Study of doubly charmed baryon at LHCb

Yixiong Zhou
on behalf of the LHCb collaboration

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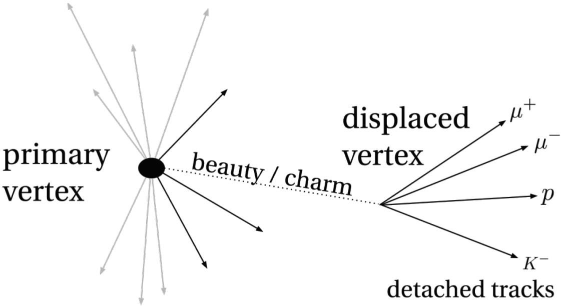
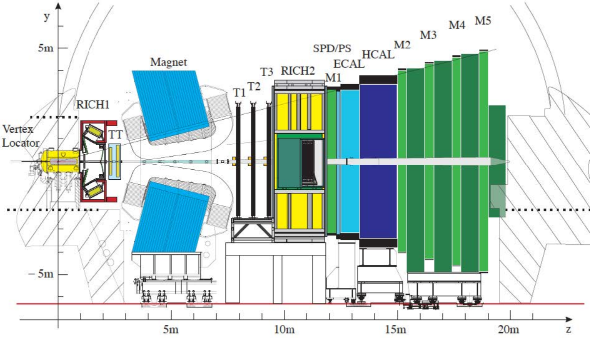
Doubly charm baryon spectroscopy at LHCb

- A huge amount of cc have been produced
  - $\sigma(pp \to ccX) \approx 90\,\mathrm{nb}@\sqrt{s} = 13\,\mathrm{TeV}$
  - Collected 9 fb^{-1} of data at 7, 8 and 13 TeV
- Doubly charm baryon decay weakly with high multiplicity
  - Requires excellent vertexing and particle identification capabilities



LHCb detector

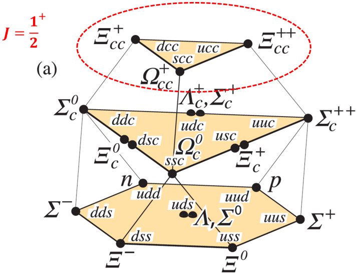
- Excellent vertex and PID performance and precise tracking resolution
- Ideal place for spectroscopy study



JINST 3 (2008) S08005

Theoretical overview

- Quark model predict the existence of the doubly charmed baryon
- SU(4) 20-plets ($J = \frac{1}{2}$) containing SU(3) triplets (ground states) : Ξ_{cc}^{+}(ccd), Ξ_{cc}^{++}(ccu) and Ω_{cc}^{+}(ccs)

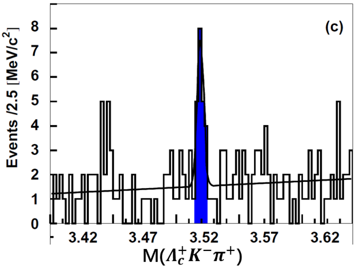


- Mass [PRD 61(2000) 057502]:
  m(Ξ_{cc}^{+}) $\approx$m(Ξ_{cc}^{++}) $\approx 3621\,\mathrm{MeV}/c^2$,
  m(Ω_{cc}) $\approx 3.7\,\mathrm{GeV}/c^2$
- Lifetime [PRD 98(2018) 113005]:
  $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) \approx 256\,\mathrm{fs}$

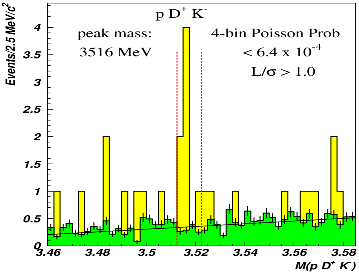
- Production [PRD 98(2018) 113005]:
  - $\sigma(\Xi_{cc}^{+}) \approx \sigma(\Xi_{cc}^{++}) \approx 3\sigma(\Omega_{cc}^{+}) \Rightarrow f_{frag} u : d : s \sim 1 : 1 : 0.26$
  - $\sigma(\Xi_{cc}^{+}) \approx \sigma(\Xi_{cc}^{++}) \sim 40\,\mathrm{nb}$; $\sigma(\Omega_{cc}^{+}) \sim 10\,\mathrm{nb}$

Experimental overview

- Ξ_{cc}^{+} first claimed by SELEX
  - Mass $3518.7 \pm 1.7\,\mathrm{MeV}/c^2$
  - Lifetime $\tau(\Xi_{cc}^{+}) < 30\mathrm{fs}$
  - Production $R = \frac{\sigma(\Xi_{cc}^{+})}{\sigma(\Lambda_c^{+})}\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}) \sim 20\%$
- Not confirmed by BaBar, Belle and FOCUS



PRL 89 (2002) 112001



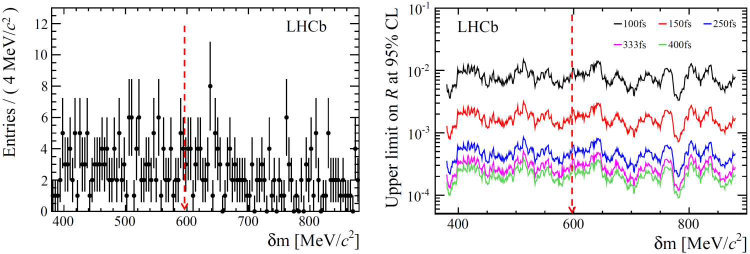
PLB 628 (2005) 18

Ξ_{cc} at LHCb [JHEP 12 (2013) 090]

- LHCb search for Ξ_{cc}^{+} using 2011 data at $\sqrt{s} = 7\,\mathrm{TeV}$ [$0.65\mathrm{fb}^{-1}$]

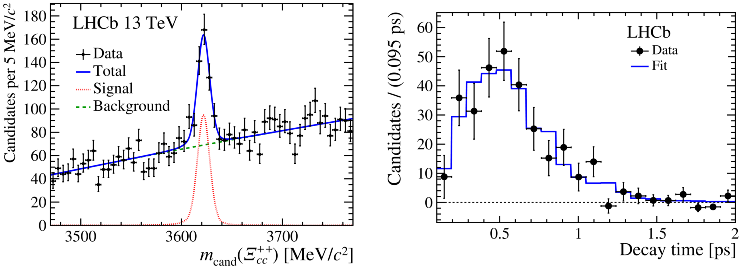
$$R = \frac{\sigma(\Xi_{cc}^{+})}{\sigma(\Lambda_c^{+})}\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}) < 1.5 \times 10^{-2}(100\,\mathrm{fs})$$

$$< 3.9 \times 10^{-4}(400\,\mathrm{fs})@95\% CL$$



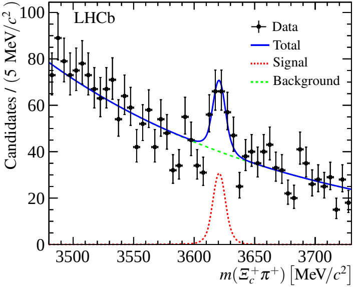
Observation of Ξ_{cc}^{++}

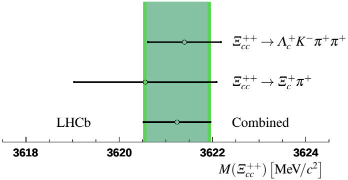
- Ξ_{cc}^{++} first observed decay to $\Lambda_c^+ K^- \pi^+ \pi^+$ by LHCb at 2017
  - Significance $> 12\sigma$ with 2016 data, $> 7\sigma$ with 2012 data
  - m(Ξ_{cc}^{++}) $= (3621.40 \pm 0.72 \pm 0.27 \pm 0.14)\,\mathrm{MeV}/c^2$ [PRL 119(2017) 112001]
  - 100 MeV/c^2 away from the SELEX result (m(Ξ_{cc}^{+})$_{SELEX}$=3519$\pm$1 MeV/c^2)
- Later the lifetime was measured
  - $\tau(\Xi_{cc}^{++}) = (0.256 \pm^{+0.024}_{-0.022} \pm 0.014)\,\mathrm{ps}$ [PRL 121(2018) 052002]
  - Weak decay confirmed



Ξ_{cc}^{++} confirmed [PRL 121 (2018) 162002]

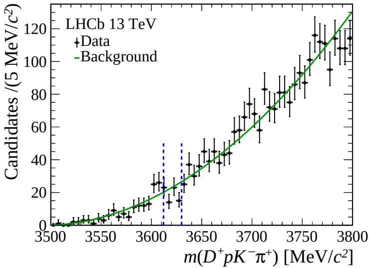
- Confirmed by another decay channel $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$
  - Significance $> 5.9\sigma$ with 2016 data
  - m(Ξ_{cc}^{++})= $(3621.24\pm0.65\pm0.31)\,\mathrm{MeV}/c^2$
  - $\frac{\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^{+}\pi^{+})\times\mathcal{B}(\Xi_c^{+}\to pK^{-}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^{+}K^{-}\pi^{+}\pi^{+})\times\mathcal{B}(\Lambda_c^{+}\to pK^{-}\pi^{+})} = 0.035 \pm 0.009 \pm 0.003$

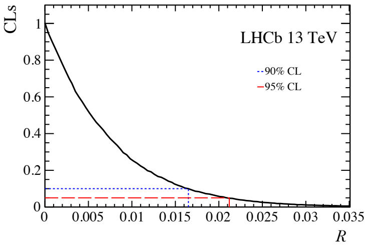




Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays [JHEP 10(2019) 124]

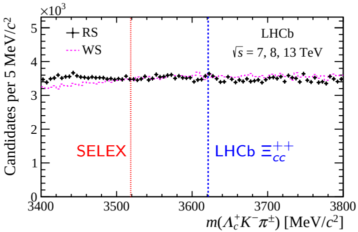
- Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ with $D^+ \to K^- \pi^+ \pi^+$
- Use 2016 data at $\sqrt{s} = 13\,\mathrm{TeV}$ [$1.7\,\mathrm{fb}^{-1}$]
- No evidence for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$, UL on ratio of $\mathcal{B}$:
  $\mathcal{R}(\frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}) < 1.7(2.1) \times 10^{-2}$@90%(95%)CL

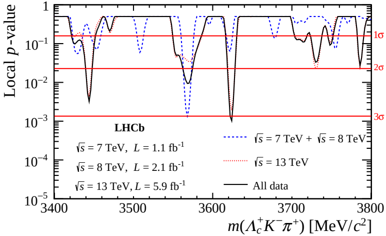




Search for the doubly charmed baryon Ξ_{cc}^{+} [SCPMA 63(2020) 221062]

- Search for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ with $\Lambda_c^+ \to p K^- \pi^+$
- Use full Run1+Run2 data, luminosity corresponds to $9.2\,\text{fb}^{-1}$



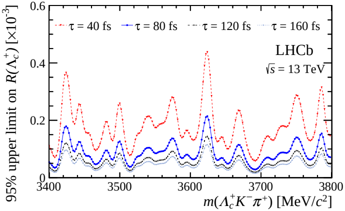


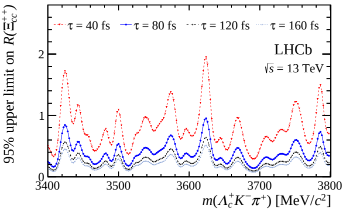
- No significant signal is found in the mass range 3400-3800 MeV/c^2
- Largest local significance 3.1σ (statistical) around $3620\,\text{MeV}/c^2$ (Global significance 1.7σ)

Search for the doubly charmed baryon Ξ_{cc}^{+} [SCPMA 63(2020) 221062]

- Set limits on the production ratios :

$$\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}; \mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$





Lifetime	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 13\,\text{TeV}$	
	$\mathcal{R}(\Lambda_c^+)$ $[\times 10^{-3}]$	$\mathcal{R}(\Xi_{cc}^{++})$	$\mathcal{R}(\Lambda_c^+)$ $[\times 10^{-3}]$	$\mathcal{R}(\Xi_{cc}^{++})$
40 fs	6.5	8.8	0.45	2.0
80 fs	2.1	2.8	0.22	1.0
120 fs	1.2	1.6	0.15	0.6
160 fs	0.9	1.2	0.12	0.5

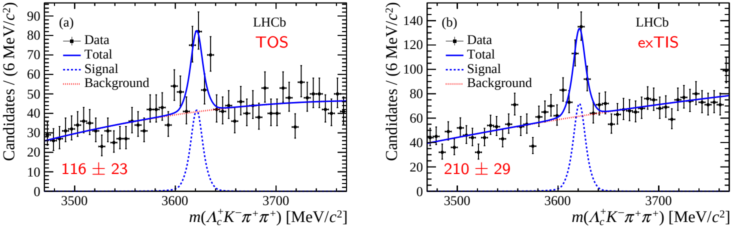
- Improve LHCb limits by order of magnitude compared to Run 1 analysis
- Limits significantly below the value reported by SELEX

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ production measurement [CPC 44(2020) 022001]

- Use 2016 data at $\sqrt{s} = 13\,\mathrm{TeV}$ $[1.7\,\mathrm{fb}^{-1}]$
- Normalizing channel: $\Lambda_c^+ \to p K^- \pi^+$

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

- $\mathcal{R} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$

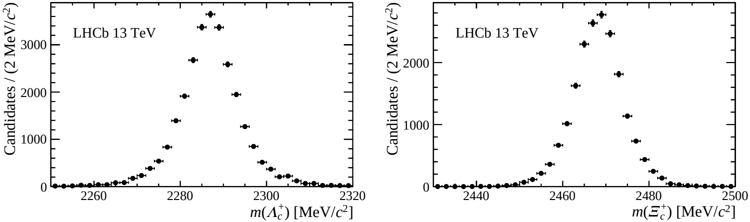


Ξ_{cc}^{++} mass measurement [JHEP 02(2020)049]

- Various theoretical models probing QCD make predictions
- Extremely important to understand the cc system in baryon
- The uncertainty on the Ξ_{cc}^{++} baryon is still large compare to the singly charmed baryons
- Update the Ξ_{cc}^{++} mass with 2016-2018 data ($\sqrt{s} = 13\,\mathrm{TeV}$)
- Luminosity correspond to $5.6\,\mathrm{fb}^{-1}$
- Use both of the observed decay modes:
  - $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [PRL 119(2017) 112001]
  - $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [PRL 121 (2018) 162002]

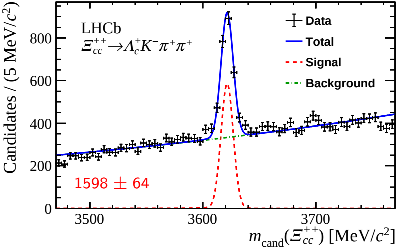
Ξ_{cc}^{++} mass measurement [JHEP 02(2020)049]

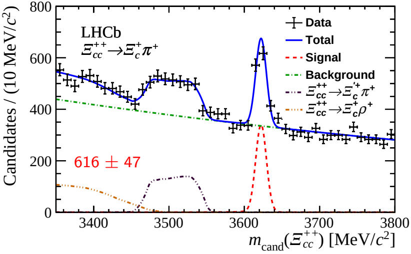
- Ξ_{cc}^{++} candidates are selected using MVA approach
- BDT method for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and MLP method for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
- Optimized with Figure of merit method ($\frac{S}{\sqrt{S+B}}$)
- Λ_c^+ and Ξ_c^+ candidates are selected with high purity



Ξ_{cc}^{++} mass measurement [JHEP 02(2020)049]

- To improve the mass resolution use mass difference as fit variable
  - $m_{\rm cand}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^- \pi^+) - m(\Lambda_c^+) + M_{\rm PDG}(\Lambda_c^+)$
  - $m_{\rm cand}(\Xi_{cc}^{++}) = m(\Xi_c^+ \pi^+) - m(\Xi_c^+) + M_{\rm PDG}(\Xi_c^+)$
- For the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ mode two feed-down decays are considered
  - $\Xi_{cc}^{++} \to \Xi_c^{\prime +}(\to \Xi_c^+ \gamma)\pi^+$
  - $\Xi_{cc}^{++} \to \Xi_c^+ \rho^+(\to \pi^+ \pi^0)$





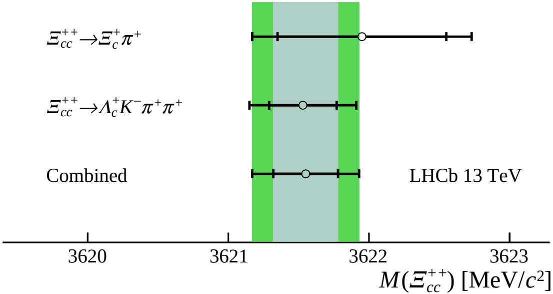
Ξ_{cc}^{++} mass measurement [JHEP 02(2020)049]

- Multiple scattering can increase/decrease the opening angle between Ξ_{cc}^{++} products
- Could bias the mass since the selection favours candidates with larger decay lengths
- Studied with charmed hadrons (Well reproduced by simulation)

	Uncertainty [MeV/c^2]	
Source	$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
Momentum-scale calibration	0.21	0.34
Energy-loss correction	0.05	0.03
Simulation/data agreement	0.09	0.05
Selection-induced bias on the Ξ_{cc}^{++} mass	0.09	0.09
Final-state radiation	0.05	0.16
Background model	0.01	0.04
Λ_c^+, Ξ_c^+ mass	0.14	0.22
Total	0.29	0.49

Ξ_{cc}^{++} mass measurement [JHEP 02(2020)049]

- By combining these two modes the uncertainty is reduced
- Combination is dominant by the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ mode



- Combined results (world's most precise value):
  - $m(\Xi_{cc}^{++}) = (3621.55 \pm 0.23 \pm 0.30)\,\mathrm{MeV}/c^2$

Summary

- A lot of important results in doubly charmed baryon sector :
  - Observed Ξ_{cc}^{++} in $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ channel
  - No evidence of $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decay in 2016 data but larger datasets are available
  - Ξ_{cc}^{++} lifetime and production rate ratio were measured for the first time
  - Precision measurements of Ξ_{cc}^{++} have started
  - Still no evidence for Ξ_{cc}^{+} at LHCb will extend our searches to different final states soon
- Run3/4 approaching $\int \mathcal{L} dt = 23\ /\ 50\ \text{fb}^{-1}$
- More results are expected in the near future

Thanks!