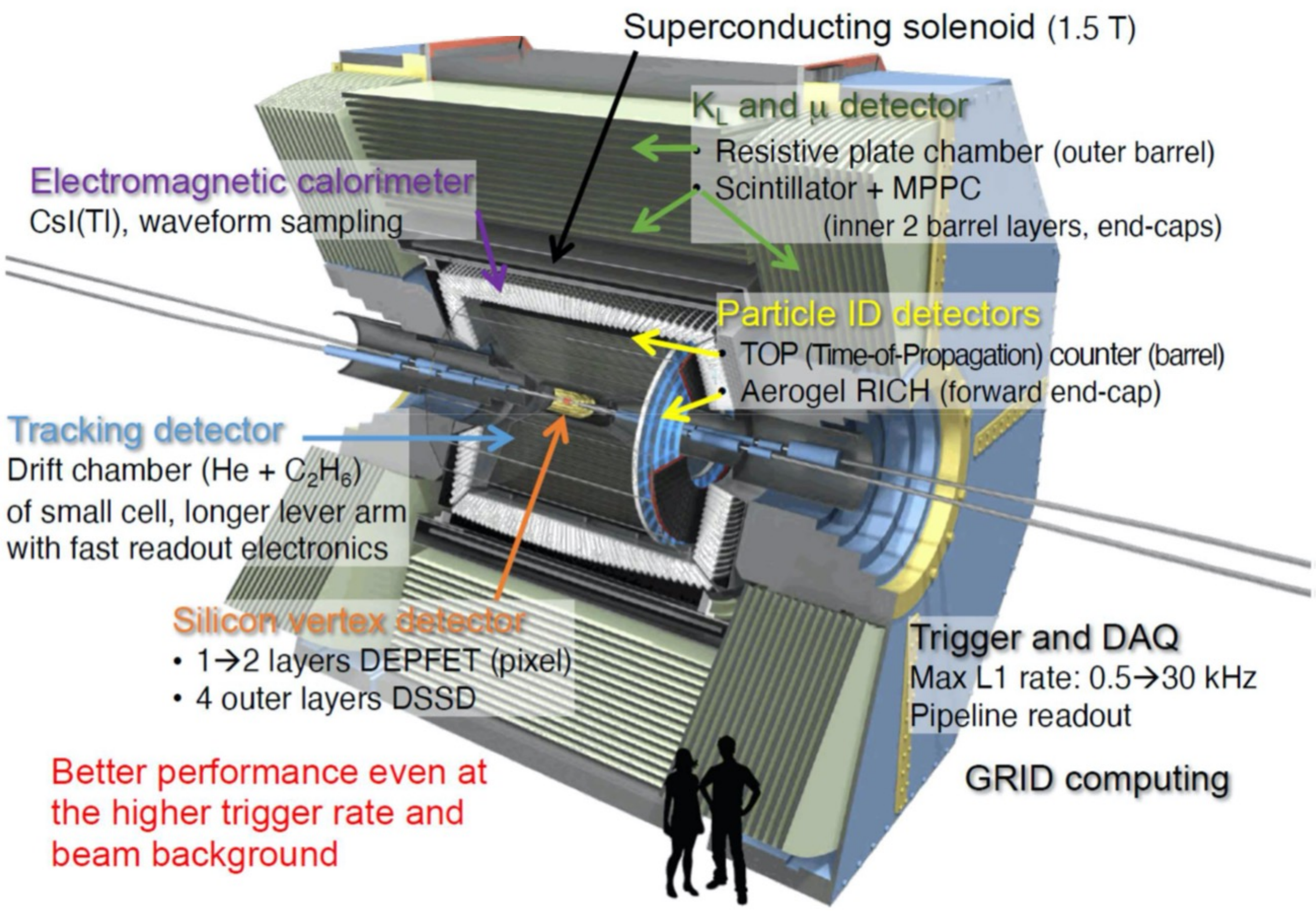
Charm physics at Belle (II)

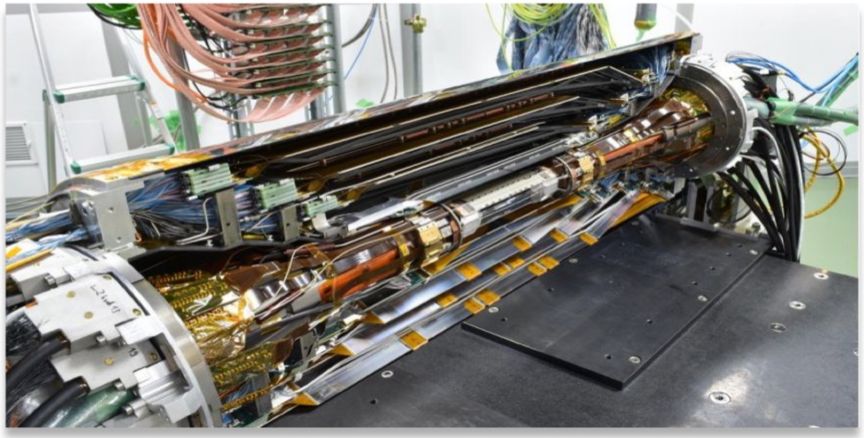
贾森
东南大学

BESIII粲强子物理研讨会，合肥
2023年4月9日

Belle II Detector

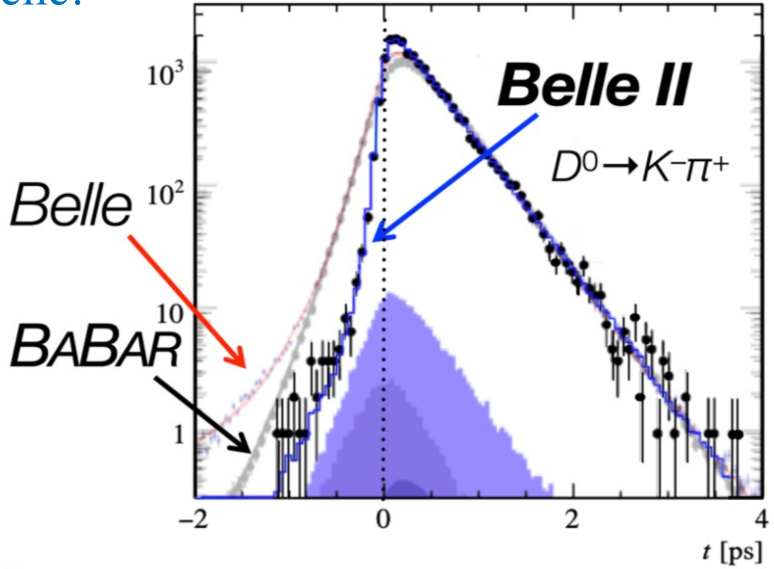


Belle II Vertex Detector (VXD)



- Pixel Detector (PXD): 2 Layers of DEPFET
- Silicon Vertex Detector (SVD): 4 Layers of Double Sided

The impact parameter resolution is ×2 better than Belle.

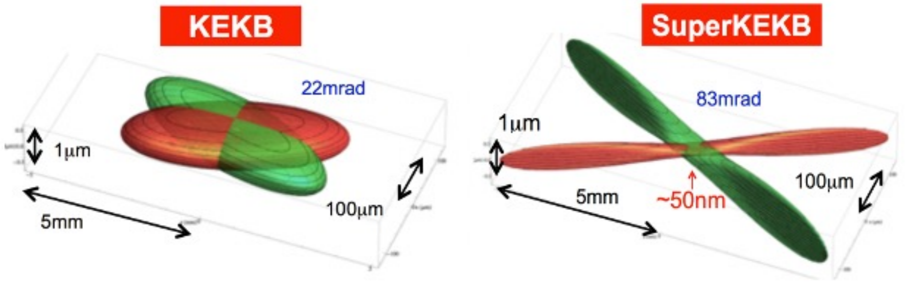


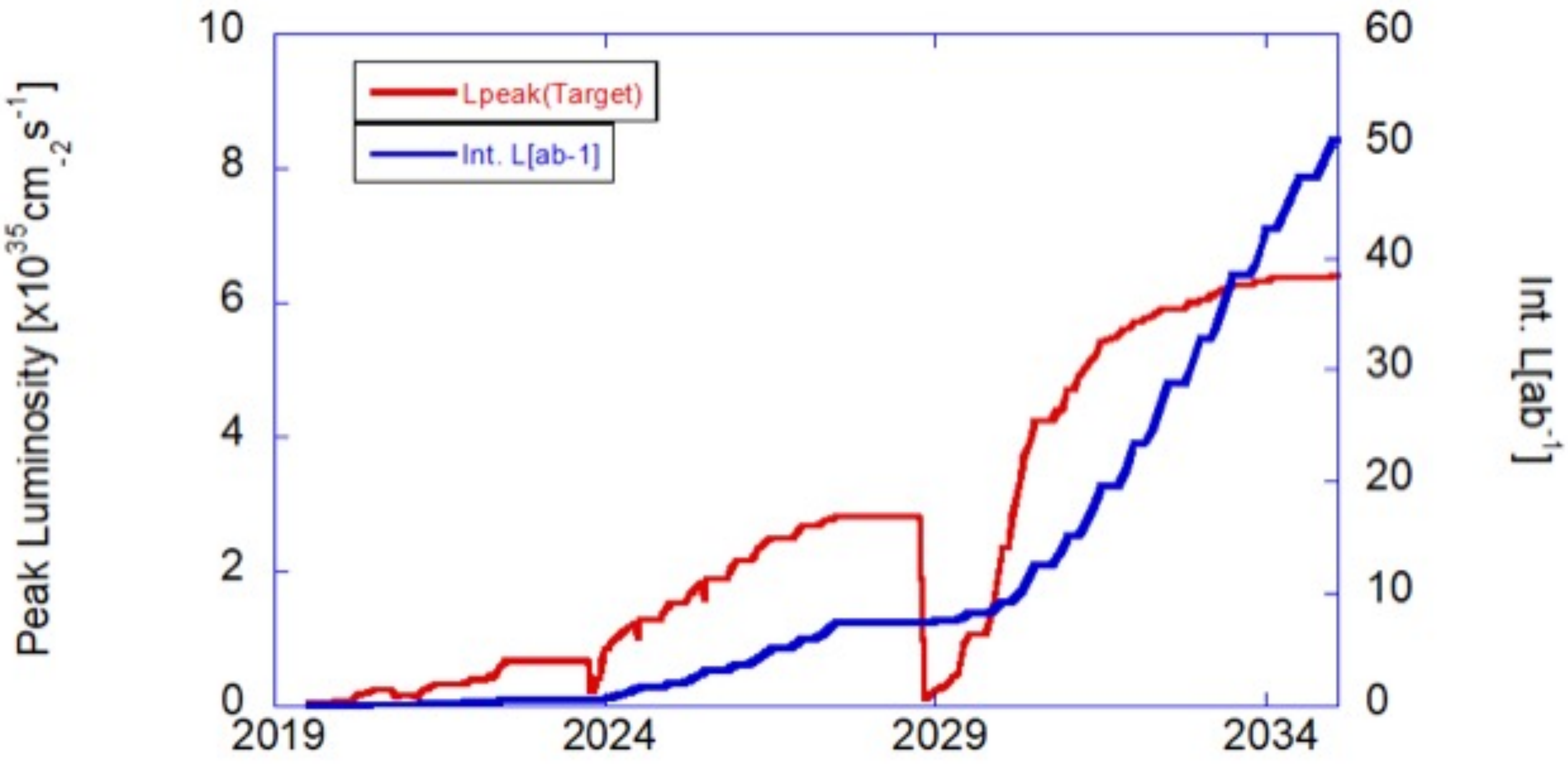
Belle II data

In June 2022

WORLD RECORD: 4.7 x 10^{34} $cm^{-2}s^{-1}$

Nano-beam design





- Collected ~428 fb^{-1} around $\Upsilon(4S)$ until now
- LS1 starts from summer 2022 to fully install the pixel detector

Selected topics

- $\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ (A_{CP}^{dir}/Br/α/A_{CP}^{α}) [Belle]
- Observation of $\Lambda_c(2910)^+ \to \Sigma_c(2455)^{0/++}\pi^{\pm}$ [Belle]
- Evidence for $\Omega_c^0 \to \Xi^- K^+$

- D lifetime [Belle II]
- Λ_c^+ lifetime [Belle II]
- Ω_c^0 lifetime [Belle II]

[Science Bulletin 68 (2023) 583]

$\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+$ (A_{CP}^{dir}/Br)

- To date, CPV has been observed in the open-flavored meson sector (i.e. K, D and B mesons), but not yet established in the baryon sector.
- Experimentally, no direct CPV searches in two-body SCS decays of charm baryons have been made to date.
- The raw asymmetry in the decays: $\boxed{A_{\rm raw} = \frac{N_{\rm sig}(\Lambda_c^+ \to f) - N_{\rm sig}(\bar{\Lambda}_c^- \to \bar{f})}{N_{\rm sig}(\Lambda_c^+ \to f) + N_{\rm sig}(\bar{\Lambda}_c^- \to \bar{f})}}$
- Several sources contribute to the raw asymmetry:

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

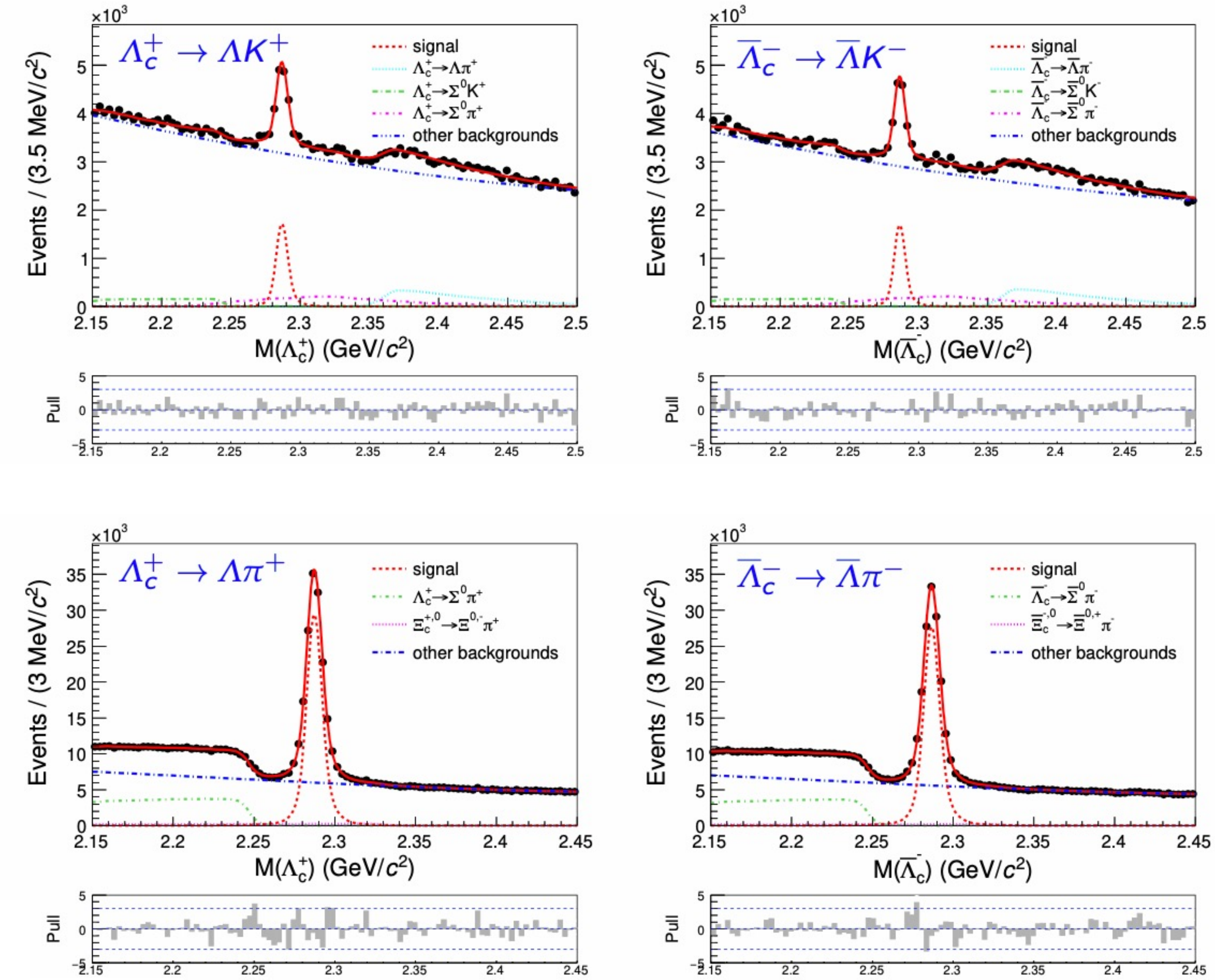
- The reference mode is used.

$$\boxed{A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda\pi^+) = A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+)}$$

$\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+$ (A_{CP}^{dir}/Br)

[Science Bulletin 68 (2023) 583]

All Belle data, 980 fb^{-1}



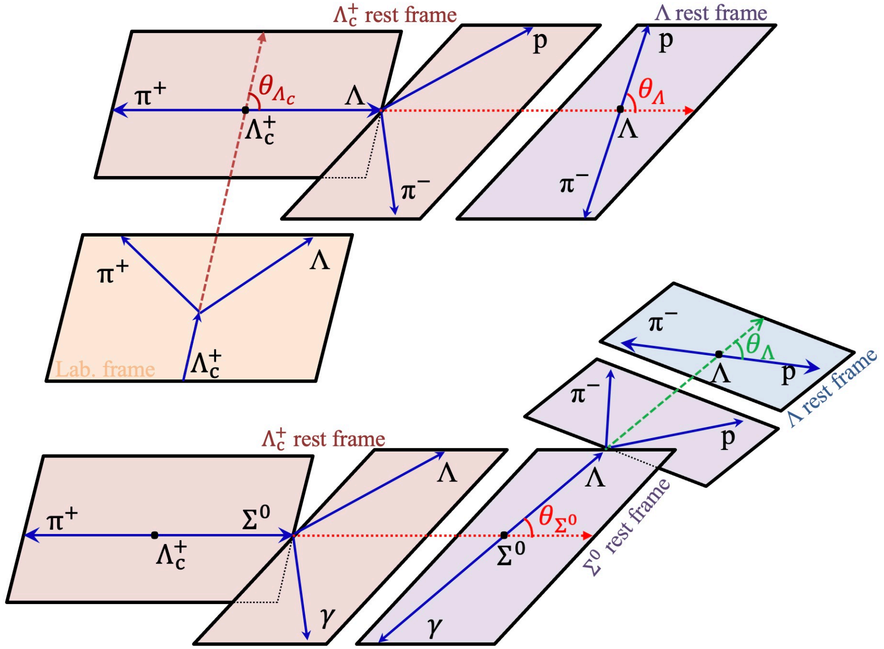
- Simultaneous fit on the $A_\varepsilon^{h^+}$-weighted $\Lambda_c^\pm$ samples gives
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$
  $A_{CP}^{\rm dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$,
  first CPV result of charmed baryon SCS two-body decays.
- Based on $M(\Lambda_c^+)$ fit on the combined $\Lambda_c^\pm$ sample and the efficiencies based on signal MC produced with our measured angular distribution, we measure $\frac{\mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm ref}} = \frac{N_{\rm sig}/\varepsilon_{\rm sig}}{N_{\rm ref}/\varepsilon_{\rm ref}}$.
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)} = (5.05 \pm 0.13 \pm 0.09)\%;$$
  (Vs. PDG: 4.7 ± 0.9)%; BESIII recent result: $(4.78 \pm 0.39)\%$.)
  $$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)} = (2.78 \pm 0.15 \pm 0.05)\%.$$
  (Vs. PDG: $(4.0 \pm 0.6)\%$; BESIII recent result: $(3.61 \pm 0.73)\%$.)
- Using the W.A. $\mathcal{B}(\Lambda_c^+ \to (\Lambda, \Sigma^0)\pi^+)$, we have
  $\mathcal{B}(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$
  $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$.
  (Vs. PDG: 6.1 ± 1.2)% and 5.2 ± 0.8)%)
  Both are consistent with W.A. but with significantly improved precision.

[Science Bulletin 68 (2023) 583]

$\Lambda_c^+ \to \Lambda h^+$, $\Sigma^0 h^+$ (A_{CP}^{dir}/Br)

- The decay asymmetry parameter α was introduced by Lee and Yang to study the parity-violating and parity-conserving amplitudes in weak hyperon decays.
- For $\Lambda_c^+ \to \Lambda h^+$ decays, the differential decay rate depends on α parameters and one helicity angle as:

$$\boxed{\frac{dN(\Lambda_c^+ \to \Lambda h^+)}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda}$$



- For $\Lambda_c^+ \to \Sigma^0 h^+$ decays, considering $\alpha(\Sigma^0 \to \gamma\Lambda)$ is zero due to parity conservation for an electromagnetic decay, the differential decay rate related to the α parameters and helicity angles is given by

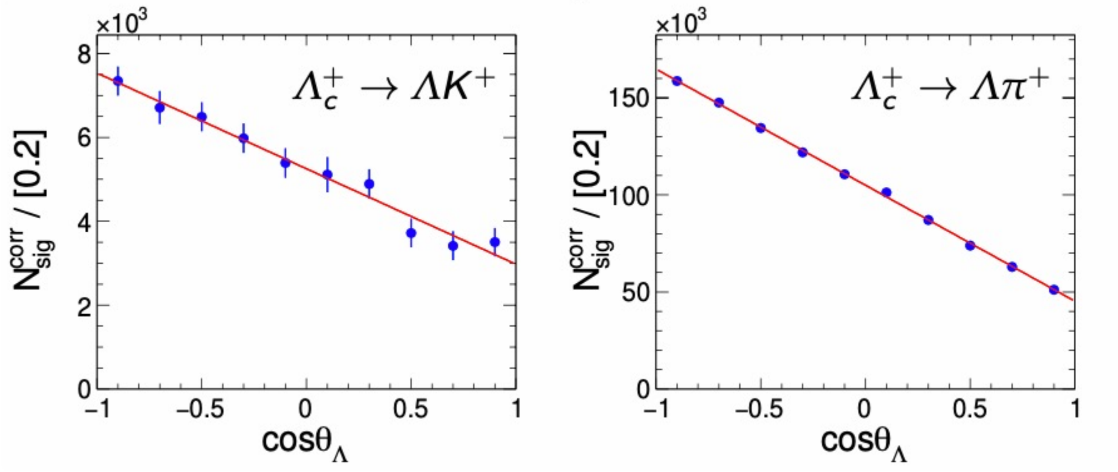
$$\boxed{\frac{dN(\Lambda_c^+ \to \Sigma^0 h^+)}{d\cos\theta_{\Sigma^0}\, d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda}$$

- Since α is CP-odd, the α-induced CP asymmetry:

$$\boxed{A_{CP}^{\alpha} \equiv \frac{\alpha_{\Lambda_c^+} - \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger}{\alpha_{\Lambda_c^+} + \widehat{CP}\alpha_{\Lambda_c^+}\widehat{CP}^\dagger} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\overline{\Lambda}_c^-}}{\alpha_{\Lambda_c^+} - \alpha_{\overline{\Lambda}_c^-}}}$$

$\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+$ (α/A_{CP}^{α})

► $\cos\theta_\Lambda$ distributions of $\Lambda_c^+ \to \Lambda h^+$ after efficiency correction, fitted with $1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$

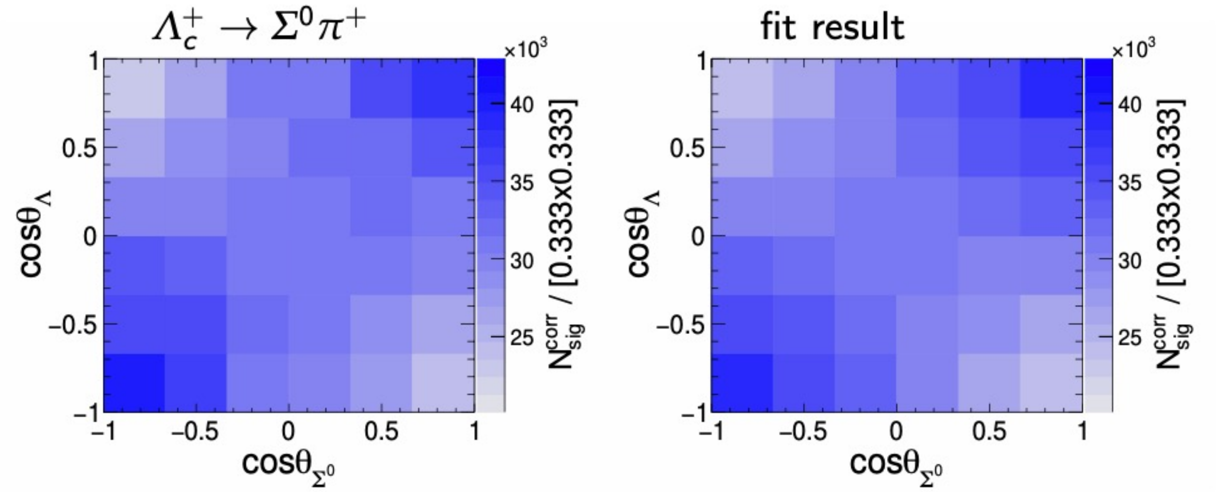


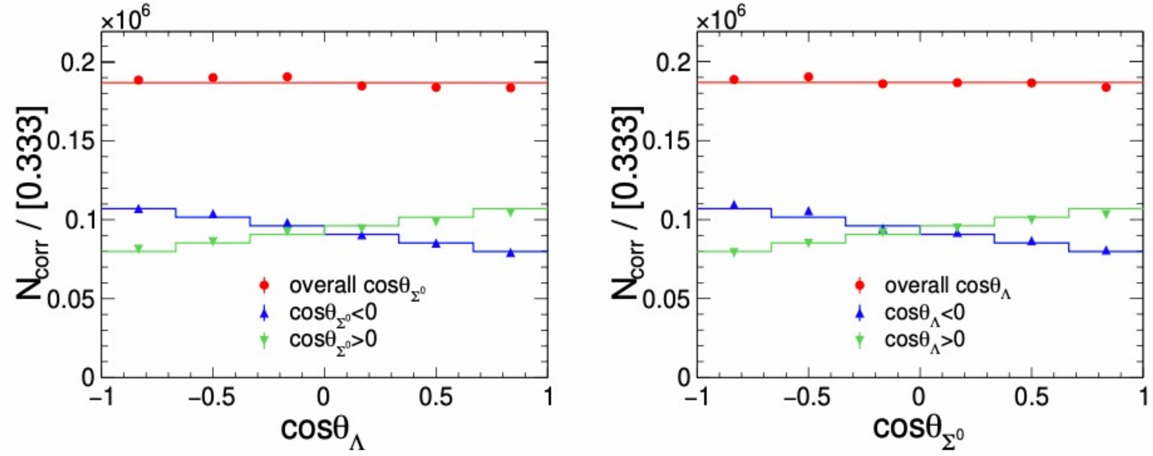
► Using the fitted slope factors and the average α_-, we have

$\alpha_{avg}(\Lambda_c^+ \to \Lambda K^+) = -0.585 \pm 0.049 \pm 0.018$
$\alpha_{avg}(\Lambda_c^+ \to \Lambda \pi^+) = -0.755 \pm 0.005 \pm 0.003$
(vs. PDG: -0.84 ± 0.09)
$\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 K^+) = -0.55 \pm 0.18 \pm 0.09$
$\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 \pi^+) = -0.463 \pm 0.016 \pm 0.008$
(vs. PDG: -0.73 ± 0.18)

First α results of SCS decays for charm baryons; and significantly improved results of CF Λ_c^+ decays.

► $(\cos\theta_\Lambda, \cos\theta_{\Sigma^0})$ 2D distributions of $\Lambda_c^+ \to \Sigma^0 h^+$ after efficiency correction, fitted with $1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda$

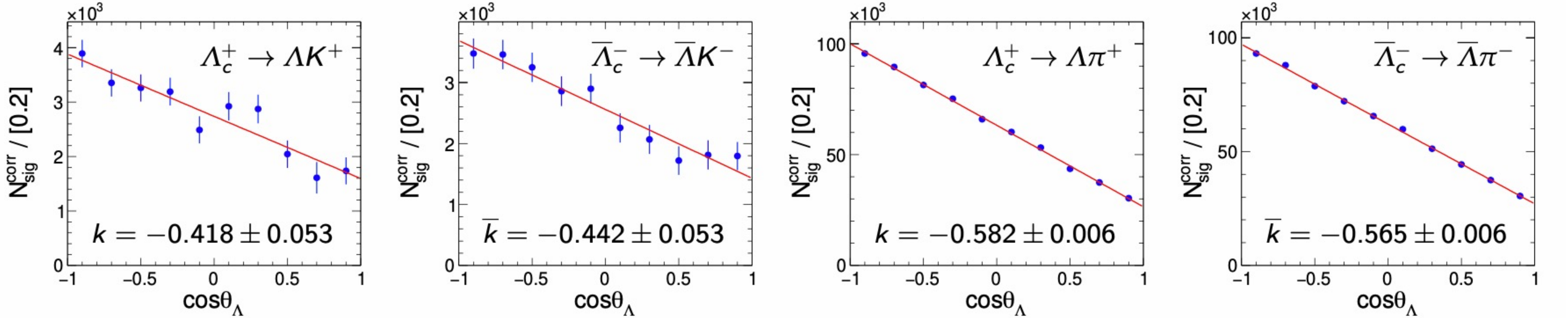




$\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+$ (α/A_{CP}^{α})

[Science Bulletin 68 (2023) 583]

- Measure α values for Λ_c^+ and $\overline{\Lambda}_c^-$ decays separately. We obtain the first or most precise $A_{CP}^{\alpha}(\Lambda_c^+)$ results.



Channel	$k = \alpha_{\Lambda_c^+}\alpha_-$	$\overline{k} = \alpha_{\overline{\Lambda}_c^-}\alpha_+$	$\alpha_{\Lambda_c^+}$	$\alpha_{\overline{\Lambda}_c^-}$	A_{CP}^{α}	W.A. A_{CP}^{α}	our $A_{CP}^{\alpha}(\Lambda \to p\pi^-)$
$\Lambda_c^+ \to \Lambda K^+$	-0.418 ± 0.053	-0.442 ± 0.053	$-0.566 \pm 0.071 \pm 0.028$	$0.592 \pm 0.070 \pm 0.079$	$-0.023 \pm 0.086 \pm 0.071$	–	–
$\Lambda_c^+ \to \Lambda \pi^+$	-0.582 ± 0.006	-0.565 ± 0.006	$-0.784 \pm 0.008 \pm 0.006$	$0.754 \pm 0.008 \pm 0.018$	$+0.020 \pm 0.007 \pm 0.013$	-0.07 ± 0.22	$+0.017 \pm 0.007 \pm 0.012$
$\Lambda_c^+ \to \Sigma^0 K^+$	-0.43 ± 0.18	-0.37 ± 0.21	$-0.58 \pm 0.24 \pm 0.09$	$0.49 \pm 0.28 \pm 0.14$	$+0.08 \pm 0.35 \pm 0.14$	–	–
$\Lambda_c^+ \to \Sigma^0 \pi^+$	-0.340 ± 0.016	-0.358 ± 0.017	$-0.452 \pm 0.022 \pm 0.023$	$0.473 \pm 0.023 \pm 0.035$	$-0.023 \pm 0.034 \pm 0.030$	–	$-0.026 \pm 0.034 \pm 0.030$

combined: $+0.013 \pm 0.007 \pm 0.011$

- In our CF Λ_c^+ decay chains, $A_{CP}^{\alpha}(\text{total}) \equiv \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+}$. Under the SM with $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda}_c^-}$ for these CF Λ_c^+ decays, $A_{CP}^{\alpha}(\text{total}) = A_{CP}^{\alpha}(\Lambda \to p\pi^-)$. $\Rightarrow$ search for hyperon CPV in charm CF decays for the first time.
- No evidence of CPV in baryon decays (charmed baryon Λ_c^+ and hyperon Λ) is found.

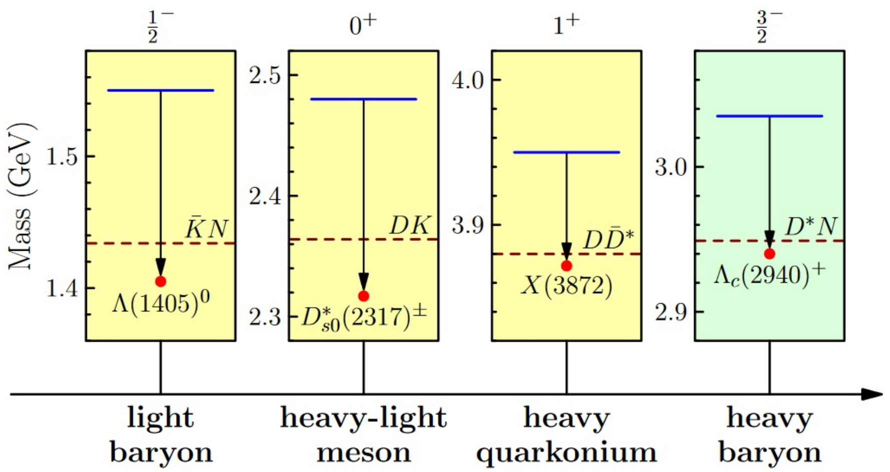
$\Lambda_c(2910)^+ \to \Sigma_c(2455)^{0/++}\pi^\pm$

[PRL 130, 031901 (2023)]

- $\Lambda_c(2940) \to \Sigma_c(2455)\pi$: the highest excited Λ_c state
- LHCb favor the $J^P = \frac{3}{2}^-$, but other values can not be excluded [JHEP 05, 030 (2017)].
- The mass of $\Lambda_c(2940)$ lower than the traditional expectation of quark model

State	J^P	Present	[9]	[10]	[11]	[16]	[20]	[21]	PDG [1]
$2P$	$\frac{1}{2}^-$	2.978	3.017	2.983	2.989	2.890		2.980	
$2P$	$\frac{3}{2}^-$	2.970	3.034	3.005	3.000	2.917		3.004	$2.9396^{+0.0014}_{-0.0015}$

[9] PLB 659, 612 (2008) [10] PRD 84, 014025 (2011) [11] PRD 91, 054034 (2015)
[16] PRD 92, 114029 (2015) [21] EPJC 77, 154 (2017)



EPJC 80, 301 (2020)

Similar to $\Lambda(1405)$, $D_s(2317)$, $X(3872)$, D^*N contribute in $\Lambda_c(2940)$

=> Mass of $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$ inverse, and larger than $\Lambda_c\left(\frac{3}{2}^-, 2P\right)$

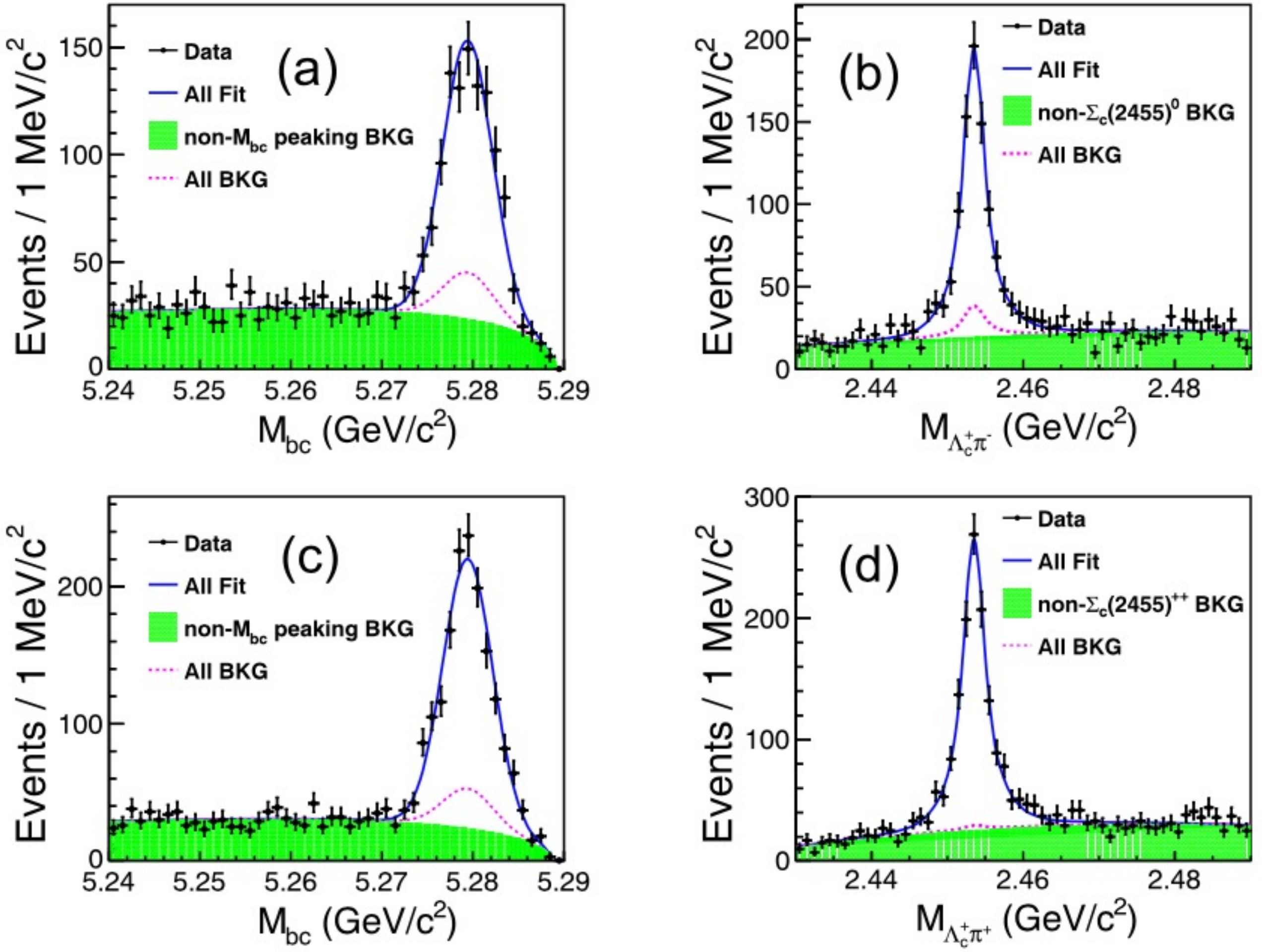
$\bar{B}^0 \to \Lambda_c^* \bar{p}$, $\Lambda_c^* \to \Sigma_c\pi$: Search for Λ_c excited states, also has constraint on J^P

$\bar{B}^0 \to \Sigma_c(2455)^{0/++}\pi^{\pm}\bar{p}$

[PRL 130, 031901 (2023)]

Belle data, 711 fb^{-1} on $\Upsilon(4S)$

Perform two-dimensional extended maximum likelihood fits:



Signal yields	
$\bar{B}^0 \to \Sigma_c(2455)^0\pi^+\bar{p}$	767 ± 44
$\bar{B}^0 \to \Sigma_c(2455)^{++}\pi^-\bar{p}$	1213 ± 73

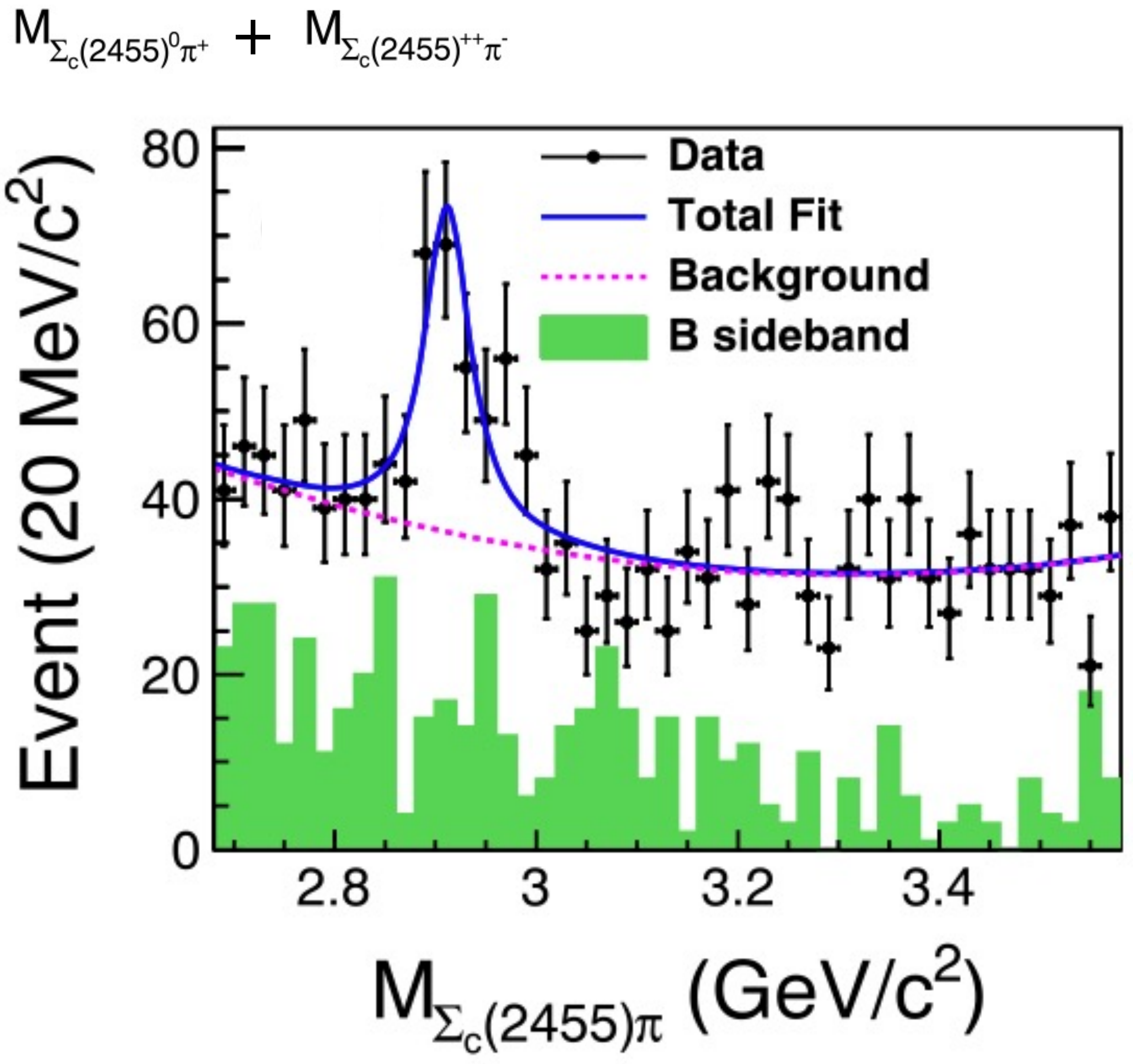
Branching fraction	
$\bar{B}^0 \to \Sigma_c(2455)^0\pi^+\bar{p}$	$(1.09\pm0.06\pm0.07)\times10^{-4}$
$\bar{B}^0 \to \Sigma_c(2455)^{++}\pi^-\bar{p}$	$(1.84\pm0.11\pm0.12)\times10^{-4}$

These branching fractions are consistent with the previous measurements [PRD 66, 091101 (2002), PRD 75, 011101 (2007), PLB 669, 287 (2008), PRD 87, 092004 (2013)] with improved precision.

Inclusion of charge conjugate states is implicit.

$\Lambda_c(2910)^+ \rightarrow \Sigma_c(2455)^{0/++}\pi^{\pm}$

[PRL 130, 031901 (2023)]



- A new structure in $M_{\Sigma_c\pi}$ spectrum is seen

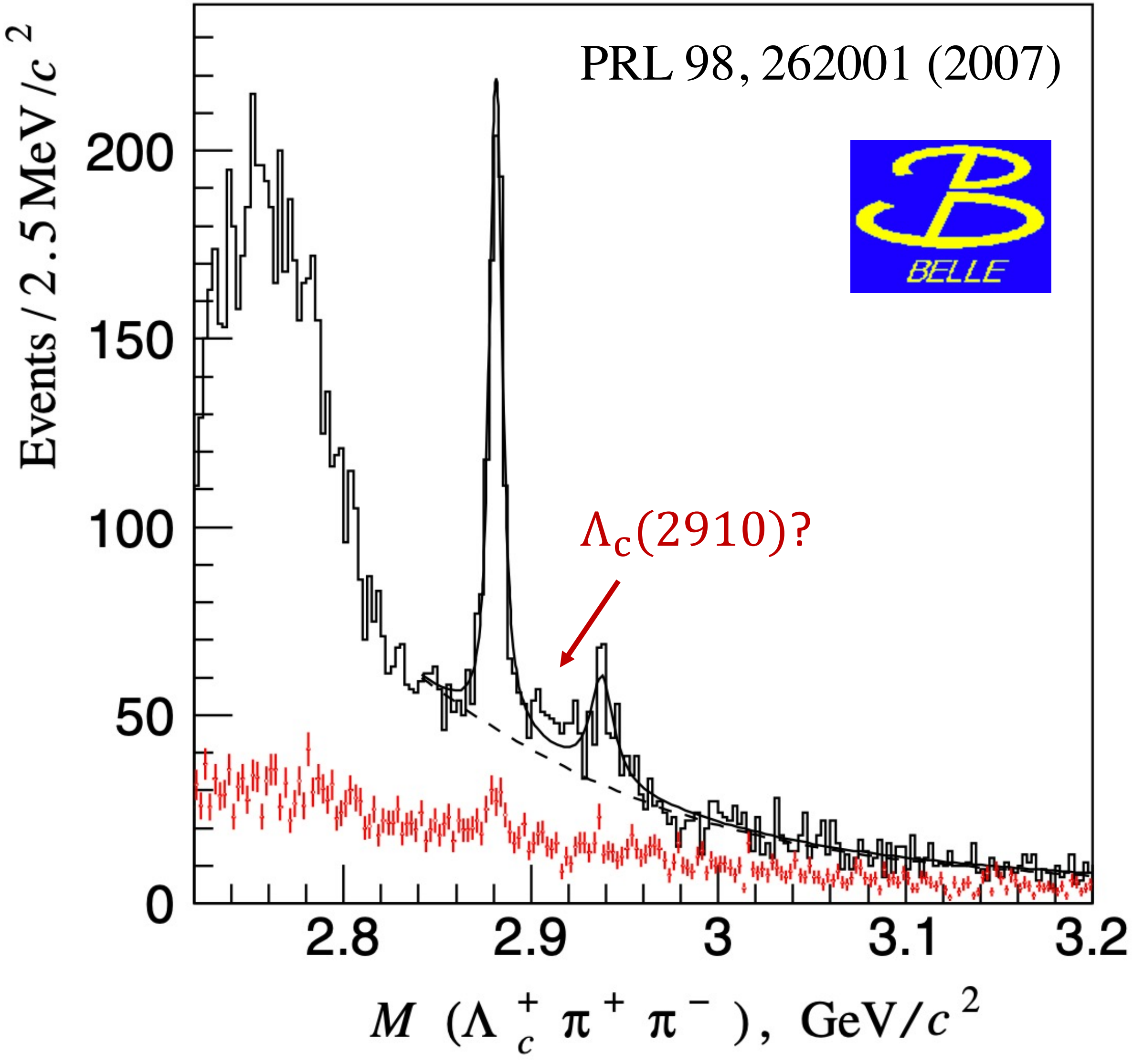
$$m = (2913.8 \pm 5.6 \pm 3.8)\ \mathrm{MeV}/c^2$$

$$\Gamma = (51.8 \pm 20.0 \pm 18.8)\ \mathrm{MeV}$$

- Statistic significance: 6.1σ
- Most conservative significance include syst. err.: 4.2σ
- Possible $J^p = \frac{1}{2}^-$, agrees with $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$, named: $\Lambda_c(2910)$
- Need more study to confirm its nature

Branching fraction	
$\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c(2910)^+\bar{p})\times$ $\mathcal{B}(\Lambda_c(2910)^+ \rightarrow \Sigma_c(2455)^0\pi^+)$	$(9.5\pm3.6\pm1.6)\times10^{-6}$
$\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c(2910)^+\bar{p})\times$ $\mathcal{B}(\Lambda_c(2910)^+ \rightarrow \Sigma_c(2455)^{++}\pi^-)$	$(1.24\pm0.35\pm0.10)\times10^{-5}$

$e^+e^- \to \Sigma_c(2455)\,(\to \Lambda_c\pi)\pi$ + anything



Searching for the $\Lambda_c(2910)$ in different production mechanisms can further confirm its existence.

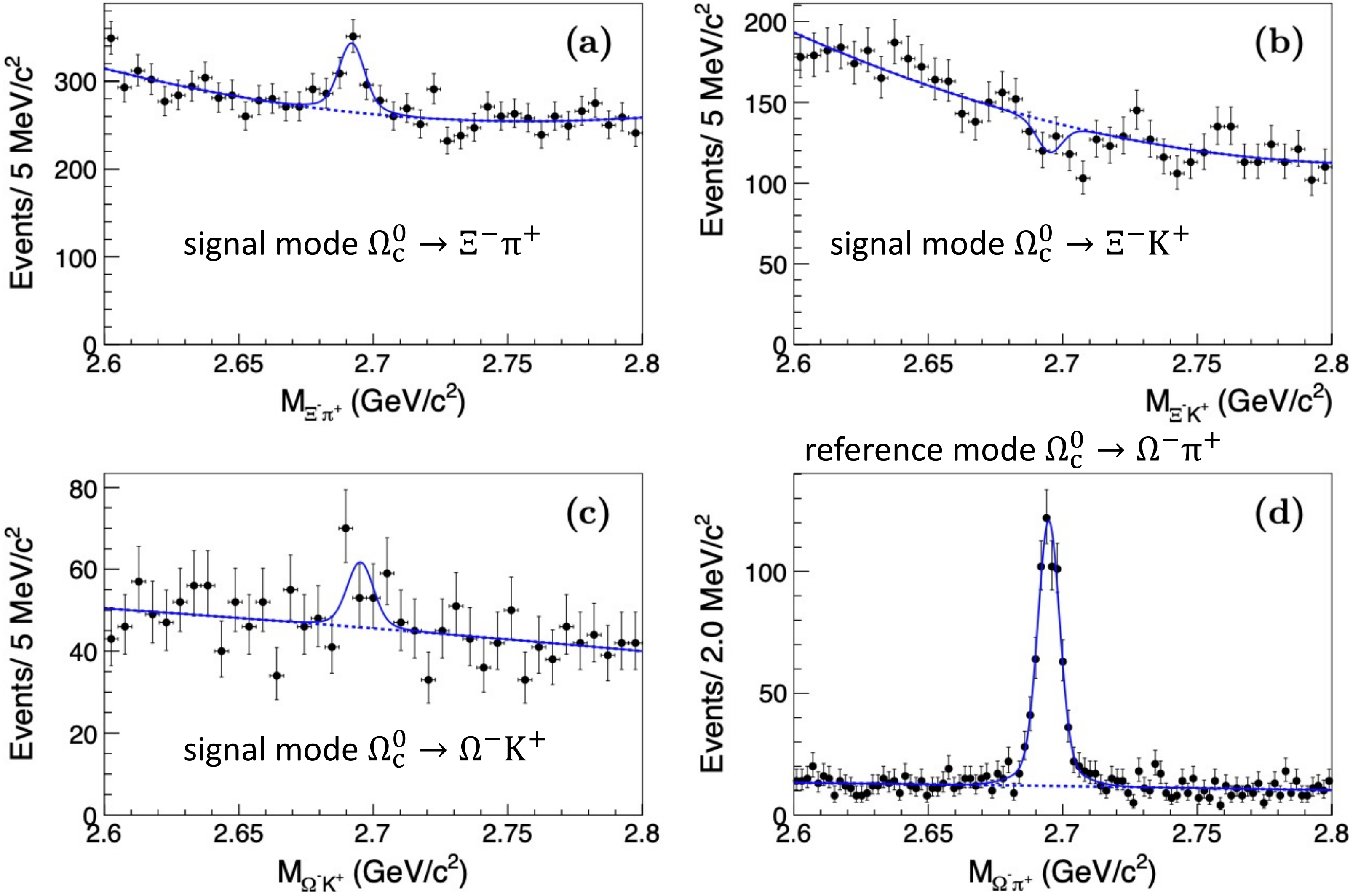
We will combine Belle and Belle II data and include more Λ_c decays modes to search for the $\Lambda_c(2910)$ in e^+e^- inclusive decays.

Evidence for $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-K^+$ and Ω^-K^+ decays

- The theoretical study of hadronic weak decays of the Ω_c^0 has a long history. But due to the low production rate of Ω_c^0 and low detection efficiency for long-lived final states, our knowledge of the Ω_c^0 state is very limited.
- The singly Cabibbo-suppressed decay $\Omega_c^0 \to \Xi^-\pi^+$ and doubly Cabibbo-suppressed decay $\Omega_c^0 \to \Xi^-K^+$ decays have been studied systematically in various theoretical models. While, no experimental information are available for these decays.

Predicted ratios of branching fractions for using light-front quark model (LFQM), pole model, and current algebra (CA).

Branching fraction ratios	LFQM CPC 42, 093101 (2018)	Pole model and CA PRD 101, 094033 (2020)
$\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$	1.96×10^{-3}	1.04×10^{-1}
$\mathcal{B}(\Omega_c^0 \to \Xi^-K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+)$	1.74×10^{-4}	1.06×10^{-2}



JHEP 01 (2023) 055

All Belle data, 980 fb^{-1}

The first evidence of $\Omega_c^0 \to \Xi^-\pi^+$ with a signal significance of 4.5σ including systematic uncertainties.

No significant signals are found in $\Omega_c^0 \to \Omega^-K^+$ and $\Omega_c^0 \to \Omega^-\pi^+$.

$\mathcal{B}(\Omega_c^0 \to \Xi^-\pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) = 0.253 \pm 0.053(\text{stat.}) \pm 0.030(\text{syst.})$
$\mathcal{B}(\Omega_c^0 \to \Xi^-K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.070$
$\mathcal{B}(\Omega_c^0 \to \Omega^-K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^-\pi^+) < 0.29$

Charm and Charmed Baryon Lifetimes at Belle II

Motivation and status

- Heavy Quark Expansion (HQE) predict beauty and charm hadron lifetimes
  - Charm lifetime measurements allow for HQE validation and refinement increasing reliability and precision of SM predictions in flavor dynamics
  - Charm hadron lifetime prediction is challenging: significant higher order correction + QCD contributions

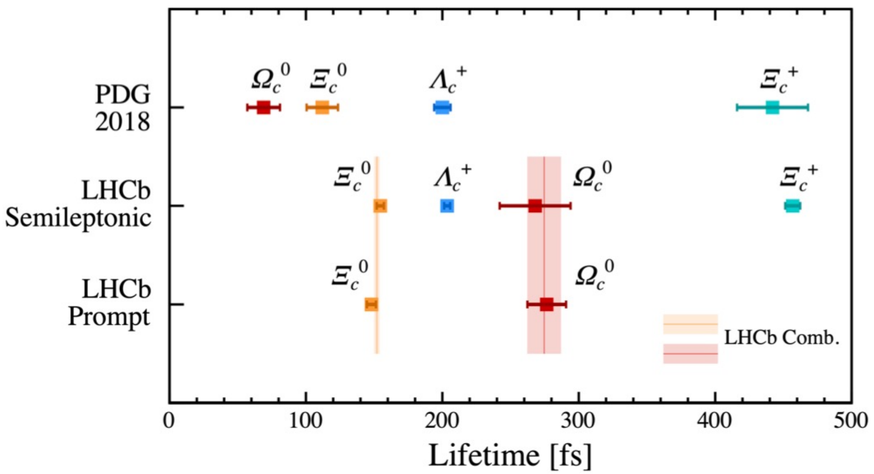
- The best measurements of charm-meson lifetimes date back to FOCUS; LHCb recently reported precise relative measurements of charm-baryon lifetimes

- The LHCb measurements changed the lifetime hierarchy of singly charmed baryons:

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \Rightarrow \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

- Possible reasons why HQE has initially failed are being debated (Science Bulletin 67 (2022) 445-447)

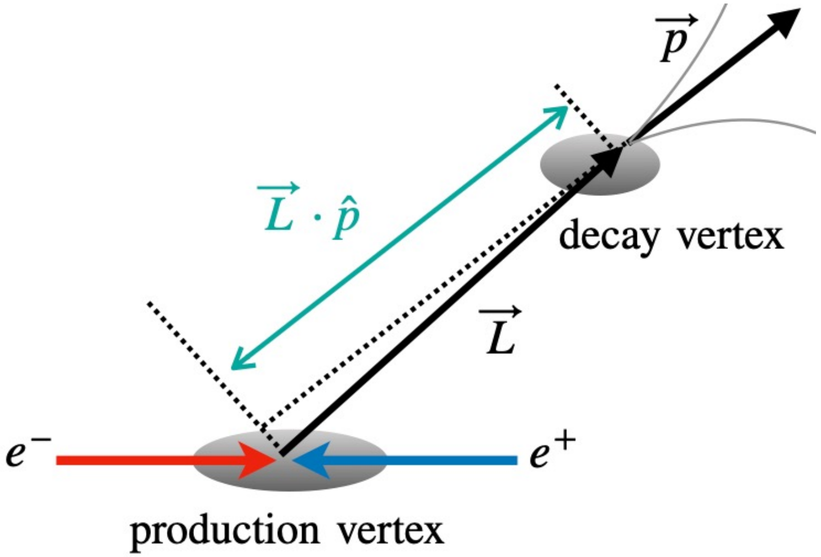
- No other experimental confirmation of the LHCb results



LHCb Semileptonic: PRL 121, 092003 (2018)
LHCb Prompt: Sci.Bull. 67 (2022) 479

Lifetime fit

- Proper decay time calculated from flight length between production and decay vertices and momentum as: $t = \frac{m}{p}(\vec{L}\,.\hat{p})$



- Lifetime (τ): unbinned maximum-likelihood fit to (t, σ)

- PDF Model:

$$\mathrm{PDF}(t,\sigma_t) = (1-\mathrm{f_b})\int_0^\infty e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}}\,|\,b, s\sigma_t)\,dt_{\mathrm{true}}\mathrm{PDF_{sig}}(\sigma_t) + \mathrm{f_b}\mathrm{PDF_{bkg}}(t,\sigma_t)$$

- b-bias
- s-scale
- R - resolution function
  - Gaussian: for D^+, Λ_c^+ and Ω_c^0
  - Double Gaussian: for D^0

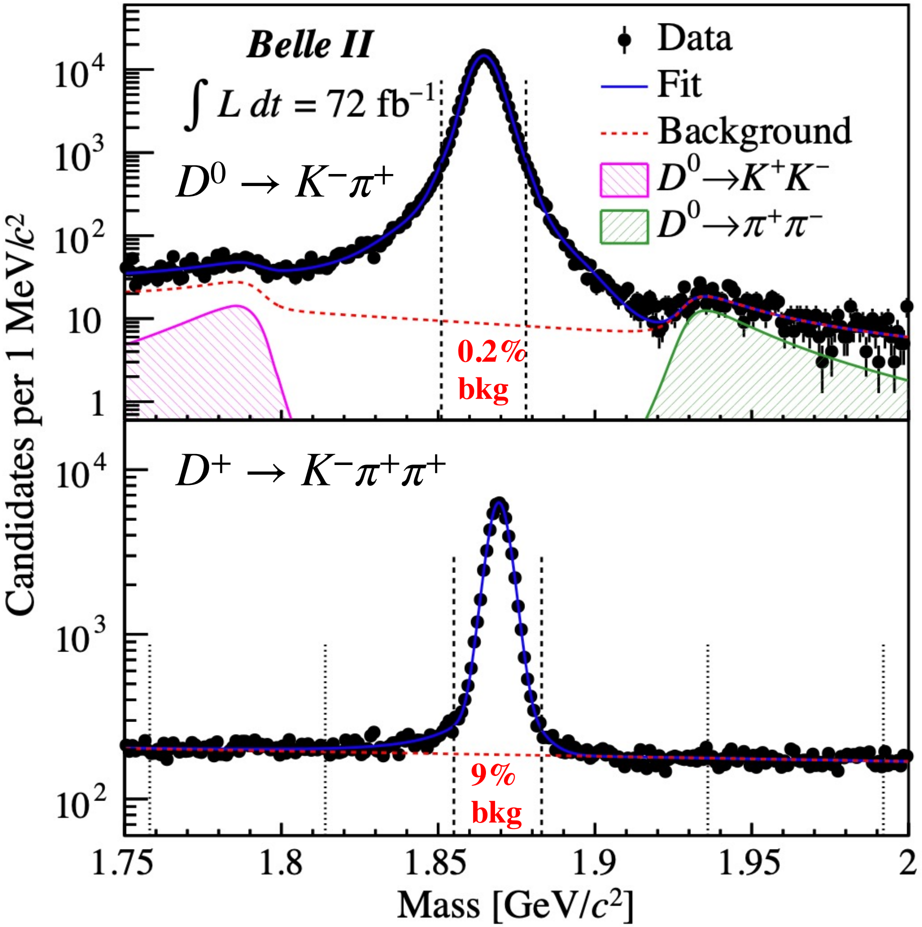
- Background PDF:

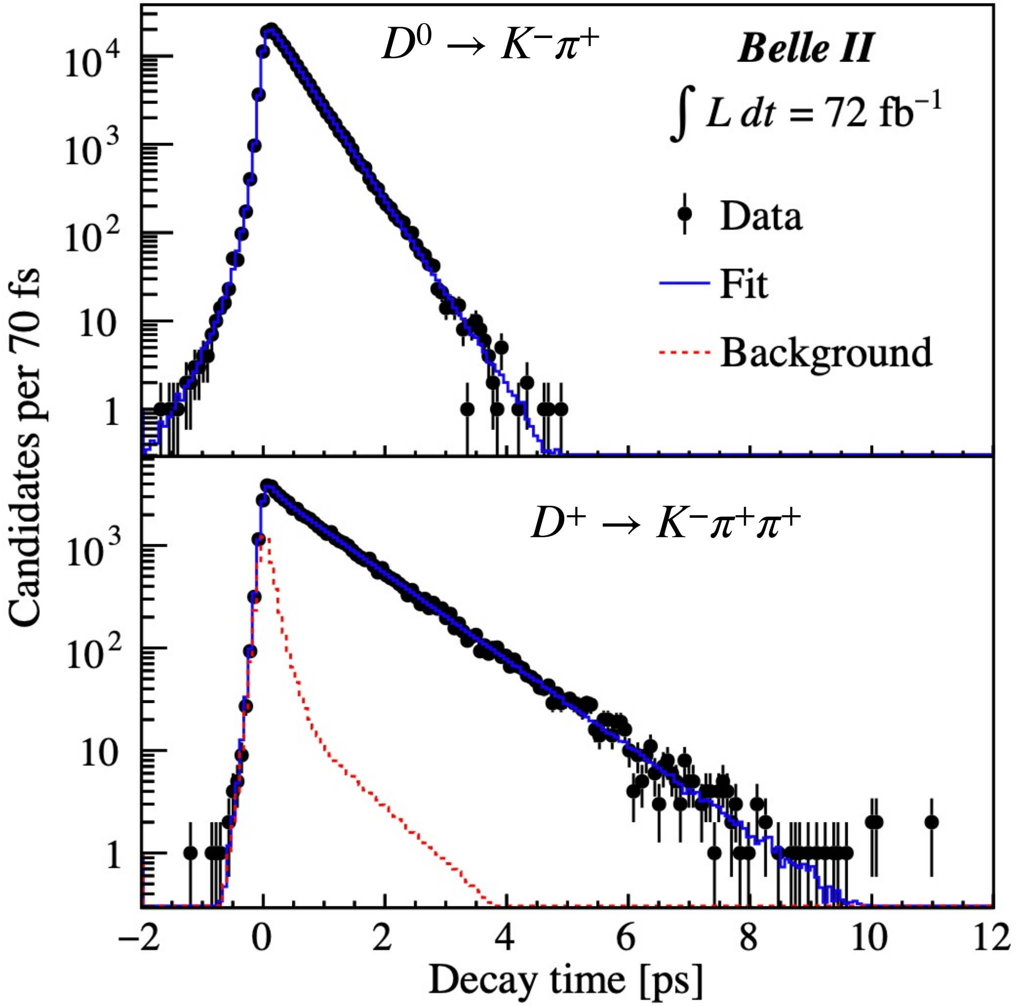
Empirical model of the sideband data, is the sum of two exponential functions convolved with Gaussian resolution functions.

D lifetime

[PRL 127, 211801 (2021)]

- Remove D from B decays with p*(D^{*+}) > 2.5(2.6) GeV/c for D^0(D^+)
- 171k and 59k signal candidates for $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ and $D^{*+} \to (D^+ \to K^-\pi^+\pi^+)\pi^0$ decays





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

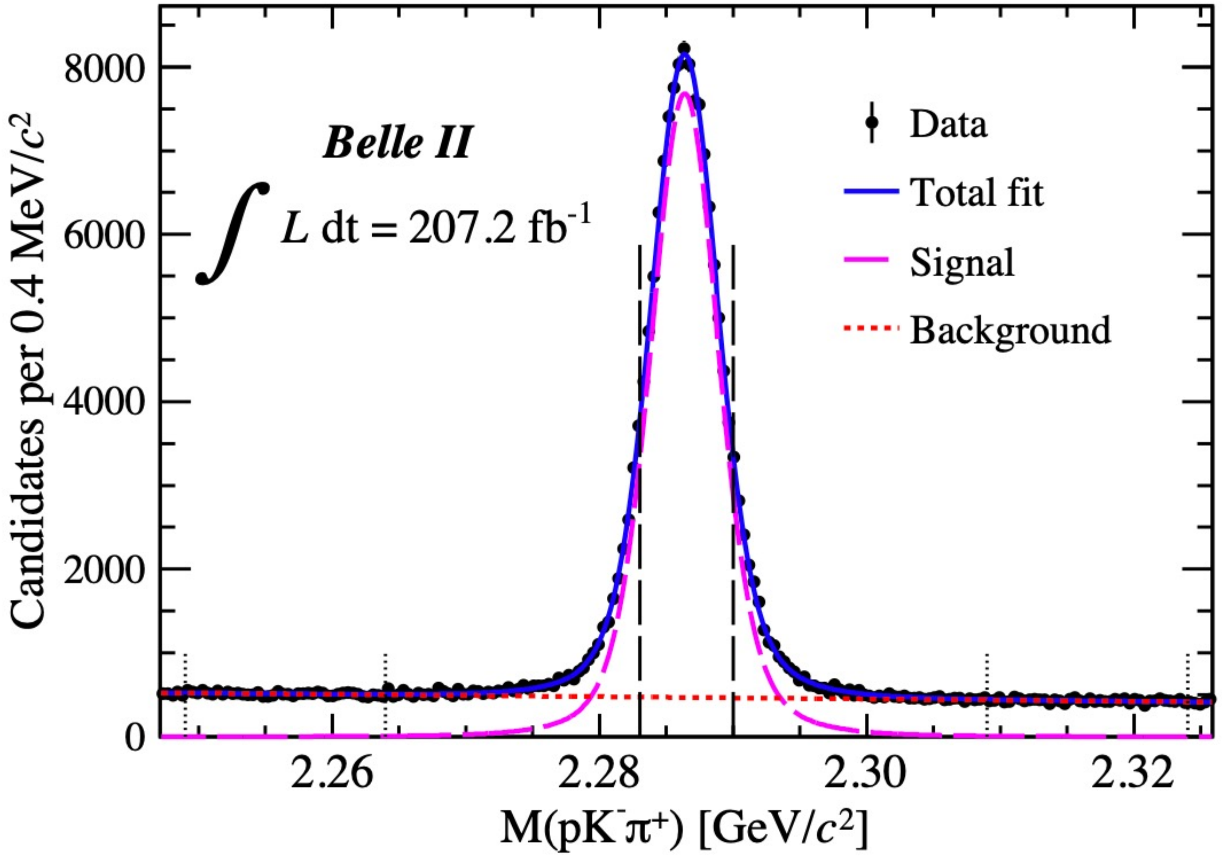
$$\tau(D^+) = 1030.4 \pm 4.7(\text{stat.}) \pm 3.1(\text{syst.})\ \text{fs}$$

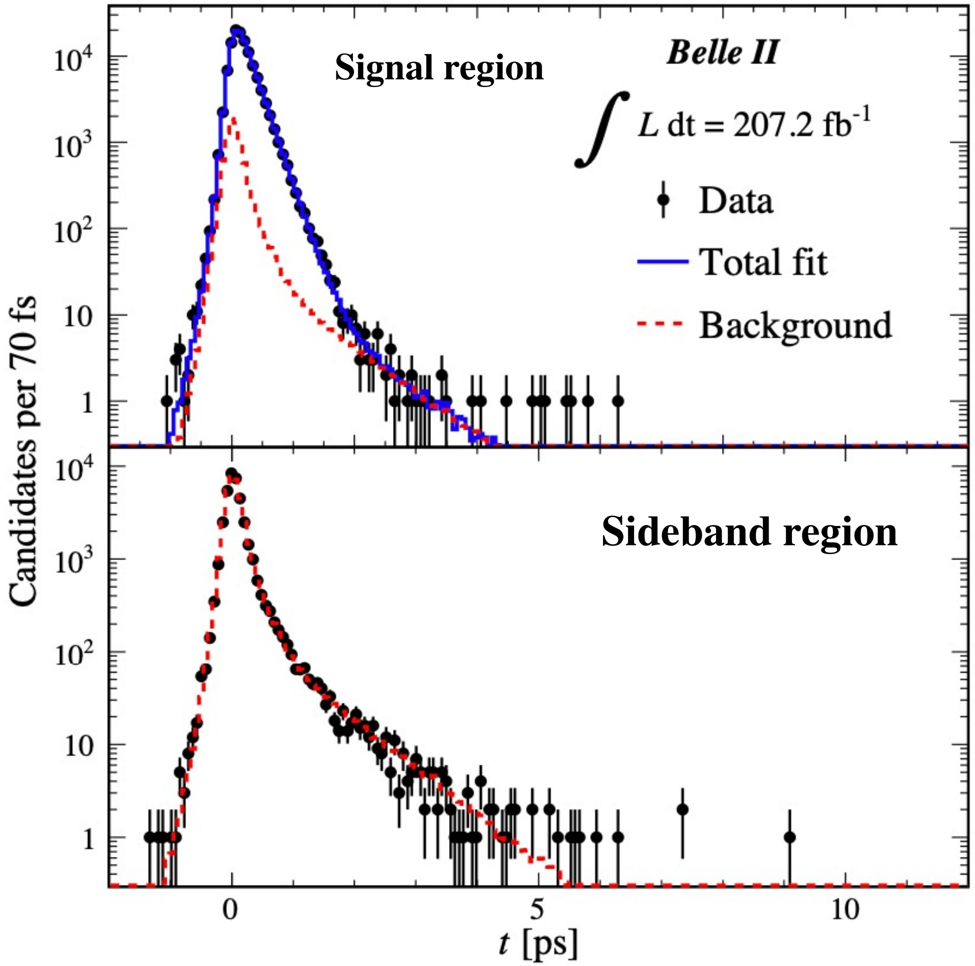
More precise than and consistent with previous measurements.

Λ_c^+ lifetime

[PRL 130, 071802 (2023)]

- Remove Λ_c^+ from B decays with $p^*(\Lambda_c^+) > 2.5$ GeV/c
- 116k $\Lambda_c^+ \rightarrow pK^-\pi^+$ signal with 7.5% background in the signal region
- Potential bias due to $\Xi_c^{0/+} \rightarrow \Lambda_c^+\pi^{-/0}$
  - veto applied and corrected for remaining contamination





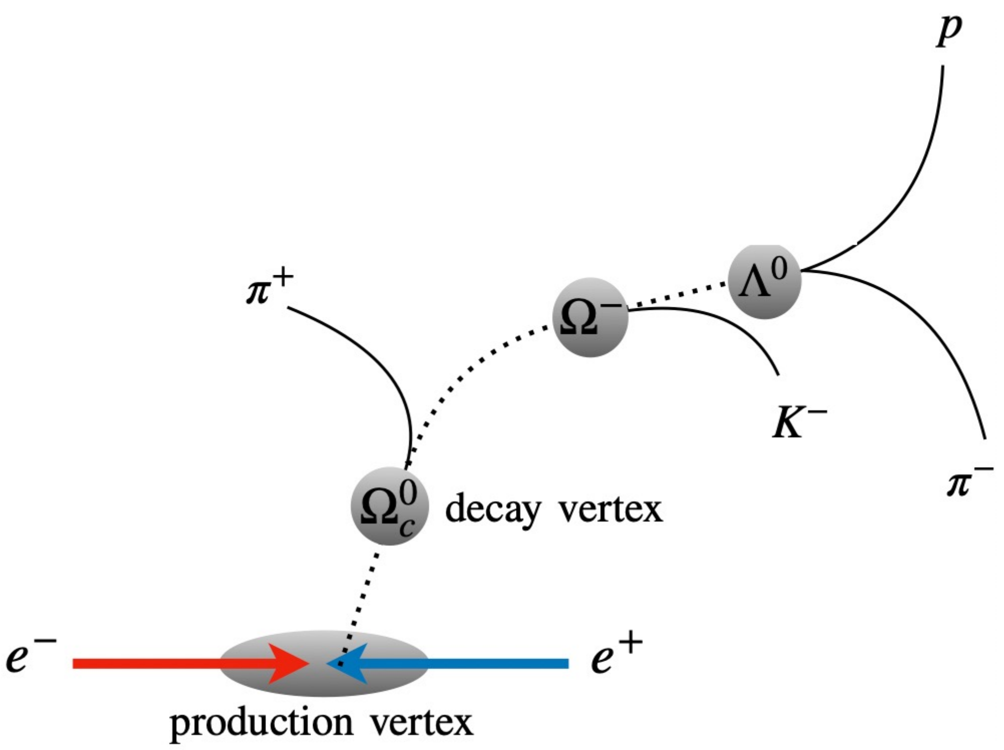
$$\tau(\Lambda_c^+) = 203.2 \pm 0.9(\text{stat.}) \pm 0.8(\text{syst.})\ \text{fs}$$

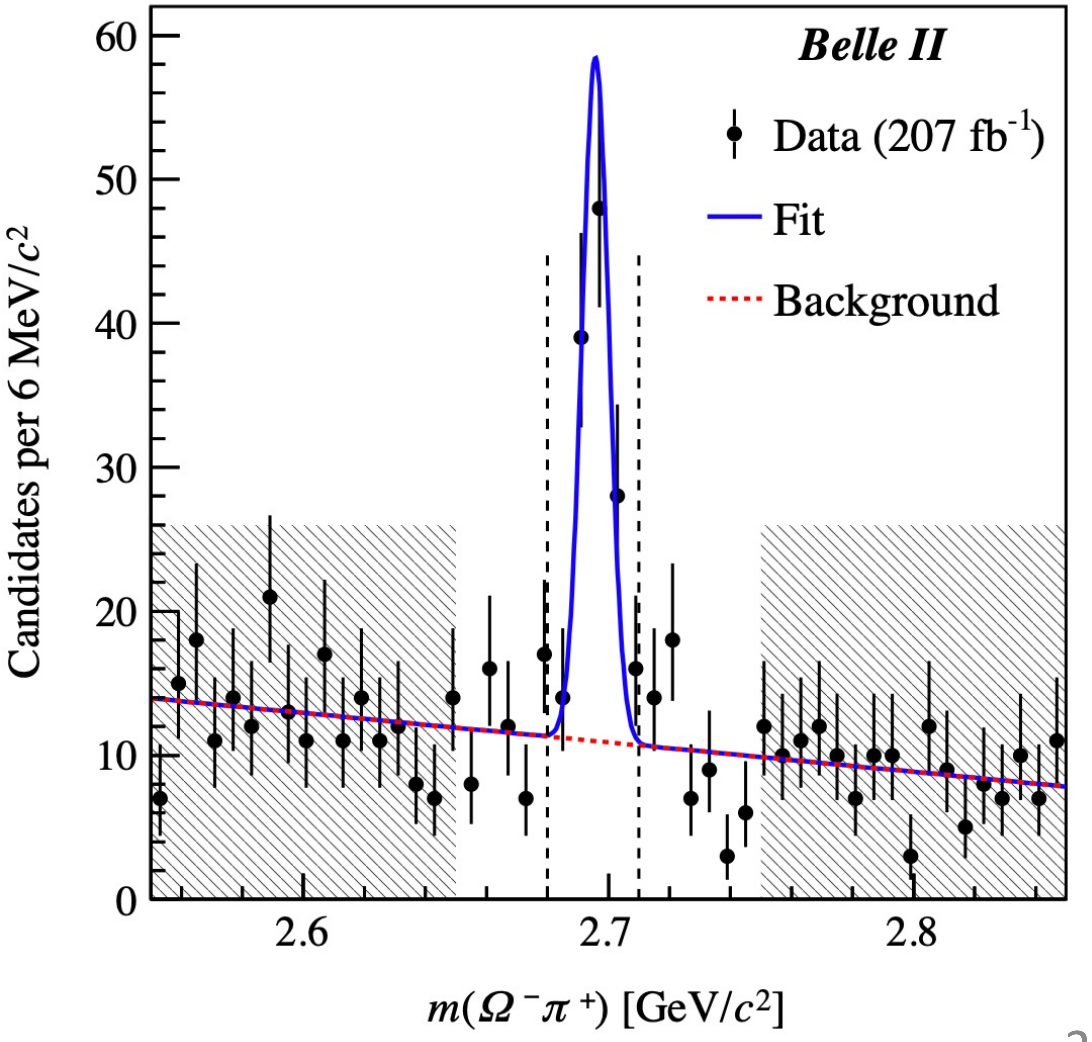
World's best measurement of the Λ_c^+ lifetime

Ω_c^0 lifetime

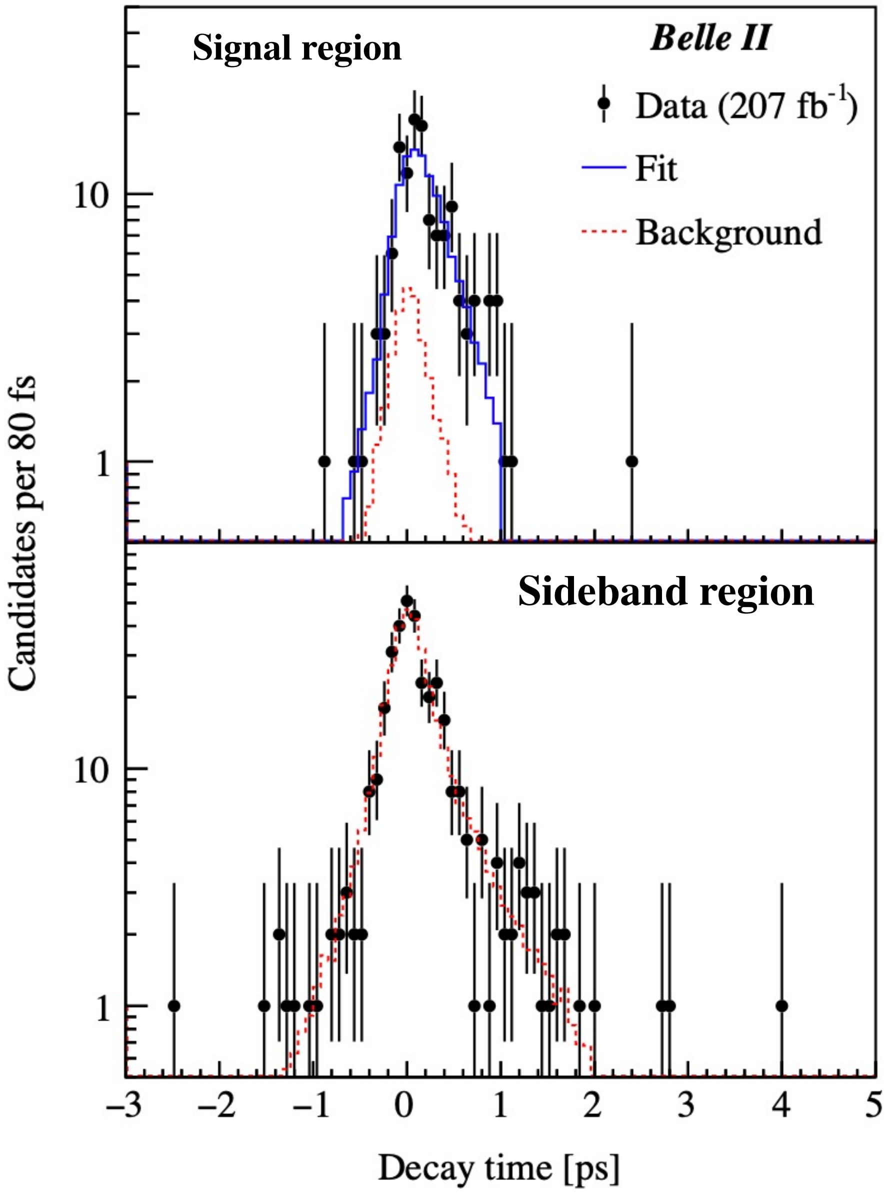
[PRD 107, L031103 (2023)]

- First Belle II lifetime measurement with complex decay topology
  - Two secondary decay vertices
- ~ 90 Ω_c^0 signal with 33% background in the signal region





Ω_c^0 lifetime



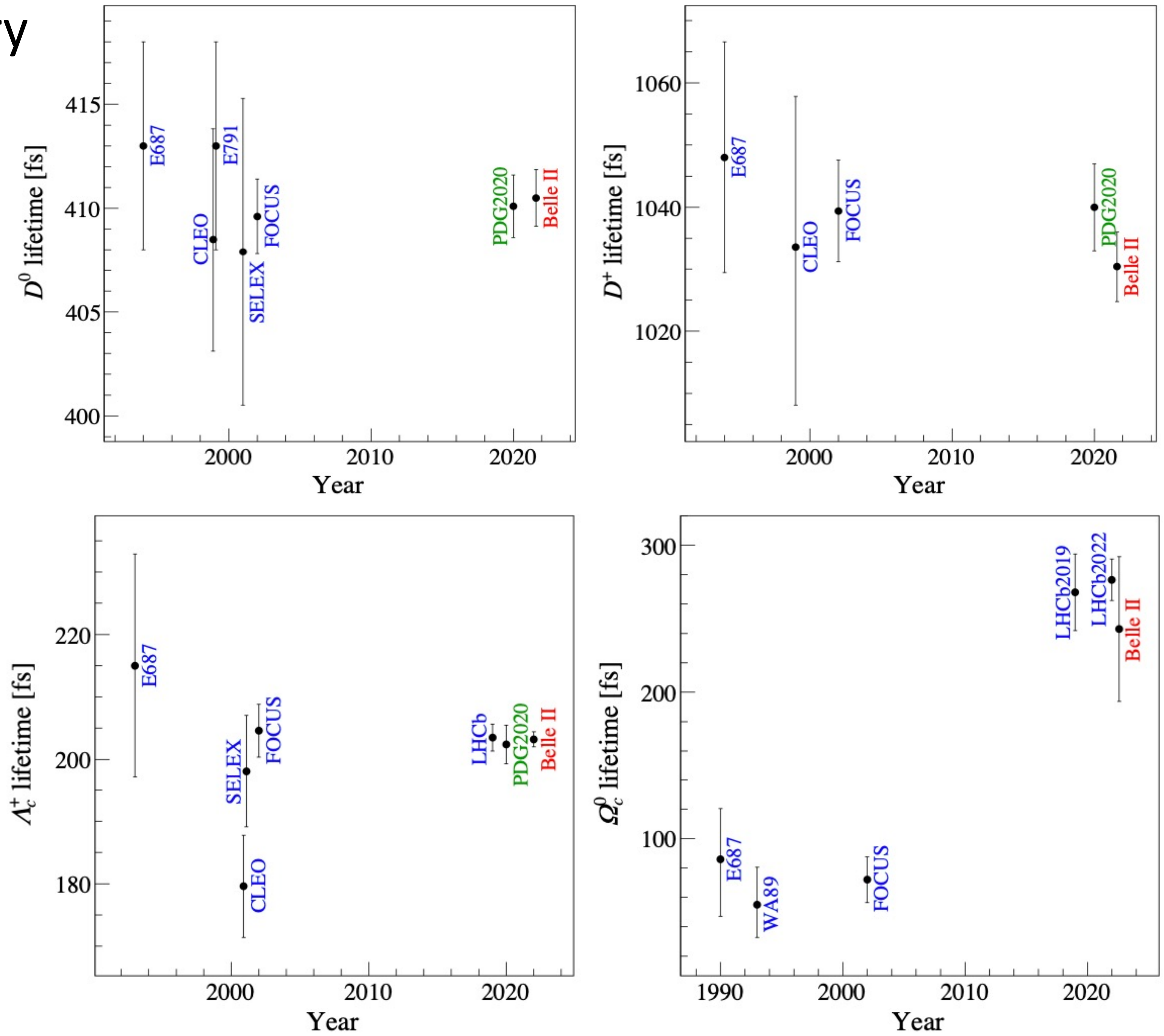
Dominant systematics: Modeling of background and resolution

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input charm masses	0.2
Total	11.0

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

- Ω_c^0 is not the shortest lived singly charmed baryon
  - consistent with LHCb average
- Domenstrate the capabilities of the Belle II detector for vertexing complex decay topologies
- Limited by statistics and can improve with larger samples and additional decay modes

A short summary



Summary

- **The first measurements of A_{CP}^{dir} and A_{CP}^{α} for singly Cabibbo-suppressed (SCS) decays of charmed baryons [$\Lambda_c^+ \to \Lambda K^+$ and $\Lambda_c^+ \to \Sigma^0 K^+$] at Belle.**

- **The observation of $\Lambda_c(2910)^+ \to \Sigma_c(2455)^{0/++}\pi^{\pm}$ at Belle**

- **The evidence for $\Omega_c^0 \to \Xi^- K^+$ at Belle**

- **Measurements of D, Λ_c^+, and Ω_c^0 lifetimes at Belle II**

SuperKEKB achieved world record peak luminosity: 4.7×10^{34} cm^{-2}s^{-1}
Belle II collected ~ 428 fb^{-1} of data

Stay tuned for more results!!

Thanks for your attentions!