Charm Results at Belle and Belle II

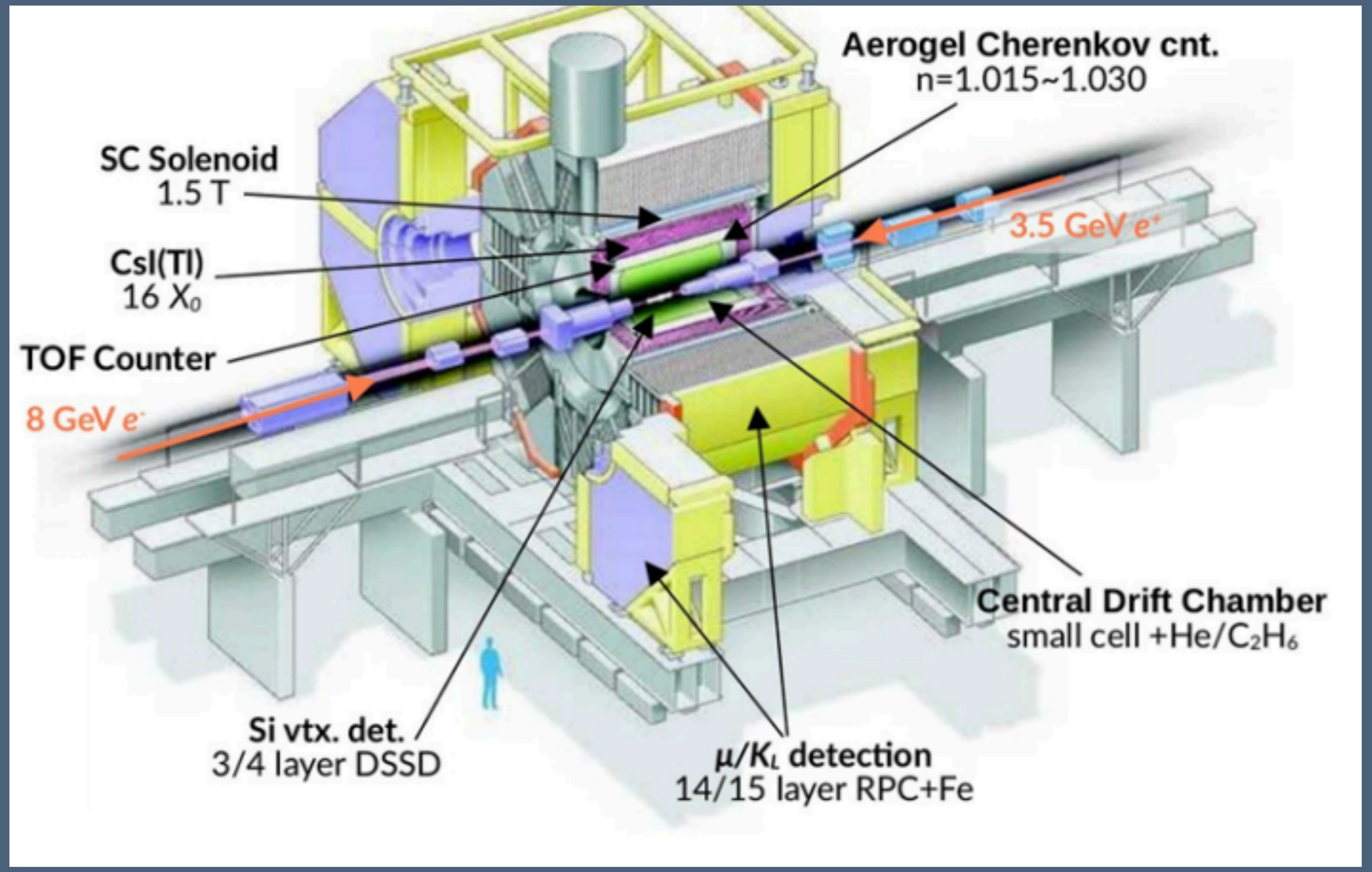
On Behalf of the Belle and Belle II collaborations

Paul Gebeline | June 5, 2024

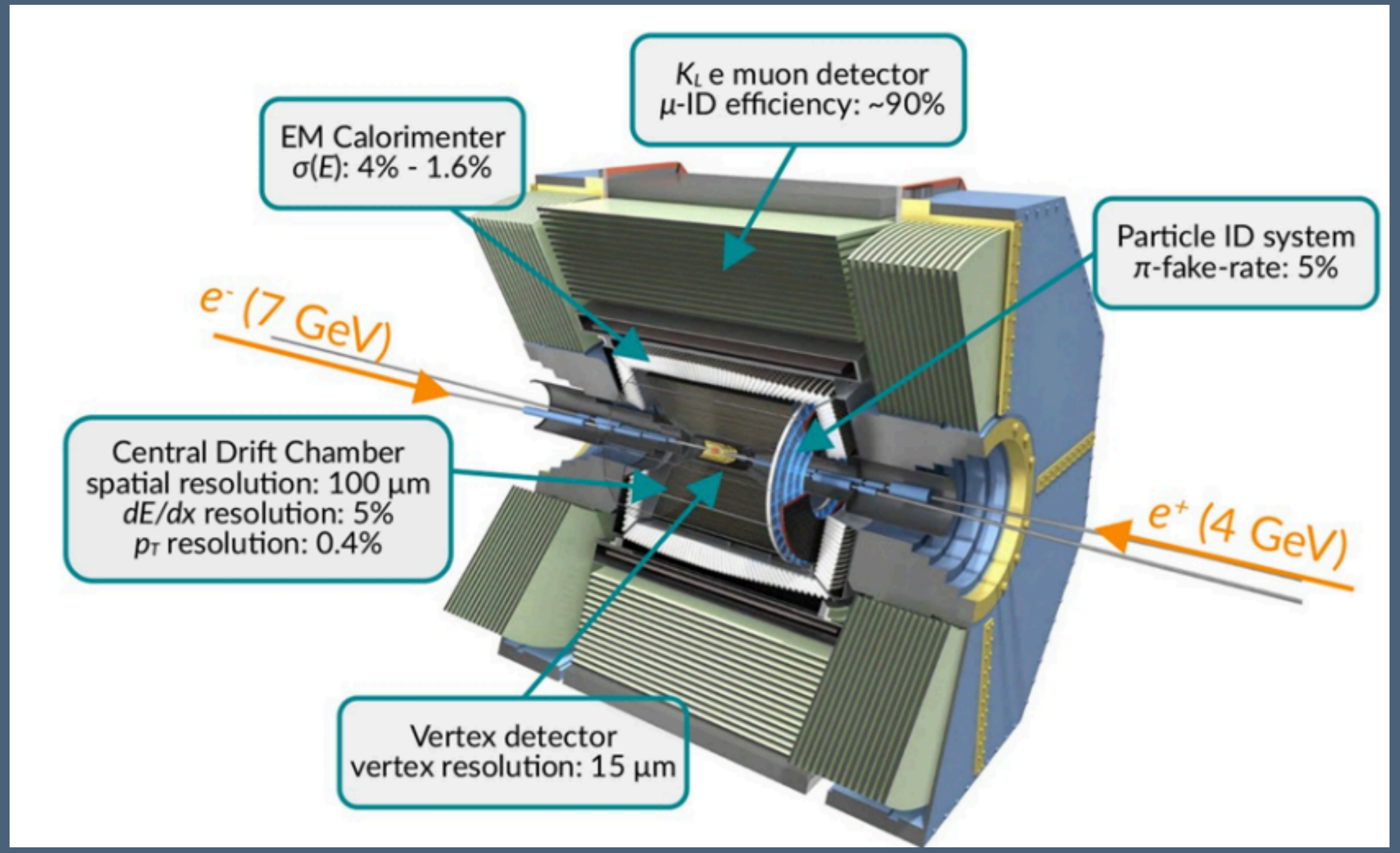
Experiments

- 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
  - Very important for charm due to reliance on high statistics for precise measurements

KEKB



SuperKEKB



Charm Production

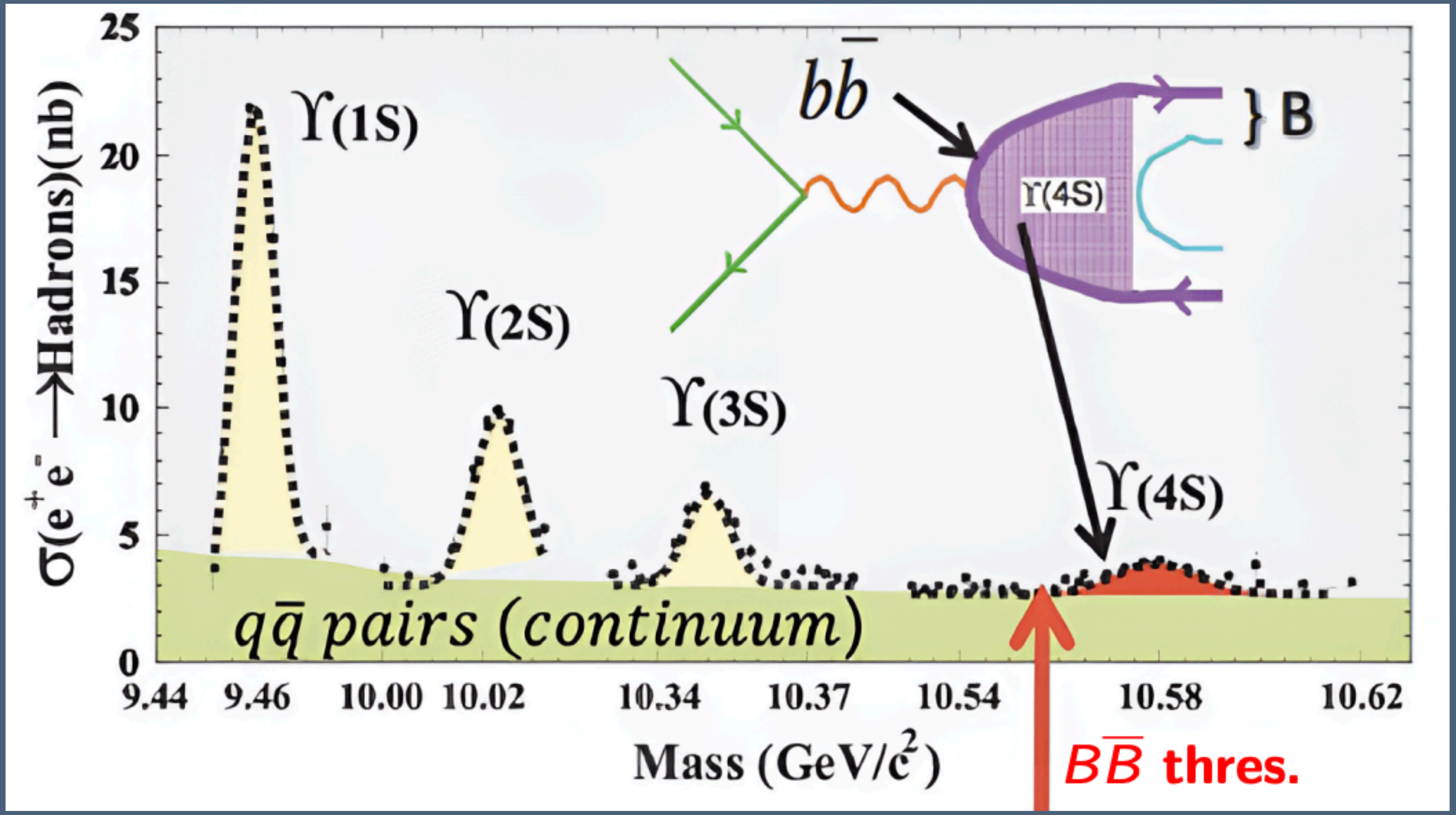
- Two primary mechanisms for charm production at Belle/Belle II:

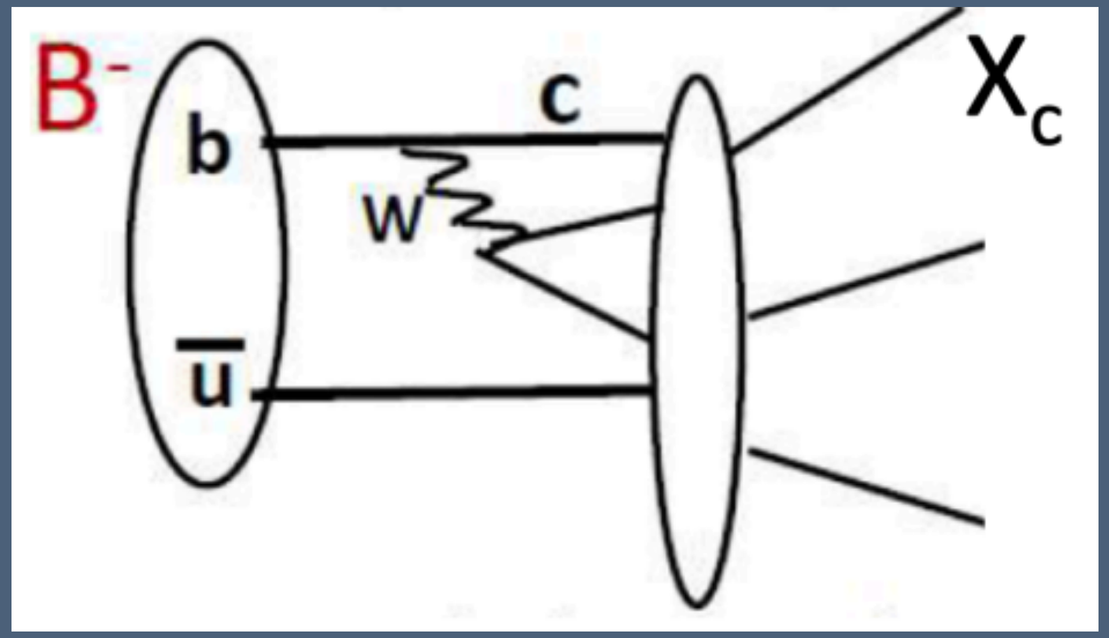
1. $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \rightarrow X_c$

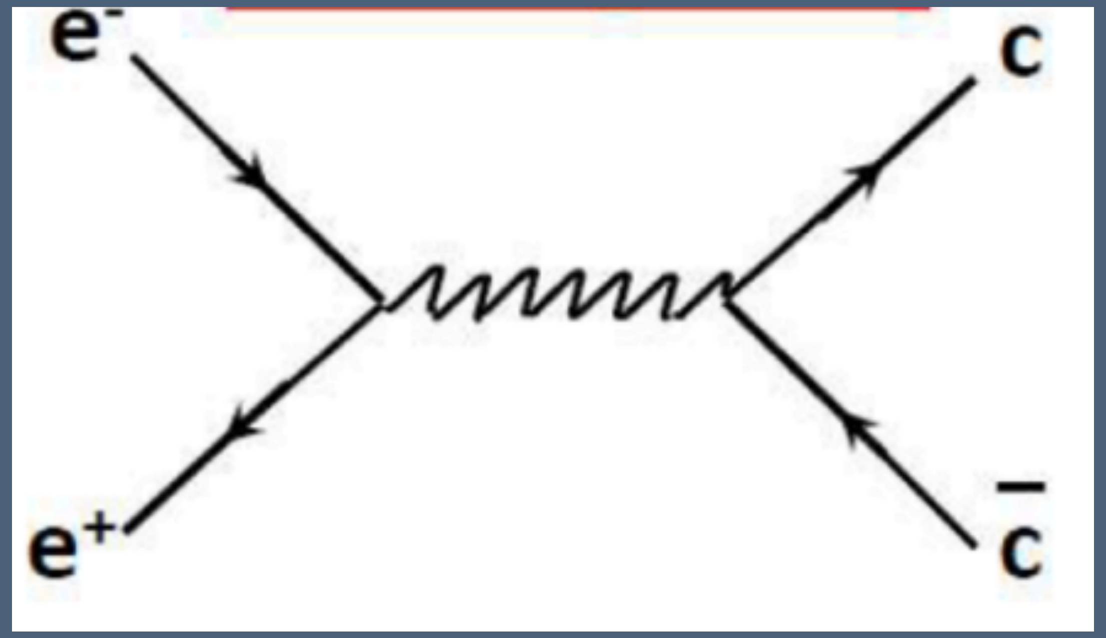
   Precise $B\bar{B}$ cross section allows for absolute measurements, but $B\bar{B} \rightarrow X_c$ is small

2. $e^+e^- \rightarrow c\bar{c}$

   Absolute measurements not possible without reference, but much higher **statistics**



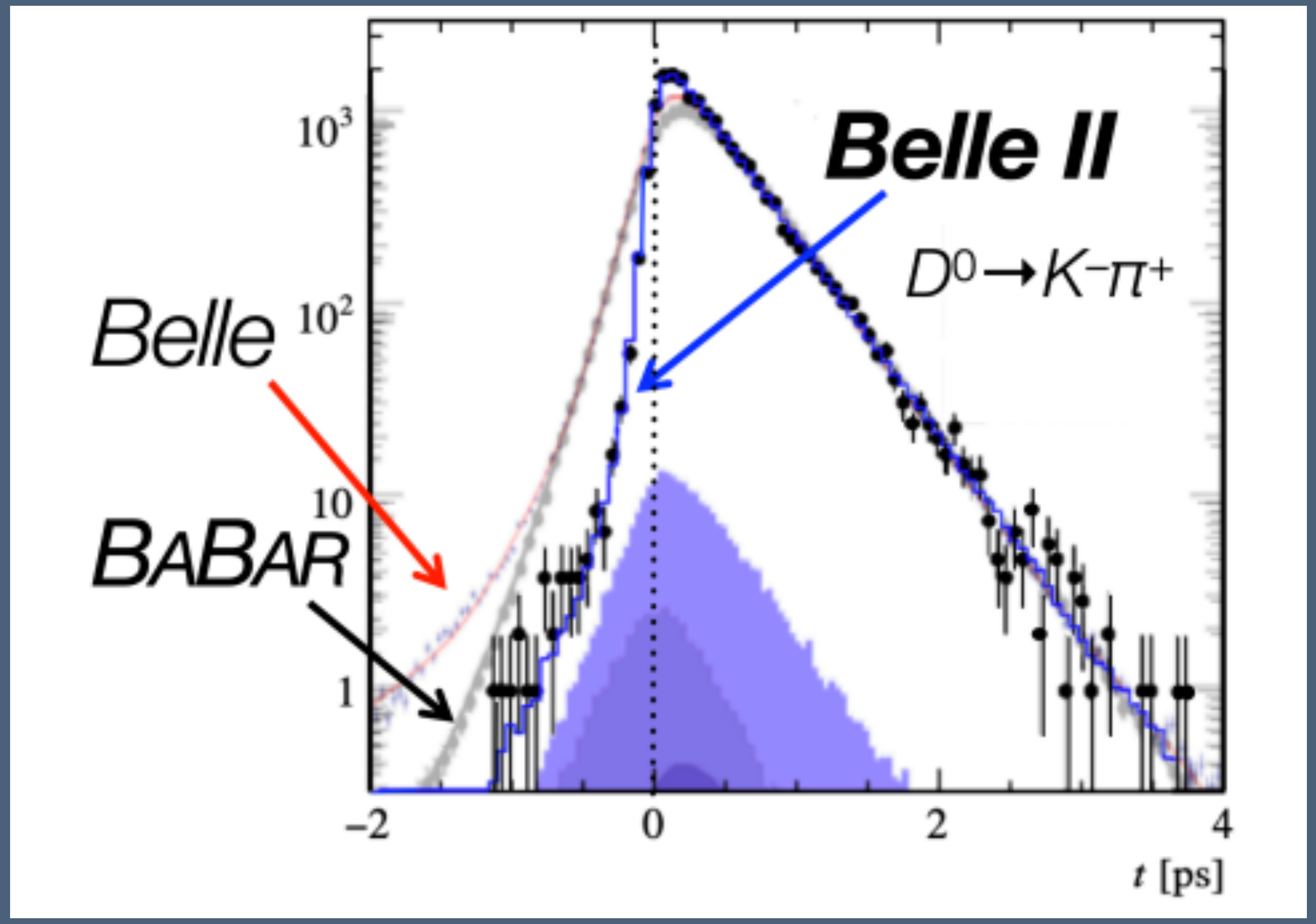


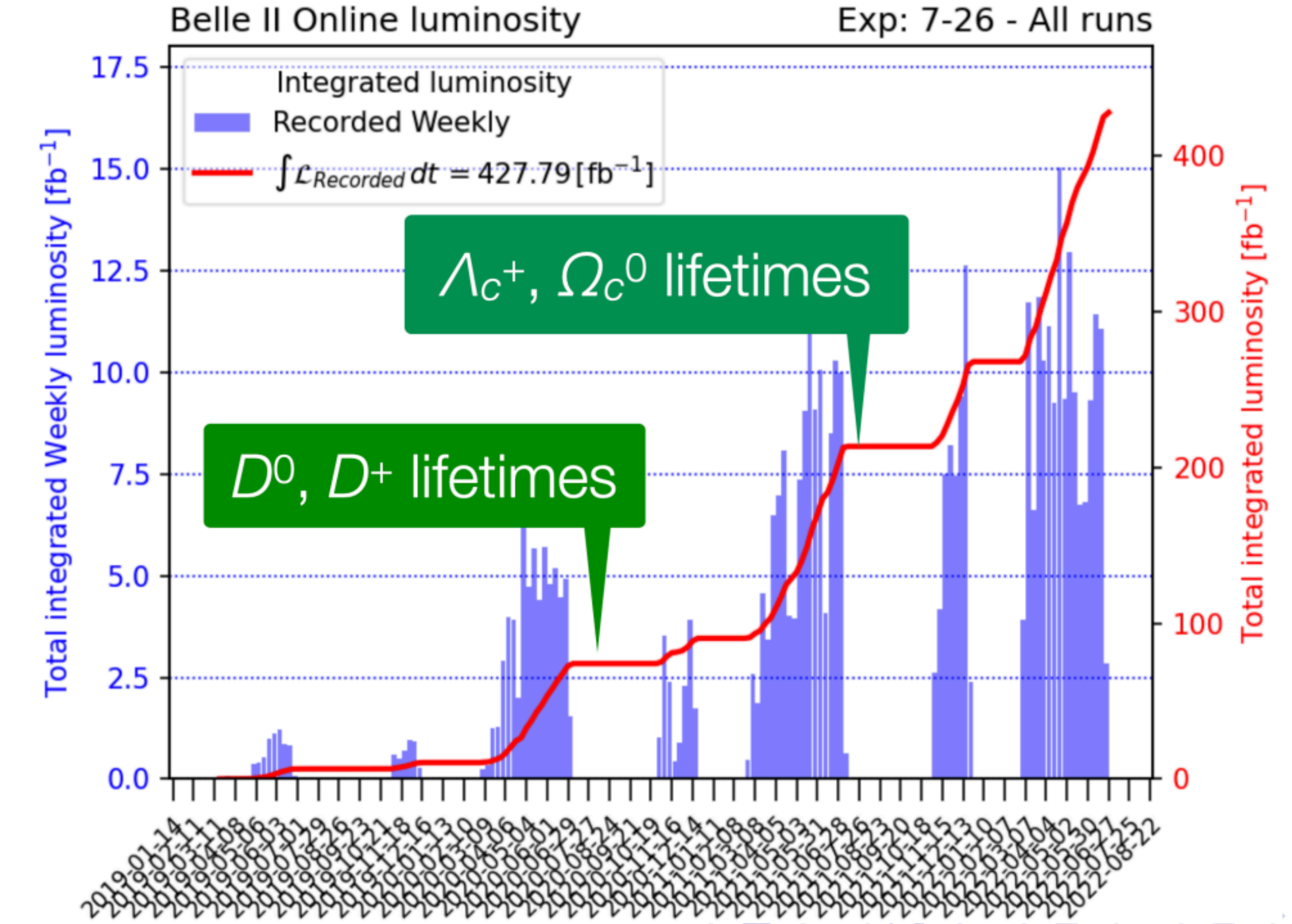


Charm Lifetimes

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):

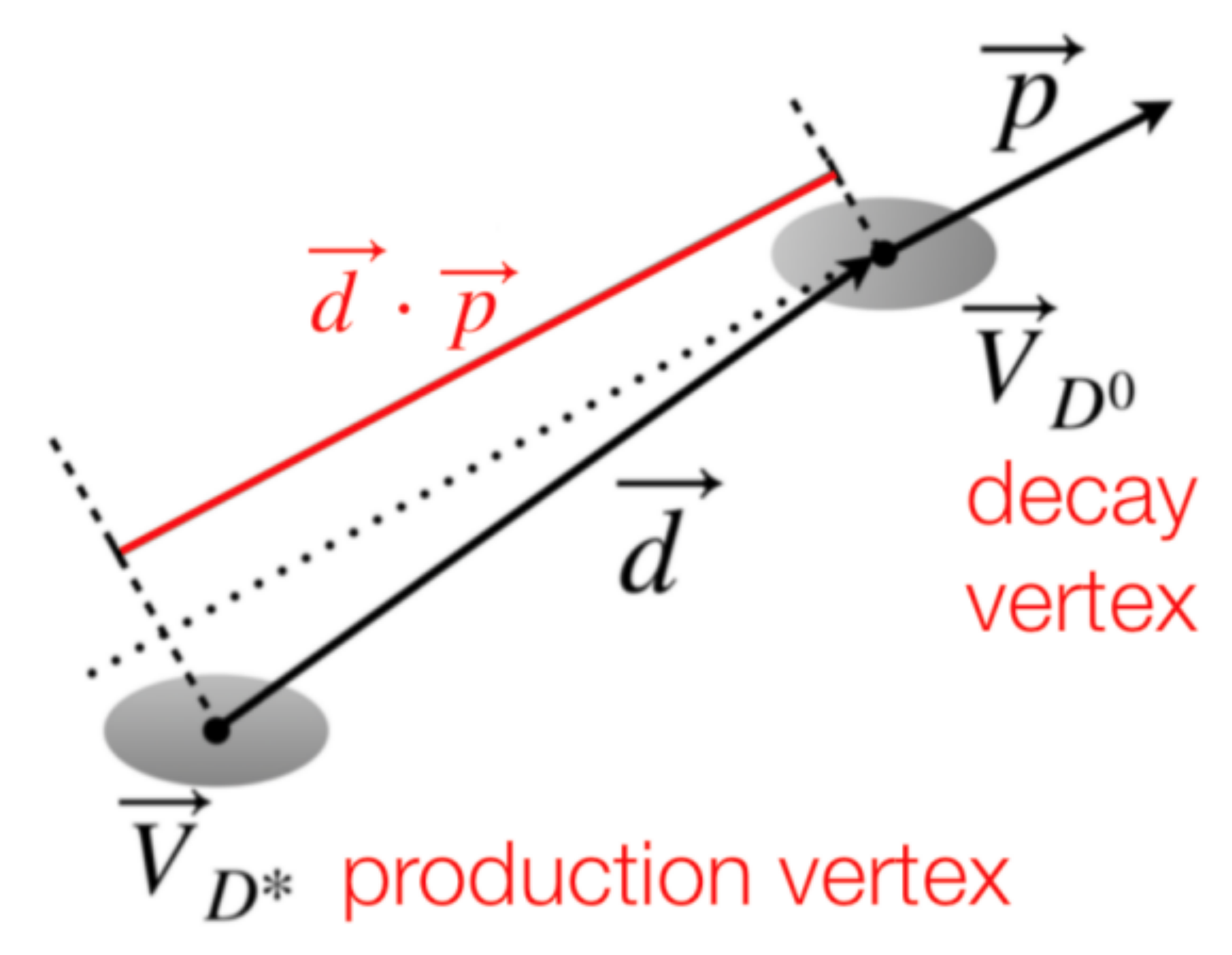
$$\Gamma(H_Q \to X) = \Gamma_3 + \Gamma_5 \frac{\langle \tilde{\mathcal{O}}_5 \rangle}{m_Q^2} + \Gamma_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \ldots + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \Gamma_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_Q^4}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

- Belle II has incredibly 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



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

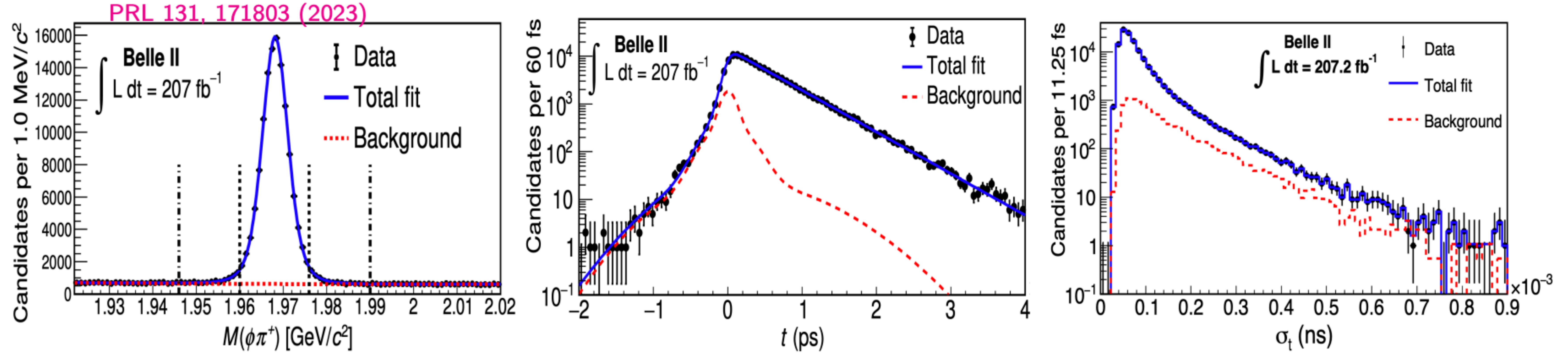
Signal pdf for Λ_c^+ lifetime measurement

D_s^+

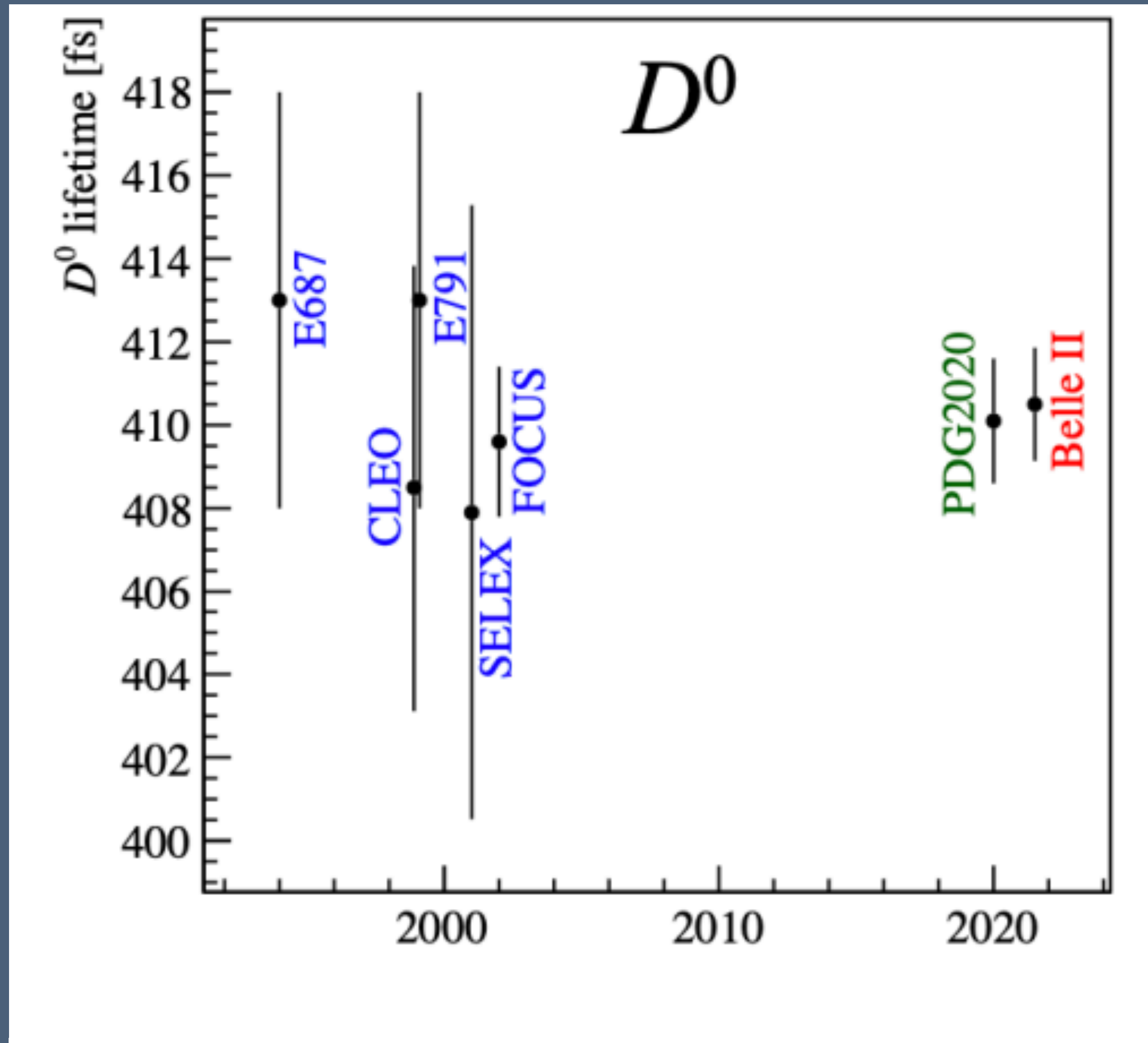
World-leading:

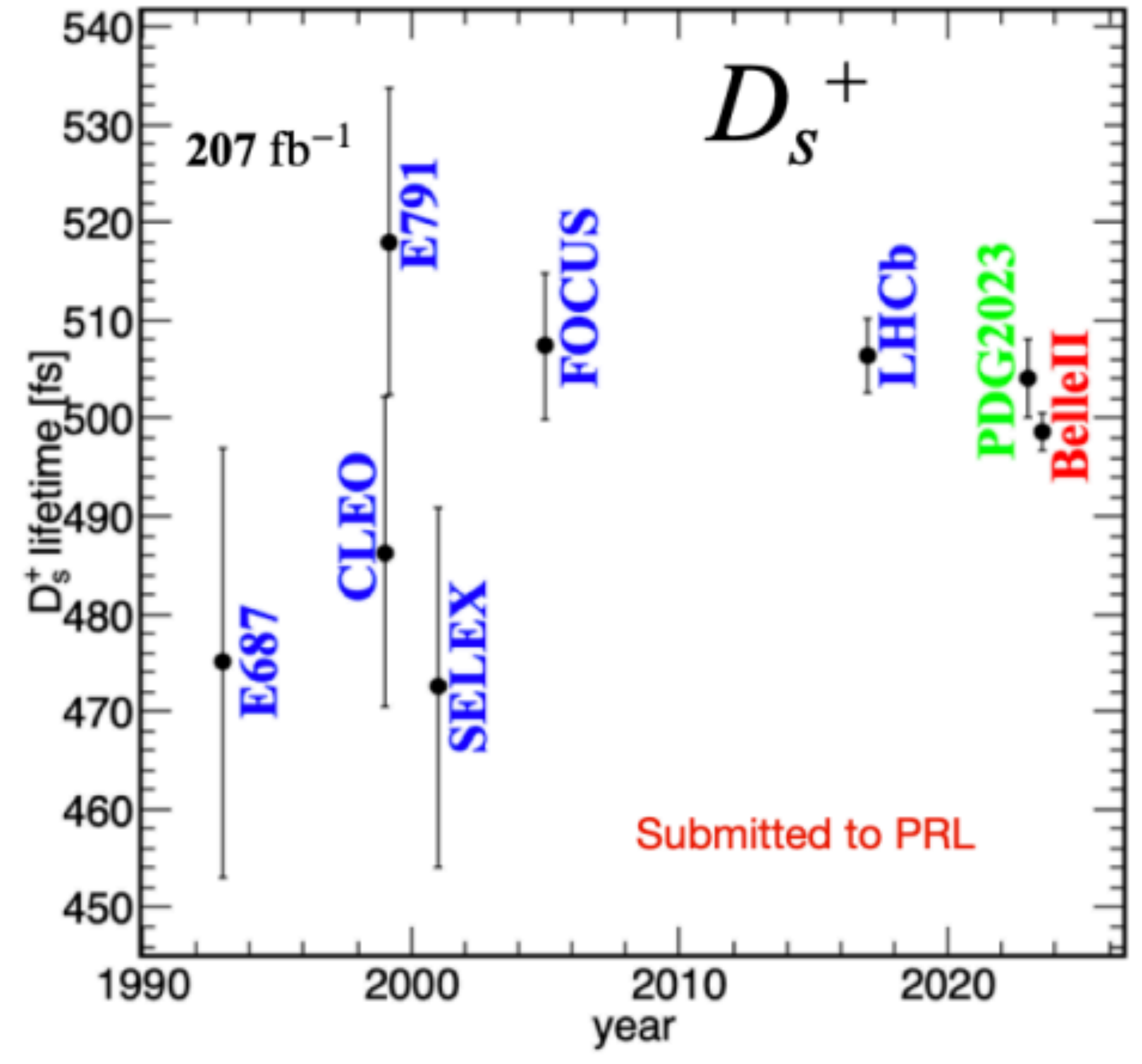
$D^0, D^+_{(s)}, \Lambda_c^+$

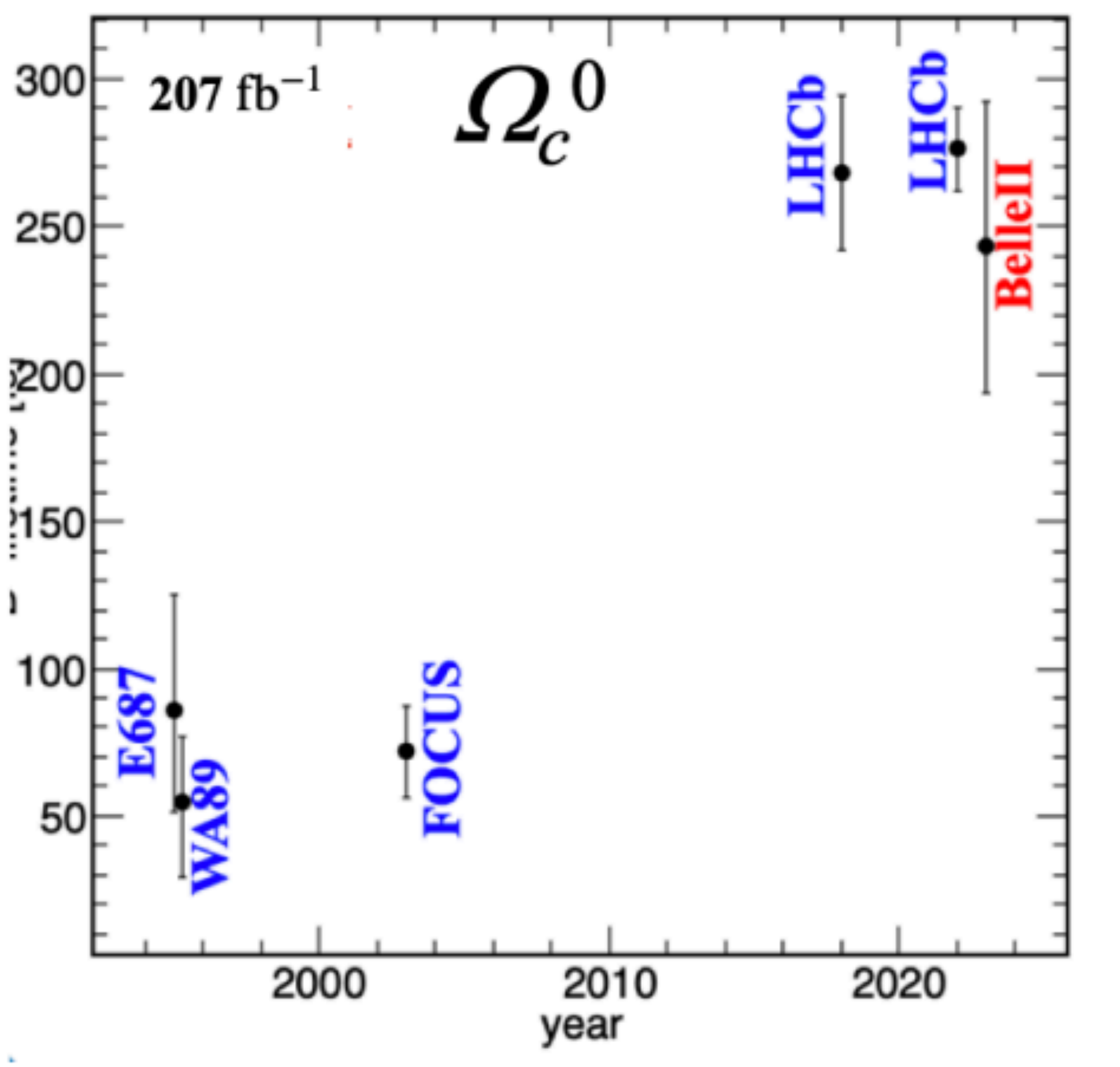
PRL 131, 171803 (2023)

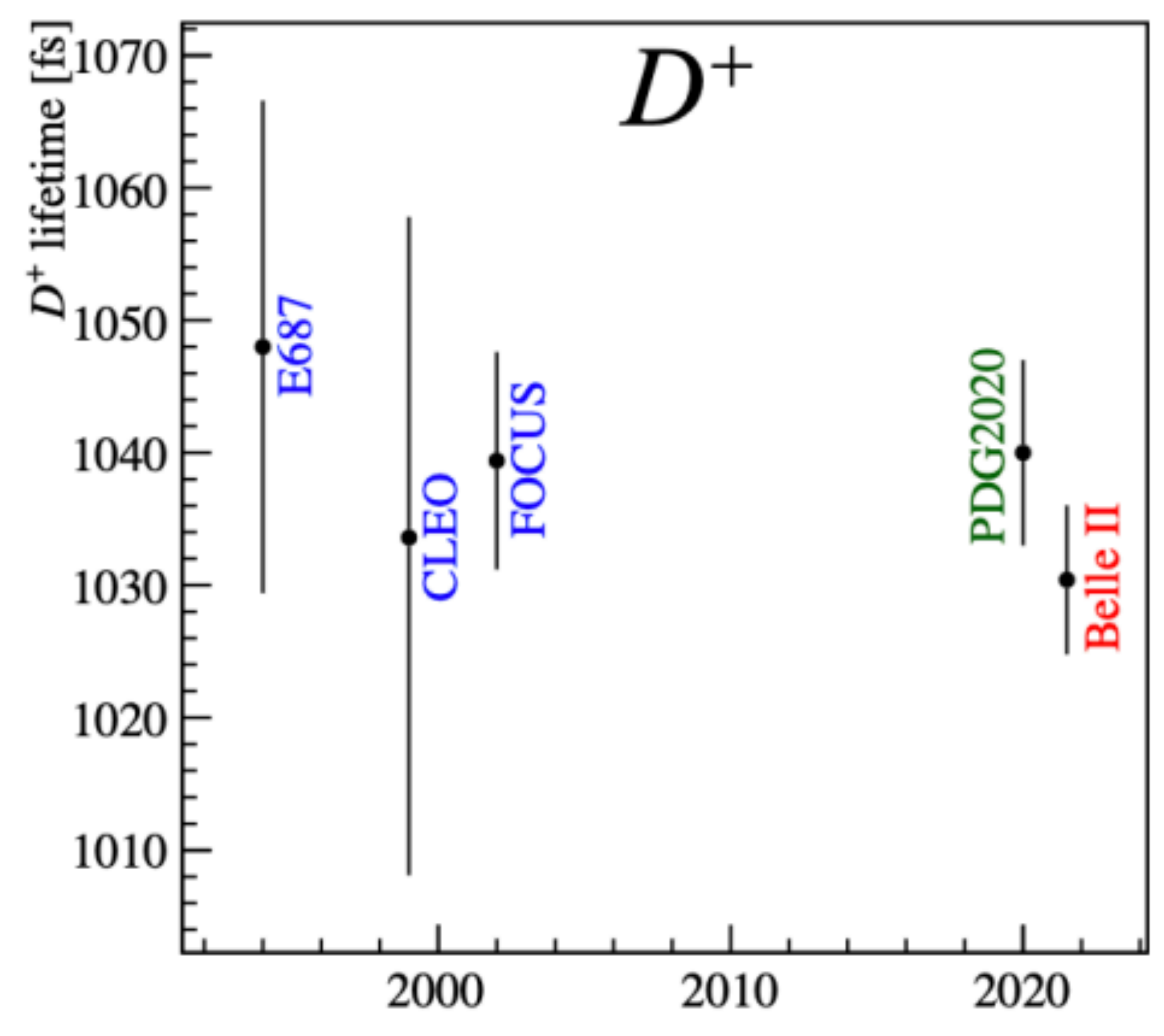


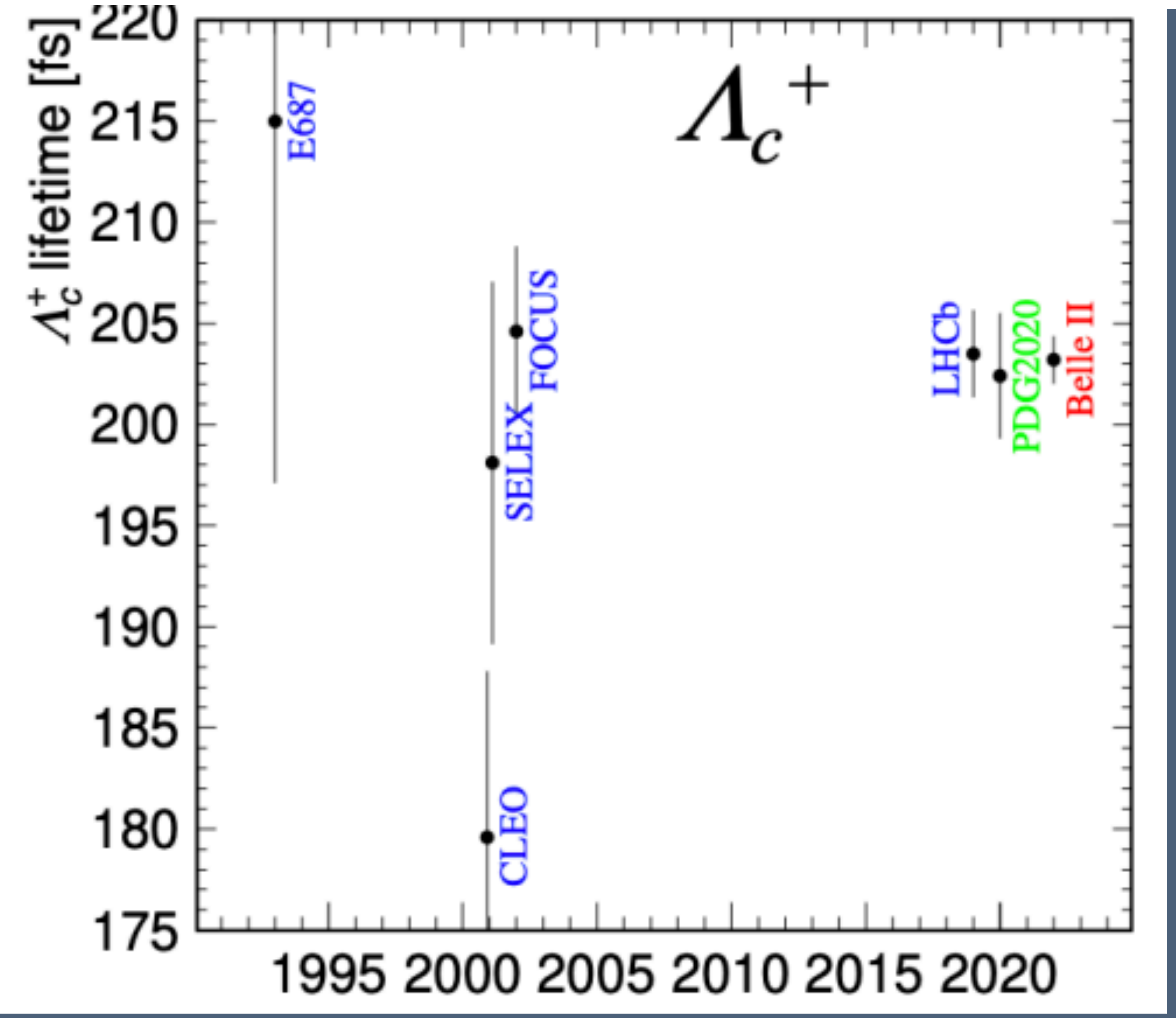
Charm Lifetime Results at Belle II









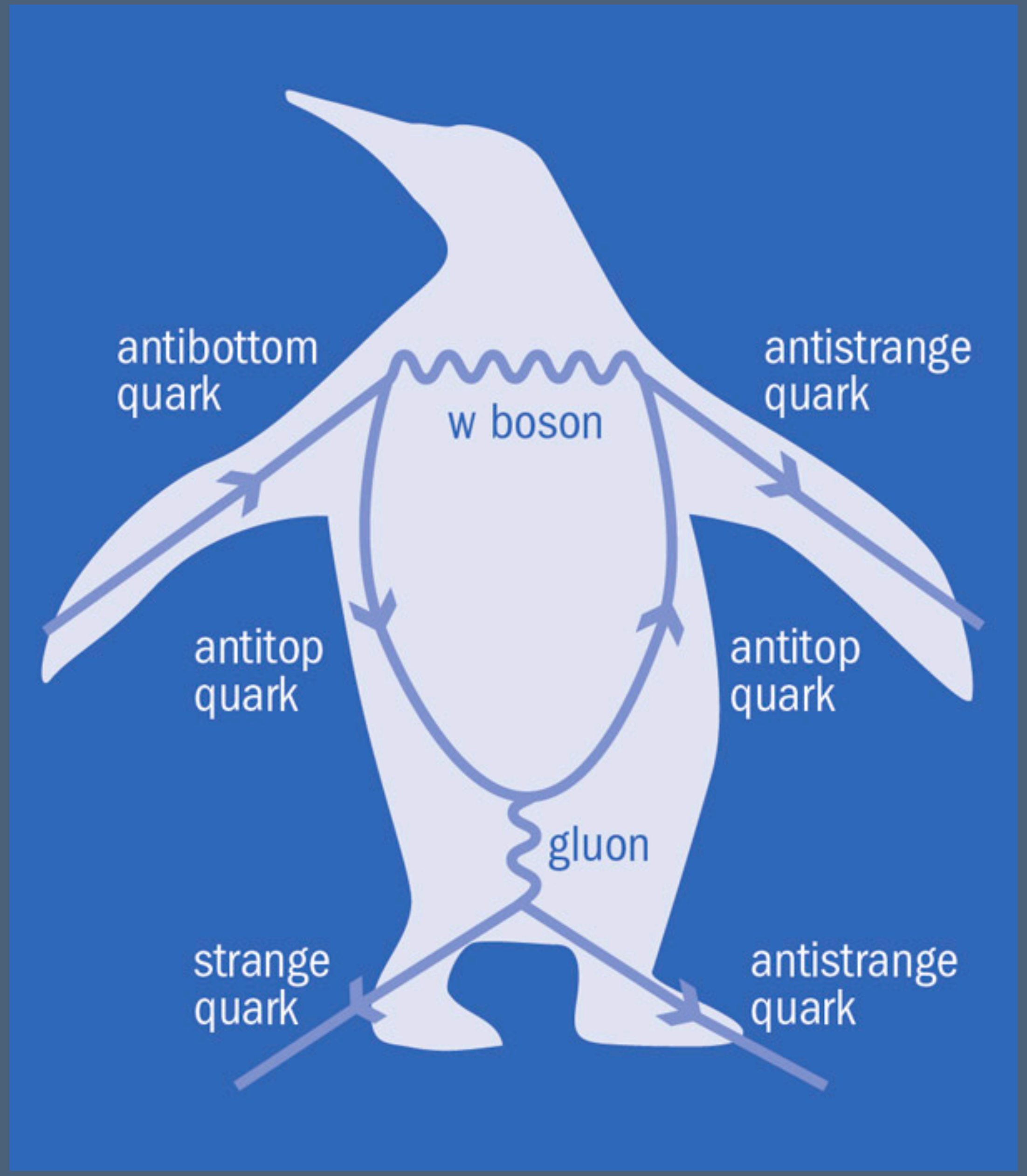


With only Run 1 Data!

Branching Fractions

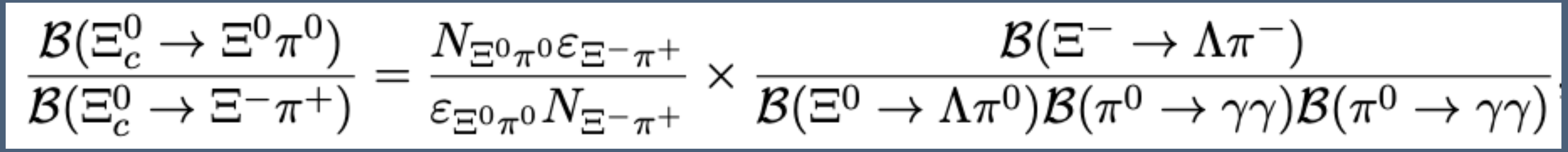
Branching Fraction of Charm Mesons

- Cabbibo-suppressed (CS) decays provide a strong probe for NP and CP Violation
  - Belle II has the capability to provide precise measurements of branching fractions for such searches
- Precise charm baryon measurements can also improve QCD transition understanding (**room for improvement**)

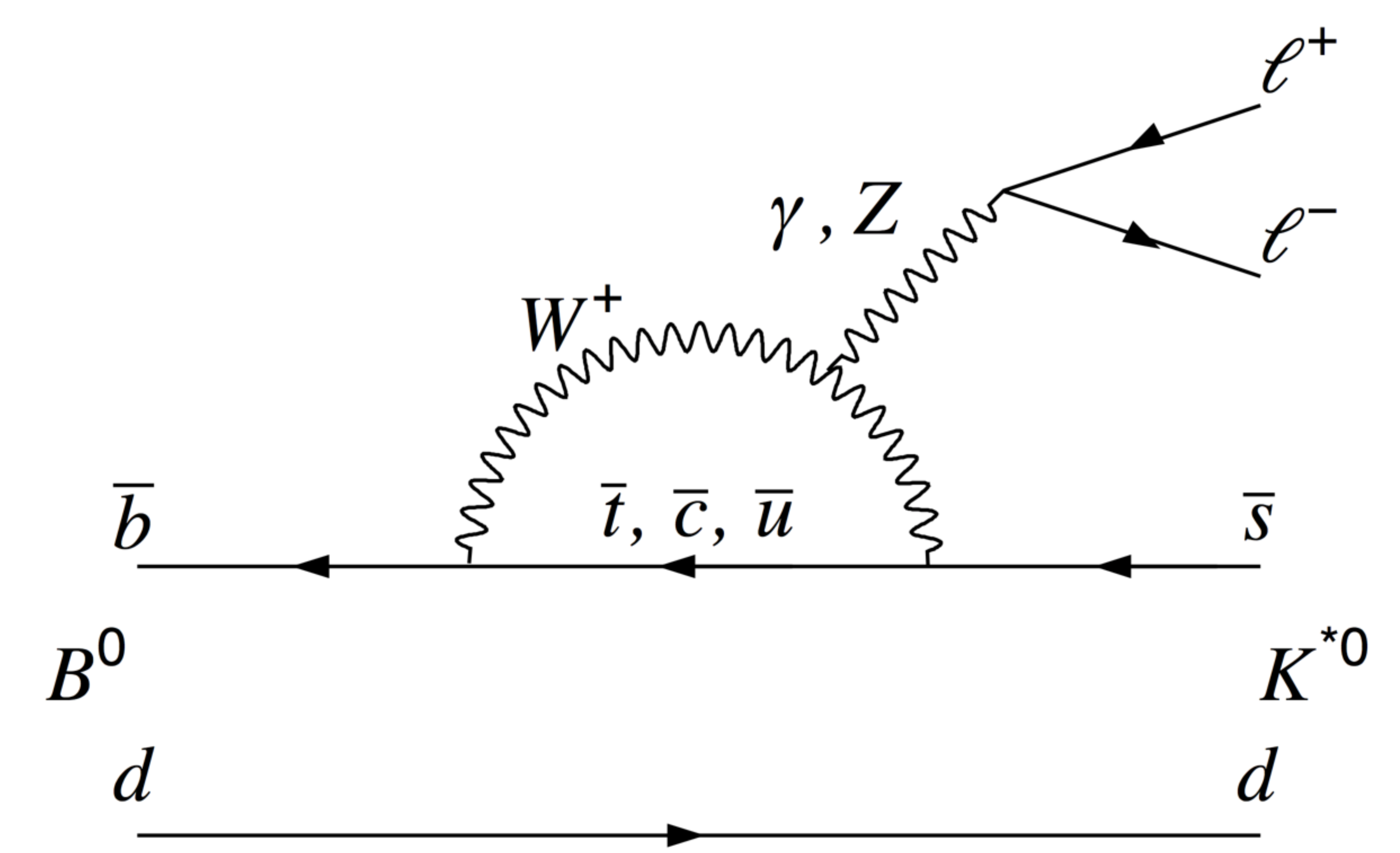


https://cerncourier.com/a/chasing-new-physics-with-electroweak-penguins

Belle II Preprint 2024-015



$$\frac{\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = \frac{N_{\Xi^0\pi^0}\varepsilon_{\Xi^-\pi^+}}{\varepsilon_{\Xi^0\pi^0}N_{\Xi^-\pi^+}} \times \frac{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}{\mathcal{B}(\Xi^0 \to \Lambda\pi^0)\mathcal{B}(\pi^0 \to \gamma\gamma)\mathcal{B}(\pi^0 \to \gamma\gamma)}$$



Branching Fraction of Charm Mesons

All measurements shown are either the first of their type or world leading

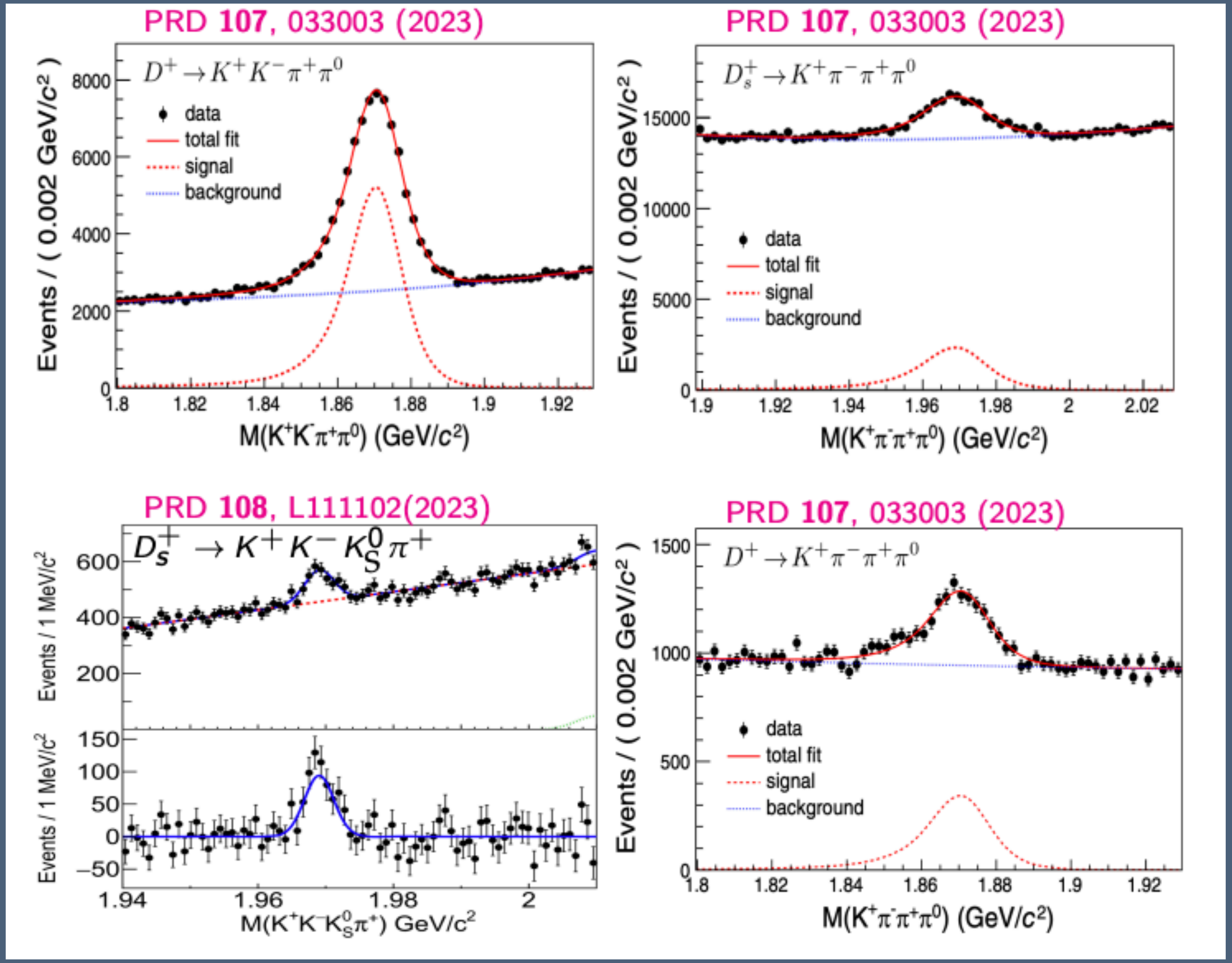
Belle (2023)

$$\mathscr{B}(D^+ \to K^+K^-\pi^+\pi^0) = (7.08 \pm 0.08 \pm 0.16 \pm 0.2) \times 10^{-3}$$

$$\mathscr{B}(D_s^+ \to K^+\pi^-\pi^+\pi^0) = (9.44 \pm 0.34 \pm 0.28 \pm 0.32) \times 10^{-3}$$

$$\mathscr{B}(D^+ \to K^+\pi^-\pi^+\pi^0) = (1.05 \pm 0.07 \pm 0.02 \pm 0.03) \times 10^{-3}$$

Consistent with prior BESIII results but with greater precision



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

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

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

First measurement; $> 10\sigma$ statistical significance

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

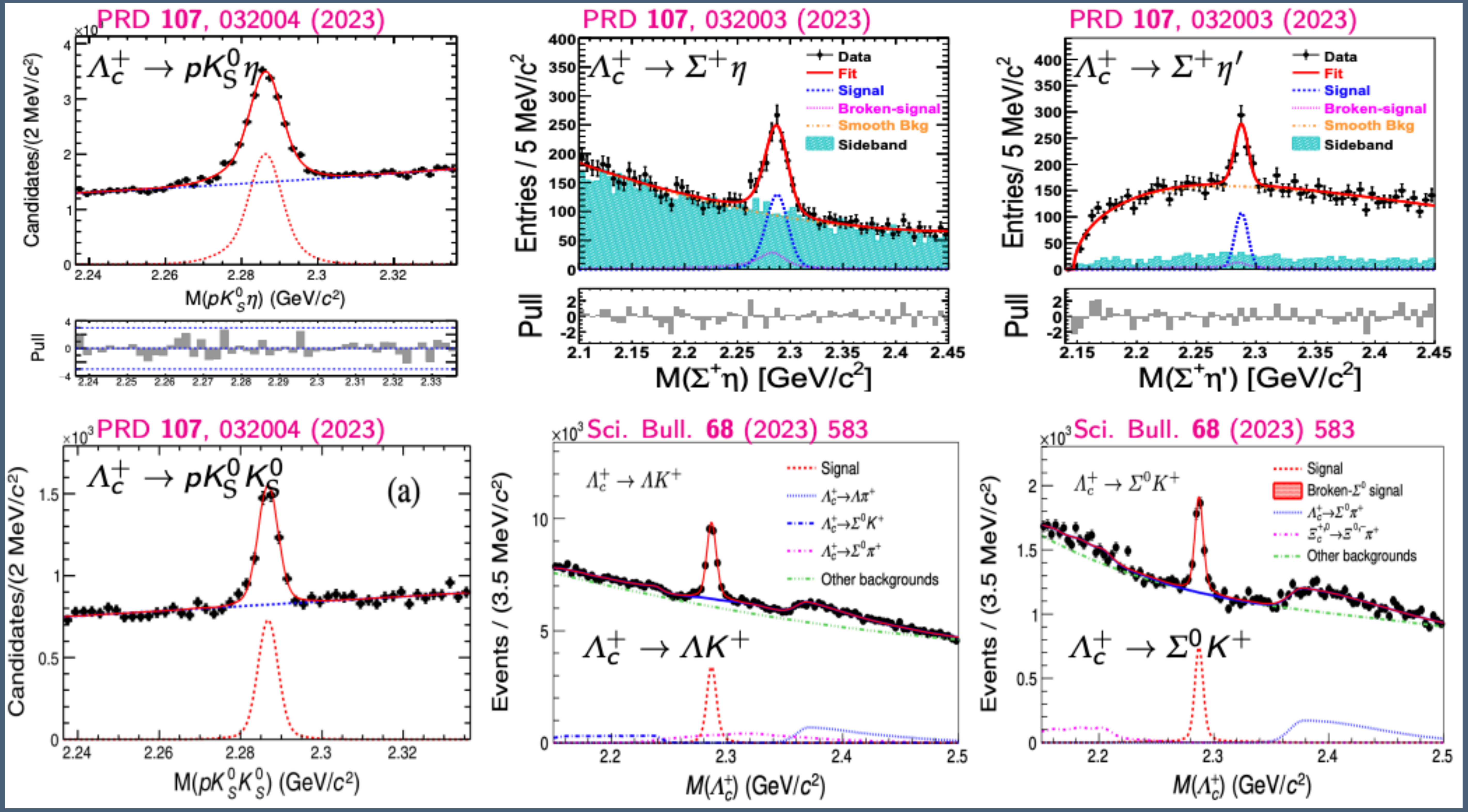
Agrees with prior results; threefold improvement in precision

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

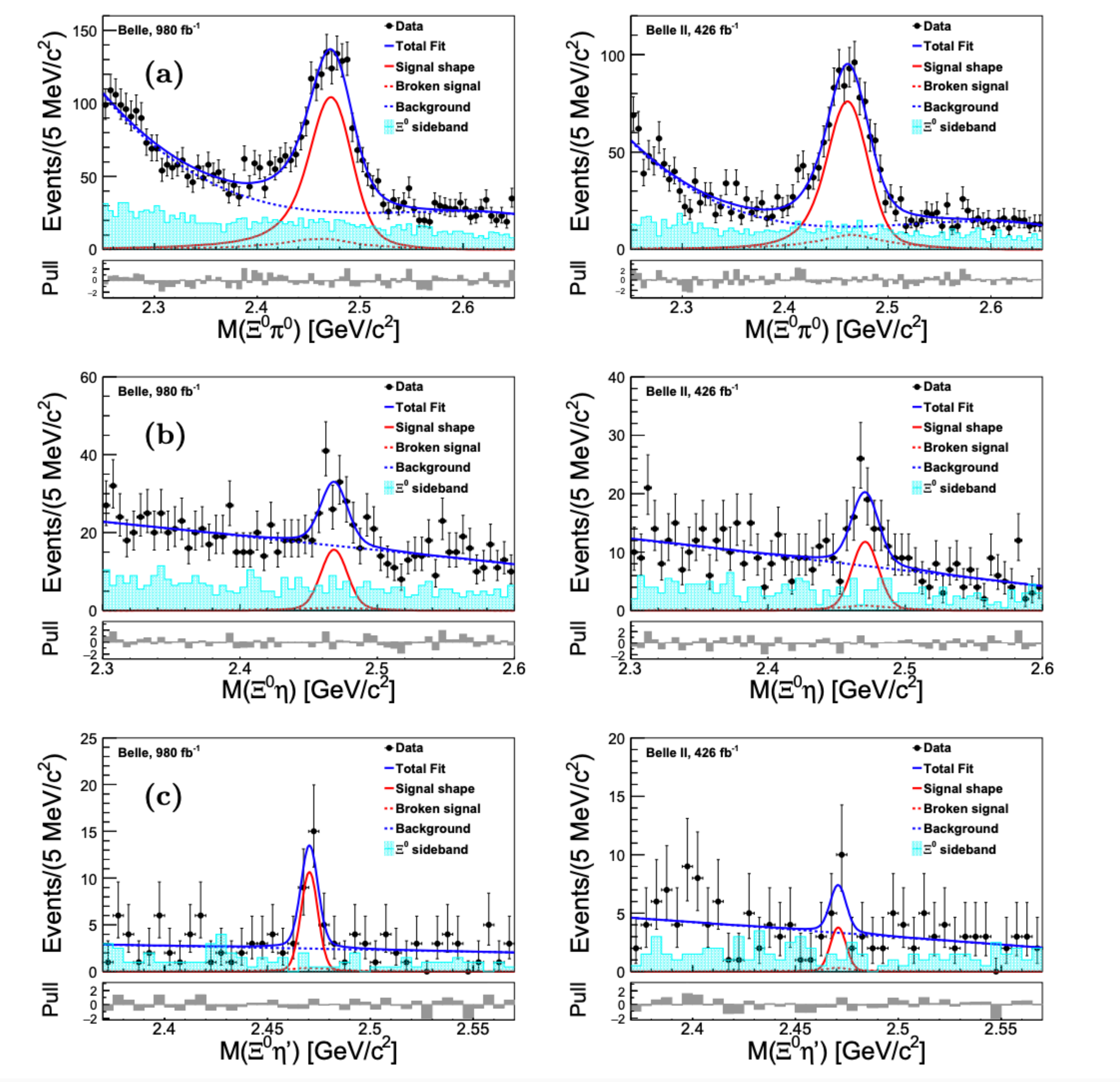
$\mathscr{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-3}$

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

First measurement; combines Belle+Belle II samples; consistent with $SU(3)_F$ – breaking model

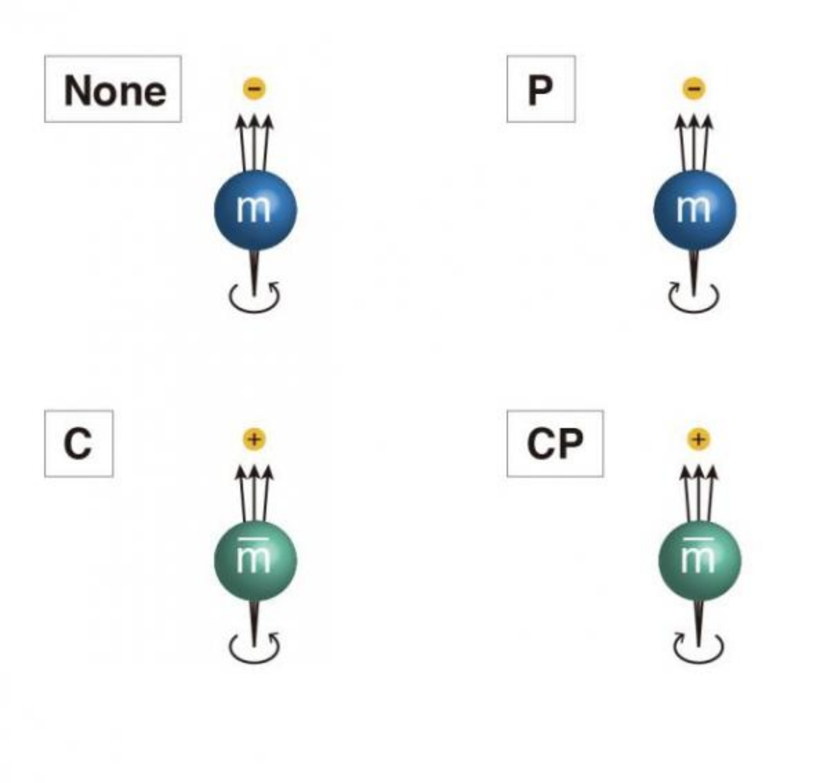


Branching Fraction of Charm Baryons



Search for CPV in the Charm Sector

Introduction to CP Violation



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

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

  - Insufficient to produce large-scale matter-antimatter asymmetry

CPV is well-established for mesons, but not for baryons

- Charm baryons —> sensitive probe for new physics (NP)

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

CKM matrix

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

Wolfenstein Parameterization

CPV in the Charm Sector

- Observed only in Singly Cabibbo-suppressed (SCS) $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays at this point (LHCb 2019, arXiv:1903.08726)
- 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

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** $C_T = \overrightarrow{p_1} \cdot \left(\overrightarrow{p_2} \times \overrightarrow{p_3}\right)$ 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
  - Quantify asymmetry via

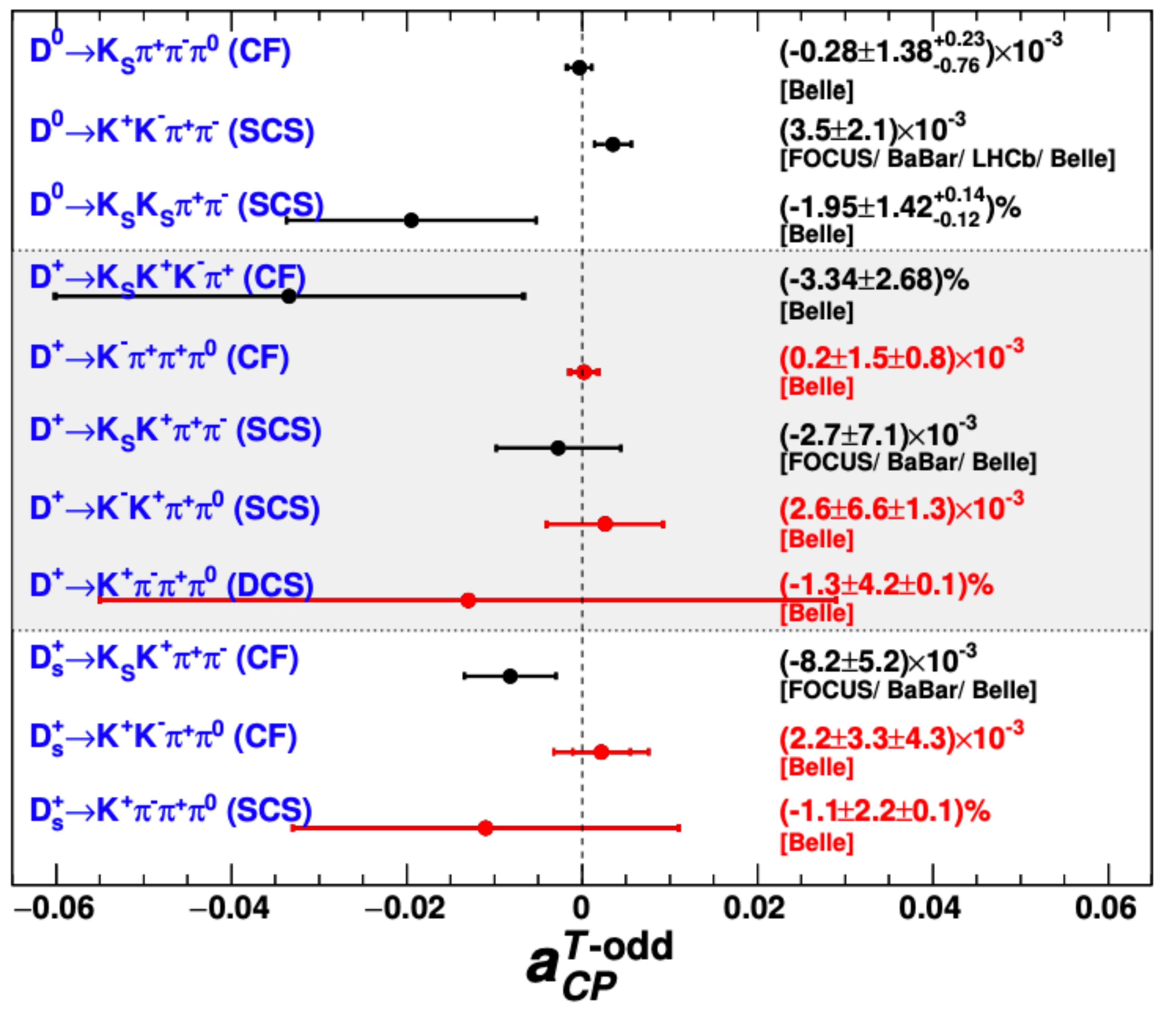
$$A_T = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$$

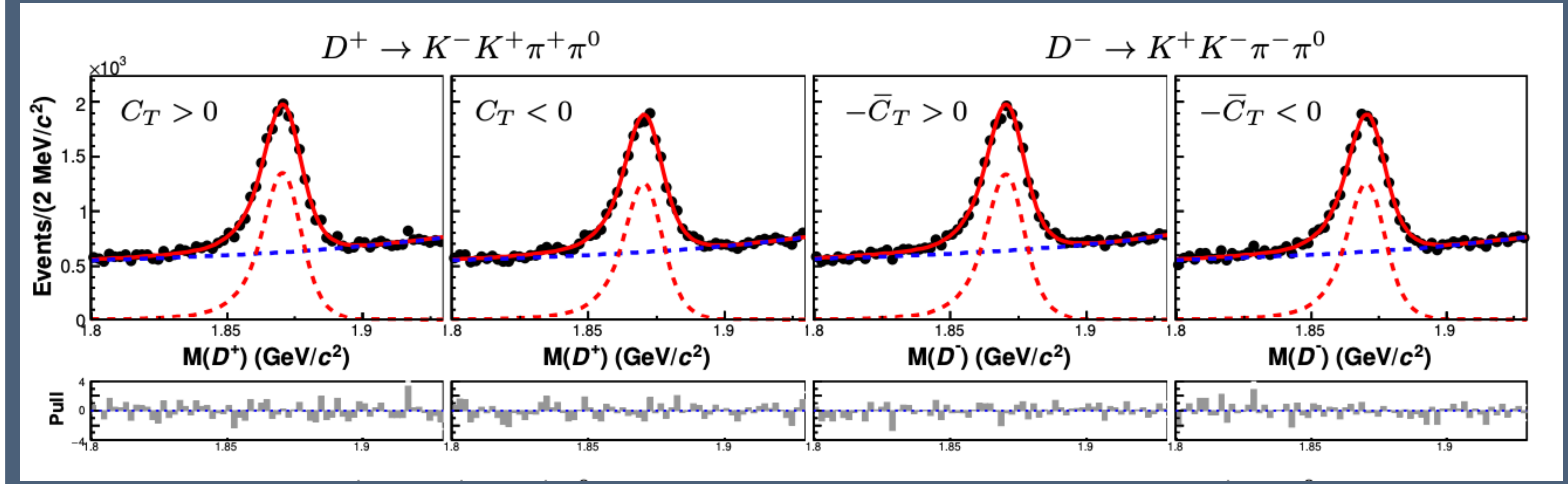
$$\bar{A}_T = \frac{\bar{N}(-\bar{C}_T > 0) - \bar{N}(-\bar{C}_T < 0)}{\bar{N}(-\bar{C}_T > 0) + \bar{N}(-\bar{C}_T < 0)}$$

Implies CPV via CPT Theorem!

Submitted to PRD, arXiv:2305.12806

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





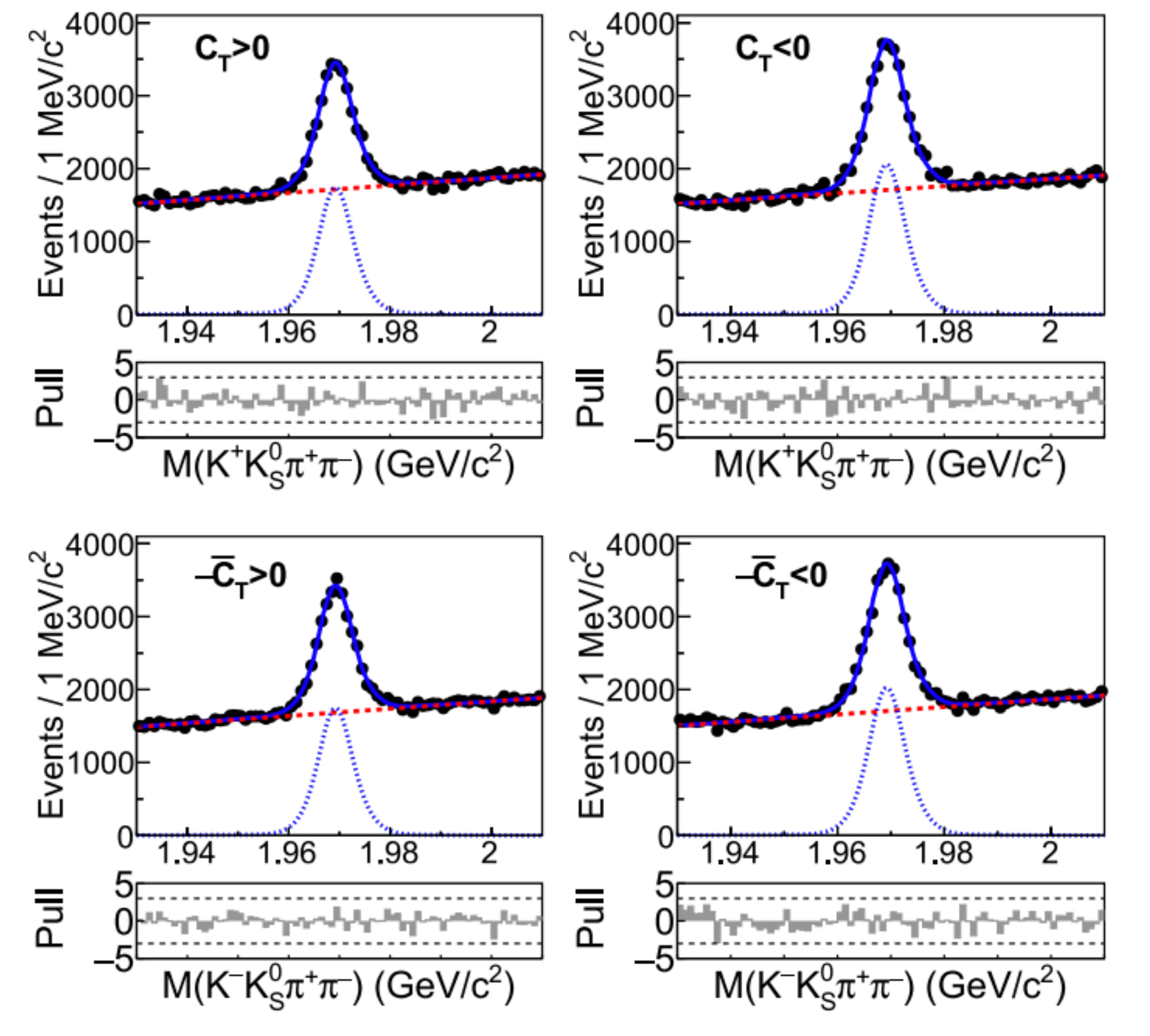
Decay	$D^+ \to f$			$D_s^+ \to f$	
Final state (f)	$K^+K^-\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+\pi^-\pi^+\pi^0$	$K^+K^-\pi^+\pi^0$
N_D	27284 ± 254	2062 ± 127	438432 ± 947	15197 ± 484	167357 ± 786
$N_{\bar{D}}$	27177 ± 255	2044 ± 125	450667 ± 961	14945 ± 479	167064 ± 788
A_T (%)	$+3.63 \pm 0.93$	-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	$+0.22 \pm 0.33$

First measurements, comparable precision to other Belle D decays; no evidence of CPV

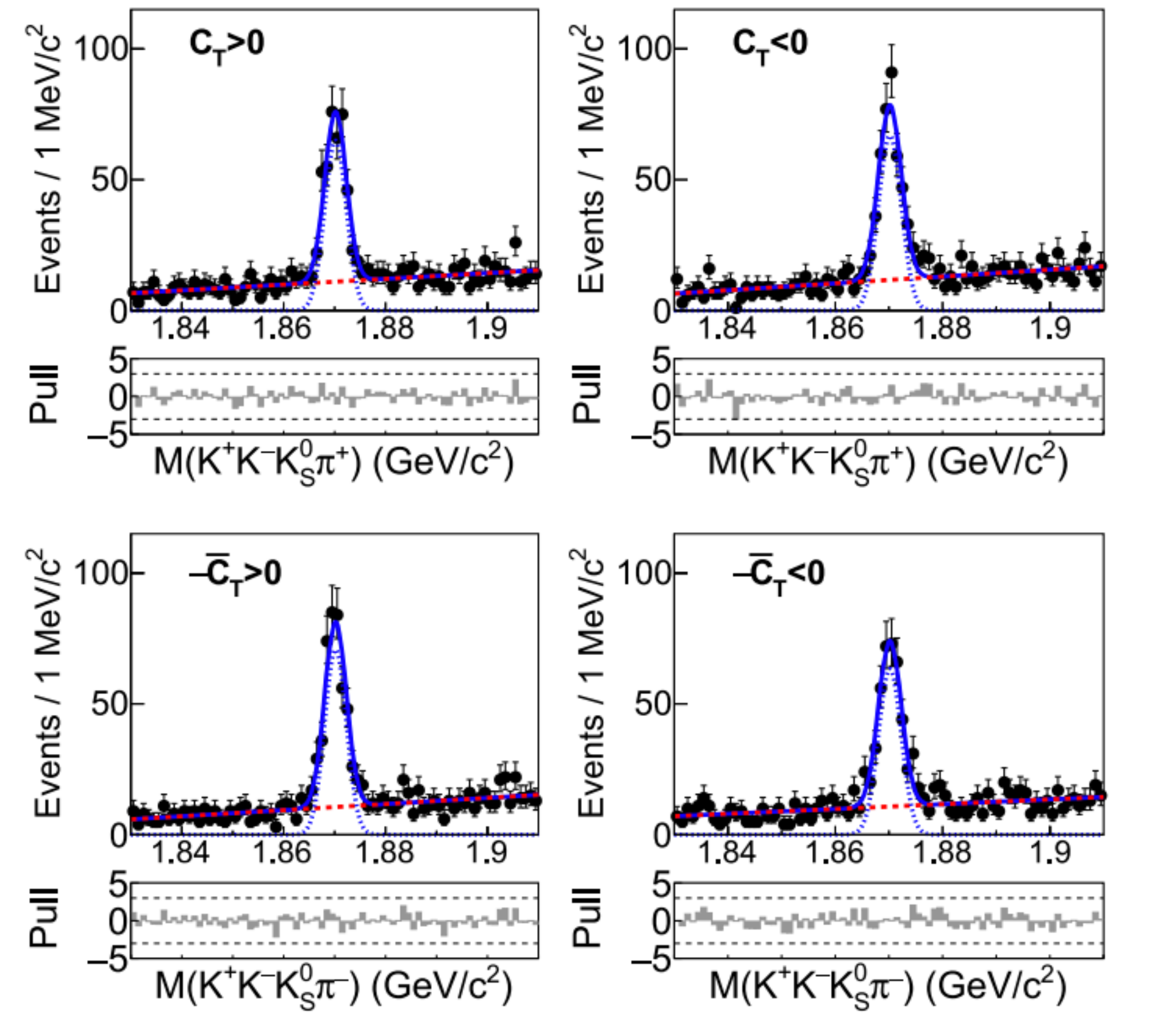
Phys.Rev.D108, L111102 (2023)

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

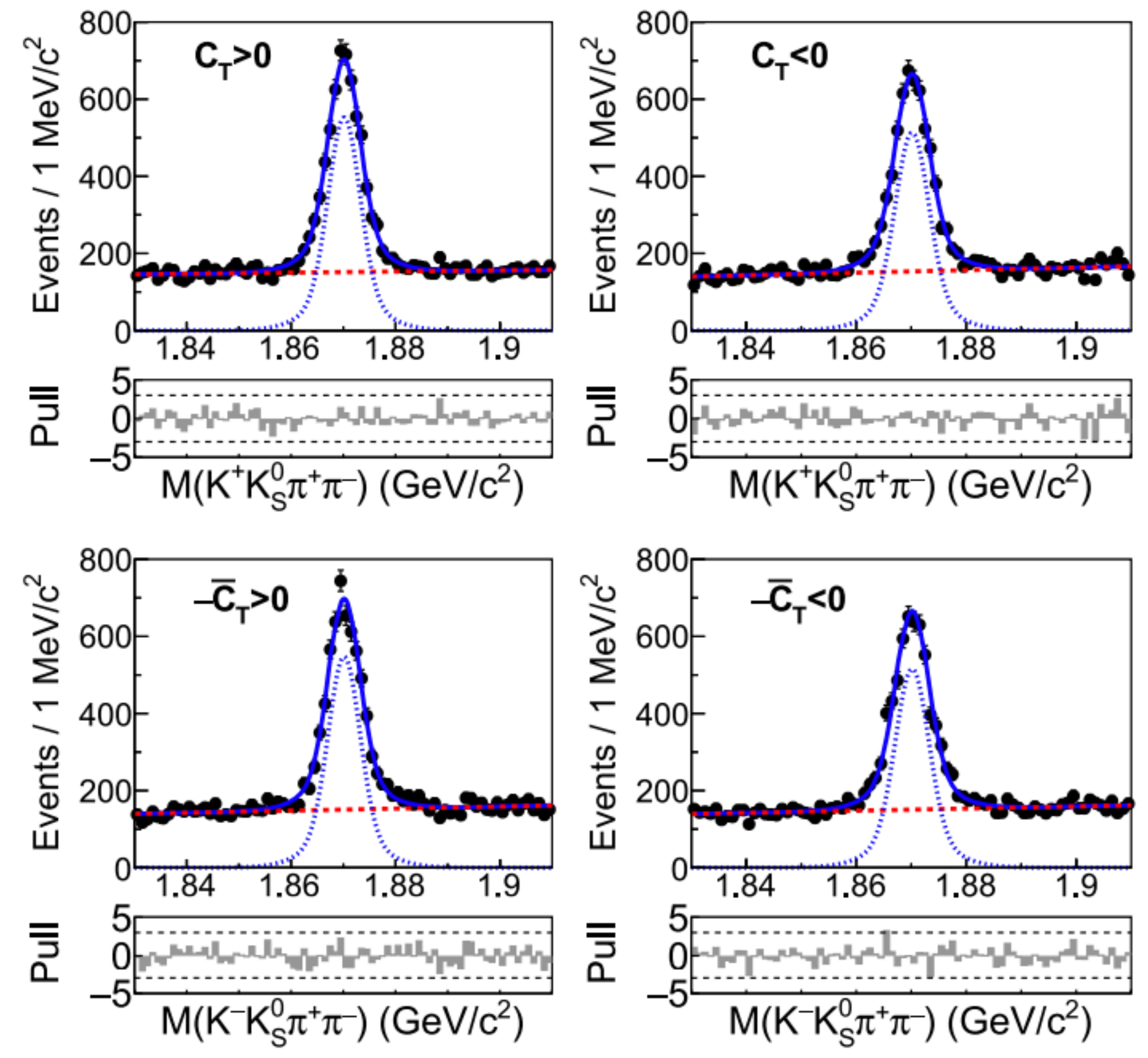
$D^+_s \to K^+K^0_s\pi^+\pi^-$



$D^+ \to K^+K^-K^0_s\pi^+$



$D^+ \to K^+K^0_s\pi^+\pi^-$



Results

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)

Most precise to date, dominated by statistical uncertainty; no evidence of CPV

Direct CPV via Asymmetry Measurements

- We will consider the recent Belle result for $\Lambda_c^+ \to \Lambda K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$.
  - 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)

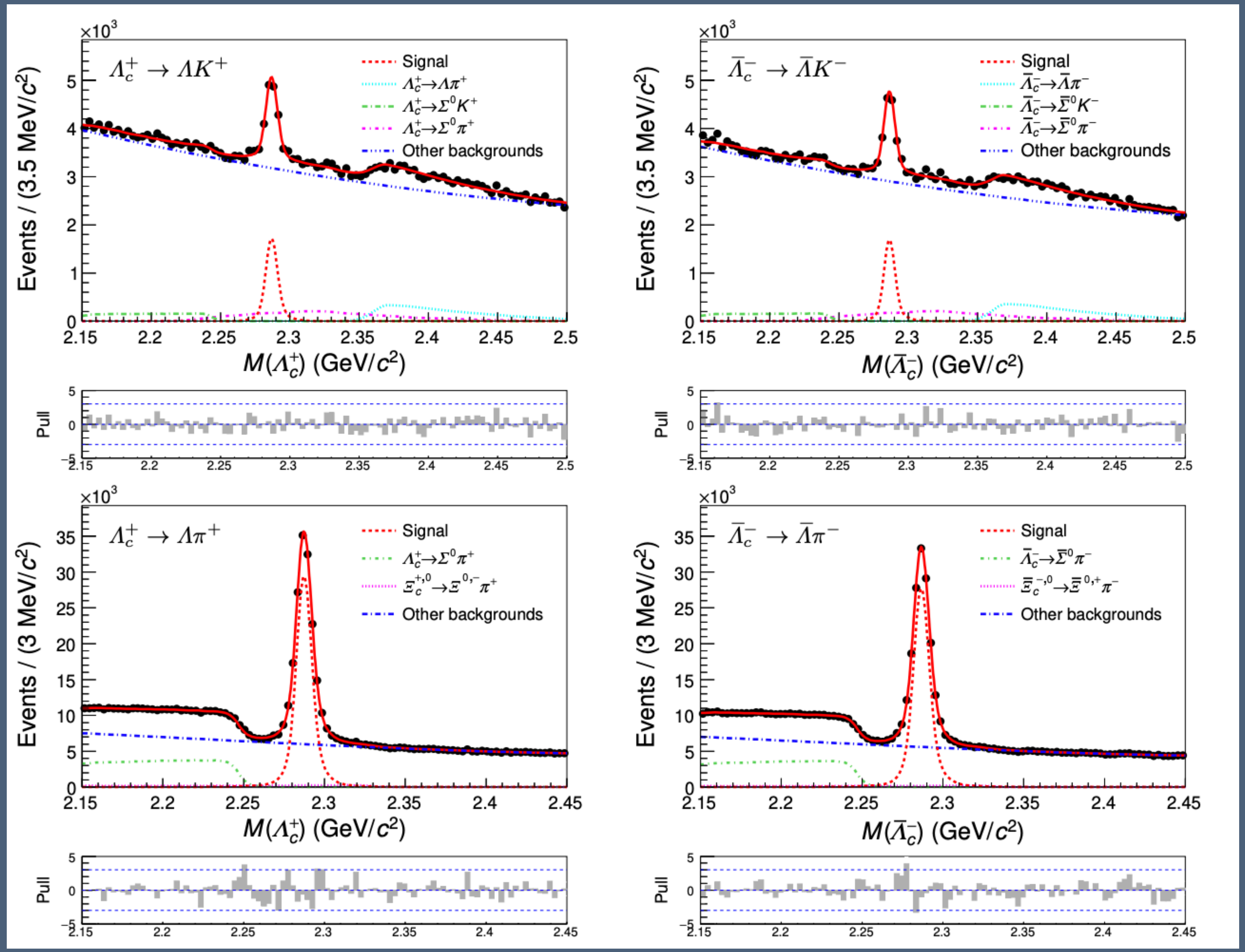
- $A_\epsilon^{K^+}$ is removed by weighting $w_{\Lambda_c, \bar{\Lambda}_c} = 1 \mp A_\epsilon^{K^+}[cos\theta, p_T]$
- Use a control mode, $\Lambda_c^+ \to \Lambda \pi^+$, to cancel out terms
  - $\Delta A_{raw} = A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{dir}(\Lambda_c^+ \to \Lambda \pi^+) = A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+)$ (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)**
  - $A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) = (2.1 \pm 2.6 \pm 0.1)\,\%$
  - $A_{CP}^{dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (2.5 \pm 5.4 \pm 0.4)\,\%$

Exotic Searches

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

Lepton Flavor Universality (LFU)

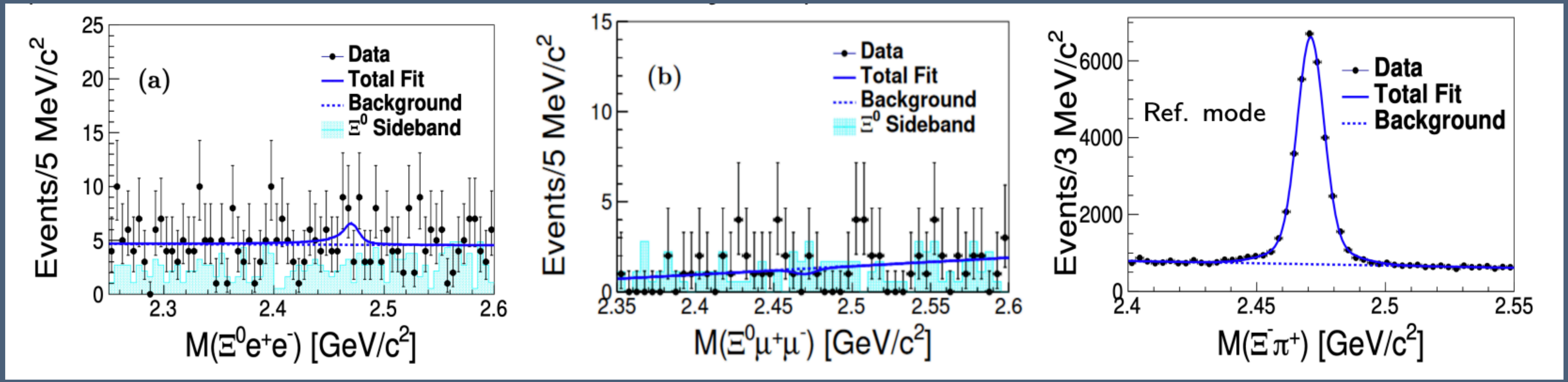
Results:

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

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

- 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)
  - FCNC semi-leptonic decay without neutrinos (sensitive to hamiltonian helicity structure through W-exchange diagrams)

arXiv:2312.02580



No signal observed but consistent with SM:

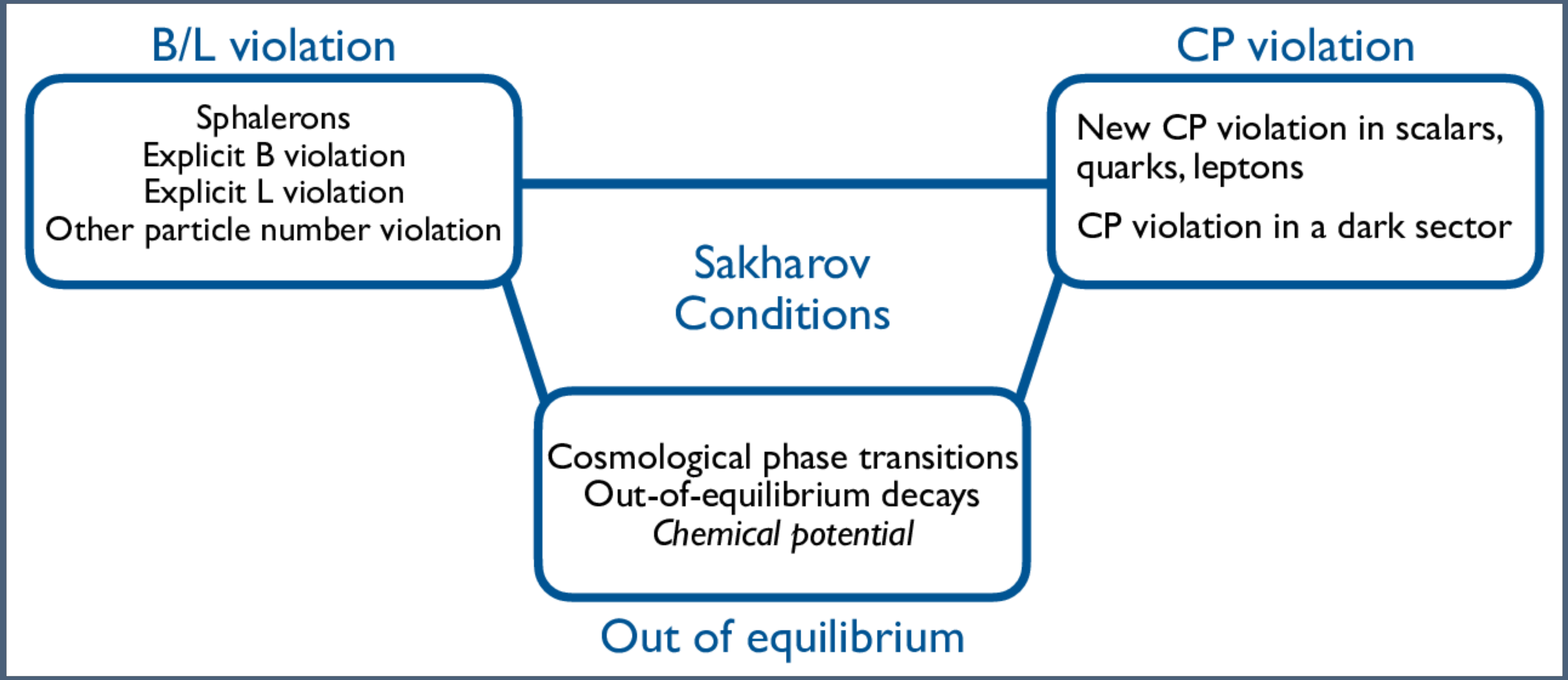
$$\mathcal{B}_{SM}(\Xi_c \to \Xi^0 e^+ e^-) < 2.35 \times 10^{-6}$$
$$\mathcal{B}_{SM}(\Xi_c \to \Xi^0 \mu^+ \mu^-) < 2.25 \times 10^{-6}$$

Expect Belle II improvement!

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
    - $\mathscr{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^-6$
    - $\mathscr{B}(D^0 \to pe^-) < 2.2 \times 10^-6$



B/L violation

Sphalerons
Explicit B violation
Explicit L violation
Other particle number violation

CP violation

New CP violation in scalars, quarks, leptons

CP violation in a dark sector

Sakharov Conditions

Cosmological phase transitions
Out-of-equilibrium decays
Chemical potential

Out of equilibrium

Phys.Rev.D109, L031101 (2024)

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

Test of Baryon Number Violation (BNV)

- Belle (2024)

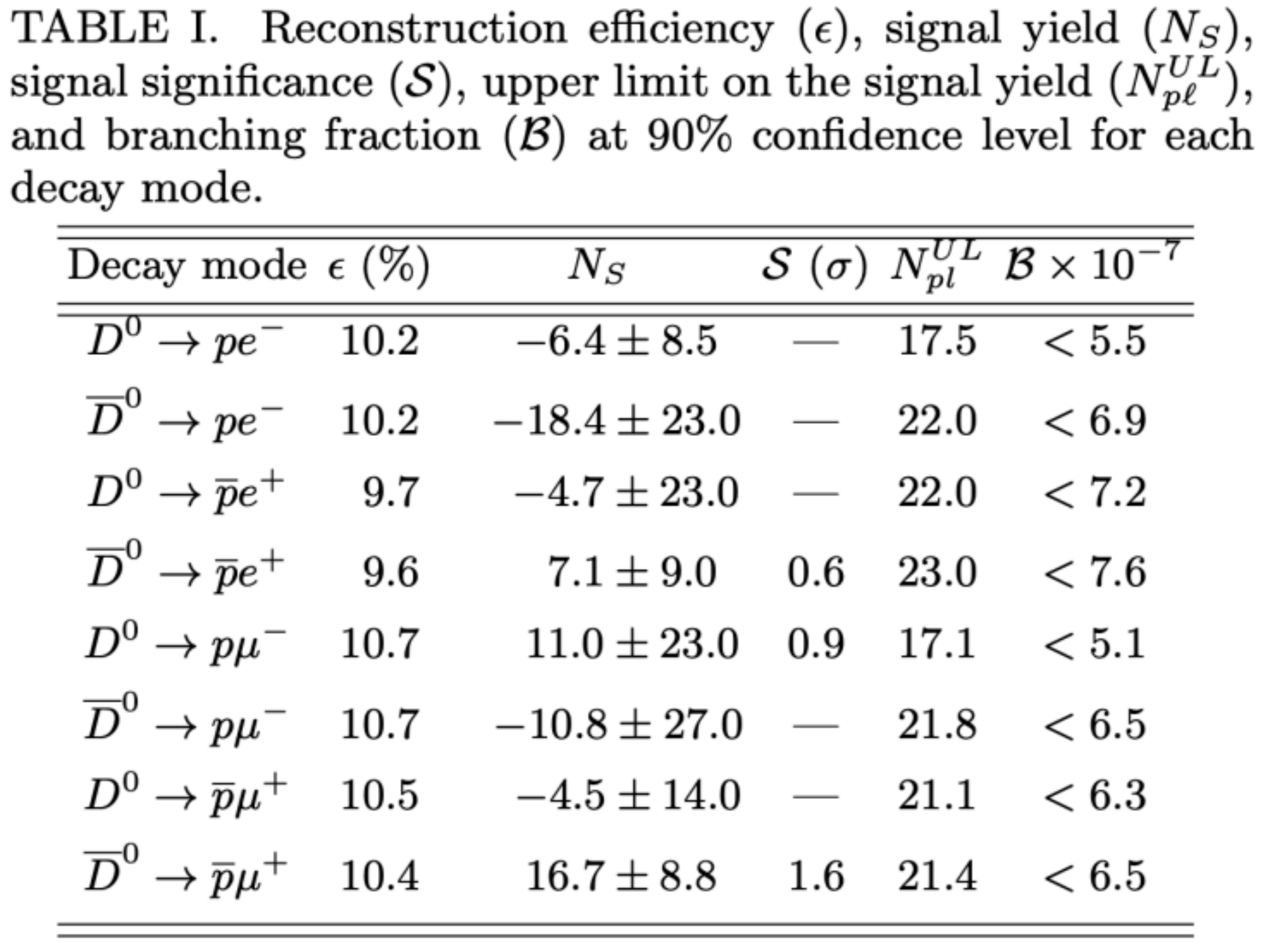
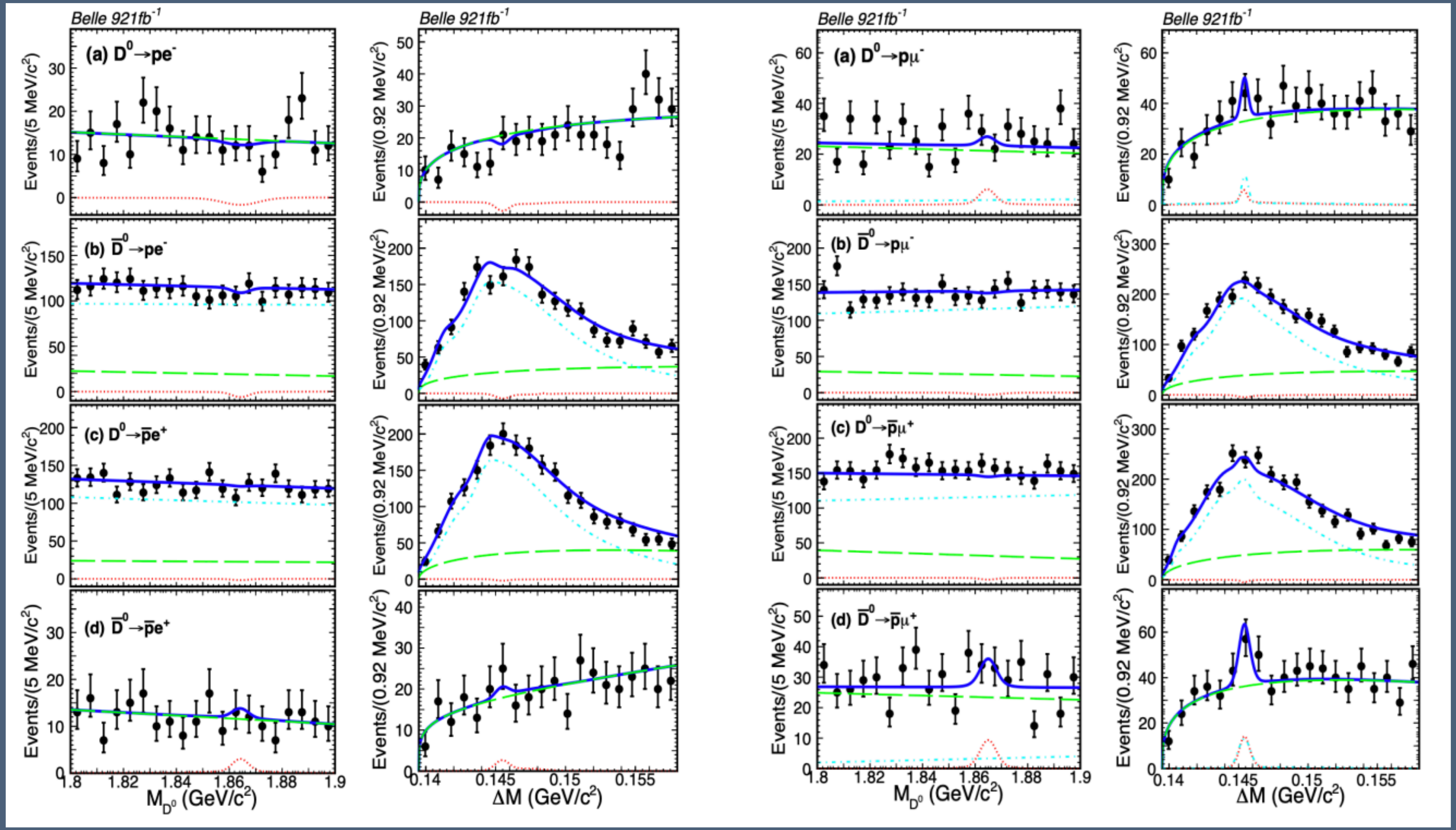


TABLE I. Reconstruction efficiency (ϵ), signal yield (N_S), signal significance ($\mathcal{S}$), upper limit on the signal yield ($N_{p\ell}^{UL}$), and branching fraction ($\mathcal{B}$) at 90% confidence level for each decay mode.

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
$D^0 \to \bar{p}e^+$	9.7	-4.7 ± 23.0	—	22.0	< 7.2
$\overline{D}^0 \to \bar{p}e^+$	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
$D^0 \to \bar{p}\mu^+$	10.5	-4.5 ± 14.0	—	21.1	< 6.3
$\overline{D}^0 \to \bar{p}\mu^+$	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

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 precision**. 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, and as time goes on their solidity will only increase.

Incomplete Things (Plan to Add Soon)

- α parameters (theory+results slide)
- search for $D^0 \to hh'e^+e^-$