Charmed Baryon Lifetimes at Belle II

Baryon 2022-International Conference on the Structure of Baryons

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Outline

- Physics Motivation & Current Status
- SuperKEKB & Belle II
- Λ_c^+ lifetime measurement
- Ω_c^0 lifetime measurement
- Summary

Physics Motivation

- Heavy Quark Expansion (HQE) is used to determine lifetimes of hadrons with heavy quarks.

- Non perturbative corrections and the presence of other light quarks in the hadron contribute to higher order terms.

- Measurements of charmed hadron lifetimes are sensitive to these higher-order contributions
  - Useful as tests of theoretical predictions.

- HQE provides the total decay rate of heavy hadrons as an expansion in $1/m_Q$(Q= quark).

- Using ratios of lifetimes, HQE can predict the lifetime hierarchy of beauty hadrons.

- This does not hold for charm hadrons, for which higher-order terms in $1/m_Q$ due to the spectators quarks, cannot be neglected and is required for theoretical predictions of charm baryon lifetimes. JHEP 07 (2022) 058, JHEP 11(2018)014.

Current Status

Λ_c^+ lifetime measurement:

- The lifetime of Λ_c^+ as measured by the LHCb in 2019: 203.5 ± 1.0 ± 1.3 ± 1.4 (due to D^+ lifetime) fs, Phys. Rev. D 100 (2019), 032001 .
    - Recent charmed meson lifetime measurement by Belle II (Phys. Rev. Lett. 127 (2021), 211801), this uncertainty and the central value will be reduced.

Ω_c^0 lifetime measurement:

- Earlier hierarchy (HQE prediction):

$$\cancel{\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \underline{\tau(\Omega_c^0)}}$$

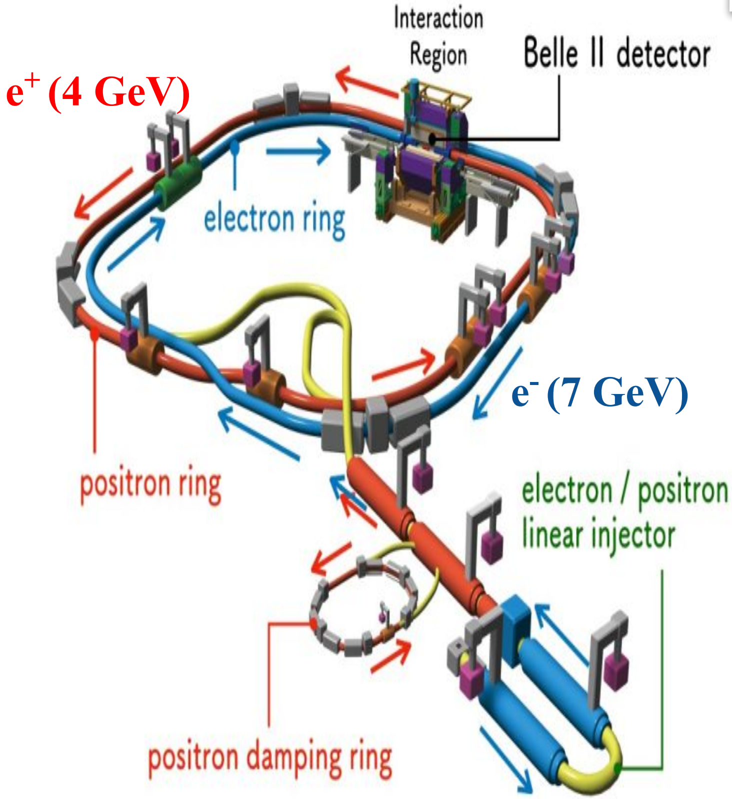
In 2018, LHCb results have turned around the lifetime hierarchy which had been unchallenged for many years using $\mathbf{\Omega_c^0} \rightarrow \boldsymbol{pK^-K^+\pi^-}$ coming from semileptonic b-hadron decays Phys. Rev. Lett. 121 (2018), 092003.

$$\tau(\Xi_c^+) > \underline{\tau(\Omega_c^0)} > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$$

- Belle II, although with lesser statistics as compared to LHCb, further confirms the LHCb result.

Experimental Facility @ Tsukuba, Japan

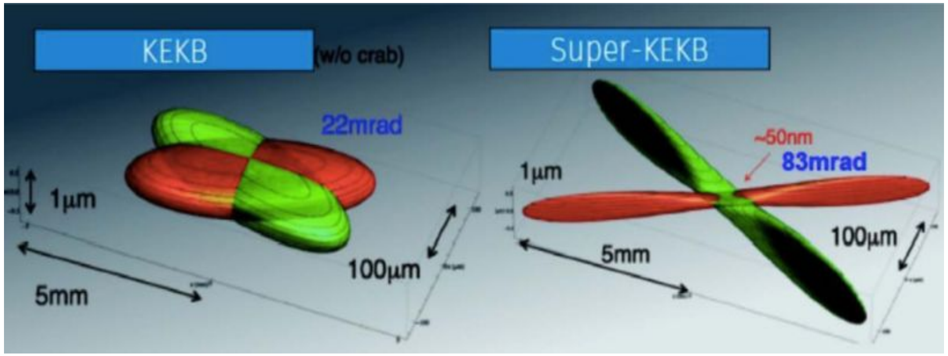
SuperKEKB



Design luminosity: 6.5 x 10^{35} $cm^{-2}s^{-1}$

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

- Nano beams with the help of super-conducting final focus quadrupoles.



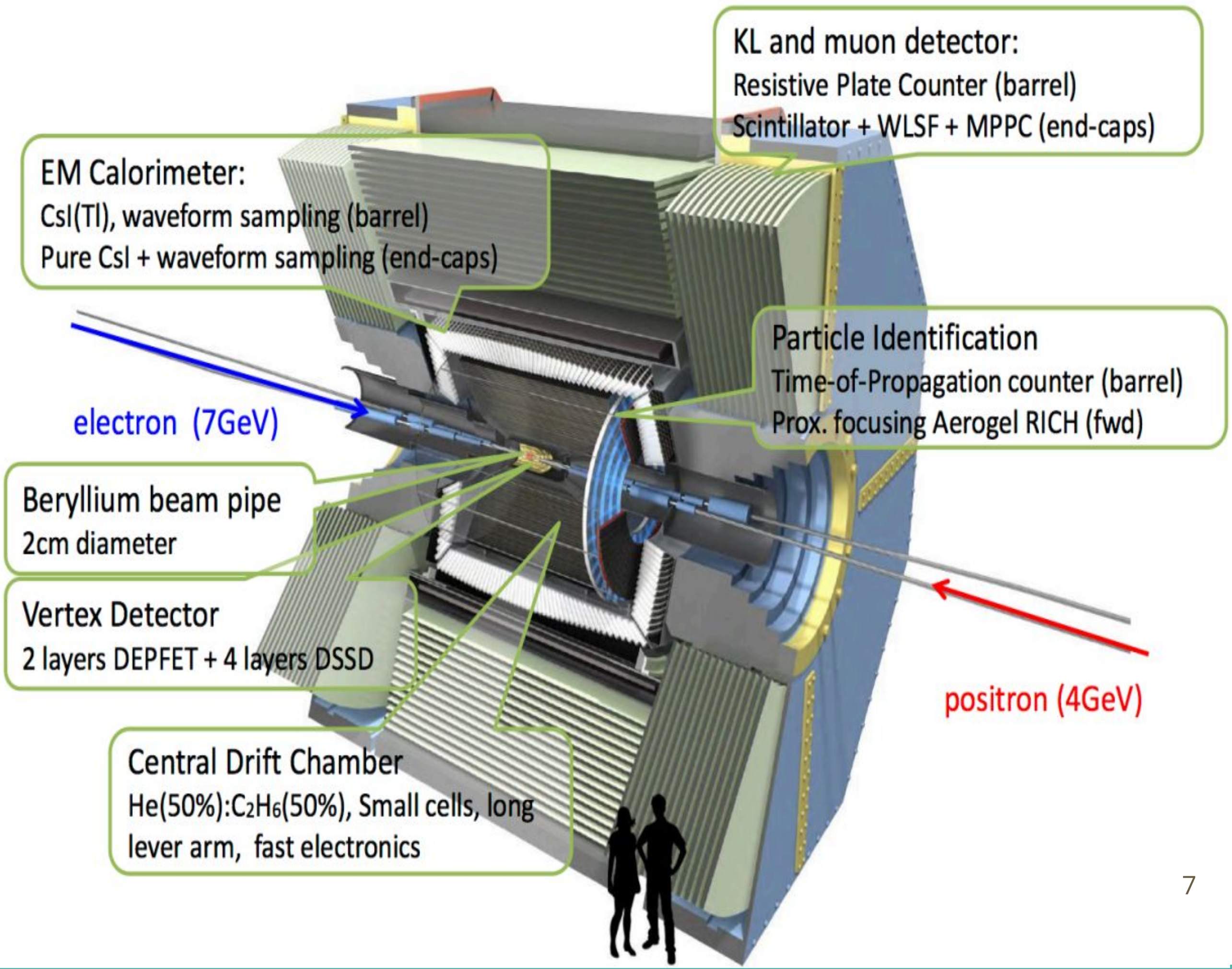
- Luminous region dimensions (x/y/z) at:
  Belle II: 10/0.2/250 μm
  Belle : 100/1/6,000 μm

- Beam spot ***y*** size is expected to be decreased to ~60 nm.

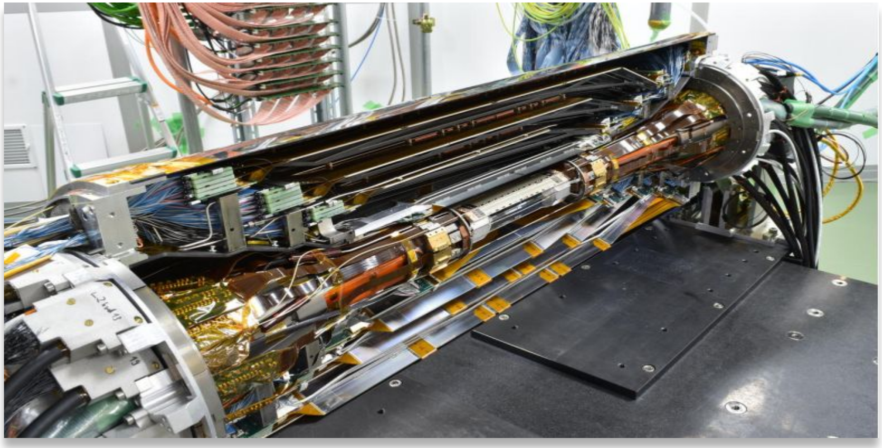
Belle II Detector

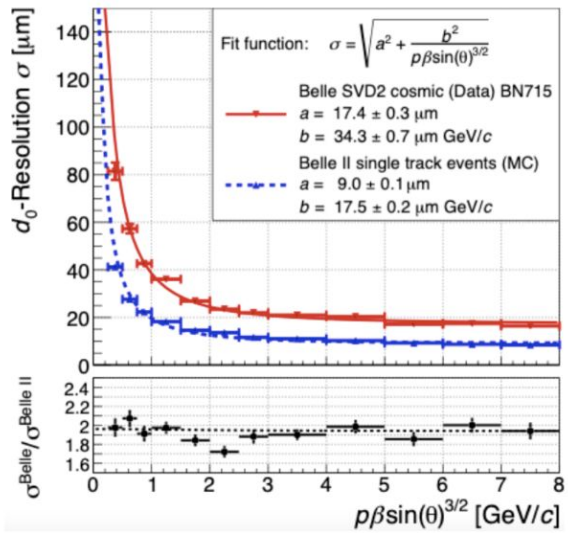
Target data set: 50 ab^{-1}

Collected (till date): ~ 428 fb^{-1}



Belle II Vertex Detector (VXD)

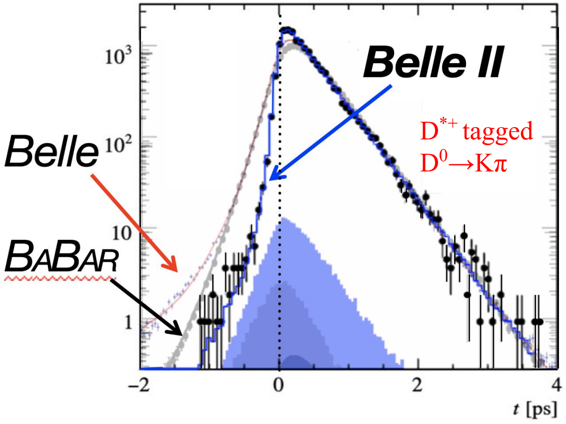




- The VXD is made up of:
  - Pixel Detector (PXD): 2 Layers of DEPFET
  - Silicon Vertex Detector (SVD): 4 Layers of Double Sided Silicon Strip Detector

- First layer of PXD is at 1.4 cm from interaction point. 2nd layer of PXD is not complete. It had 15% azimuthal coverage during the collection of the data used here.

- 2x better impact parameter resolution; shows up in the decay time distribution of D^0 meson.

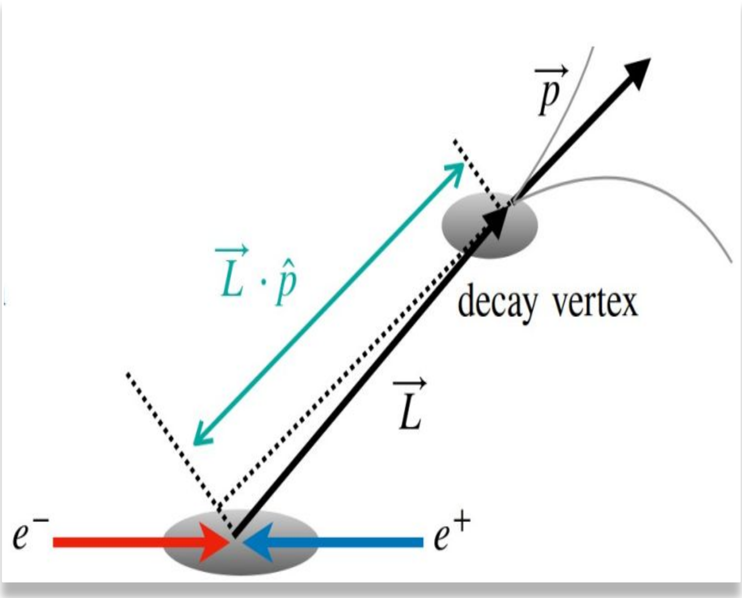


Measurement of Λ_c^+ Lifetime

Procedure to measure Λ_c^+ Lifetime

- Promptly produced Λ_c^+ candidates from continuum $e^+e^- \to c\bar{c}$ events.
- $\Lambda_c^+ \to \mathbf{pK^-\pi^+}$ are reconstructed. Charge conjugate decays are always implied.
- Decay time (**t**) is calculated using the displacement of the Λ_c^+ decay vertex from the e^+e^- interaction point (**L**), projected along the direction of the momentum (**p**) of the Λ_c^+, while **m** is its mass.

$$t = \frac{m}{p}(\vec{L} \cdot \hat{p})$$



- The position and size of the interaction region is determined using $e^+e^- \to \mu^+\mu^-$ events.
- For the Λ_c^+ candidates, the VXD provides a decay-length resolution of **40 µm**, corresponding to an average decay time resolution of **87 fs** for an average decay length of **96 µm** .
- σ_t is the uncertainty on *t,* is also an important variable in the following analyses.

Selection Criteria

- 207 fb^{-1} of collision data is used.
- For particle identification, efficiency is from the studies of $\Lambda^0 \to p\pi^-$ and D^{*+}tagged $D^0 \to K^-\pi^+$ decays.
- Λ_c^+ from B decays are removed with $p_{cms}(\Lambda_c^+) > 2.5$ GeV/c .
- Misidentified charm-meson decays $\mathbf{D^{*+}(D^+) \to \pi^+ K^- \pi^+}$ are suppressed by a veto on $M(\pi^+K^-\pi^+)$.
- Other charm-related backgrounds are suppressed using $p_T(\pi^+/p) > 0.35/0.7$ GeV/c .
- Candidate $\mathbf{\Lambda_c^+}$ from $\mathbf{\Xi_c^{0/+} \to \Lambda_c^+ \pi^{-/0}}$ can bias measurements as their production vertices shifted away from the interaction point (IP).
  - Such events are removed by a veto on the invariant mass of $\mathbf{\Xi_c^{0/+}}$.
  - About 61% of $\mathbf{\Xi_c^{0/+}}$ decays still remain according to Monte Carlo (MC) study.
  - Systematic added.

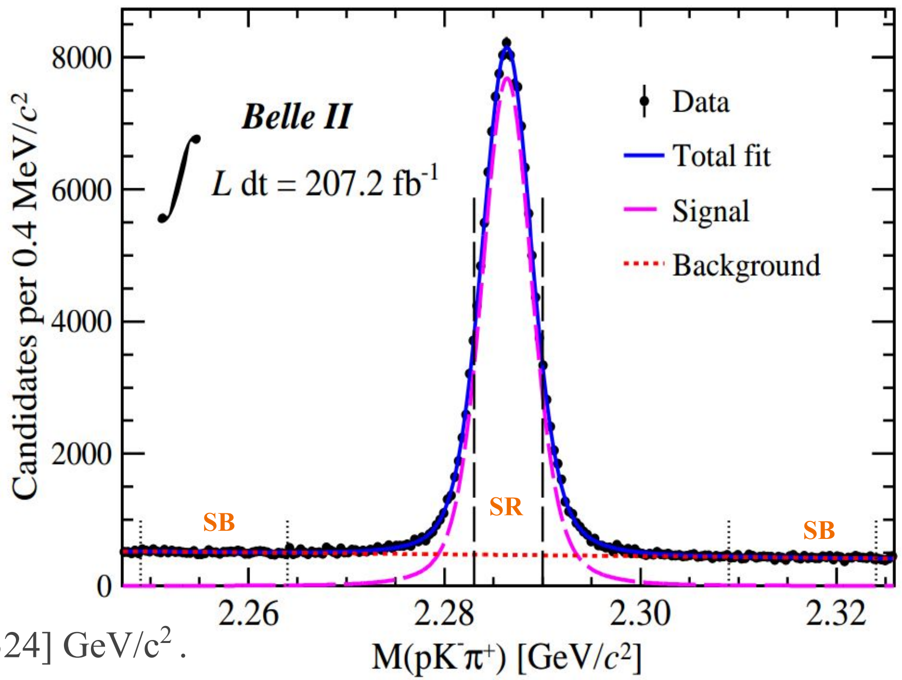
Signal yield

- Selection criteria and the fit strategy are optimized and validated using MC, no input is used therefrom to fit the collision data.

- Binned least squares fit to $M(pK^-\pi^+)$.

- Probability Density Function (PDF) Model:
  - Signal: Johnson's S_U + Gaussian, with common mode
  - Background: Linear function

- For $M(pK^-\pi^+)$:
  - Signal Range: [2.283, 2.290] GeV/c^2.
  - Side Bands: [2.249, 2.264] GeV/c^2 and [2.309, 2.324] GeV/c^2 .



- Signal Candidates: 116K with 7.5% background in the signal region.

- Λ_c^+ lifetime is extracted from fit to ($\mathbf{t}$, $\boldsymbol{\sigma}_\mathbf{t}$).

Fit to (t, σ_t)

- Unbinned ML fit to (***t*** , $\boldsymbol{\sigma_t}$) for candidates in the signal region.

- PDF Model:

  - Signal PDF :

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

f is the fraction of events in the Gaussian, and **b** is a mean parameter for a possible bias in **t**. **R** is the resolution function as:

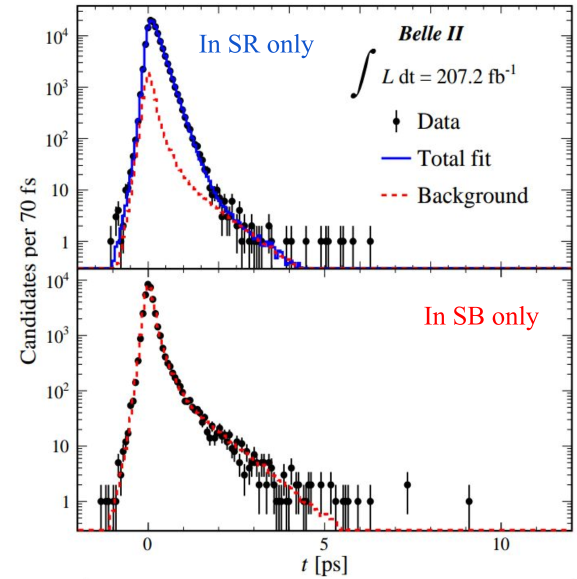
$$R(t - t_{true}|\sigma_t, f, b, s_1, s_2) = f\ G(t - t_{true}|b, s_1\sigma_t) + (1 - f)G(t - t_{true}|b, s_2\sigma_t)$$

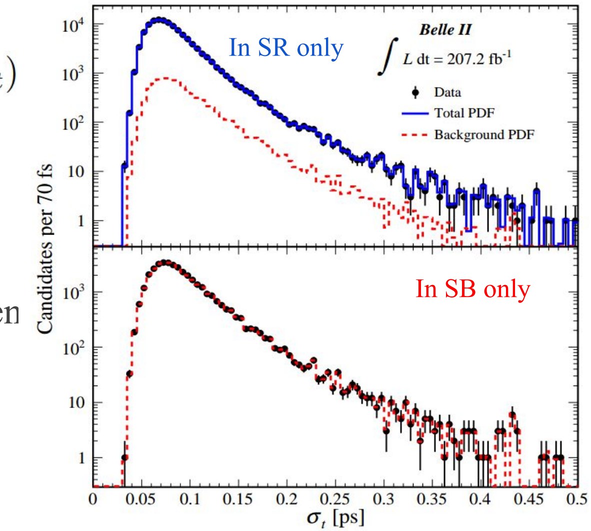
$s_1\sigma_t$ and $s_2\sigma_t$ are the Gaussian widths.

  - Background PDF:

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

    - A simultaneous fit to the events in the signal region and sidebands is also performed.





Systematic Uncertainties

Source	Uncertainty [fs]
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

Major sources of systematic error:

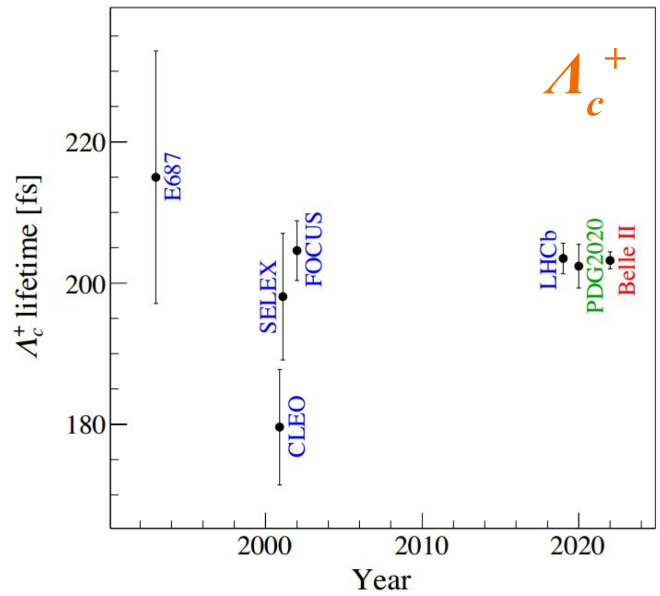
- $\Xi_c^{0/+}$ *contamination*
- *Resolution Model:* Correlations between the decay time and the decay-time uncertainty are neglected.
- *Background model:* Sideband data that differ from the background in the signal region. Systematic is estimated using the differences in data-MC.
- *Alignment of the detector:* Periodic calibrations are necessary to account for detector misalignment. Misalignment can can bias the measurement of the decay lengths.

Results

$\tau(\Lambda_c^+)$ = 203.20 ± 0.89 (stat)± 0.77 (syst) fs

https://arxiv.org/abs/2206.15227
(accepted by Physical Review Letters)

- Most precise measurement to date.
- Consistent with current world averages *PTEP 2020, 083C01 (2020)*.
- Slight tension with CLEO measurement remains *Phys. Rev. Lett. 86, 2232(2001)*.
- Benchmark for future baryon lifetime measurements.



Measurement of Ω_c^0 Lifetime

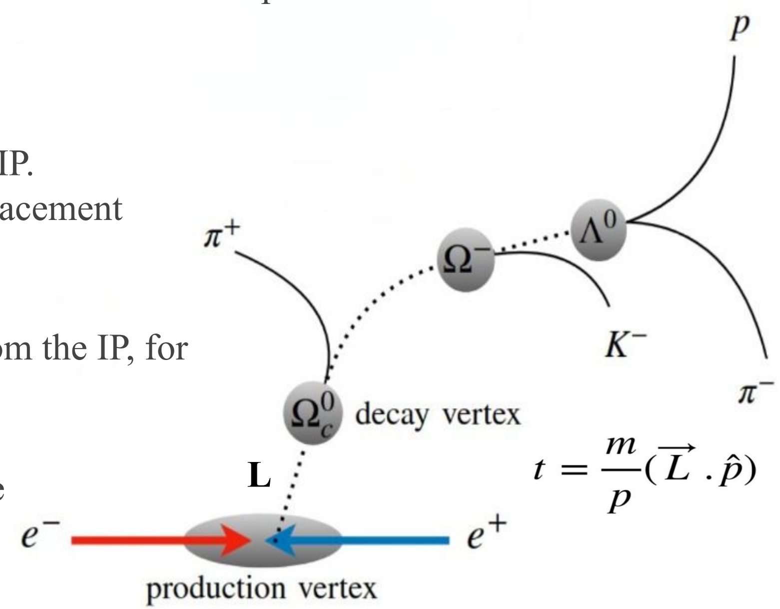
Sample and Selection

(3) $\Omega_c^0 \to \Omega^-\pi^+$

(2) $\Omega^- \to \Lambda^0 K^-$

(1) $\Lambda^0 \to p\pi^-$

- 207 fb^{-1} of collision data is used. $\mathbf{\Omega_c^0 \to \Omega^- \pi^+}$ decay is considered.
- Complex topology of reconstructed decay chain with two secondary vertices.
- $\mathbf{\Lambda^0 \to p\pi^-}$ are reconstructed using oppositely charged tracks one of which must be a proton. Decay vertex of the $\mathbf{\Lambda^0}$ must be at least 0.35 cm from IP.
- Λ^0 are combined with $\mathbf{K^-}$ for which $p_T > 0.15$ GeV/c, forming $\mathbf{\Omega^-}$.
  Ω^- decay vertex lies between Λ^0 and IP and at least 0.5 mm from IP.
  For Ω^- and Λ^0 , angle between their respective momenta and displacement from IP is less than 90^o .
- $\mathbf{\Omega_c^0 \to \Omega^- \pi^+}$ are formed by combining positively charged track from the IP, for which momenta is at least 0.5 GeV/c.
- $\mathbf{\Omega_c^0}$ from B are removed by requesting its scaled momentum to be larger than 0.6 GeV/c. Scaled momentum is defined as:



$$t = \frac{m}{p}(\vec{L} \cdot \hat{p})$$

$$p_{\mathrm{cms}}/\sqrt{s/4 - m(\Omega^-\pi^+)^2}$$

where $\boldsymbol{p_{cms}}$ is the momentum of the Ω_c^0 , $\boldsymbol{s}$ is the squared center-of-mass energy, and $m(\Omega^-\pi^+)$ is the reconstructed Ω_c^0 mass.

Signal yield

- Unbinned maximum likelihood fit to m($\Omega^{-}\pi^{+}$).

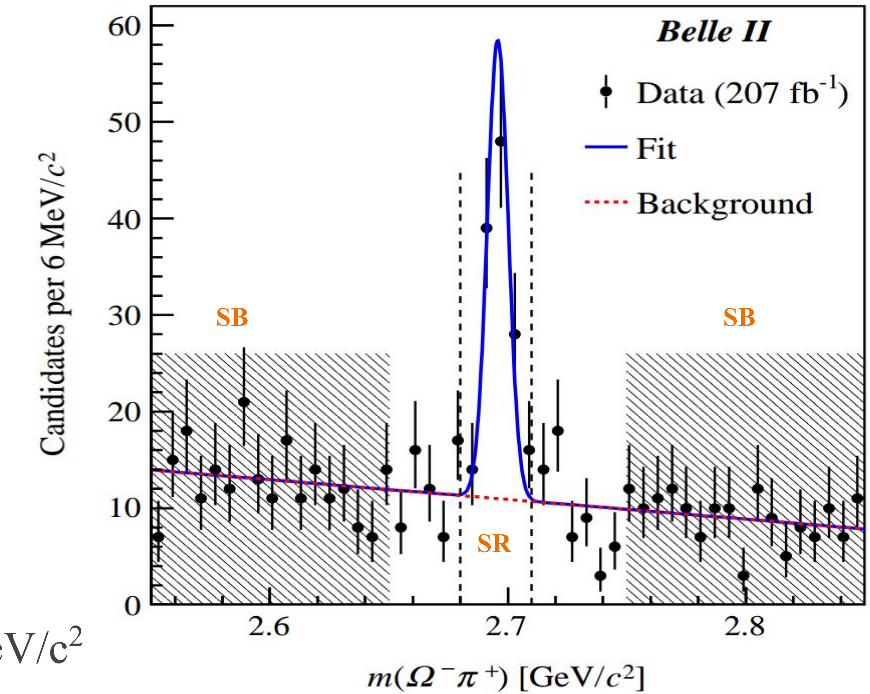
- PDF Model:
  - Signal: Gaussian
  - Background: Linear function

- Signal Candidates: 132 with 33% background contamination in the signal region.

- Signal Purity: (66.5 ± 3.3)%

- For M($\Omega^{-}\pi^{+}$):
  - Signal Range: [2.68, 2.71] GeV/c^2.
  - Side Bands: [2.55, 2.65] ∪ [2.75, 2.85] GeV/c^2

- Ω_c^0 lifetime is extracted from fit to ($\mathbf{t}$, $\boldsymbol{\sigma}_{\mathbf{t}}$).



Fit to (t, σ_t)

- Unbinned ML fit to ($\boldsymbol{t}$, $\boldsymbol{\sigma_t}$) for candidates in the Ω_c^0 signal region.

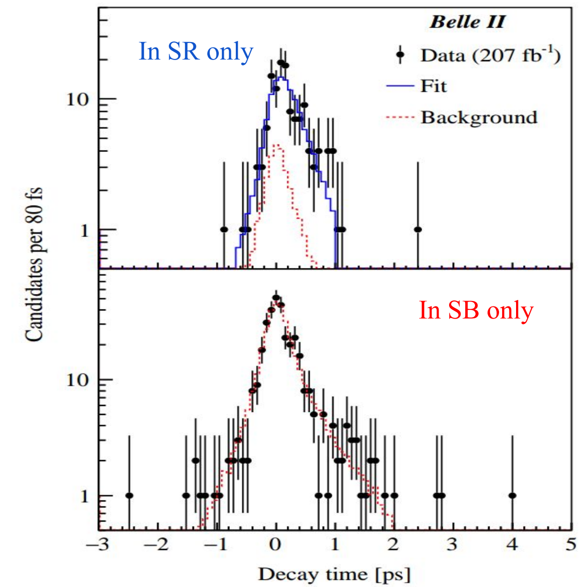
- PDF Model:
  - Signal PDF :

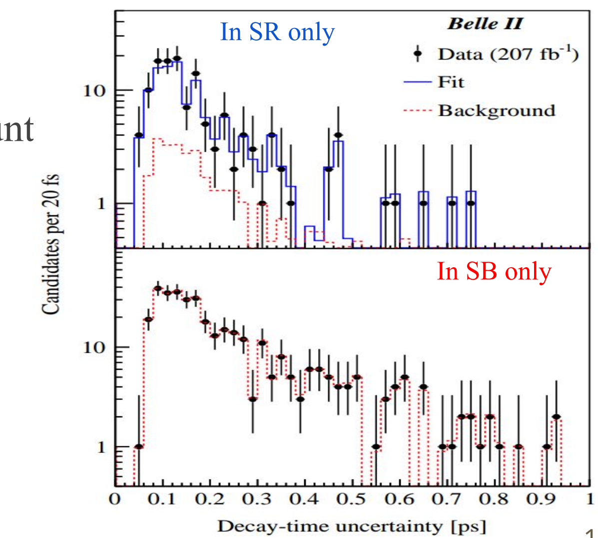
$$P_s(t, \sigma_t | \tau, b, s) = P_s(t | \sigma_t, \tau, b, s)\, P_s(\sigma_t)$$
$$\propto \int_0^{\infty} e^{-t'/\tau} G(t - t' | b, s\sigma_t) dt'\, P_s(\sigma_t)$$

    Mean of the resolution function mean **b** is a free parameter of to account for possible bias in decay time.

    Width is the per-candidate $\boldsymbol{\sigma_t}$ scaled by a free parameter **s** to account for a possible misestimation of the decay-time uncertainty

  - Background PDF:
    - SB events are assumed to represent background in signal region.
    - A simultaneous fit to the events in the signal region and sidebands is also performed.





Systematic Uncertainties

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input Ω_c^0 mass	0.2
Total	11.0

Major sources of systematic error are:

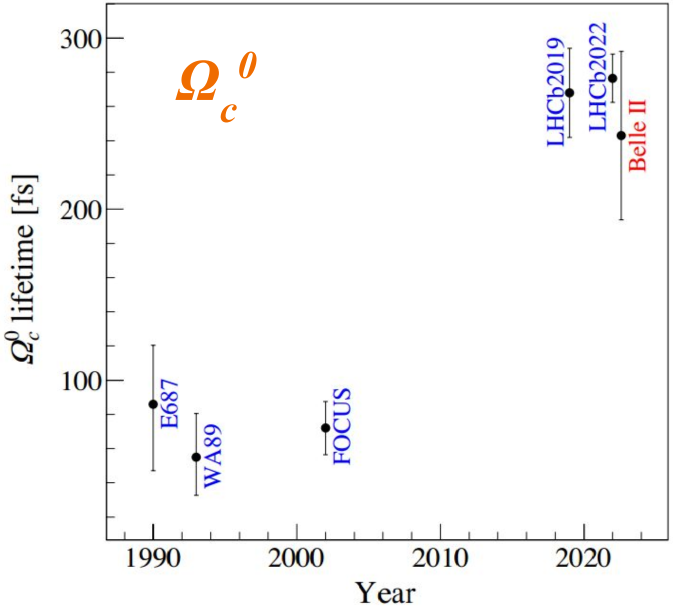
- *Background model:* Sideband data that differ from the background in the signal region. Systematic is estimated using the differences in data-MC.
- *Resolution model:* Simulation shows that the resolution function has tails that are inconsistent with a Gaussian model.
- *Fit Bias:* Due to small sample size.

Results

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

[*https://arxiv.org/abs/2208.08573*](https://arxiv.org/abs/2208.08573)
(accepted by Physical Review D Letters)

- Belle II confirms that Ω_c^0 is not the shortest lived singly charmed baryon.
- Benchmark for decays with complex topologies.



Summary

- SuperKEKB achieved world record peak luminosity: 4.7 x 10^{34} $cm^{-2}s^{-1}$.
- Belle II collected ~ 428 fb^{-1} of data.
- World's best Λ_c^+ lifetime measurement:

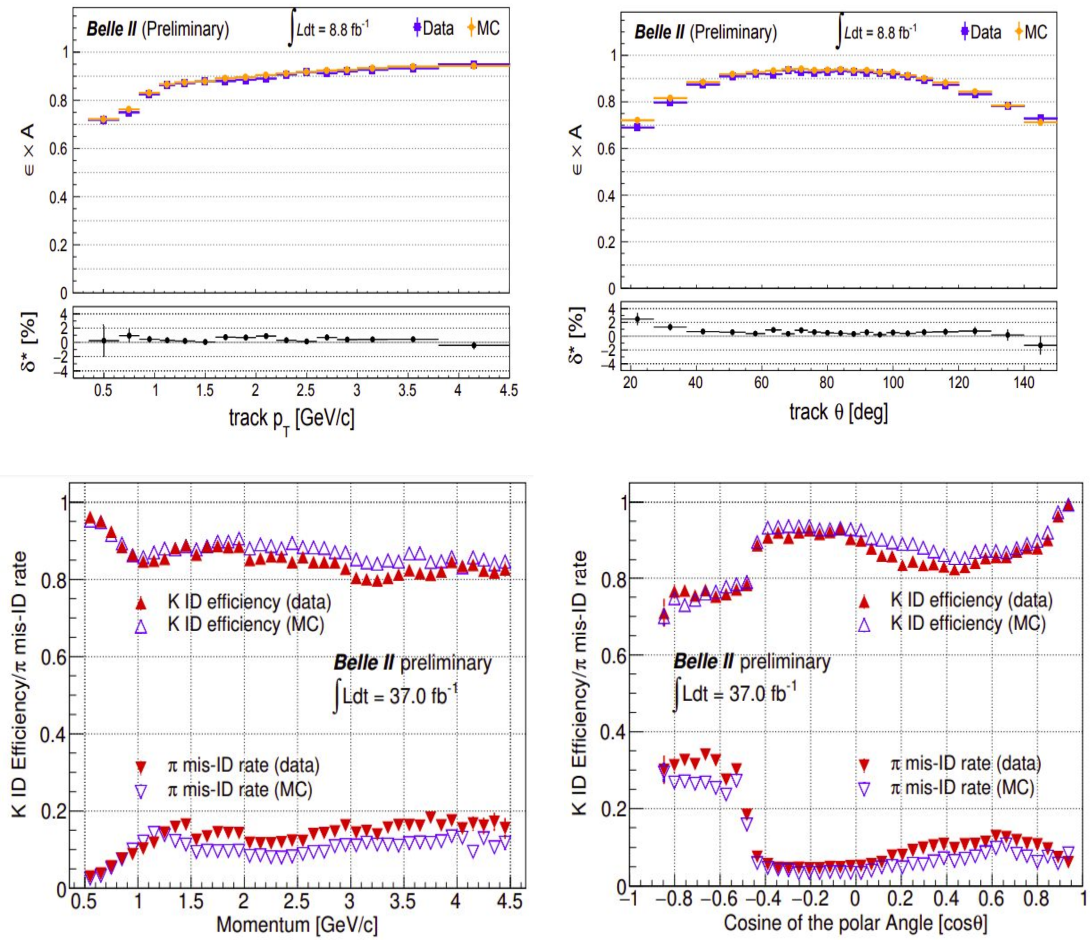
  $\tau(\Lambda_c^+) = 203.20 \pm 0.89$ (stat)$\pm$ 0.77 (syst) fs
- Consistent with current world averages.
- Belle II independently confirms that Ω_c^0 is not the shortest lived, weakly decaying singly charmed baryon.

  $\tau(\Omega_c^0) = 243 \pm 48$ (stat) $\pm$ 11 (syst) fs
- Inconsistent with with pre-LHCb world average at 3.4σ.

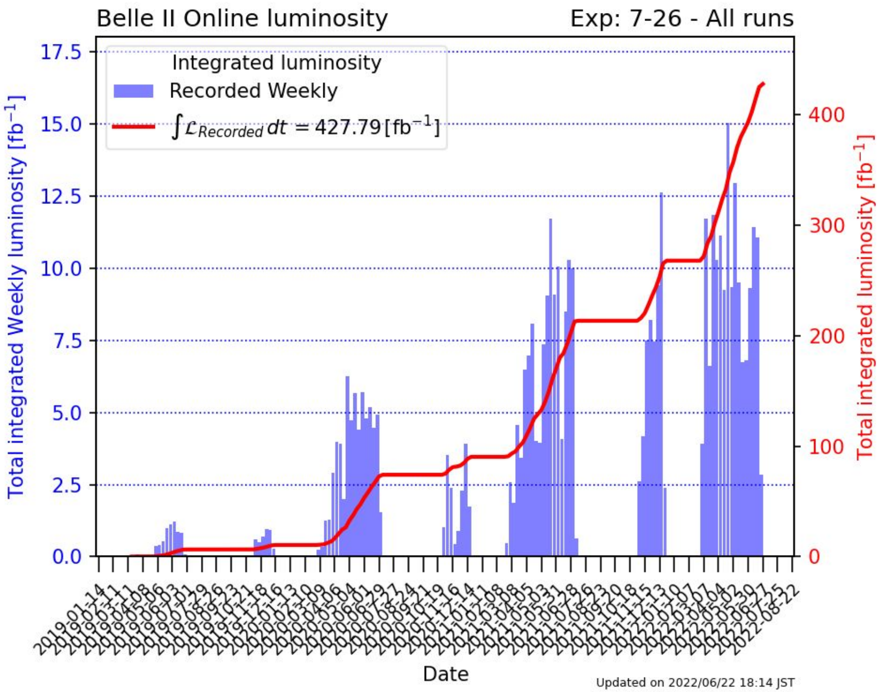
Stay tuned for more results!!

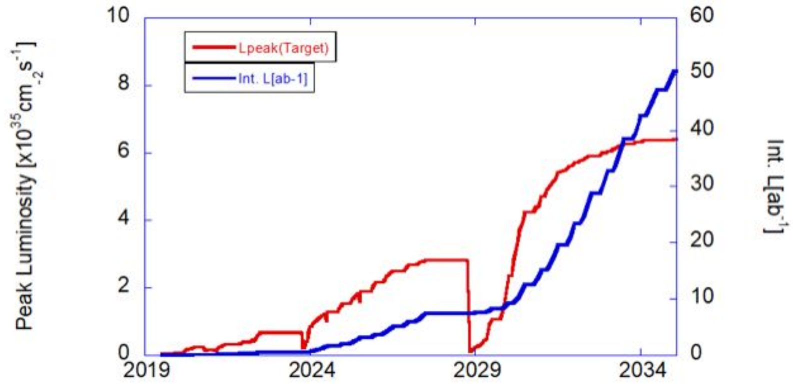
Backup Slides

Belle II Performance



Current Status of Data Taking

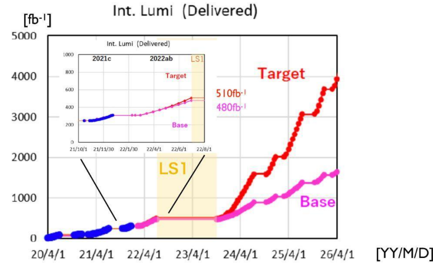




Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027