Properties of Single and Double Charm Hadrons

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Update on Double Charm Baryons

1. The Discovery of Double Charm Baryons
2. Features, Problems, and Solutions
3. Observation of $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$
4. Observation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ , \Xi_c^+ \pi^- \pi^+ \pi^+$

Hadro-Production of Charm

3. $\Lambda_c^+$ Semi-leptonic Decay

4. Cabibbo-Suppressed $\Xi_c^+$ Decays
   - First Observation of $\Xi_c^+ \rightarrow \Sigma^+ \pi^- \pi^+$, $\Xi_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$

Summary
An exited state and a pair of isodoublets?
Features and Problems in Original Analysis...

- All Signals have very low statistics
- There is nearly no background (→ difficult to determine)
- Entries in histograms only from baryon ($\Sigma^-$, proton) beams
- Other experiments do not see the states (but: nobody else has baryon beams...)
- Lifetime is short ($< 33$ fs)
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Hadro-Production of Charm
Λ⁺ C Semi-leptonic Decay
Cabibbo-Suppressed Ξ⁺ C Decays
Summary

The Discovery of Double Charm Baryons
Features, Problems, and Solutions
Observation of Ξ⁺ CC → Ξ⁺ C π⁺ π⁻
Observation of Ξ⁺ CC → Λ⁺ C K⁻ π⁺ π⁺, Ξ⁺ C π⁻ π⁺ π⁺

...and Possible Solutions

- Look for other decay modes to confirm DCB hypothesis
- Develop new method for background determination
- Include single-charm in vertex fit of double-charm vertex
- Redo full analysis chain to increase statistics
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Other Decay Modes of Double Charm Baryons

Cabibbo allowed decay of $\Xi_{cc}^+$:

\[ u \rightarrow d, \quad W^+ \rightarrow c \quad s \quad d \quad c \]

In Final State:
- Baryon
- Quarks $csdu\bar{d}$
- plus pairs from sea
- Cascaded decay chain

Easily accessible in SELEX:

- $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
- $\Xi_{cc}^+ \rightarrow pD^+ K^-$
- $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+$
- $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
- $\Xi_{cc}^{++} \rightarrow pD^+ K^- \pi^+ (?)$
- $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$
- $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+ \pi^+ \pi^-$
- $\Omega_{cc}^+ \rightarrow \Xi_c^+ K^- \pi^+$
- $\Omega_{cc}^+ \rightarrow \Xi_c^+ K^- \pi^+ \pi^+ \pi^-$
Other Decay Modes of Double Charm Baryons

Cabibbo allowed decay of $\Xi_{cc}^+$:

\[ \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \]
\[ \Xi_{cc}^+ \rightarrow pD^+ K^- \]
\[ \Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \]
\[ \Xi_{cc}^{+++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \]
\[ \Xi_{cc}^{+++} \rightarrow pD^+ K^- \pi^+ (?) \]
\[ \Xi_{cc}^{+++} \rightarrow \Xi_c^+ \pi^+ \]
\[ \Xi_{cc}^{+++} \rightarrow \Xi_c^+ \pi^+ \pi^+ \pi^- \]

Easily accessible in SELEX:

\[ \Omega_{cc}^+ \rightarrow \Xi_c^+ K^- \pi^+ \]
\[ \Omega_{cc}^+ \rightarrow \Xi_c^+ K^- \pi^+ \pi^+ \pi^- \]

In Final State:

- Baryon
- Quarks $c s d u \bar{d}$
- plus pairs from sea
- Cascaded decay chain
Other Decay Modes of Double Charm Baryons

**Cabibbo allowed decay of \( \Xi^{+}_{cc} \):**

![Diagram showing the decay of \( \Xi^{+}_{cc} \)]

In Final State:
- Baryon
- Quarks \( csdu\bar{d} \)
  - plus pairs from sea
- Cascaded decay chain

**Easily accessible in SELEX:**

\[ \Xi^{+}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \]
\[ \Xi^{+}_{cc} \rightarrow pD^{+} K^{-} \]
\[ \Xi^{+}_{cc} \rightarrow \Xi^{+}_{c} \pi^{-} \pi^{+} \]
\[ \Xi^{++}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \pi^{+} \]
\[ \Xi^{++}_{cc} \rightarrow pD^{+} K^{-} \pi^{+} (?) \]
\[ \Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} \pi^{+} \]
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Cabibbo-Suppressed $\Xi_c^+$ Decays

Summary

The Discovery of Double Charm Baryons
Features, Problems, and Solutions
Observation of $\Xi_{cc}^{+} \rightarrow \Xi_c^{+} \pi^+ \pi^-$
Observation of $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^- \pi^+ \pi^+, \Xi_c^{+} \pi^- \pi^+ \pi^+$

$\Xi_{cc}^{+} \rightarrow pD^+ K^-$ (PLB628 (2005) 18)

(a) $pD^+ K^-$
- peak mass: 3516 MeV
- 4-bin Poisson Prob < $6.4 \times 10^{-4}$
- $L/\sigma > 1.0$

(b) wrong sign: $pD^- K^-$
- $L/\sigma > 1.0$

$\Lambda_c^+ K^+ \pi^-$ and $D^+ p K^-$
- fitted masses: 3518(3) and 3519(2) MeV/$c^2$
Background Determination: Event Mixing

- First decay vertex close to primary vertex: assume all bkgd is combinatoric
- Make combinatoric bkgd by taking first decay vertex from one event, second from other
- Use each single-charm event 25 times to increase statistics

Resulting combinatoric bkgd is absolutely normalized ⇒ Bkgd shape known

- PLB628 (2005) 18
Update on Double Charm Baryons

The Discovery of Double Charm Baryons
Features, Problems, and Solutions

Observation of \( \Xi^{+}_{cc} \rightarrow \Xi^{+}_{c} \pi^{+} \pi^{-} \)
Observation of \( \Xi^{+}_{cc} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{-} \pi^{+} \), \( \Xi^{+}_{c} \pi^{-} \pi^{+} \pi^{+} \)

\( \Xi^{+}_{cc} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} - \text{New Analysis} \)

Re-analysis of full data set \( \Rightarrow \) More \( \Lambda_{c} \) cands (1630 \( \rightarrow \) 2450)

- Refit \( \Xi^{+}_{cc} \) vertex using \( \vec{p}_{\Lambda_{c}^{+}} \) together with \( K^{-} \pi^{+} \) tracks
  \( \Rightarrow \) Better \( L1 \) resolution
- Use event mixing for background
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The Discovery of Double Charm Baryons

Features, Problems, and Solutions

Observation of $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$

Observation of $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^+ \pi^+ \pi^+$, $\Xi_c^- \pi^+ \pi^+$

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

Jürgen Engelfried

Properties of Single and Double Charm Hadrons 19/38
Features of new Analysis

- **Re-Analysis and Relaxing Cuts on Single Charm:**
  - some more background, but shape is well understood from combinatoric analysis
  - more signal

- **Improved sec. vertex resolution:**
  - Cleaner Signals, access to other modes
  - Possibility (but challenging) to measure lifetime (is around 1 $\sigma$)
\[ \Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^- \] — First Observation

**FIRST OBSERVATION:**

\[ \Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^- \]

\[ \Xi_c^+ \rightarrow pK^- \pi^+ \]
Comparing the Mass of the Three Decay Modes

\[ \Lambda_c^+ K^+ L / \sigma \geq 1.8 \]

Mass \(3521.8 \pm 1.7\) MeV/c\(^2\)

\[ \Xi_c^+ K^+ L / \sigma \geq 0. \]

\[ p D^+ K L / \sigma \geq 1. \]
Observation of $\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$

- If we have a ccd state ($\Xi_{cc}^{+}$), there has to be a ccu state as well ($\Xi_{cc}^{++}$).
- Look in $\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$.
- Use same cuts as before:
  - Use same code
  - Just ask for one more $\pi^{+}$

Green: Absolutely-normalized background
Gaussian with fixed width (MC)

If we have a ccd state ($\Xi_{cc}^{+}$), there has to be a ccu state as well ($\Xi_{cc}^{++}$).

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$\Xi_{c}^{+}\pi^{-}\pi^{+}\pi^{+}$

New $\Xi_{cc}^{++}$ at 3452!
Observation of $\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} \pi^{-} \pi^{+} \pi^{+}$

- Now look in $\Xi^{+}_{c} \pi^{-} \pi^{+} \pi^{+}$
- Same as before, ask for additional $\pi^{+}$
- Only use $\Xi^{+}_{c} \rightarrow pK^{-}\pi^{+}$

- Add data from both modes
- Significance 6.5 $\sigma$
- Mixed event background describes sidebands
$$\Xi_{cc}(3780)^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$

- Re-Analyzed Data
- Restrict to $\Sigma^-$ Beam
- Peak wider than Resolution
- Half decay to $\Xi_{cc}^+(3520)$
- Still working on Details
Hadro-Production of Charm

- Usual parametrization of material dependent cross section: \( \sigma \propto A^\alpha \)
- From \( \Lambda \)-Production: \( \alpha = \alpha(x_F, p_t) \)
- Charm: Published \( \alpha \) vary between 2/3 and 1, different(?) for open and hidden charm.
- Usually experiments only give one \( \alpha \) averaged over their \((x_F, p_t)\) acceptance
- No model on first principle exists, even less for double charm
- Still problems calculating double-double-charm production in \( e^+e^- \rightarrow J/\psi \eta_c \)!!
- Important input for other fields like Heavy-Ion Collisions
Hadro-Production of Charm in SELEX

- SELEX has charm signals with decent statistics in 13 particles and modes, in several $x_F$ and $p_t$ bins.
- 2 Copper and 3 Carbon Targets
- 4 different beam particles: $\Sigma^-$, $\pi^-$, $p$, $\pi^+$
- Cross check results with $\Lambda$ and $K^0$ production
- Average results in different categories: beams, charm/anticharm, leading/nonleading

Results shown in Poster by Alex Blanco
\( \Lambda_c^+ \) Semi-leptonic Decay

History:

- **Mark II (1982):** \( \Gamma(\Lambda_c^+ \rightarrow e^+ X)/\Gamma = (4.5 \pm 1.7)\%\)
- **CLEO (1994):** \( \Gamma(\Lambda_c^+ \rightarrow \Lambda e^+ \nu)/\Gamma(pK\pi) = 0.43 \pm 0.08\)
- **PDG:** \( \Gamma(\Lambda_c^+ \rightarrow pK^-\pi^+)/\Gamma = 5\%\)

What are the rest of the modes?

- **D mesons:** ground state and p-wave \( (K^*(892)) \)
  \( \sim 85\% \) of total semileptonic rate

*SELEX observed* \( \Lambda_c^+ \rightarrow \Lambda(1520)e^+\nu \)
Measure $\Gamma(\Lambda_c^+ \rightarrow \Lambda(1520)e^+\nu)/\Gamma(\Lambda_c^+ \rightarrow pK^−\pi^+)$. 

- Use all features of SELEX: tracking, RICH, eTRD, BTRD, Pb glass
- eTRD separates $e$ from $\pi$ up to 120 GeV/c, momentum dep. efficiency measured with Pb glass
- Look for 3-prong vertices, $pK^-e^+, pK^-\pi^+, L/\sigma > 8$, RICH id for $p$, $K^-$, $M(pKe) < M(\Lambda_c^+)$
- Combinatoric Background via event mixing
The $pK^-$ Mass Spectrum from $pK^-e^+$ vertex

Fit to $\Lambda(1520)$ with fixed width (PDG) and MC resolution:
Yield: $132 \pm 26$

$pK^-\pi^+$ yield: $1544 \pm 34$
\( \Lambda_c^+ \) Branching Ratios

- correct for eTRD Efficiency (\( \sim 93\% \)), relative acceptance (\( \sim 1.2 \)), \( \Lambda(1520) \rightarrow pK^- \) BR

\[
\Gamma(\Lambda_c^+ \rightarrow \Lambda(1520)e^+\nu)/\Gamma(\Lambda_c^+ \rightarrow pK^-\pi^+) = 0.47 \pm 0.010
\]
SELEX Preliminary

\[
\Gamma(\Lambda_c^+ \rightarrow pK^-\pi^+)/\Gamma = 0.05 \pm 0.013 \text{ (PDG)}
\]
(Can this be measured well by BES or Panda?)

\[
(\Gamma(\Lambda e^+\nu) + \Gamma(\Lambda(1520)e^+\nu))/\Gamma = (4.5 \pm 1.3) \%
\]

- These two semileptonic modes saturate the Mark II measurement

PhD Thesis Jorge Amaro-Reyes
Cabibbo-Suppressed Weak Decay of Charm

- Cabibbo-Suppressed weak decay of charm ($c \to s$ vs $c \to d$):
  - Expect (phase space corrected) ratio of $\sim \tan^2 \Theta_c = 0.05$
  - *if* rescattering effects are not important

- Results from $D$ mesons: rescattering is important

- Need to measure as many channels as possible to understand rescattering effects
First Observation of $\Xi_c^+ \rightarrow \Sigma^+ \pi^+ \pi^+$, $\Xi_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$

**Summary**

From PDG:

- $\Lambda_c^+$:
  - $\Lambda K^+/\Lambda \pi^+ = 0.047 \pm 0.009$
  - $\Sigma^+ K^+ \pi^-/\Sigma^+ \pi^+ \pi^- = 0.047 \pm 0.015$
  - $p \pi^- \pi^+/p K^- \pi^+ = 0.07 \pm 0.04$

- $\Xi_c^+$:
  - $p K^- \pi^+/\Sigma^+ K^- \pi^+ = 0.22 \pm 0.03$
  - $\Sigma^+ K^+ K^-/\Sigma^+ \pi^+ K^- = 0.16 \pm 0.06$

- Generally not close to 0.05
First Observation of $\Xi_C^+ \rightarrow \Sigma^+ \pi^- \pi^+$, $\Xi_C^+ \rightarrow \Sigma^- \pi^+ \pi^+$

Can cross check analysis method with $\Lambda_C^+$ modes

PhD Thesis Eric Vázquez-Jáurequi
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Summary


<table>
<thead>
<tr>
<th>Branching Ratio</th>
<th>This Analysis</th>
<th>Other Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\Xi_c^+ \to \Sigma^+\pi^-\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$</td>
<td>$0.48 \pm 0.20$</td>
<td>$\alpha = 6.4 \pm 2.7$</td>
</tr>
<tr>
<td>$B(\Xi_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$</td>
<td>$0.18 \pm 0.09$</td>
<td>$\alpha = 2.5 \pm 1.2$</td>
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<tr>
<td>$B(\Xi_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Xi_c^+ \to \Sigma^+\pi^-\pi^+)$</td>
<td>$0.42 \pm 0.24$</td>
<td>$\alpha = 0.43 \pm 0.25$</td>
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<td>$B(\Xi_c^+ \to pK^-\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$</td>
<td>$0.194 \pm 0.054$</td>
<td>$\alpha = 2.6 \pm 0.7$</td>
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<td>$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Lambda_c^+ \to pK^-\pi^+)$</td>
<td>$0.314 \pm 0.067$</td>
<td>$\alpha = 0.30 \pm 0.07$</td>
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<td>$B(\Lambda_c^+ \to \Sigma^+\pi^-\pi^+)$ / $B(\Lambda_c^+ \to pK^-\pi^+)$</td>
<td>$0.72 \pm 0.14$</td>
<td>$\alpha = 0.68 \pm 0.14$</td>
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<td>$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Lambda_c^+ \to \Sigma^+\pi^-\pi^+)$</td>
<td>$0.38 \pm 0.10$</td>
<td>$\alpha = 0.39 \pm 0.11$</td>
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There are many more interesting results on strange and charm hadrons:

- Excited States of $\Lambda_c^+$, $\Xi_c^+$
- The Pentaquarks are dying... again...
- But the Tetraquarks are alive? The $D_s^+$? The $X$'s, $Y$'s, $Z$'s
- ...
Conclusions – Double Charm Baryons

- SELEX is still the only experiment observing Double Charm Baryons (until LHCb trigger upgrade?)
- Published results on $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^+ \rightarrow pD^+ K^-$
- SELEX is re-analyzing the data, with improved efficiency
- Presented $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+$
- Presented $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^- \pi^+ \pi^+$
- Working on determination of the $\Xi_{cc}$ Lifetime
- Searching for $\Omega_{cc}^+$
Conclusions

- Working on Double Charm Baryons
- Study of Charm Hadro-Production
- Preliminary result on semi-leptonic decay of $\Lambda_c^+$
- Study Cabibbo Suppressed Decays of charm baryons
  - First Observation of $\Xi_c^+ \rightarrow \Sigma^+ \pi^- \pi^+$, $\Xi_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$
  - More modes to come...