Properties of Single and Double Charm Hadrons

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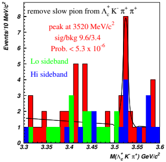
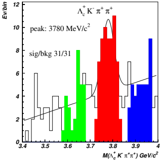
Outline

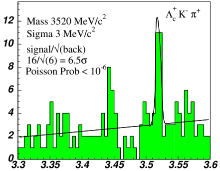
1. Update on Double Charm Baryons
   - The Discovery of Double Charm Baryons
   - Features, Problems, and Solutions
   - Observation of $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$
   - Observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_c^+ \pi^- \pi^+ \pi^+$
2. Hadro-Production of Charm
3. Λ_c^+ Semi-leptonic Decay
4. Cabibbo-Suppressed Ξ_c^+ Decays
   - First Observation of $\Xi_c^+ \to \Sigma^+ \pi^- \pi^+$, $\Xi_c^+ \to \Sigma^- \pi^+ \pi^+$
5. Summary

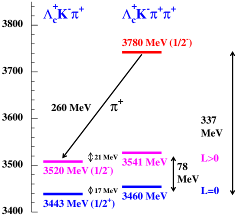
SELEX Double Charmed Baryon States – 2003

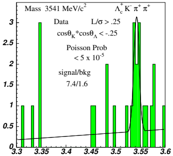


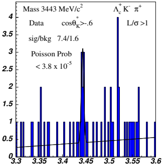
An exited state and a pair of isodoublets?

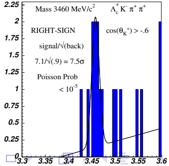












Features and Problems in Original Analysis...

- All Signals have very low statistics
- There is nearly no background ($\to$ difficult to determine)
- Entries in histograms only from baryon (Σ^-, proton) beams
- Other experiments do not see the states
  (but: nobody else has baryon beams...)
- Lifetime is short (< 33 fs)

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. . . 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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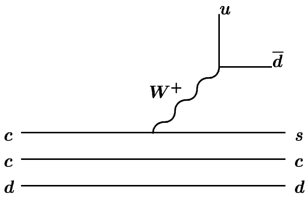
Other Decay Modes of Double Charm Baryons

Cabibbo allowed decay of Ξ_{cc}^+:



In Final State:

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

Easily accessible in SELEX:

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

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

$$\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+$$
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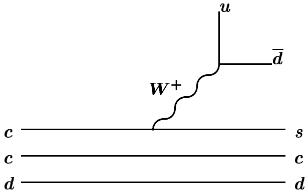

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$\Xi_{cc}^{++} \to p D^+ K^- \pi^+$ (?)
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$
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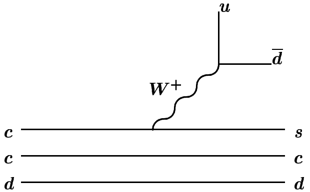

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$\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+$
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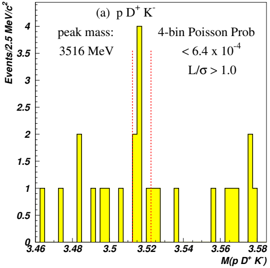
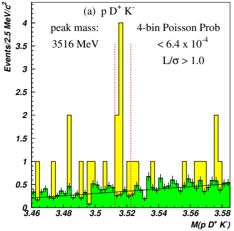
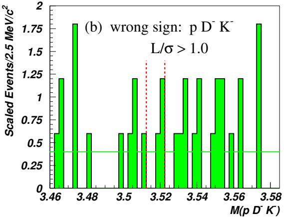
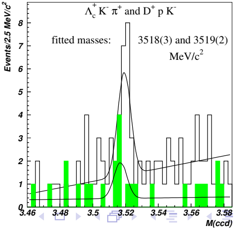
$\Xi_{cc}^+ \to pD^+K^-$ (PLB628 (2005) 18)

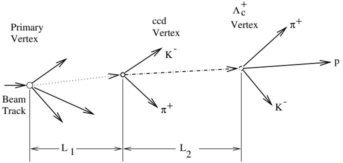








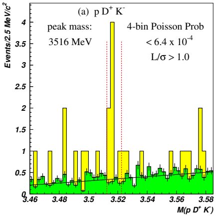
Background Determination: Event Mixing



Ξ_{cc}^+ Decay Schematic

- 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

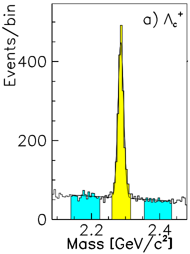
Resulting combinatoric bkgd is absolutely normalized $\Rightarrow$ Bkgd shape known

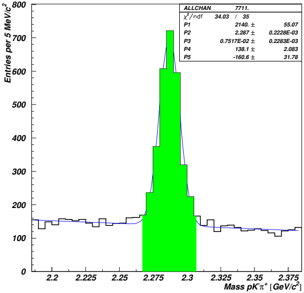


PLB628 (2005) 18

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

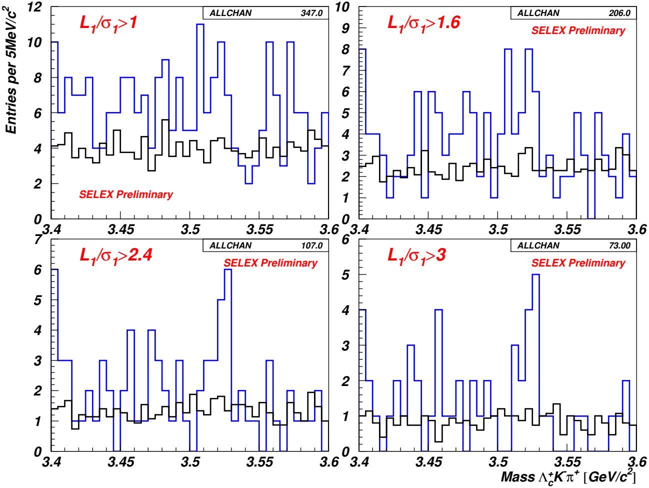
Re-analysis of full data set $\Rightarrow$ More Λ_c cands ($1630 \to 2450$)





- Refit Ξ_{cc}^+ vertex using $\vec{p}_{\Lambda_c^+}$ together with $K^-\pi^+$ tracks
  $\Rightarrow$ Better $L1$ resolution
- Use event mixing for background

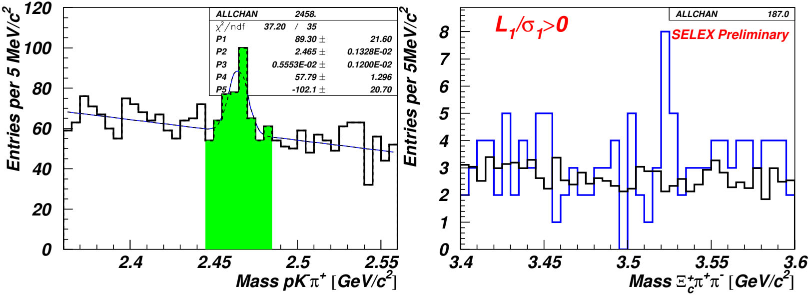
$\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$ – New Analysis



Features of new Analysis

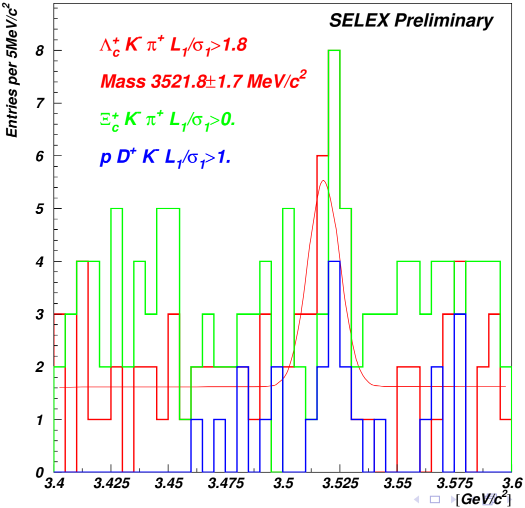
- Re-Analysis and Relaxing Cuts on Single Charm:
  - some more background, but shape is well understood from combinatoric analysis
  - more signal
- Improved sec. vertex resolution:
  - Cleaner Signals, access to other modes
  - Possibility (but challenging) to measure lifetime (is around 1 σ)

$\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$ – First Observation



FIRST OBSERVATION: $\Xi_{cc}^+ \to \Xi_c^+ \pi^+ \pi^-$, $\Xi_c^+ \to pK^- \pi^+$

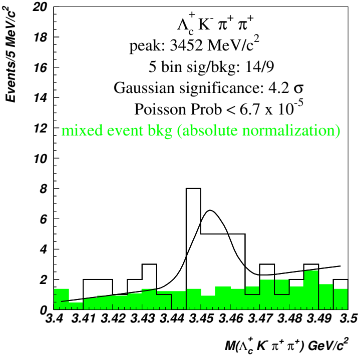
Comparing the Mass of the Three Decay Modes



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

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

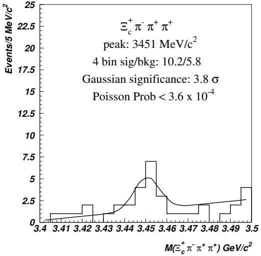
Green: Absolutely-normalized background
Gaussian with fixed width (MC)

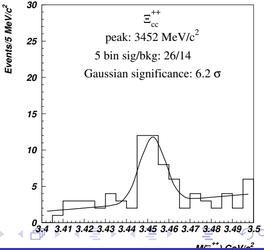


New Ξ_{cc}^{++} at 3452!

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

- Now look in $\Xi_c^+\pi^-\pi^+\pi^+$
- Same as before, ask for additional π^+
- Only use $\Xi_c^+ \to pK^-\pi^+$

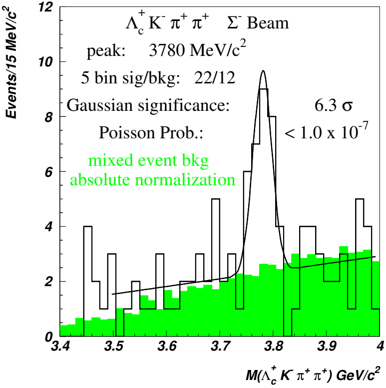




- Add data from both modes
- Significance 6.5 σ
- Mixed event background describes sidebands

$\Xi_{cc}(3780)^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

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



Hadro-Production of Charm

- Usual parametrization of material dependend cross section: $\sigma \propto A^{\alpha}$
- From Λ-Production: $\alpha = \alpha(x_F, p_t)$
- Charm: Published α vary between 2/3 and 1, different(?) for open and hidden charm.
- Usually experiments only give one α 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 $e^+e^- \to J/\Psi\eta_c$!!!
- 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: Σ^-, π^-, p, π^+
- Cross check results with Λ and K^0 production
- Average results in different categories: beams, charm/anticharm, leading/nonleading
- Results shown in Poster by Alex Blanco

Λ_c^+ Semi-leptonic Decay

History:

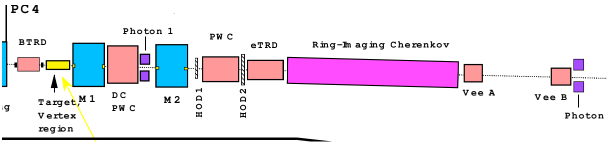
- Mark II (1982): $\Gamma(\Lambda_c^+ \to e^+ X)/\Gamma = (4.5 \pm 1.7)\,\%$
- CLEO (1994): $\Gamma(\Lambda_c^+ \to \Lambda e^+ \nu)/\Gamma(pK\pi) = 0.43 \pm 0.08$
- PDG: $\Gamma(\Lambda_c^+ \to pK^-\pi^+)/\Gamma = 5\,\%$

What are the rest of the modes?

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

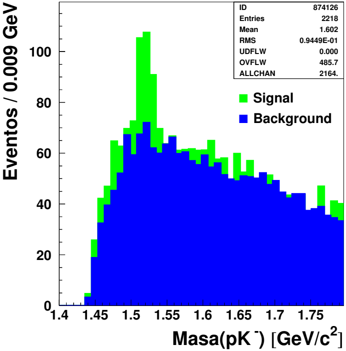
SELEX observed $\Lambda_c^+ \to \Lambda(1520) e^+ \nu$

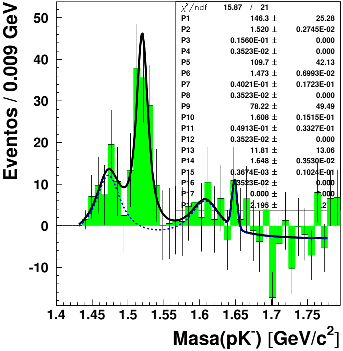
Measure $\Gamma(\Lambda_c^+ \to \Lambda(1520)e^+\nu)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$



- Use all features of SELEX: tracking, RICH, eTRD, BTRD, Pb glass
- eTRD separates e from π 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 ± 26 $\qquad$ $pK^-\pi^+$ yield: 1544 ± 34

Λ_c^+ Branching Ratios

- correct for eTRD Efficiency ($\sim 93\,\%$), relative acceptence ($\sim$ 1.2), $\Lambda(1520) \to pK^-$ BR
- $\Gamma(\Lambda_c^+ \to \Lambda(1520) e^+ \nu)/\Gamma(\Lambda_c^+ \to pK^-\pi^+) = 0.47 \pm 0.010$
  SELEX Preliminary
- $\Gamma(\Lambda_c^+ \to pK^-\pi^+)/\Gamma = 0.05 \pm 0.013$ (PDG)
  (Can this be measured well by BES or Panda?)
- $\Rightarrow (\Gamma(\Lambda e^+\nu) + \Gamma(\Lambda(1520) e^+\nu))/\Gamma = (4.5 \pm 1.3)\,\%$
- These two semileptonic modes saturate the Mark II measurement

PhD Thesis Jorge Amaro-Reyes

Cabibbo-Suppressed Weak Decay of Charm

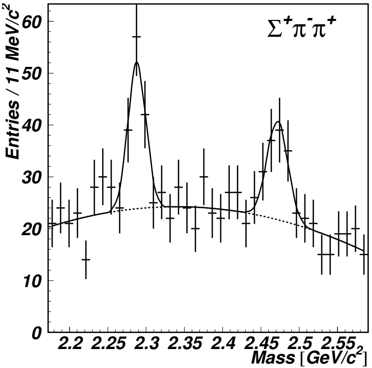
- Cabibbo-Suppressed weak decay of charm ($c \to s$ vs $c \to d$):
  Expect (phase space corrected) ratio of $\sim \tan^2 \Theta_c = 0.05$
  if rescattering effects are not important
- Results from D mesons: rescattering is important
- Need to measure as many channels as possible to understand rescattering effects

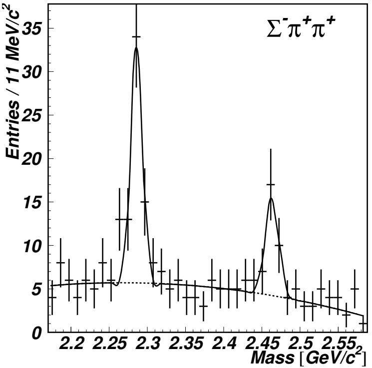
Cabibbo Suppression for Charmed Baryons

From PDG:

- Λ_c^+:
  - $\Lambda K^+/\Lambda\pi^+ = 0.047 \pm 0.009$
  - $\Sigma^+K^+\pi^-/\Sigma^+\pi^+\pi^- = 0.047 \pm 0.015$
  - $p\pi^-\pi^+/pK^-\pi^+ = 0.07 \pm 0.04$
- Ξ_c^+:
  - $pK^-\pi^+/\Sigma^+K^-\pi^+ = 0.22 \pm 0.03$
  - $\Sigma^+K^+K^-/\Sigma^+\pi^+K^- = 0.16 \pm 0.06$
- *G*enerally not close to 0.05

First Observation of $\Xi_c^+ \to \Sigma^+\pi^-\pi^+$, $\Xi_c^+ \to \Sigma^-\pi^+\pi^+$





Can cross check analysis method with Λ_c^+ modes

PhD Thesis Eric Vázquez-Jáurequi

Branching Ratio Results: PLB666 (2008) 299; arXiv:0804.2298

Branching Ratio	This Analysis	Other Measurements
$B(\Xi_c^+ \to \Sigma^+\pi^-\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	0.48 ± 0.20 $\alpha = 6.4 \pm 2.7$	–
$B(\Xi_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	0.18 ± 0.09 $\alpha = 2.5 \pm 1.2$	–
$B(\Xi_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Xi_c^+ \to \Sigma^+\pi^-\pi^+)$	0.42 ± 0.24 $\alpha = 0.43 \pm 0.25$	–
$B(\Xi_c^+ \to pK^-\pi^+)$ / $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$	0.194 ± 0.054 $\alpha = 2.6 \pm 0.7$	$0.234 \pm 0.047 \pm 0.022$ $0.20 \pm 0.04 \pm 0.02$
$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Lambda_c^+ \to pK^-\pi^+)$	0.314 ± 0.067 $\alpha = 0.30 \pm 0.07$	–
$B(\Lambda_c^+ \to \Sigma^+\pi^-\pi^+)$ / $B(\Lambda_c^+ \to pK^-\pi^+)$	0.72 ± 0.14 $\alpha = 0.68 \pm 0.14$	$0.74 \pm 0.07 \pm 0.09$ $0.54^{+0.18}_{-0.15}$
$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+)$ / $B(\Lambda_c^+ \to \Sigma^+\pi^-\pi^+)$	0.38 ± 0.10 $\alpha = 0.39 \pm 0.11$	$0.53 \pm 0.15 \pm 0.07$

What I whould have liked to talk about as well...

There are many more interesting results on strange and charm hadrons:

- Excited States of Λ_c^+, Ξ_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 $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^+ \to p D^+ K^-$
- SELEX is re-analyzing the data, with improved efficiency
- Presented $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^+ \to \Xi_c^+ \pi^- \pi^+$
- Presented $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_{cc}^{++} \to \Xi_c^+ \pi^- \pi^+ \pi^+$
- Working on determination of the Ξ_{cc} Lifetime
- Searching for Ω_{cc}^+

Conclusions

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