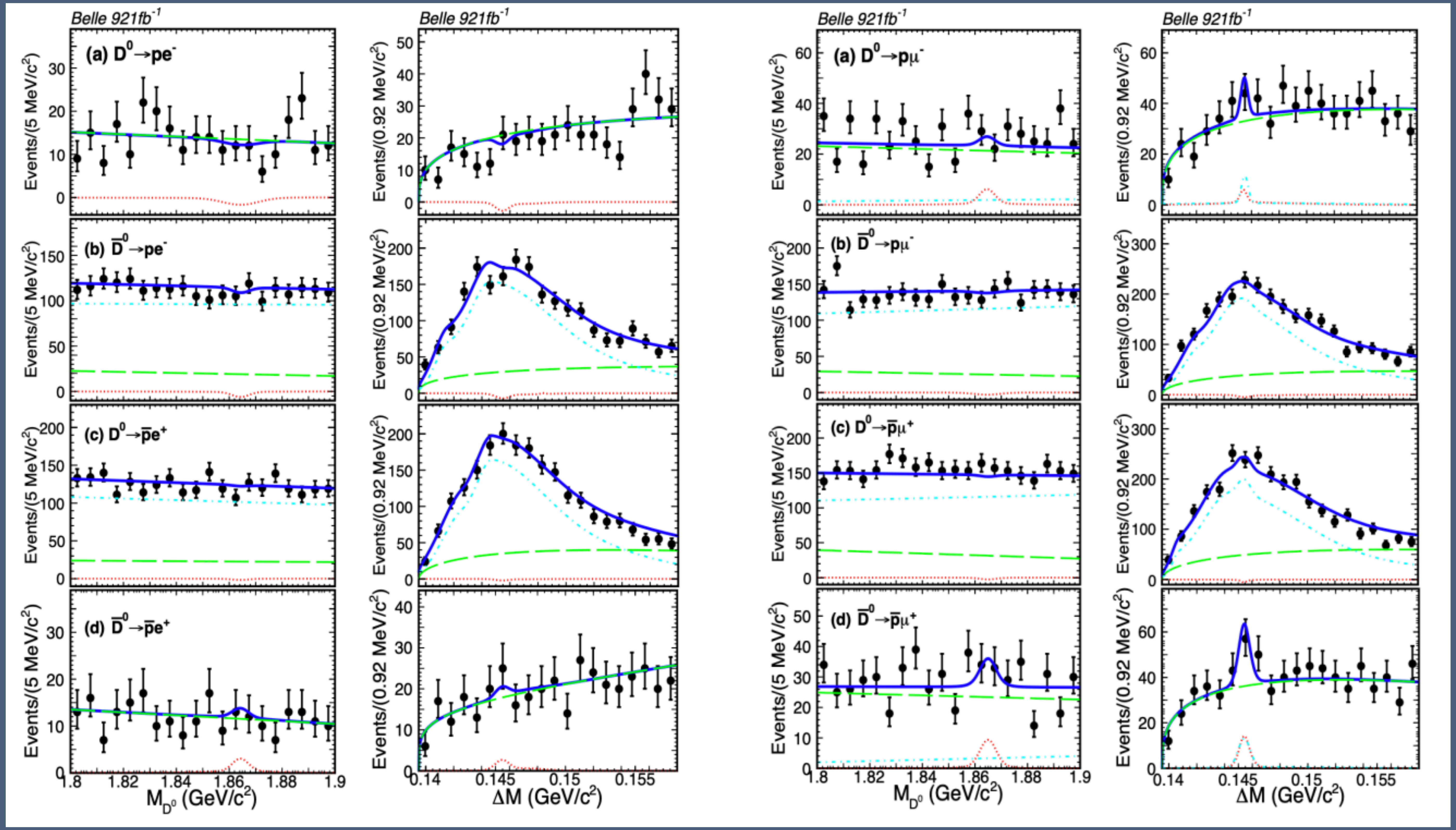
Search for $D \to p\ell$ at Belle

Test of Baryon Number Violation (BNV)

- Belle (2024)

TABLE I. Reconstruction efficiency (ϵ), signal yield (N_S), signal significance ($\mathcal{S}$), upper limit on the signal yield ($N_{p\ell}^{UL}$), and branching fraction ($\mathcal{B}$) at 90% confidence level for each decay mode.

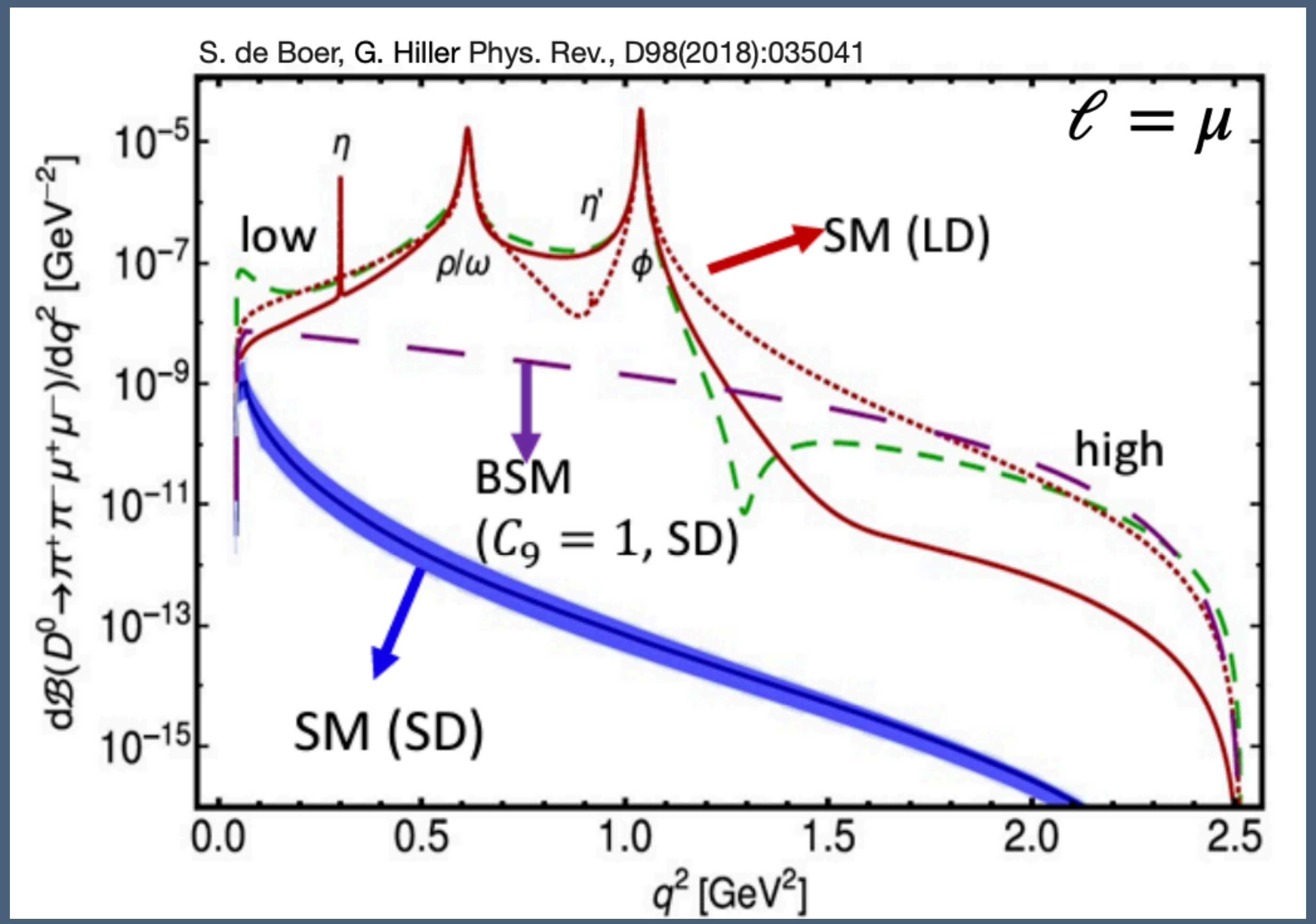
Decay mode	ϵ (%)	N_S	$\mathcal{S}$ (σ)	N_{pl}^{UL}	$\mathcal{B} \times 10^{-7}$
$D^0 \to pe^-$	10.2	-6.4 ± 8.5	—	17.5	< 5.5
$\overline{D}^0 \to pe^-$	10.2	-18.4 ± 23.0	—	22.0	< 6.9
$D^0 \to \overline{p}e^+$	9.7	-4.7 ± 23.0	—	22.0	< 7.2
$\overline{D}^0 \to \overline{p}e^+$	9.6	7.1 ± 9.0	0.6	23.0	< 7.6
$D^0 \to p\mu^-$	10.7	11.0 ± 23.0	0.9	17.1	< 5.1
$\overline{D}^0 \to p\mu^-$	10.7	-10.8 ± 27.0	—	21.8	< 6.5
$D^0 \to \overline{p}\mu^+$	10.5	-4.5 ± 14.0	—	21.1	< 6.3
$\overline{D}^0 \to \overline{p}\mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5



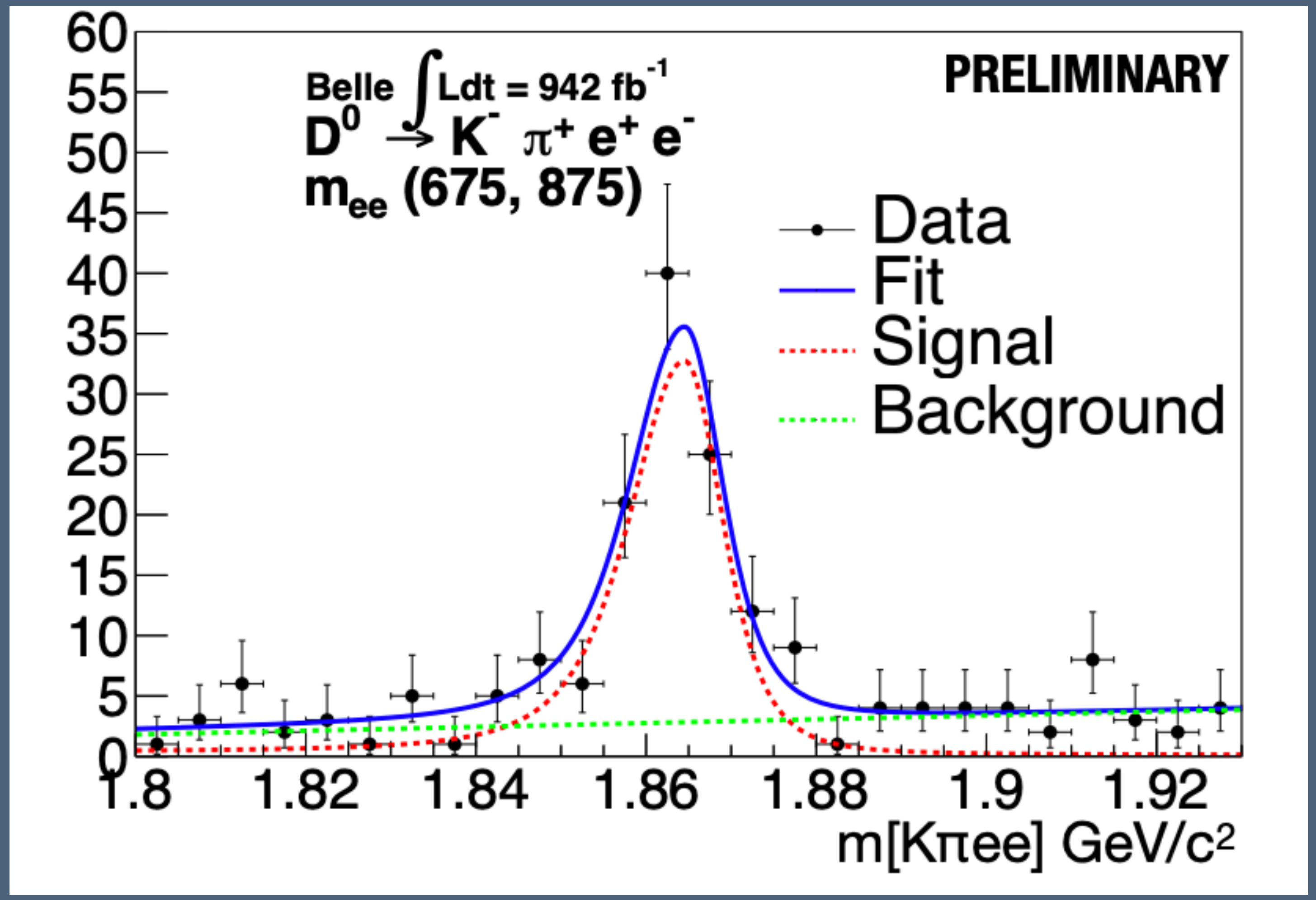
90% CL upper limits; most precise for e channels and first measurement for μ channels

Phys.Rev.D109, L031101 (2024)

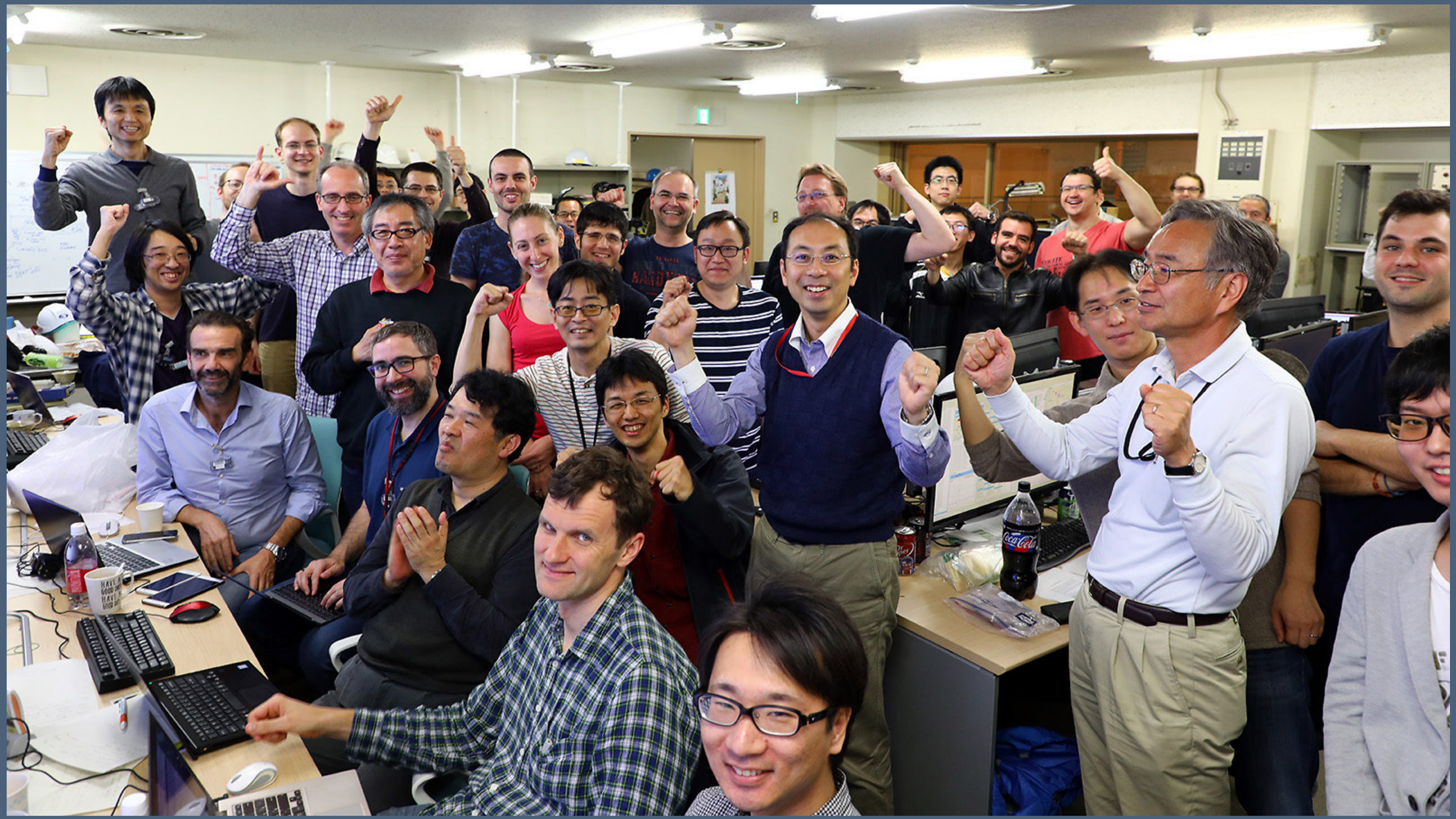
Search for $D^0 \to hh'e^+e^-$ at Belle



- FCNC process with $c \to u\ell\ell$ (suppressed in SM)
- Distinct $q^2 = m^2(e^+e^-)$ resonances
- Near resonance dominated by SM (BR) and BSM may be visible far from resonances
- **New** Belle results
  - Signal in ρ/ω region: $\mathcal{B}(D^0 \to K\pi e^+e^-) = (39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$ $(11.8\sigma$ significance), matches BABAR with higher precision and SM expectations
  - 90% CL upper limits set at $(2-8) \times 10^{-7}$ for other regions

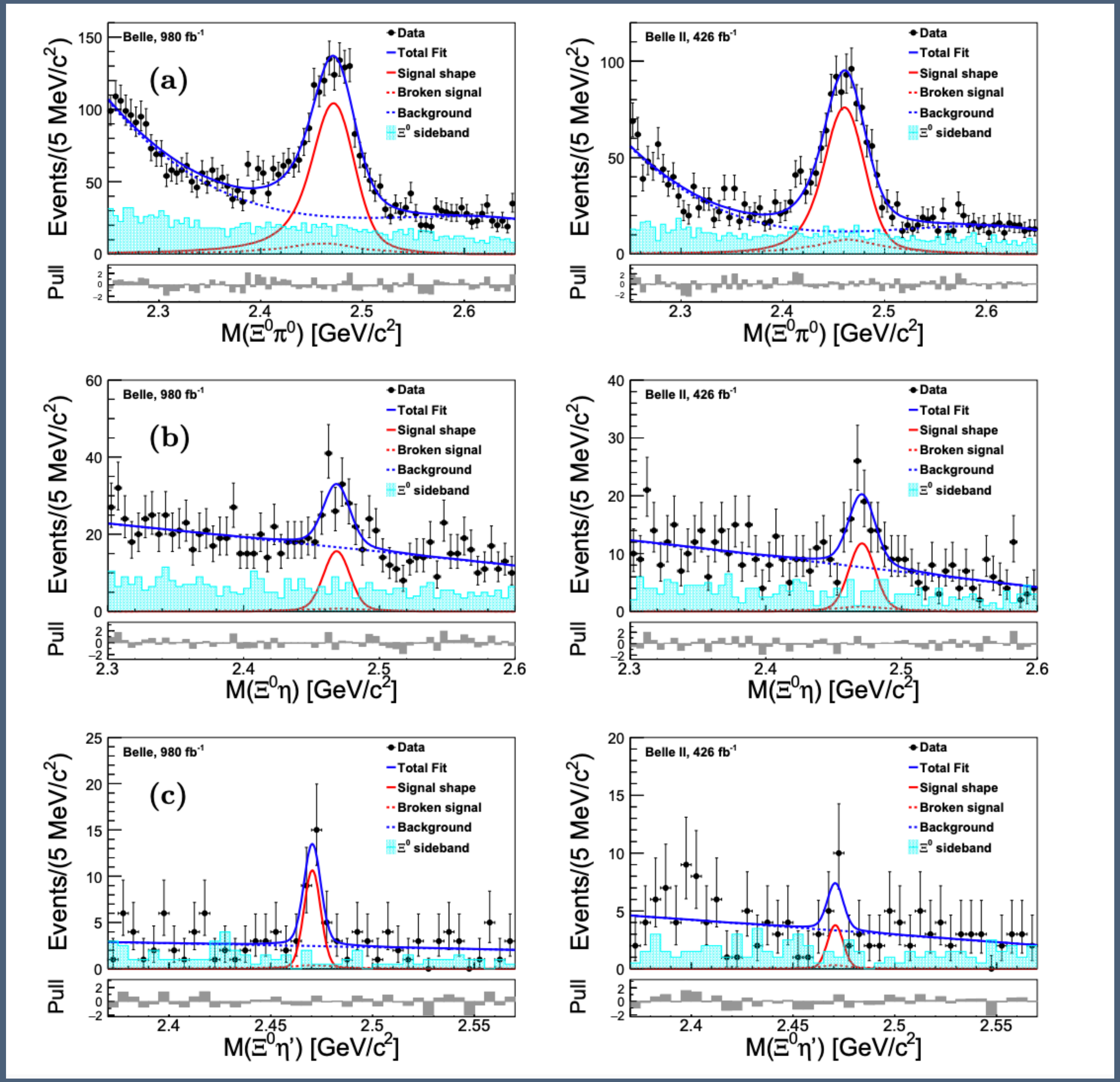


Summary



- Belle stopped data production **nearly 15 years ago**, yet still boasts a large charm sample
- Belle II has resumed data taking after Long Shutdown 1 (LS1) and provides a smaller charm sample with **increased capability for precision measurements**. Eventually, the size will be comparable as well.
  - High precision —> strong capabilities for measuring **lifetimes and branching fractions**
- Large charm samples allow **probes into NP** through CPV and BPV
- Belle and Belle II have produced **several world-leading measurements** in the charm sector

Backup



Reference	Model	$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$	$\alpha(\Xi_c^0 \to \Xi^0\pi^0)$
Körner, Krämer [5]	quark	0.5	3.2	11.6	0.92
Xu, Kamal [7]	pole	7.7	-	-	0.92
Cheng, Tseng [8]	pole	3.8	-	-	-0.78
Cheng, Tseng [8]	CA	17.1	-	-	0.54
Żenczykowski [9]	pole	6.9	1.0	9.0	0.21
Ivanov *et al.* [6]	quark	0.5	3.7	4.1	0.94
Sharma, Verma [11]	CA	-	-	-	-0.8
Geng *et al.* [12]	$SU(3)_F$	4.3 ± 0.9	$1.7^{+1.0}_{-1.7}$	$8.6^{+11.0}_{-6.3}$	-
Geng *et al.* [13]	$SU(3)_F$	7.6 ± 1.0	10.3 ± 2.0	9.1 ± 4.1	$-1.00^{+0.07}_{-0.00}$
Zhao *et al.* [14]	$SU(3)_F$	4.7 ± 0.9	8.3 ± 2.3	7.2 ± 1.9	-
Zou *et al.* [10]	pole	18.2	26.7	-	-0.77
Huang *et al.* [15]	$SU(3)_F$	2.56 ± 0.93	-	-	-0.23 ± 0.60
Hsiao *et al.* [16]	$SU(3)_F$	6.0 ± 1.2	$4.2^{+1.6}_{-1.3}$	-	-
Hsiao *et al.* [16]	$SU(3)_F$-breaking	3.6 ± 1.2	7.3 ± 3.2	-	-
Zhong *et al.* [17]	$SU(3)_F$	$1.13^{+0.59}_{-0.49}$	1.56 ± 1.92	$0.683^{+3.272}_{-3.268}$	$0.50^{+0.37}_{-0.35}$
best fit → Zhong *et al.* [17]	$SU(3)_F$-breaking	$7.74^{+2.52}_{-2.32}$	$2.43^{+2.79}_{-2.90}$	$1.63^{+5.09}_{-5.14}$	$-0.29^{+0.20}_{-0.17}$
Xing *et al.* [18]	$SU(3)_F$	1.30 ± 0.51	-	-	-0.28 ± 0.18

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