Doubly charmed hadrons at LHCb

Murdo Traill
on behalf of the LHCb collaboration
University of Glasgow

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• Overview of LHCb detector
• Introduction and history
• Observation of doubly charmed baryon $\Xi_{cc}^{++}$: arXiv:1707.01621
• Plans for the future
• Summary
LHCb detector

Main challenges in hadron spectroscopy include hadronic background and particle mis-ID

LHCb is well equipped to handle both!

VerteX LOcator (VELO):
- Vertex reconstruction
- Impact parameter resolution: 20 μm
- Decay time resolution: 45 fs
- Allows identification of weak decays

RICH sub-detectors:
- K/π/p separation
- $\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 5\%$
- $\epsilon(p \to p) \sim 95\%$ with $\epsilon(\pi \to p) \sim 5\%$
- Effectively distinguish $K$ and $p$ from $\pi$

Tracking system:
- $\epsilon(Tracking) \sim 96\%$
- $\delta p/p \sim 0.5-1\%$ (5-200 GeV)
- Easily separate neighboring structures

Aiming for precision measurements in $b$ and $c$ flavor physics

Single forward arm detector covering $2 < \eta < 5$

The LHCb Detector at the LHC 2008 JINST 3 S08005
Constituent-quark model predicts 3 SU(3) triplets with $C=2$; $\Omega^{+}_{cc}(ccs), \Xi^{+}_{cc}(ccd), \Xi^{++}_{cc}(ccu)$

- Excited decay to ground states via strong/electromagnetic interactions
- Ground states decay weakly with a charm quark transitioning into lighter quarks

- (QQq) baryons are not exotic – predicted by SM
- No unambiguous evidence for doubly charmed baryons before 2017
- $\Xi_{cc}$ are the lightest doubly heavy baryon
- $\Xi_{cc}$ offered best chance of discovery;

$$\sigma(c\bar{c}, c\bar{c}) \gg \sigma(b\bar{b}, c\bar{c}) \gg \sigma(b\bar{b}, b\bar{b})$$

SU(4) flavor multiplets, PDG Review of Particle Physics, Phys.Rev.D86, 010001.
Masses and lifetime of ground states

- Many models been applied to determine masses of ground state and excitations: QCD sum rules, (non-)relativistic QCD potential models, etc

- Most agree $\Xi^+_cc$ and $\Xi^{++}_{cc}$ states between 3.5 - 3.7 GeV and $\Omega^+_{cc}(ccs) \approx \Xi_{cc} + 0.1$ GeV

- Mass splitting between $\Xi^+_cc/\Xi^{++}_{cc}$ is only a few MeV due to approximate isospin symmetry

- Recent lattice QCD computations:
  $m(\Xi^+_cc/\Xi^{++}_{cc}) \approx 3.6$ GeV, $m(\Omega^+_{cc}) \approx 3.7$ GeV

- Lifetimes: expect $\tau(\Xi^{++}_{cc}) \gg \tau(\Xi^+_cc) > \tau(\Omega^+_{cc})$; $\tau(\Xi^{++}_{cc}) \approx 200-700$ fs, $\tau(\Omega^+_{cc}) \approx \tau(\Xi^+_cc)$
SELEX and $\Xi_{cc}^+$

- SELEX, a fixed-target Fermilab experiment, claimed first observation of $\Xi_{cc}^+$ state in $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ decays in 2002.
- Followed by a confirmation in $D^+ p^+ K^-$ mode in 2004:
  - $\Lambda_c^+ K^- \pi^+$: 15.9 signals over 6.1 bkg ($6.3\sigma$)
  - $D^+ p^+ K^-$: 5.62 signals over 1.38 bkg ($4.8\sigma$)
- Unexpected properties of this observation:
  - Short lifetime: $\tau < 33$ fs at 90% C.L. (Strong decay?)
  - Large production of $\Lambda_c^+$ with 20% from $\Xi_{cc}^+$ decays
- Main problem with SELEX findings; never reproduced by other groups
- Unique production environment:
  - Hyperon beam is admixture of $\Sigma^-, p^+, \pi^-$ and target was Cu/diamond
  - Production cross-section could be much different than in p-p colliders
LHCb search for $\Xi_{cc}^+$

- In 2013, LHCb searched for $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays with 0.65 fb$^{-1}$ of 2011 data.
- Initial SELEX mode with a large expected BF.
- Examined mass range 3.3-3.8 GeV but found no evidence of $\Xi_{cc}^+$ production.
- Experiment sensitivity strongly depends on $\Xi_{cc}^+$ lifetime however:
  \[ R = \frac{\sigma(\Xi_{cc}^+) \times BF(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \]
  \[ R < 0.013 \text{ for } \tau(\Xi_{cc}^+) = 100\text{fs} \]
  \[ R < 3.3 \times 10^{-4} \text{ for } \tau(\Xi_{cc}^+) = 400\text{fs} \]
- Due to limited sensitivity at short lifetimes, this non-observation is not inconsistent with the SELEX claim.
Switch to $\Xi_{cc}^{++}$

- Searching for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays: theorists suggest BF could as high as $\sim 10\%$, see arXiv:1703.09086

- $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^+)$; $\Xi_{cc}^{++}$ travels further from PV making online selection better at observing $\Xi_{cc}^{++}$ state

- Reconstruct $\Lambda_c^+$ through $p^+ K^- \pi^+$ final state

Analysis strategy:

- Use $\sim 1.7 \, fb^{-1}$ 2016 Run2 data at $\sqrt{s} = 13$ TeV
- Dedicated exclusive trigger ensuring high efficiency
- Full event reconstruction done at trigger level
- $2 \, fb^{-1}$ 2012 Run1 data also analysed to check results
Candidate selection

• $\Sigma_{cc}^{++}$ cross-section much smaller ($\sim \times 10^{-5}$) than inelastic cross-section in $pp$ so expecting large hadronic backgrounds

• Expect high-pure sample of $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$

$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ selection:

• $p^+, K^-, \pi^+$ tracks: positive particle ID and not produced from primary vertices

• $\Lambda_c^+$: good vertex quality, separated from primary vertices

• $\Lambda_c^+, p^+, K^-, \pi^+$ tracks must have large $p_T$

LHCb has some of largest charm data sets in the world

$\sigma(pp \rightarrow c\bar{c}X; 13\text{TeV}) \text{LHCb} = 2369 \pm 3 \pm 192 \ \mu b$ \cite{JHEP1603(2016)159}

60 M fully reconstructed

$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ signal decays

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Machine learning

• $\Lambda_c^+$ combined with PID-selected $K^-\pi^+\pi^+$ tracks to form $E_{cc}^{++}$ candidates
• Candidates with cloned tracks are removed

$$E_{cc}^{++} \rightarrow K^-\pi^+\pi^+\Lambda_c^+ (p^+ K^-\pi^+)$$

$\tau(\Lambda_c^+) \sim 200 \text{ fs}$
$\sigma_t(\Lambda_c^+) \sim 45 \text{ fs}$

• Multivariate selector further explores:
  - Decay Fit quality of $E_{cc}^{++}$ candidates
  - Kinematics of final states
  - $E_{cc}^{++}$ vertex separation from PV

Neural-network selector trained on simulated signal and un-physical wrong-sign (WS) data represented background as:

$$E_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^-$$
\[ \Lambda_c^+ K^- \pi^+ \pi^+ \] Mass spectrum

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

Signal yield = 313 ± 33

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

Local significance > 12σ
Mass measurement

\[ M(\Xi_{cc}^{++}) - M(\Lambda_c^+) = 1134.94 \pm 0.72 \text{(stat)} \pm 0.27 \text{(syst)} \text{ MeV} \]

\[ M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \text{ (stat)} \pm 0.27 \text{ (syst)} \pm 0.14(\Lambda_c^+) \text{ MeV} \]
Cross-checks

- Varying threshold value of MVA selector has **no effect** on signal significance
- MVA efficiency as a function of mass: **very smooth, no biasing**
- Multiple candidates **do not** create fake narrow structures
- Checking combinations of tracks from $\Lambda_c^+$ and $\Xi_{cc}^{++}$: again **no** peaking structures

- Varying particle ID selections: no peaking structure emerge in WS combinations but structure remains in RS sample
- Tried cut based selection instead of MVA:
  - requiring good vertex fit quality
  - $\Xi_{cc}^{++}$ vertex displaced
  - tracks are not produced from PV
  - Peak significance still $> 12\sigma$
Confirmation in Run 1

- Similar search done with 2 fb\(^{-1}\) of Run1 data recorded in 2012, \(\sqrt{s} = 8\) TeV
- Different trigger and data processing configuration than in Run2
- But again a clear peak is seen in \(\Lambda_c^+ K^- \pi^+ \pi^+\) mass spectrum
- Signal yield: \(113 \pm 21\)
- Local significance: \(>7\sigma\)
- Resolution: \(6.6 \pm 1.4\) MeV
- \(\Delta m(\text{Run1, Run2}) = 0.8 \pm 1.4\) MeV (consistent between samples)
Weak Decay

- Peaking structure remains significant after requiring minimum decay time, $t > 5\sigma$ w.r.t PV:
  - Run1 significance: $>7\sigma$
  - Run2 significance: $>12\sigma$

Inconsistent with a strong decay
Comparison with SELEX

- Large mass difference:
  \[ m(\Xi^{++}_{cc})_{LHCb} - m(\Xi^{++}_{cc})_{SELEX} = 103 \pm 2 \text{ MeV} \]

Prospects

• Searching for $\Xi_{cc}^{++}$ in additional decay modes:
  \[ \Xi_{cc}^{++} \rightarrow \Xi^{-}_c \pi^+, \quad \Xi_{cc}^{++} \rightarrow D^+ p^+ K^- \pi^+, \quad \Xi_{cc}^{++} \rightarrow \Lambda_c^+ \pi^+ \]

• Measurement of $\Xi_{cc}^{++}$ lifetime is making good progress

• Production cross-section

• Confirming its spin-parity is $J^P = \frac{1^+}{2}$

• Searching for its isospin partner $\Xi_{cc}^+$ in larger sample than previous LHCb measurement

  • Also searching for $\Omega_{cc}^+$ in the near future

  • The excited states?

  • Now a new sector to study strong force and CP violation

Just the beginning. A long list of studies ahead.
Summary

- LHCb very active in hadron spectroscopy studies
- Observed narrow structure in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum this year
- Significant displacement consistent with a weakly decaying particle
- Observed in two LHCb data sets
- Consistent with $\Xi_{cc}^{++}$ (ccu)
- Inconsistent with $\Xi_{cc}^+$ observed by SELEX being its isospin partner

Stay tuned for more doubly charming results

Thank you.
Back-up
Searches by other experiments

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

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

- **Belle@KEK:** $e^-e^+$ at $\sqrt{s} = 10.58$ GeV
  - Searched for $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^-\pi^+$
  - Found new $\Xi_c^+$ resonance decaying to $\Lambda_c^+ K^-\pi^+$
  - But still no evidence of a $\Xi_{cc}$ state

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$M(\Lambda_c^+) \text{ vs. } M(\Xi_{cc}^+)$
Intermediate resonances

RS, sideband-subtracted

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References (not exhaustive)


More references (not exhaustive)


C. Alexandrou and C. Kallidonis, *Low-lying baryon masses using $N_f = 2$ twisted mass clover-improved fermions directly at the physical point*, \texttt{arXiv:1704.02647}.

Even more references (not exhaustive)


