New results on charmed baryons from the LHCb experiment

Hang Yin
Central China Normal University
On behalf of the LHCb collaboration

CERN LHC Seminar, 10th July 2018

Outline

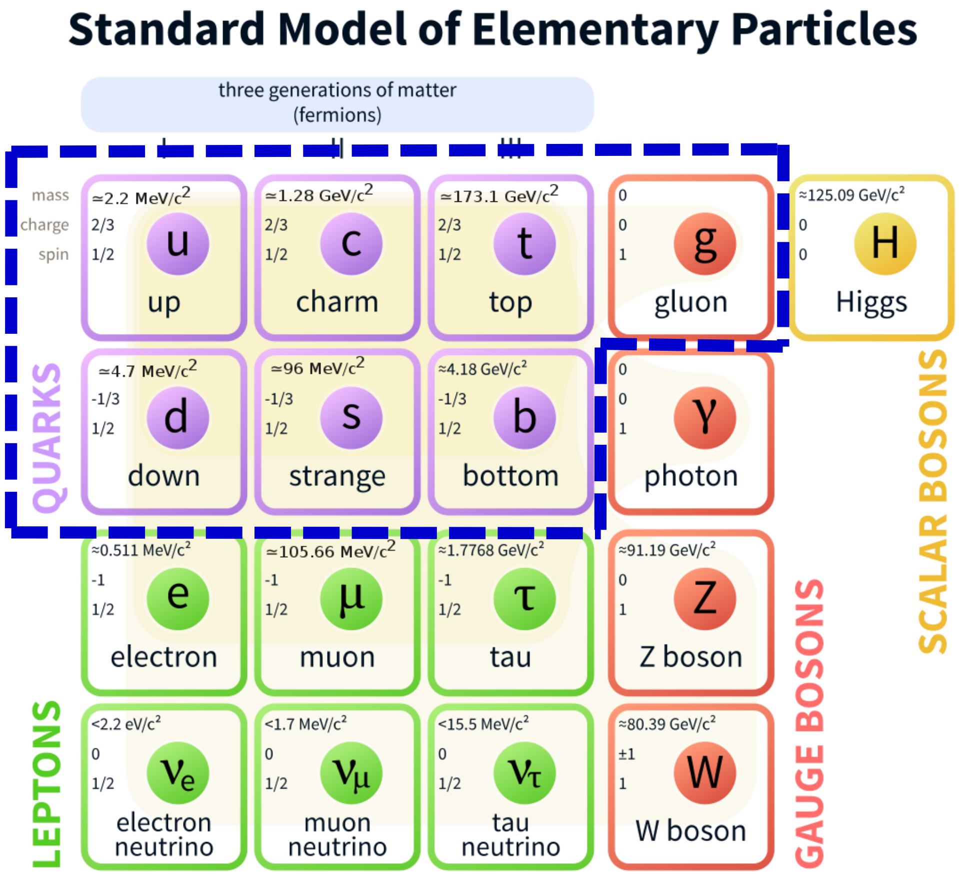
- Introduction
- LHCb detector
- Recent results on charmed baryons
  - Rediscovery of Ξ_{cc}^{++}, with $\Xi_c^{+}\pi^{+}$ — **Submitted to PRL, arXiv: 1807.01919**
  - Ξ_{cc}^{++} lifetime measurement — **Accepted by PRL, arXiv: 1806.02744**
  - Ω_c^{0} lifetime measurement — **Submitted to PRL, arXiv: 1807.02024**
- Summary

Hadron spectroscopy and QCD

- Quantum Chromodynamics (QCD) as the theory of the strong interaction very successful

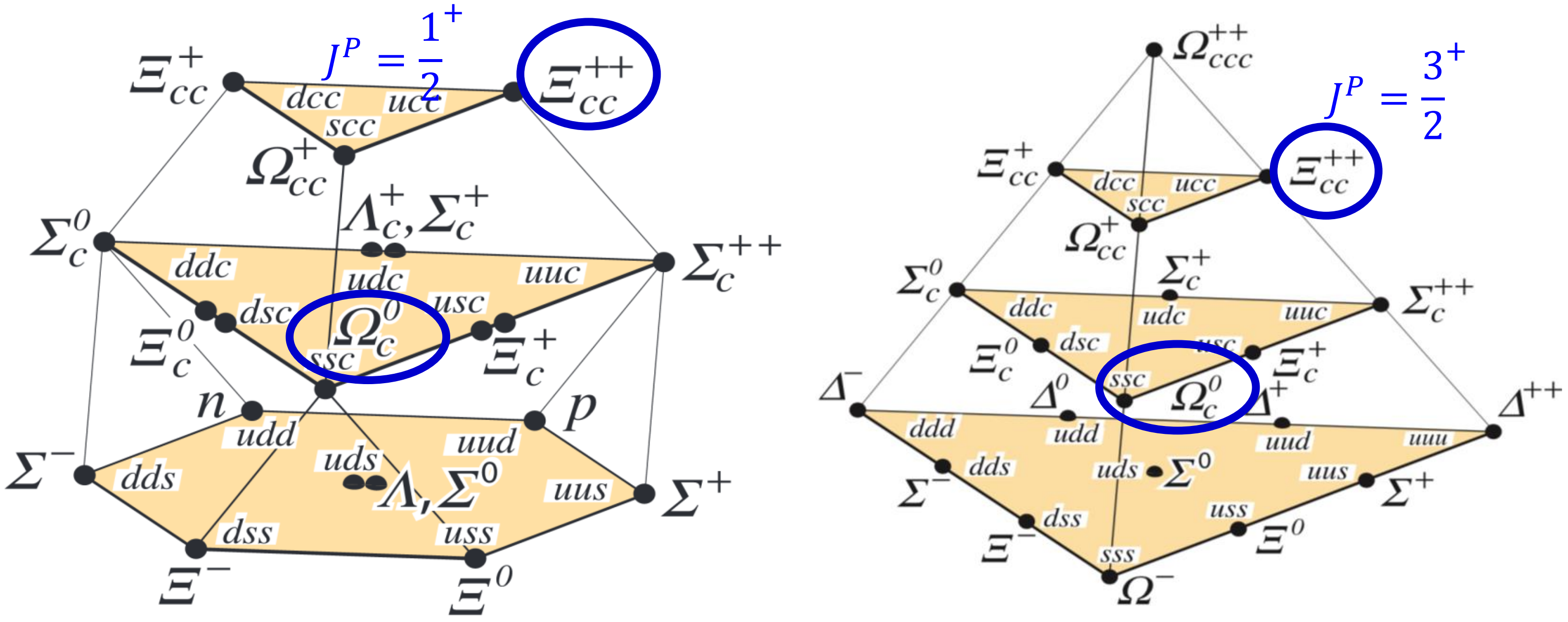
- Understanding structure and properties of hadrons from first principle of QCD remains a challenge
  - non-perturbative long distance effects involved

- Study of heavy hadron spectroscopy provides an ideal place to test different theoretical approaches in QCD



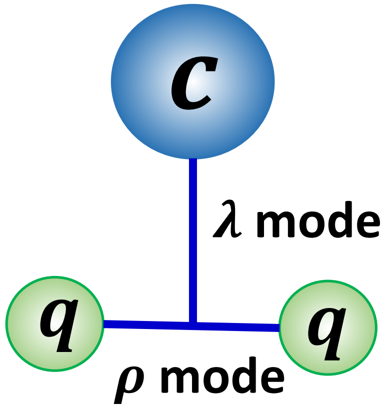
Success of the constituent quark model

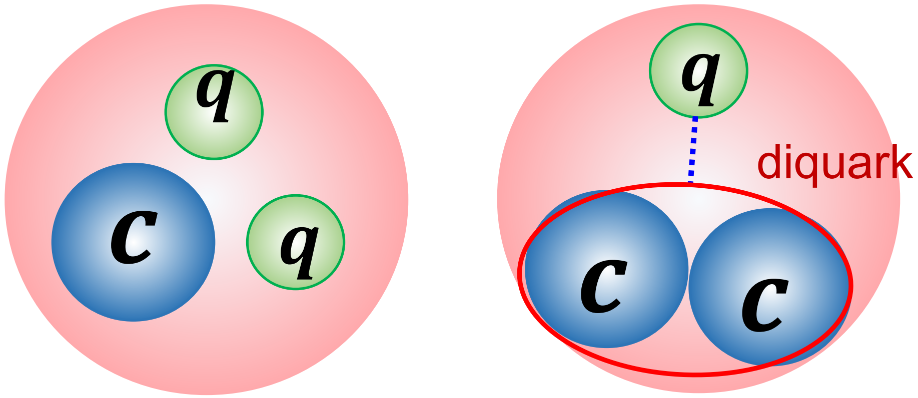
- Quark model, introduced by Gell-Mann and Zweig, in 1964
  - Construct the numerous hadrons using quarks
  - SU(4) and SU(5) to include new quarks: charm (c), and bottom (b)



Why charmed baryons?

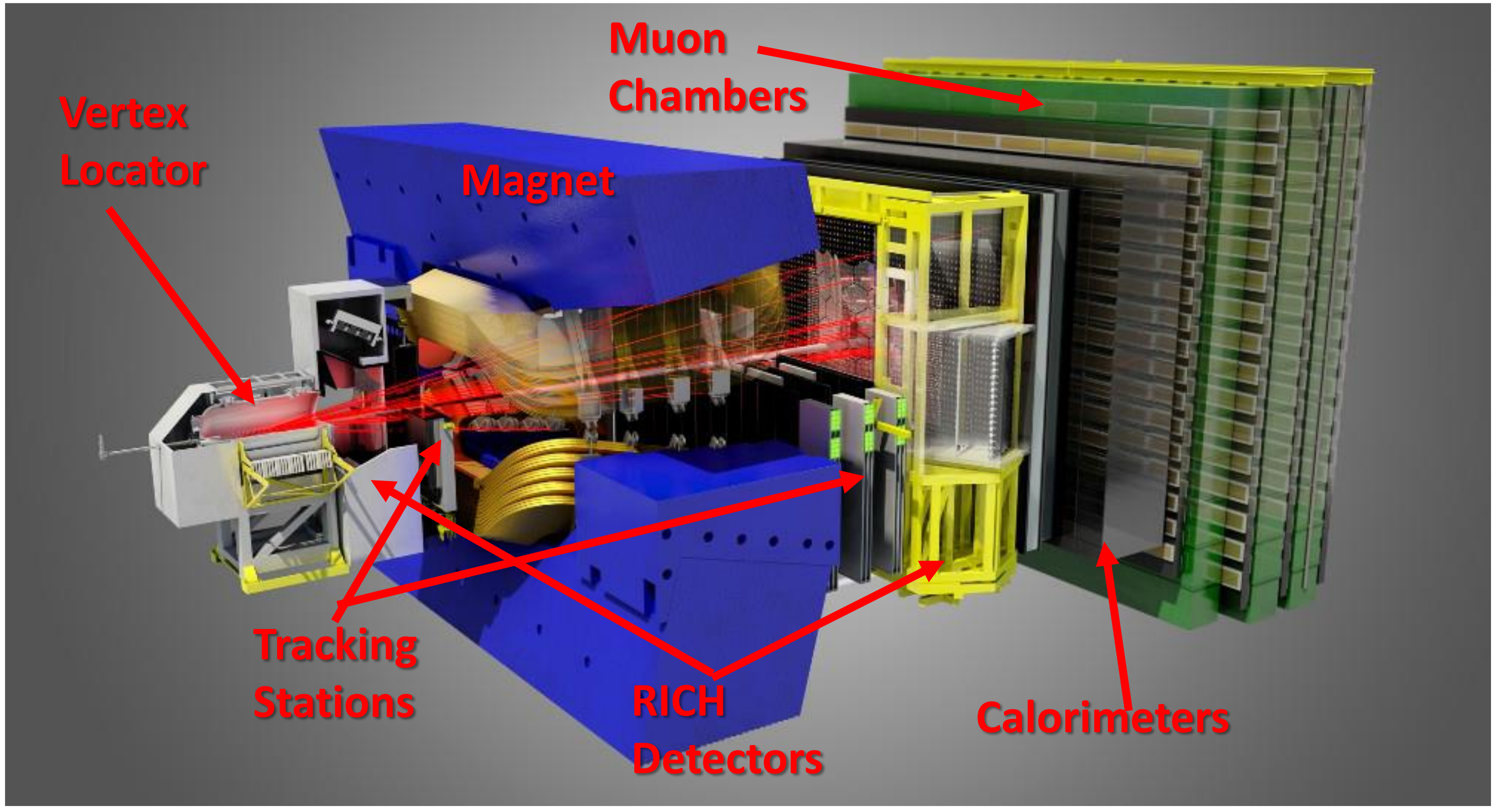
- Offer a rich spectroscopy of quark combinations
- **Strong decays**: test heavy quark symmetry of the heavy quark and chiral symmetry of the light quarks
- **Lifetimes**: offer insights into the interplay between strong and weak interactions
- Charm quark heavy but not as heavy as beauty: correction to Heavy Quark Expansion needed





JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

LHCb detector

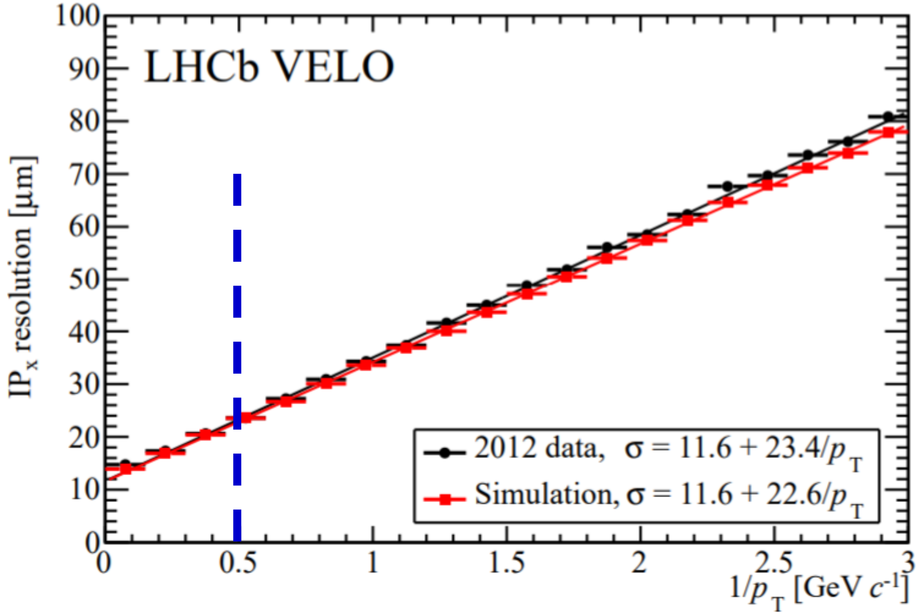


- LHCb is a forward spectrometer suited for b, c hadrons: $2 < \eta < 5$
- Momentum resolution:
  - 0.5% at 5 GeV, 1.0% at 200 GeV
- Excellent track and vertex reconstruction
- Good PID separation

Vertex detector

- 21 silicon strip detector stations, 8 mm from beam
  - IP resolution of $p_T > 2$ GeV/c tracks: $< 20\ \mu\text{m}$
  - Typical decay time resolution: ~ 45 fs

2014 JINST 9 P09007



JINST 3 (2008) S08005
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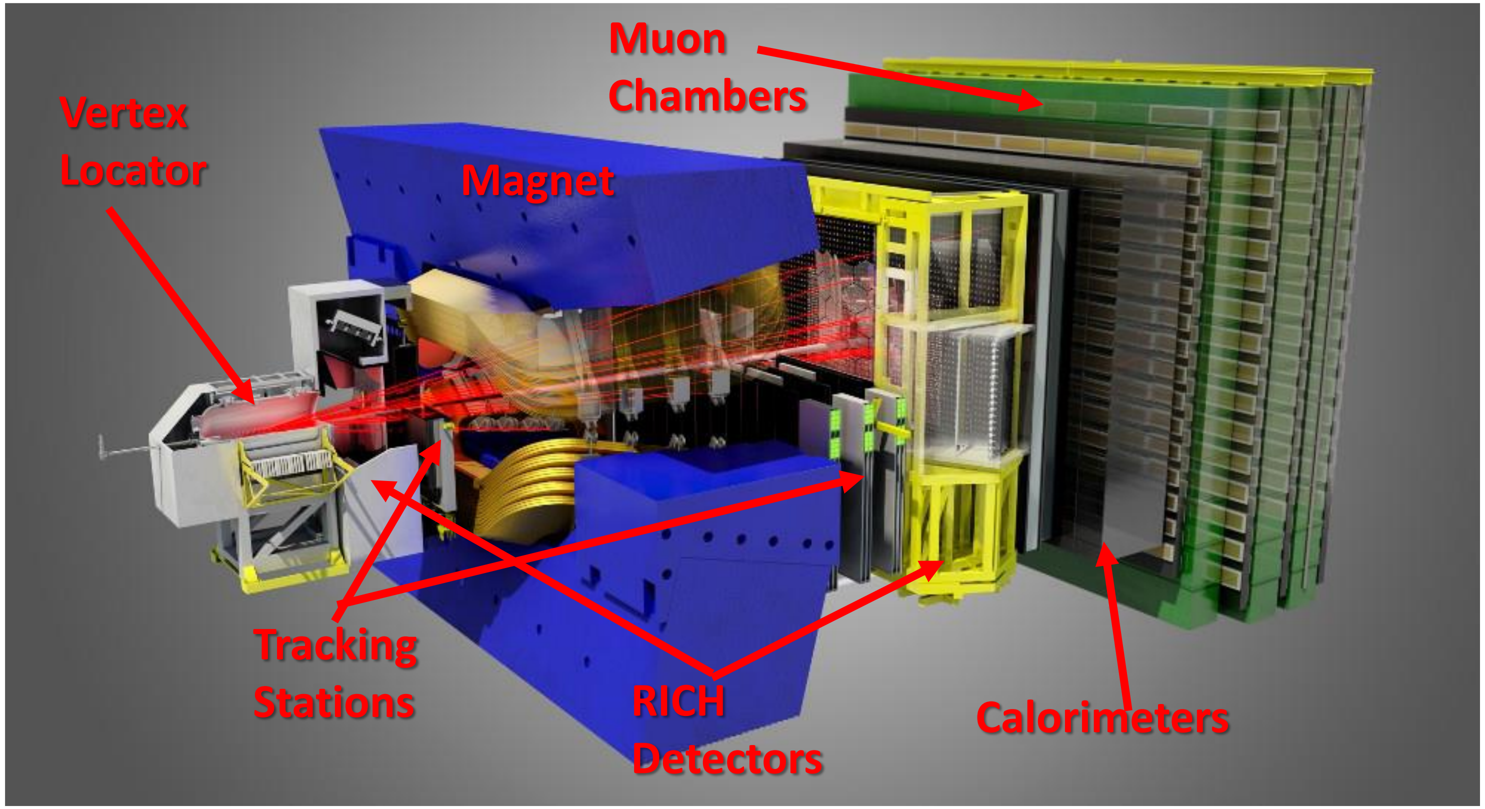
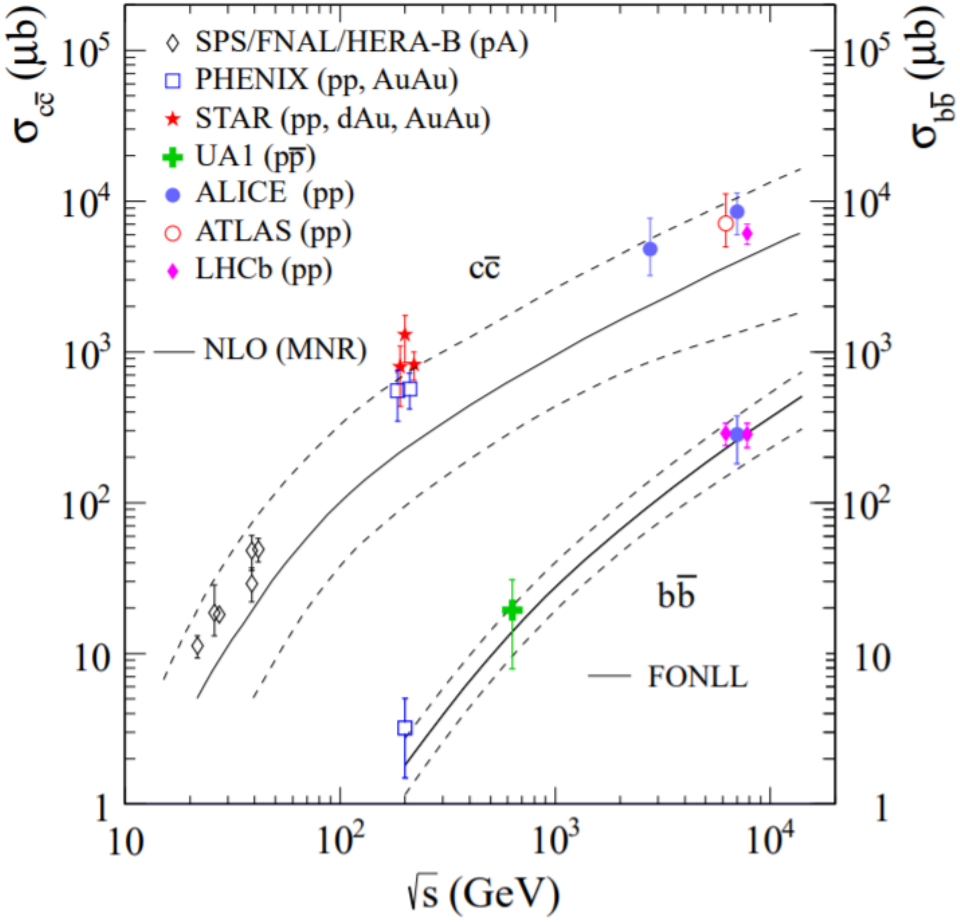
LHCb detector



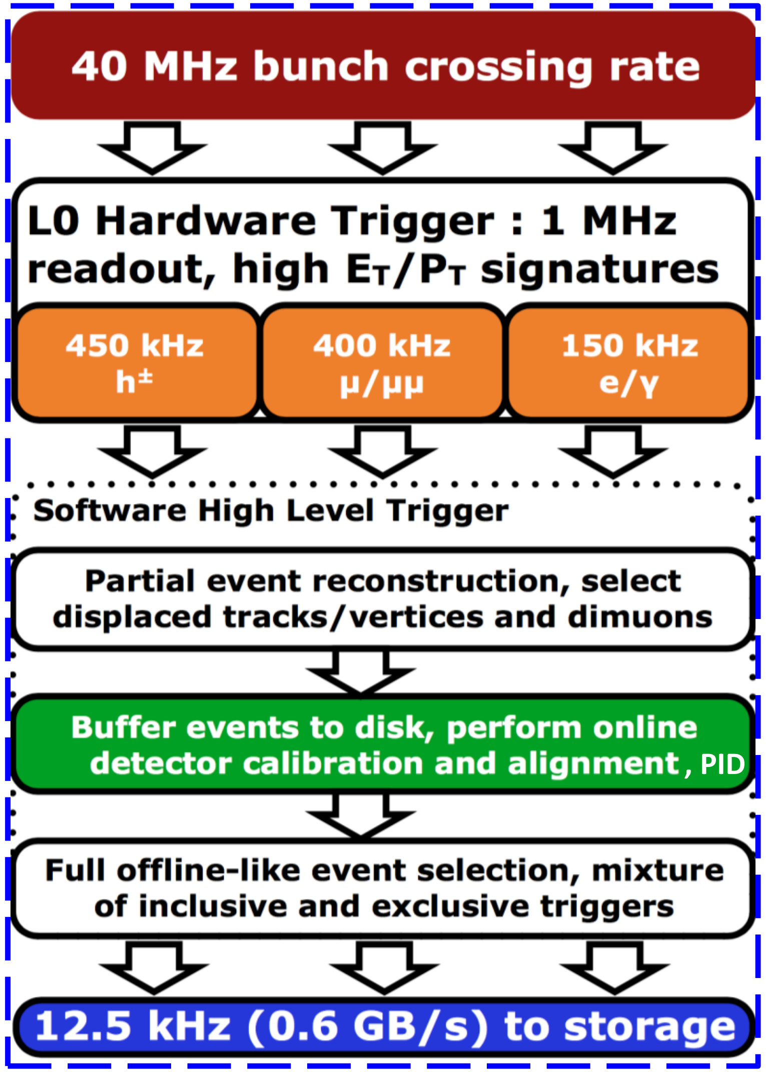


LHCb is a charm factory

J.Phys. G41 (2014) no.12, 124006

LHCb trigger

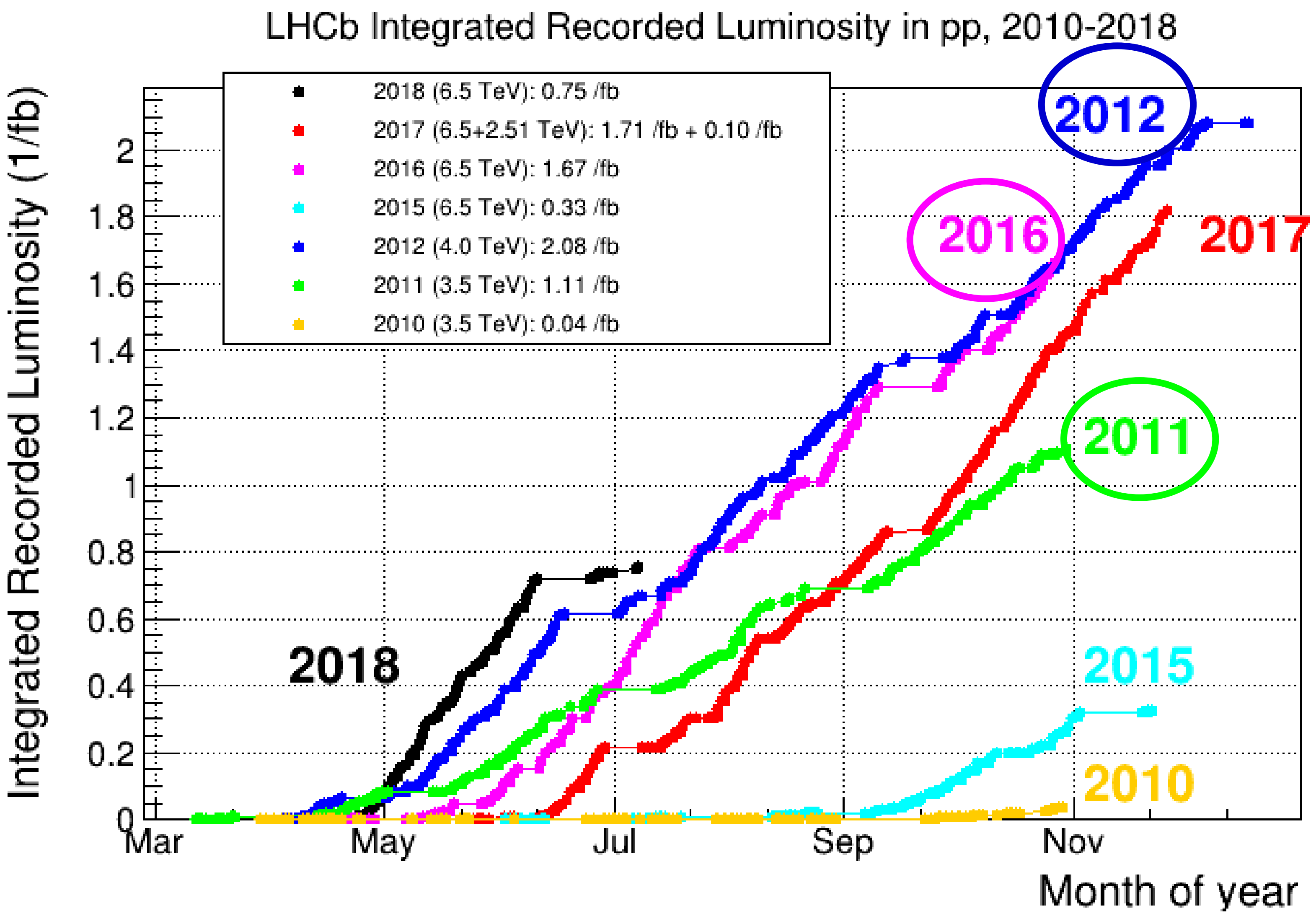
Comput. Phys. Commun. 208 (2016) 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)



- Run real-time alignment and calibration of the detector
- Data buffered out of first software trigger stage
- Second software trigger runs asynchronously
- Permits Turbo real-time analysis strategy
  - Candidates reconstructed at the trigger level saved directly for offline analysis + (online alignment and calibration)

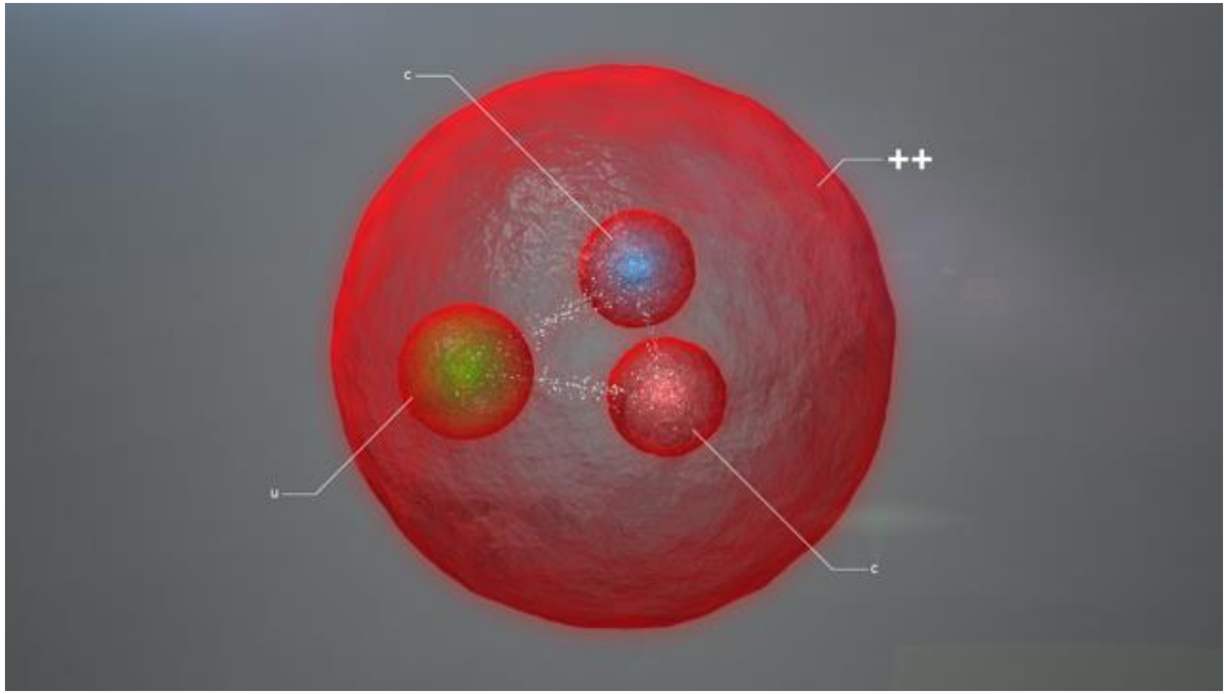
The first two analyses of today's talk benefit from the Turbo stream.

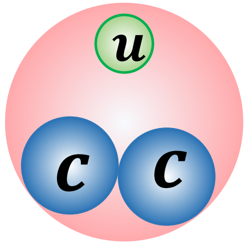
LHCb integrated luminosity



Today's talk with
2011 ($1\ fb^{-1}$)
2012 ($2\ fb^{-1}$)
2016 ($1.7\ fb^{-1}$)
data

Thanks to the LHC team!

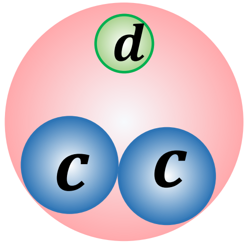




Rediscovery of Ξ_{cc}^{++}

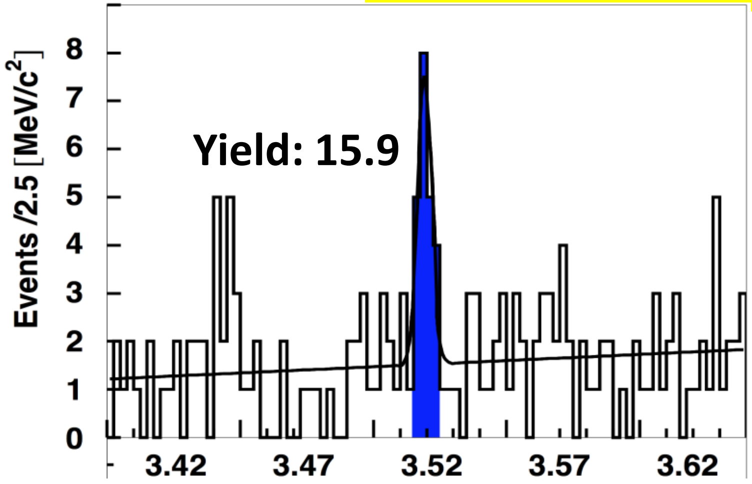
Studies of Ξ_{cc} by SELEX experiment

- **SELEX** (Fermilab E781) claimed observation of $\Xi_{cc}^{+}(ccd)$ in $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ and $\Xi_{cc}^{+} \to p D^{+} K^{-}$ decays
  - Short lifetime: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - Large production: $R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%$
  - Mass (combined): 3518.7 ± 1.7 MeV

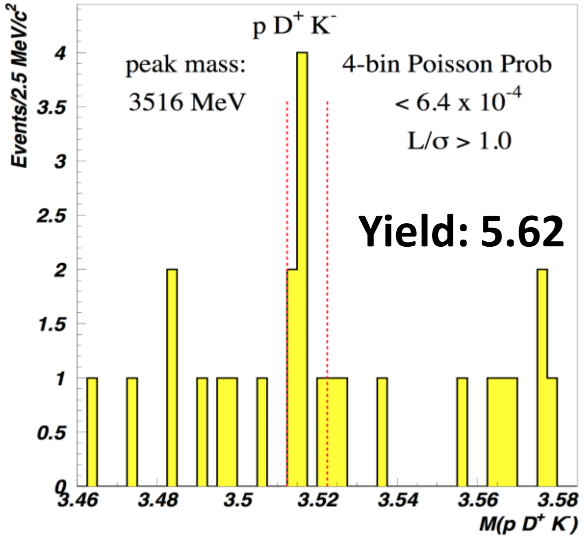


Ξ_{cc}^{+}

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ **PRL 89 (2002) 112001**



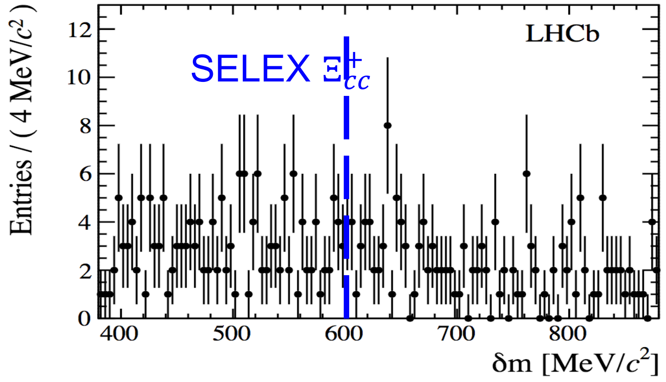
$\Xi_{cc}^{+} \to p D^{+} K^{-}$ **PLB 628 (2005) 18**

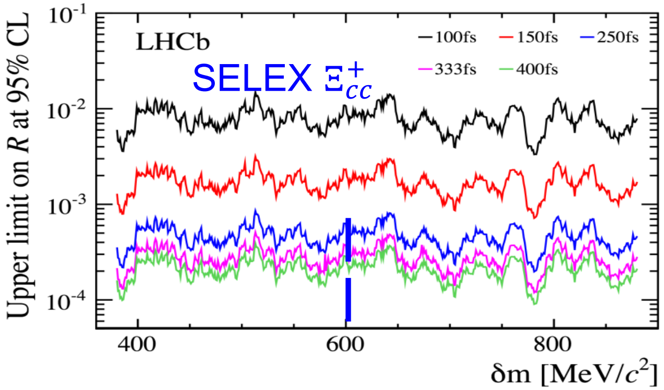


No confirmation from other experiments

- Fixed target: **FOCUS** (Fermilab E831) **Nucl. Phys. Proc. Suppl. 115 (2003) 33**
  - Studies charm hadrons produced in photon-nuclear fixed target collisions
- Electron colliders: **Babar, Belle** **BaBar: PRD 74 (2006) 011103** **Belle: PRL 97 (2006) 162001**
  - Large Λ_c^+ yields, 0.6 (0.8) M at Babar (Belle)
- Hadron Collider: **LHCb**

JHEP 12 (2013) 090

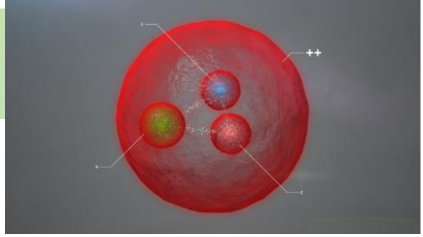




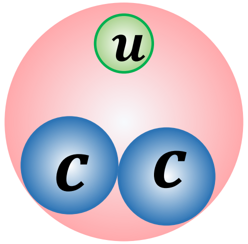
Observation of Ξ_{cc}^{++}

06/07/2017

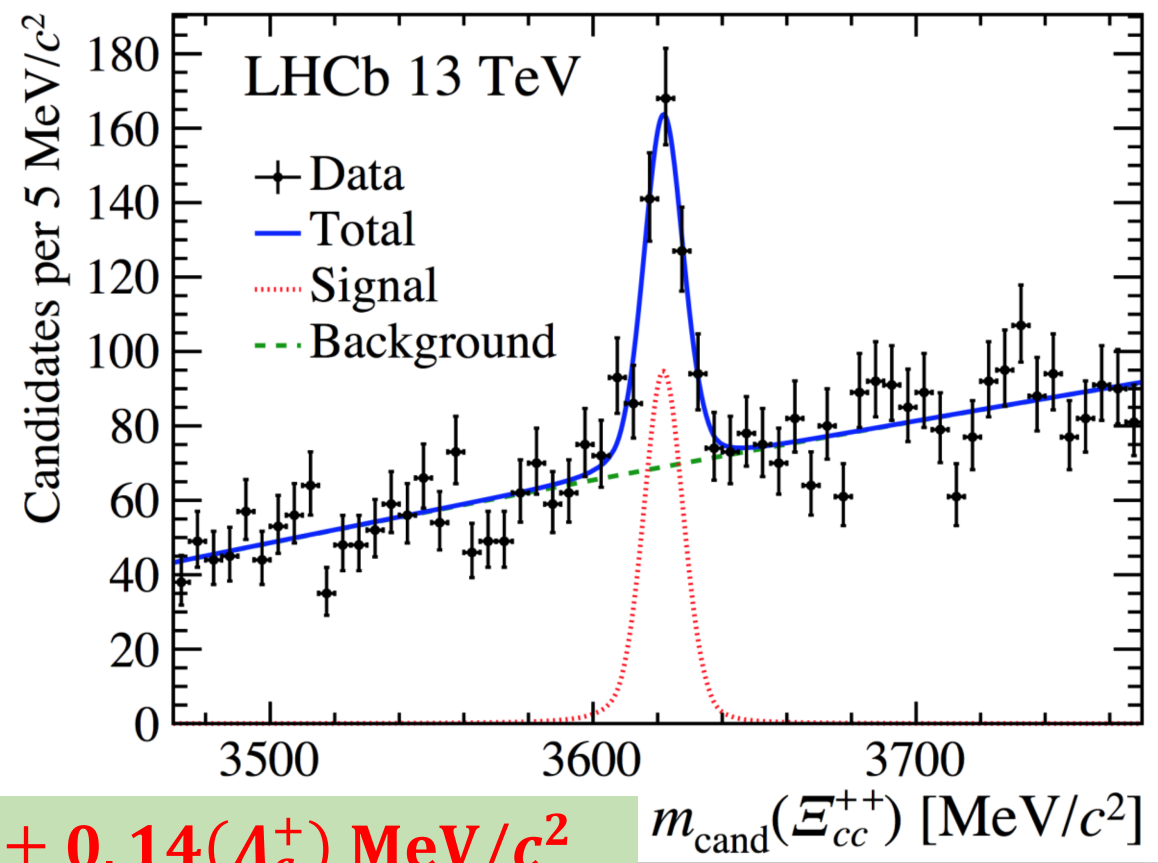
Phys. Rev. Lett. 119, 112001 (2017)



- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ observed by LHCb using 2016 data
  - Signal yield: 313 ± 33
  - Local significance > 12σ
  - Decaying only via weak interaction



Ξ_{cc}^{++}

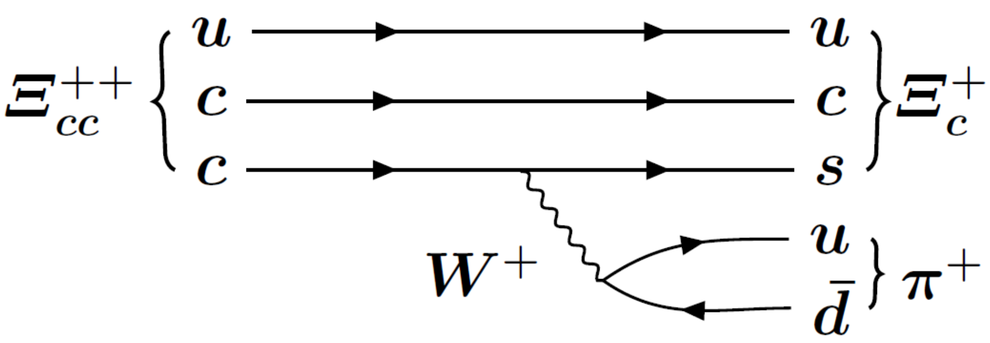


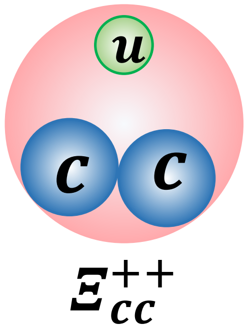
$$3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

F.-S. Yu et al., Chin. Phys. C 42, 051001 (2018)

Search for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

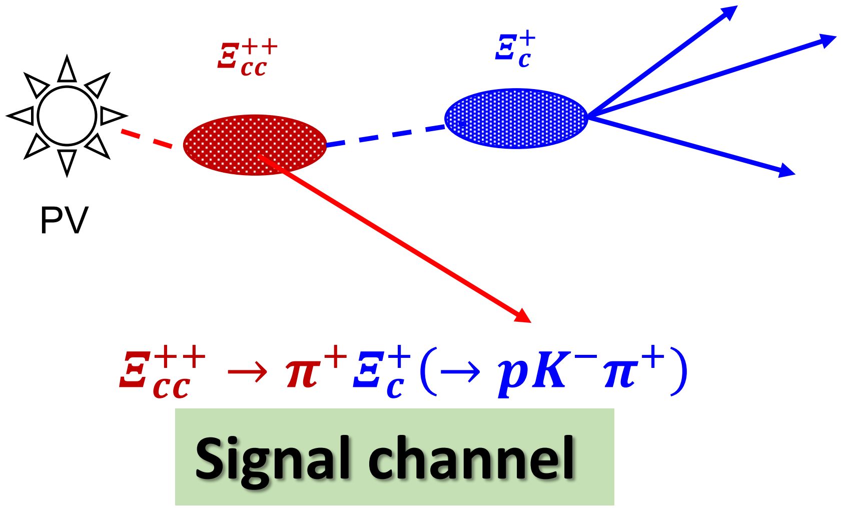
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: one of the best channels to confirm Ξ_{cc}^{++}
  - $BR(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \sim \mathcal{O}(1\%)$ **Prediction**
  - $BR(\Lambda_c^+ \to p^+ K^- \pi^+)$~(6.35%), **Measurement**
    $BR(\Xi_c^+ \to p^+ K^- \pi^+)$~(2%) **Prediction**
  - Fewer tracks (4 tracks) → higher efficiency

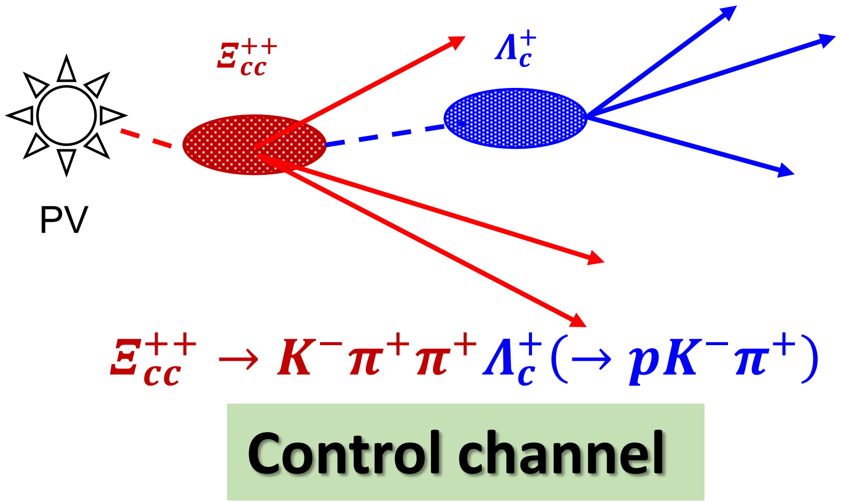




Signal and control channels

- Signal channel: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$, with $\Xi_c^+ \to pK^-\pi^+$
- Control channels:
  - $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, with $\Lambda_c^+ \to pK^-\pi^+$
  - $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$, $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, with $\Lambda_c^+ \to pK^-\pi^+$
  - Λ_b^0 data is used to calibrate trigger efficiency, and life time measurement



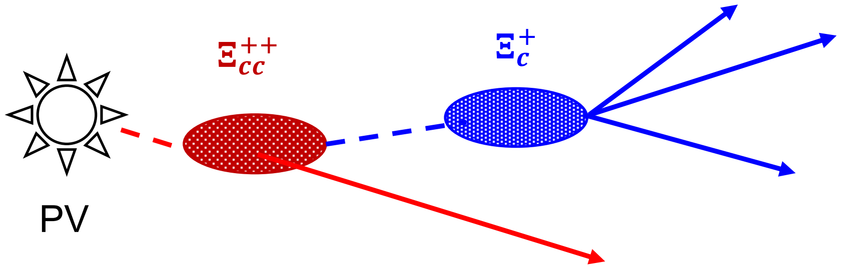


Event selection

- **Hadron trigger**: hardware trigger (p, K, π), and high level software trigger (Ξ_c^+)
- **Final state hadrons, p, K, π**: particle ID, not produced from primary vertex (PV)
- **Λ_c^+ or Ξ_c^+**: good vertex quality, separated from PV
- **Multivariate selector** is used to further suppress the backgrounds
  - p_T, decay angle, vertex fitting quality, IP χ^2, flight distance

As a follow-up analysis of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ has similar selection cuts as in previous analysis.

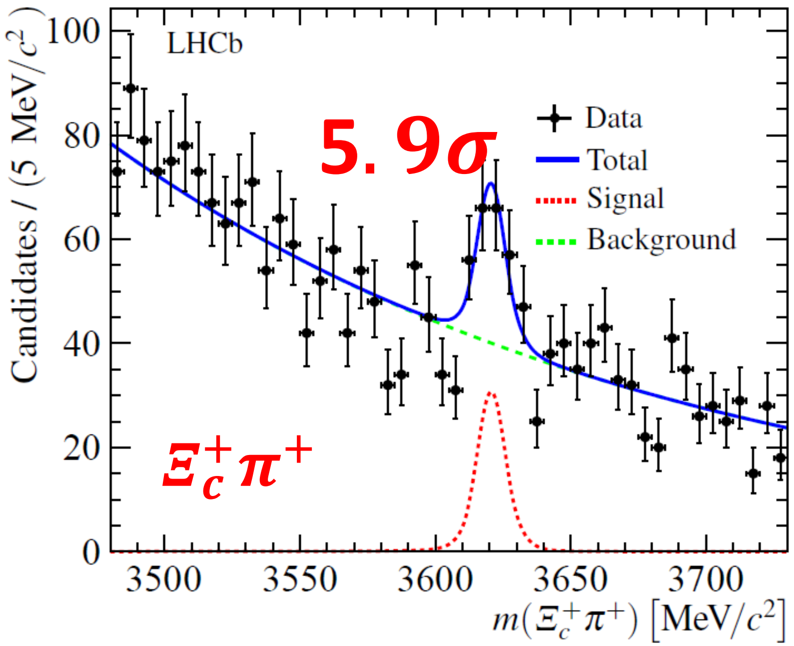
$\Xi_{cc}^{++} \to \pi^+ \Xi_c^+ (\to pK^- \pi^+)$

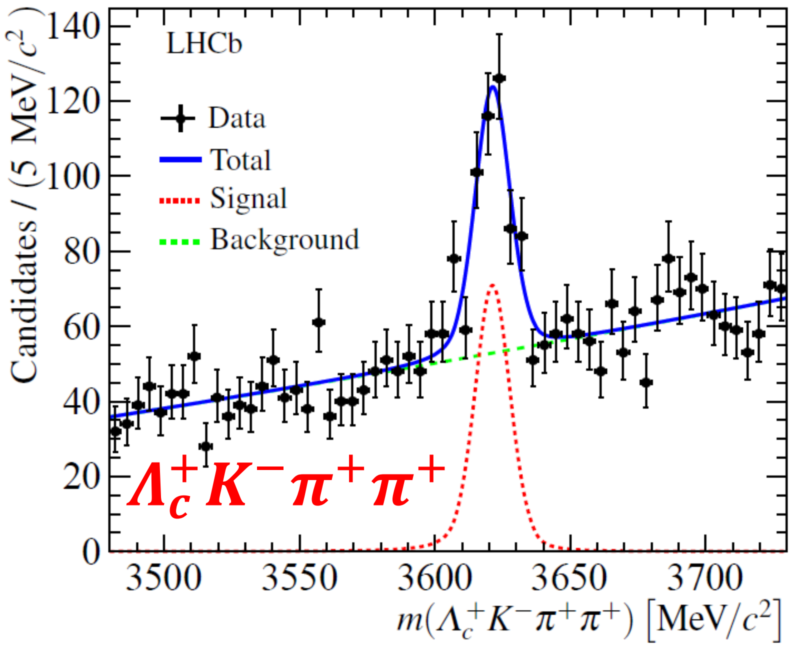


Mass fit

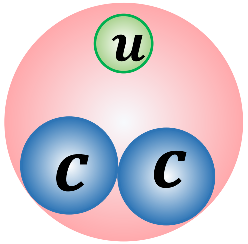
- **Signal**: Double-Sided Crystal-Ball + Gaussian
- **Background**: Exponential function
- $M(\Xi_{cc}^{++}) = M(\Xi_c^+\pi^+) - M(\Xi_c^+) + M_{PDG}(\Xi_c^+)$

Yields: (2016)
$\Xi_c^+\pi^+: 91 \pm 20$
$\Lambda_c^+K^-\pi^+\pi^+: 289 \pm 35$





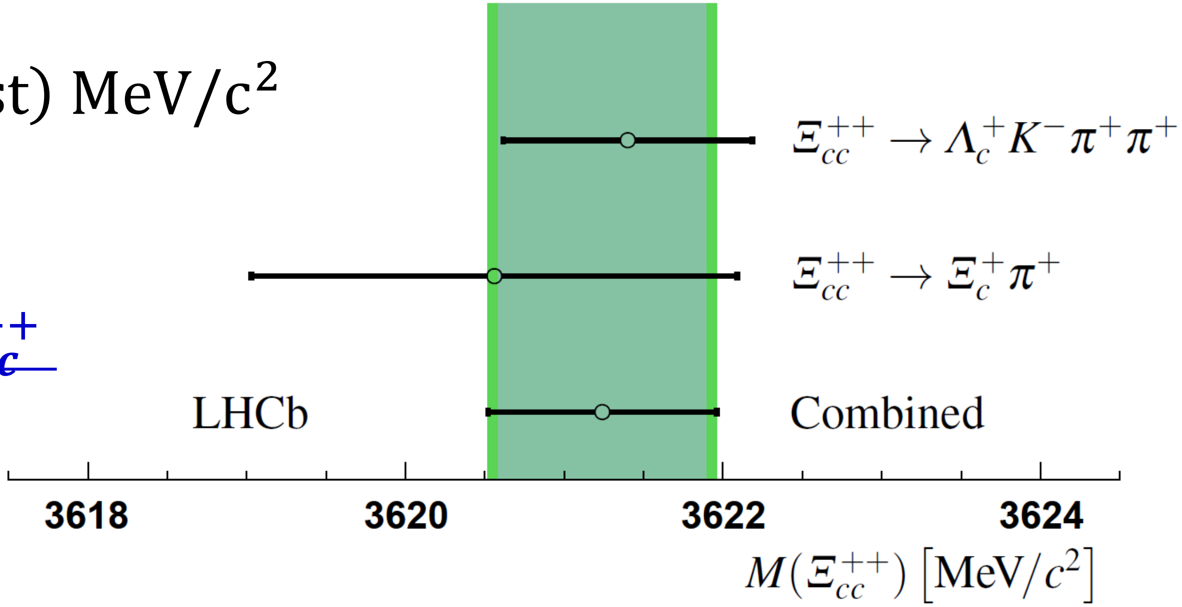
Mass measurement



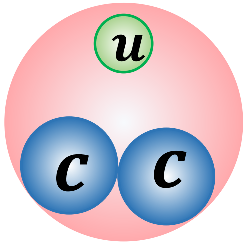
Ξ_{cc}^{++}

- The measured Ξ_{cc}^{++} mass is (with $\Xi_c^+\pi^+$ channel):
  - $\mathbf{3620.56 \pm 1.5\ (stat) \pm 0.4\ (syst) \pm 0.3\ (\Xi_c^+)\ MeV/c^2}$
- Consistent with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ result:
  - $3621.40 \pm 0.72\ (stat) \pm 0.27\ (\mathrm{syst}) \pm 0.14\ (\Lambda_c^+)\ \mathrm{MeV/c^2}$
- Combined results:
  - $3621.24 \pm 0.65\ (stat) \pm 0.31\ (\mathrm{syst})\ \mathrm{MeV/c^2}$

Confirm previous LHCb observation of Ξ_{cc}^{++}



Branching fraction measurement



Ξ_{cc}^{++}

- The ratio of branching fraction is defined as:

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

$$= \frac{N(\Xi_c^+ \pi^+)}{N(\Lambda_c^+ K^- \pi^+ \pi^+)} \cdot \frac{\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)}{\varepsilon(\Xi_c^+ \pi^+)}$$

No direct branching fraction measurement of $\Xi_c^+ \to pK^-\pi^+$ from experiments.

- Measure the signal yields and efficiency for each channel
- $\mathcal{R} = 0.035 \pm 0.009\ (stat) \pm 0.003\ (syst)$
  - Consistent with prediction

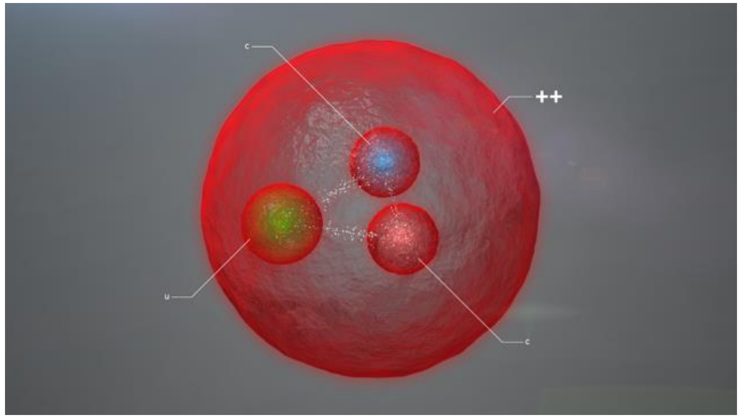
F.-S. Yu et al., Chin. Phys. C 42051001 (2018)

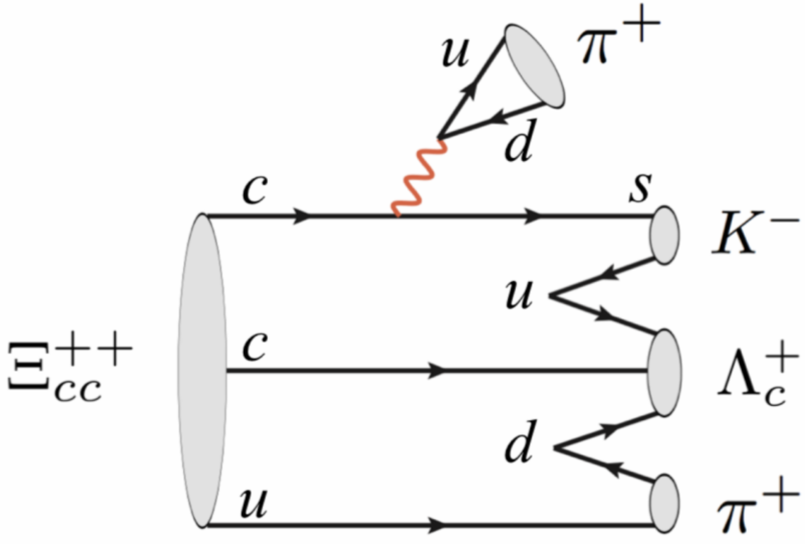
Uncertainty

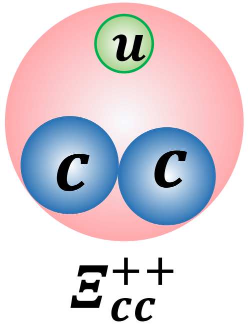
$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ channel

Source	Mass [MeV/c^2]	$\mathcal{R}(\mathcal{B})$ [%]
Momentum calibration	0.38	—
Selection bias correction	0.10	—
Fit model	0.05	5.2
Relative efficiency	—	6.5
Simulation modelling	—	1.2
Selection	—	0.7
Sum in quadrature	0.40	8.5

With limited statistics of both signal and control samples, the dominated uncertainty is statistical uncertainty (1.5 MeV, 0.009)







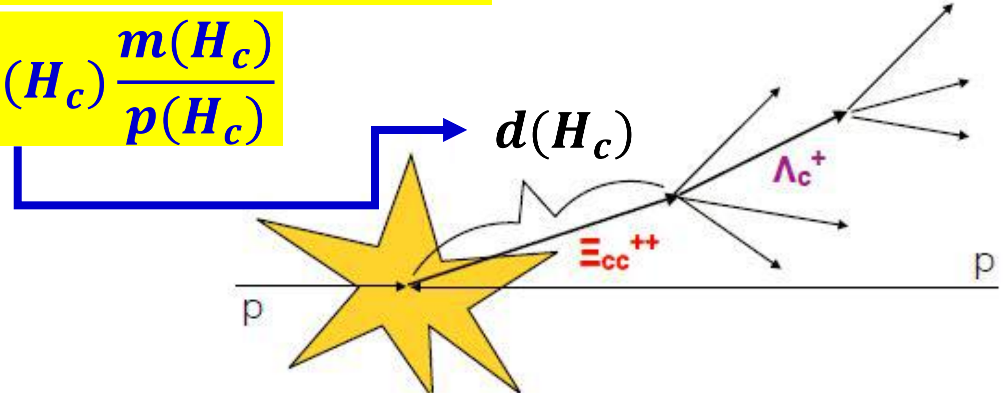
First measurement of the lifetime of Ξ_{cc}^{++}

Ξ_{cc}^{++} lifetime

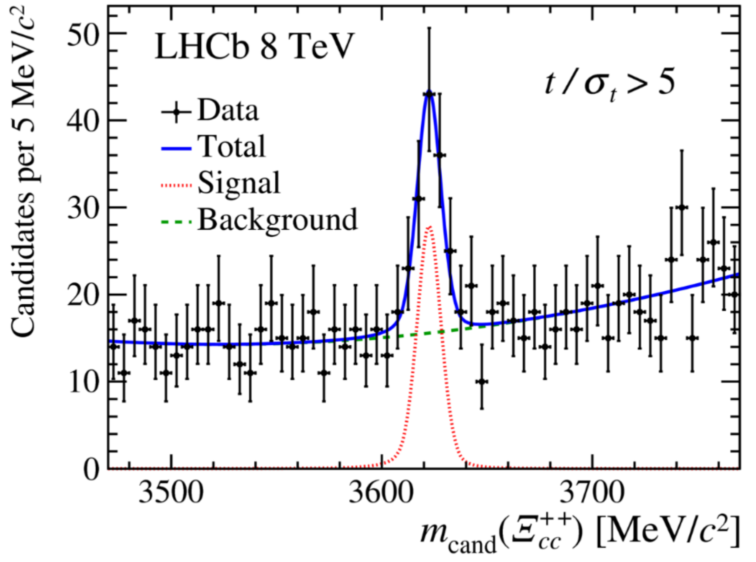
- Inconsistent with zero in the observation paper
- A lifetime measurement is critical:
  - Confirm it is a weakly decay
  - Necessary ingredient for theoretical prediction of BR
  - Important information for experimental exploration of Ξ_{cc}^{++}
  - Test various predictions in QCD models

Decay time measurement:

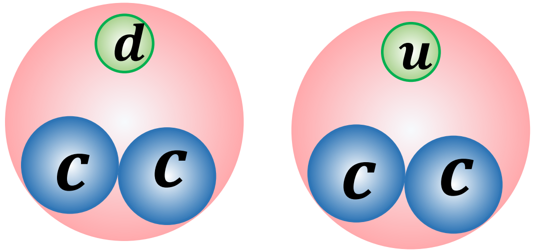
$$\tau(H_c) = d(H_c)\frac{m(H_c)}{p(H_c)}$$



Phys. Rev. Lett. 119, 112001 (2017)

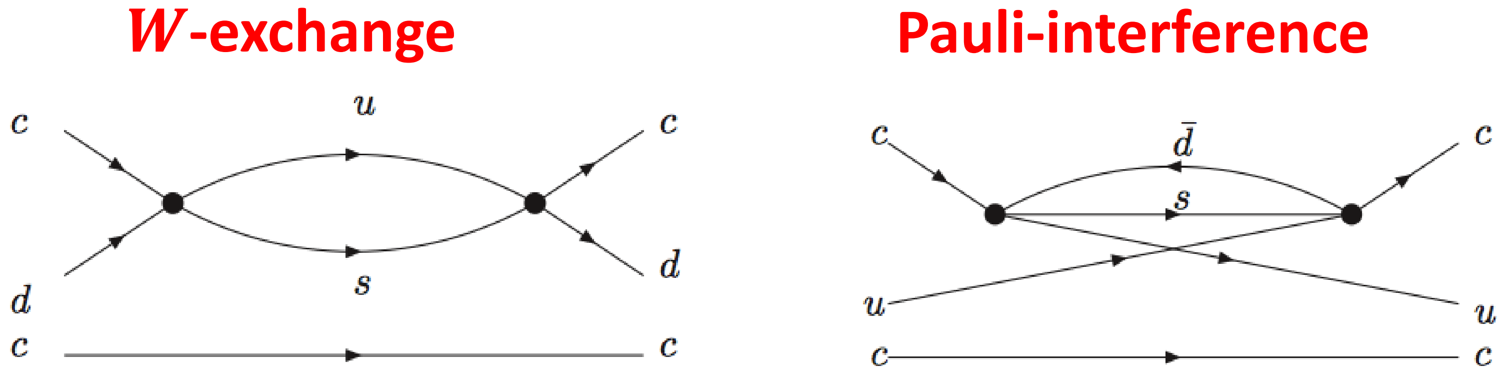


Predictions: long lived Ξ_{cc}^{++}



Ξ_{cc}^{+} Ξ_{cc}^{++}

- Predicted $\tau(\Xi_{cc}^{++})$ in range of [0.20, 1.05] ps
  - Diquark model, effective constituent model, NRQCD potential model, harmonic oscillator model …
  - Significant non-spectator contribution from Pauli-Interference diagrams



- $\tau(\Xi_{cc}^{++}) \sim 3-4\ \tau(\Xi_{cc}^{+})$
  - Destructive Pauli interference in Ξ_{cc}^{++} decays
  - W-exchange between c and d quarks only in Ξ_{cc}^{+} decays

Analysis strategy

- Same data sample, event selection as previous Ξ_{cc}^{++} observation
  - Specific trigger requirement to simplify trigger efficiency determination
  - Signal yields (2016): 313 → 304
- **Measure decay time distribution relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$**
  - Acceptance correction based on MC
- Weighted unbinned maximum likelihood fit (sFit)

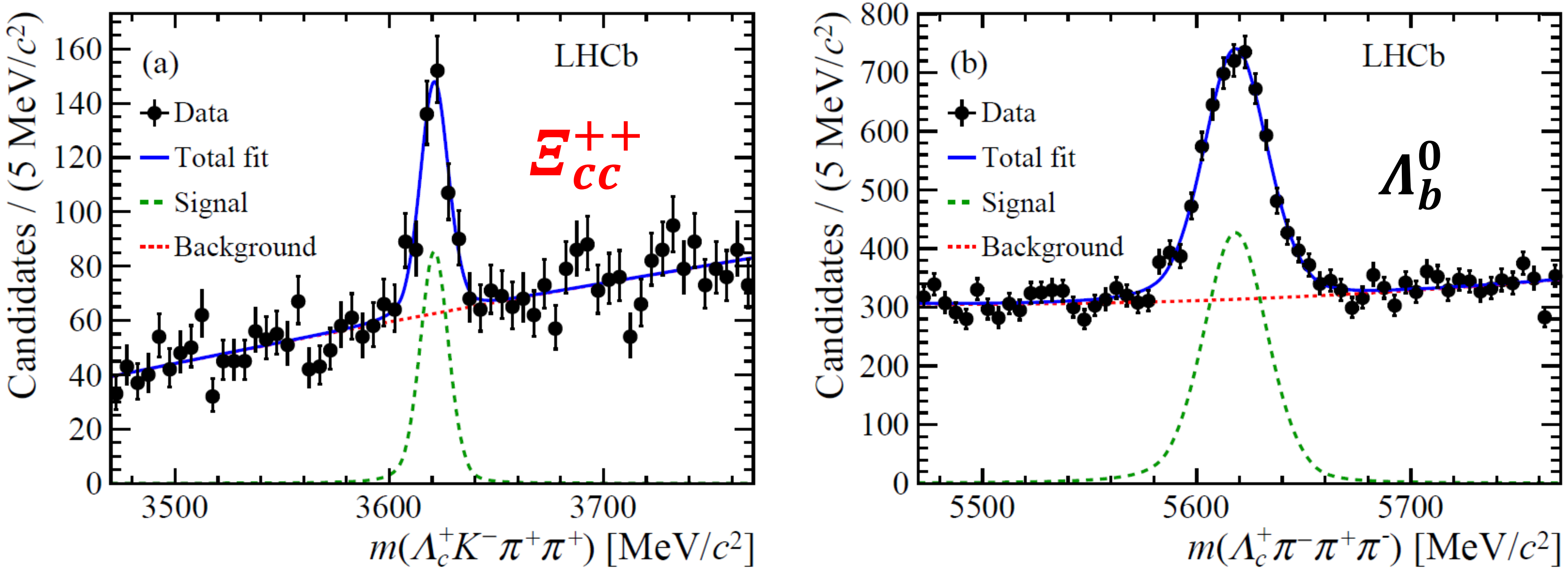
Y. Xie, arXiv:0905.072

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

Selected candidates

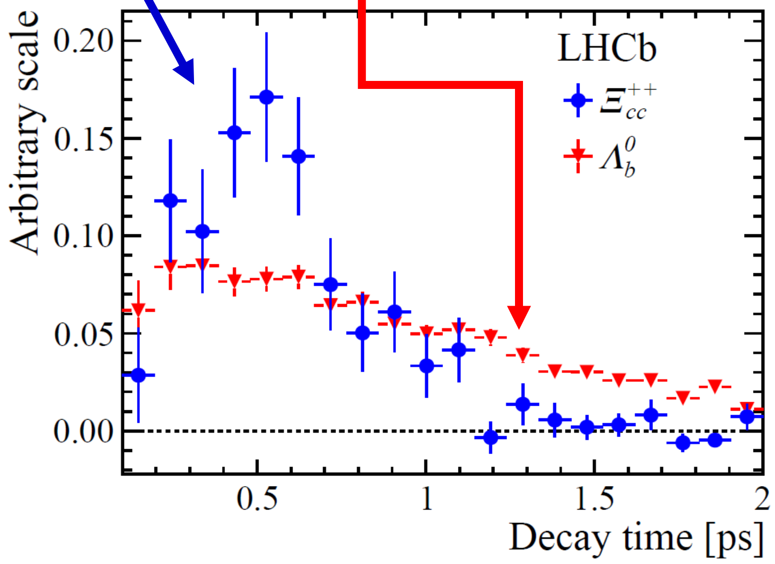
- **Signal**: Double-sided Crystal-Ball + Gaussian
- **Background**: 2[nd] order Chebychev

Yields: (2016)
Ξ_{cc}^{++}: 304±35
Λ_b^0: 3379 ± 119



Lifetime fit

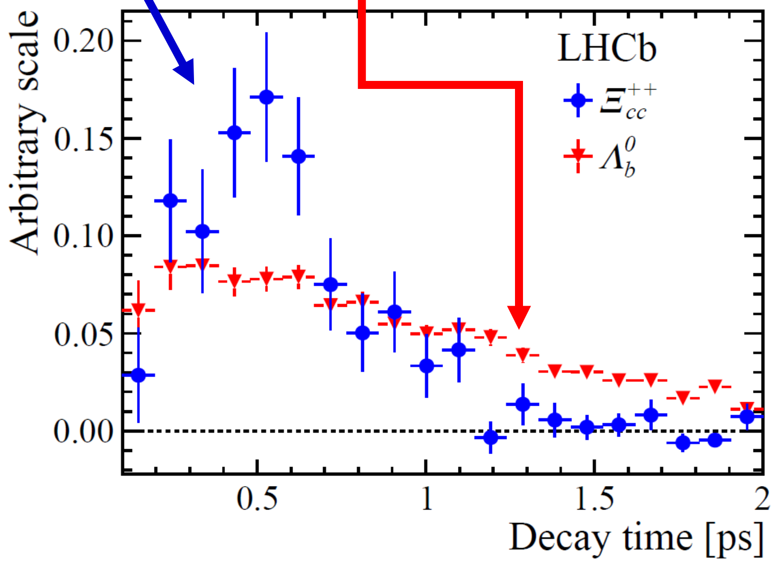
$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



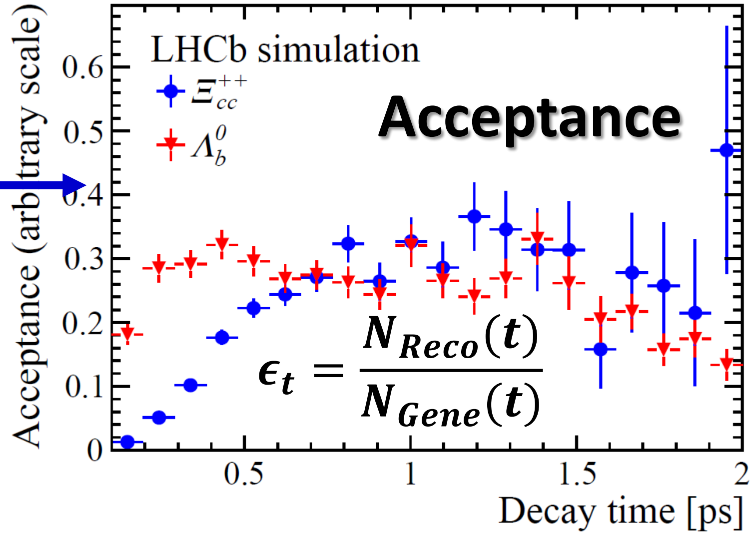
Background subtracted decay time distributions

Lifetime fit

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



Background subtracted decay time distributions



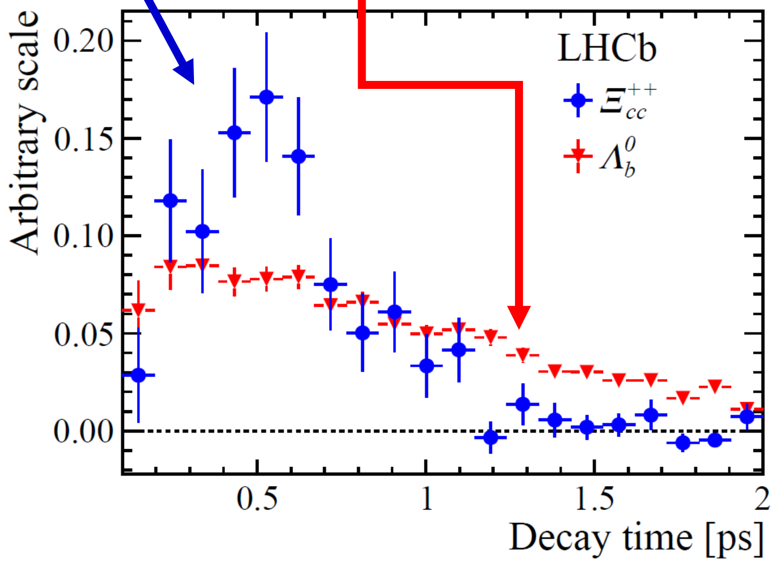
Lifetime fit

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

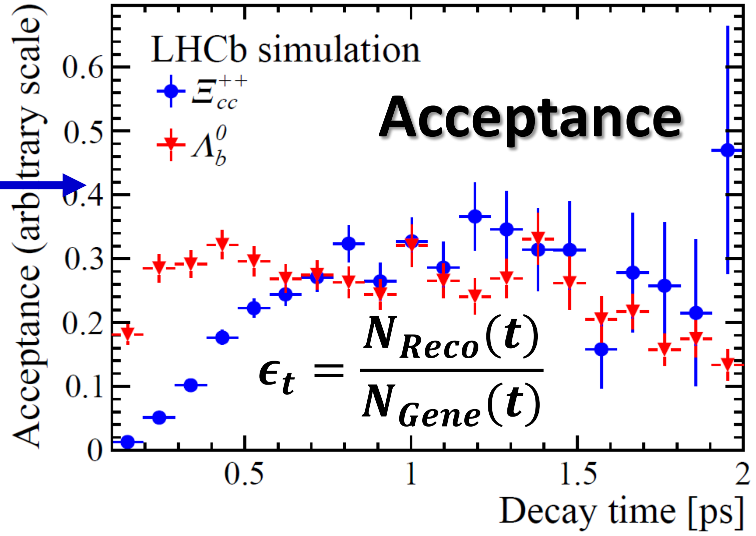
PDG 2018

$\tau_{\Lambda_b^0} = 1.470 \pm 0.010$ ps (PDG)

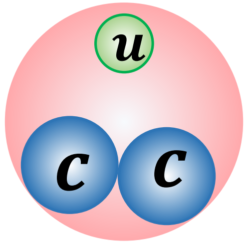
Free parameter



Background subtracted decay time distributions

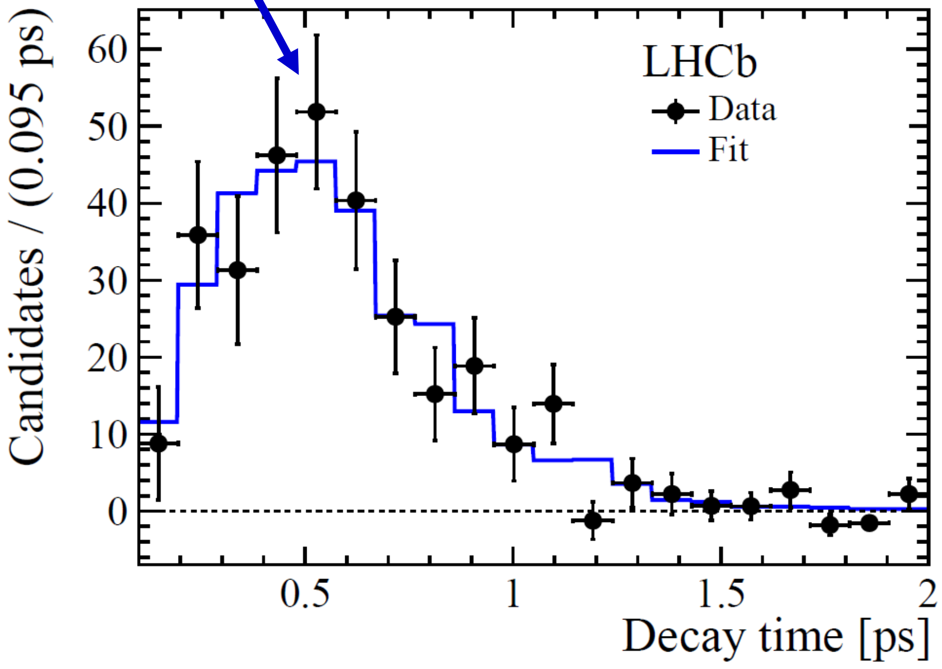


Lifetime fit



Ξ_{cc}^{++}

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}\ \text{ps}$$

Systematic Uncertainty

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

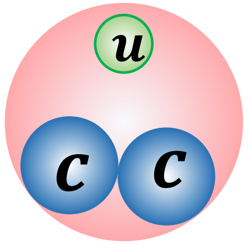
- **Binning**:
  - Systematics due to binned acceptance estimated with pseudo experiments
- **Resonant**:
  - Weight MC to match $M(K^-\pi^+\pi^+)$ (for Ξ_{cc}^{++}), and $M(\pi^-\pi^+\pi^-)$ (for Λ_b^0) distributions in data

Measured results: $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014\ (\text{syst})\ \text{ps}$

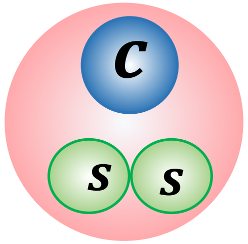
Cross-checks and Results

- Various cross-checks had been done: no evidence of other effects
  - Charge: Ξ_{cc}^{++} vs. $\bar{\Xi}_{cc}^{--}$
  - Magnet polarities: Down vs. Up
  - Number of PV
- Binned χ^2 fit: consistent with nominal result
- Λ_b^0 lifetime using simulation-based acceptance correction, consistent with PDG Value

Confirmation of Ξ_{cc}^{++} with $\Xi_c^+\pi^+$ channel
First measurement of Ξ_{cc}^{++} lifetime: weakly decay



Ξ_{cc}^{++}



Measurement of the lifetime of Ω_c^0

Ω_c^0 lifetime measurement motivation

- Test theoretical approaches, like Heavy quark expansion (HQET)
  - Higher order effects are important: expansion in powers of $1/m_Q$
  - c-hadrons: sizeable correction
- The least well-measured charmed baryons is Ω_c^0: 69 ± 12 fs (17%)

PDG 2018

VALUE (10^{-15} s)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{69 \pm 12}$	**OUR AVERAGE**				
$72 \pm 11 \pm 11$	64	LINK	2003C	FOCS	$\Omega^- \pi^+$, $\Xi^- K^- \pi^+ \pi^+$
$55\ ^{+13}_{-11}\ ^{+18}_{-23}$	86	ADAMOVICH	1995B	WA89	$\Omega^- \pi^- \pi^+ \pi^+$, $\Xi^- K^- \pi^+ \pi^+$
$86\ ^{+27}_{-20} \pm 28$	25	FRABETTI	1995D	E687	$\Sigma^+ K^- K^- \pi^+$

- Expected lifetime hierarchy should be:

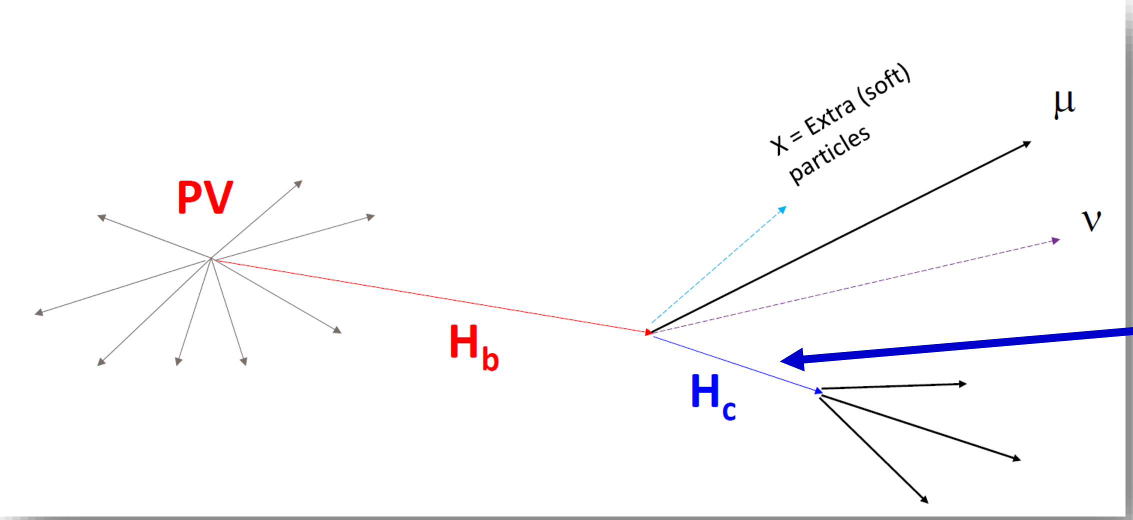
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

H-Y Cheng, arXiv: 1807.00916

Front. Phys. (Beijing) 10 (2015) 101406
Riv. Nuovo Cim. 26N7 (2003) 1
Proceedings, 3rd Workshop, Marbella, Spain, June 1-6, 1993, 1991
Phys. Rev. D56 (1997) 2783
Phys. Rept. 289 (1997) 1
Sov. J. Nucl. Phys. 41 (1985) 120

Signal and control channels

- Signal channel: $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X$, with $\Omega_c^0 \to pK^-K^-\pi^+$
- Control channel: $B \to D^+ \mu^- \bar{\nu}_\mu X$, with $D^+ \to K^-\pi^+\pi^+$



Decay time measurement:

$$\tau(H_c) = d(H_c)\frac{m(H_c)}{p(H_c)}$$

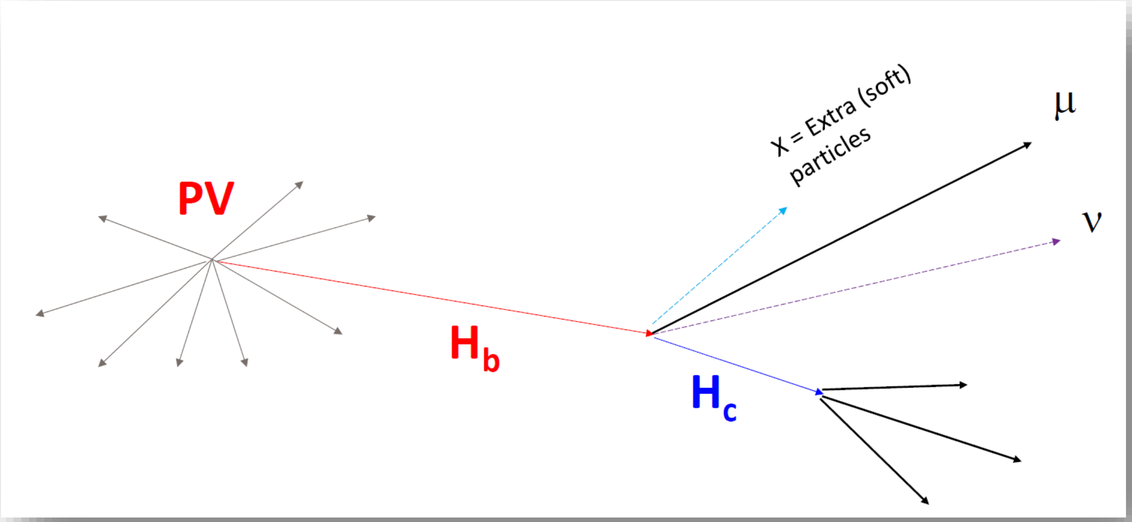
Using Ω_c^0 from Ω_b^- to avoid bias from trigger and online selections

- Well-separated from PV: long b-hadron lifetime.

SL channel has larger branching fraction than hadronic channels

Event selection

- Final state hadrons, p, K, π: Particle ID, not produced from PV
- Final state muon, μ : muon ID, not produced from PV
- c-hadrons, Ω_c^0, D^+: good vertex quality, separate from PV
- b-hadrons, Ω_b^-, B: good vertex quality, mass, c-hadron is not upstream of b-hadrons decay
- Multivariate selector

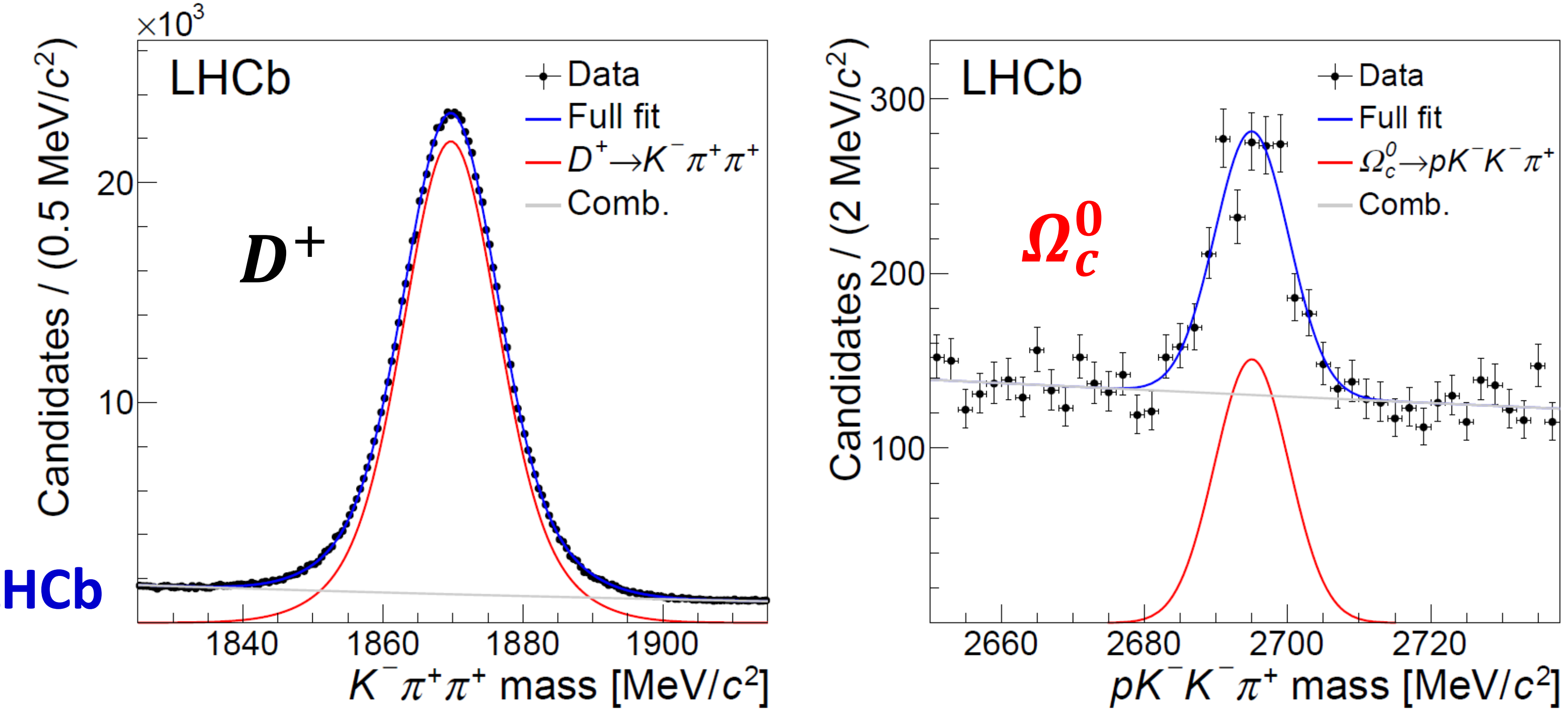


Signal samples

Yields: (2011+2012)
$\Omega_c^0\mu^-$: 978 ± 60
$D^+\mu^-$: $(809 \pm 1) \times 10^3$

- **Signal**: Double Gaussian function
- Combinatorial **background**: Exponential function

Ω_c^0 : ~10 times more larger than any previous sample used to measure Ω_c^0 lifetime



D^+: 10% of LHCb Run-I data!

Lifetime fit

- Signal PDF: $S(t_{rec}) = f(t_{rec})g(t_{rec})\beta(t_{rec})$
  - $f(t_{rec})$: binned template from simulation, using input lifetime τ_{sim}
  - $g(t_{rec})$: accounting for a different lifetime than that used in the simulation (τ_{sim})

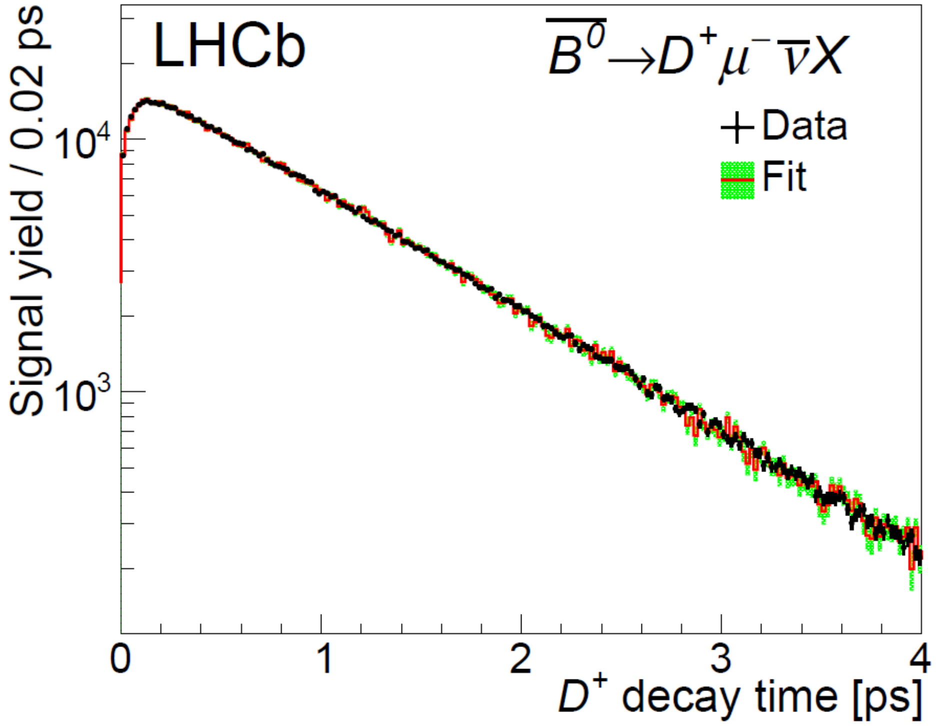
$$g(t_{rec}) = e^{-\left(\frac{t_{rec}}{\tau_{fit}} - \frac{t_{rec}}{\tau_{sim}}\right)}$$

  - $\beta(t_{rec})$: a correction that accounts for a small difference in efficiency between data and simulation
    - Obtained from D^+ decay and used for Ω_c^0 decay

$$\beta(t_{rec}) = 1 + \beta_0 t_{rec}$$

D^+ decay time fit

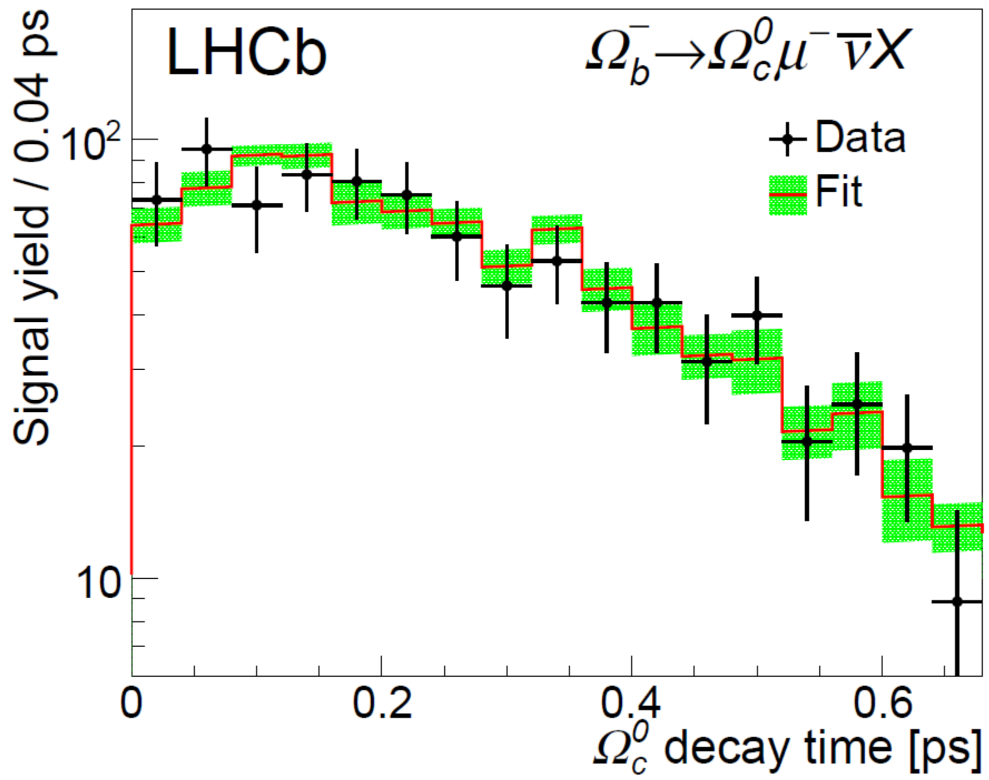
- With PDG D^+ lifetime of 1040 fs, $\beta(t_{rec})$ is calibrated
  - The fitted D^+ lifetime is consistent with PDG value, as expected



The $\beta(t_{rec})$ correction changes the D^+ lifetime by 10 fs, which is 1.2σ

Ω_c^0 decay time fit results

- **Simultaneous fit** to both Ω_c^0, D^+: free parameters $r(\Omega_c^0)$ and $\tau(D^+)$
- Use D^+ in $B \to D^+\mu^- X$, calibrate the acceptance efficiency



$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$

D^+ lifetime

4 times larger than PDG value!

69 ± 12 fs

Cross-checks

- Signal from Ω_b^- SL decay: $\Omega_c^0\mu$ mass, p_T, lifetime spectrum comparison between s-weighted data and simulation
- Background subtraction: sideband subtraction vs. sPlot
- 13 TeV 2016 data: and an additional D^0 lifetime measurement
  - D^0 lifetime: 88,000 $B^- \to D^0(\to K^+K^-\pi^+\pi^-)\mu^-X$
- Selection cuts: tighter particle ID, tighter BDT

All of test results consistent with expectations/uncertainties.

Systematic Uncertainty

Source	$r_{\Omega_c^0}$ (10^{-4})
Decay time acceptance	13
Ω_b^- prod. spectrum	3
Ω_b^- lifetime	4
Decay time resolution	3
Background subtraction	18
$H_c(\tau^-, D)$, random μ^-	8
Simulated sample size	98
Total systematic	101
Statistical uncertainty	230

- **Decay time acceptance: ~ 1%** correction to lifetime
- **Simulated sample size**

Ω_c^0 lifetime results

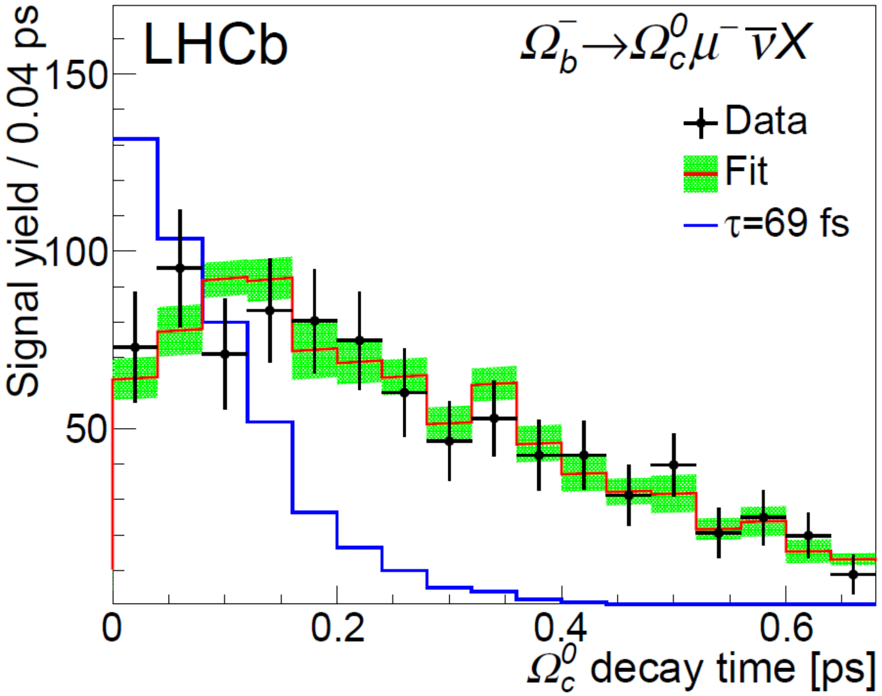
- Measured Ω_c^0 **lifetime** in SL Ω_b^- decays

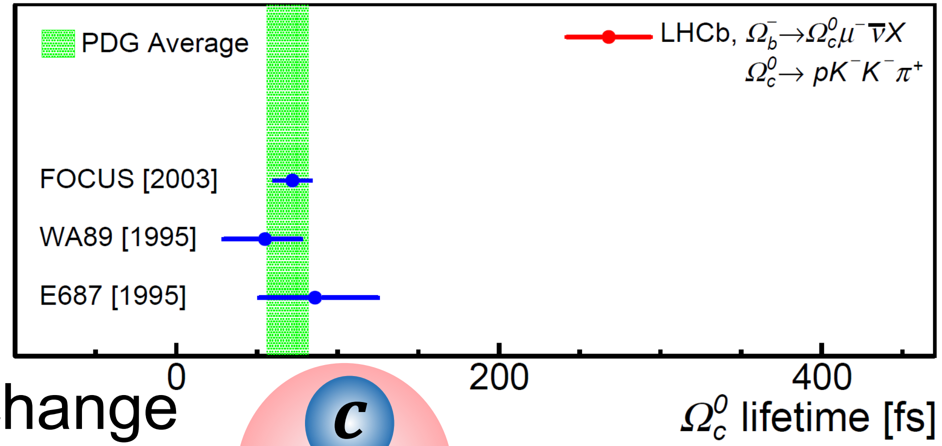
  $$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$

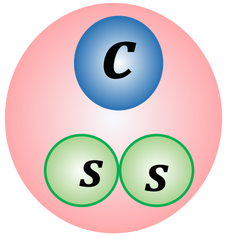
  $$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

- Most theoretical predictions expect Ω_c^0 lifetime to be short
  - Larger constructive Pauli-interference between s-quark in final state
- Possible explanations:
  - At $\mathcal{O}(1/m_c^2)$: spin-spin interaction
  - At $\mathcal{O}(1/m_c^3)$: Pauli-interference and W-exchange

Need theoretical investigation!







Ω_c^0

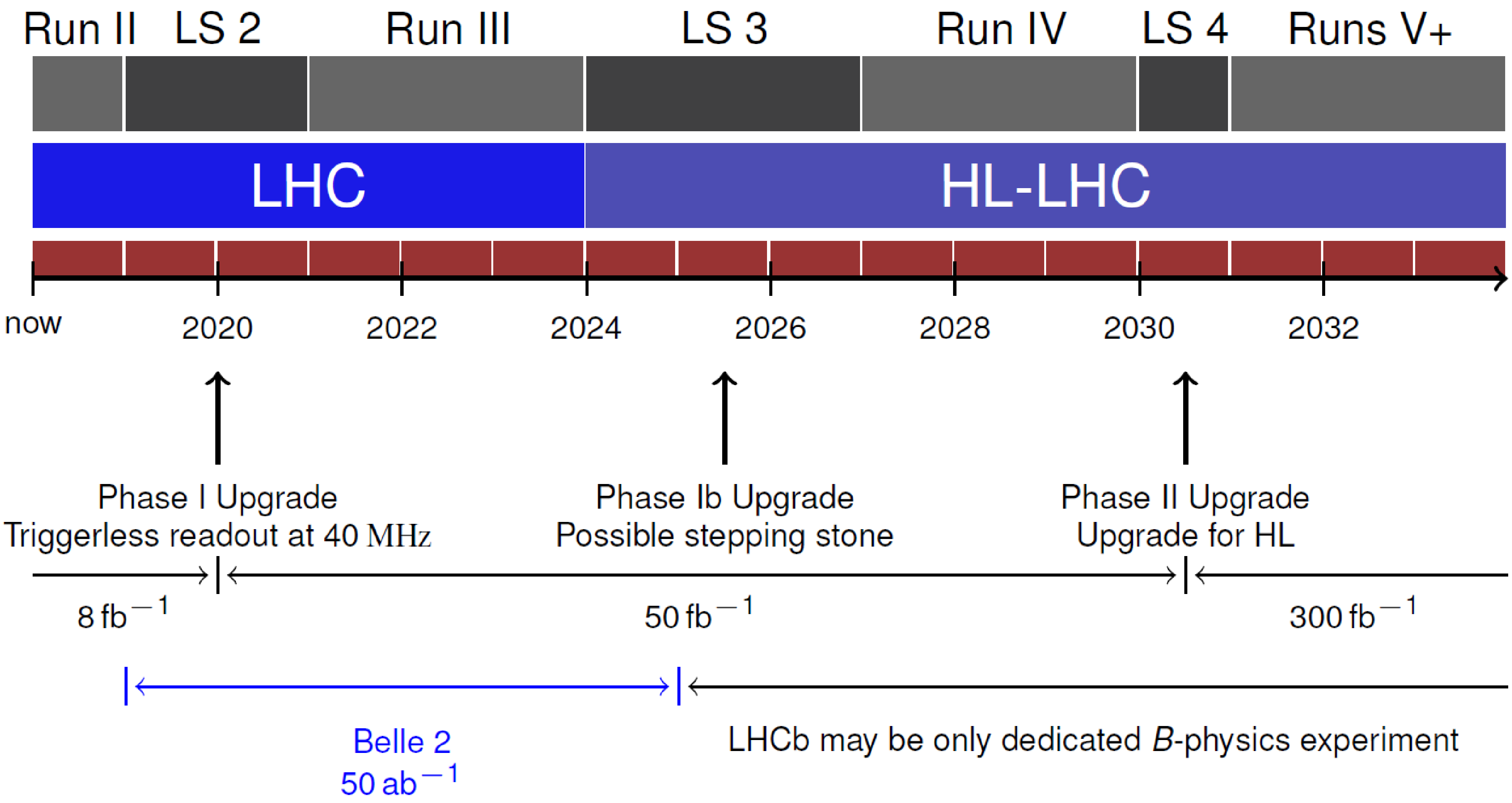
Summary

- LHCb detector is designed for the heavy flavour physics
- LHCb has made significant progresses in the study of **charmed baryons**
  - Confirmation of the observation of Ξ_{cc}^{++} using $\Xi_c^+\pi^+$ channel
  - Measurement of Ξ_{cc}^{++} lifetime: long lifetime as expected
  - Measurement of Ω_c^0 lifetime, four times larger than previous measurements

- More data collected in Run-II

Stay tuned for new results !

Summary



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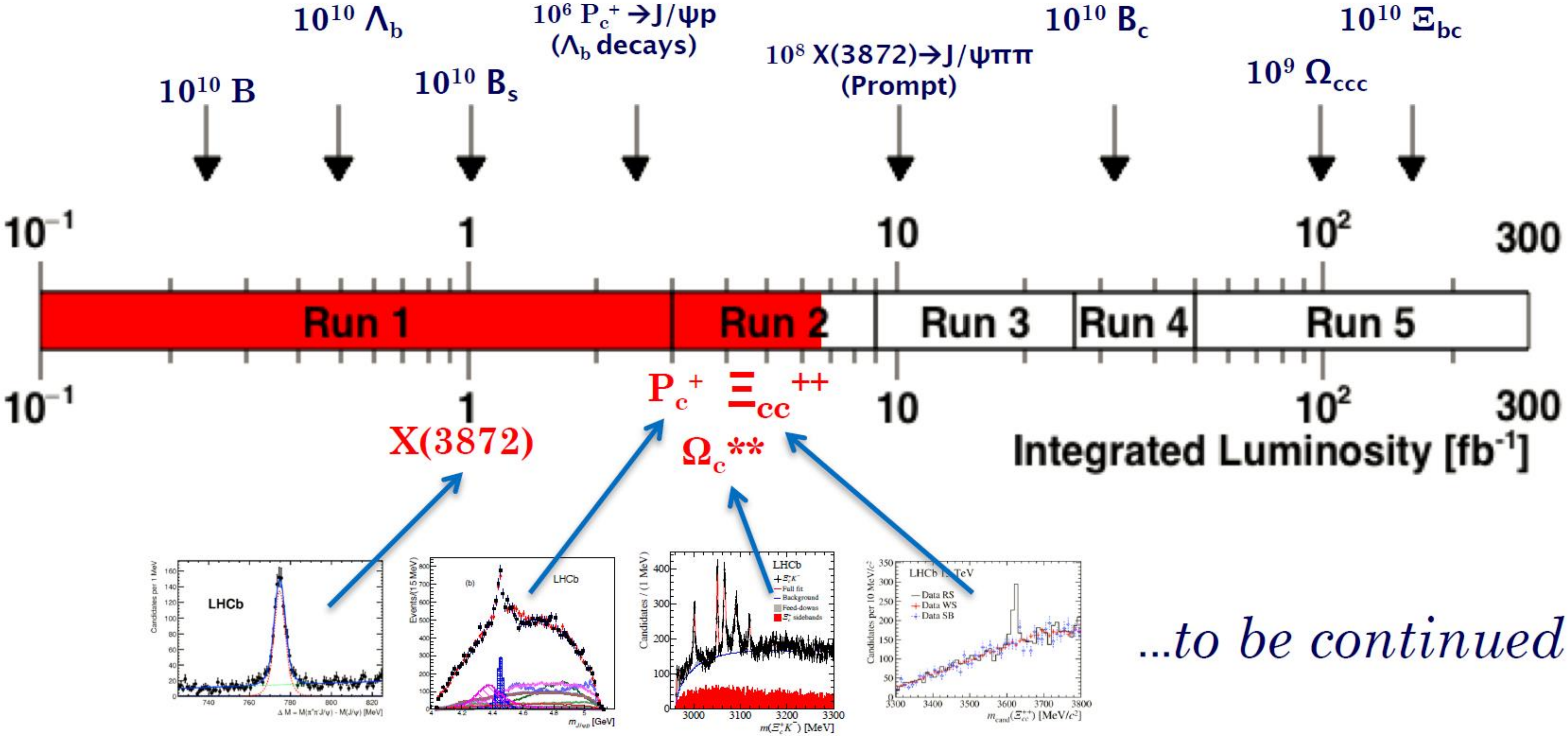
urements

Backup

Hadron spectroscopy @ LHCb



...to be continued

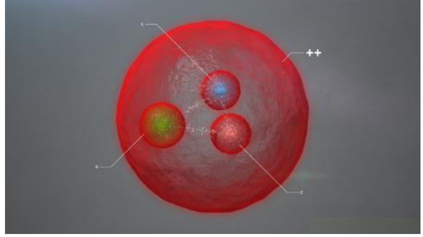
Get from M. Pappagallo

Prospects

- Searching for Ξ_{cc}^{++} with more channels: $\Xi_c^+\pi^+$, $\Lambda_c^+\pi^+, pD^+K^-\pi^+\ldots$
- Measurement of the Ξ_{cc}^{++} lifetime
- Measurement of the production cross-section
- Confirming its spin-parity: $½^+$
- Searching for its isospin partner Ξ_{cc}^+ in a larger sample than the previous measurement
- Searching for Ω_{cc}^+
- Doubly heavy baryons with bottom quark: Ξ_{bc}, Ω_{bc}, Ξ_{bb} …
- The excited states?
- And new systems for CP violations

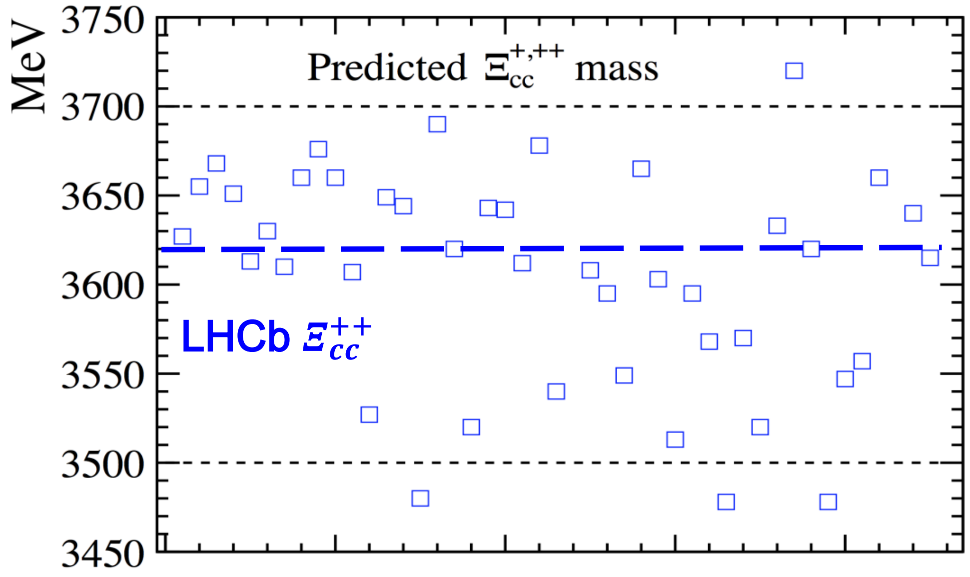
Observation of Ξ_{cc}^{++}

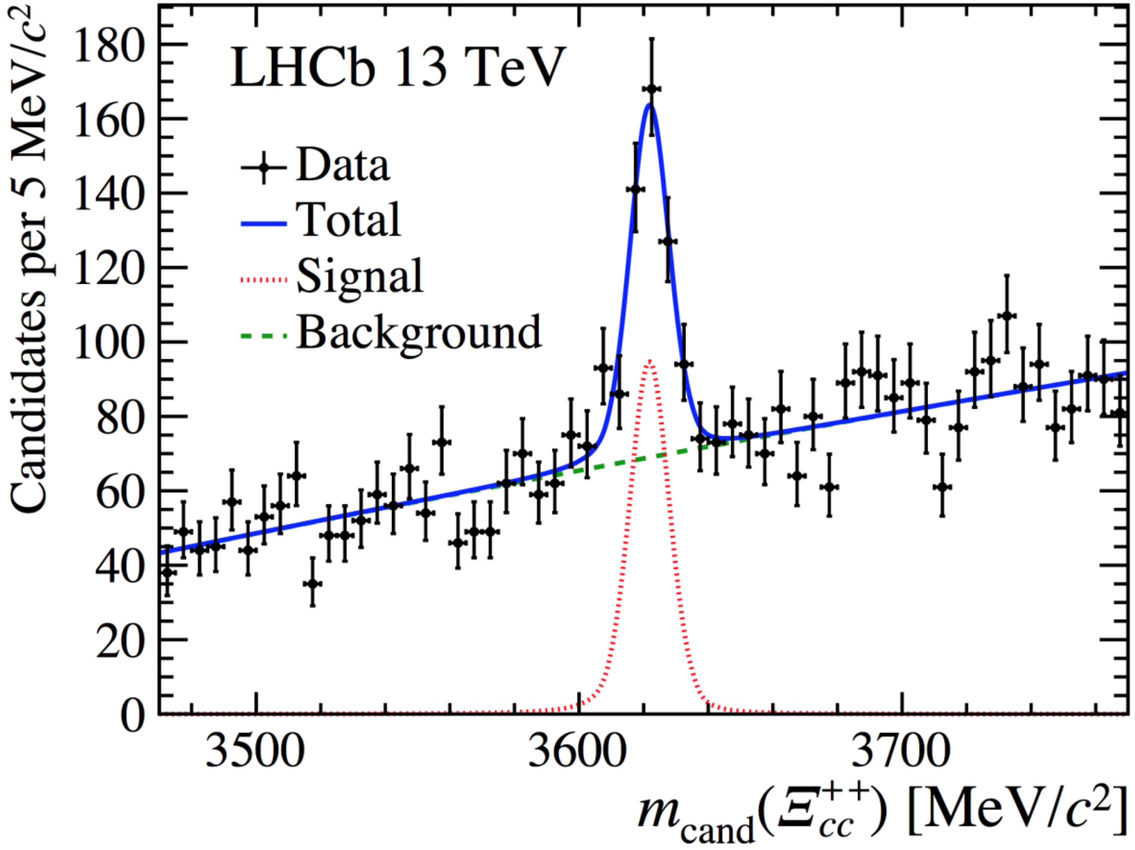
11/07/2017



- $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ observed by LHCb experiment using 2016 data
  - Signal yield: 313 ± 33
  - Local significance > 12
  - Weakly decay

Phys. Rev. Lett. 119, 112001 (2017)

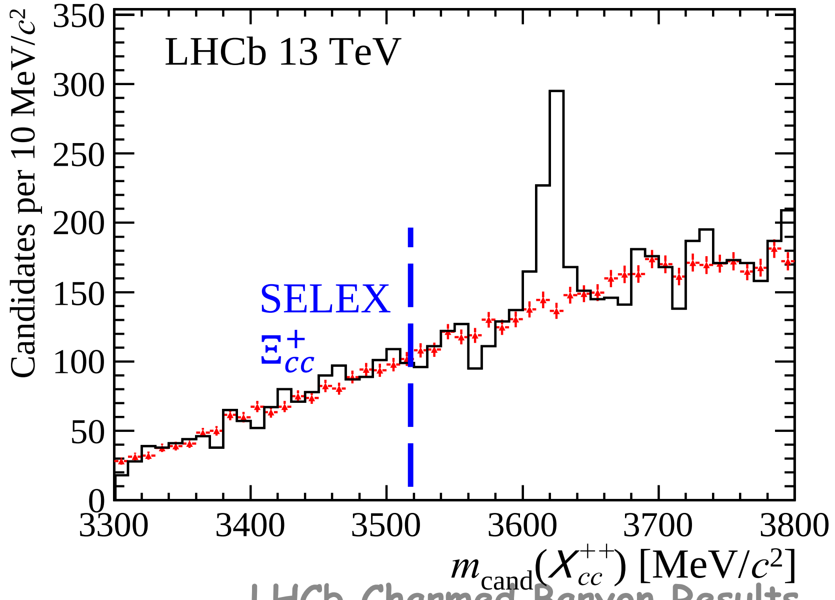




Compared with SELEX results

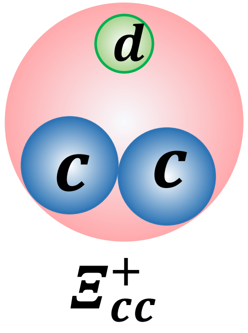
- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV
  - Inconsistent with being isospin partners

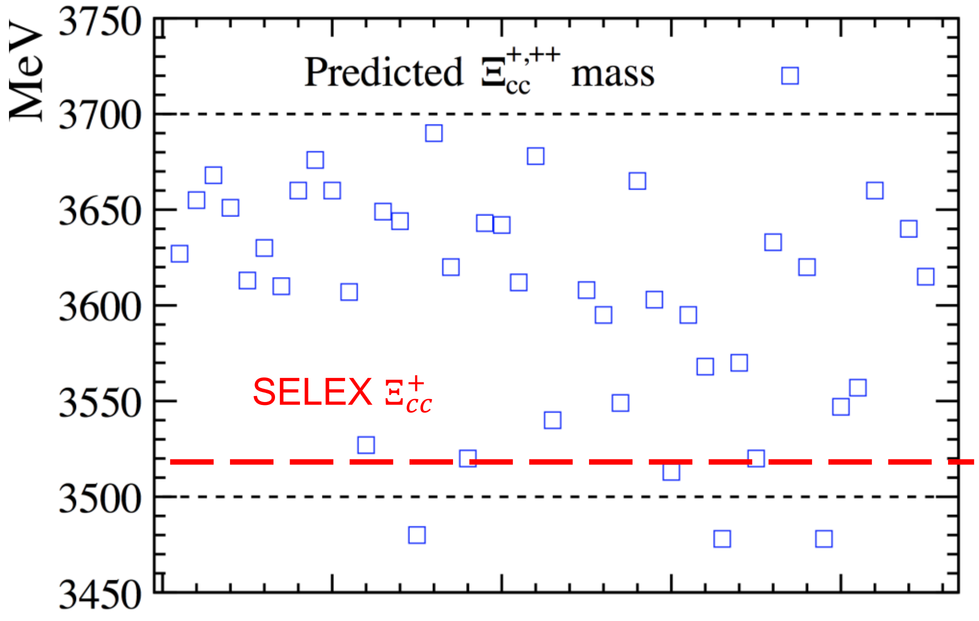
- Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller in LHCb result



SELEX result in tension with predictions

- Models to determine masses of ground state and excitations:
  - (non-) relativistic QCD potential models, triple harmonic-oscillator potential model, QCD sum rules, bag model or quark model …
  - Predicted $\Xi_{cc}^{+,++}$ masses in range $\mathbf{3.5-3.7}$ GeV,
  - Masses of Ξ_{cc}^{+} and Ξ_{cc}^{++} only differ by a few MeV due to u, d symmetry





Analysis strategy $\Xi_c^+\pi^+$ (Blinded analysis)

- Event selection of $\Xi_c^+\pi^+$ candidates, 2016 data

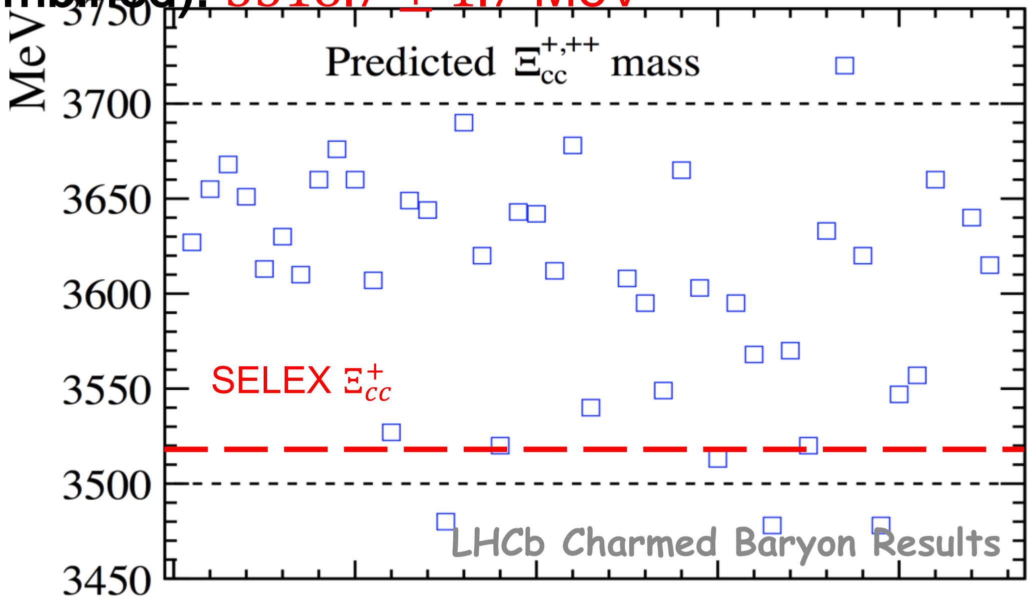
- Multivariate selector to suppress combinatorial background
  - Simulation as signal, data upper sideband as background

- Open signal window
  - $> 3\sigma$ signal: mass measurement, ratio of branching fraction
  - Otherwise: upper limit setting

Studies of Ξ_{cc} by SELEX experiment

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to pD^+K^-$ decays
  - Signal yields: $15.9\ (\Lambda_c^+ K^- \pi^+)$ and $5.62\ (pD^+K^-)$
  - Short lifetime: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
  - Large production: $R = \frac{\sigma(\Xi_{cc}^+)\times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - Mass (combined): 3518.7 ± 1.7 MeV

Very puzzling



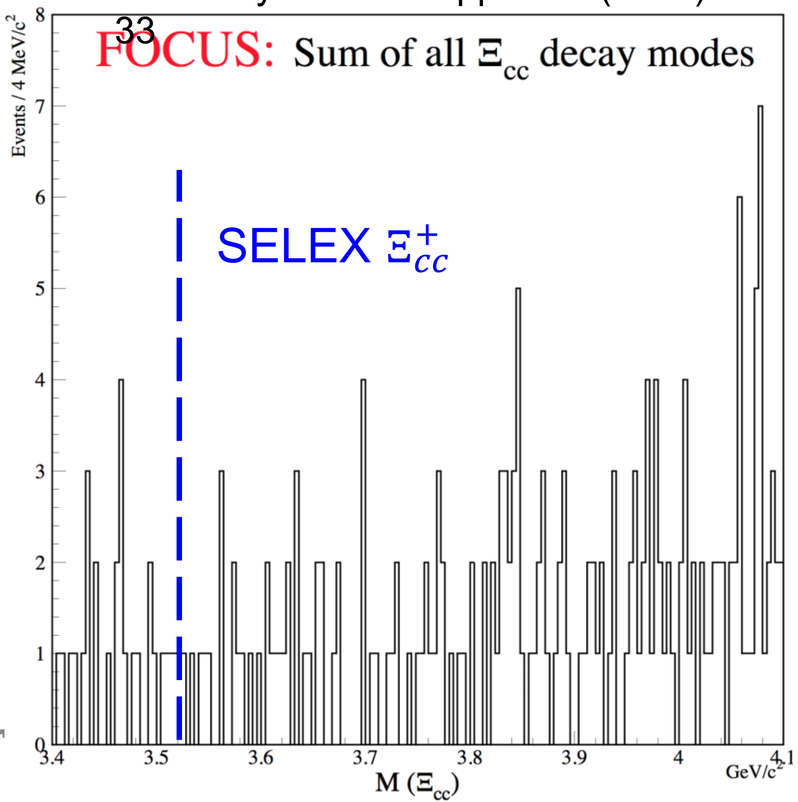
Studies of Ξ_{cc} by FOCUS

- FOCUS (Fermilab E831) studies charm hadrons produced in photon-nuclear fixed target collisions
- FOCUS didn't confirm Ξ_{cc}^{+} observed by SELEX in $\Lambda_c^+ K^- \pi^+$ decay

Decay Mode	$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$	
Experiment	FOCUS	SELEX
Ξ_{cc} Events	<2.21 @ 90%	15.8
Reconstructed Λ_c	19,444 ± 262	1650
Relative Efficiency	5%	10%
Ξ_{cc}/Λ_c^+	<0.23% @ 90%	9.6%
$\frac{\text{SELEX}}{\text{FOCUS}}$ Rel $\frac{\Xi_{cc}}{\Lambda_c}$ Prod	>42 @ 90%	

- Other modes also studied: $\Xi_{cc}^+ \to \Lambda_c^+ X$, $D^0 X$ $D^+ X$, no SELEX-like signal peak observed

Nucl. Phys. Proc. Suppl. 115 (2003) 33

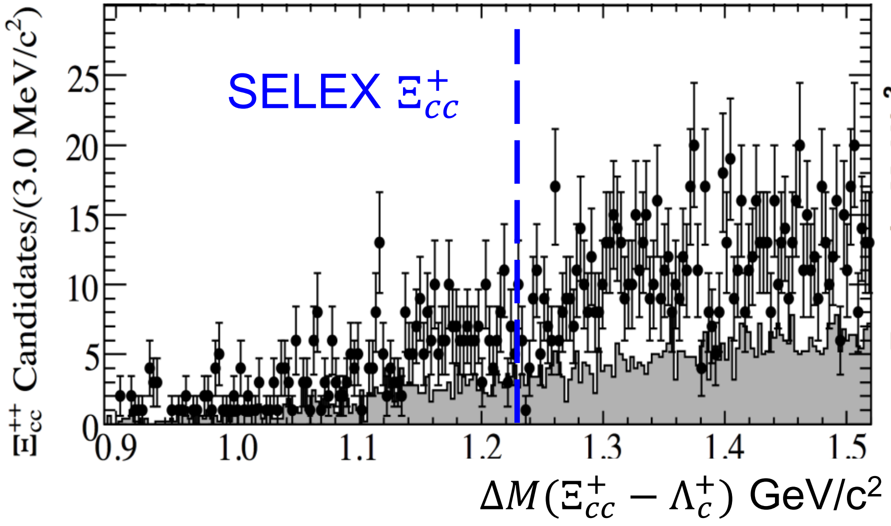


Studies of Ξ_{cc} by BaBar and Belle

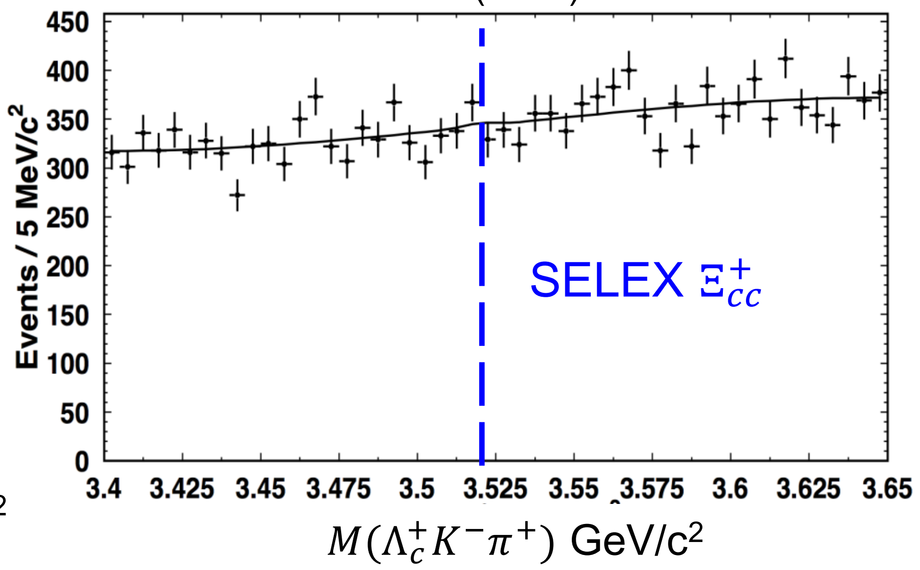
- e^+e^- colliders working at $\Upsilon(4S)$ mass $\sqrt{s} = 10.58$ GeV
- Large Λ_c^+ yields: ≈ 0.6 M at BaBar, ≈ 0.8 M at Belle
- SELEX-like Ξ_{cc}^+ signal not confirmed in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays

$$R = \frac{\sigma(\Xi_{cc}^+)\times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 2.7\times10^{-4} \text{ (BaBar)} \quad 1.5\times10^{-4} \text{ (Belle)} \quad @\ 95\% \text{ CL}$$

BaBar: PRD 74 (2006) 011103



Belle: PRL 97 (2006) 162001



Studies of Ξ_{cc}^{+} by LHCb: Run-I

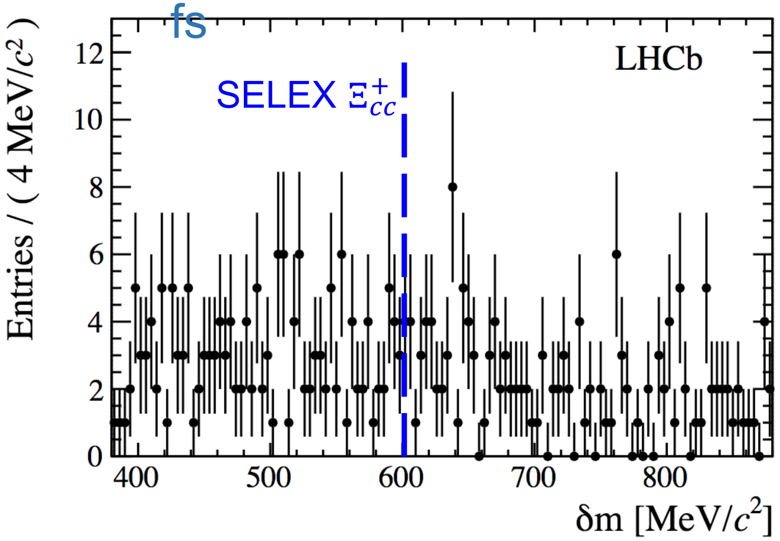
JHEP 12 (2013) 090

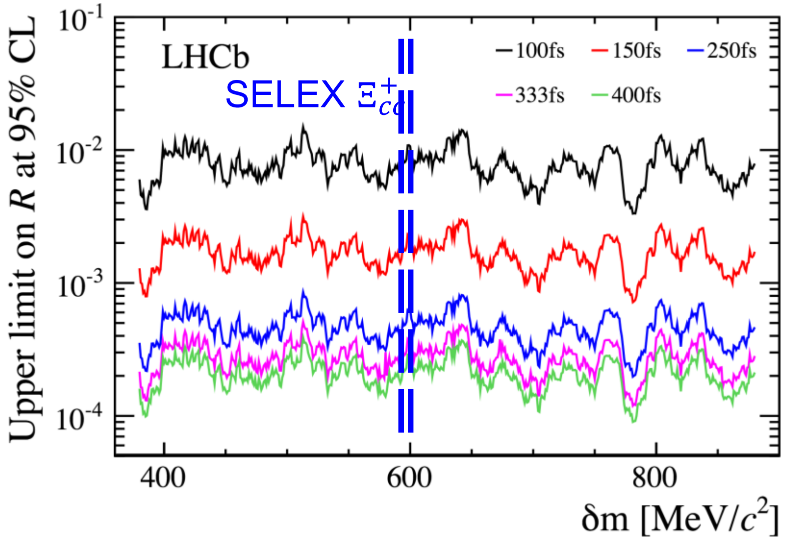
- LHCb searched for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decay with 0.65 fb^{-1} of 7 TeV data
- $N(\Lambda_c^+) \approx 0.8$ M, requiring high-p_T
- No significant peaking structure observed with $m \in [3.3, 3.8]$ GeV
- Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 0.013 \text{ for } \tau = 100 \text{ fs},$$

$< 3.3 \times 10^{-4}$ for $\tau = 400$ fs @95%

Increased by ~40 from 100 fs to 400 fs





$$\delta m = m\left([pK^-\pi^+]_{\Lambda_c^+} K^- \pi^+\right) - m\left([pK^-\pi^+]_{\Lambda_c^+}\right) - m(K^-) - m(\pi^+)$$

F.-S. Yu et al., Chin. Phys. C 42, 051001 (2018)

$\Xi_c^+ \pi^+$ Prediction

$$\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300\,\mathrm{fs}}\right) \times 7.2\%.$$

$$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (2.2 \pm 0.8)\%.$$

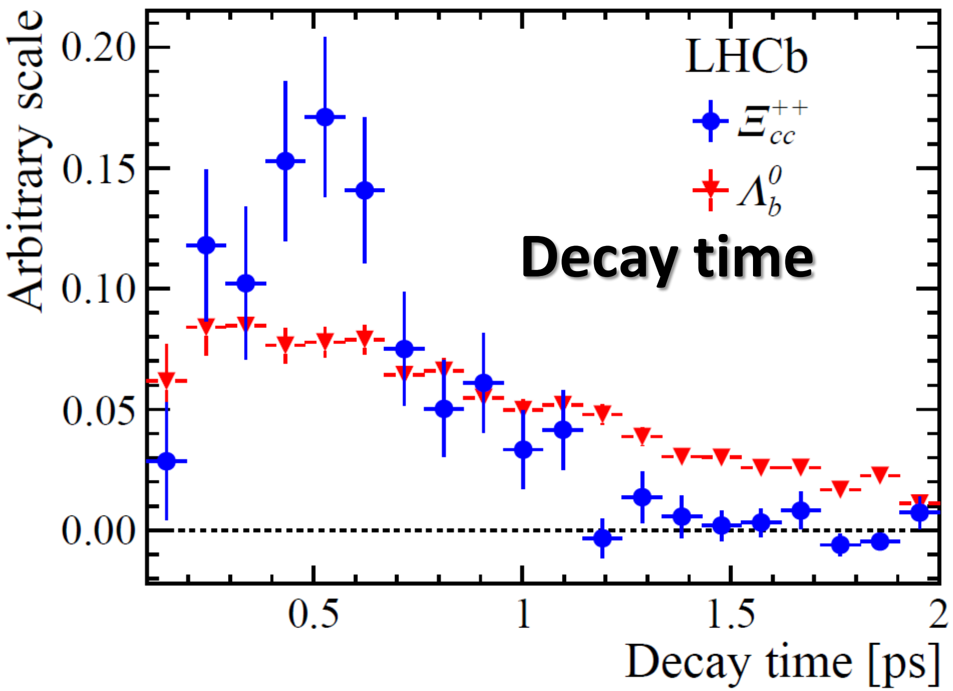
as $\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54 \pm 0.10$ [33]. Besides, the relation $\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+ K^{*0})$ holds under U-spin symmetry. With the measurement of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K^{*0}) = (0.36 \pm 0.10)\%$ [34], the branching

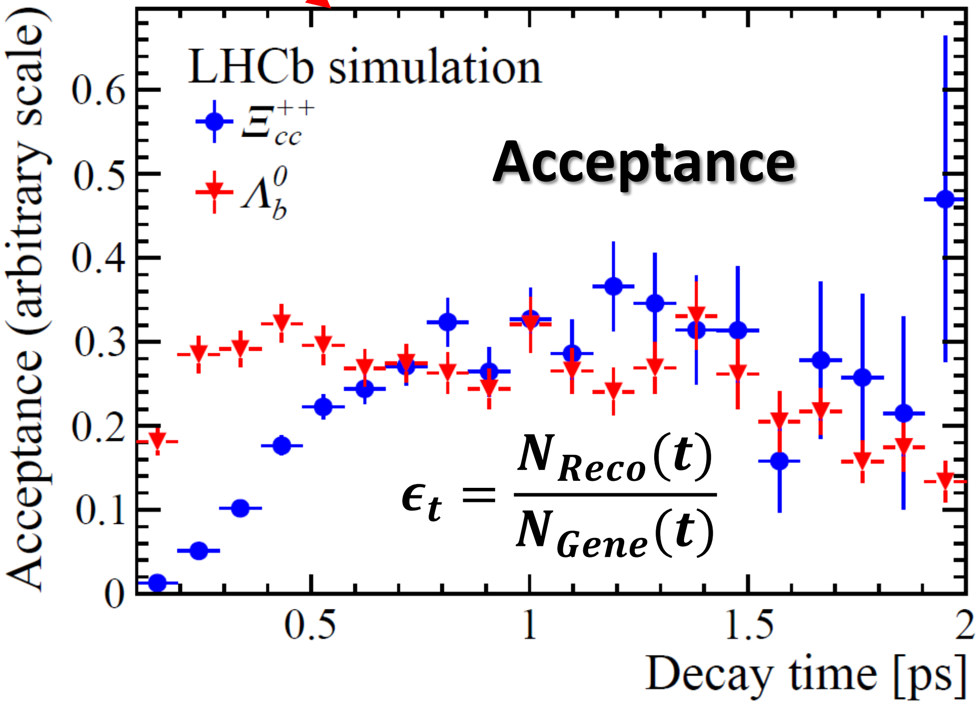
$$\mathcal{B}(\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)\overline{K}^{*0}) = \left(\frac{\tau_{\Xi_{cc}^{++}}}{300\,\mathrm{fs}}\right) \times (3.8 \sim 24.6)\%, \tag{11}$$

Decay time distributions and acceptance

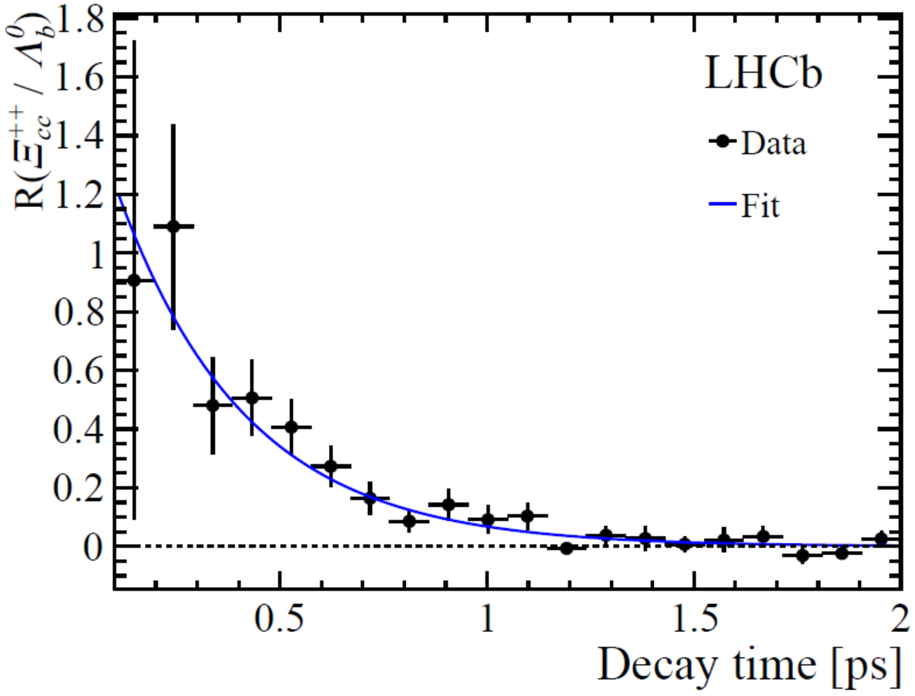
$$\mathcal{R}(t) = \frac{f_{\Xi_{cc}^{++}}(t)}{f_{\Lambda_b^0}(t)} \times \frac{\epsilon_{\Lambda_b^0}(t)}{\epsilon_{\Xi_{cc}^{++}}(t)} = \mathcal{R}(0)e^{-\left(\frac{1}{\tau_{\Xi_{cc}^{++}}} - \frac{1}{\tau_{\Lambda_b^0}}\right)t}$$

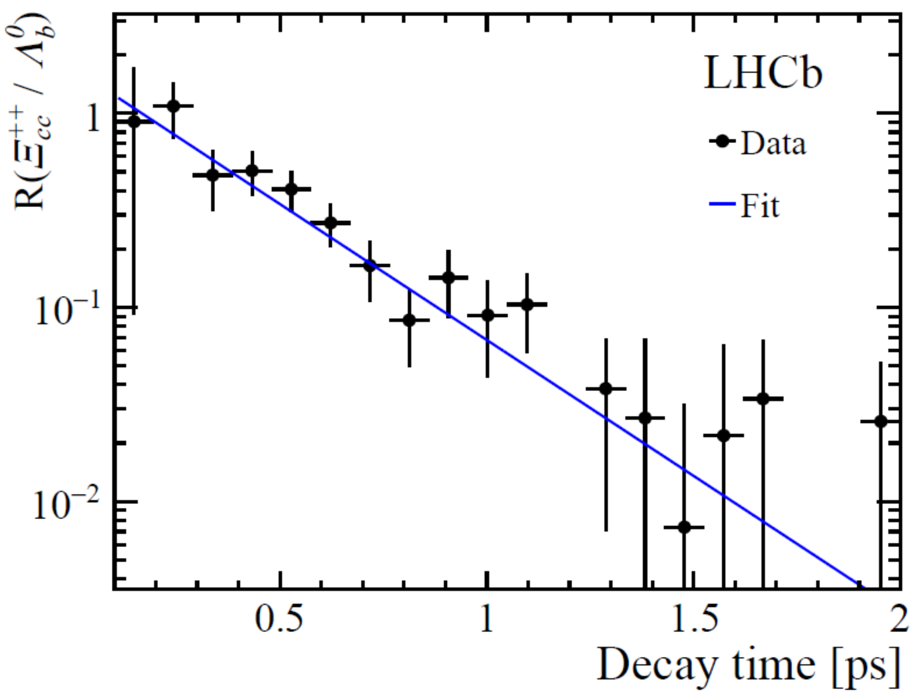
S-weighted data
to subtract background





$\Xi_{cc}^{++}/\Lambda_b^0$ lifetime ratio comparison

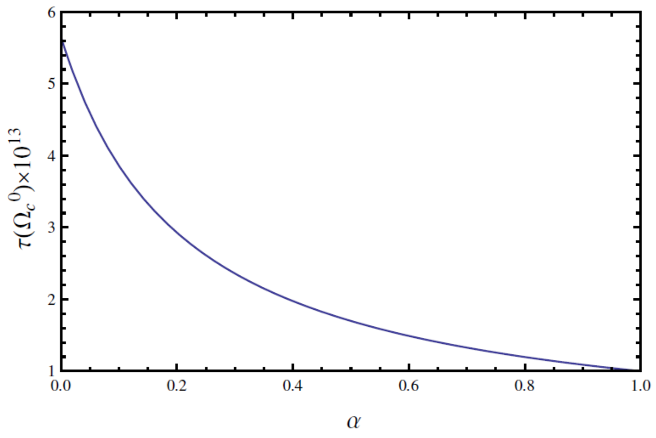




Latest Ω_c^0 lifetime prediction

arXiv:1807.00916

- By Prof. Hai-Yang Cheng, submitted in July 2nd, 2018
- c quark mass is not too heavy
  - sub-leading 1/mc corrections to spectator effects
- α : describe the degree of suppression
- Guideline:



$\Gamma_+^{\rm int}(\Omega_c)$ and $\Gamma^{\rm SL}(\Omega_c)$ should be positive with values not far from that of Ξ_c baryons.

- Additional contribution from SL channel

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

- Heavy quark expansion (HQE)

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3} V_{\mathrm{CKM}} \left(A_0 + \frac{A_2}{m_Q^2} + \frac{A_3}{m_Q^3} + \frac{A_4}{m_Q^4} + \mathcal{O}\left(\frac{1}{m_Q^5}\right)\right)$$

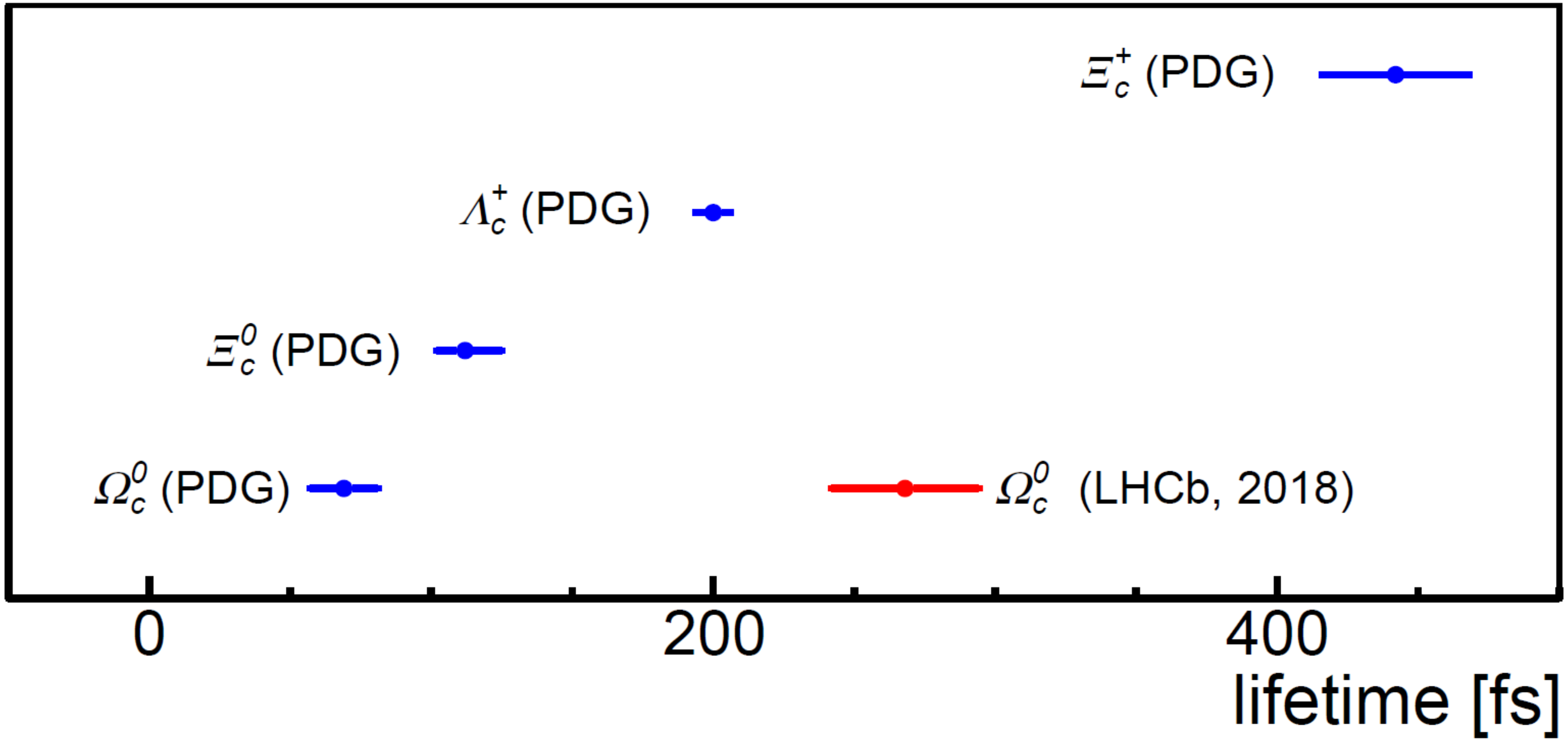
  - No linear $^1/_{m_Q}$ correction: lack of gauge0invariant dimension-four operators, Luke's theorem
  - Pauli-interference and W-exchange in $^1/_{m_Q^3}$
  - $^1/_{m_Q}$ expansion not well convergent and sensible

Ω_c^0 lifetime analysis strategy

- Reconstruct $\Omega_c^0\mu^-$ and $D^+\mu^-$ Semileptonic (SL) decay sample: 2011+2012 data
- Fit Ω_c^0, D^+ mass distribution to get s-weight
- Sweight out the decay time spectrum of c-hardons
- Calibrate decay time acceptance using D^+ mode $(1040 \pm 7$ fs)
- Simultaneous fit to D^+ and Ω_c^0 decay time spectrum, get the ratio

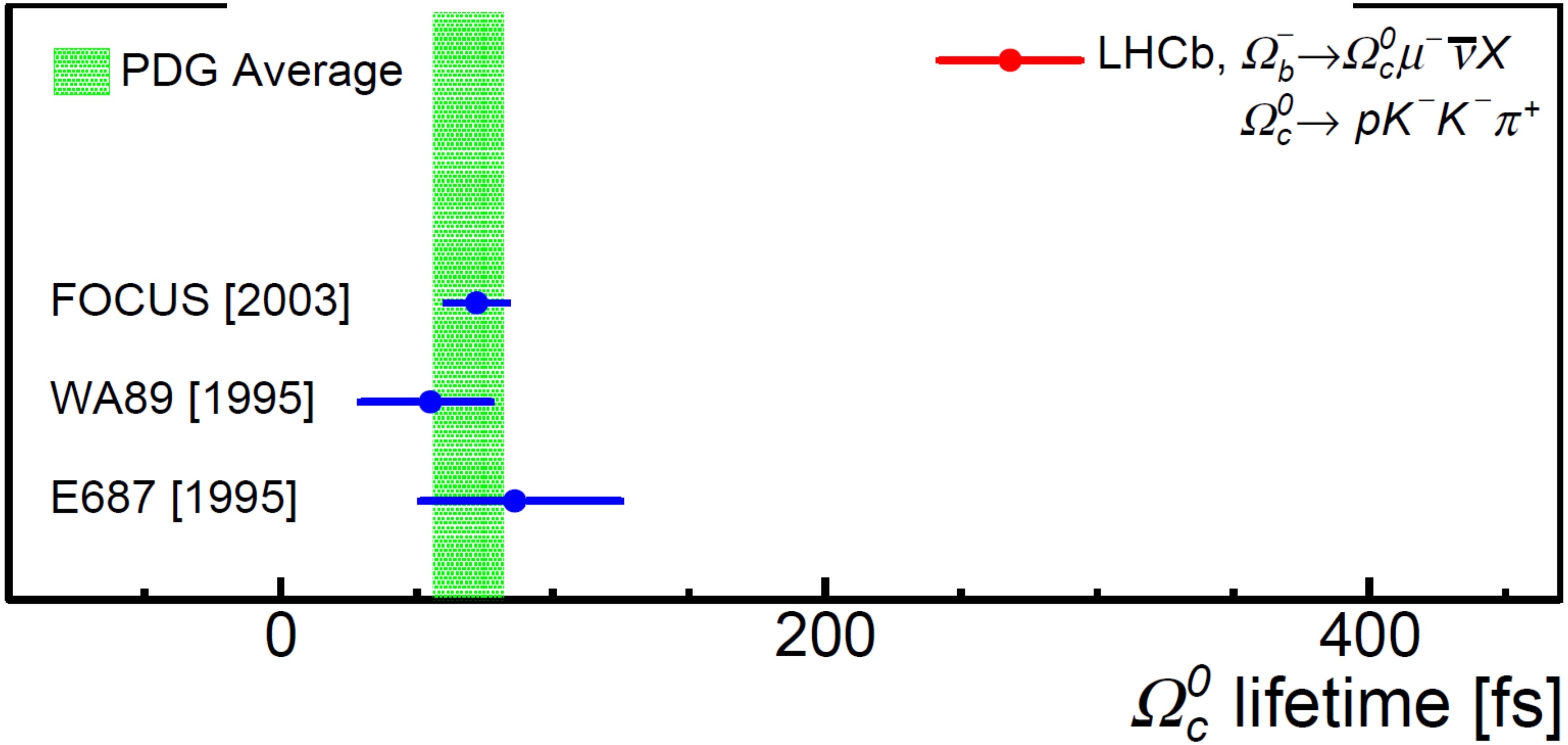
  $r(\Omega_c^0) = \tau(\Omega_c^0)/\tau(D^+)$

Baryon lifetime



Ω_c^0 lifetime results

FOCUS	$72 \pm 11 \pm 11$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+$
E687	$86\ ^{+27}_{-20} \pm 28$ fs	$\Sigma^+ K^- K^- \pi^+$
WA89	$55\ ^{+13}_{-11}\ ^{+18}_{-23}$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+ \pi^+ \pi^-$



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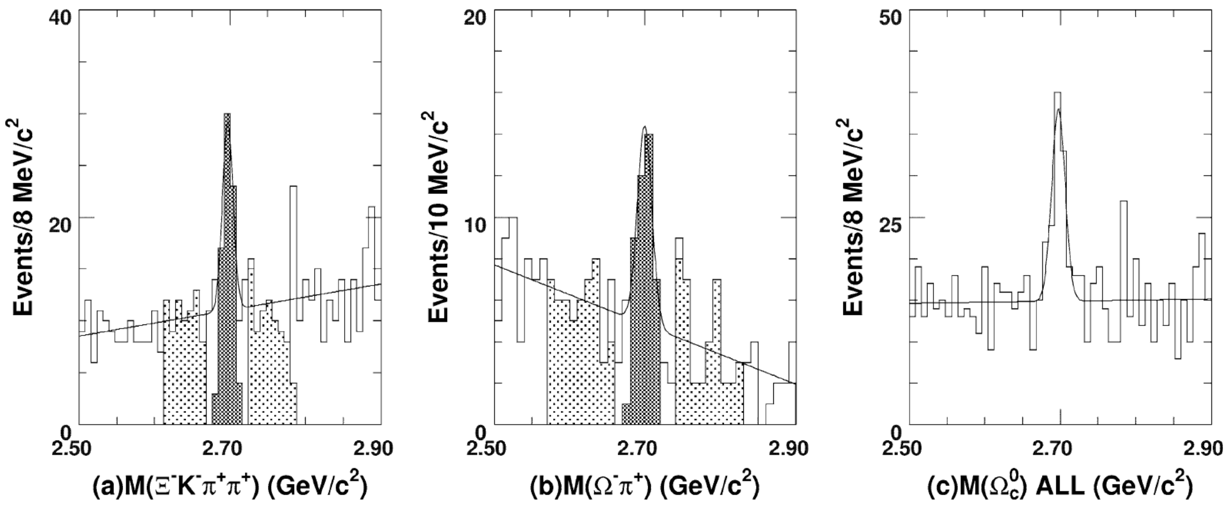
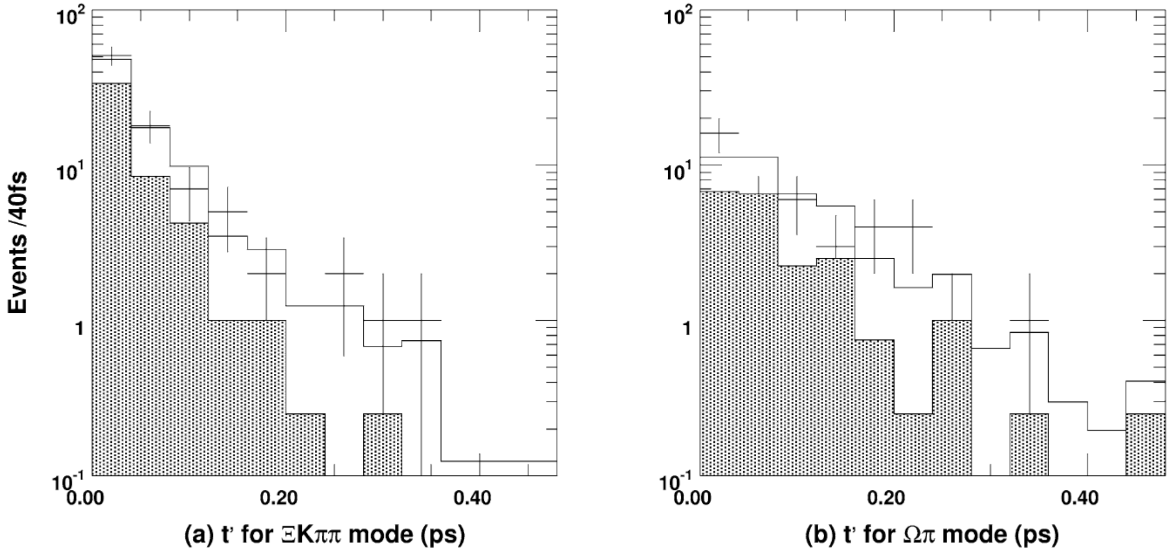
FOCUS Ω_c^0 lifetime result

- Signal yields: 64 ± 14





$72 \pm 11 \pm 11$ fs

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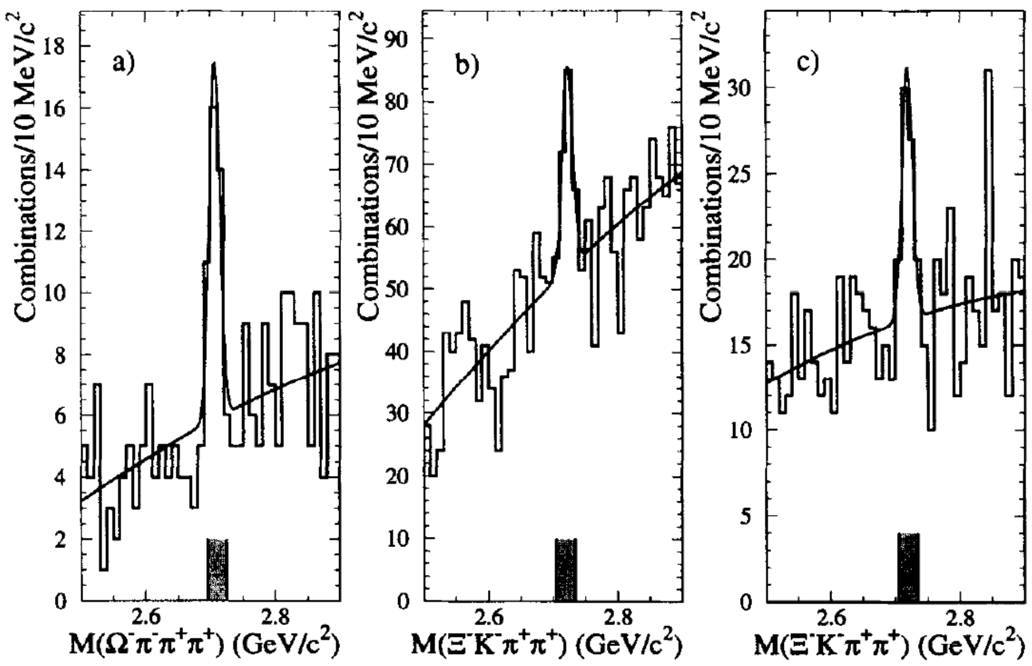
WA89 Ω_c^0 lifetime result

- Signal yields: 122



Sample	Channel	Mass [MeV/c^2]	Width [MeV/c^2]	S/B
A	$\Omega^-\pi^+\pi^-\pi^+$	2707.5 ± 3.9	8.3 ± 2.9	23/18
B	$\Xi^-K^-\pi^+\pi^+$ (Carbon)	2720.0 ± 3.4	8.8 ± 3.4	62/162
C	$\Xi^-K^-\pi^+\pi^+$ (high K-momenta)	$2719.8 + 4.7$	8.9 ± 3.0	27/50

$$\tau(\Omega_c^0) = 55^{+13}_{-11}(\text{stat.})^{+18}_{-23}(\text{syst.})\ \text{fs}.$$

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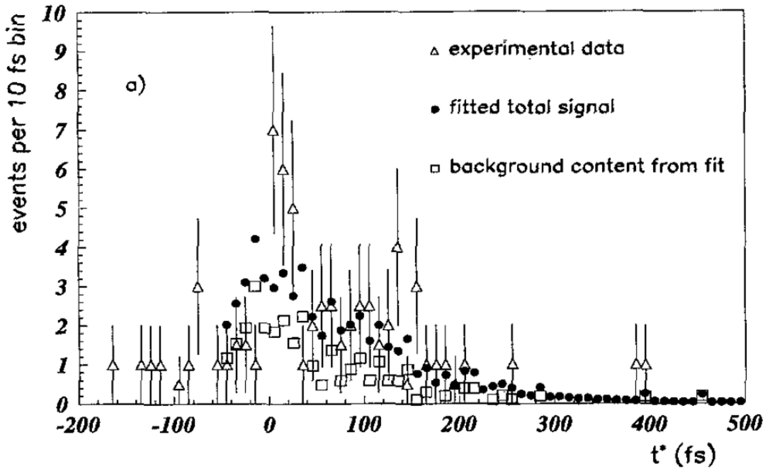
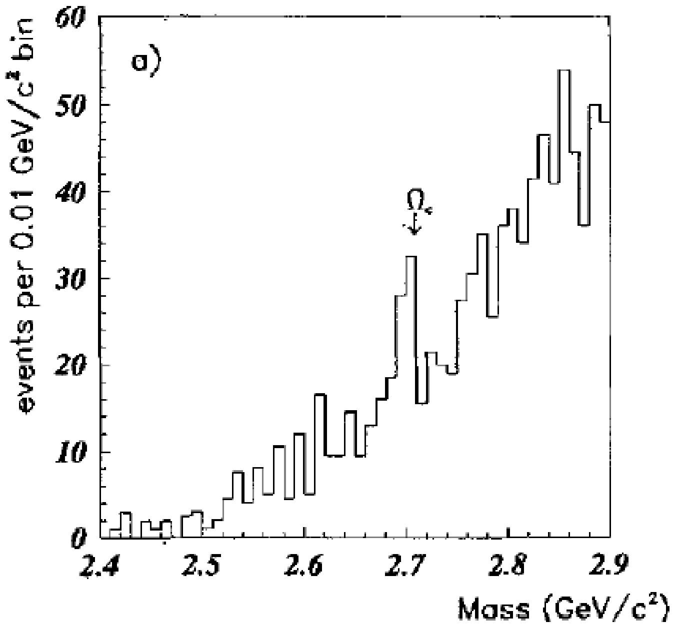
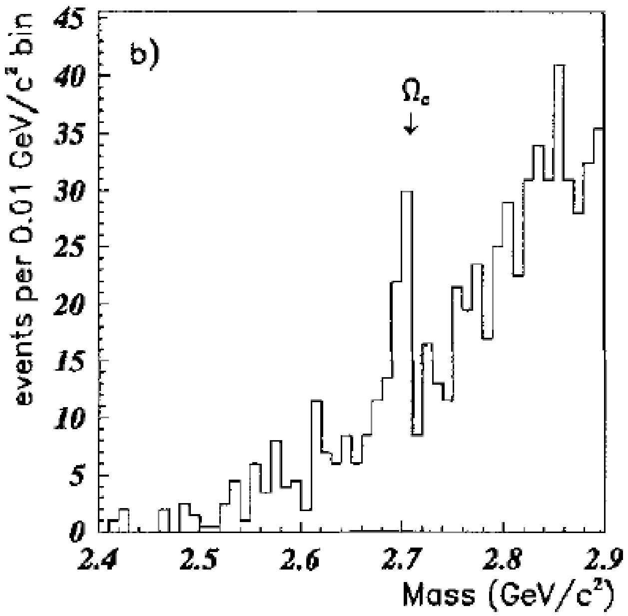
E687 Ω_c^0 lifetime result

- Signal yields: 68







$$\tau = 86^{+27}_{-20}(\text{stat.}) \pm 28(\text{syst.})\ \text{fs.}$$

IP