Doubly charmed baryons

Les Rencontres de Physique de la Vallée d'Aoste

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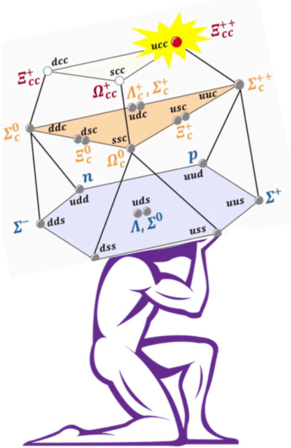
1. Overview of doubly charmed baryons
2. LHCb detector
3. Ξ_{cc}^{++} discovery
4. Ξ_{cc}^{++} lifetime
5. Additional decay modes of Ξ_{cc}^{++} [NEW]
6. Prospects and outlook
7. Summary



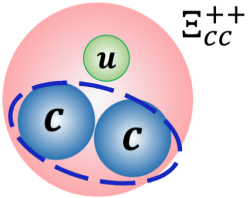
Overview and status

- Doubly charmed baryons (DCBs) of the form $\boldsymbol{QQq\,(Q \equiv c; q \in u, d, s)}$
  - Ground states: $\boldsymbol{\Xi_{cc}^{++}(ccu), \Xi_{cc}^{+}(ccd)}$ and $\boldsymbol{\Omega_{cc}^{+}(ccs)}$ with $J^P = 1/2^+$
  - Only one DCB discovered so far: Ξ_{cc}^{++} (mass & lifetime measured)
  - Production cross-section and quantum numbers remain unmeasured

Motivation

- DCBs provide new and unique testing grounds for studies of QCD

- e.g. In HQET two heavy charm quarks can be considered as a single static di-quark reducing it to a simpler Qq system

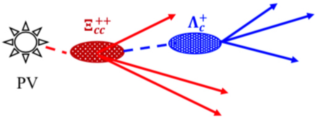


Expected properties

- $m(\Xi_{cc}^{+}) \simeq m(\Xi_{cc}^{++})$ & $m(\Omega_{cc}^{+}) \simeq m(\Xi_{cc}^{++}) + 100$ **MeV**
  - From Lattice QCD, bag model, QCD sum rules, quark model etc. [1–7]
- Large spread in lifetime predictions for DCBs:
  - **Between 100−250fs** and $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$ [8–11]
  - $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^{+}) = 3{-}4 \implies$ main reason Ξ_{cc}^{++} searches were prioritised

Generation and decay properties

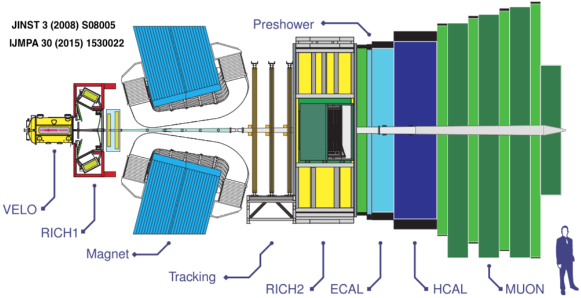
- Dedicated doubly heavy MC generator: GENXICC [12]
  - Dominated by $gg \to [cc] + \bar{c} + \bar{c}$ process
- Decay weakly with high multiplicity
  $\implies$ makes reconstructing decays challenging

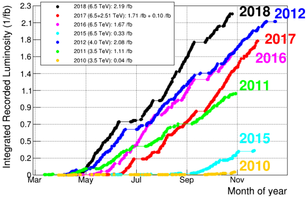


LHCb detector and data

Why are we good at finding doubly charmed baryons?

- Excellent particle identification (RICHes & Muon stations)
- Superb vertex resolution to isolate DCBs from lighter hadrons (VELO)



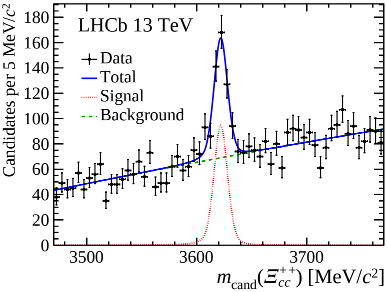


- Most measurements discussed in this talk are from 2016 *pp* data (around 18% of total recorded luminosity at LHCb)

Discovery of the Ξ_{cc}^{++} doubly charmed baryon

- LHCb announced discovery of Ξ_{cc}^{++} baryon in 2017 after studying the decay chain $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ (CF), $\Lambda_c^+ \to p K^- \pi^+$ (CF)

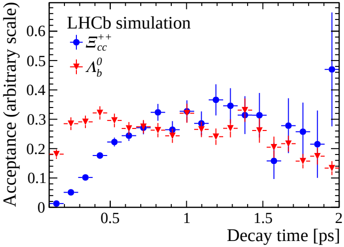
- Analysis selection developed using simulated signal and data control modes
- Significance $> 12\sigma$ with $1.67\,\text{fb}^{-1}$ ($\sqrt{s} = 13$ TeV) of pp data
- Significance $> 7\sigma$ with $2.08\,\text{fb}^{-1}$ ($\sqrt{s} = 8$ TeV) of pp data



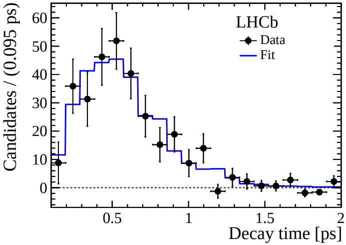
- m (Ξ_{cc}^{++}) $= 3621.40 \pm 0.72$ (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV/c^2 [13]
  - Last uncertainty is due to the limited knowledge of Λ_c^+ mass

Weak decay confirmed

- Same data as $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ analysis with extra trigger requirement
- Decay-time distribution measured relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$
  - Same selection requirements applied to both decays and common systematic effects largely cancel
  - Lifetime acceptances taken from simulation



Ξ_{cc}^{++} background subtracted data



- Result from fit to data: $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}$ (stat) $\pm$ 0.014 (syst) ps [14]

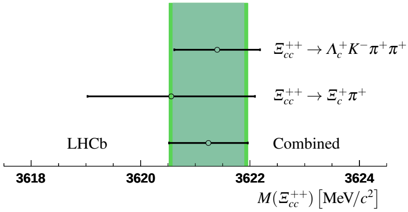
Confirmed existence

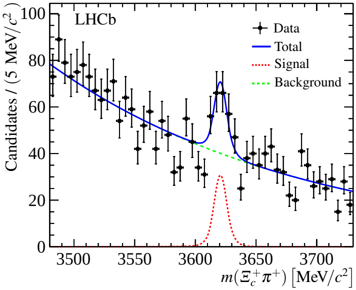
- Searching for more modes to understand decay dynamics of DCBs
- Searched for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ (CF), $\Xi_c^+ \to pK^-\pi^+$ (SCS) in 2016 data

  - $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \simeq 10\%\ \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)$ [15]
  - 4 final-state tracks $\implies$ better reconstruction efficiency

Branching fractions
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 6.35\%$ [16]
$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 2.20\%$ [15]

$\mathrm{m}(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\ (\mathrm{stat}) \pm 0.31\ (\mathrm{syst})$

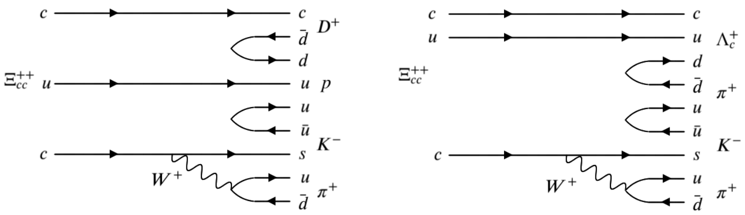




$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst})\ [17]$$

Trying for 3 in a row!

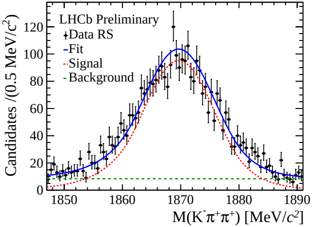
- Searched for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ (CF), $D^+ \to K^- \pi^+ \pi^+$ (CF) in 2016 data
- Reasons motivated by experimental expectations:
  - Excellent $D^+ \to K^- \pi^+ \pi^+$ trigger
  - Long lifetime of D^+ (1 ps) $\implies$ flies further from Ξ_{cc}^{++} decay point
  - Could expect $\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+) \simeq \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)$

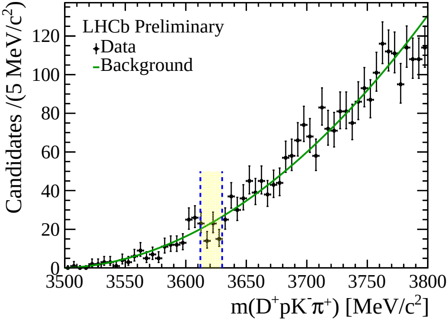


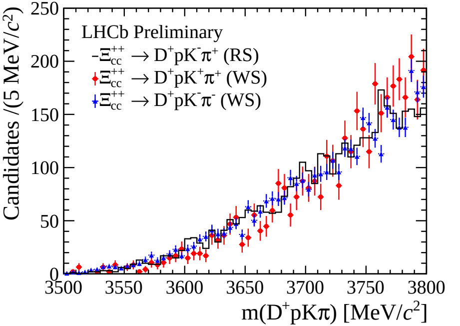
- Selection of data designed similarly to $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ analysis; performed blind and with use of multivariate machine learning techniques

After selection

- High purity (80%) of D^{+} candidates
- No $\Xi_{cc}^{++} \rightarrow D^{+}pK^{-}\pi^{+}$ signal in 2016 data
- Mass distributions of wrong-signed (WS) data and real-signed (RS) data look similar







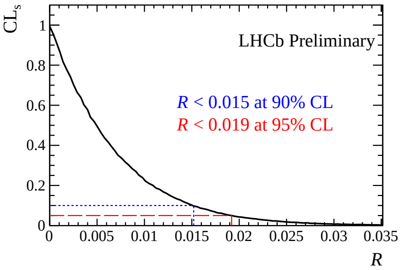
Setting limits

Using CLs method [18] to set upper limits on:

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = \frac{N(D^+ p K^- \pi^+)}{N(\Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)}{\varepsilon(D^+ p K^- \pi^+)} \times \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$$

- $N(\Lambda_c^+ K^- \pi^+ \pi^+)$ $= 184 \pm 29$ (from data)
- $\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)/\varepsilon(D^+ p K^- \pi^+)$ $= 0.46 \pm 0.01$ (from simulation)
- $\mathcal{R} < 1.5\,(1.9) \times 10^{-2}$ @ 90% (95%) CL

  [preliminary result]



- Better understanding of resonant and non-resonant contributions in $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ needed to explain large difference in branching fractions

DCB roadmap

Current work

- Production cross-section $\sigma(pp \to \Xi_{cc}^{++} + X)$ analysis progressing well
- Update on $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ search soon
  - SELEX collaboration reported signals of Ξ_{cc}^{+} in this mode in 2002 [19] but is inconsistent with being isospin partner of LHCb's Ξ_{cc}^{++} state [20]
- Searching for Ξ_{cc}^{+} baryon in decays of $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^-$
- Dedicated Ω_{cc}^{+} search programme started as well

What about in the future?

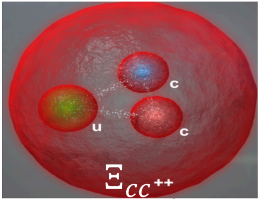
- Establishing quantum numbers (J^P etc.)
- Searches for excited Ξ_{cc}^{*} and Ω_{cc}^{*} states

LHCb aims to build an accurate and concise picture of doubly charmed baryons as a whole

Summary

LHCb are very active in the studies of doubly charmed baryons

- Observed Ξ_{cc}^{++} baryon decaying to $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ final states
  - Established its mass and lifetime
- No evidence of $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decay in 2016 data but larger data sets are available
  - Implications for dynamics of weakly decaying doubly charmed baryons



- Diverse programme of DCB studies currently in progress with more data
  - Includes the much anticipated search of singly charged Ξ_{cc}^+ baryon

Hopefully some more doubly charming results coming very soon!

References I

[1] C. Alexandrou and C. Kallidonis, *Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical pion mass*, Phys. Rev. **D96** (2017) 034511, arXiv:1704.02647.

[2] W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

[3] D.-H. He *et al.*, *Evaluation of spectra of baryons containing two heavy quarks in bag model*, Phys. Rev. **D70** (2004) 094004, arXiv:hep-ph/0403301.

[4] Z.-G. Wang, *Analysis of the $\frac{1}{2}^+$ doubly heavy baryon states with QCD sum rules*, Eur. Phys. J. **A45** (2010) 267, arXiv:1001.4693.

[5] C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, *Estimate of the hadronic production of the doubly charmed baryon Ξ_{cc} under GM-VFN scheme*, Phys. Rev. **D73** (2006) 094022, arXiv:hep-ph/0601032.

[6] A. Valcarce, H. Garcilazo, and J. Vijande, *Towards an understanding of heavy baryon spectroscopy*, Eur. Phys. J. **A37** (2008) 217, arXiv:0807.2973.

[7] J.-R. Zhang and M.-Q. Huang, *Doubly heavy baryons in QCD sum rules*, Phys. Rev. **D78** (2008) 094007, arXiv:0810.5396.

References II

[8] C.-H. Chang, T. Li, X.-Q. Li, and Y.-M. Wang, *Lifetime of doubly charmed baryons*, Commun. Theor. Phys. **49** (2008) 993, arXiv:0704.0016.

[9] D. Ebert, R. N. Faustov, V. O. Galkin, and A. P. Martynenko, *Mass spectra of doubly heavy baryons in the relativistic quark model*, Phys. Rev. **D66** (2002) 014008, arXiv:hep-ph/0201217.

[10] B. Guberina, B. Melic, and H. Stefancic, *Inclusive decays and lifetimes of doubly charmed baryons*, Eur. Phys. J. **C9** (1999) 213, arXiv:hep-ph/9901323.

[11] A. V. Berezhnoy, A. K. Likhoded, and A. V. Luchinsky, *Doubly heavy baryons at the LHC*, Phys. Rev. **D98** (2018) 113004, arXiv:1809.10058.

[12] C.-H. Chang, J.-X. Wang, and X.-G. Wu, *GENXICC2.0: An upgraded version of the generator for hadronic production of double heavy baryons Ξ_{cc}, Ξ_{bc} and Ξ_{bb}*, Comput. Phys. Commun. **181** (2010) 1144, arXiv:0910.4462.

[13] LHCb collaboration, R. Aaij *et al.*, *Observation of the doubly charmed baryon Ξ_{cc}^{++}*, Phys. Rev. Lett. **119** (2017) 112001, arXiv:1707.01621.

References III

[14] LHCb collaboration, R. Aaij *et al.*, *Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}*, Phys. Rev. Lett. **121** (2018) 052002, arXiv:1806.02744.

[15] F.-S. Yu *et al.*, *Discovery Potentials of Doubly Charmed Baryons*, Chin. Phys. **C42** (2018) 051001, arXiv:1703.09086.

[16] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. D **98** (2018) 030001.

[17] LHCb collaboration, R. Aaij *et al.*, *First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay*, Phys. Rev. Lett. **121** (2018) 162002, arXiv:1807.01919.

[18] A. L. Read, *Presentation of search results: The CL(s) technique*, J. Phys. **G28** (2002) 2693.

[19] SELEX collaboration, M. Mattson *et al.*, *First observation of the doubly charmed baryon Ξ_{cc}^+*, Phys. Rev. Lett. **89** (2002) 112001, arXiv:hep-ex/0208014.

[20] M. Karliner and J. L. Rosner, *Isospin splittings in baryons with two heavy quarks*, Phys. Rev. **D96** (2017) 033004, arXiv:1706.06961.