Doubly heavy baryons at LHCb

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Outline

- Overview of doubly charmed baryons
- LHCb detector
- Ξ_{cc}^{++} discovery
- Ξ_{cc}^{++} lifetime
- Additional decay modes of Ξ_{cc}^{++}
- Prospects and outlook
- Summary

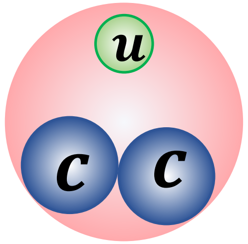
Doubly charmed baryons

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 $Q\bar{q}$ system

Overview and status

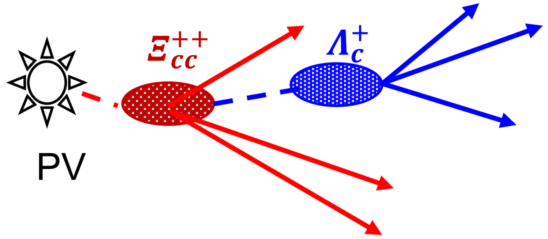
- Doubly charmed baryons (DCBs) of the form $\boldsymbol{QQq(Q \equiv c; q \in u, d, s)}$
  - Ground states: $\boldsymbol{\Xi_{cc}^{++}}$**(ccu)**, $\boldsymbol{\Xi_{cc}^{+}}$**(ccd)** and $\boldsymbol{\Omega_{cc}^{+}}$**(ccs)** with $J^P = 1/2^+$
  - Only one DCB discovered so far, Ξ_{cc}^{++} (mass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



$\boldsymbol{\Xi_{cc}^{++}}$

Doubly charmed baryons

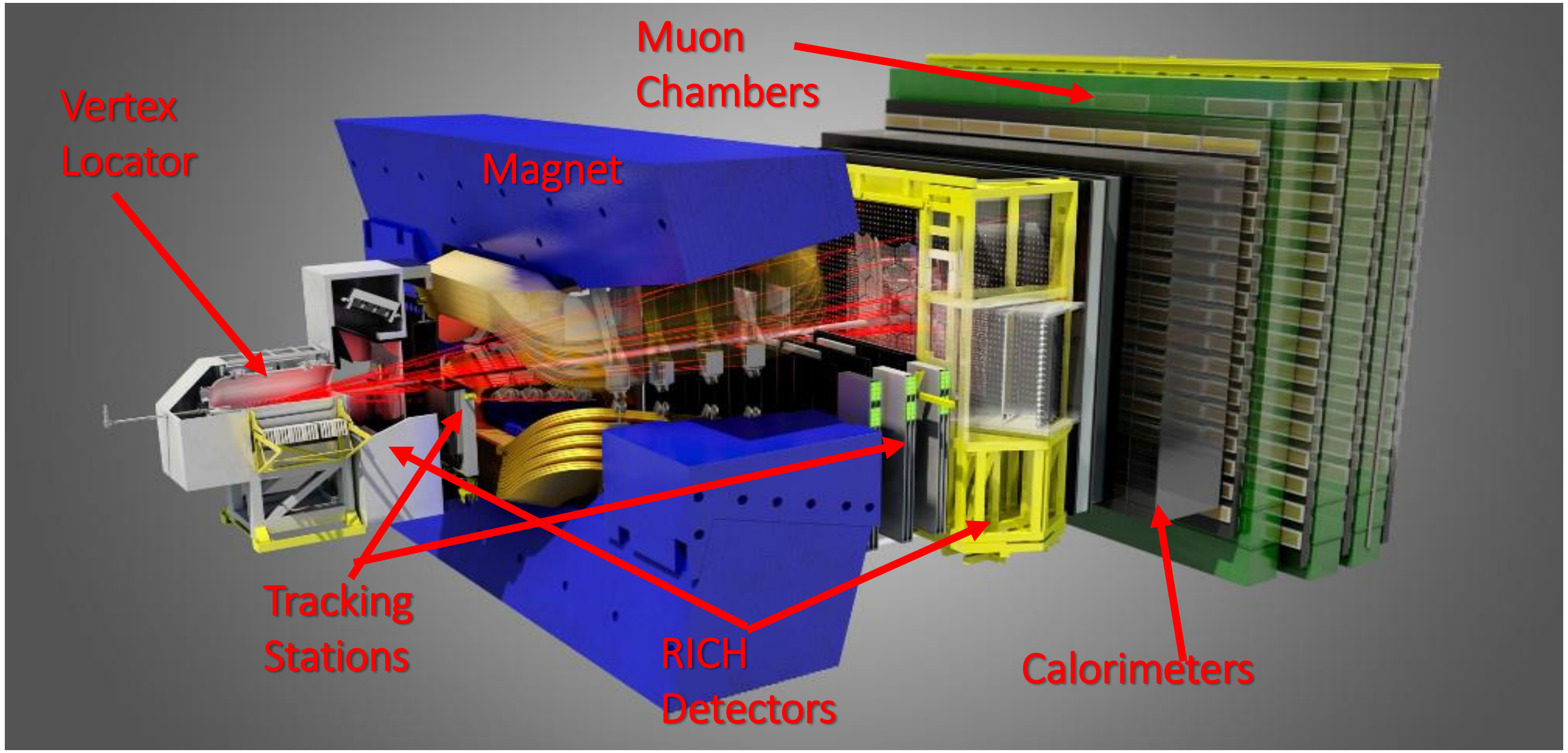
- Expected properties
  - $\boldsymbol{m(\Xi_{cc}^{+}) \simeq m(\Xi_{cc}^{++})}$ **&** $\boldsymbol{m(\Omega_{cc}^{+}) \simeq m(\Xi_{cc}^{++}) + 100\ \mathrm{MeV}}$
    - From Lattice QCD, bag model, QCD sum rules, quark model etc[1-7]
  - Large spread in τ predictions for DCBs:
    - Between 100fs – 250fs [8-11]
    - $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+}) \implies$ main reason Ξ_{cc}^{++} searches were prioritize [8-11]
- Production and decay
  - Dedicated doubly heavy MC generator: GENXICC [12]
    - Dominated by $gg \to [cc] + \bar{c} + \bar{c}$ process
    - Single parton scattering produces $[cc]$ diquark fragmenting into DCB
  - **Decay weakly** to high multi-body final states $\implies$ makes reconstructing decays challenging



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

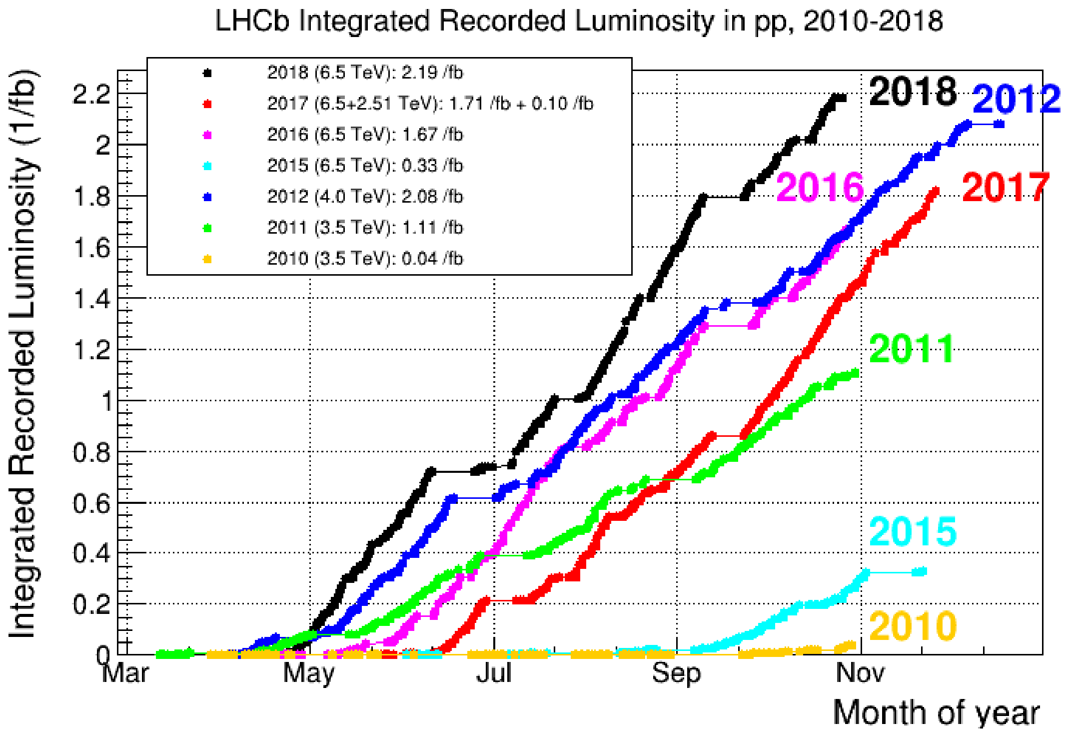
LHCb detector

- Advantages
  - Good particle identification (Muon station & RICHes)
  - Excellent vertex resolution to isolate DCBs from lighter hadrons (VELO)



LHCb integrated luminosity

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



LHC era			HL_LHC era	
Run1 (2010-12)	**Run2 (2015-18)**	**Run3 (2021-24)**	**Run4 (2027-30)**	**Run5+ (2031+)**
3 fb^{-1}	**9 fb^{-1}**	**23 fb^{-1}**	**46 fb^{-1}**	**>300 fb^{-1} ??**

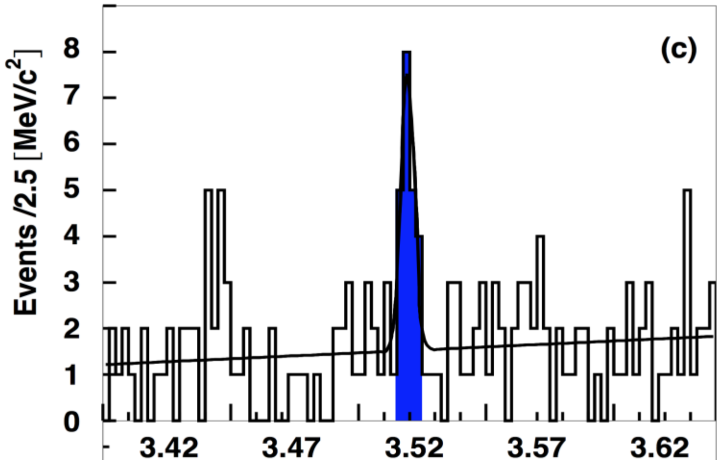
Phase-1 Upgrade
Phase-1b Upgrade?
Phase-2 Upgrade?

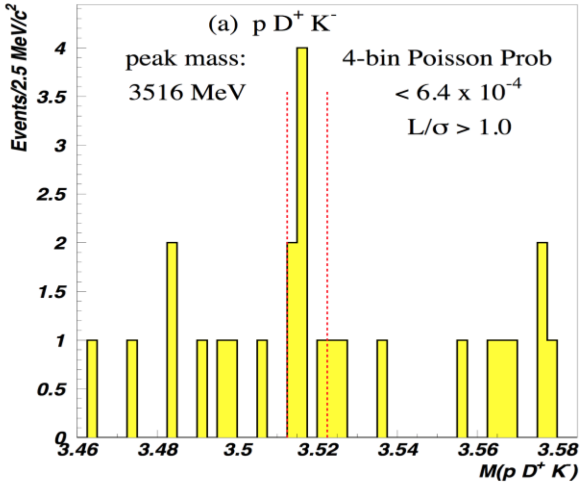
Ξ_{cc}^{++} @ SELEX

- SELEX (Fermilab E781) claimed observation of $\Xi_{cc}^{+}(ccd)$ in $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^{+} \to pD^+K^-$ 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 (not consistent with most theory predictions)

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

PRL 89 (2002) 112001





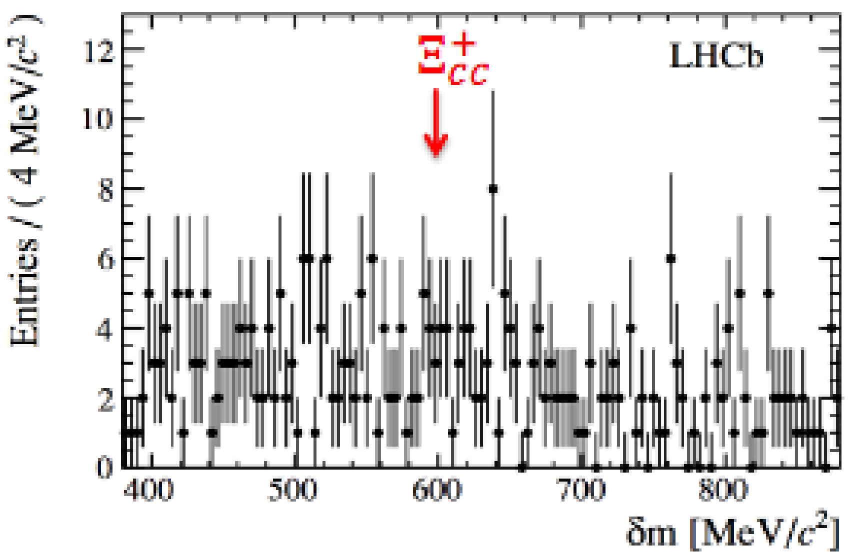
$\Xi_{cc}^{+} \to pD^+K^-$

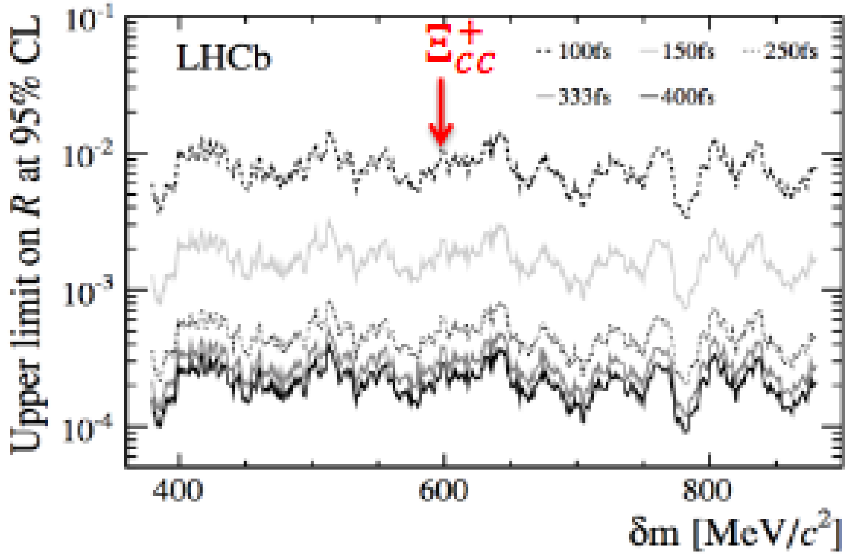
PLB 628 (2005) 18

Ξ_{cc}^{+} @ LHCb & others

- SELEX results **not confirmed** by FOCUS, Baber, Belle & LHCb

- $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ searched by LHCb 2011 data
  - $\delta m \equiv m\left([pK^-\pi^+]_{\Lambda_c} K^-\pi^+ - m([pK^-\pi^+]_{\Lambda_c})\right) - m(K^-) - m(\pi^+)$
    - $380 < \delta m < 880 \mathrm{MeV}/c^2$ corresponding to $3300 < m(\Xi_{cc}^{+}) < 3800 \mathrm{MeV}/c^2$.
  - **No** significant signal was found

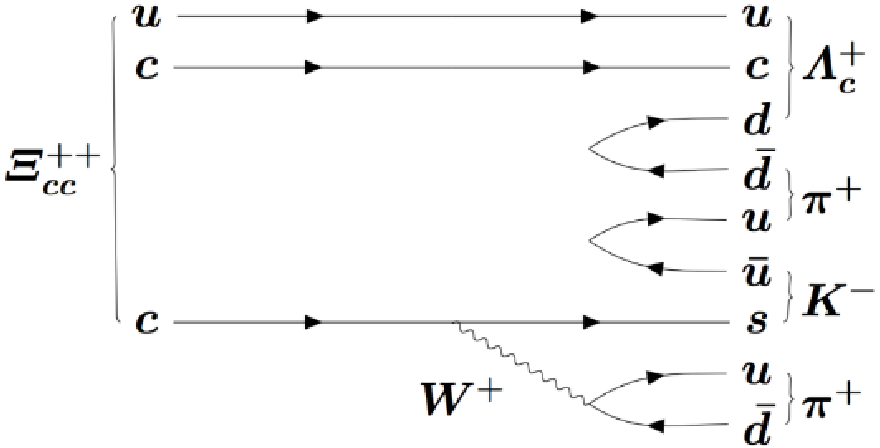


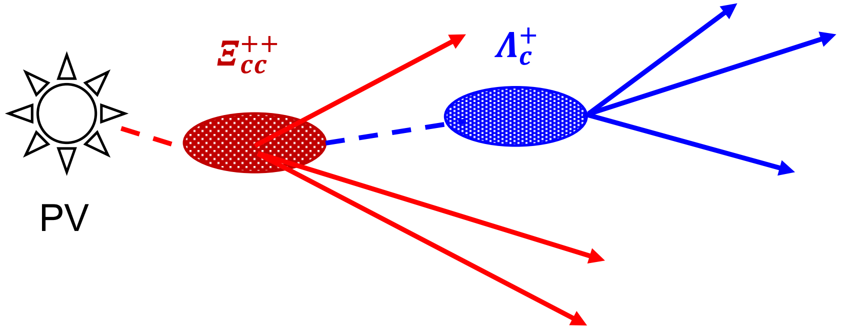


Searching for $\Xi_{cc}^{++}(ccu)$

- Expected to have **longer** lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, branching fraction up to 10% [15]
- Data sample: LHCb run II at $\sqrt{s} = 13\text{TeV}, \sim 1.7\ \text{fb}^{-1}$
  - Dedicated exclusive trigger ensuring high efficiency, full event reconstruction at trigger level
  - Run I data (2012) also analyzed for cross-check

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

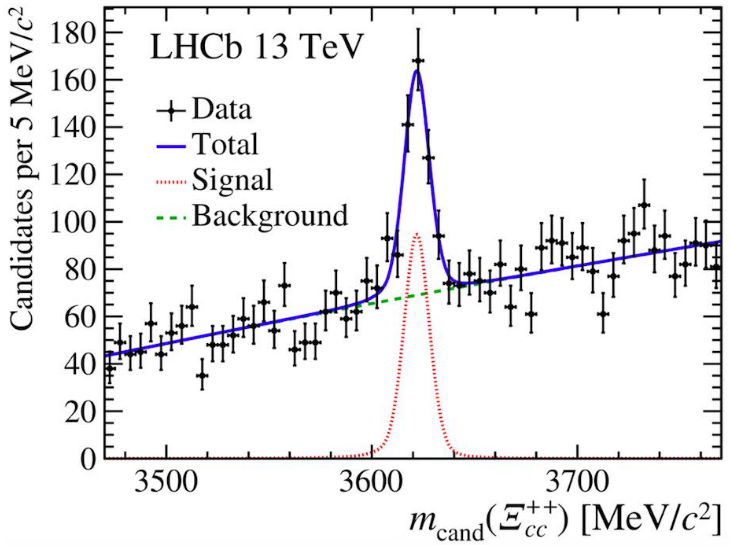


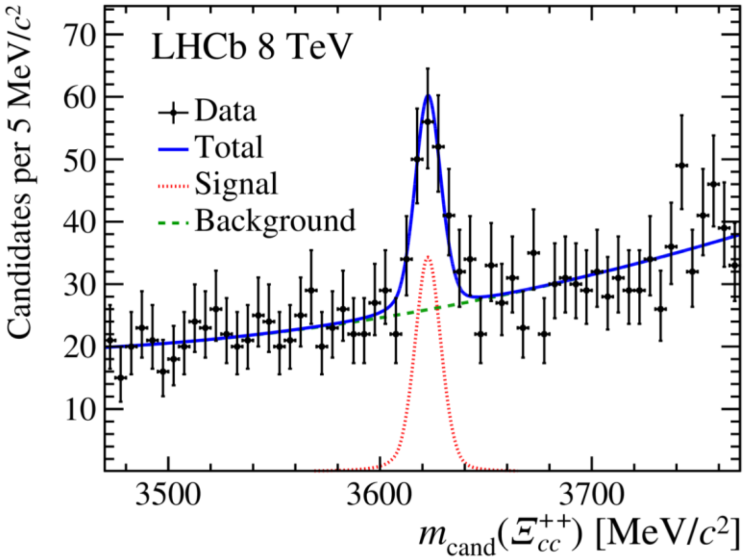


$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to p K^- \pi^+)$

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ [PRL 119 (2017) 112001]

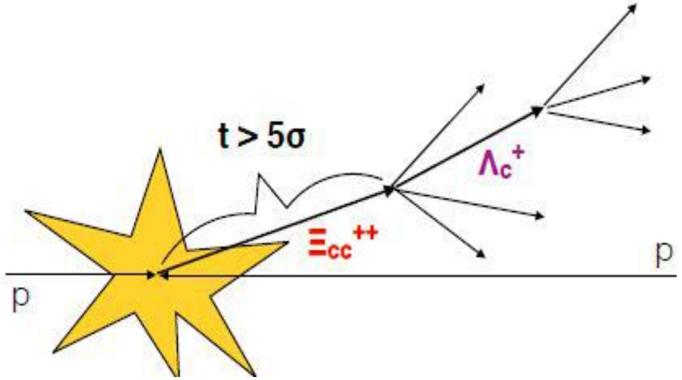
- Doubly charmed baryon **first** observation
  - LHCb announced discovery Ξ_{cc}^{++} baryon in 2017 after studying the decay chain $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ (\Lambda_c^+ \rightarrow pK^-\pi^+)\, K^-\pi^+\pi^+$
- Properties
  - Signal yield: 313 ± 33
  - Significance $> 12\sigma$ with 1.67 fb^{-1} ($\sqrt{s} = 13\mathrm{TeV}$)
  - Significance $> 7\sigma$ with 2.08 fb^{-1} ($\sqrt{s} = 8\mathrm{TeV}$)
  - Peak width consistent with simulation
  - $\boldsymbol{m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\ (\mathrm{stat}) \pm 0.27\ (\mathrm{syst}) \pm 0.14\ (\Lambda_c^+)\mathrm{MeV}/c^2}$ [13]
  - $\boldsymbol{t/\sigma_t > 5} \Rightarrow \tau(\Xi_{cc}^{++})$ measurement is needed





Ξ_{cc}^{++} lifetime [PRL 121 (2018) 052002]

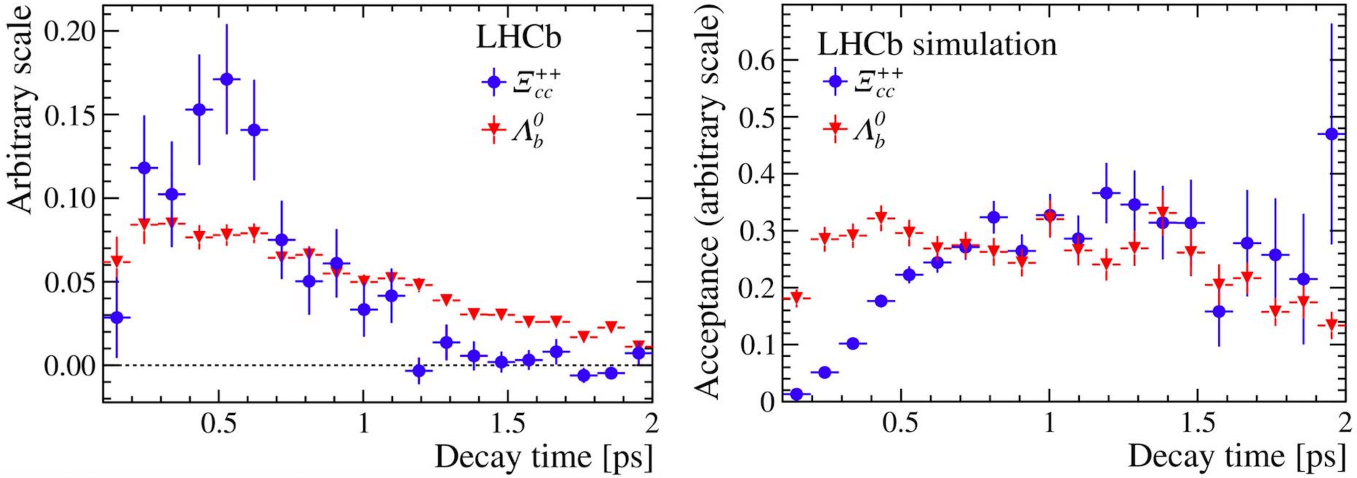
- Inconsistent with **zero** in the observation paper
- Lifetime measurement is critical:
  - Confirm it is a **weakly** decay
  - Necessary ingredient for theoretical prediction of BR
  - Important information for experimental exploration of Ξ_{cc}^{++}
  - Test various predictions in QCD models



Ξ_{cc}^{++} lifetime [PRL 121 (2018) 052002]

Weak decay confirmed

- Same 2016 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



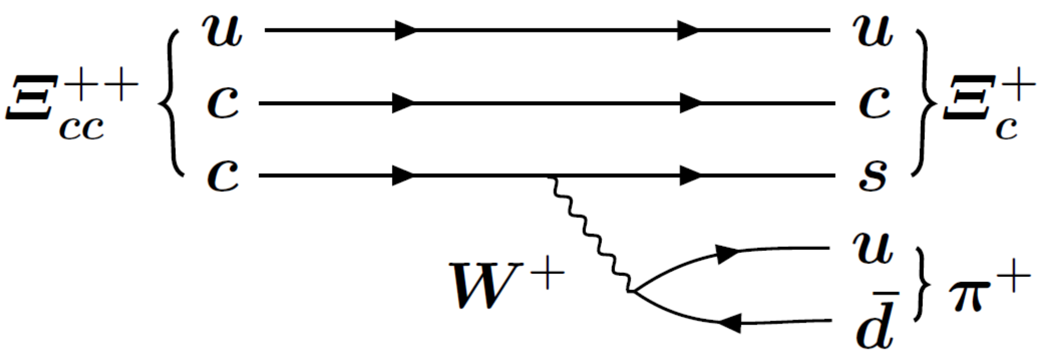
- $\boldsymbol{\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}\ (\mathrm{stat}) \pm 0.014\ (\mathrm{syst})\,\mathrm{ps}}$ [14]

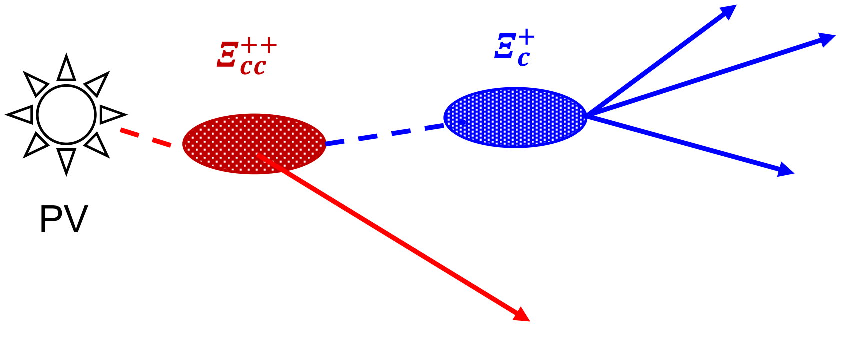
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [PRL 121 (2018) 162002]

□ Confirmed existence

- Searching for more modes to understand the decay dynamics of DCBs
- Looked at decay chain: $\Xi_{cc}^{++} \to \Xi_c^+ \, (\Xi_c^+ \to pK^-\pi^+) \, \pi^+$
  - Expect $\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \simeq 10\%, \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \simeq 10\%$ [15]
  - Less final-state tracks $\Longrightarrow$ better efficiency

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



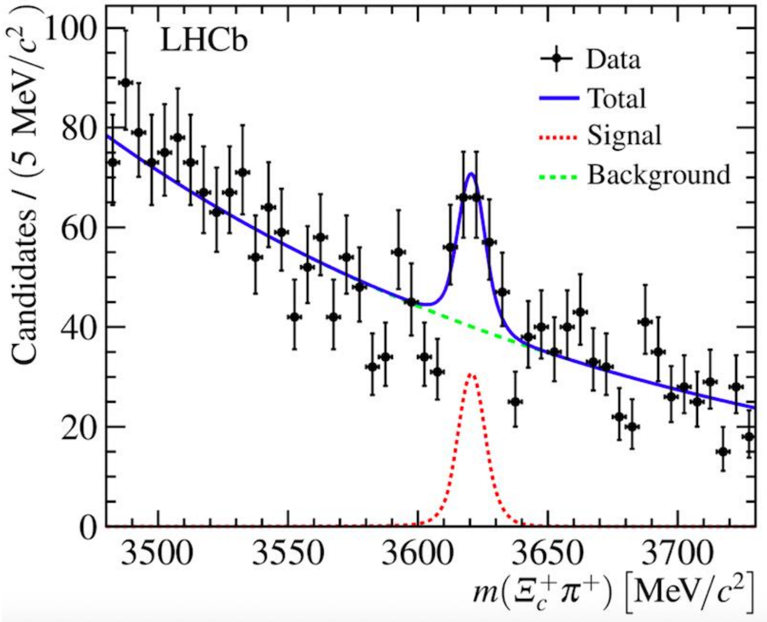


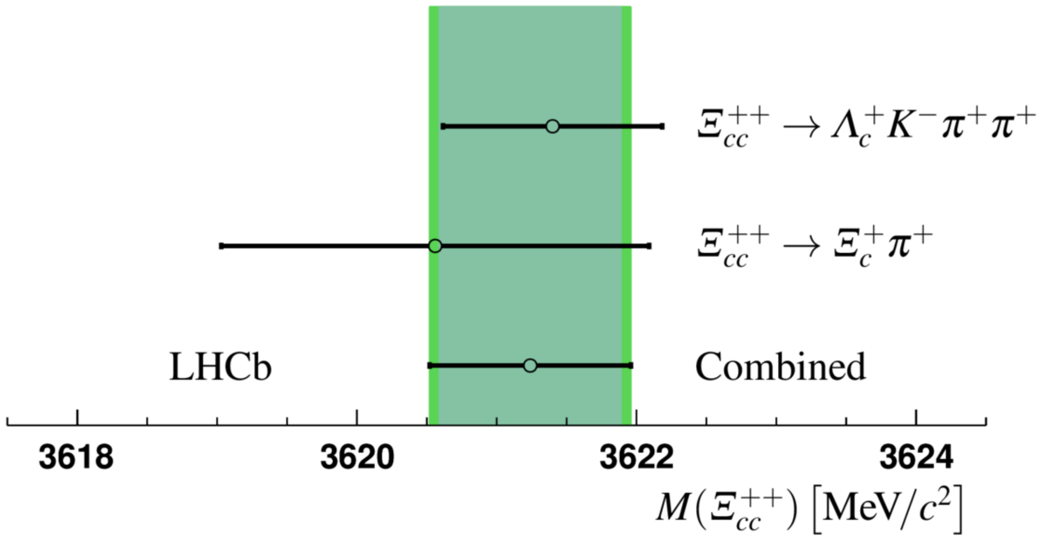
$\Xi_{cc}^{++} \to \pi^+ \Xi_c^+ (\to pK^-\pi^+)$

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [PRL 121 (2018) 162002]

□ Re-discovery of Ξ_{cc}^{++}

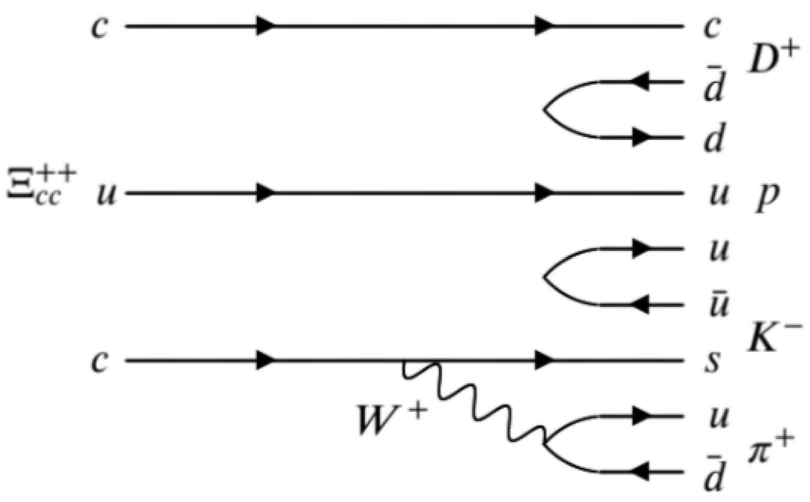
- $m(\Xi_c^+\pi^+) = 3620.56 \pm 1.45\,(\text{stat}) \pm 0.40\,(\text{syst}) \pm 0.30\,(\Xi_c^+)\ \text{MeV}/c^2$
- $m(\Lambda_c^+ K^-\pi^+\pi^+) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$
- Combined: $\boldsymbol{m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\,(\text{stat}) \pm 0.31\,(\text{syst})\ \text{MeV}/c^2}$
- $\boldsymbol{\frac{\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+)\times\mathcal{B}(\Xi_c^+\to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+ K^-\pi^+\pi^+)\times\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)} = 0.035 \pm 0.009\,(\text{stat}) \pm 0.003\,(\text{syst})}$ [17]





$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ [LHCb-PAPER-2019-011]]

- Searched for $\Xi_{cc}^{++} \to D^+(D^+ \to K^-\pi^+\pi^+)\, pK^-\pi^+$ in 2016 data
- Motivation
  - Excellent $D^+ \to K^-\pi^+\pi^+$ trigger
  - **Long lifetime** of D^+ (1 ps) $\Longrightarrow$ files further from Ξ_{cc}^{++} decay point
  - Expect $\mathcal{B}(\Xi_{cc}^{++} \to D^+ pK^-\pi^+) \simeq \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)$



$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ [LHCb-PAPER-2019-011]]

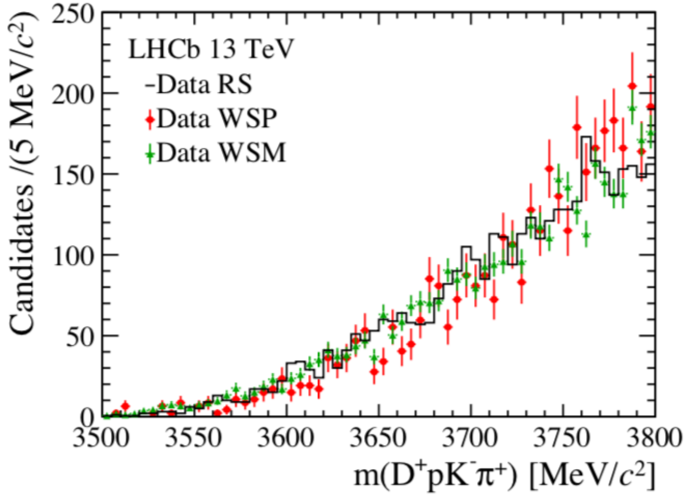
Results

- **No $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ signal in 2016 data**
- Using CLs method to set upper limits on:
  - $\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = \frac{N(D^+ p K^- \pi^+)}{N(\Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)}{\varepsilon(D^+ p K^- \pi^+)} \times \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^-)}$
  - $\boldsymbol{\mathcal{R} < 1.5\ (1.9) \times 10^{-2}}$ **@ 90% (95%) CL**

RS: $D^+ p K^- \pi^+$
WSP: $D^+ p K^+ \pi^+$
WSM: $D^+ p K^- \pi^-$

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

- Likely suppression from **low Q-value** of decay



Prospects with DCBs

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 [17]
  - Inconsistent with being isospin partner of LHCb's Ξ_{cc}^{++} state [18]
- Searching for Ξ_{cc}^{+} baryon in decay of $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^-$
- Dedicated Ω_{cc}^{+} search programme started as well

Plan

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

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

Summary

- World-leading works on doubly charmed baryons spectroscopy.
  - **Observed** $\Xi_{cc}^{++}(ccu)$ state decaying to $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ final states
  - **No evidence** of $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decay
    - Implications for dynamics of **weakly** decaying doubly charmed baryons
  - Established **mass and lifetime** of $\boldsymbol{\Xi_{cc}^{++}}$ state
- Expect more of doubly charmed baryons
  - Diverse programmed of DCB studies currently in progress
    - Includes the much anticipated search of singly charged $\boldsymbol{\Xi_{cc}^{+}}$ **(ccd)** baryon

Hopefully more doubly charming results coming soon

Thanks for your attention!

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