Charmed and Doubly Charmed Baryons
Recent Results from SELEX

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Introduction

Charm about 8-10 years ago:

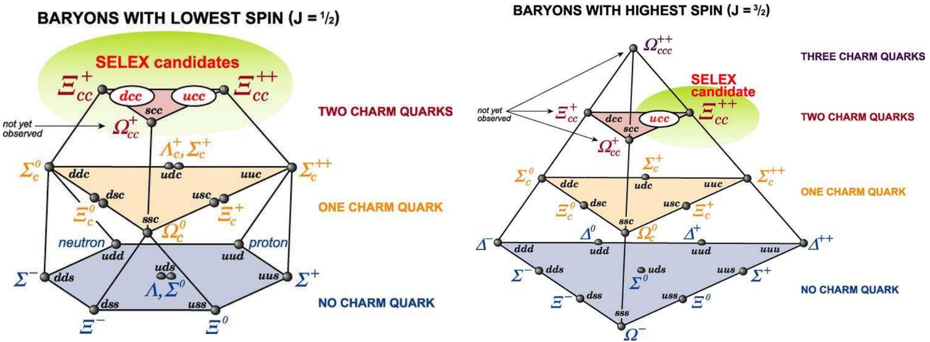
- The "Traditional" Charm Experiments: E791, FOCUS, SELEX, (WA89, WA92), CLEO, H1/ZEUS
- "Traditional" Topics: Production, Lifetime, rare decays, resonances in decay, $D^0 - \overline{D^0}$ mixing
- Small number of theory and phenomenology papers

In the last 5 years or so:

- New players: BaBar and Belle, CDF, D0 (beauty)
- New charm states: double charm baryons, hidden double charm ($J/\Psi\ c\overline{c}$), D_s^*, X (Y, Z)
- Penta-quark Euphoria
- Large number of "theory" papers: spectroscopy, production
- Shift of used words in papers: di-quark

Outline

Doubly Charmed Baryons



Model Predictions for DCB Masses

- Several Authors (Bjorken 1986, Fleck&Richard 1989, Roncaglia 1995, Ellis 2002)
- Different models (Phenomenology, Bag, Quarkonium, Lattice)
- Masses (J=1/2): $3.516 - 3.66\,\mathrm{GeV}/c^2$
- Masses (J=3/2): $3.636 - 3.81\,\mathrm{GeV}/c^2$

Overall Features

- ground states near $3.6\,\mathrm{GeV}/c^2$
- ground states Isospin=1/2 multiplets degenerate
- Hyperfine splitting around $60 - 120\,\mathrm{MeV}/c^2$
- Most predict electromagnetic hyperfine transition (but some pionic)
- Model dependent predictions for orbital and radial excitations

The SELEX Collaboration

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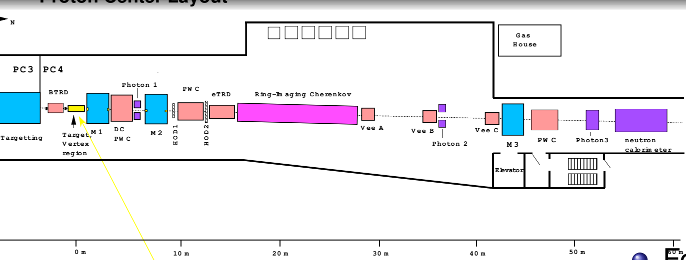
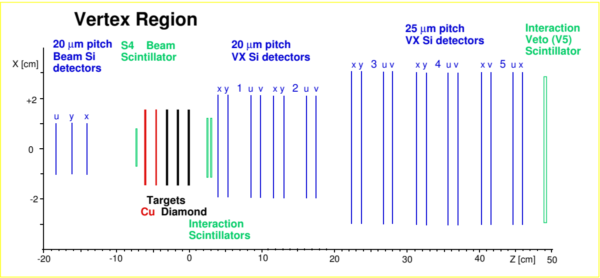
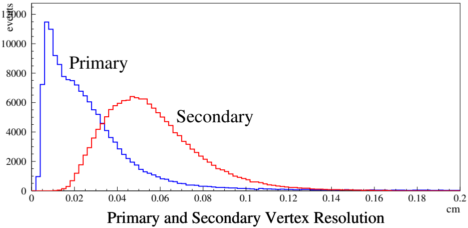
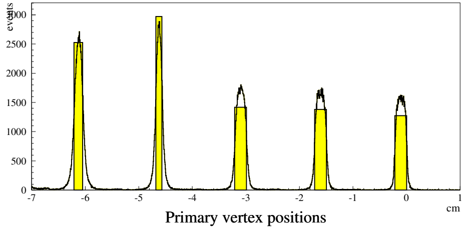




- Forward ($x_F > 0.1$) charm production
- Σ^-, $\pi^\pm$, p beam at 600 GeV/c
- RICH PID above ~ 22 GeV/c
- 20 plane Si-Vertex.
- Data taken 1996/7

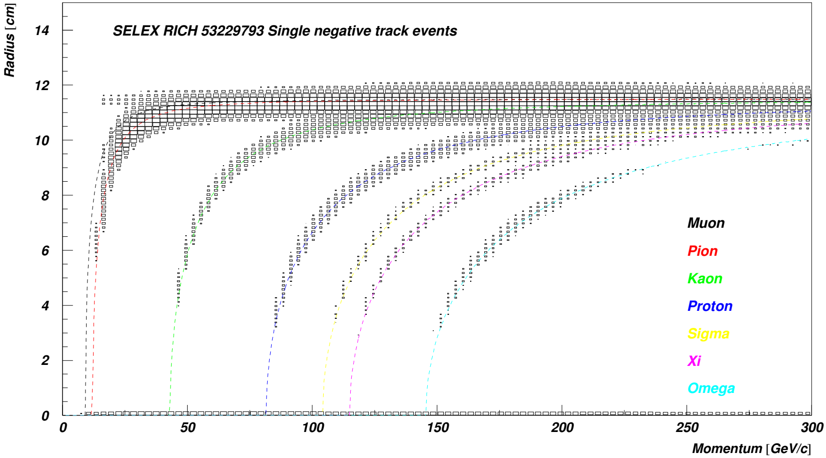
Vertex Spectrometer Performance



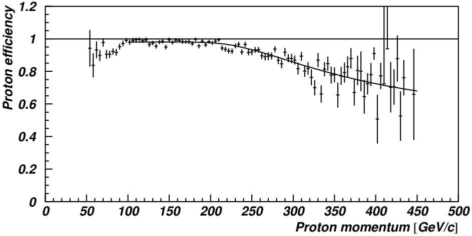


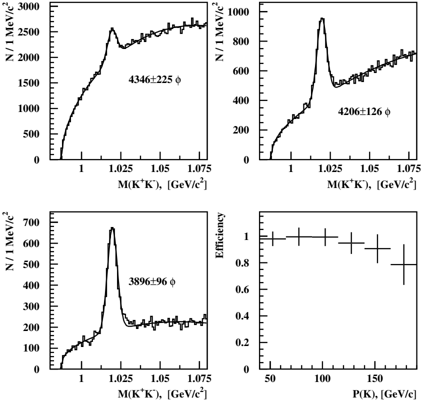
- transverse vtx resolution 8-15 μm
- 20 highly-efficient vertex planes over-determine tracks, reduce tracking confusion in high-multiplicity events
- target foils 0.8-2.2 mm thick with 1.5 cm spacing to localize primary interaction
- Lifetime resolution $\sim$ 20 fs

Ring Imaging Cherenkov Counter Performance (1)

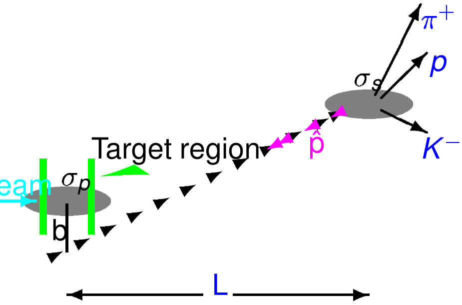


Ring Imaging Cherenkov Counter Performance (2)





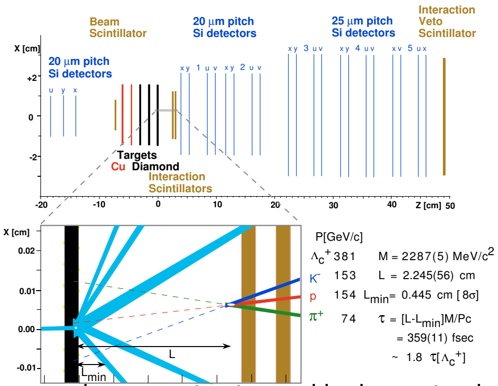
SELEX Single Charm Analysis



Charm Analysis Cuts

- Decay vertex separation significance L/σ
- Charm vector momentum points back to primary: cut on $(b/\sigma_b)^2$ (point-back cut)
- Decay vertex lies outside target material
- Proton and Kaon identified in RICH detector

SELEX Charm Selection Criteria

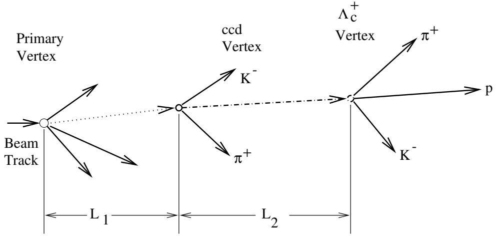


- primary vertex tagged by beam track
- secondary vertex must lie outside material

Charm Selection Cuts for single charm studies:

- secondary vertex significance:
  - $L/\sigma \geq 1$ short-lived states (Ξ_c^0, Ω_c^0)
  - $L/\sigma \geq 8$ long-lived states (Λ_c^+, D^+)
- Pointback ≤ 4 ($2\sigma_b$)
- *second*-largest miss significance among decay tracks ≥ 4.

SELEX Search Strategy for Doubly-Charmed Baryons

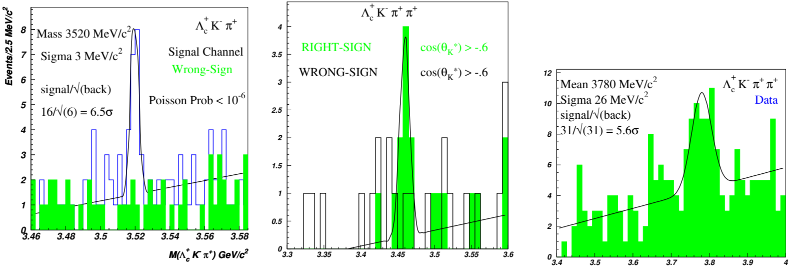


Ξ_{cc}^+ Decay Schematic

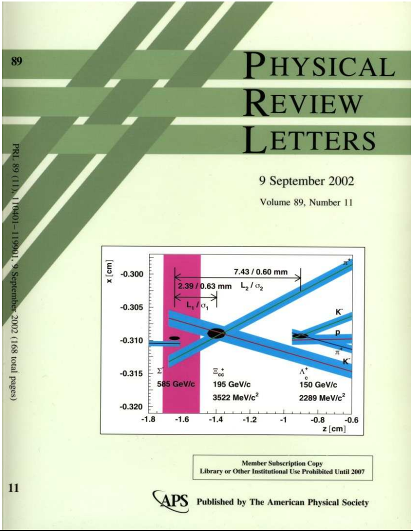
- *ccq* decays to $csqu\bar{d}$. Look for charm, strange and baryon in final state. SELEX started with $\Lambda^+_c K^- \pi^+ (\pi^+)$.
- Look for new secondary vertex between primary and Λ^+_c
- no RICH PID on new $K^- \pi^+$ tracks (too soft)
- All other cuts fixed from previous searches

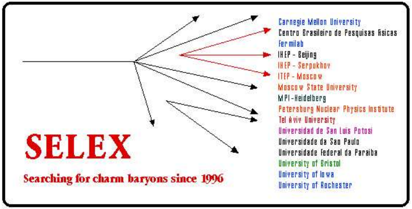
SELEX: Experimental Evidence from 2002

SELEX reported 3 significant high mass peaks



SELEX argued that these states are doubly-charmed baryons





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First Observation of the Doubly Charmed Baryon Ξ_{cc}^+

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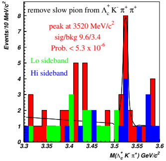
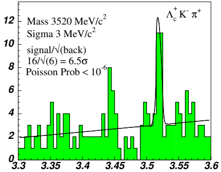
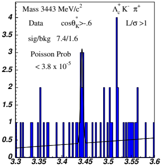
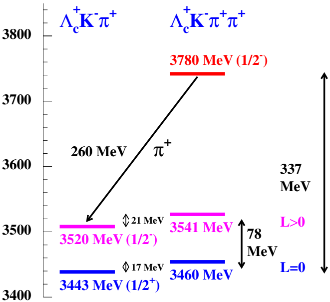
SELEX Double Charmed Baryon States – 2003

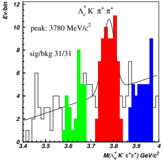


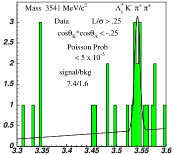


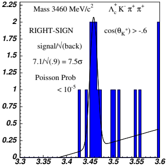


An exited state and a pair of isodoublets?









Features and Problems in Original Analysis. . .

- All Signals have very low statistics
- There is nearly no background ($\rightarrow$ 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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- 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

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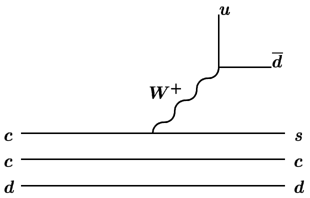

In Final State:

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

Easily accessible in SELEX:

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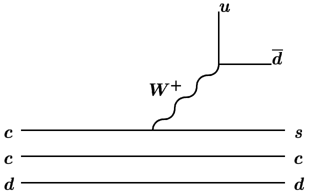

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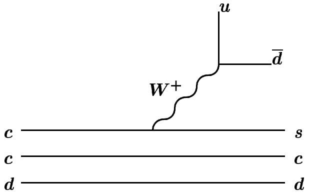

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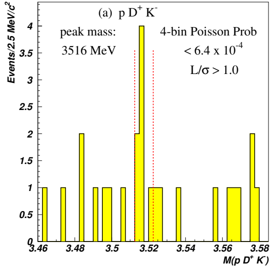
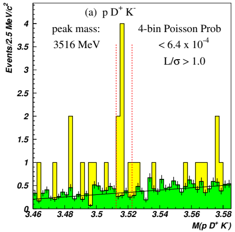
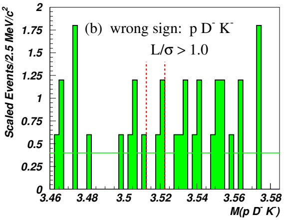
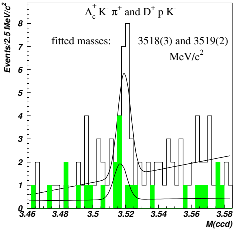
$\Xi_{cc}^+ \to pD^+K^-$ (PLB628 (2005) 18)

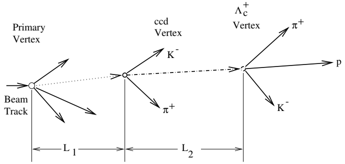








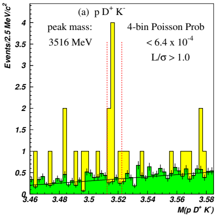
Background Determination: Event Mixing



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

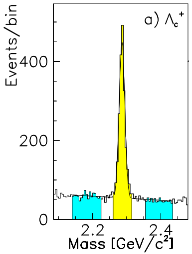
Resulting combinatoric bkgd is absolutely normalized ⇒ Bkgd shape known

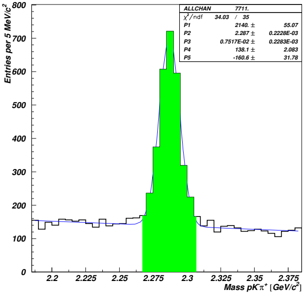


PLB628 (2005) 18

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

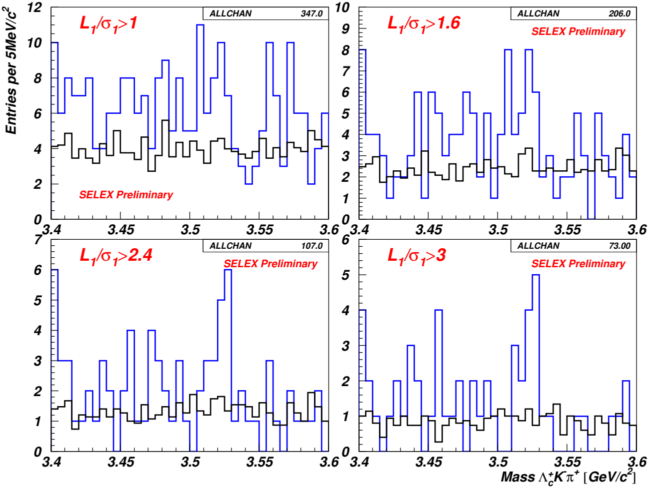
Re-analysis of full data set $\Rightarrow$ More Λ_c cands ($1630 \to 2450$)





- Refit Ξ_{cc}^{+} vertex using $\vec{p}_{\Lambda_c^+}$ together with $K^{-}\pi^{+}$ tracks
  $\Rightarrow$ Better L_1 resolution
- Use event mixing for background

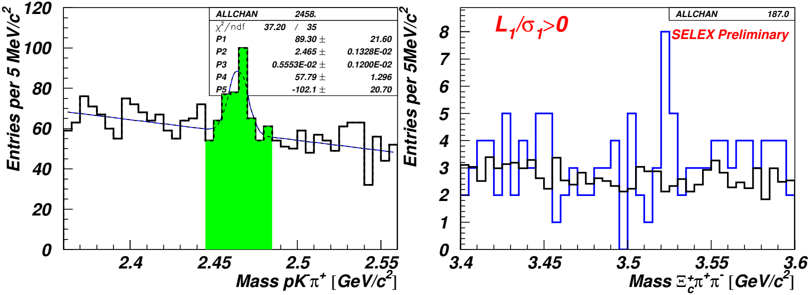
$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, $\Lambda_c^+ \to p K^- \pi^+$ – New Analysis



Features of new Analysis

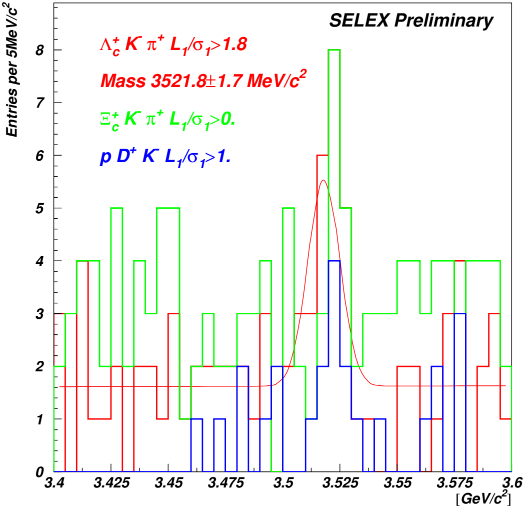
- Re-Analysis and Relaxing Cuts on Single Charm:
  - some more background, but shape is well understood from combinatoric analysis
  - more signal
- Improved sec. vertex resolution:
  - Cleaner Signals, access to other modes
  - Possibility (but challenging) to measure lifetime (is around 1 σ)

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



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

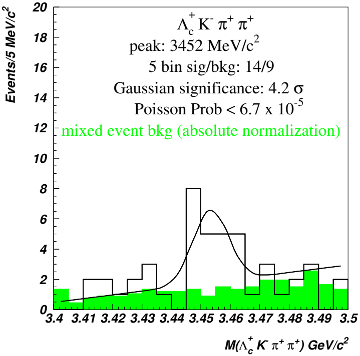
Comparing the Mass of the Three Decay Modes



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^+

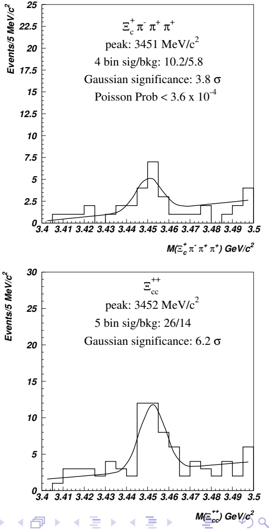
Green: Absolutely-normalized background
Gaussian with fixed width (MC)



New Ξ_{cc}^{++} at 3452!

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

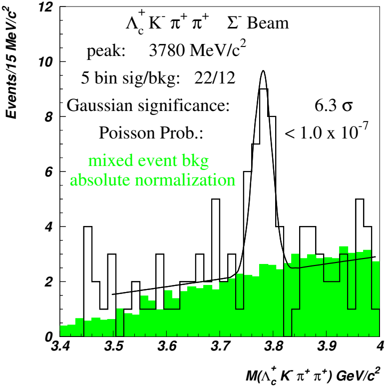
- Now look in $\Xi_c^{+}\pi^{-}\pi^{+}\pi^{+}$
- Same as before, ask for additional π^{+}
- Only use $\Xi_c^{+} \to pK^{-}\pi^{+}$



- 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



Why weakly decaying Doublet?

- If Excitation is Chromomagnetic:
  - Expect dominant E1 Dipole Transition (like in $D^\star \to D\gamma$)
  - Weak decay of Chromomagnetic Excited State Suppressed by $\sim$ 6 orders of magnitude
- Bardeen, Eichten and Hill: spectroscopy of cc compared to $c\bar{s}$ (PRD68 054024, hep-ph/0305049)

$$\text{Ground State:} \quad J^P = \frac{1}{2}^+ \left[c\uparrow\ c\uparrow\ L=0, J^P = 1^+\right] q\downarrow$$

$$\text{Excited State:} \quad J^P = \frac{1}{2}^- \left[c\uparrow\ c\downarrow\ L=1, J^P = 1^-\right] q\downarrow$$

- First excited state is $L = 1$ of heavy (cc) di-quark
- In at least one version of the model splitting is consistent with observed 78 MeV$/c^2$
- First EM transition is M2.

Doubly Charmed Baryons Production

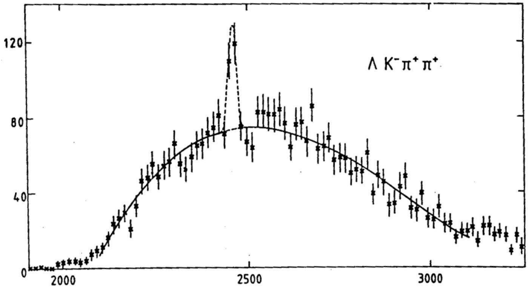
- SELEX: Dominantly produced by baryon beam.
- E791 has looked in 250 GeV/c π^{-} production
  no signal
- FOCUS looked in 250 GeV/c photo-production
  no signal
- BaBar looked:
  no signal
- Hadro-Production Theory/Phenomenology:
  - Most just assume independent production
  - But: Are instrinsic components important?

My Personal List of Mysteries in Charm and Beauty

Mysteries: Observations which have no commenly accepted explanation within the usually accepted theory.

Charm Mysteries (1) – Discovery of the Ξ_c^+

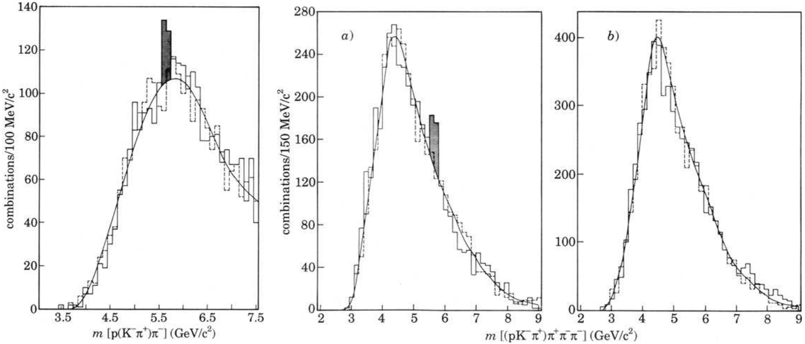
CERN WA62 (1983)



- Beam: 135 GeV/c Σ^-
- 3 weeks of running
- no silicon detectors
- 83 events $\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$
- measured Ξ_c^+ lifetime correctly

Beauty Mysteries – Λ_b in ISR

CERN-ISR R422 (Split Field Magnet), 1988/1991

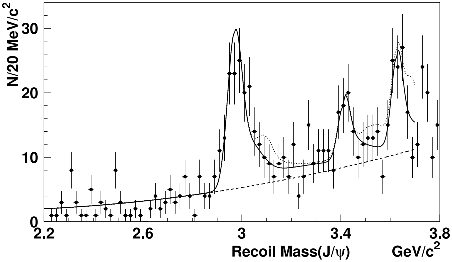


$\Lambda_b^0 \to p D^0 \pi^-$

$\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$

Il Nuovo Cimento 104, 1787

(Double)-Charm Mysteries (2) – $J/\Psi\,\eta_c$ Production

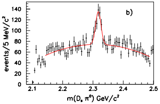


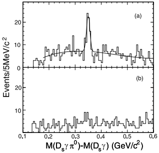
- Belle observed high double charm production in $e^+e^- \to J/\Psi\, c\bar{c}$, $e^+e^- \to J/\Psi\, \eta_c$ (PRL 89 (2002) 142001)
- At publication, factor x40 higher cross section than theory.
- BaBar confirms a few years later
- Belle arXiv:0901.2775: still x10 higher

Charm Mysteries (3) – Narrow D_s Resonances

BaBar, CLEO, Belle (2003)

$D^{\star}_{sJ}(2315) \to D_s\pi^0$,
$D_{sJ}(2463) \to D_s\gamma\pi^0$

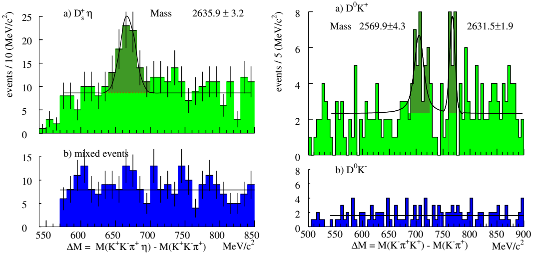




PRL90 (hep-ex/0304021);
PRD68;
PRL91 (hep-ex/0308019)

SELEX 2004

$D^{\star}_{sJ}(2632) \to D_s^+\eta$ and D^0K^+



PRL 93, 242001 (hep-ex/0406045)

Charm Mysteries (4) – X, Y, Z

- Charmonium-like states
- Are they Charmonium? Are they Tetra-quark states?
- Do the charged states (observed by Belle) really exist?

Baryon Mysteries – “Missing” Resonances

- Experiments at Jefferson Lab (and other places) search for Baryon Resonances
- About half the states predicted by $SU(6)_{\mathrm{SF}} \times SO(3)$ are missing
- $SU(6)_{\mathrm{SF}} \times SO(3)$ is non-relativistic,
  spin and angular momentum are separate.
- Other schemes predicting the correct number of resonances exist
  (e.g. $SU(3)_{\mathrm{F}} \times SO(3,1)$, $SO(3,1)$ is Lorentz-Group)

Hadro–Production Mysteries – Cronin Effect

- p_t distributions depend on particle type and target material
- First Observations:
    - Cronin, Frisch, Shochet, et al.: *Production of Hadrons with Large Transverse Momentum at 200-GeV and 300-GeV* Phys.Rev.Lett.31:1426-1429,1973.
    - Kluberg, et al.: *Atomic Number Dependence of Large Transverse Momentum Hadron Production by Protons.* Phys.Rev.Lett.38:670-673,1977.
- Another interpretation: $\alpha = \alpha(x_F, p_t)$
- Consequences for charm signature of Quark-Gluon-Plasma
- Not enough experimental data available over full range of kinematic variables

Other SELEX Charm Results

- Hadro-Production of Charm
- Cabibbo-Suppressed Ξ_c^+ Decays
- Λ_c^+ Semi-leptonic Decay

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 and Cosmics

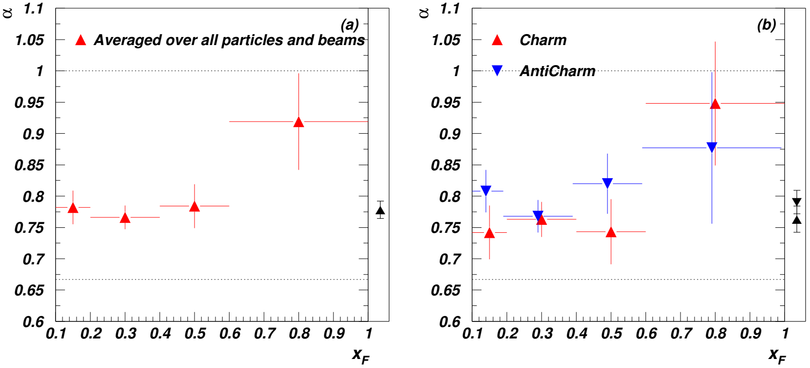
Hadro-Production of Charm in SELEX

- SELEX has charm signals with decent statistics in 14 particles and modes, in several x_F and p_t bins.
- D^+, D^0, D_s^+, $D^+(2010)$, Λ_c^+, and charge-conjugate
- 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

PhD Thesis E. Alejandro Blanco-Covarrubias

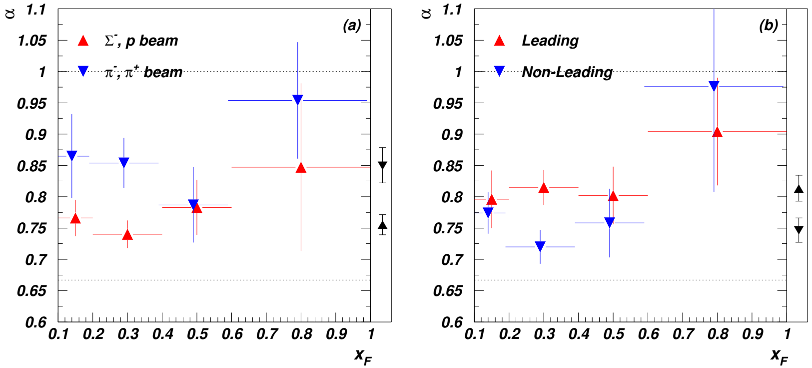
submitted to EPJC, arXiv:0902.0355 [hep-ex]

Hadro-Production of Charm (cont.)



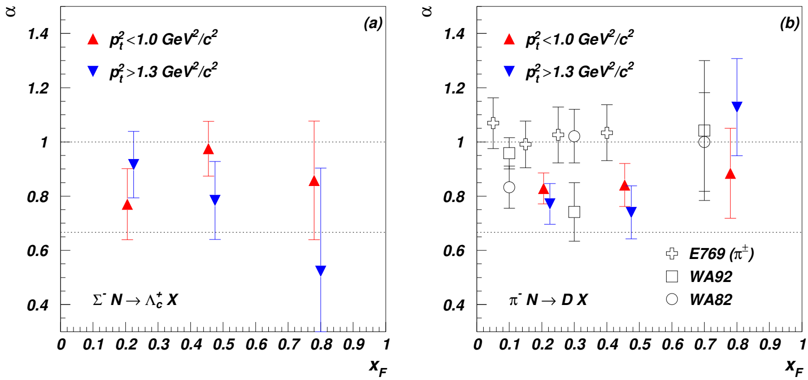
No difference when separating in charm and anti-charm final states

Hadro-Production of Charm (cont.)



3 σ difference in production by baryon and meson beams
2.3 σ difference when separating in leading and non-leading final states

Hadro-Production of Charm (cont.)



No difference for low/high p_t^2 production

Cabibbo-Suppressed Weak Decay of Charm

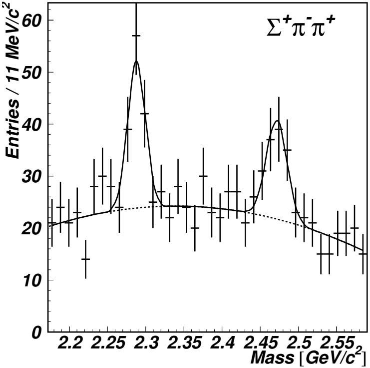
- Cabibbo-Suppressed weak decay of charm ($c \to s$ vs $c \to d$):
  Expect (phase space corrected) ratio of $\sim \tan^2 \Theta_c = 0.05$
  if rescattering effects are not important
- Results from *D* mesons: rescattering is important
- Need to measure as many channels as possible to understand rescattering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

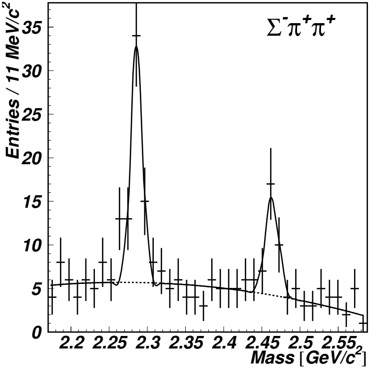
Cabibbo Suppression for Charmed Baryons

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 $\alpha = 0.39 \pm 0.11$	$0.53 \pm 0.15 \pm 0.07$

Λ_c^+ Semi-leptonic Decay

History:

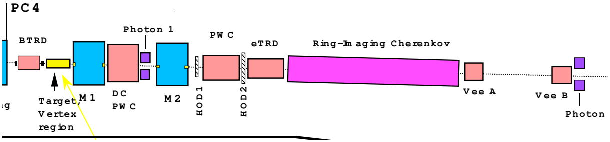
- Mark II (1982): $\Gamma(\Lambda_c^+ \to e^+ X)/\Gamma = (4.5 \pm 1.7)\,\%$
- CLEO (1994): $\Gamma(\Lambda_c^+ \to \Lambda e^+ \nu)/\Gamma(pK\pi) = 0.43 \pm 0.08$
- PDG: $\Gamma(\Lambda_c^+ \to pK^-\pi^+)/\Gamma = 5\,\%$

What are the rest of the modes?

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

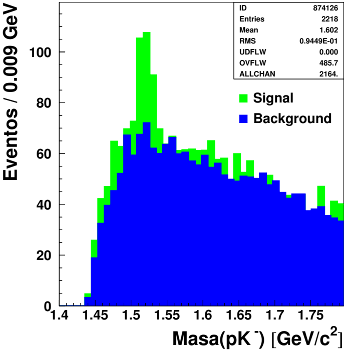
SELEX observed $\Lambda_c^+ \to \Lambda(1520) e^+ \nu$

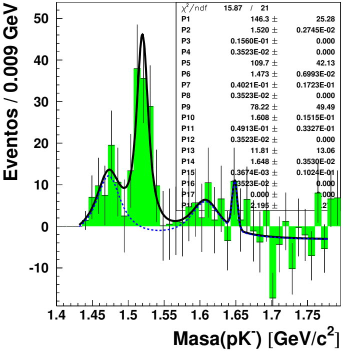
Measure $\Gamma(\Lambda_c^+ \to \Lambda(1520)e^+\nu)/\Gamma(\Lambda_c^+ \to pK^-\pi^+)$



- 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 $pK^-\pi^+$ yield: 1544 ± 34

Λ_c^+ Branching Ratios

- correct for eTRD Efficiency ($\sim 93\,\%$), relative acceptence (~ 1.2), $\Lambda(1520) \to pK^-$ BR
- $\Gamma(\Lambda_c^+ \to \Lambda(1520)e^+\nu)/\Gamma(\Lambda_c^+ \to pK^-\pi^+) = 0.47 \pm 0.10$
  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

Conclusions – Double Charm Baryons

- SELEX is still the only experiment observing Double Charm Baryons (until LHCb trigger upgrade?)
- Published results on $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^+ \to pD^+ K^-$
- 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...

My Personal Wishlist for Theory (and Phenomen.)

- What is the correct potential (model) for heavy-light systems?
- What is the correct potential in charmonium?
- How to transfer this to double-heavy baryons? ($c\bar{c} \rightarrow cc$)
- Make a good pre(post)diction of the mass of the Ξ_{cc}
- What is the mass difference between Ξ_{cc}^{+} and Ξ_{cc}^{++} (including sign!)?
- What are the quantum numbers of the lowest exited state of the Ξ_{cc}?

- In this field, Experiments are Ahead!