Belle II Perspectives for Baryon Physics

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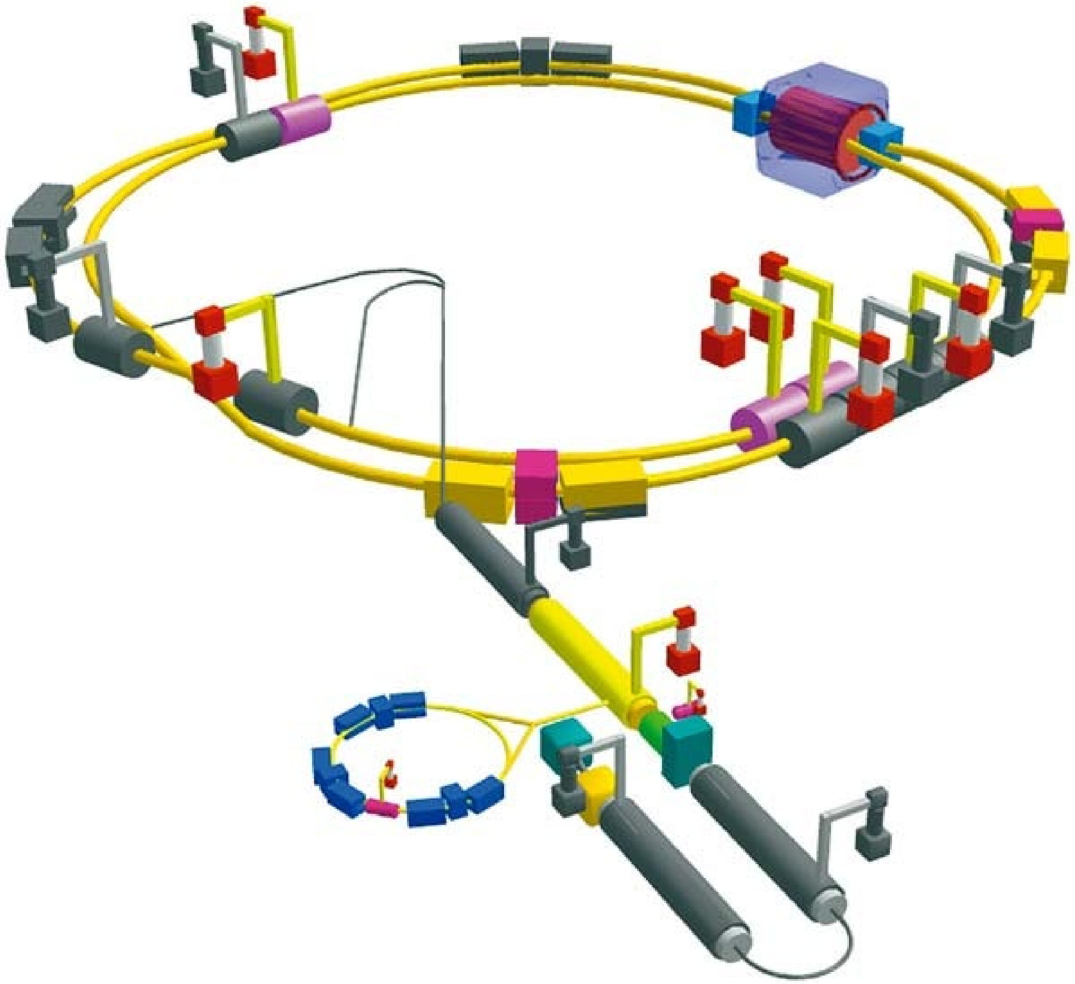
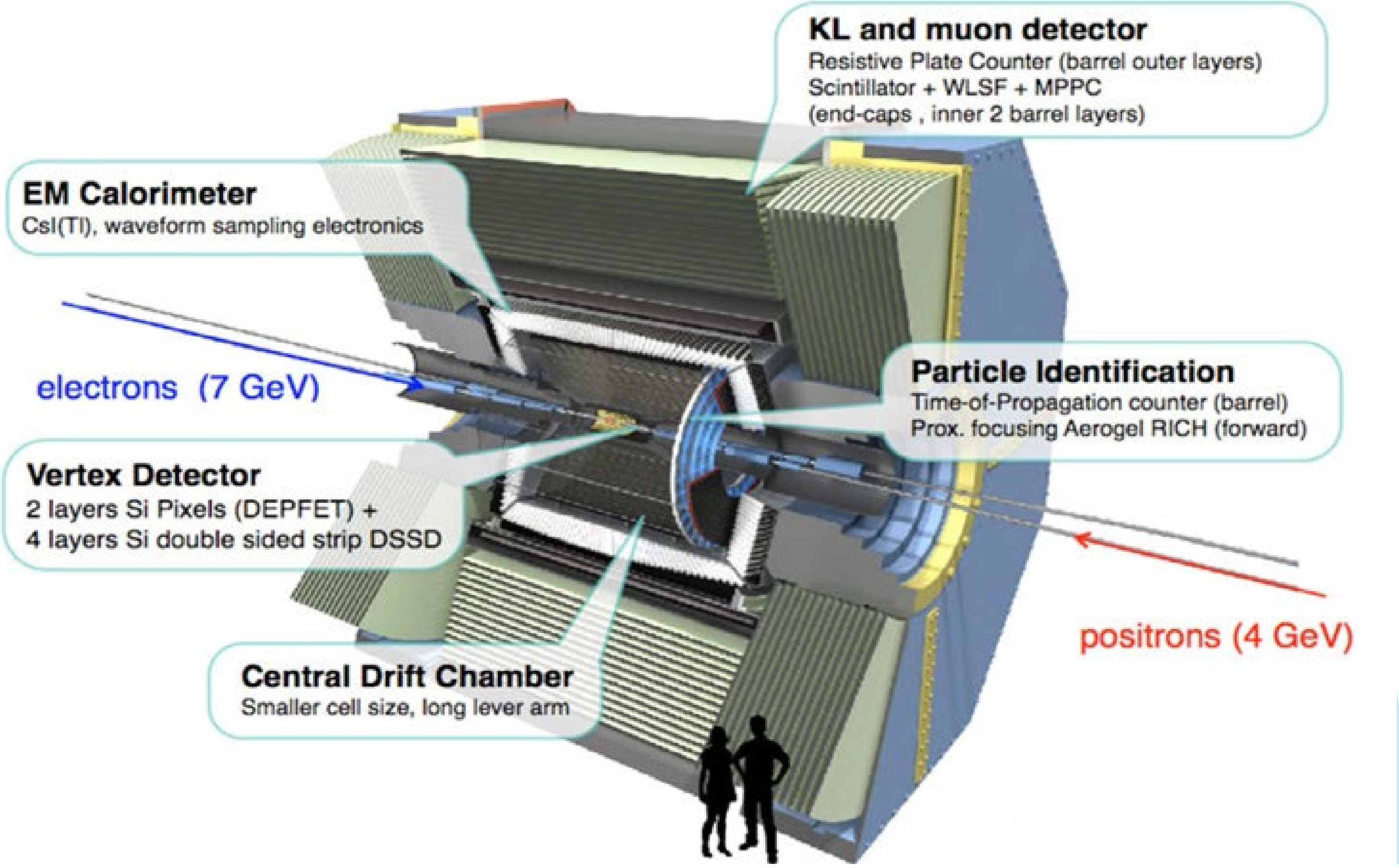
1. Recent results from Belle II on charmed baryon lifetimes
2. Some selected examples of future Belle II analyses

NSTAR Conference, October 2022, Santa Margherita Ligure

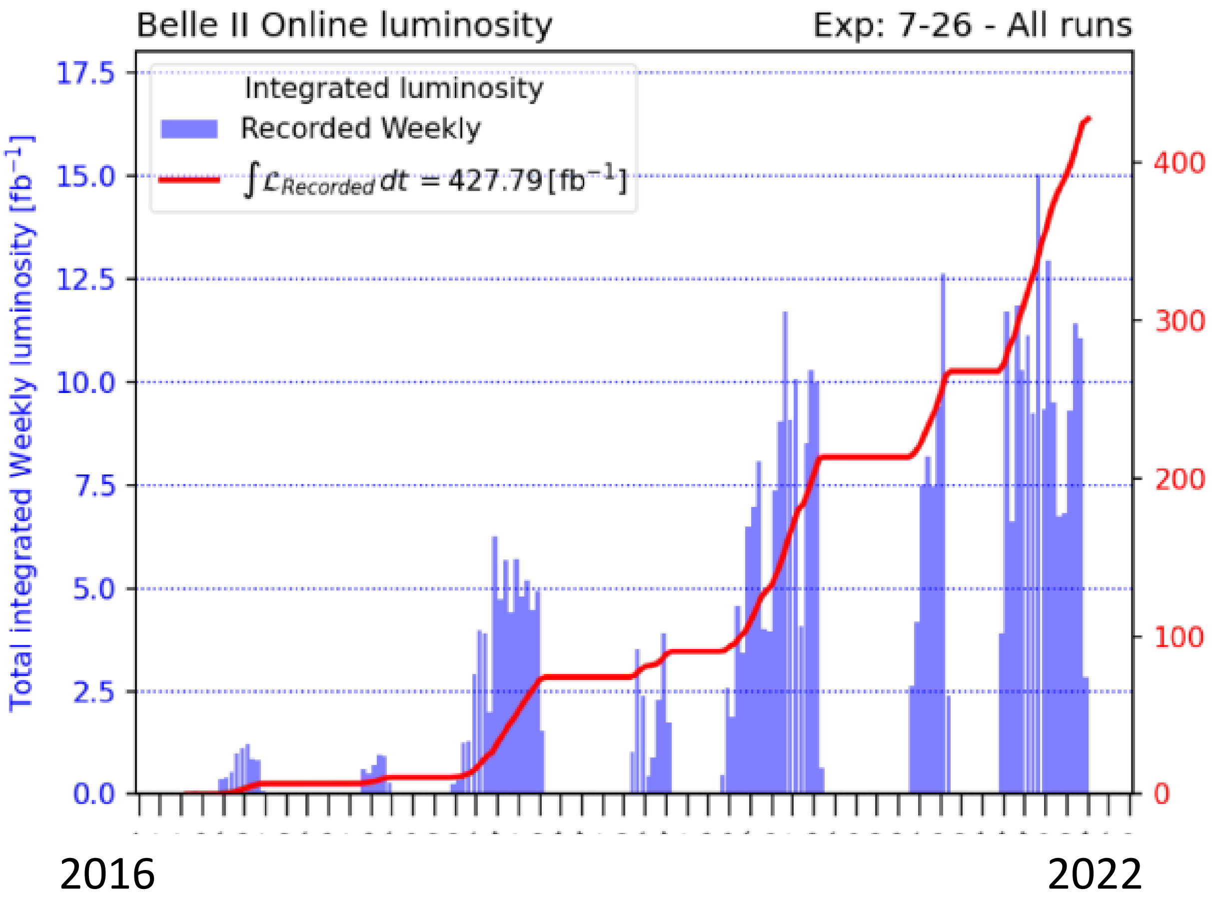
SuperKEKB and Belle II: 2nd generation "Super B Factory"





$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

BELLE II Luminosity



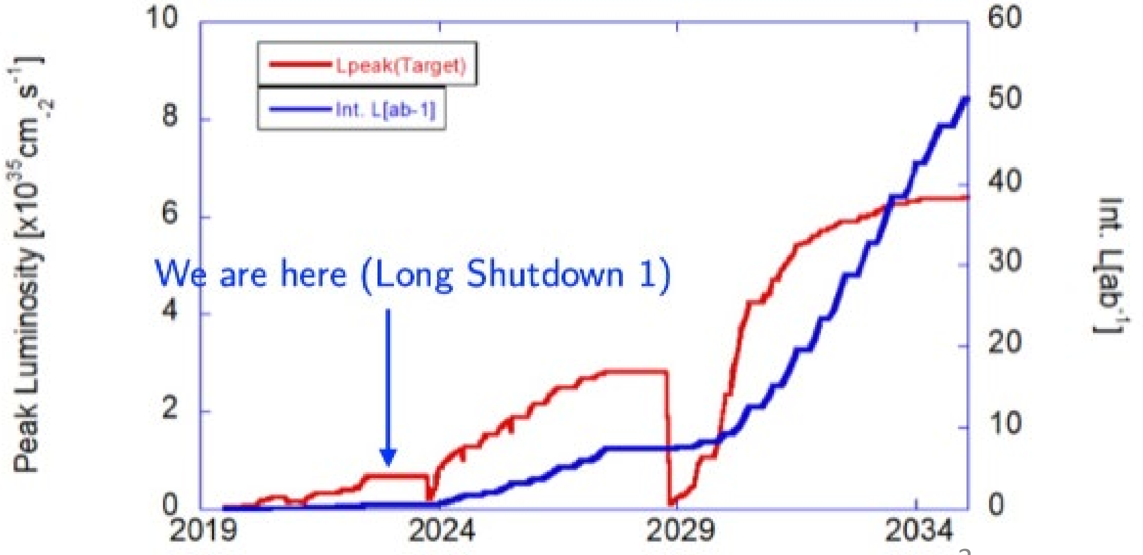
Peak instantaneous luminosity:
4.7 x 10^{34} cm^{-2} s^{-1}
(world record)

Integrated luminosity:

~362 fb^{-1} recorded at $\Upsilon(4S)$, which decays to BB ~1/3 of the time

~42 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$, for background studies

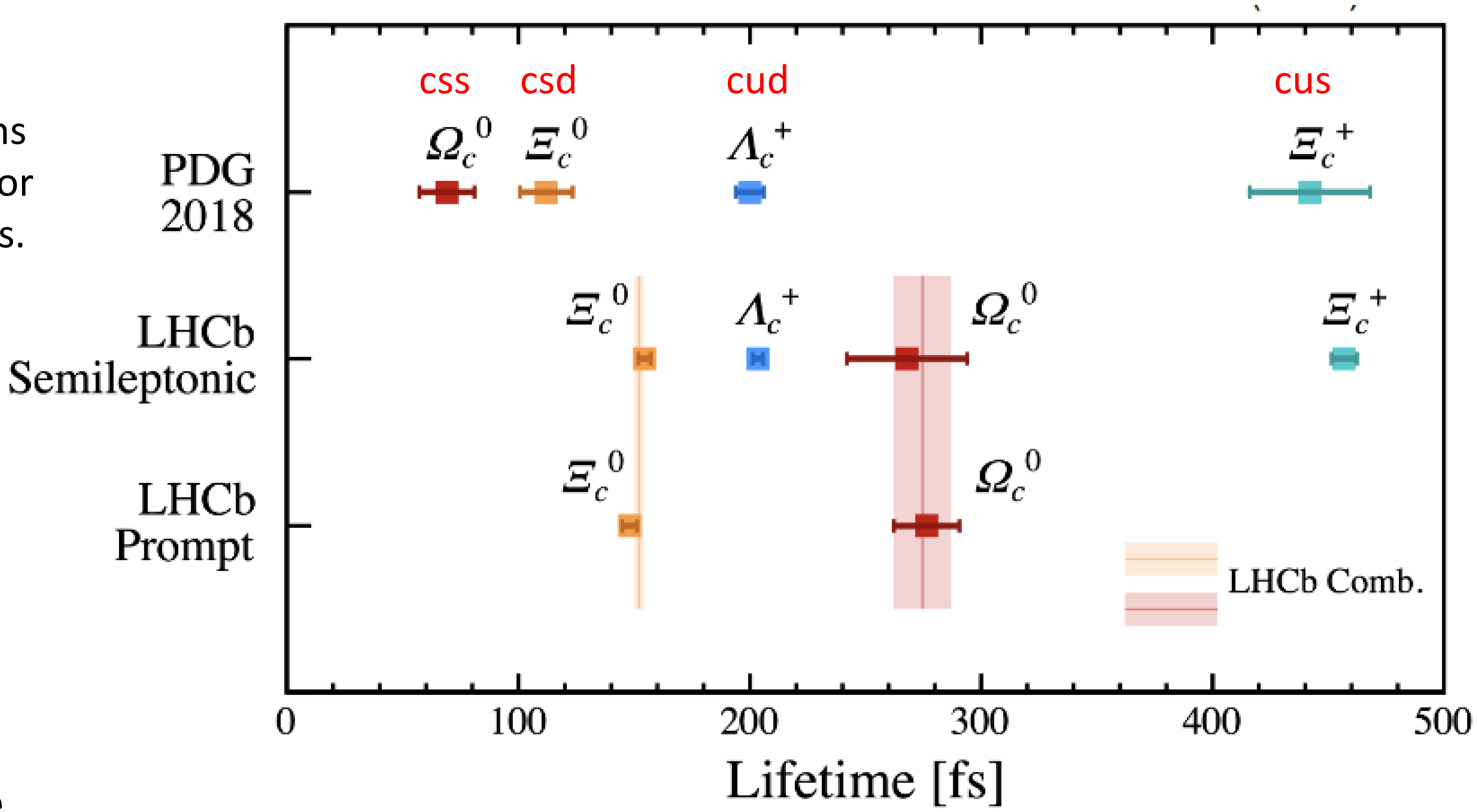
~19 fb^{-1} recorded at ~10.8 GeV for exotic hadron searches



Previous record instantaneous luminosity 2.1 x 10^{34} $cm^{-2}s^{-1}$
Belle integrated luminosity 1000 fb^{-1}
BaBar integrated luminosity 500 fb^{-1}

Lifetime measurements of weakly-decaying charmed baryons

Charmed baryon lifetimes are difficult to describe because of the interplay of different decay diagrams including external W-decay spectator diagrams and W-exchange diagrams.



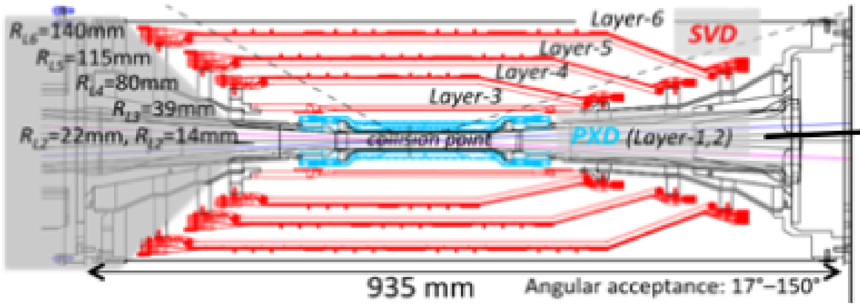
Recent LHCb results have turned around the lifetime hierarchy which had been unchallenged for many years

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

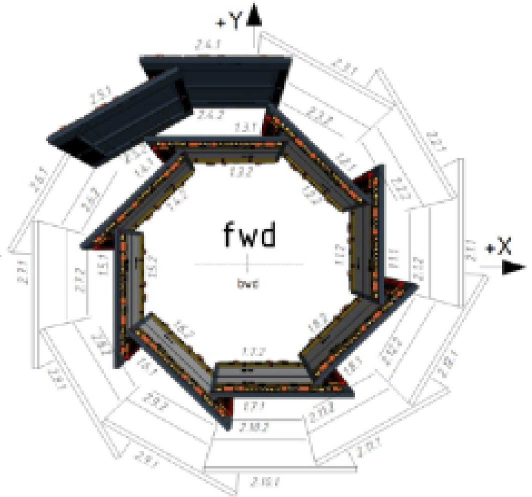
Belle II Lifetime Measurement

Precise lifetime measurements by Belle II

- Upgraded vertex detector
  - More robust tracking
  - Better vertex resolution



Silicon Vertex Detector (SVD)

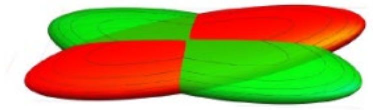


Pixel Detector (PXD)

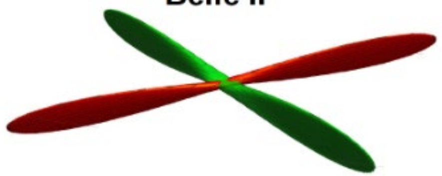
New Drift Chamber with longer lever arm than Belle .
60,0000 parameters used for the alignment of the 14336 wires

Not fully instrumented in the current dataset (Will be after present shutdown)

Belle



Belle II

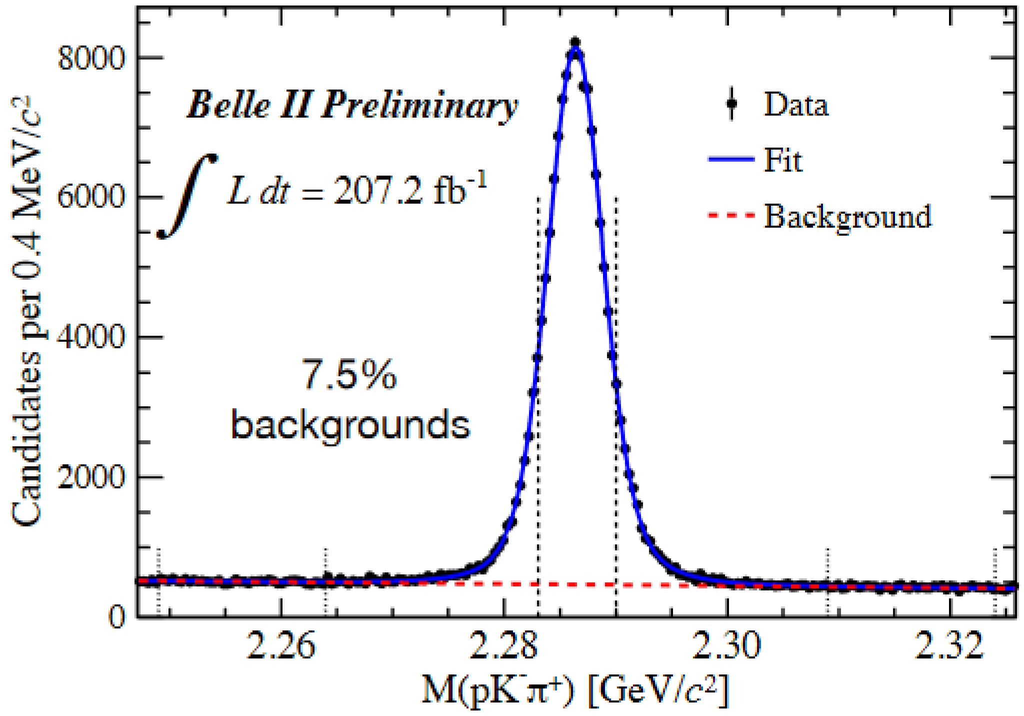


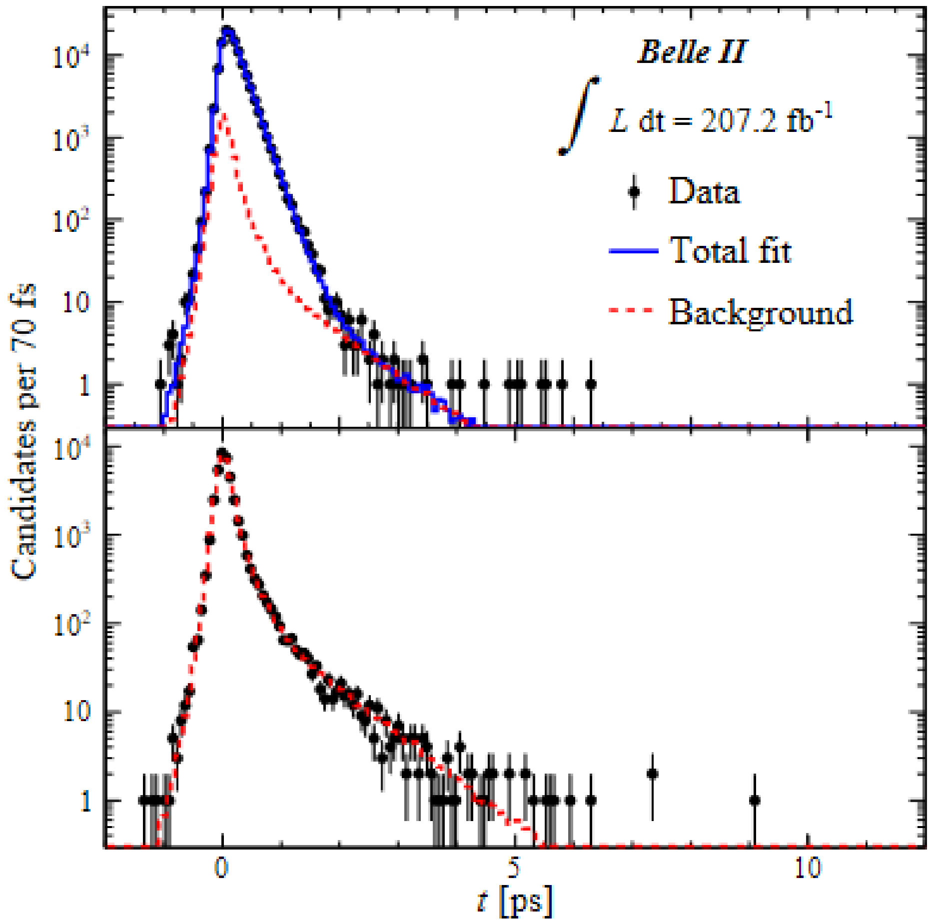
Beamspot effectively point-like in x,y and small in z

Resolution in pathlength 40 μm (around 87 ps)

Λ_c^+ Lifetime Measurement at Belle II

Use $\Lambda_c^+ \to pK^-\pi^+$ decays at high momentum (not from B decays)





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

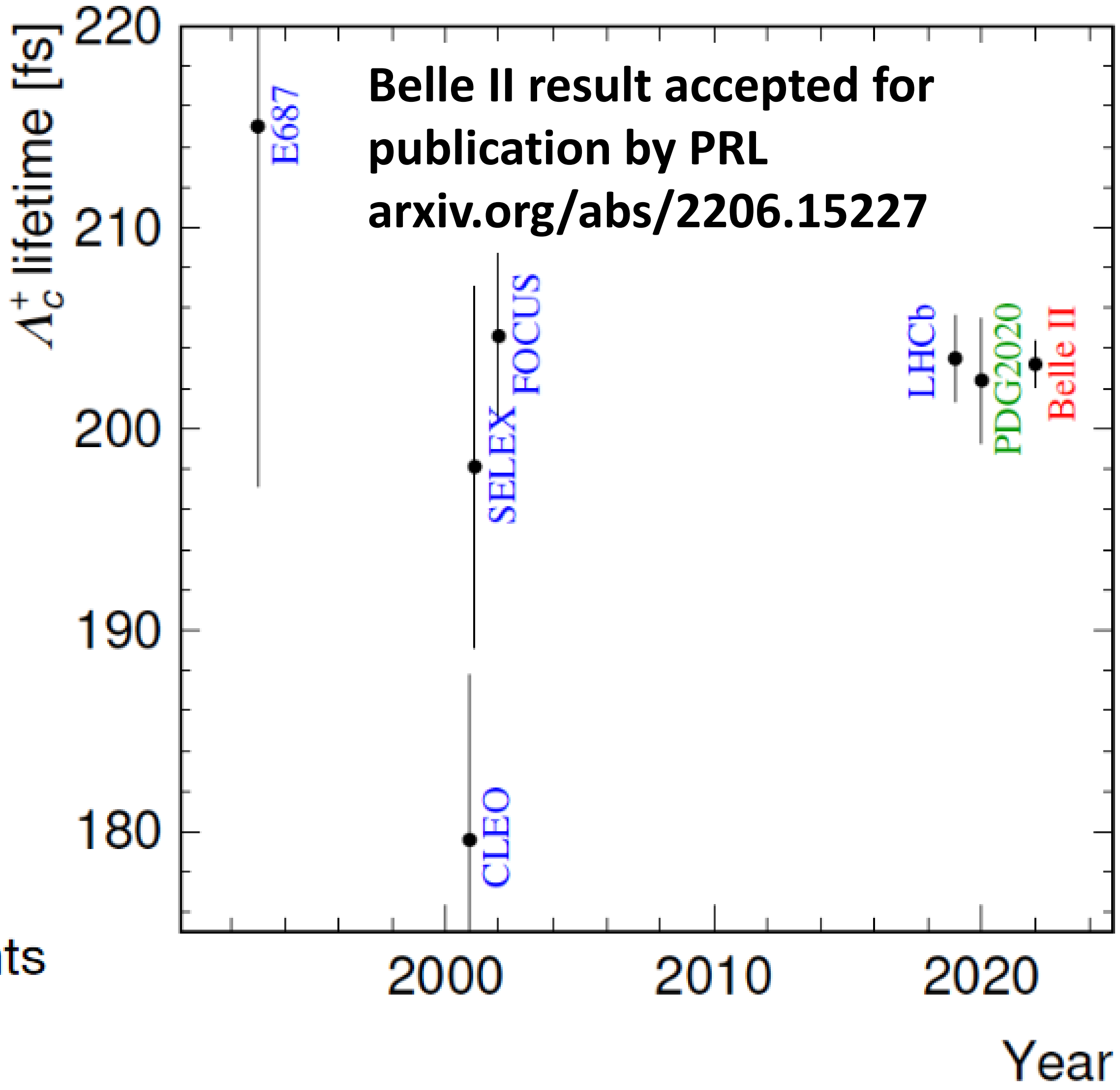
Measured Lifetime: 203.20 ± 0.89 ± 0.77 ps

Decays of $\Xi_c^0 \to \Lambda_c^+\pi^-$ (discovered by Belle, measured by LHCb and by Belle) and $\Xi_c^+ \to \Lambda_c^+\pi^0$ (theoretically estimated and experimentally limited by looking at the distributions in the data)

Λ_c^+ lifetime measurement at Belle II

Experiment	Lifetime (fs)
This measurement	$203.20 \pm 0.89 \pm 0.77$
LHCb (2019)	$203.5 \pm 1.0 \pm 1.3 \pm 1.4$
FOCUS (2002)	$204.6 \pm 3.4 \pm 2.5$
SELEX (2001)	$198.1 \pm 7.0 \pm 5.6$
CLEO (2001)	$179.6 \pm 6.9 \pm 4.4$

- **World's best measurements of the Λ_c^+ lifetime**
  - Consistent with current world averages
  - Slight tension with CLEO measurement remains
  - Benchmark for future baryon lifetime measurements



Belle II result accepted for publication by PRL arxiv.org/abs/2206.15227

Ω_c^0 Lifetime Measurement

Previous measurements: WA89 $55^{+22}_{-25} \times 10^{-15}$s, 86 events, modes: $\Omega^-\pi^+\pi^-\pi^+$, $\Xi^- K^- \pi^+ \pi^+$ ← Wrong mass!

E687 $86^{+39}_{-30} \times 10^{-15}$s, 25 events, mode: $\Sigma^+ K^- K^- \pi^+$ ← Decay mode not seen by any other experiment!

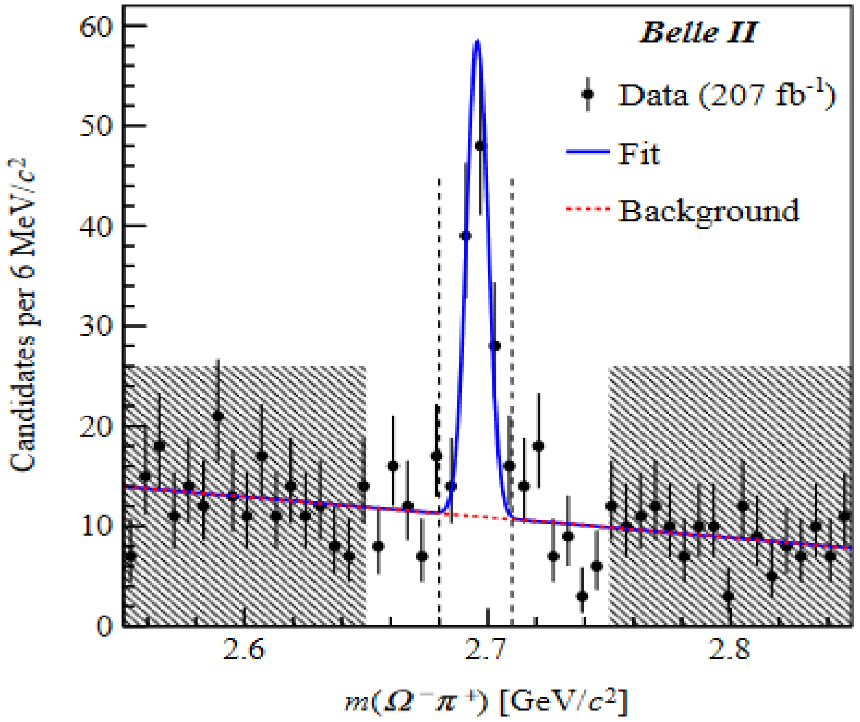
FOCUS $72 \pm 16 \times 10^{-15}$ s, 64 events, modes: $\Omega^-\pi^+$, $\Xi^- K^- \pi^+ \pi^+$

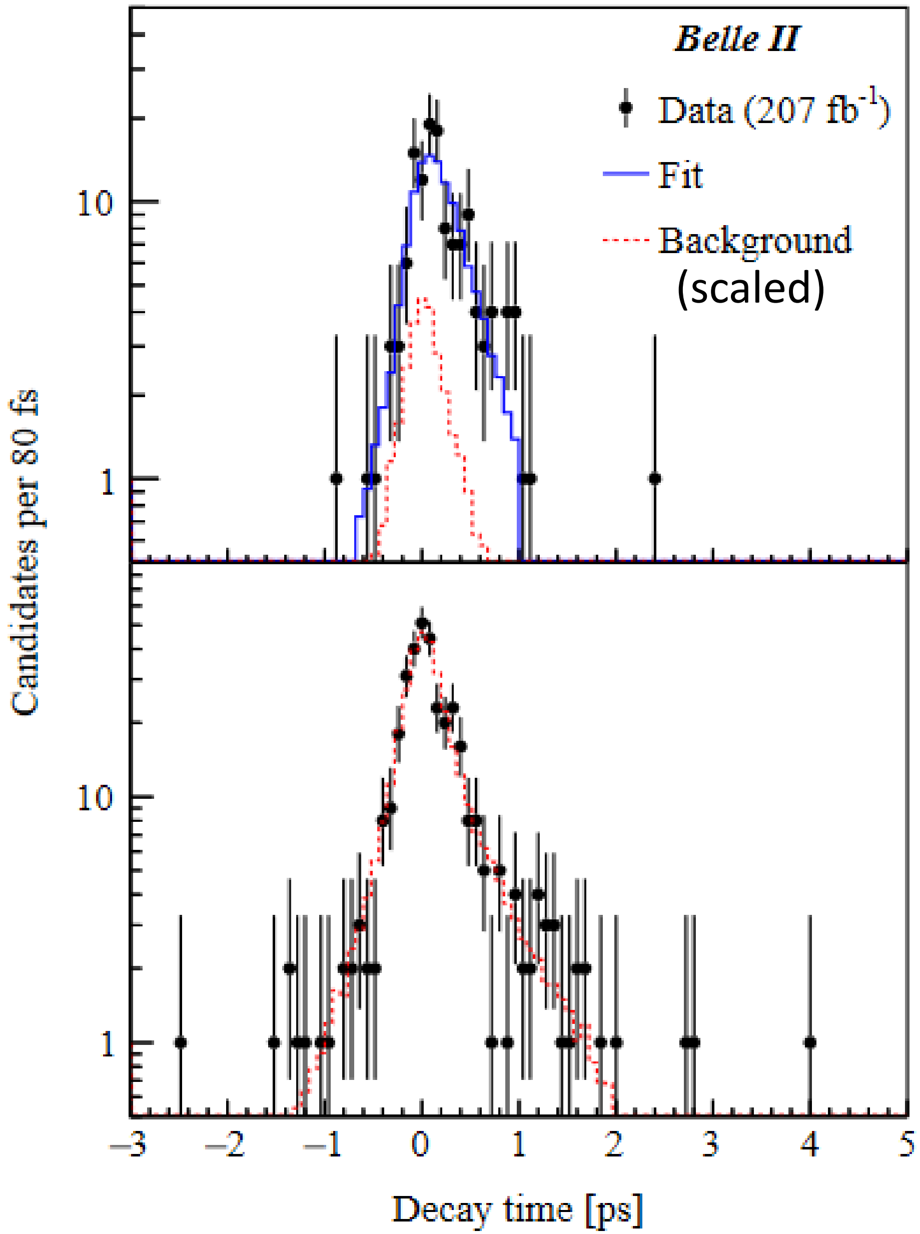
LHCb $268 \pm 26 \times 10^{-15}$ s, $pK^-K^-\pi^+$ (in semi-leptonic decays)
$276.5 \pm 13.7 \times 10^{-15}$ s, modes: inclusive $pK^-K^-\pi^+$

For Belle II we knew already that $\Omega^-\pi^+$ was decay mode with the best statistics and signal:noise ratio.

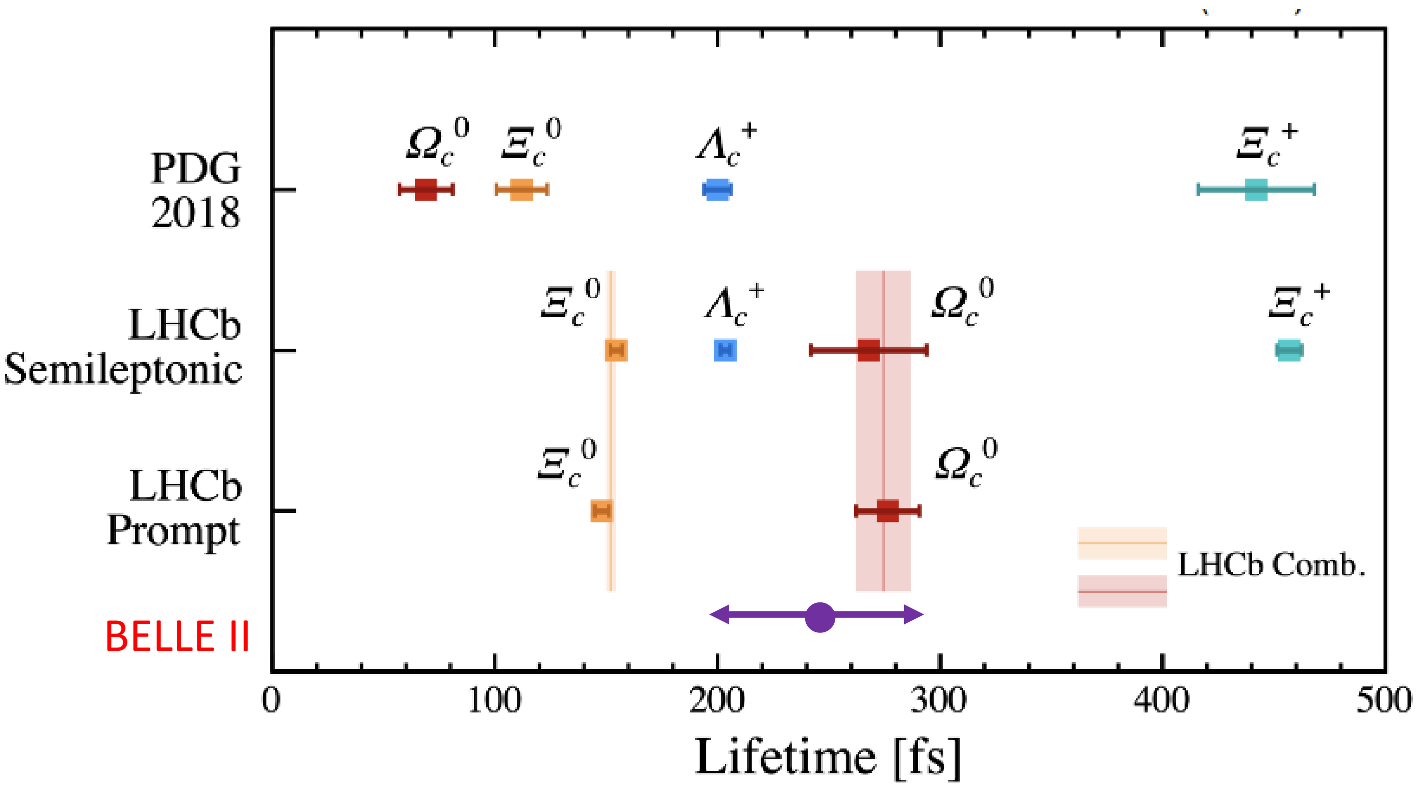
All cut were defined before looking at any lifetime distribution.

132 candidates with a signal purity 66.5%





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



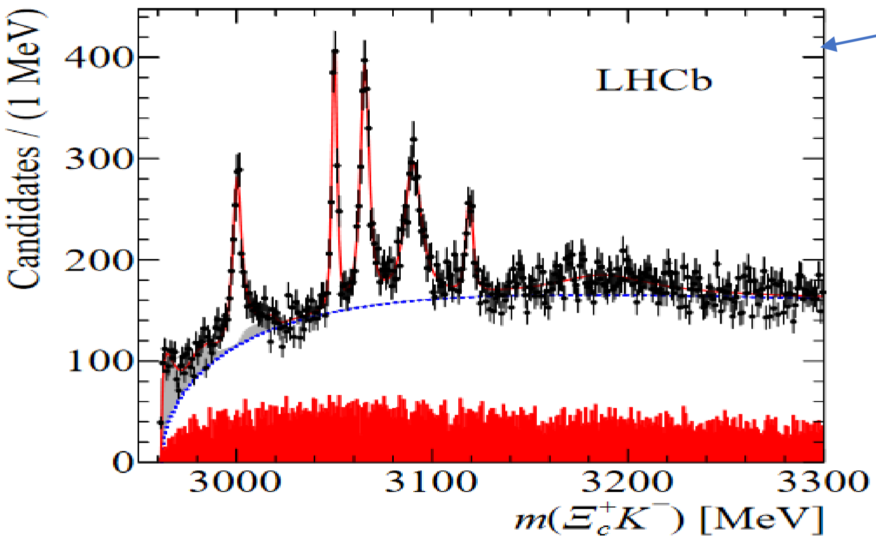
Prospect for future BARYON analyses in BELLE II

Look at what has been done recently in Belle, and we can extrapolate

1. Charmed baryon spectroscopy
2. Other baryon spectroscopy (e.g. excited strange baryons)
3. Charmed baryon decay modes
4. CP Violation in charmed baryons

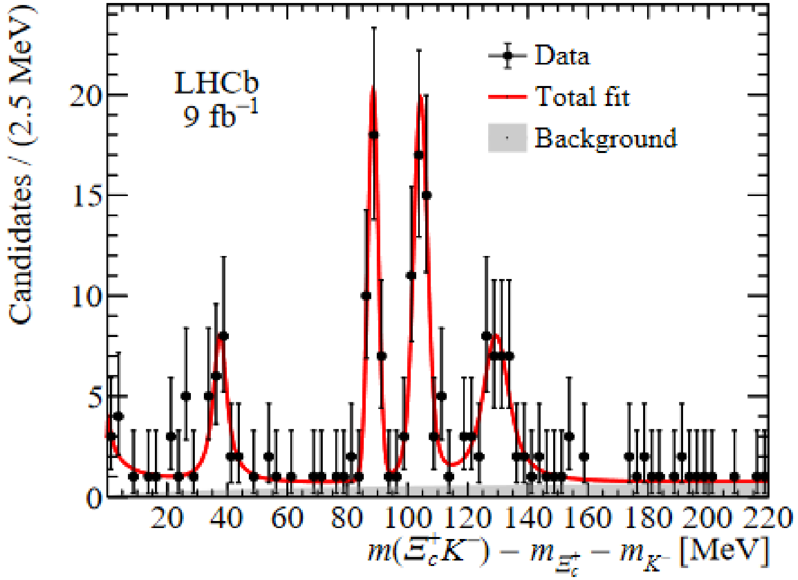
Clearly too much to say – we can just demonstrate some examples of each

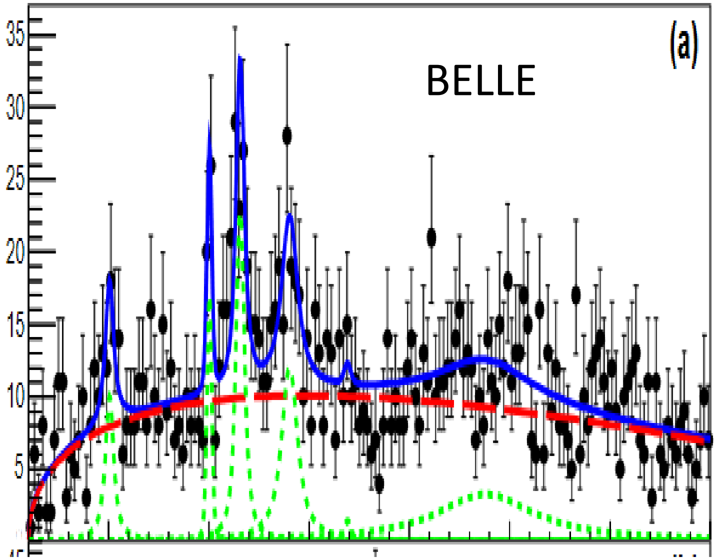
Excited Ω_c Spectroscopy



LHCb inclusive

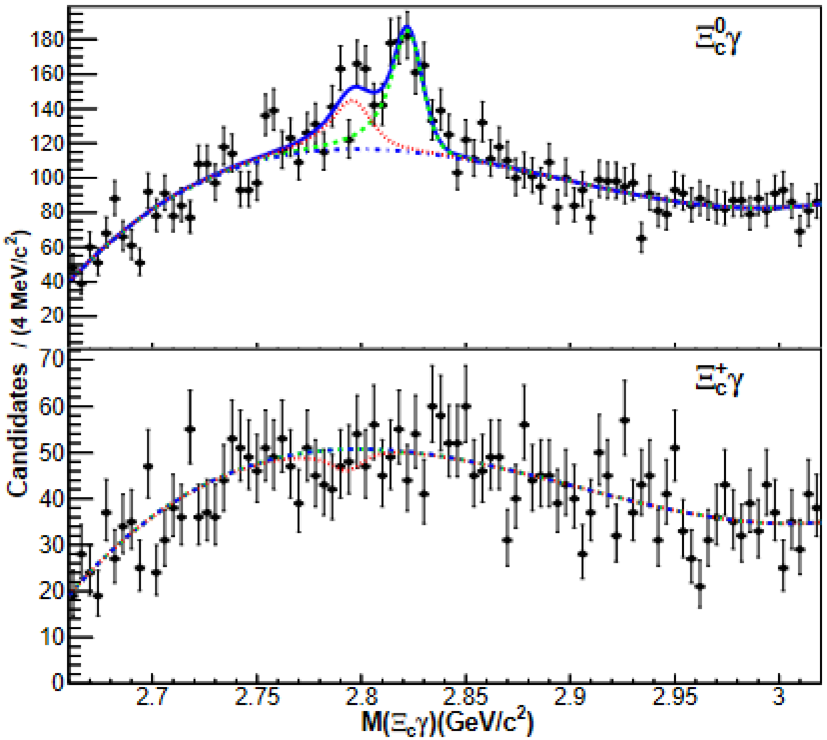
LHCb in Ω_b decays





We may not be able to compete with LHCb for the inclusive cross-section of excited states, but:

a) We have a specific production mechanism that is understood
b) We will, with enough luminosity, be able to make similar plots with Ξ_c'
c) We can also look for electromagnetic decays as we have for $\Xi_c\gamma$



Spectroscopy of (non-charmed) baryons

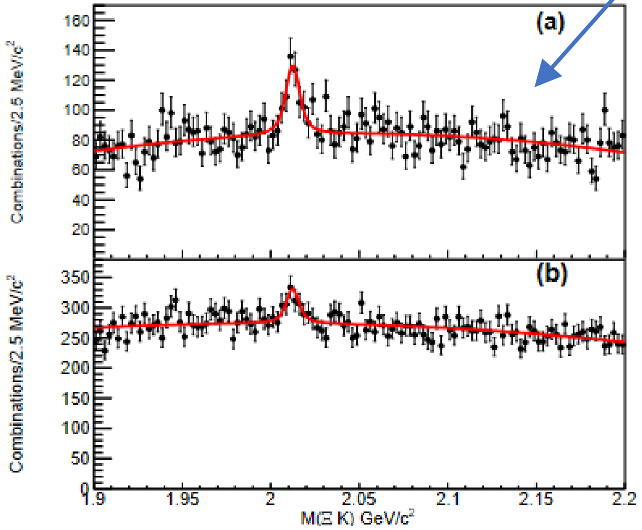
Many excited singly/doubly/triply strange baryons can be found, particularly in charmed baryons decays

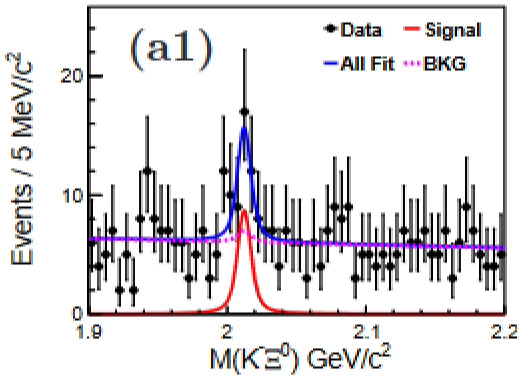
Example: $\Omega^{-}(2012)$

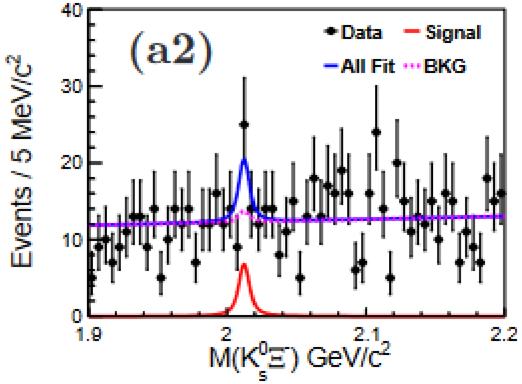
Found in narrow resonance data

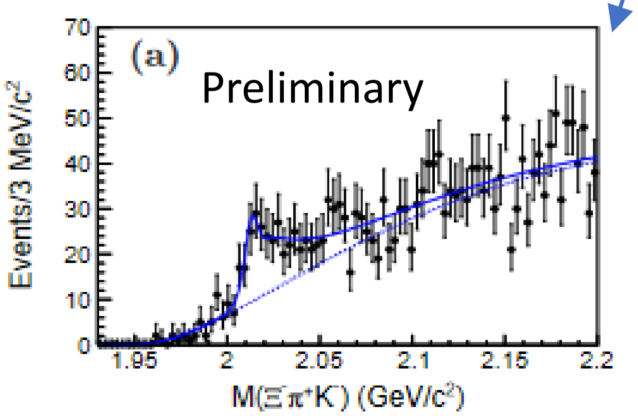
Confirmed in Ω_c decays

Confirmed in 3-body decay (through tail of $\Xi(1520)$)









Strong indication that it is an orbital excitation $J^P = (3/2)^-$ state, or a molecular state.

It would be expected to have a $(1/2)^-$ partner; Belle II can look for these and other states.

Other example: Investigation of excited Ξ baryons in Ξ_c decays. Belle II uniquely positioned for this kind of physics.

PRL 121 (2018) 5, 052003
e-Print 2207.03090
Phys. Rev. D 104 (2021), 5, 052005

Charmed Baryon Decays: Branching Fractions

Λ_c^+ has two measurements of the absolute branching fraction: BES III ($pK^-\pi^+$) $5.84 \pm 0.27 \pm 0.23\%$

Belle ($pK^-\pi^+$) $6.84 \pm 0.24^{+0.21}_{-0.27}\%$

This "tension" needs to be resolved. If absolute branching fraction is 6.4% or so, all major decay modes have been discovered and only "rare" decays searches remaining.

BELLE II/BES III will both contribute

Ξ_c^+ has one measurement of the absolute branching fraction: Belle ($\Xi^-\pi^+\pi^+$) $2.86 \pm 1.21 \pm 0.38\%$

Statistically limited!

Many decay modes remain unmeasured or poorly measured. Not close to getting the overall picture of decays.

BELLE II best placed to contribute

Ξ_c^0 has one measurement of the absolute branching fraction: Belle ($\Xi^-\pi^+$) $1.80 \pm 0.50 \pm 0.14\%$

Belle ($\Lambda K^-\pi^+$) $1.07 \pm 0.37 \pm 0.09\%$

Statistically limited!

Many decay modes remain unmeasured or poorly measured. Not close to getting the overall picture of decays.

BELLE II best placed to contribute

Ω_c^0 has NO measurement of the absolute branching fractions.

Clearly the lifetime saga shows us that Ω_c^0 decays have not been understood.

BELLE II best placed to contribute

For instance $B(\Omega_c \to \Omega^-\pi^+\pi^-\pi^+)/ B(\Omega_c \to \Omega^-\pi^+) = 0.31 \pm 0.05$

whereas $B(\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+)/ B(\Lambda_c^+ \to \Lambda\pi^+) = 2.80 \pm 0.27$

CP violation searches using charmed baryons

CP violation in baryons very important to understand (baryon asymmetry in the universe……)
CPV in baryons has to be *direct* as there is no mixing between particle and anti-particle

Some clear experimental advantages over searches in B-baryons:

- e^+e^- machines can get good signals for many charmed baryon modes
- comparatively low multiplicity makes for final states that are easier to analyze

Looking for CPV in charmed baryon decays is a several step process:

1. Choose a suitable decay mode and measure the branching fraction

(Nothing measurable expected in Cabibbo-favored decays)

2. Measure the asymmetry parameter, α

For a decay such as $\Lambda_c^+ \rightarrow$ BP (baryon + pseudoscalar meson), the α parameter is defined to be:

$$\alpha = \frac{2Re(s.p)}{|s|^2+|p|^2}$$

(where s and p are the parity-violating s-wave and the parity-conserving p-wave amplitudes in the decay)

3. Measure the difference in the asymmetry parameters for particles/antiparticles

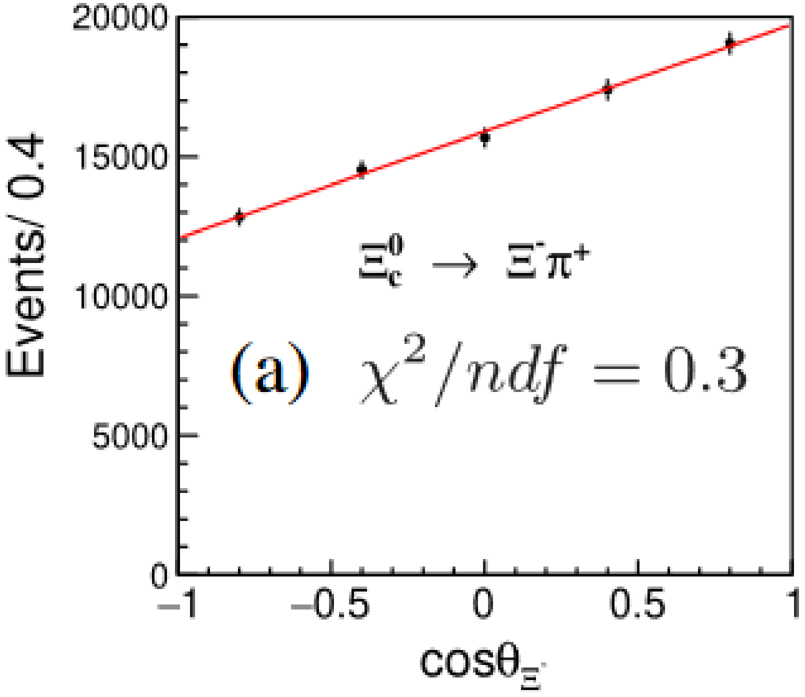
(Note that Belle II has excellent hyperon detection efficiency and purity)

Example Search for CP Violation in Charmed Baryons - BELLE data

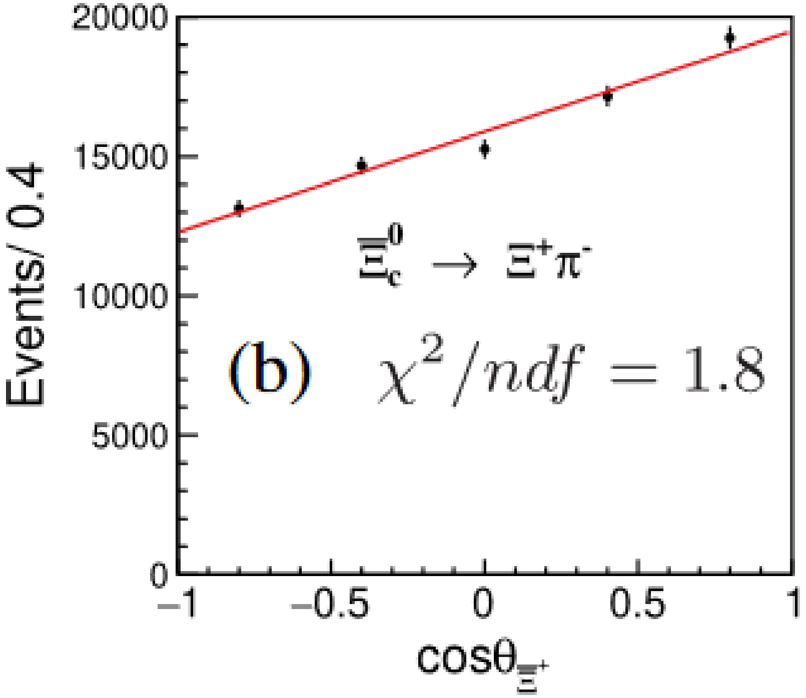
Asymmetry measurement of the (Cabibbo-allowed) decay $\Xi_c^0 \to \Xi^- \pi^+$

$$A_{CP}^{\alpha} = \frac{\alpha(\Lambda_c^+) + \alpha(\Lambda_c^-)}{\alpha(\Lambda_c^+) - \alpha(\Lambda_c^-)}$$

α Is the slope of the line of $dN/d\cos(\theta)$



Baryons



Anti-Baryons

For Ξ_c^0 $\alpha^+ = -0.64 \pm 0.05$

$\alpha^- = 0.61 \pm 0.05$

$\mathcal{A}_{CP} = 0.024 \pm 0.052 \pm 0.014$

No Evidence of CP Violation

Y.B. Li et al, PRL 127, 121803 (2021)

For each 1 ab^{-1} data expected $\boldsymbol{A_{CP}^{\alpha}}$ precision for the Cabibbo-suppressed modes $\Lambda_c^+ \to \Lambda K^+$ and $\Sigma^0 K^+$ are ~0.1 and ~0.3

Not very precise, but who knows?

CONCLUSIONS

I presented two Belle II Measurements of charmed baryons

Λ_c^+ $203.20 \pm 0.89 \pm 0.77$ fs (world's most precise measurement)
Ω_c^0 $243 \pm 48 \pm 11$ fs (consistent with LHCb measurement)

I have reviewed some (of the many) lines of research in baryons for which Belle II is uniquely placed

1. Charmed Baryon Spectroscopy (particularly involving γ decays)
2. Strange Baryon Spectroscopy (particularly using hyperons in charmed baryon decays)
3. Charmed Baryon Decay Modes
4. CP Violation searches

For all of these, Belle II has the working experiment, it is well calibrated and understood, and now all we need is the luminosity

BACKUP

CP violation searches using charmed baryons continued

What sort of modes should we look for?

$\Lambda_c^+ \rightarrow \Lambda K^+$ and $\Sigma^0 K^+$ are the theoretically simplest decay modes to look at

Branching Fractions: $(6.1 \pm 1.2) \times 10^{-4}$ and $(5.2 \pm 0.8) \times 10^{-4}$

(dominated by statistical uncertainty)

At e^+e^- machines:

Λ efficiency and purity are good

$\Sigma^0 \rightarrow \Lambda\gamma$ efficiency and purity OK

For 1 ab^{-1} (Belle integrated luminosity, but small fraction of what Belle II WILL take)

ΛK^+ will have around 10,000 events and statistical uncertainty $\sim 3\%$

$\Sigma^0 K^+$ will have around 3,000 events and statistical uncertainty $\sim 6\%$

CP violation searches using charmed baryons continued

For a decay such as $\Lambda_c^+ \rightarrow$ BP (baryon + pseudoscalar meson), the α parameter is defined to be:

$$\alpha = \frac{2Re(s.p)}{|s|^2+|p|^2}$$

(where s and p are the parity-violating s-wave and the parity-conserving p-wave amplitudes in the decay)

Operationally, for a decay such as $\Lambda_c^+ \rightarrow \Lambda K^+$ we define an angle θ_Λ, which is the angle between the proton momentum in the Λ frame and the Λ in the Λ_c^+ frame. We divide the data into bins of cos(θ_Λ) and then use the equation:

$$dN/d\cos\theta_\Lambda \propto 1 + \alpha(\Lambda_c^+ \rightarrow \Lambda K^+)\, \alpha(\Lambda \rightarrow p\pi^-)\cos\theta_\Lambda$$

In other words, split the data into bins of $\cos\theta_\Lambda$, fit the peak in each one, make a plot, find the slope and extract the product of the α parameters

(α for a Λ is well known)

Luckily for these analyses, the efficiency tends to be rather flat over varying $\cos\theta_\Lambda$