Experimental review of doubly charmed baryons

Workshop on singly and doubly charmed baryons

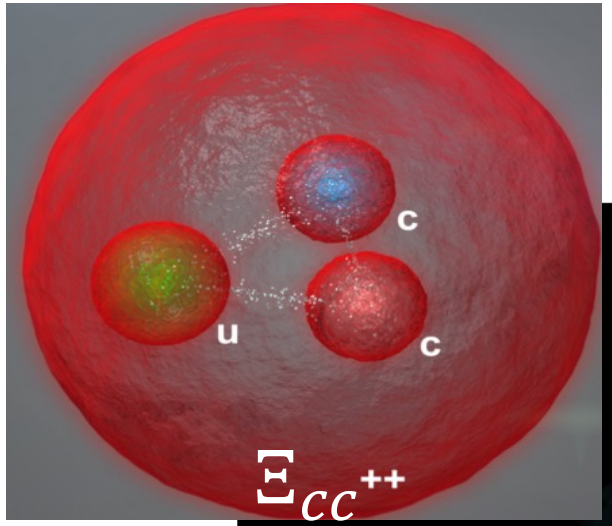
LPNHE PARIS

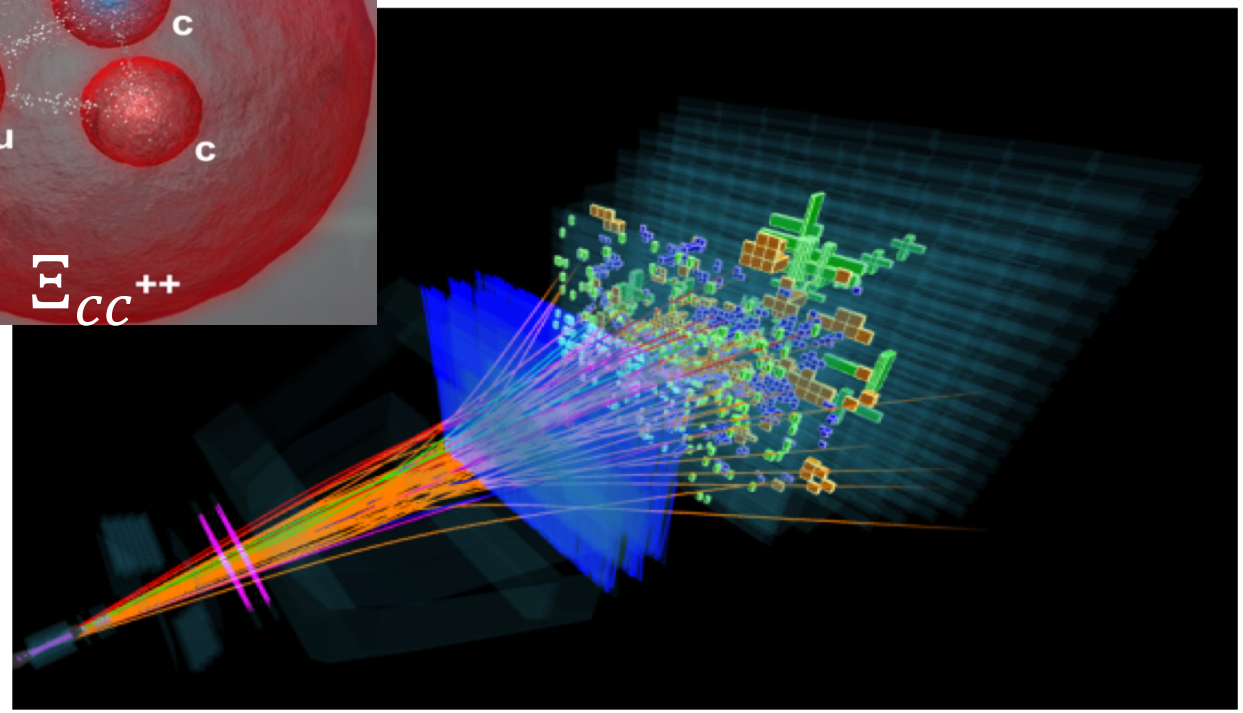
26th - 27th June 2018

Murdo Thomas Traill

on behalf of the LHCb collaboration

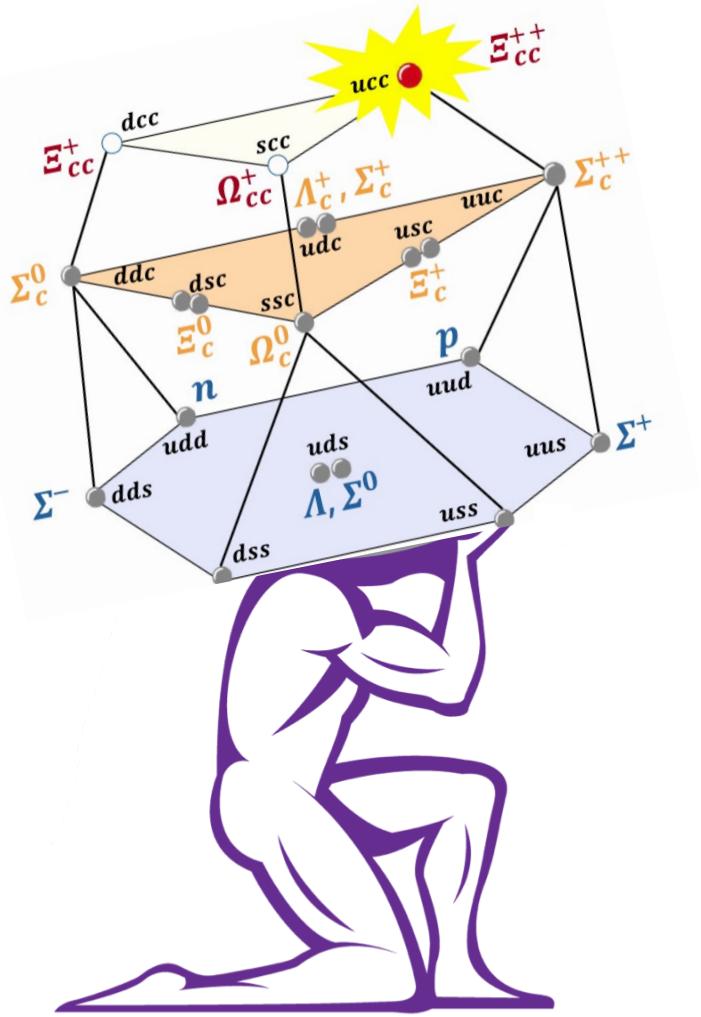
University of Glasgow | Experimental Particle Physics





Outline

- Introduction and properties of doubly charmed baryons
- History of doubly charmed baryon searches
- Discovery of the Ξ_{cc}^{++} state
- **Branching fraction measurements of Ξ_{cc}^{++} decays** NEW!
- **Lifetime measurement of Ξ_{cc}^{++}** NEW!
- Future work



Overview of doubly charmed baryons

- SM predicts 3 quasi-stable states with C=2 and $J^P = \frac{1^+}{2}$

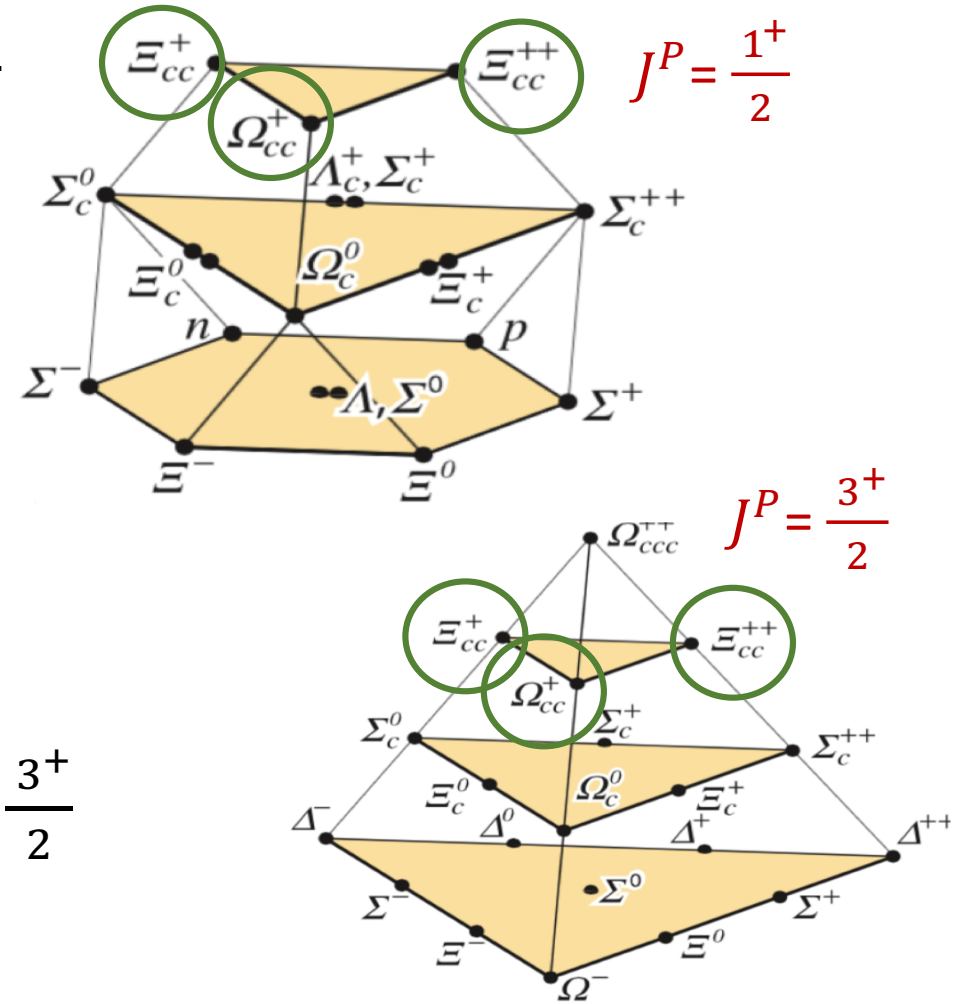
  ✓ $\Xi_{cc}^+(ccd)$, $\Xi_{cc}^{++}(ccu)$ and $\Omega_{cc}^+(ccs)$

- Lightest Ξ_{cc} isodoublet states offered best chance of discovery

- Ground states decay weakly with $c \longrightarrow$ lighter quarks
  $\Longrightarrow$ leads to many tracks in the final state

- Should also exist resonances of these states with $J^P = \frac{3^+}{2}$

  ➢ Decay instantaneously via strong or EM force

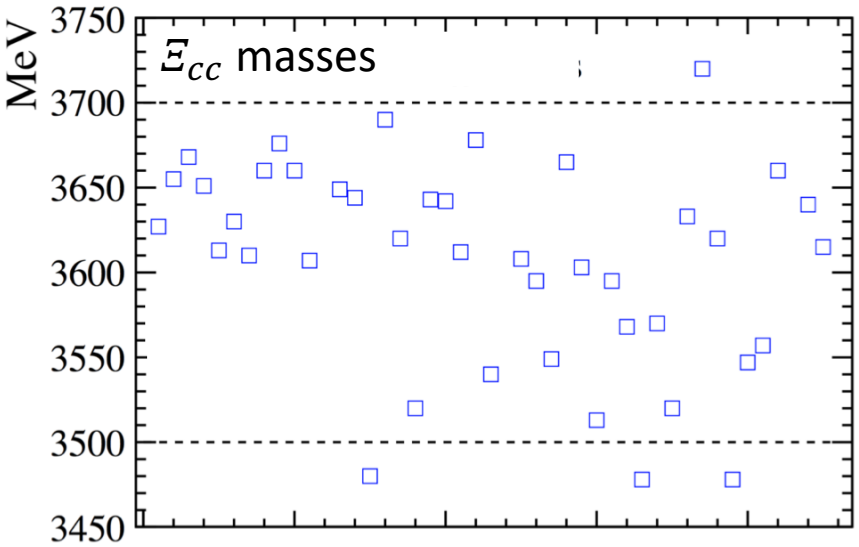


SU(4) flavor multiplets, PDG Review of Particle Physics, Phys.Rev. D86, 010001

Mass and lifetime predictions

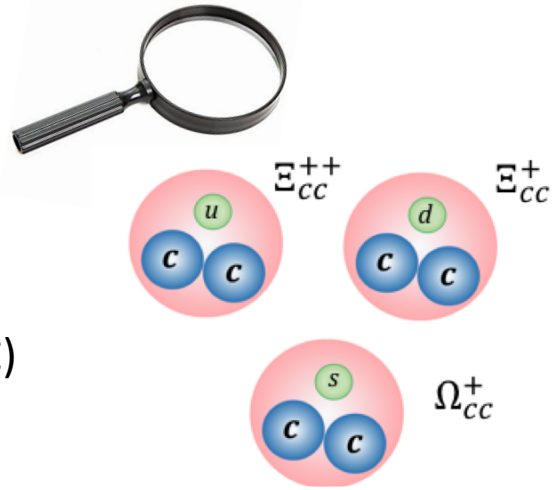
- Many models used to determine masses: Phys. Rev. D 90, 094007 (2014)
  - QCD sum rules, relativistic QCD potential models, bag model, LQCD etc.

Checkout J-M Richard's talk



- Mass around 3500-3700 MeV
- Important: Mass splitting between $\Xi_{cc}^{+}/\Xi_{cc}^{++}$ expected to be a few MeV (assuming conventional isospin doublet)

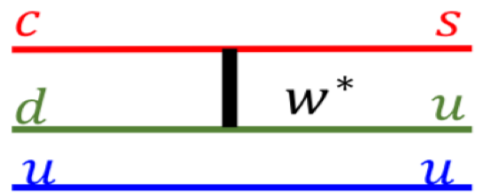
arXiv:1706.06961



- Large spread in lifetime theoretical predictions:

arXiv:9807354

arXiv:9901323



  - Important roles of spectators and Pauli interference
  - W^+ exchange between *c* and *d* quarks only in Ξ_{cc}^{+}
  - $\tau(\Xi_{cc}^{++})/\ \tau(\Xi_{cc}^{+}) \sim 3$ to 4

$\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc}^{+})$

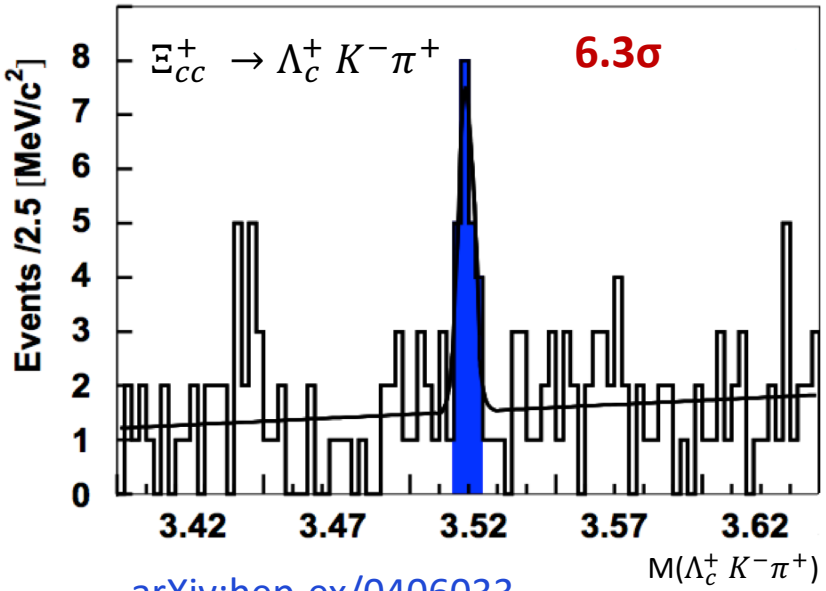
$\tau(\Xi_{cc}^{++}) \in$ 200-700 *fs*

$\tau(\Xi_{cc}^{+}) \in$ 50-250 *fs*

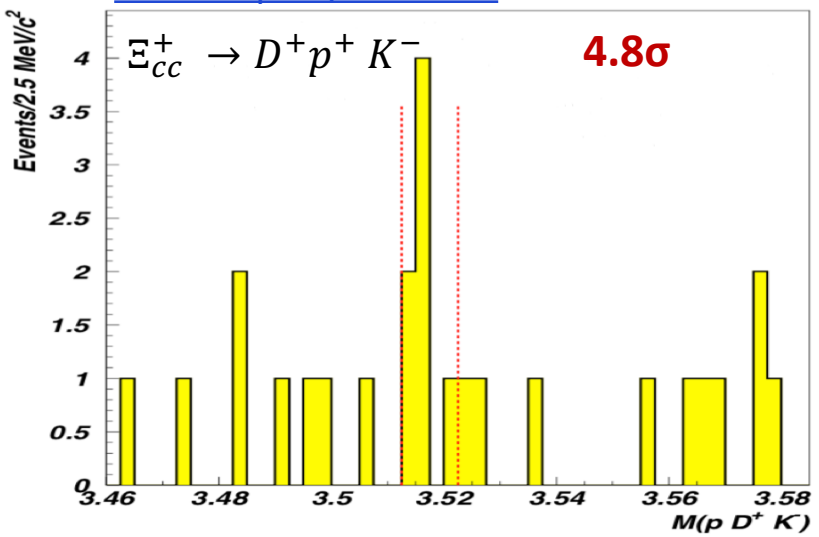
SELEX and Ξ_{cc}^{+}

- SELEX was a fixed-target charm experiment at Fermilab
  - ➢ 600 GeV beam of hyperons on Cu or diamond foil target
- 2002: Observation of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+}$ decays
- 2004: Evidence of $\Xi_{cc}^{+} \to D^{+}p^{+} K^{-}$ decays
- Signal had very unexpected properties:
  - ✓ Average M(Ξ_{cc}^{+}) = 3518.7 $\pm$ 1.7(stat) MeV
  - ✗ τ < 33 fs at 90% C.L
  - ✗ 20% of all Λ_c^{+} came from Ξ_{cc}^{+} decays
- Could be a narrow, strongly decaying misidentified Ξ_c resonance...does not explain non-observation of $\Xi_c(2970)$, $\Xi_c(3055)$, etc.
- Longstanding experimental puzzle!

arXiv:hep-ex/0208014



arXiv:hep-ex/0406033

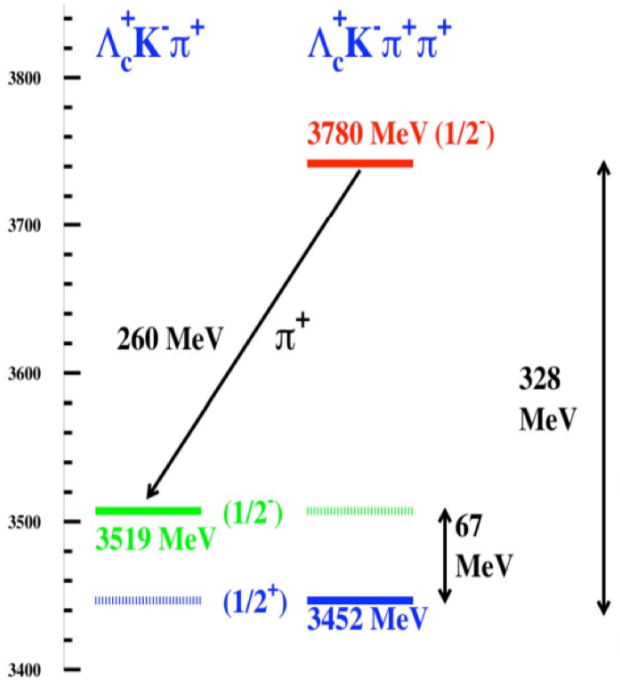


SELEX and Ξ_{cc}^{++}

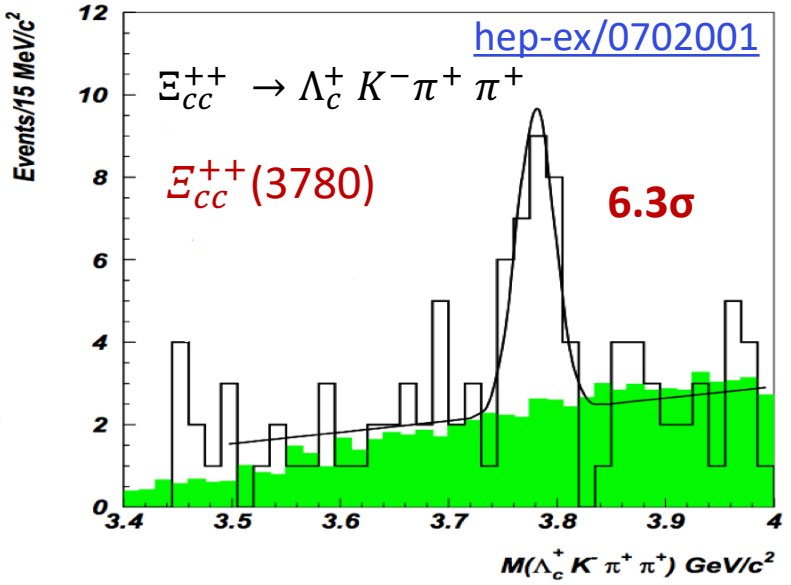
- In unpublished work, shown at several conferences, SELEX claimed to also observe Ξ_{cc}^{++} states

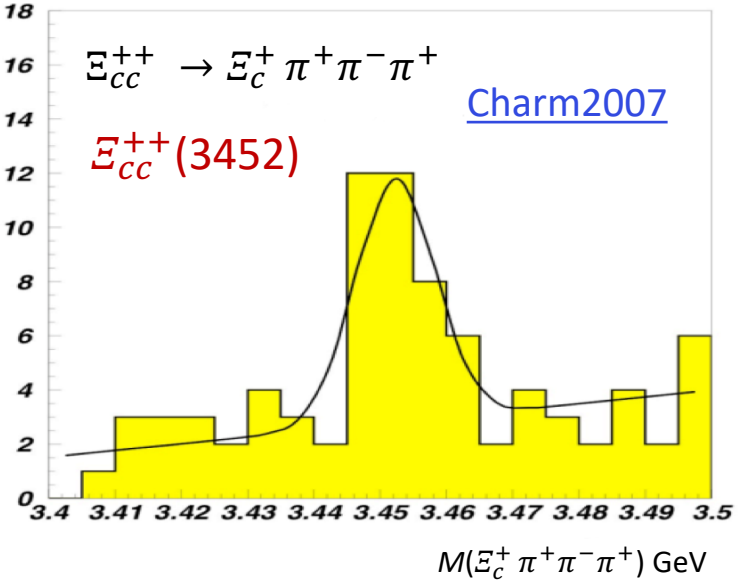
- $\Lambda_c^+ K^-\pi^+ \pi^+$ channel:
  - Width was not consistent with detector resolution*
  - Contained $\Lambda_c^+ K^-\pi^+$combinations from Ξ_{cc}^+ observation

- $\Xi_c^+ \pi^+\pi^-\pi^+$channel:
  - Found 2nd ground state Ξ_{cc}^{++}(3452)
  - 67 MeV below their Ξ_{cc}^+ mass!



Very strange spectroscopy

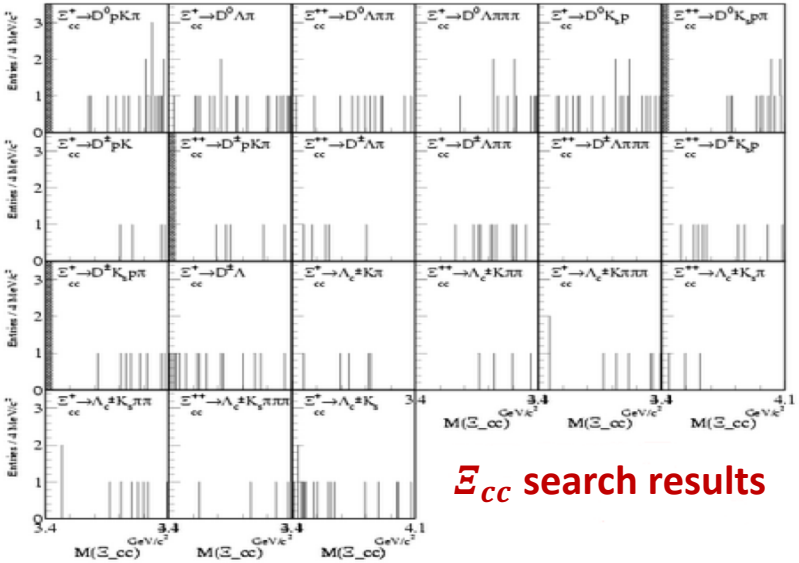




*SELEX actually found the Ξ_{cc}^{++}(3780) state before Ξ_{cc}^+(3519)

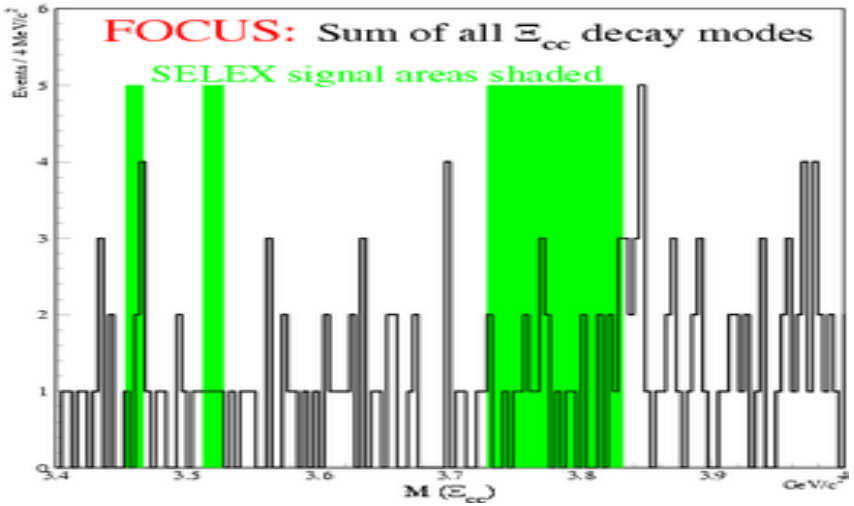
Searches by FOCUS

- Focus also at Fermilab looked for doubly charmed baryons at the same time as SELEX
- Different production environment to SELEX
  - ➢ Photon beam on Be fixed target
- Searches in variety of different channels for both the Ξ_{cc}^{+} and Ξ_{cc}^{++} states
  - ➢ 7 exclusive $\Xi_{cc} \to \Lambda_c^+ X$ modes
  - ➢ 14 exclusive $\Xi_{cc} \to D^{0/+} X$ modes
- Focus did not see doubly charm baryons from photo-production
  - ➢ Even with 12 x Λ_c^+ events in $\Xi_{cc} \to \Lambda_c^+ X$ modes



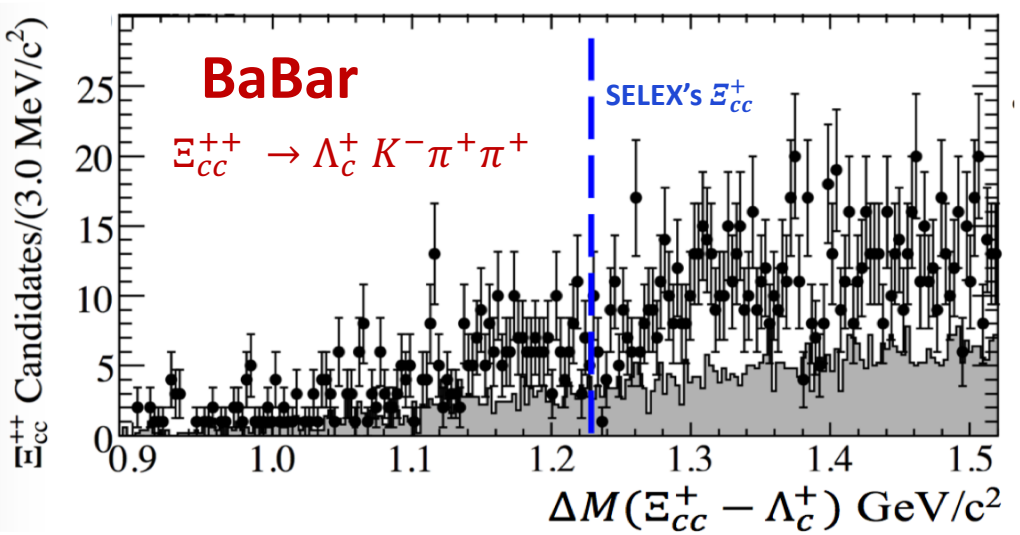
Ξ_{cc} search results

Nucl.Phys.Proc.Suppl. 115 (2003) 33-36

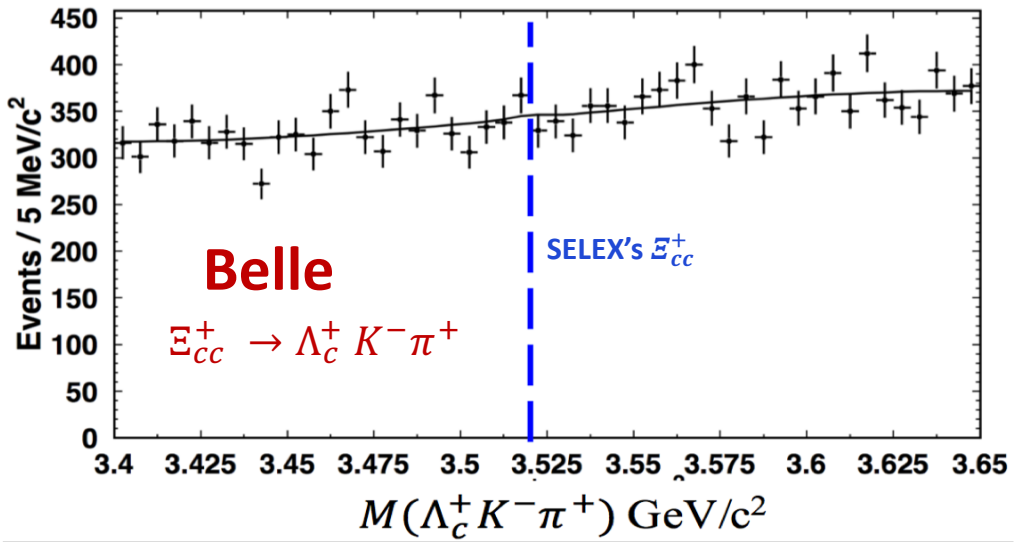


Searches by Belle and BaBar

Phys.Rev. D74 (2006) 011103



Phys.Rev.Lett. 97 (2006) 162001



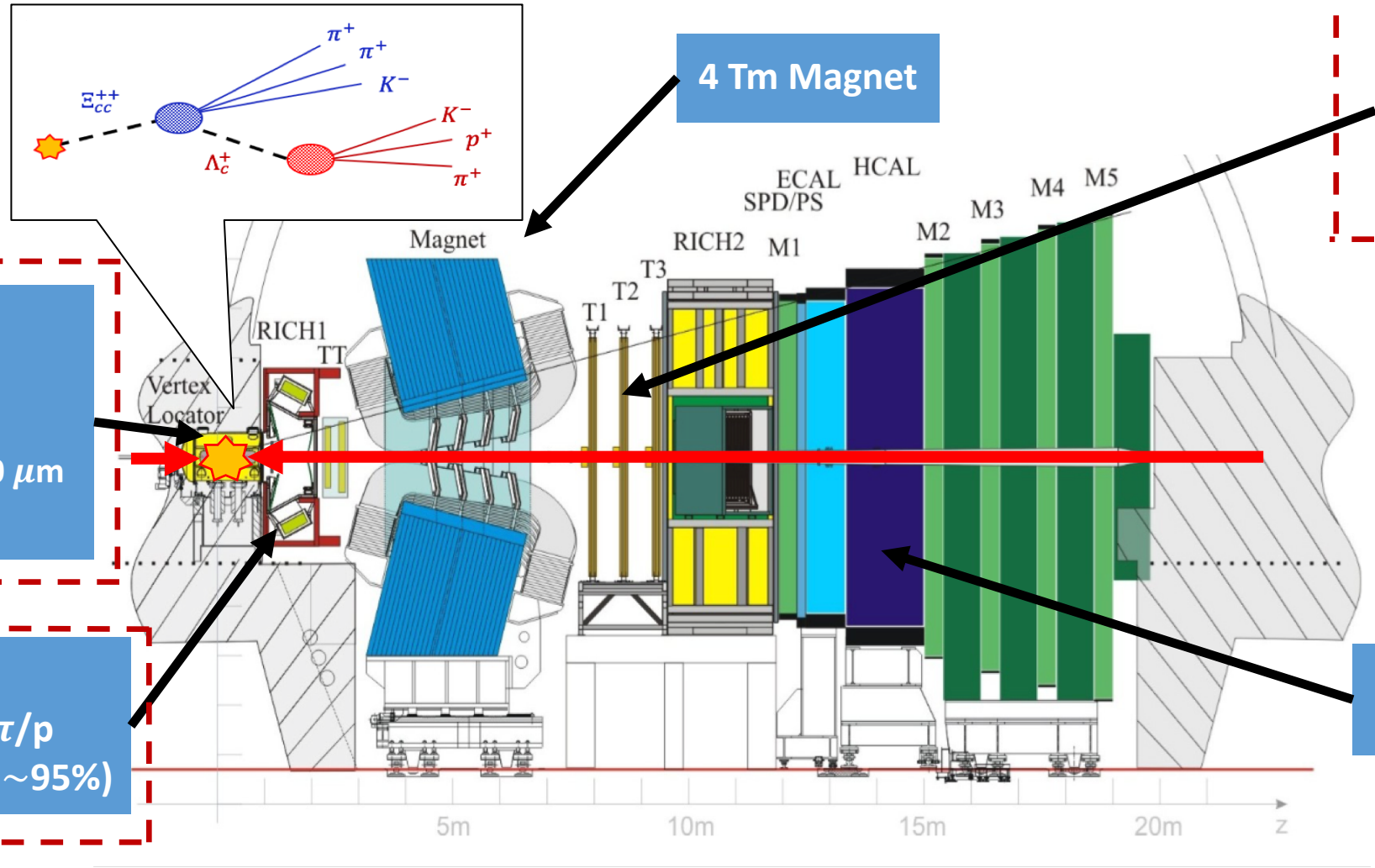
- 2006: BaBar@SLAC: e^-e^+ at $\sqrt{s}$ = 10.58 GeV (4Υ)
  - Searched for both Ξ_{cc}^+ and Ξ_{cc}^{++} states
  - Searched for $\Xi_{cc}^{+(+)} \to \Lambda_c^+ K^-\pi^+(\pi^+)$
  - Searched for $\Xi_{cc}^{+(+)} \to \Xi_c^0 \pi^+(\pi^+)$
  - No evidence of Ξ_{cc} states

- 2006: Belle@KEK: e^-e^+ at $\sqrt{s}$ = 10.58 GeV (4Υ)
  - Searched for $\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+$
  - Found new Ξ_c^+ resonance decaying to $\Lambda_c^+ K^-\pi^+$
  - But still no evidence of a Ξ_{cc} state

… SELEX results seem unreproducible

LHCb detector

- Why can LHCb do better in searching for doubly charmed baryons?



4 Tm Magnet

Tracking systems: Easily separates neighboring structures (~96%)

VELO: Excellent vertex reconstruction
- IP resolution: 20 μm
- τ resolution: 45

RICHes: Efficient K/π/p separation (~95%)

Hadronic calorimeters

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

LHCb search for Ξ_{cc}^{+} JHEP 12 (2013) 090

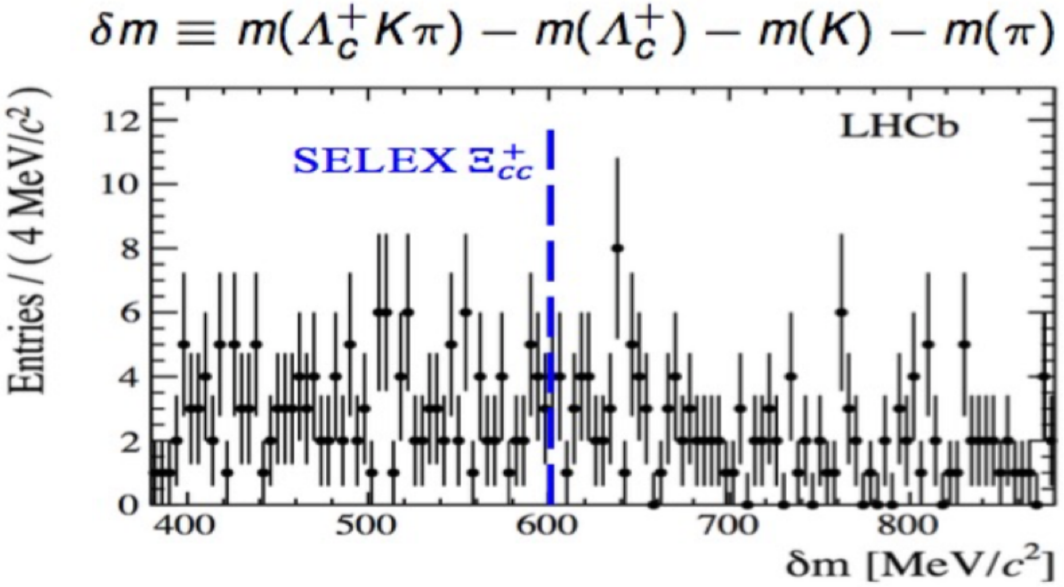
- 2013: LHCb searched for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decays with 2011 data (0.65 fb^{-1})
- Examined mass range 3.3-3.8 GeV but found no evidence of Ξ_{cc}^{+} state
- Experiment sensitivity strongly depends on $\tau(\Xi_{cc}^{+})$:

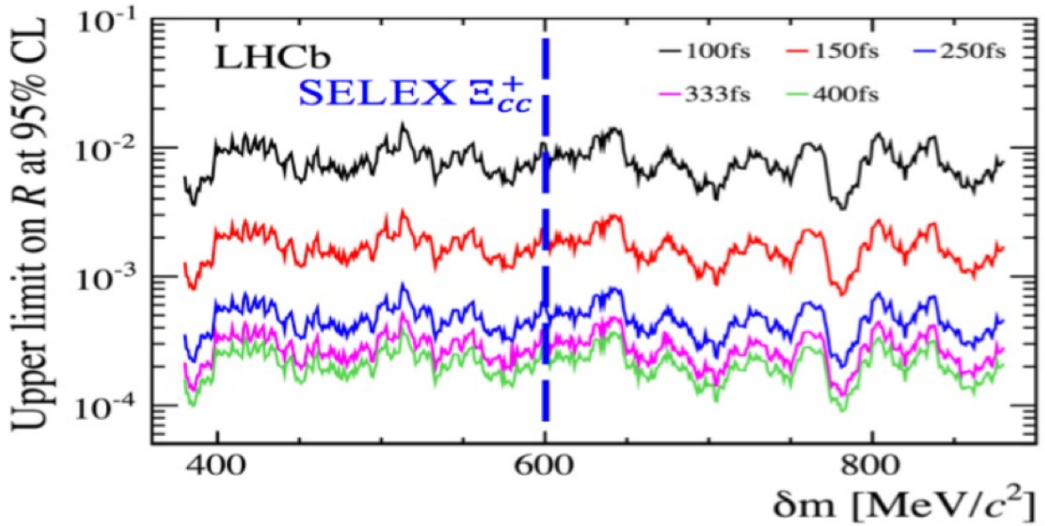
$$R = \frac{\sigma(\Xi_{cc}^{+}) \times BF(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

$R < 0.013$ for $\tau(\Xi_{cc}^{+}) = 100$ fs

$R < 3.3 \times 10^{-4}$ for $\tau(\Xi_{cc}^{+}) = 400$ fs

- Limited sensitivity $\Longrightarrow$ non-observation is not inconsistent with the SELEX claim



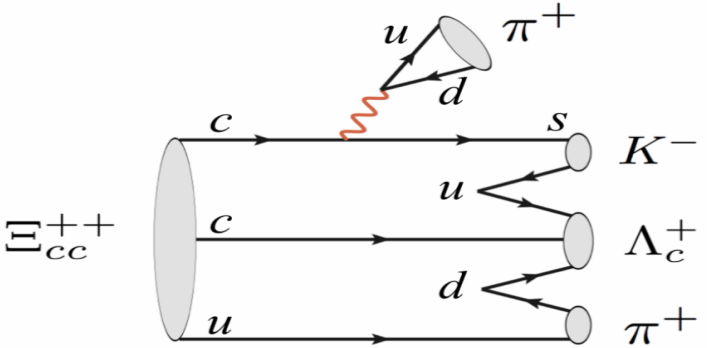


LHCb search for Ξ_{cc}^{++} PRL 119, 112001 (2017)

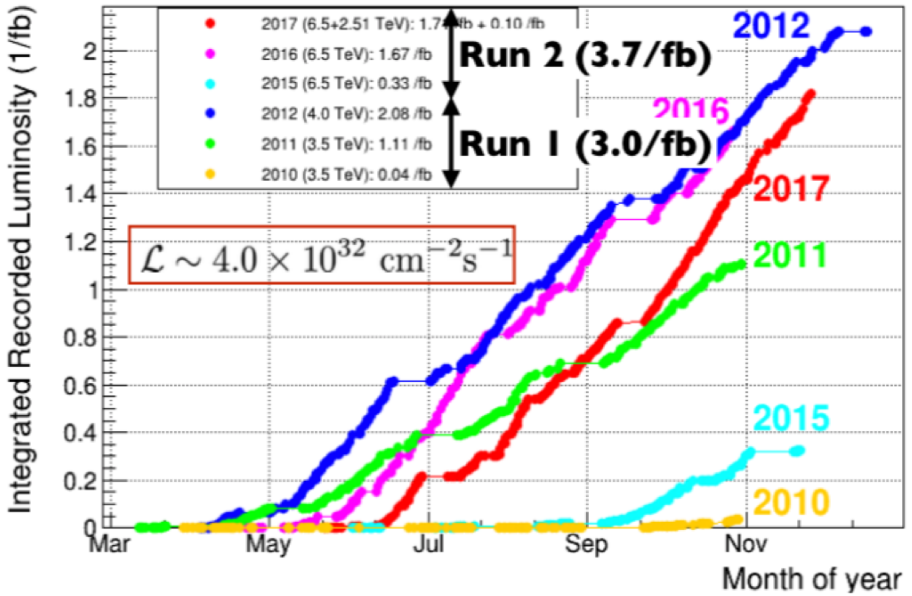
- 2017: Search for doubly charged state in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays with $\Lambda_c^+ \to p K^- \pi^+$

arXiv:1703.09086

- Channel expected to have largest *BF* (as high as 10%?)



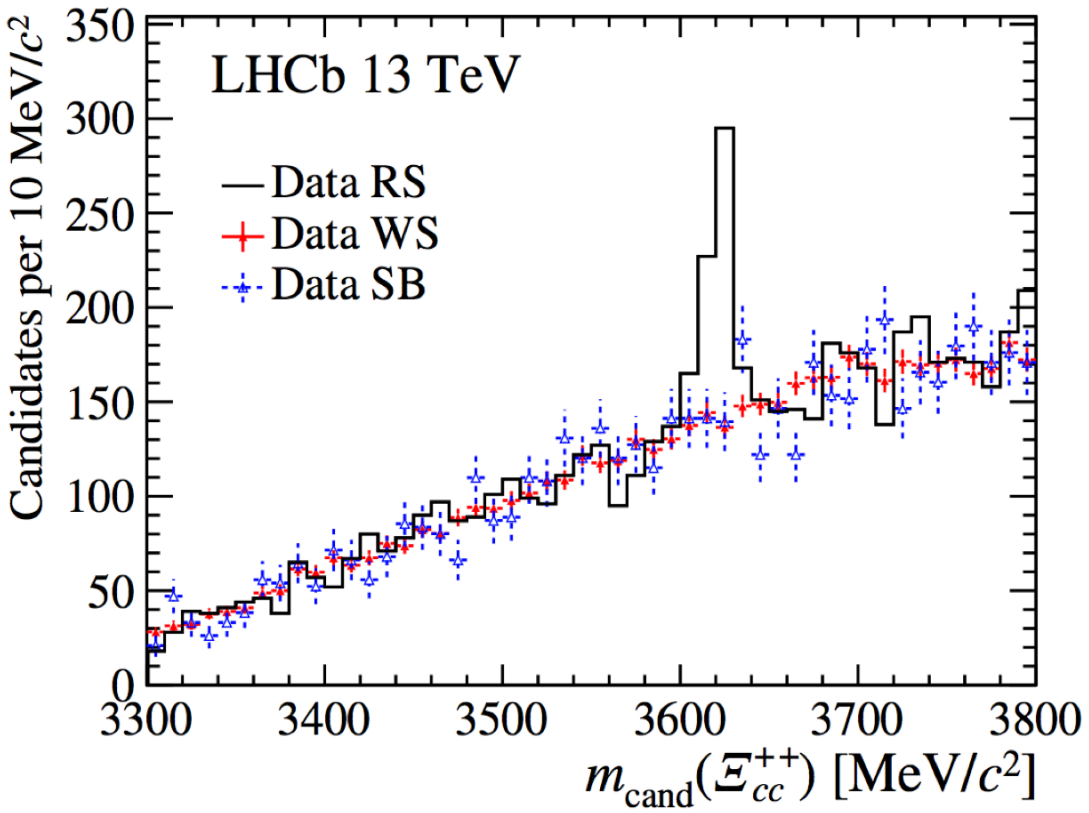
- $\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+})$ so Ξ_{cc}^{++} travels further from PV
  $\Longrightarrow$ easier for selections to suppress background



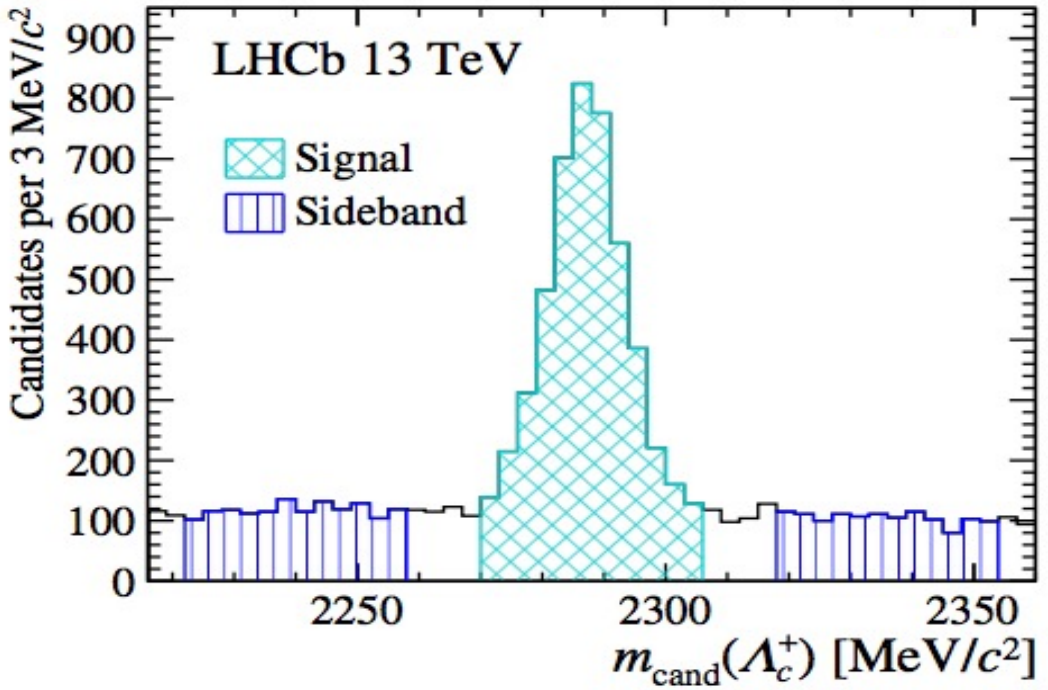
Analysis strategy:

- Using a larger data sample (1.7 fb^{-1} from 2016) than previous LHCb Ξ_{cc}^{+} search
- Increase in cross-section with $\sqrt{s}$ = 13 TeV
- Dedicated exclusive trigger ensuring high efficiency
- Cut based selections and multivariate techniques used to select Ξ_{cc}^{++} candidates

$\Lambda_c^+ K^-\pi^+\pi^+$ mass spectrum [PRL 119, 112001 (2017)]



- A significant structure in right sign (RS) data
- Not present in wrong sign (WS) combinations
- Not observed for Λ_c^+ background candidates (SB)
- Distributions similar except the peak in RS



CHEAT SHEET:

RS: $\Xi_{cc}^{++} \to \Lambda_c^+(\to p^+ K^-\pi^+)\, K^-\pi^+\pi^+$

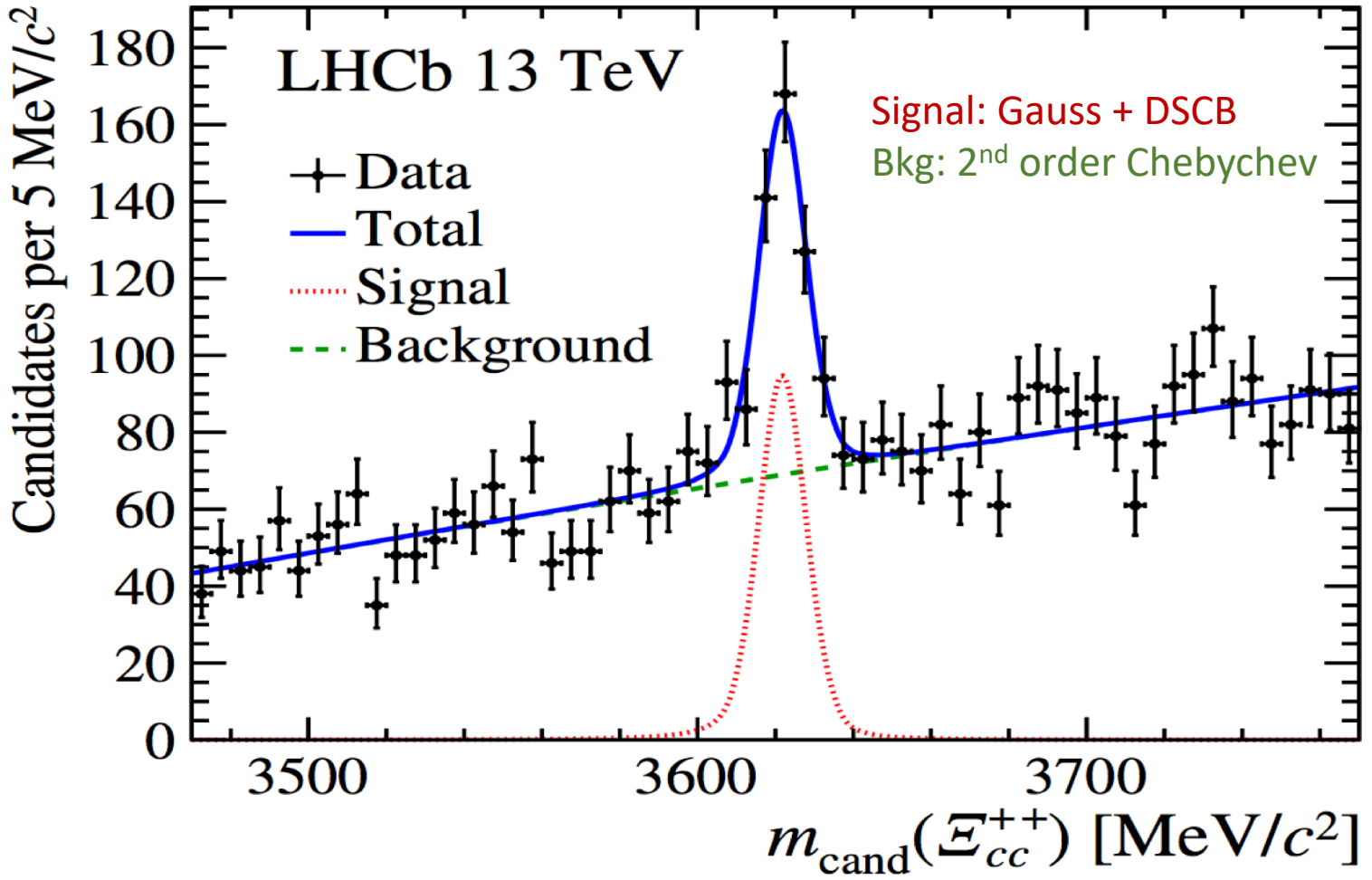
WS: $\Xi_{cc}^{++} \to \Lambda_c^+(\to p^+ K^-\pi^+)\, K^-\pi^+\pi^-$

SB: $\Xi_{cc}^{++} \to [\Lambda_c^+(\to p^+ K^-\pi^+)]_{SB}\, K^-\pi^+\pi^+$

Discovery of the Ξ_{cc}^{++} state

PRL 119, 112001 (2017)

- ✓ Local significance > 12σ
- ✓ Resolution = 6.6 ± 0.8 MeV
  (consistent with detector resolution)
- ✓ Signal yield = 313 ± 33 events



Summary of systematics

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

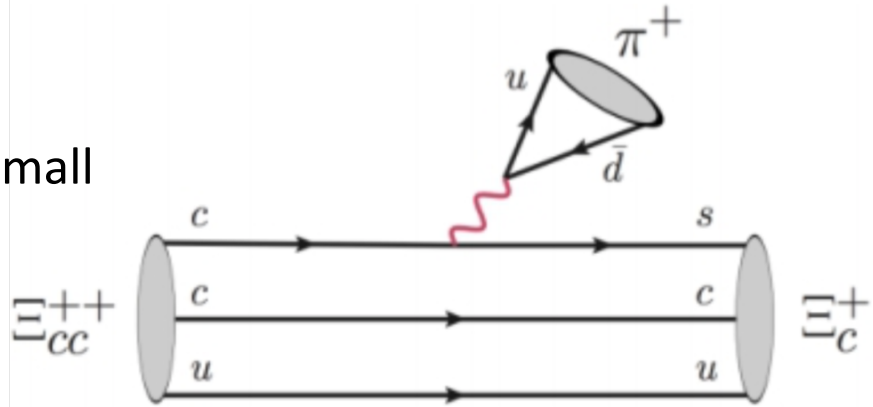
$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\ (\text{stat}) \pm 0.31\ (\text{syst})$

Further searches of Ξ_{cc}^{++} LHCb-PAPER-2018-026

- Searching for new decay modes is critical to understand dynamics of weak decays of Ξ_{cc}
- $\Xi_{cc}^{++} \to \Xi_c^+ (\to pK^-\pi^+)\pi^+$ offered promise for discovery:
  - *BF*($\Xi_{cc}^{++} \to \Xi_c^+\pi^+$) is CF and likely to be O(%)
  - *BF*($\Xi_c^+ \to pK^-\pi^+$) is SCS and unknown but seems to be non-small (easy to reconstruct efficiently at LHCb)
  - Only 4 tracks in final state
    $\Longrightarrow$ higher trigger + reconstruction efficiency

"$\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ is the best external W-emission processes to search for doubly charmed baryons "

arXiv:1703.09086

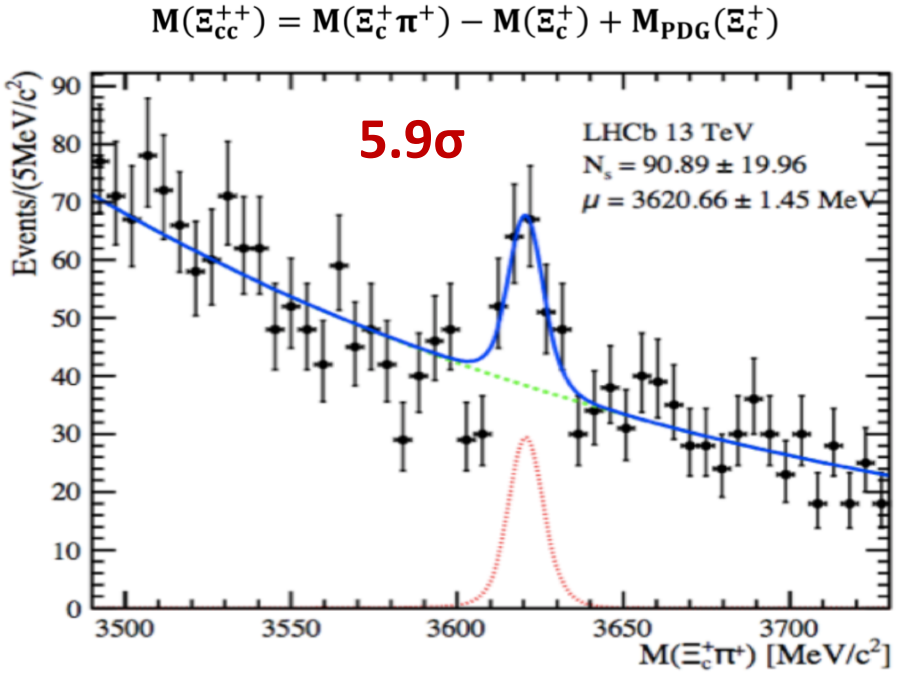


Analysis strategy:

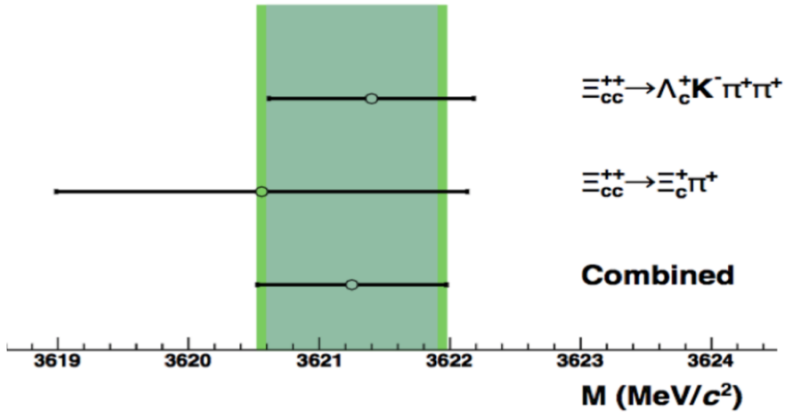
- Using very similar event selection structure to $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$ analysis
  - Use of two separate multivariate selectors to suppress background from Ξ_c^+ and then Ξ_{cc}^{++}
- Analysis is done blindly using MC and wrong-sign data to optimize offline event selection

Confirmation of Ξ_{cc}^{++} LHCb-PAPER-2018-026

- 2018: $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decays observed by LHCb using 2016 data:
  - ✓ Signal yield: 91 ± 20 events
  - ✓ Significance: 5.9σ
- Signal: DSCB function + Gaussian
  - ➢ Mass, resolution and yield are free parameters
- Background: Exponential function



- The measured mass from $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ analysis:
  - ➢ $M(\Xi_{cc}^{++}) = 3620.56 \pm 1.45$ (stat) ± 0.61 (syst) MeV
  - ✓ Good agreement with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ result:
    - ➢ $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72$ (stat) ± 0.31 (syst) MeV



Relative branching fraction

LHCb-PAPER-2018-026

- Want to determine relative *BF (R)* between decays of $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$:

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

- r_N = ratio of Ξ_{cc}^{++} yields between decay modes
- r_ε = ratio of efficiencies between decay modes

N.B. There is no experimental measurement of *BF* ($\Xi_c^+ \to pK^-\pi^+$) fraction

BF ($\Lambda_c^+ \to pK^-\pi^+$) = (6.35 ±0.33)%
N(Λ_c^+ $K^-\pi^+\pi^+$) = 289 ± 35
N($\Xi_c^+\pi^+$) = 91 ± 20

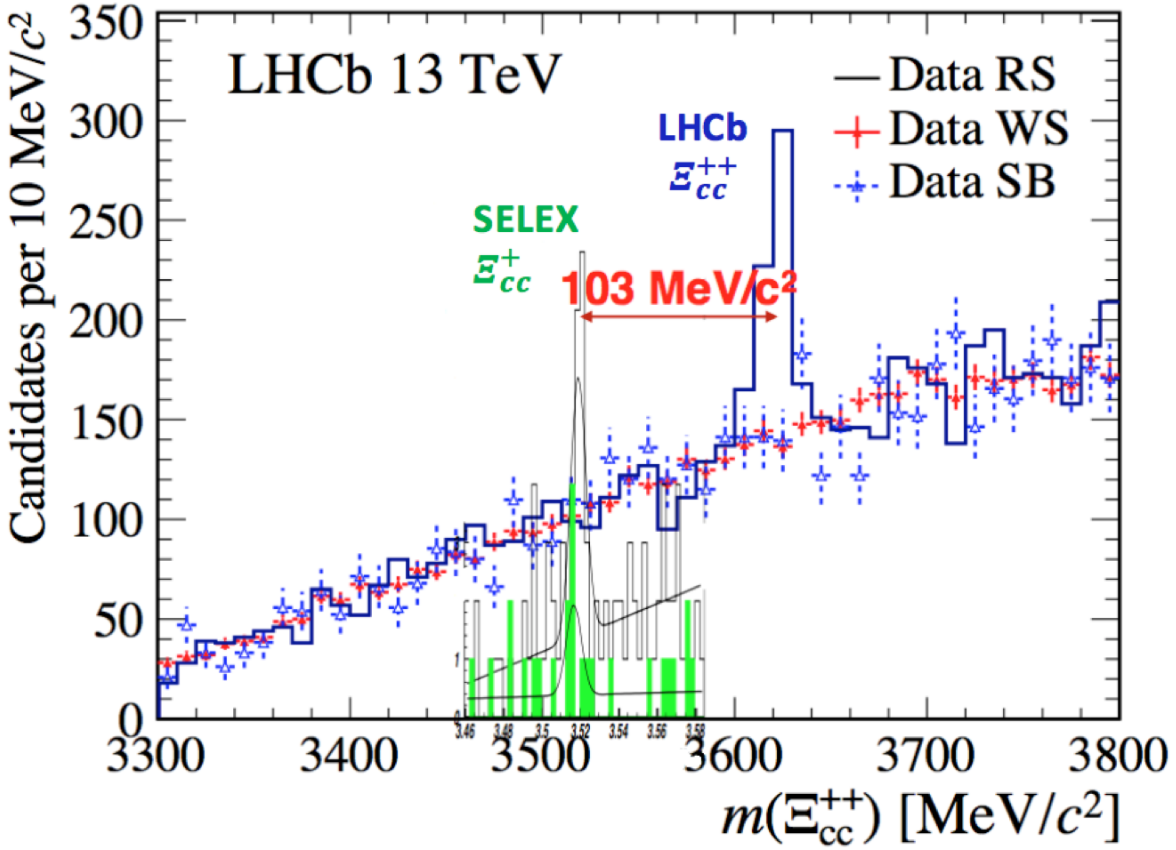
$$\mathcal{E}^{Tot} = \mathcal{E}^{Acc} \times \mathcal{E}^{Rec/Sel} \times \mathcal{E}^{Pid} \times \mathcal{E}^{Trg}$$

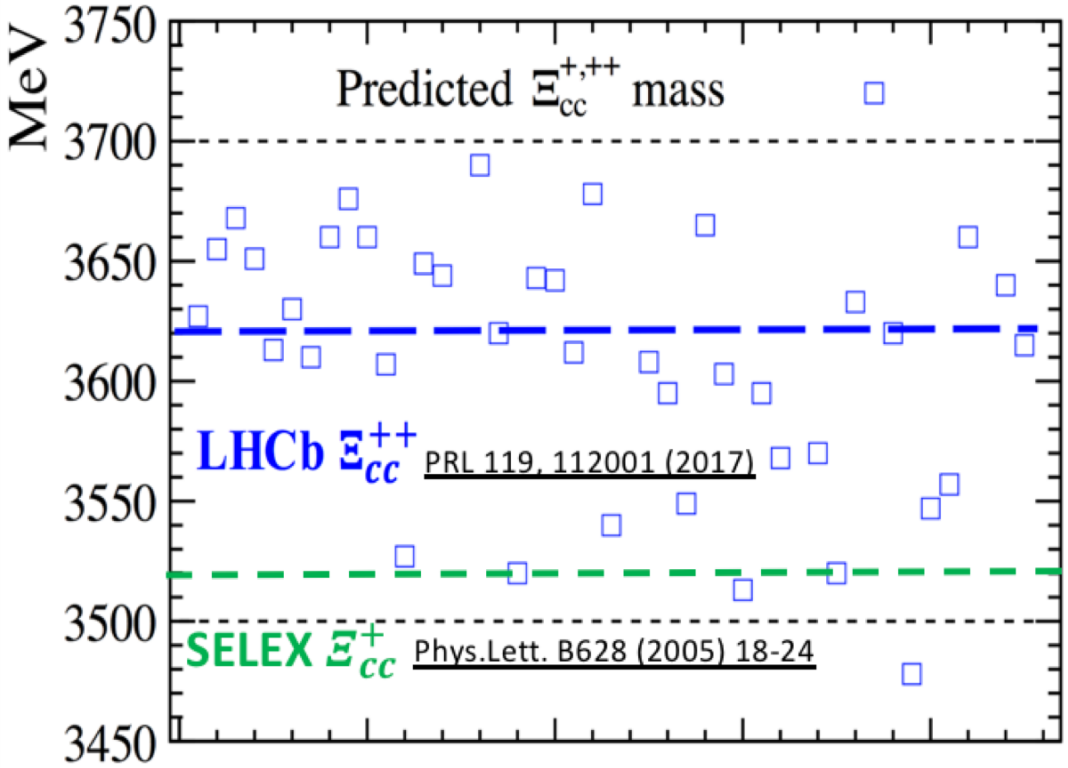
Each relative efficiency calculated from MC

Final result

✓ $\mathcal{R}(B)$ = 0.035 ± 0.008 (stat) ± 0.003 (syst)

Comparison with SELEX



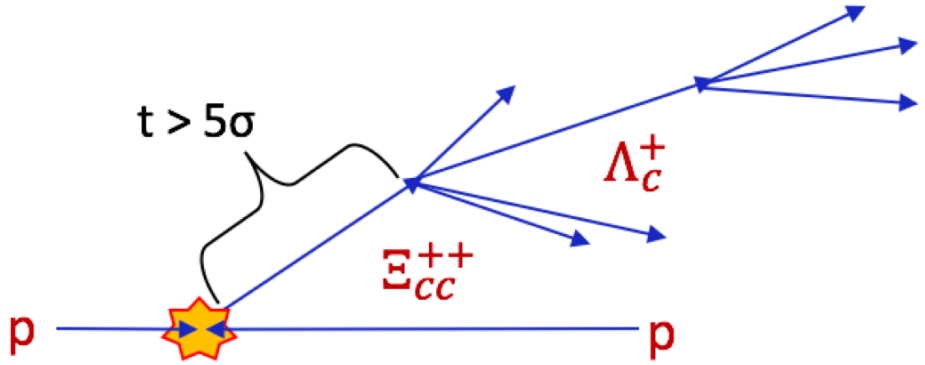


- $m(\Xi_{cc}^{++})_{LHCb} - m(\Xi_{cc}^{+})_{SELEX} \approx 103 \Longrightarrow$ Cannot be a *conventional* isospin-doublet!
- Attempts to reconcile LHCb with SELEX but most assume LHCb's Ξ_{cc}^{++} is 3/2 spin state

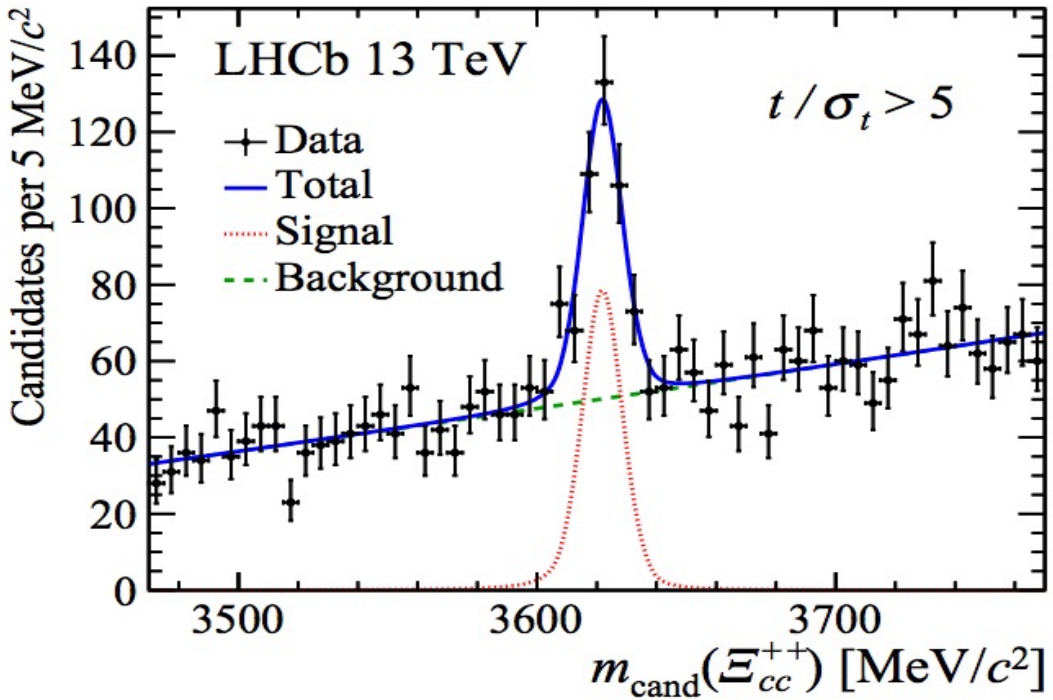
arXiv:1709.09903

Looks weak [PRL 119, 112001 (2017)]

- Established during $\Lambda_c^+ K^-\pi^+\pi^+$ analysis that Ξ_{cc}^{++} state has non-zero lifetime
  - ✓ Peaks remains significant after requiring minimum time $t > 5\sigma$ w.r.t PV



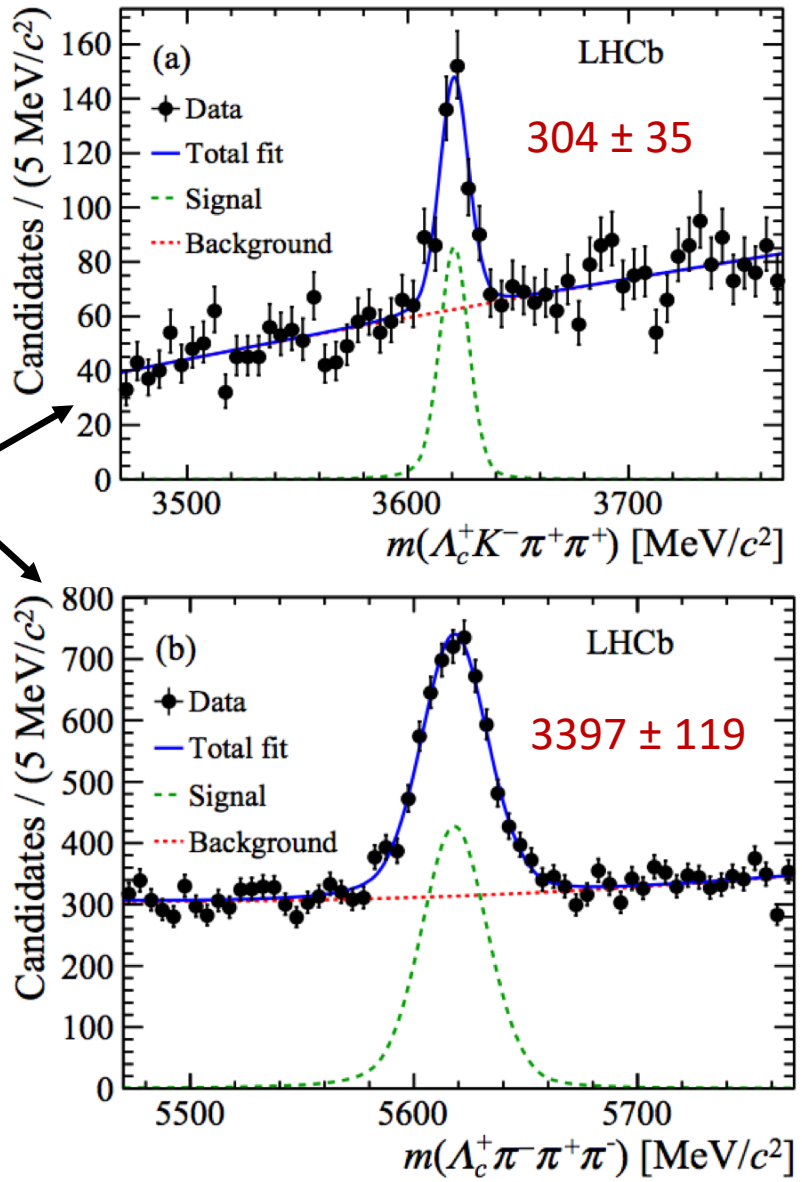
- Full lifetime analysis critical however:
  - ➢ Further confirm LHCb observed state Ξ_{cc}^{++} is ground state spin-1/2
  - ➢ Necessary ingredient for theoretical predictions of BRs
  - ➢ Provide important info for experimental exploration of Ξ_{cc}^{+} and Ω_{cc}^{+}



Lifetime strategy arXiv:1806.02744 [Submitted to PRL]

- 2018: Lifetime measurement performed using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays relative to the control mode $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^+$
  - ➢ Reduced systematic uncertainty ⟹ only sensitive to ratio of decay time acceptance

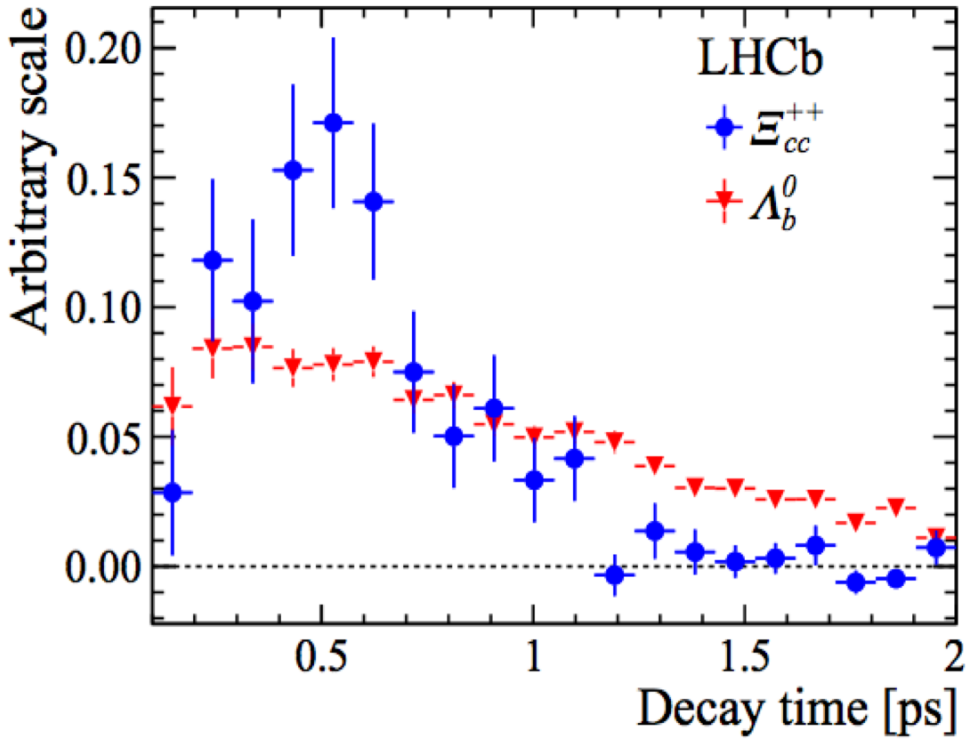
Signal: Gauss + DSCB
Bkg: 2nd order Chebychev



- Same 2016 data as for search analysis (plus extra hardware trigger requirements)
- Same selections applied to both channels (different PID cuts for different final state tracks)
- Systematic differences between channels corrected using MC

Fitting to Ξ_{cc}^{++} data arXiv:1806.02744 [Submitted to PRL]

- Fit PDF to decay time distribution of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - PDF uses histograms for acceptance and Λ_b^0
  - sWeights from mass fit for background subtraction



Obtained from histograms

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

Target measurement

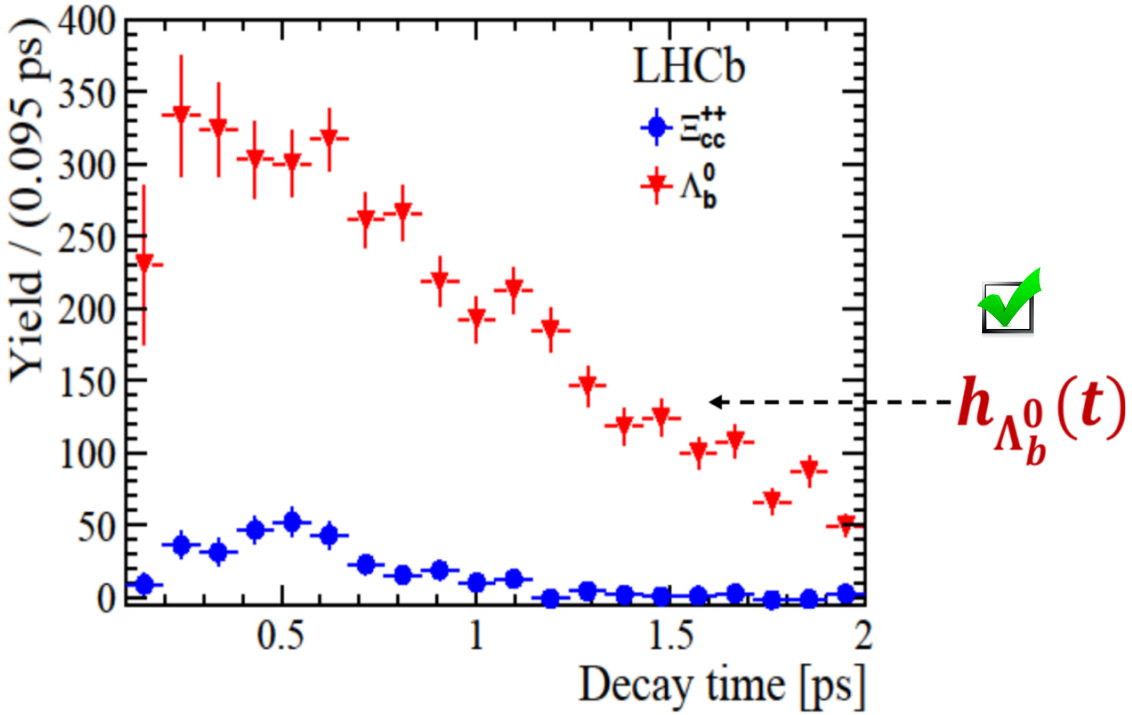
$h_{\Lambda_b^0}(t)$: time distribution of Λ_b^0 in data

$\frac{\epsilon_{\Xi_{cc}^{++}}(t)}{\epsilon_{\Lambda_b^0}(t)}$: time acceptance ratio from MC

$\tau(\Lambda_b^0)$: Λ_b^0 lifetime in PDG, 1.470 ± 0.010 ps

Decay time histograms arXiv:1806.02744 [Submitted to PRL]

- Decay time of Ξ_{cc}^{++} candidates plotted between 0.1-1.0 ps in 20 bins
- Background subtracted using sWeights technique

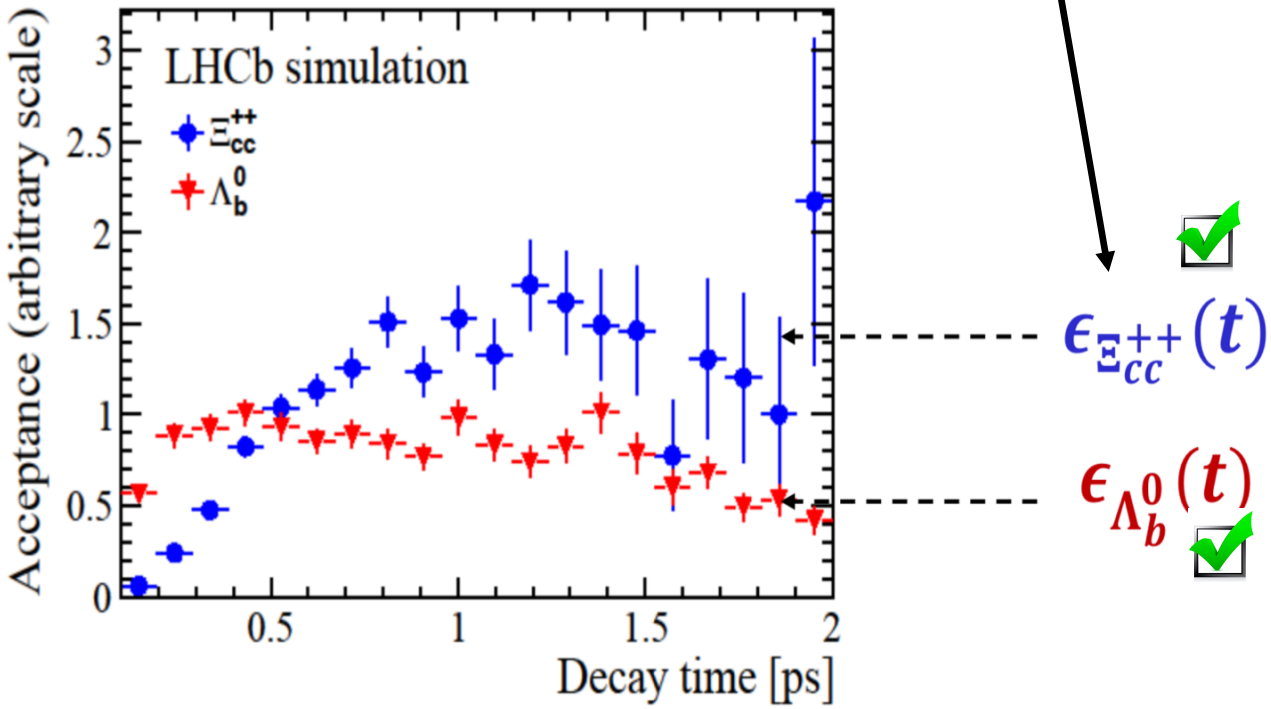


$h_{\Lambda_b^0}(t)$

- $\varepsilon(t)$ calculated from P_T reweighted MC:

$$\varepsilon(t) = \frac{Reconstructed\ distribution}{Generator\ level\ distribution}$$

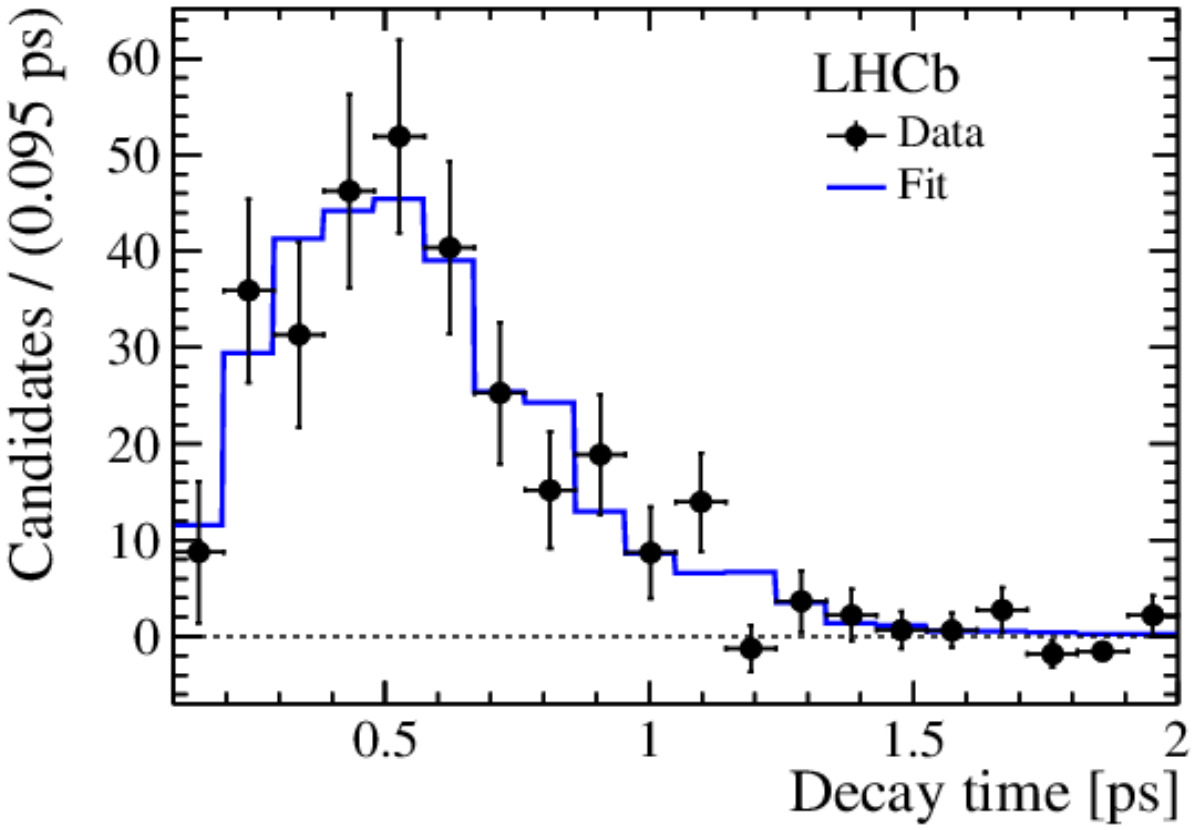
- Effectively describes both acceptance and resolution effects



$\epsilon_{\Xi_{cc}^{++}}(t)$

$\epsilon_{\Lambda_b^0}(t)$

Lifetime of Ξ_{cc}^{++} arXiv:1806.02744 [Submitted to PRL]

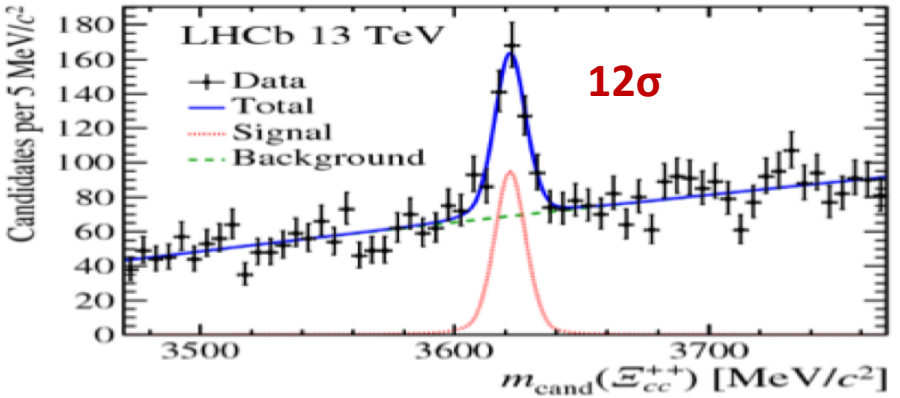
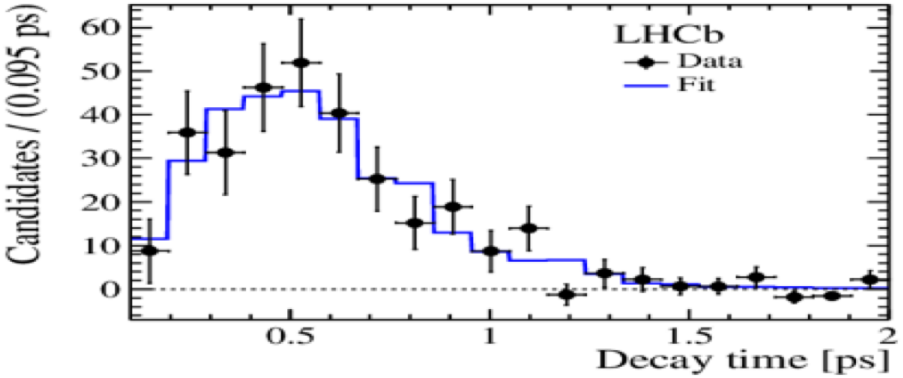
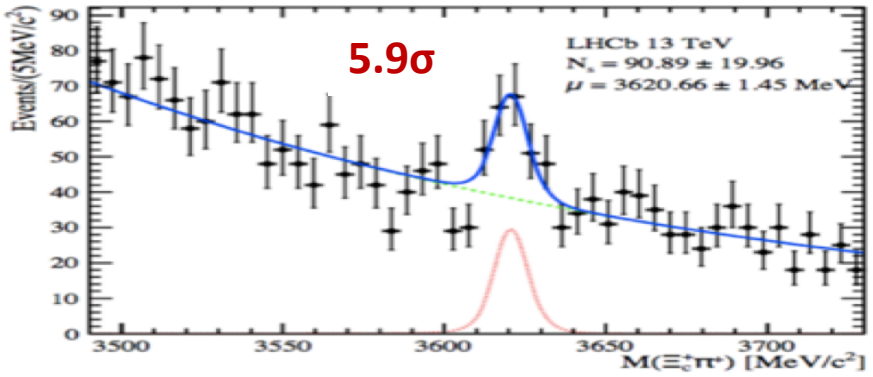


Final result

✓ $\tau(\Xi_{cc}^{++}) = 256^{+22}_{-20}$ (stat) $\pm$ 14 (syst) fs

Summary of systematics

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

Summary

- History of doubly charmed baryon searches is long and puzzling
- LHCb have made great progress in the last few years with work on the Ξ_{cc}^{++} state:
  - ✓ Discovery of the Ξ_{cc}^{++} state in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay modes
  - ✓ Lifetime analysis of the Ξ_{cc}^{++} state complete, confirming it is weakly decaying
- Focus remains on searching for shorter lived Ξ_{cc}^{+}
  - ➢ Need a direct measurement to compare to SELEX
- Work also continues on the Ξ_{cc}^{++} production cross-section and searches for Ξ_{cc}^{++} in other decay modes
- See Jibo's talk at the end of the workshop discussing future ideas at LHCb