Doubly charmed baryon studies at LHCb

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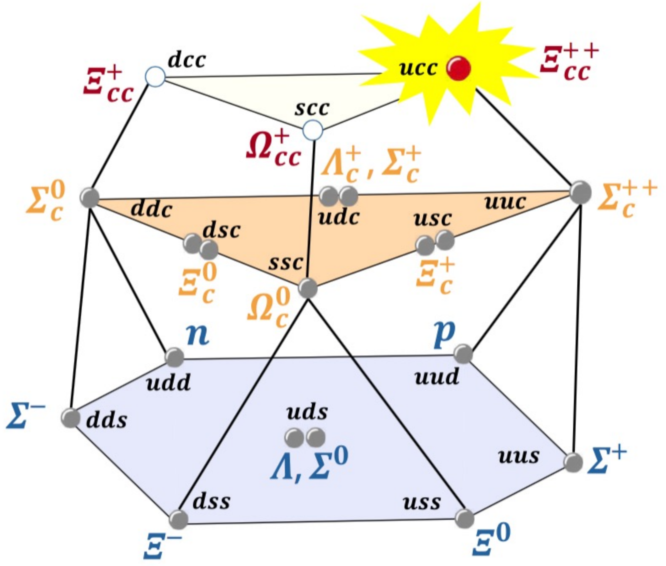
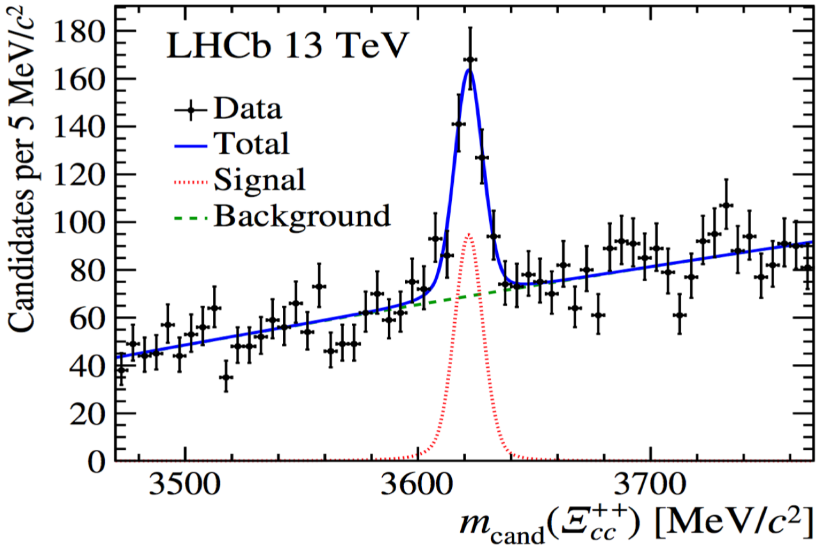




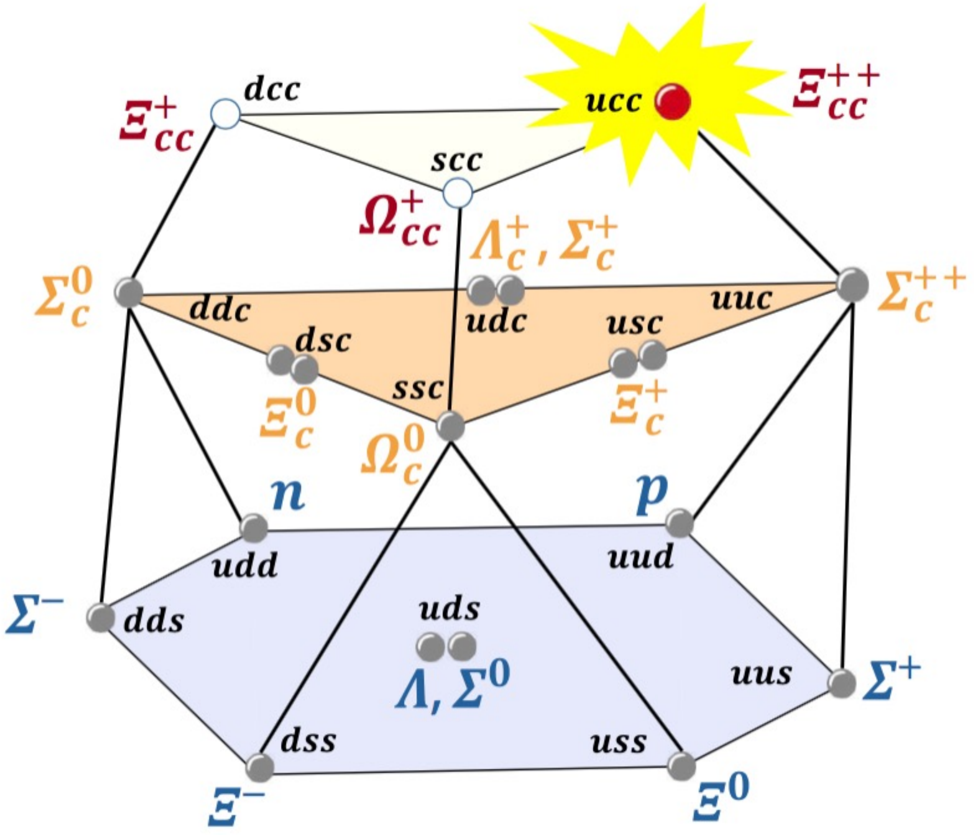
University of Glasgow

LHCb

中国科学院大学
University of Chinese Academy of Sciences

Outline

- The LHCb Experiment
- Doubly-charmed baryons
  - Introduction & motivation
  - Previous searches
- First observation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
  - Mass measurement
- Outlook



The LHCb detector

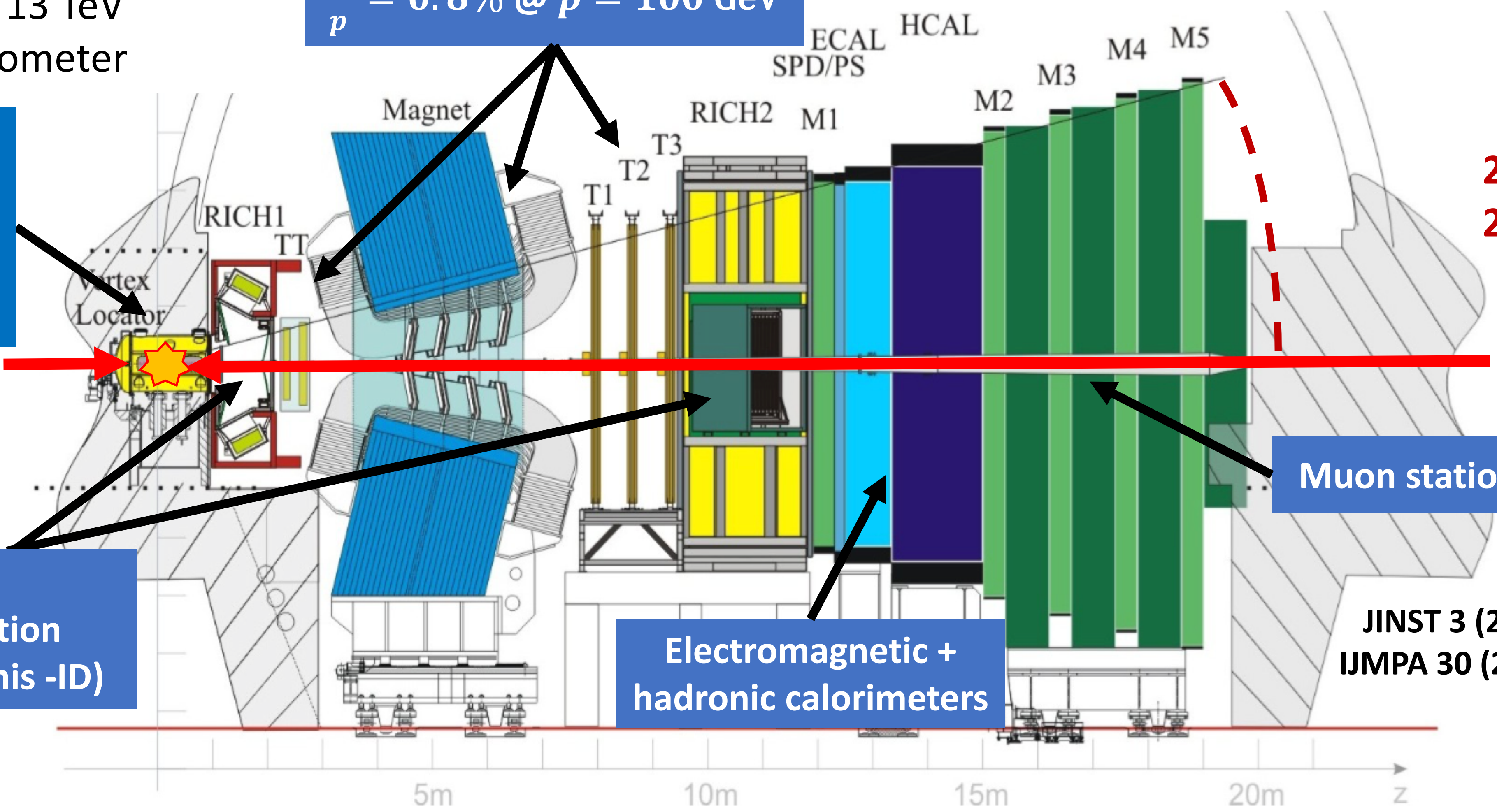
LHCb is a unique laboratory for hadron spectroscopy studies

- pp collisions @ 13 TeV
- Forward spectrometer

Magnet & tracking stations :
Bending power 4 Tm
$$\frac{\delta p}{p} = 0.8\% \;@\; p = 100\ \text{GeV}$$

Designed for precision measurements in b and c flavor physics

Vertex Locator:
Excellent vertex reconstruction
- **IP resolution: 20 μm**
- **τ resolution: 45 fs**



RICH detectors:
Good K/π/p separation
(eff: ~95% @ 5% mis -ID)

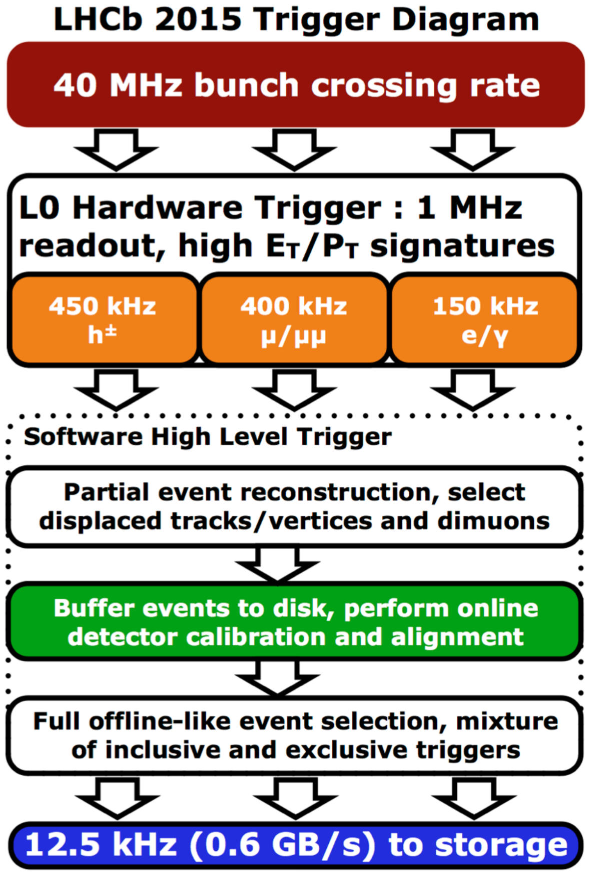
Electromagnetic + hadronic calorimeters

Muon stations

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

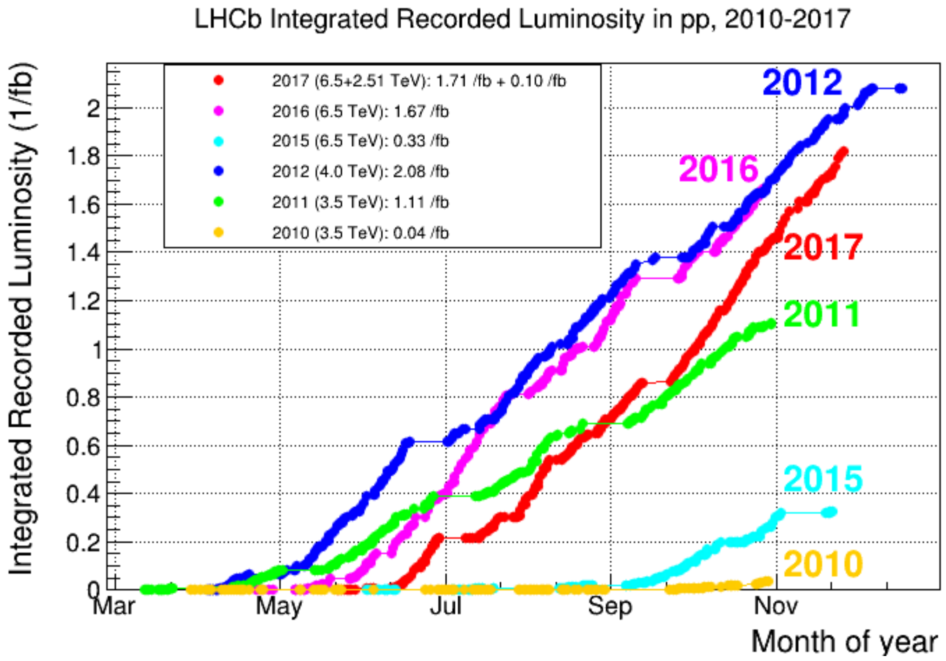
LHCb trigger and data

arXiv:1604.05596



LHCb can perform full detector alignment and calibration in real-time in Run II

- Integrated luminosity to date: 6.9 fb^{-1}
- Results presented here
  - 0.65 fb^{-1} record 2011
  - 2.1 & 1.7 fb^{-1} recrded in 2012 & 2016
- Expectation for 2018: approximately 2 fb^{-1}
- Triggers re-optimied regularly



Run II Turbo stream:

- Candidates reconstructed at trigger level saved for offline analyses directly

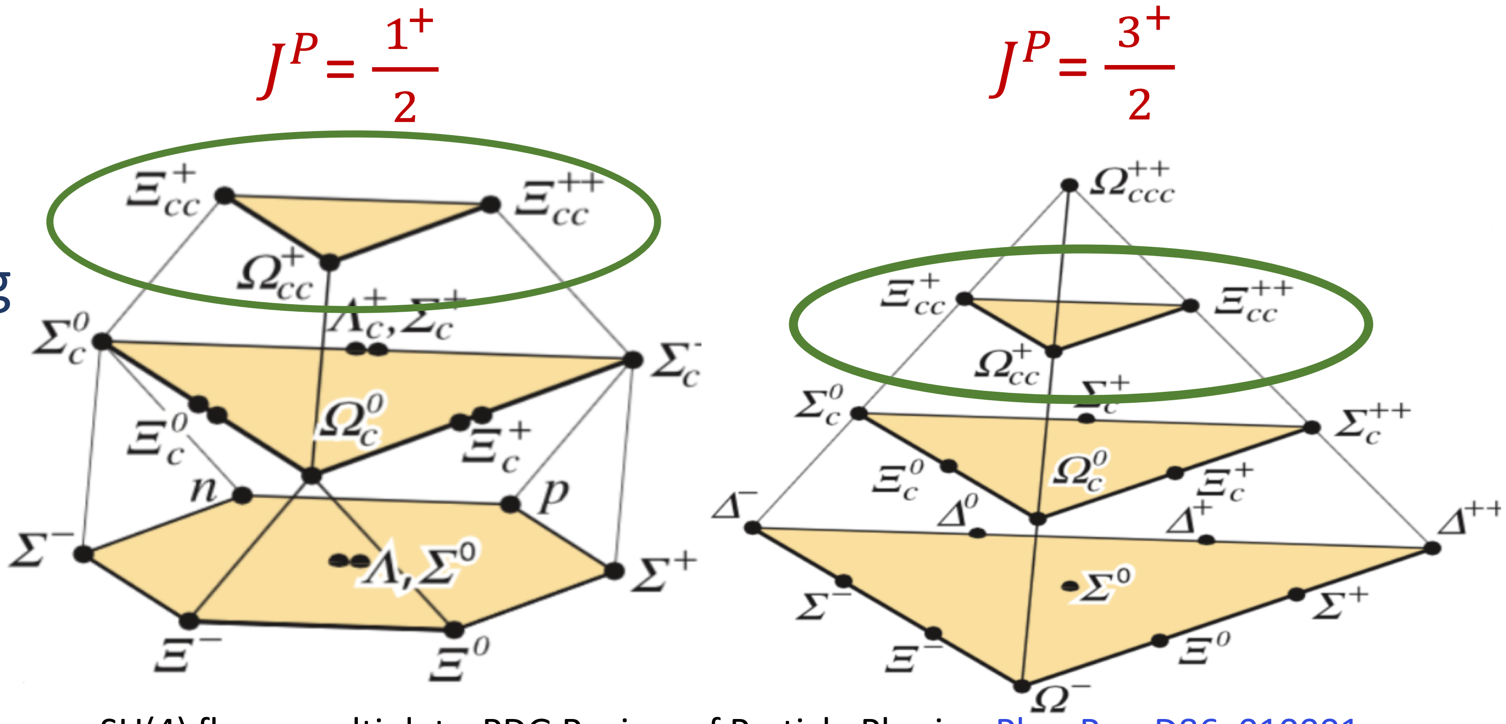
Doubly heavy baryons

- Quark model predicts doubly-heavy baryons: QQq ($Q \in c, b$; $q \in u, d, s$)
  - Predicted states: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Omega_{cc}^{+}(ccs)$, $\Xi_{bc}^{+}(bcu)$, Ξ_{bc}^{0}(bcd) etc.
  - More doubly charmed baryons produced at LHCb: $\sigma(c\bar{c}, c\bar{c}) >> \sigma(b\bar{b}, c\bar{c}) >> \sigma(b\bar{b}, b\bar{b})$

- Lightest doubly charmed states Ξ_{cc} offered best chance of discovery
  - Ground states decay weakly with a charm quark transitioning into lighter quarks
  - Excitations decay to ground states via Strong/EM interaction

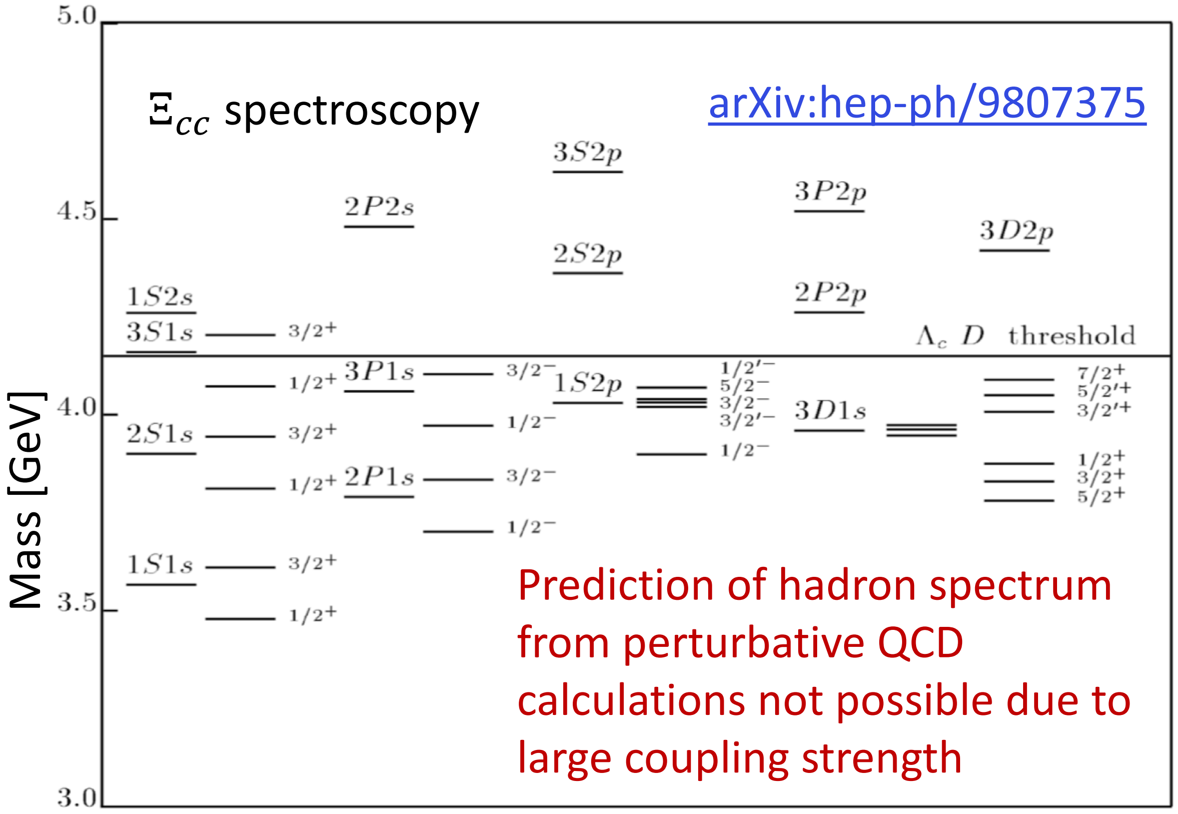
LHCb see thousands of $B_c^{+}(c\bar{b})$ mesons

- Should see doubly heavy baryons!

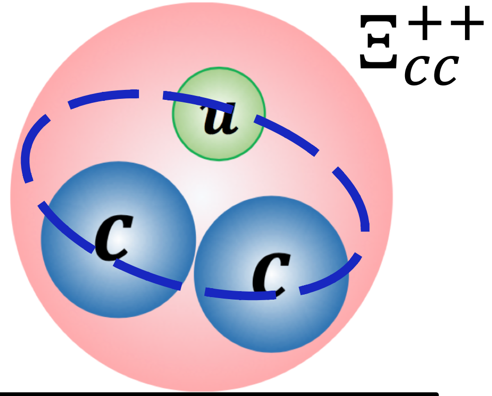


SU(4) flavor multiplets, PDG Review of Particle Physics, Phys.Rev. D86, 010001

Physics motivation



Example: HQET where two charm quarks considered as static heavy di-quark reducing it to simple $Q\bar{q}$ system



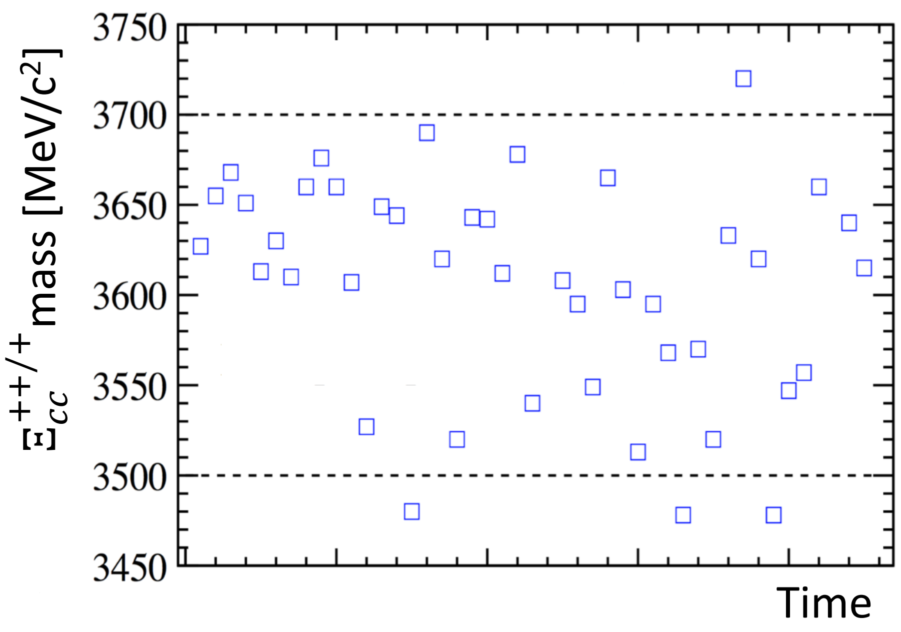
($Q \in c, b; q \in u, d, s$)

- Heavy hadrons ($Q\bar{q}$, $Q\bar{Q}$, QQq, QQQ etc) are all of much interest in QCD studies
- Allow great testing grounds for phenomenological models and lattice QCD techniques

- Doubly heavy baryons will open new sector to study strong force and CPV in baryonic matter

Mass and lifetimes predictions

- Many models been applied to determine masses of ground states of (QQq) baryons;
  - QCD sum rules, (non-)relativistic QCD potential models, bag model, quark model…



- Recent lattice QCD computations:
  - $m(\Xi_{cc}^{+}/\Xi_{cc}^{++}) \approx 3.6$ GeV
  - $m(\Xi_{cc}^{+}) - m(\Xi_{cc}^{++}) \approx$ few MeV
  - $m(\Omega_{cc}^{+}) \approx 3.7$ GeV

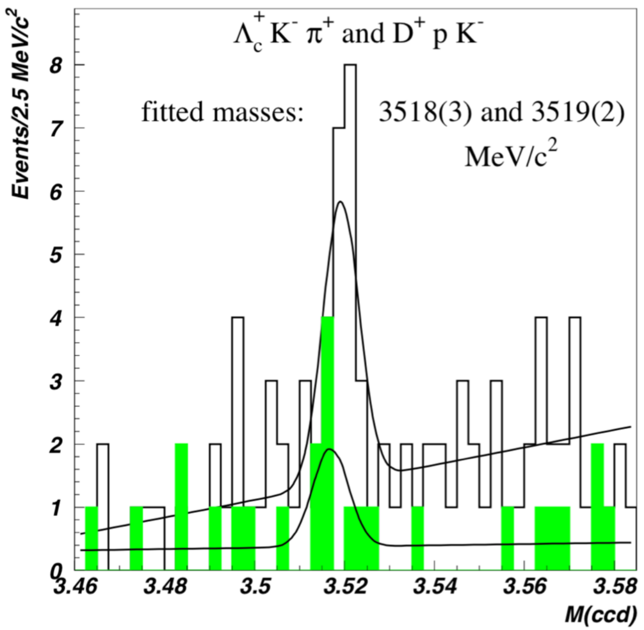
- Lifetime predictions
  - $\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+}) \sim \tau(\Omega_{cc}^{+})$
  - $\tau(\Xi_{cc}^{++}) \in$ 200-700 fs
  - $\tau(\Xi_{cc}^{+}) \in$ 50-250 fs

- Ξ_{bc} higher at 6.75 - 7.1 GeV with $m(\Xi_{bc}^{0}) \approx m(\Xi_{bc}^{+})$
- Ξ_{bc} lifetimes predicted to be generally longer than Ξ_{cc} with: $\tau(\Xi_{bc}^{+}) > \tau(\Xi_{bc}^{0})$

SELEX and Ξ_{cc}^{+}

SELEX: fixed-target experiment @ Fermilab

- Observation of Ξ_{cc}^{+} in $\Xi_{cc}^{+} \to \Lambda_c^+ K^-\pi^+$, 2002 (6.3σ)
- Evidence of Ξ_{cc}^{+} in $\Xi_{cc}^{+} \to D^+p^+ K^-$, 2004 (4.8σ)



SELEX $\Lambda_c^+ K^-\pi^+$ and $D^+p^+ K^-$ distributions superposed
[Phys.Lett. B628 (2005) 18-24]

- Signal had some unexpected properties:
  - Short lifetime: τ < 33 fs at 90% C.L., suggests a strong decay
  - Large production: 20% Λ_c^+ came from Ξ_{cc}^{+} decays
- SELEX findings never reproduced by other groups
- Unique production environment:
  - 600 GeV beam of hyperons on fixed target of Cu/diamond
  - Production cross-section could be very different than in pp colliders

Combined mass:
$3518.7 \pm 1.7(\text{stat})$ MeV/c^2

LHCb search for Ξ_{cc}^{+}

JHEP 12 (2013) 090

- In 2013, LHCb searched for $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-}\pi^{+}$ decays with 0.65 fb^{-1} of 2011 data
- Examined mass range 3.3-3.8 GeV but found no evidence of Ξ_{cc}^{+} production
- Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime however

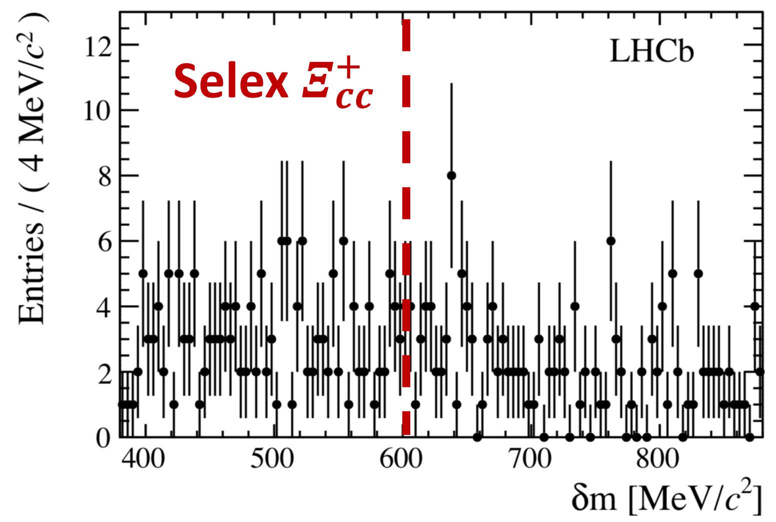
$$R = \frac{\sigma(\Xi_{cc}^{+})\times BF(\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})}$$

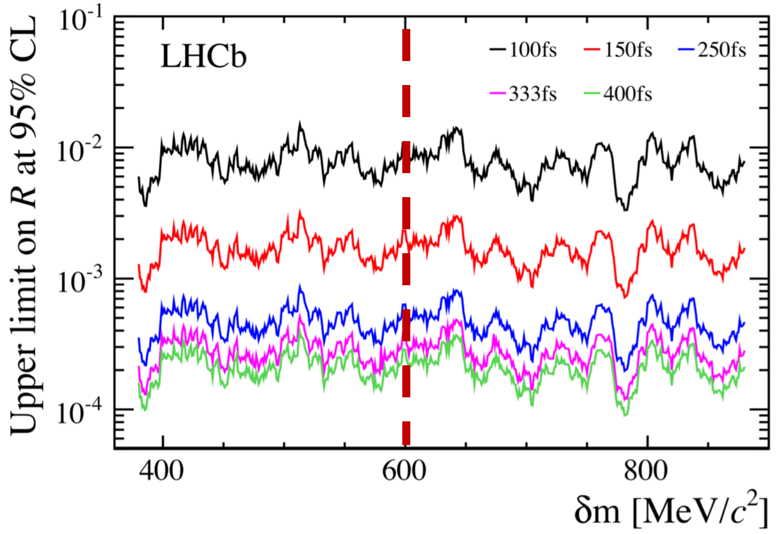
R < 0.013 for $\tau(\Xi_{cc}^{+})$ = 100 fs

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

- Due to limited sensitivity at short lifetimes, this non-observation is not inconsistent with the SELEX claim

$$\delta m \equiv m(\Lambda_c^{+} K\pi) - m(\Lambda_c^{+}) - m(K) - m(\pi)$$



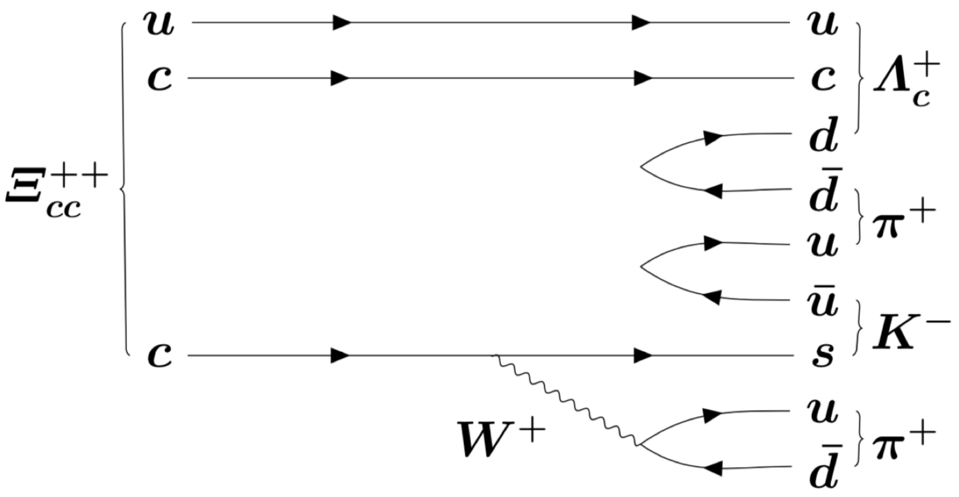


LHCb search for Ξ_{cc}^{++}

PRL 119, 112001 (2017)

- In 2016 Started searching for doubly charged state in $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decays
- BF suggested to be as high as ~10% (arXiv:1703.09086)
- $\tau(\Xi_{cc}^{++}) >> \tau(\Xi_{cc}^{+})$
  - ➢ Ξ_{cc}^{++} travels further from PV, increasing the selection efficiency

$\Xi_{cc}^{++} \rightarrow (csu)W^+ \rightarrow (csu)(\pi^+, \rho^+, a_a^+)$



Analysis strategy:

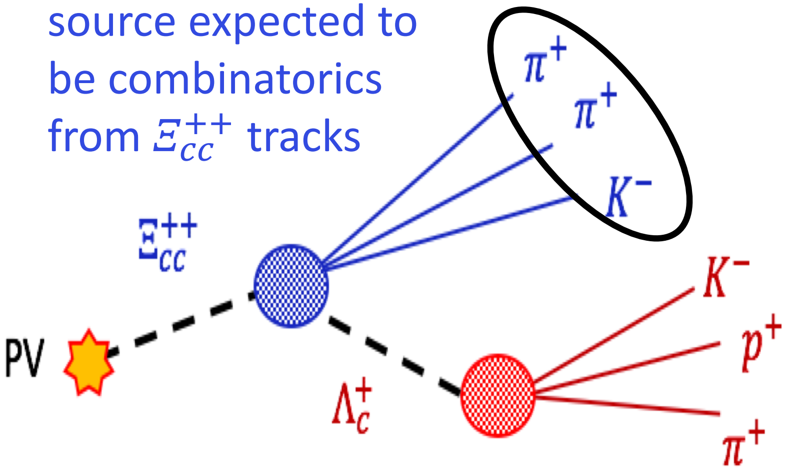
- Use 1.7 fb^{-1} 2016 Run II data at $\sqrt{s}$ = 13 TeV
- Dedicated exclusive trigger ensuring high efficiency
- Full event reconstruction done at trigger level
- 2 fb^{-1} 2012 Run I data also analysed to cross check results

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ selections

PRL 119, 112001 (2017)

- $\sigma(\Xi_{cc}^{++}) \ll \sigma_{\text{inelastic}}$ (by $\sim\times 10^5$)
  - Very large hadronic background
- Pure, high-yield sample of $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ (cuts-based)
  - Tracks: positive particle ID, displaced and large p_T
  - Λ_c^+: good vertex quality and displaced from primary vertex
- Λ_c^+ combined with PID-selected $K^- \pi^+ \pi^+$ tracks to form Ξ_{cc}^{++} candidates

Largest background source expected to be combinatorics from Ξ_{cc}^{++} tracks



Multivariate selector used to select Ξ_{cc}^{++} candidates:

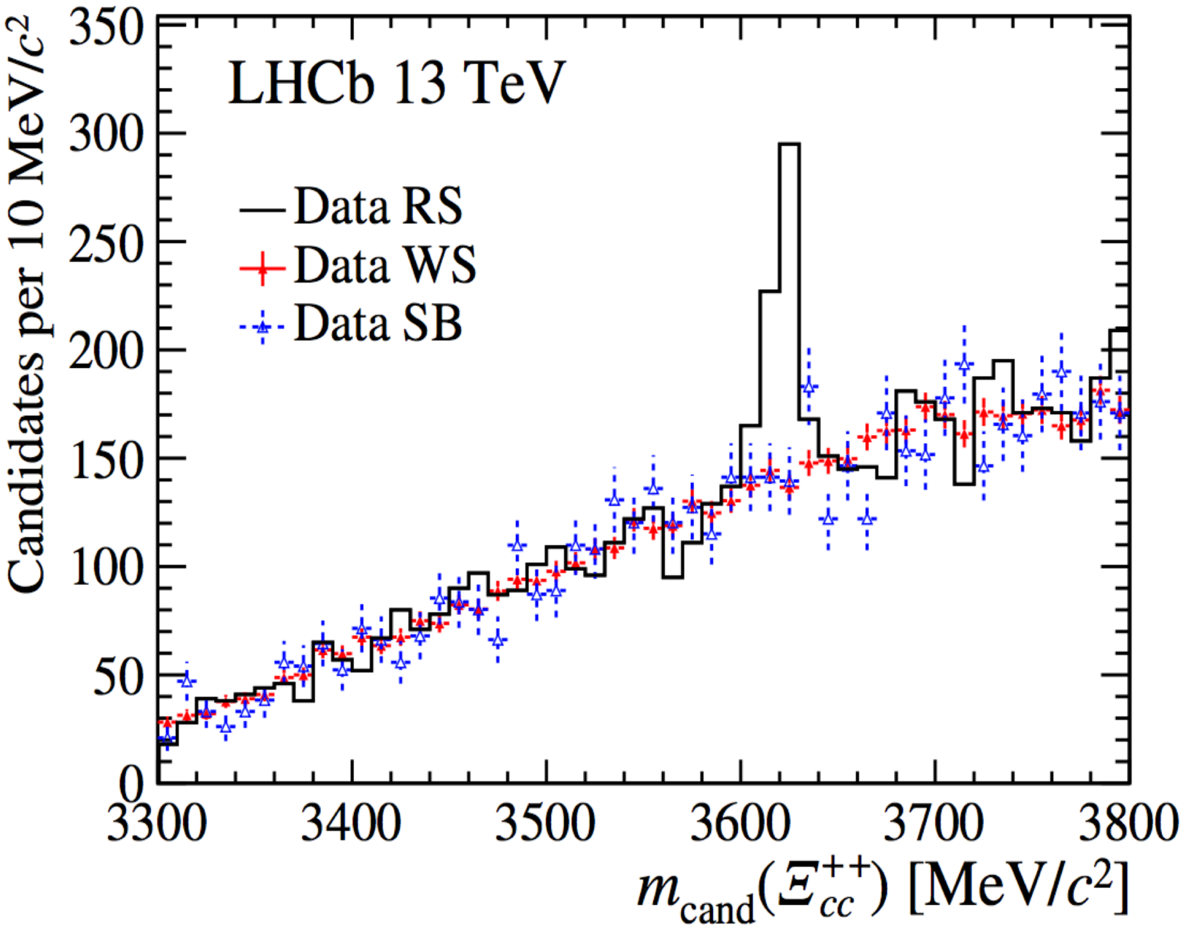
- Decay Fit quality of Ξ_{cc}^{++} candidates
- Kinematics of final states
- Ξ_{cc}^{++} vertex separation from PV

Selector trained on simulated signal and un-physical wrong-sign (WS) data

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$$

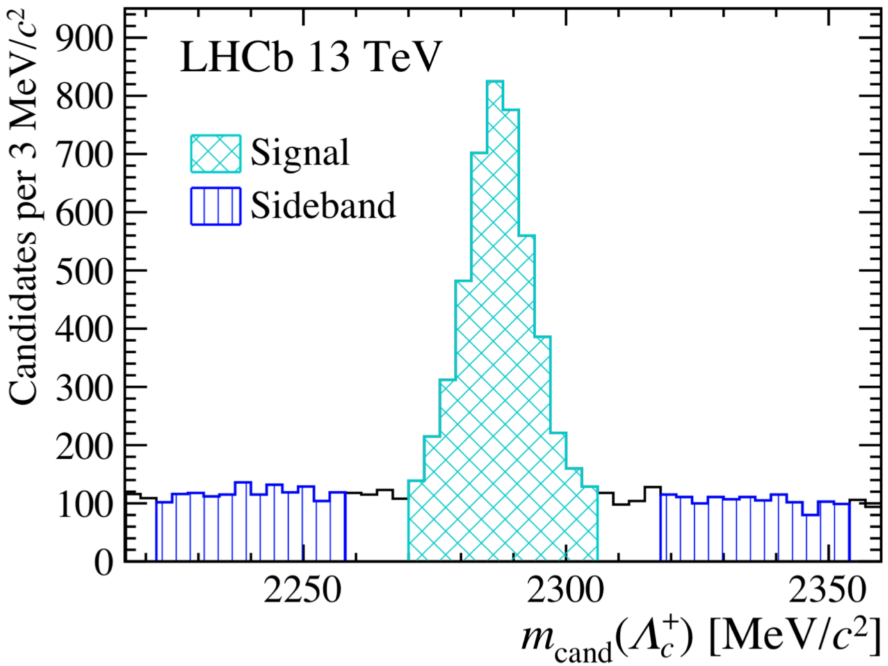
$\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum

PRL 119, 112001 (2017)



$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$$

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



Mass measurement

PRL 119, 112001 (2017)

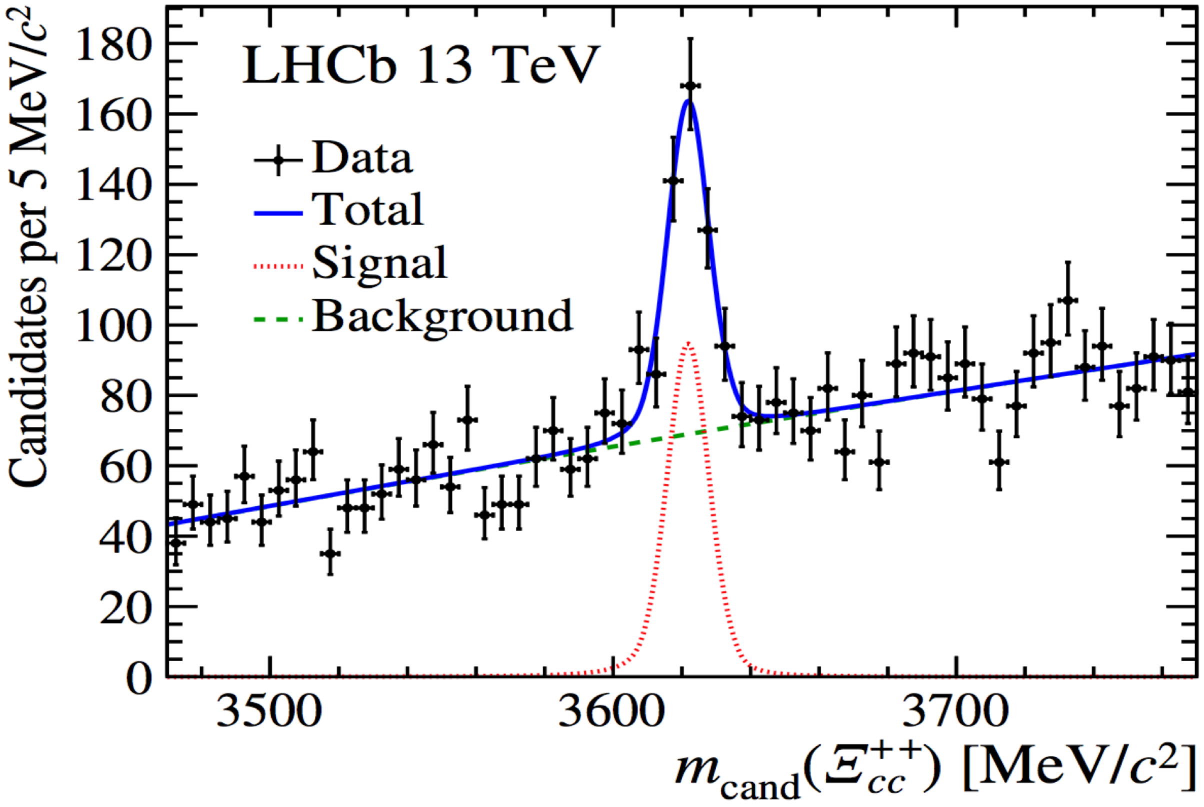
Local significance > 12σ

Resolution = 6.6 ± 0.8 MeV
(consistent with the detector resolution)

Signal yield = 313 ± 33

Systematics of mass measurement

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



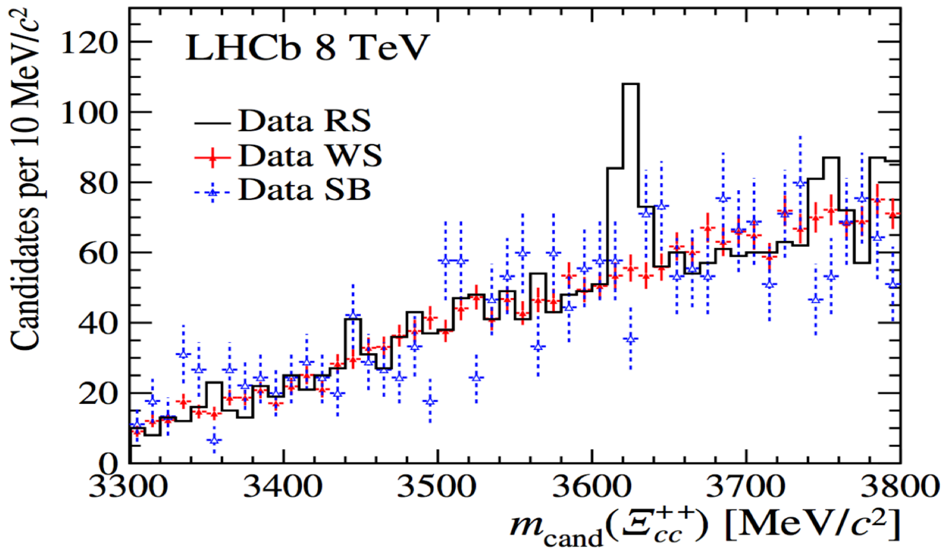
$M(\Xi_{cc}^{++}) - M(\Lambda_c^+)$ = 1134.94 ± 0.72 (stat) ± 0.27 (syst) MeV

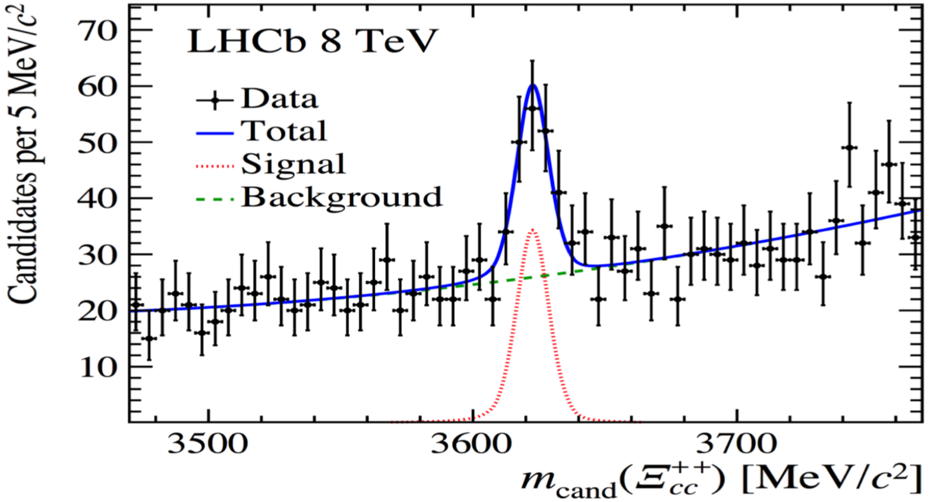
$M(\Xi_{cc}^{++})$ = 3621.40 ± 0.72 (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV

Confirmation on Run I data

[PRL 119, 112001 (2017)]

- Similar search done with 2 fb^{-1} of Run I data recorded in 2012, $\sqrt{s}$ = 8 TeV
- Different trigger and data processing configuration than in Run II
- But again a clear peak is seen in $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum:
  - ➢ Local significance: >7σ
  - ➢ Signal yield: 113 $\pm$ 21
  - ➢ Resolution: 6.6 $\pm$ 1.4 MeV
- Δm(Run I, Run II) = 0.8 $\pm$ 1.4 MeV (consistent between the samples)

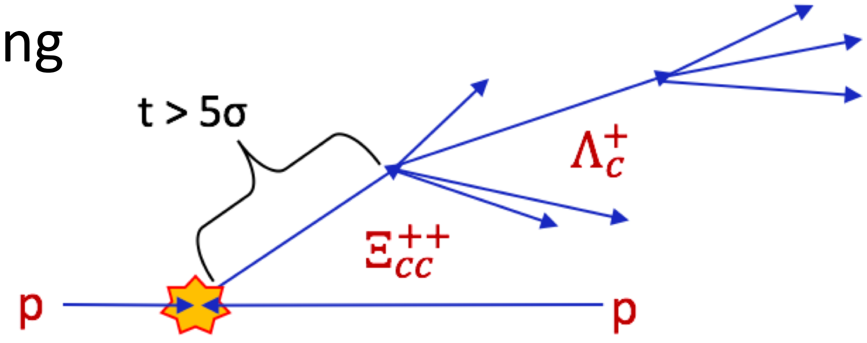


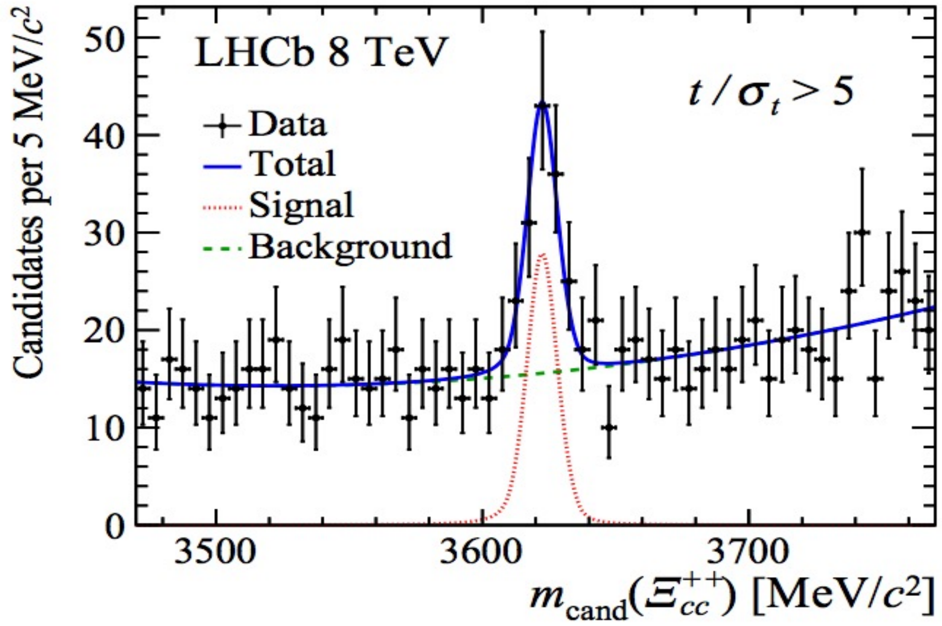


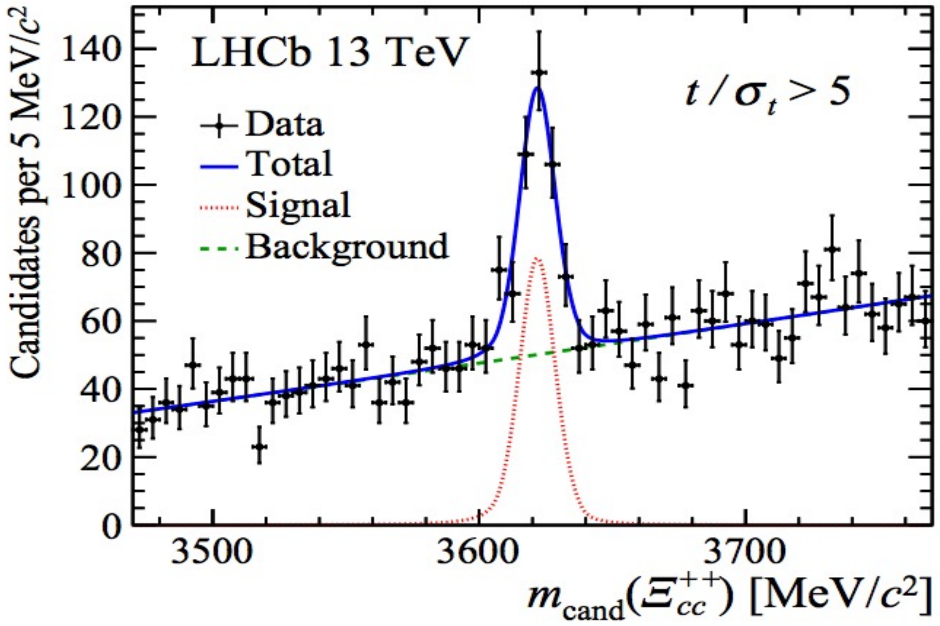
Weak Decay

PRL 119, 112001 (2017)

- Peaking structure remains significant after requiring minimum decay time, $t > 5\sigma$ w.r.t. the PV:
  - ➢ Run I significance: >7σ
  - ➢ Run II significance: >12σ

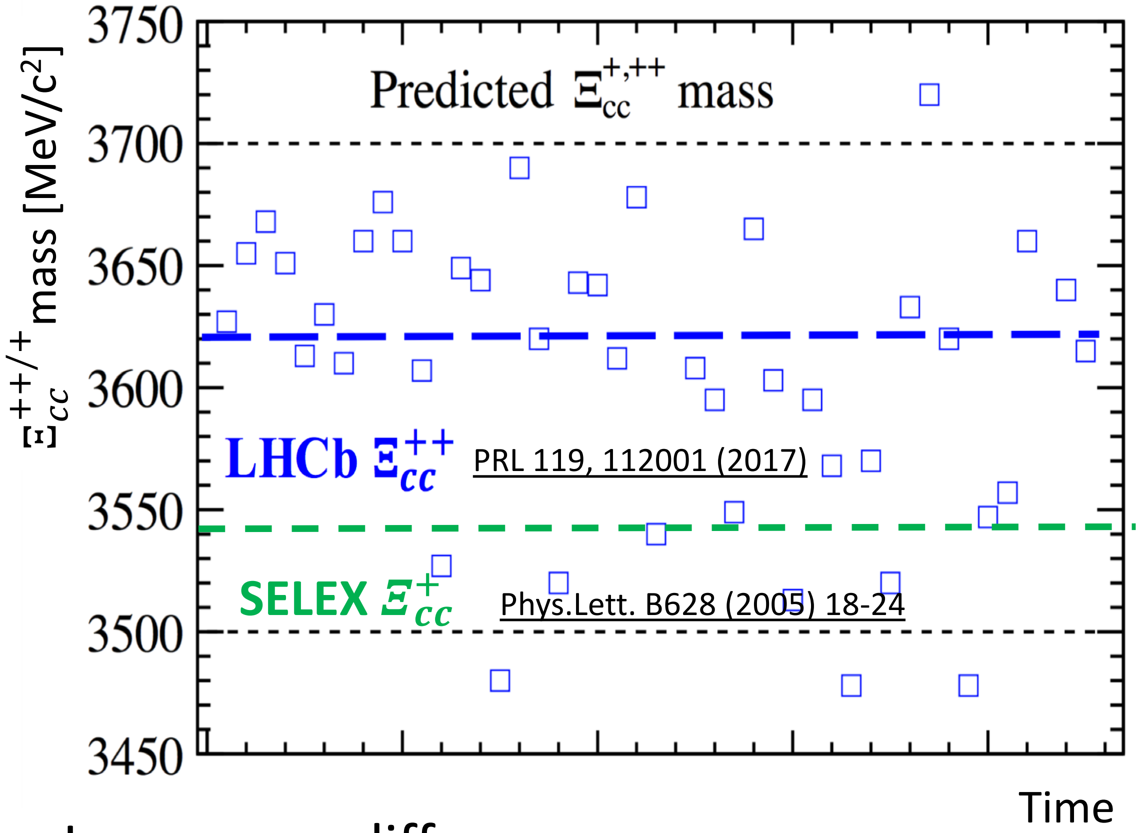


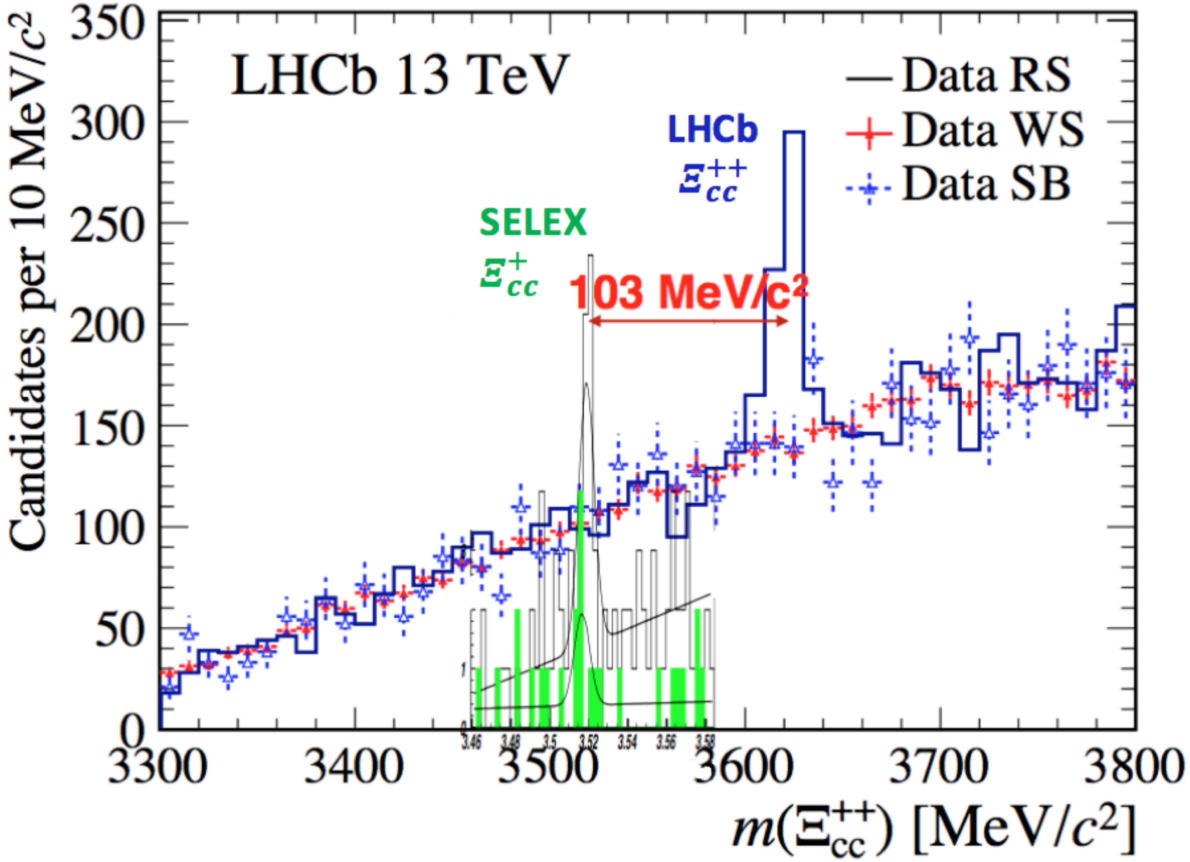




Consistent with a weak decay: Lifetime measurement in progress

Comparison with SELEX





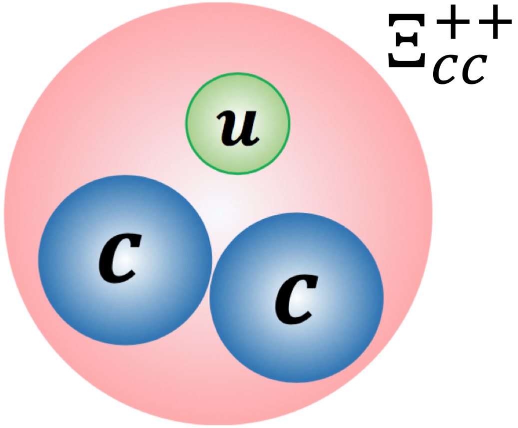
- Large mass difference:

$m(\Xi_{cc}^{++})_{LHCb} - m(\Xi_{cc}^{+})_{SELEX}$ = 103 ± 2 MeV

Inconsistent with being isospin partners: E.g. Guo, Hanhart, and Meissner, PLB 698 251-255; Karliner and Rosner, arXiv:1706.06961

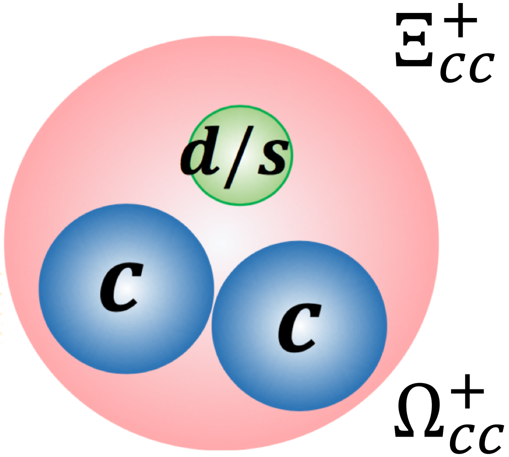
Future doubly-heavy baryon studies @ LHCb

- Searches for additional decay modes of Ξ_{cc}^{++} (ccu)
  - e.g. $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ & $\Xi_{cc}^{++} \to D^+ p^+ K^- \pi^+$
  - Relative BR, mass & lifetime measurements
  - Production cross-section, quantum numbers (J^P)



- Searches for the isospin partner Ξ_{cc}^{+} (ccd)
  - e.g. $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$*, $\Xi_{cc}^{+} \to D^+ p^+ K^-$* & $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^-$
  - Mass & lifetime measurements

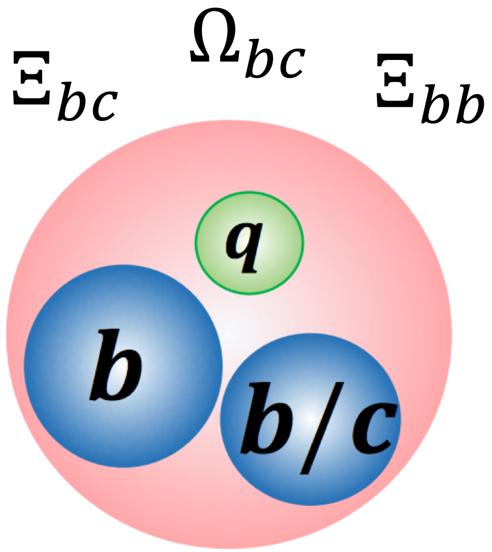
- Searches for Ω_{cc}^{+} (ccs)
  - e.g. $\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+$ & $\Omega_{cc}^{+} \to \Omega_c^0 \pi^+$
  - Mass & lifetime measurements



*modes with observation and evidence claimed by Selex

Future doubly-heavy baryon studies @ LHCb

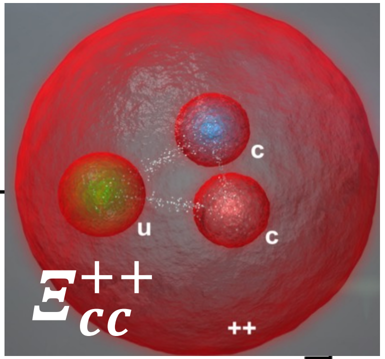
- Searches for excited states of doubly charmed baryons
  - Adding tracks to ground states
- Searches for Ξ_{bc}, Ω_{bc}, Ξ_{bb} baryons
  - Smaller production cross section than Ξ_{cc}
  - Smaller BF for accessible final states
- Additional data sets with improved triggers
  - 2017 recorded: 1.7 fb^{-1}
  - 2018 expected: $\sim$ 2 fb^{-1}
- LHCb upgrade: 5x instantaneous luminosity
  - Data taking from 2021
  - Full detector readout @ 40 MHz rate
    - S/W trigger beneficial for complex hadronic final states

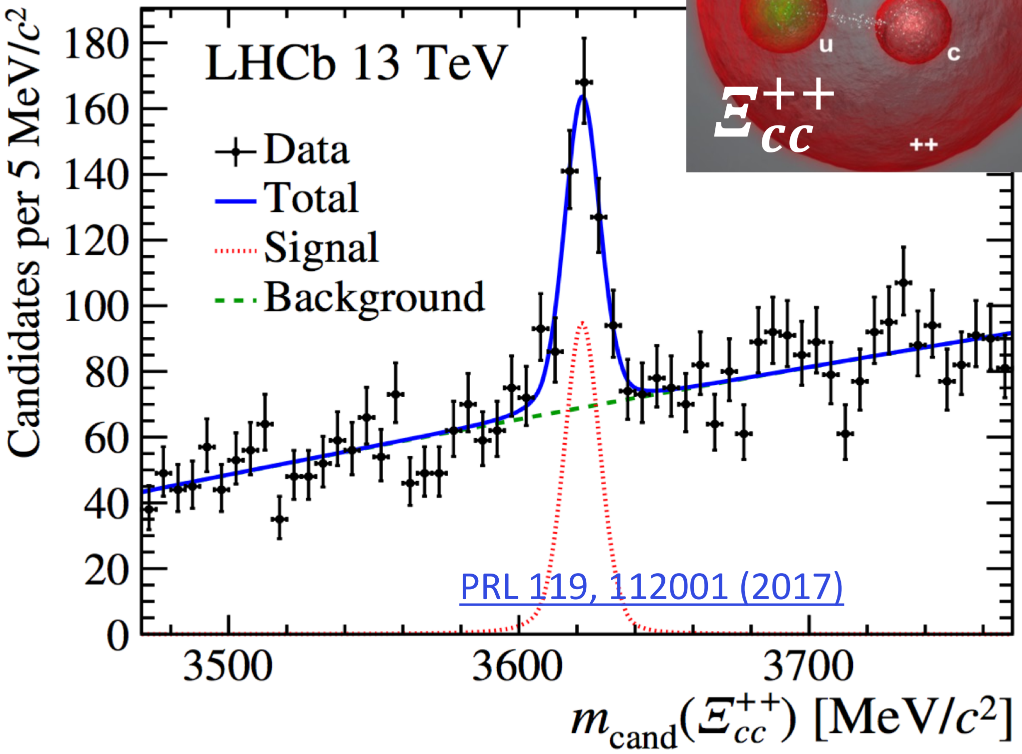


Summary

LHCb very active in hadron spectroscopy studies

- Observed narrow structure in $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum
  - Consistent with a weak decay of Ξ_{cc}^{++}(ccu)
  - Observed in two independent data sets (2012 & 2016)
  - Inconsistent with being an isospin partner of Selex’ Ξ_{cc}^{+}(ccd)
- Doubly charmed studies in LHCb continues
  - Lifetime & mass measurements
  - More decay modes
  - Searches for Ξ_{cc}^{+}(ccd) and Ω_{cc}^{+}(ccd)
  - Further ahead: excited states and Ξ_{bc}, Ω_{bc}, Ξ_{bb}





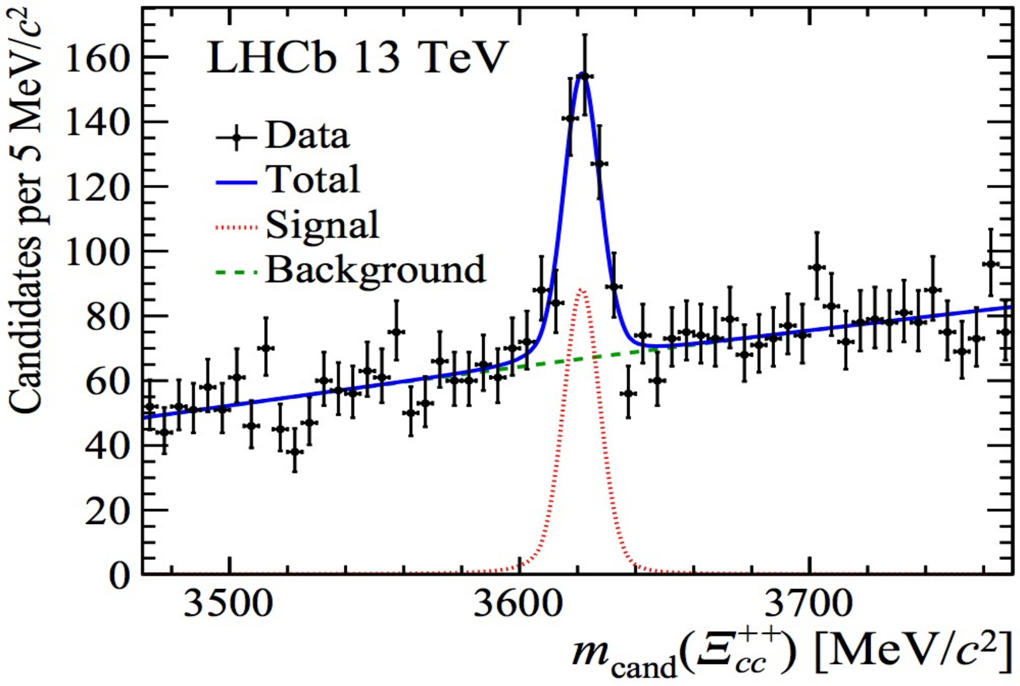
$M(\Xi_{cc}^{++})$ = 3621.40 ± 0.78 (tot) MeV/c^2

Back-up

Cross-checks

PRL 119, 112001 (2017)

1. Varying threshold value of MVA selector has no effect on signal significance
2. MVA efficiency as a function of mass: very smooth, no biasing
3. Multiple candidates do not create fake narrow structures
4. Checking combinations of tracks from Λ_c^+ and Ξ_{cc}^{++}: again no peaking structures
5. Varying particle ID selections: no peaking structure emerges in WS combinations but structure remains in RS sample
6. Tried cut based selection instead of MVA:
   - requiring good vertex fit quality
   - Ξ_{cc}^{++} vertex displaced
   - tracks are not produced from PV
     - ✓ Peak significance still > 12σ



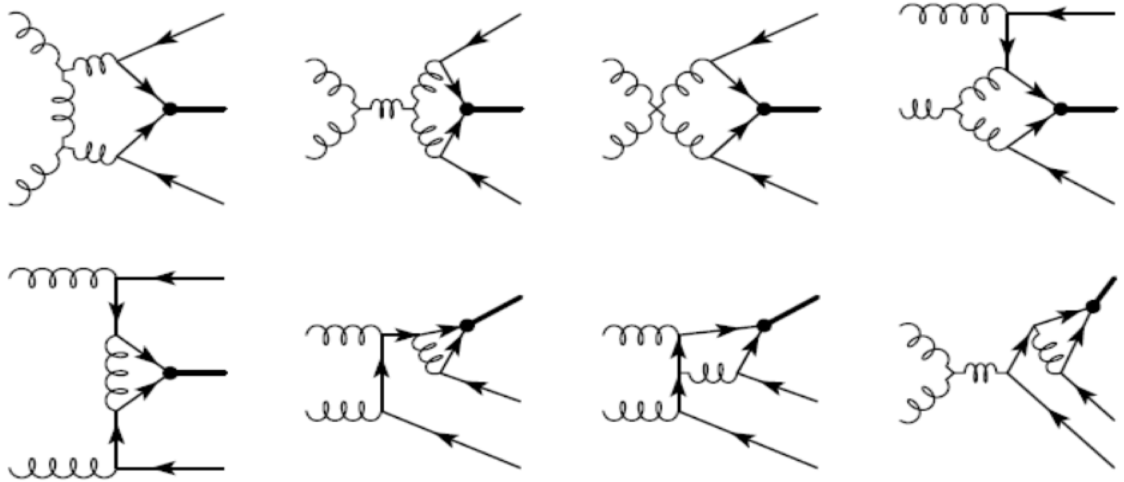
Production in pp collisions

arXiv:hep-ph/9710339

- Many theoretical studies on production of such states at LHC
- Double parton scattering believed to be dominant according to double heavy production LHCb measurements
- Typical approach is factorization of the two $Q\bar{Q}$ pair production, computed in pQCD
- Heavy di-quark formation and hadronization then treated non-perturbatively

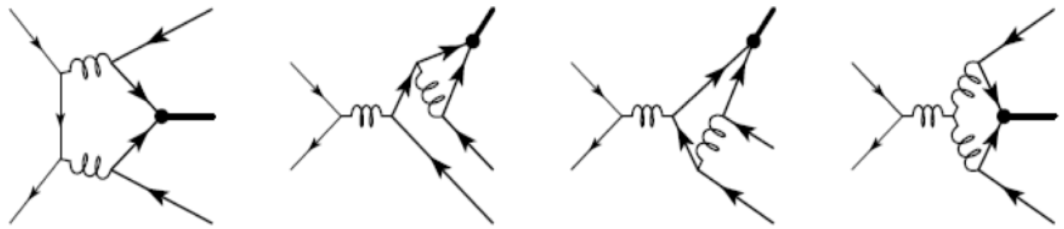
gluon-gluon fusion

$gg \rightarrow (cc)_{\bar{3}} + X$



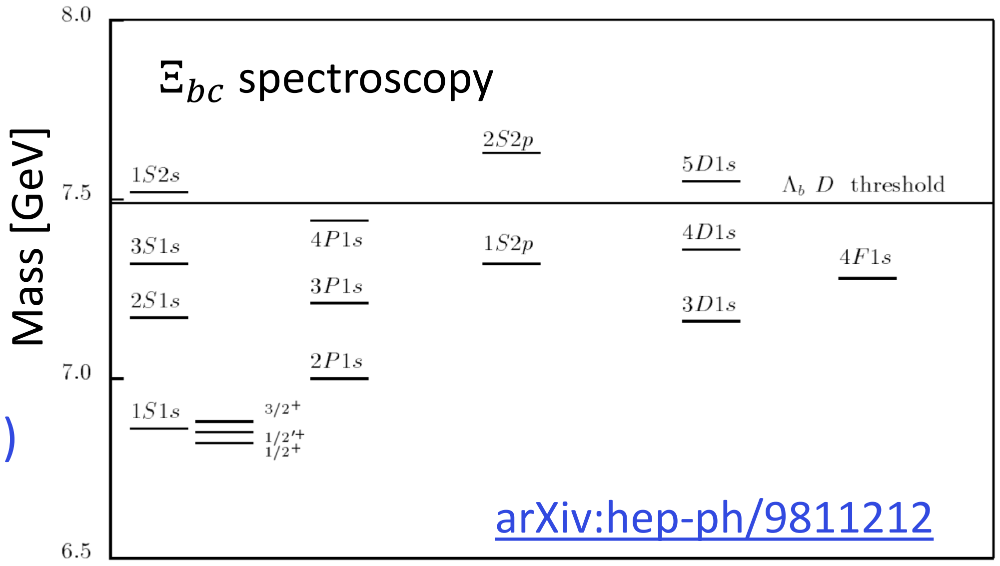
charm-charm collisions

$q\bar{q} \rightarrow (cc)_{\bar{3}} + X$

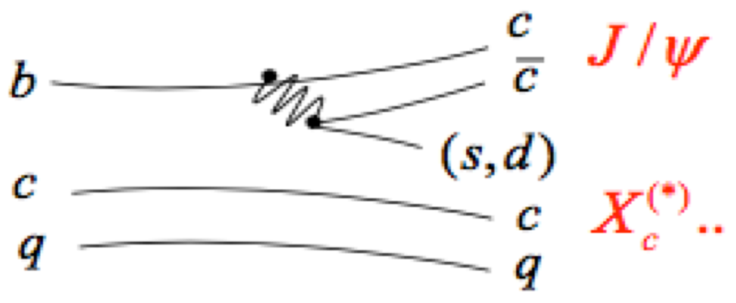


More on Ξ_{bc} baryons

- Easier final states signatures (higher p_T, J/Ψ modes)
- Lifetimes could be longer than Ξ_{cc} arXiv:hep-ph/9901224
- Smaller *XS* and *BF* expected however
- Production rate in order of magnitude: $\sigma(\Xi_{bc})\sim$ (0.1-0.5)$\times\sigma(B_c^+)$



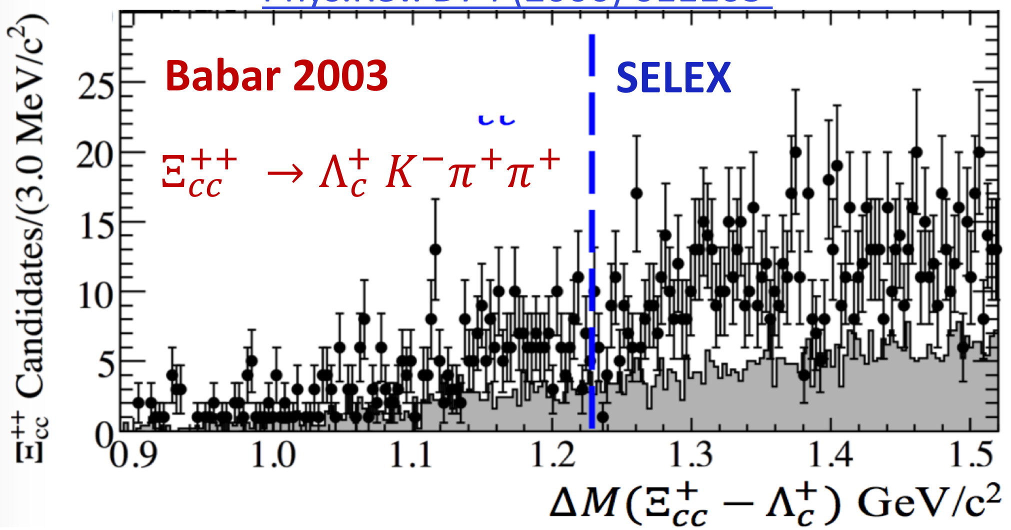
$\Xi_{bc} \rightarrow J/\Psi(\Lambda_c^+, \Xi_c^+, \Xi_c^0)$



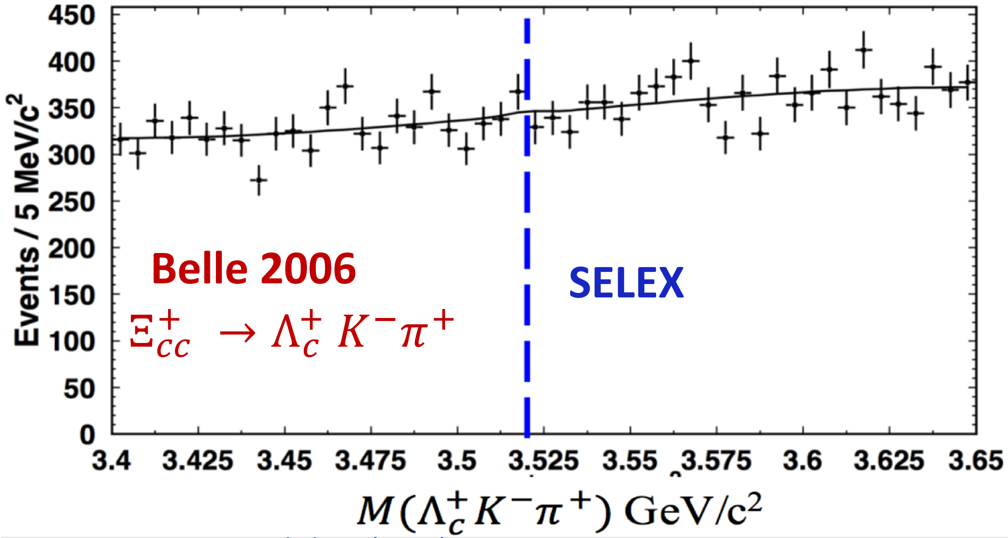
- Unlike Ξ_{cc} decays under investigation, likely to be no single golden mode for Ξ_{bc}
- Multiple channels will be studied in parallel for best chance of a discovery
- Ongoing work in J/Ψ , $D^+$and D^0 modes

Searches for Ξ_{cc} by other experiments

Phys.Rev. D74 (2006) 011103



Phys.Rev.Lett. 97 (2006) 162001



- FOCUS@Fermilab: Photon beam on Be fixed target
  - Searched for both Ξ_{cc}^+ and Ξ_{cc}^{++} states
  - 7 exclusive $\Xi_{cc} \rightarrow \Lambda_c^+ X$ modes
  - 14 exclusive $\Xi_{cc} \rightarrow D^{0,+} Y$ modes
  - No evidence of a Ξ_{cc} state

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

- BaBar@SLAC: $e^- e^+$ at $\sqrt{s}$ = 10.58 GeV
  - Searched for both Ξ_{cc}^+ and Ξ_{cc}^{++} states
  - Searched for $\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+)$
  - Searched for $\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0 \pi^+ (\pi^+)$
  - No evidence of a Ξ_{cc} states
- Belle@KEK: $e^- e^+$ at $\sqrt{s}$ = 10.58 GeV
  - Searched for $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
  - Found new Ξ_c^+ resonance decaying to $\Lambda_c^+ K^- \pi^+$
  - No evidence of a Ξ_{cc} state

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