Belle II (Belle) perspectives for Baryon Physics

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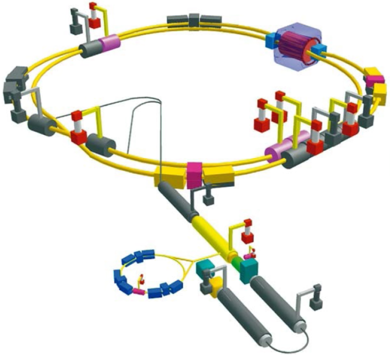
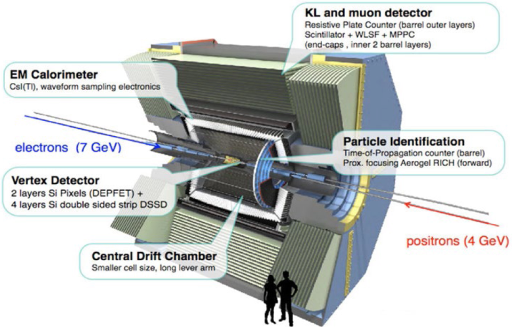
for Belle II/Belle

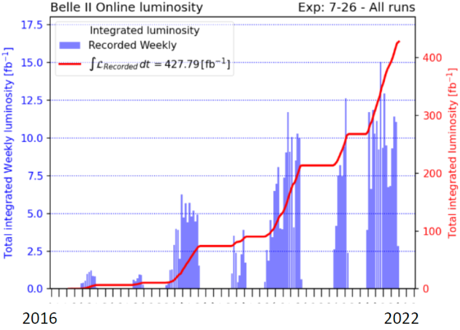
1. Recent results from Belle II on Charmed baryon lifetime
2. Belle II perspective based on Belle results
   - Charmed baryon spectroscopy,
   - Other baryon spectroscopy,
   - CP violation in Charmed baryon

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





Belle II luminosity



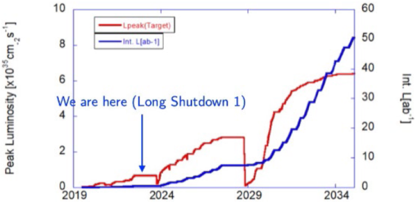
Peak instantaneous luminosity:
4.7×10^{34} cm^{-2} s^{-1}
(world record)

Integrated luminosity:

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

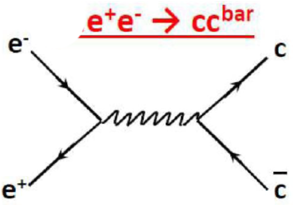
~42 fb^{-1} *recorded 60 MeV below $\Upsilon(4S)$, for background studies*

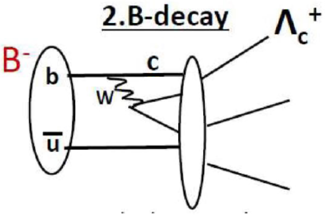
~19 fb^{-1} *recorded at ~10.8 GeV for exotic hadron searches*



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

Charmed Baryon Production at B-Factories





- B meson is efficiently produced via $\Upsilon(4S)$
- Once bottom is produced, it favorably decays into charm

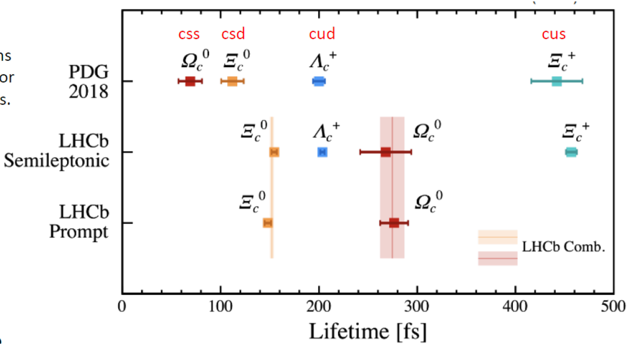
Baryons produced via fragmentation

- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

Huge statistics

Lifetime measurments 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.



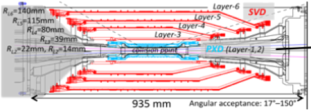
Recent LHCb results have turned around the lifetime hierarchy which had been unchallenged for many years

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

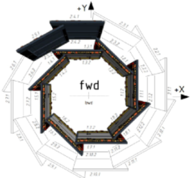
Belle II Lifetime Measurements

Precise lifetime measurements by Belle II

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



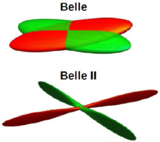
Silicon Vertex Detector (SVD)



Pixel Detector (PXD)

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

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



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

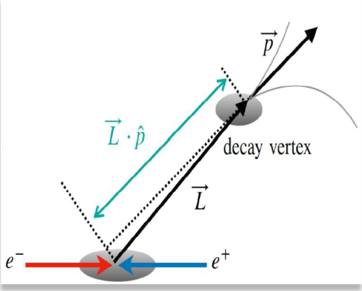
Resolution in pathlength 40 μm (around 87 ps)

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

Procedure to measure Λ_c^+ lifetime

- Promptly produced Λ_c^+ candidates from continuum $e^+e^- \to c\bar{c}$ events.
- $\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$ 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.

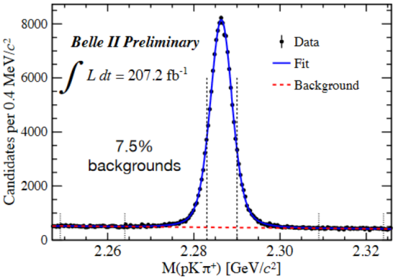
$$t = \frac{m}{p}(\vec{L}\,.\,\hat{p})$$

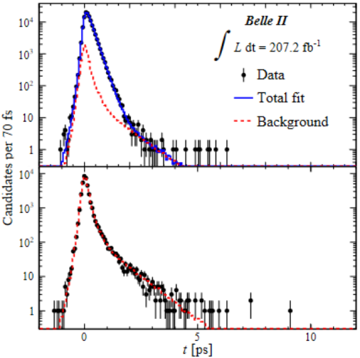


- The position and size of the interaction region is determined using $e^+e^- \to \mu^+\mu^-$ events.
- For the Λ_c^+ candidates, the VXD provides a decay-length resolution of **40 μm**, corresponding to an average decay time resolution of **87 fs** for an average decay length of **96 μm** .
- $\boldsymbol{\sigma_t}$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

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

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





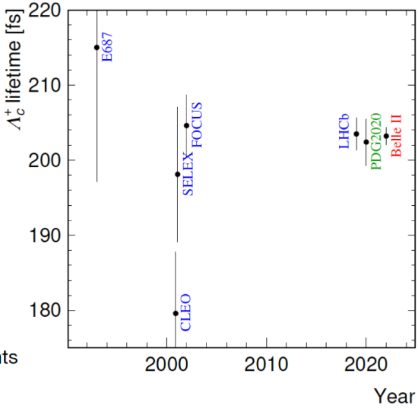
Source	Uncertainty [fs]
Ξ_c contamination	0.34
Resolution model	0.46
Backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

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

Phys. Rev. Lett. 130, 071802 (2023)

Ω_c^+ Lifetime Measurement at Belle II

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

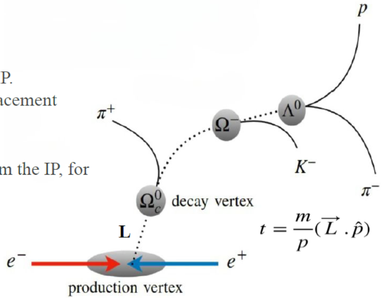
(2) $\Omega^- \to \Lambda^0 K^-$

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

- 207 fb^{-1} of collision data is used. $\boldsymbol{\Omega_c^0 \to \Omega^- \pi^+}$ decay is considered.
- Complex topology of reconstructed decay chain with two secondary vertices.
- $\boldsymbol{\Lambda^0 \to p\pi^-}$ are reconstructed using oppositely charged tracks one of which must be a proton. Decay vertex of the $\boldsymbol{\Lambda^0}$ 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 $\boldsymbol{\Omega^-}$.
  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° .
- $\boldsymbol{\Omega_c^0 \to \Omega^- \pi^+}$ are formed by combining positively charged track from the IP, for which momenta is at least 0.5 GeV/c.
- $\boldsymbol{\Omega_c^0}$ from B are removed by requesting its scaled momentum to be larger than 0.6 GeV/c. Scaled momentum is defined as:

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

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



Ω_c^+ Lifetime Measurement at Belle II

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!

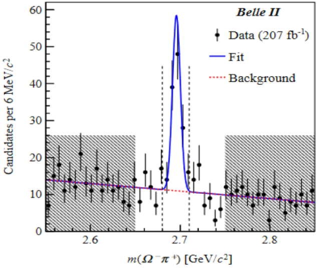
FOCUS $72 \pm 16 \times 10^{-15}$ s, 64 events, modes: $\Omega^- \pi^+$, $\Xi^- K^- \pi^+ \pi^+$

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 $pK^- K^- \pi^+$

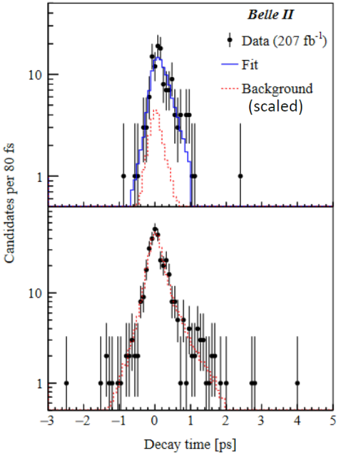
For Belle II we knew already that $\Omega^- \pi^+$ was decay mode with the best statistics and signal:noise ratio.

All cut were defined before looking at any lifetime distribution.

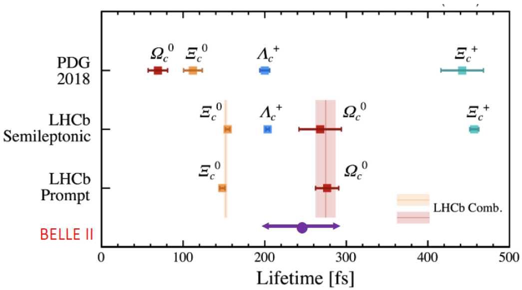
132 candidates with a signal purity 66.5%



Ω_c^+ Lifetime Measurement at Belle II



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



Prospects for future baryon analyses in Belle II

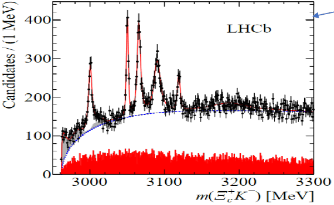
We can extrapolate from what has been done recently in Belle

- Charmed baryon spectroscopy
- Other baryon spectroscopy (e.g.excited strange baryons)
- Charmed baryon decay modes
- CP Violation in charmed baryons

Resent charmed baryon results Belle

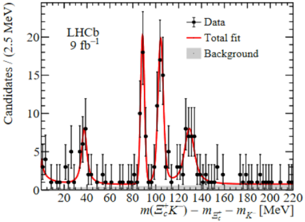
Process	Reference	Physics Covered
$\Omega_c^0 \to \pi^+[\Omega(2012)^- \to \bar{K}\Xi]$	PRD 104, 052005 (2021)	Evidence: 4.2σ
$\Lambda_c^+ \to p\pi^0/p\eta$	PRD 103, 072004 (2021)	SCS decays
$\Lambda_c^+ \to p\omega$	PRD 104, 072008 (2021)	SCS decay, 3pi mode
$\Lambda_c^+ \to p\eta'$	JHEP 03, 090 (2022)	SCS decay, 5.4σ
$\Lambda_c^+ \to \eta\Lambda\pi^+$	PRD 103, 052005 (2021)	$\Lambda(1670), \Sigma(1385)^+$
$\Lambda_c^+ \to \Lambda h^+/\Sigma^0 h^+$	Belle note #625	Direct CPV search, Br, Acp
$\Lambda_c^+ \to \Sigma^+\pi^0/\Sigma^+\eta/\Lambda_c^+ \to \Sigma^+\eta'$	Belle note #626	Br, Acp
$\Lambda_c^+ \to \Sigma^+\gamma/\Xi_c^0 \to \Xi^0\gamma$	arXiv: 2206.12517	Weak radiative decays, UL
$\Xi_c^0 \to \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-$	PRD 105, L011102 (2022)	Br, CF decays
$\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$	PRL 127, 121803 (2021)	Br, Acp, LFU
$\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv: 2206.08527	Heavy-flavor-conserving decay
$\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$	PRD 105, L091101 (2022)	Br, LFU
$\Sigma_c(2455)^+, \Sigma(2520)^+$	PRD 104, 052003 (2021)	mass and widths
$\Sigma_c(2455)^{0,++}\pi^\pm$	arXiv: 2206.08822	New excited charmed baryon, 4.2σ

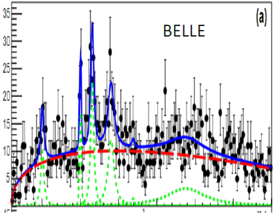
Ω_c Spectroscopy



LHCb inclusive

LHCb in Ω_b decays



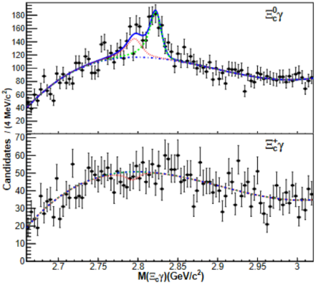


We may not be able to compete with LHCb for the inclusive cross-section of excited states, but:

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

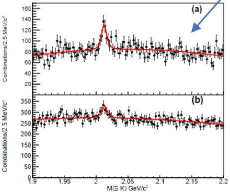
Many excited singly/doubly/triply strange baryons can be found, particularly in charmed baryons decays

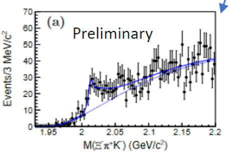
Example: $\Omega^{-}(2012)$

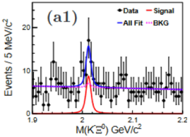
Found in narrow resonance data

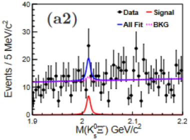
Confirmed in Ω_c decays

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

Measurements of $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ and $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$

Semi-leptonic decays of charmed baryons:

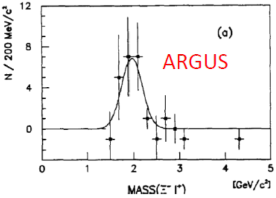
- Ideal test of QCD in transition region of (non-)perturbative.
- The cleanest processes among charm decays
- Test lepton flavor universality (LFU).

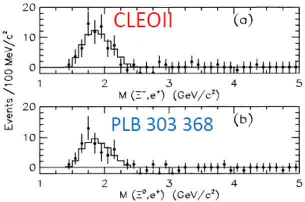
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, e^+ \nu_e) = (3.6 \pm 0.4)\%$ PRL 115, 221805(2015)
$\mathcal{B}(\Lambda_c^+ \to \Lambda\, \mu^+ \nu_e) = (3.5 \pm 0.4)\%$ PLB 767, 42 (2017)

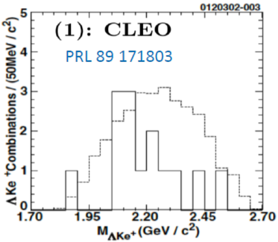
Experimentally:

- BESIII measured the $\mathcal{B}(\Lambda_c^+ \to \Lambda l^+ \nu)$
- ARGUS and CLEOII measured $\mathcal{B}(\Xi_c \to \Xi\, l^+ \nu)$
- CLEO measured $\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)$

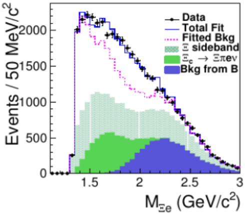
} **large uncertainty**

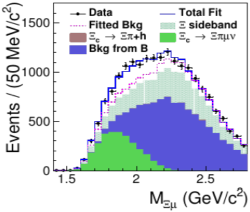






Measurements of $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ and $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$





Data-driven method for bkg

- Mis-selected ℓ^+
- Wrongly constructed Ξ
- $\Xi_c \to \Xi\pi\ell^+\nu_\ell$
- $\Xi_c \to \Xi\pi + h$
- B decay

PRL 127, 121803 (2021)

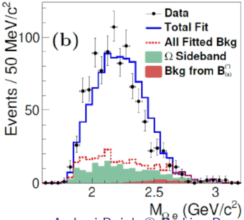
$\mathcal{B}r(\Xi_c^0 \to \Xi^- e^+ \nu_e) = (1.31 \pm 0.39)\%$

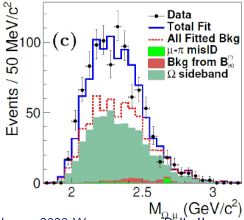
$\mathcal{B}r(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu) = (1.27 \pm 0.39)\%$

Previous: $(2.34 \pm 1.59)\%$

Consistent with LFU

PRD 105, L091101 (2022)





$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.98 \pm 0.15$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.94 \pm 0.21$$

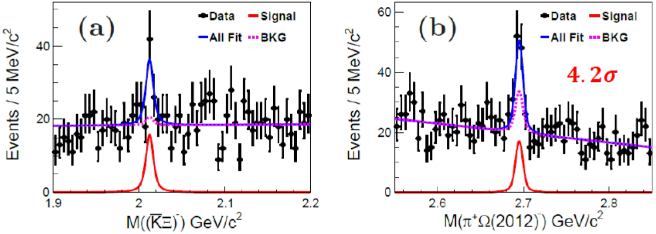
Previous: 2.4 ± 1.2

Consistent with LFU

Measurement of $\Lambda_c^+ \to p\omega, \Lambda_c^+ \to p\eta'$

- Searching for new production model is very important to understand the nature of $\Omega(2012)^-$
- A theoretical study of the $\Omega(2012)^-$ in the nonleptonic weak decays of $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ was reported [1]
- We do the search in both $K_S^0\Xi^-$ and $K^-\Xi^0$ final states

PRD 104, 052005 (2021)



Combined

$$= \frac{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times \mathcal{B}(\Omega(2012)^- \to (\bar{K}\Xi)^-)}{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega^-)}$$

$$= \frac{N_{\rm sig.}^{\rm obs} \times \epsilon_{\pi^+\Omega^-}}{N_{\pi^+\Omega^-}^{\rm obs} \times (f_1 \times \epsilon_1 \times \mathcal{B}_1 + f_2 \times \epsilon_2 \times \mathcal{B}_2)}$$

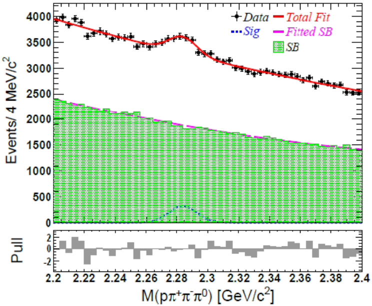
$$= 0.220 \pm 0.059(\text{stat.}) \pm 0.035(\text{syst.}),$$

[1] PRD 102, 076009

Measurement of $\Lambda_c^+ \to p\omega, \Lambda_c^+ \to p\eta'$

- LHCb reported the first observation of a SCS decay $\Lambda_c^+ \to p\omega[\to \mu^+\mu^-]$, $\mathrm{Br}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.9) \times 10^{-4}$
- We perform same measurement by reconstructing $\omega \to \pi^+\pi^-\pi^0$ decay

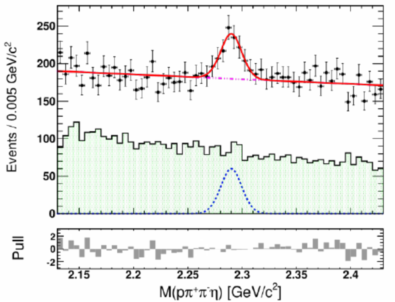
PRD 104, 072008 (2021)



$\mathrm{Br}(\Lambda_c^+ \to p\omega) =$
$(8.27 \pm 0.75 \pm 0.62 \pm 0.42) \times 10^{-4}$

- Most precise measurement
- Consistent with LCHb result

JHEP 03, 090 (2022)



$\mathrm{Br}(\Lambda_c^+ \to p\eta') =$
$(4.73 \pm 0.82 \pm 0.47 \pm 0.24) \times 10^{-4}$

- First observation of Λ_c^+ in $\Lambda_c^+ \to p\eta'$
- Consistent with the $SU(3)_F$ calculation

CP violation search 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

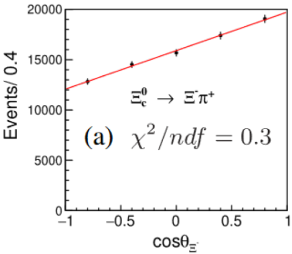
(Note that Belle II has excellent hyperon detection efficiency and purity)

CP violation search using charmed baryons

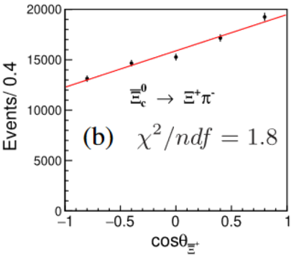
Asymmetry measurement of the (Cabibbo-allowed) decay $\Xi_c^0 \to \Xi^- \pi^+$

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

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



Baryons



Anti-Baryons

For Ξ_c^0
$$\alpha^+ = -0.64 \pm 0.05$$
$$\alpha^- = 0.61 \pm 0.05$$

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

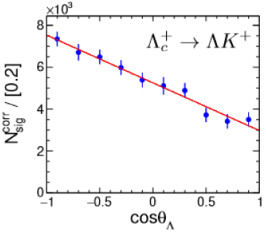
No Evidence of CP Violation

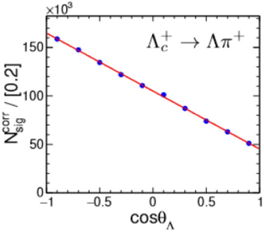
Y.B. Li et al, PRL 127, 121803 (2021)

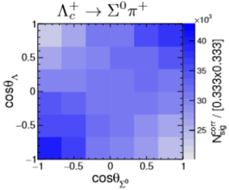
For each 1 ab^{-1} data expected A_{CP}^{α} precision for the Cabibbo-suppressed modes $\Lambda_c^+ \to \Lambda K^+$ and $\Sigma^0 K^+$ are ~0.1 and ~0.3

Not very precise, but who knows?

CP violation search using charmed baryons







Averaged decay asymmetry parameters:

- First measurements of K^+ modes
- Improved precision of π^+ modes

$$\begin{aligned}
\alpha_{avg}(\Lambda_c^+ \to \Lambda K^+) &= -0.585 \pm 0.049 \pm 0.018\,, \\
\alpha_{avg}(\Lambda_c^+ \to \Lambda \pi^+) &= -0.755 \pm 0.005 \pm 0.003\,, \\
\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 K^+) &= -0.55 \pm 0.18 \pm 0.09\,, \\
\alpha_{avg}(\Lambda_c^+ \to \Sigma^0 \pi^+) &= -0.463 \pm 0.016 \pm 0.008\,,
\end{aligned}$$

α-induced CP asymmetry:

- First measurements of A_{CP}^{α} for SCS decays of charmed baryons

Channel	A_{CP}^{α}
$\Lambda_c^+ \to \Lambda K^+$	$-0.023 \pm 0.086 \pm 0.071$
$\Lambda_c^+ \to \Lambda \pi^+$	$+0.020 \pm 0.007 \pm 0.013$
$\Lambda_c^+ \to \Sigma^0 K^+$	$+0.08 \pm 0.35 \pm 0.14$
$\Lambda_c^+ \to \Sigma^0 \pi^+$	$-0.023 \pm 0.034 \pm 0.030$

Λ-hyperon CP violation:

- First measurement of hyperon CPV searches in CF charm decays.

$$A_{CP}^{\alpha} = +0.013 \pm 0.007 \pm 0.011$$

No evidence of baryon CPV is found

Conclusions

- Two Belle II results on charmed baryon lifetime

  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)

- Rich recent research results from Belle
  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

- Belle II is the working experiment, it is well calibrated and understood and now all we need is the luminosity. We can do it and much more.

Backup

Measurement of $\Lambda_c^+ \to p\pi^0 / p\eta$

PRD 103, 052005 (2021)

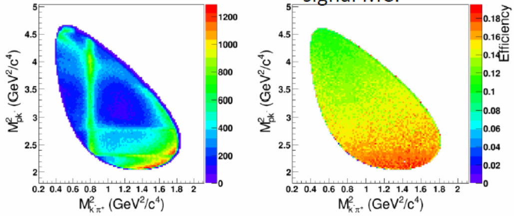
A method of branching ratio with respect to Cabibbo-Favored decay $\Lambda_c^+ \to pK^-\pi^+$ (reference mode) is applied to measure the branching fractions of signal decay.

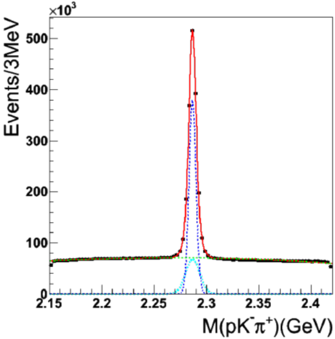
$$\frac{B(Signal)}{B(CF)} = \frac{N^{obs}(Signal)}{\epsilon^{MC}(Signal)} \times \frac{\epsilon^{MC}(CF)}{N^{obs}(CF)}$$

$\Lambda_c^+ \to pK^-\pi^+$ efficiency estimation: Dalitz method.

Data

Efficiency from signal MC.





Fit to M($pK^-\pi^+$) from data using double Gaussian + second-order polynomial

$$\varepsilon = \sum s_i \Big/ \sum_j (s_j/\varepsilon_j) = (14.06 \pm 0.01)\%.$$

Yield: 1476200 ± 1560

χ^2/ndf=1.06