Doubly charmed baryon results from SELEX

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Introduction

Charm about 15 years ago:

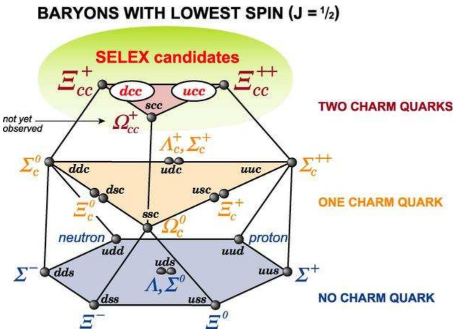
- The "Traditional" Charm Experiments: E791, FOCUS, SELEX, (WA89, WA92), CLEO, H1/ZEUS
- "Traditional" Topics: Production, Lifetime, rare decays, resonances in decay, $D^0 - \overline{D}^0$ mixing
- Small number of theory and phenomenology papers

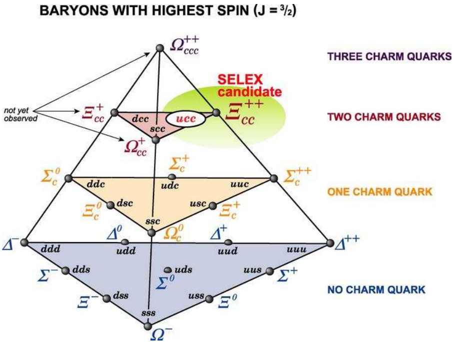
In the last 10 years or so:

- New players: BaBar and Belle, CDF, D0 (beauty), LHCb, Atlas
- 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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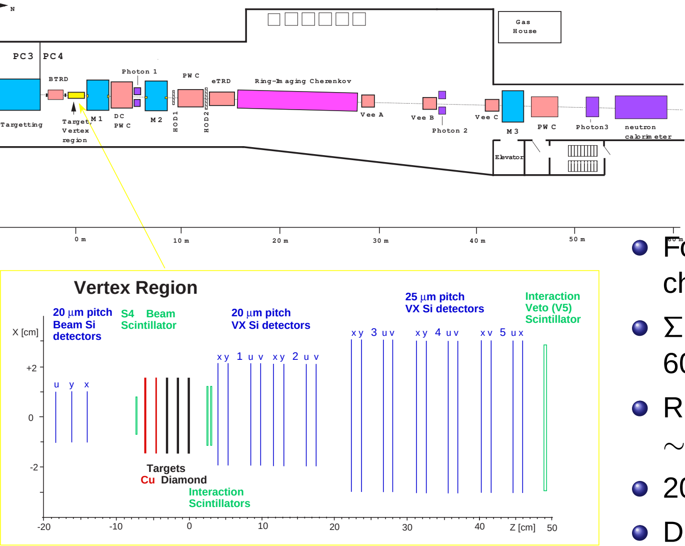
Selex (E781)

Proton Center Layout

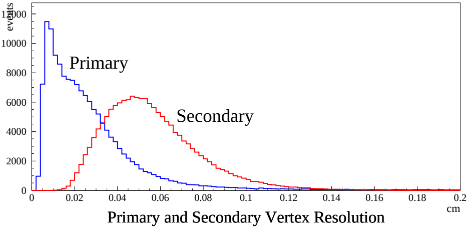


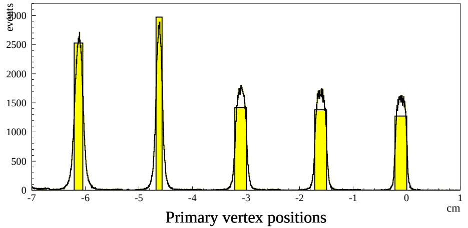
- Forward ($x_F > 0.1$) charm production
- Σ^-, $\pi^\pm$, p beam at $600\,\mathrm{GeV}/c$
- RICH PID above $\sim 22\,\mathrm{GeV}/c$
- 20 plane Si-Vertex.
- Data taken 1996/7

Hyperon Beam

- 800 GeV/c protons from Tevatron
- $\sim$ 40 cm long Be-Target ($\sim$ 1 Interaction Length)
- $\sim$ 7.3 m, $B = 3.5$ T Magnet with Tungsten filling
- curved slit with $\sim$ 1.5 mm opening at thinnest point
  650 GeV/c nominal, 610 GeV/c mean
- Beam composition: neg 50/50 Σ^{-}/π^{-}, pos 92/8 p/π^{+}
- Tagging with a TRD
- Rates: 10^{12} Protons per 20 sec spill, $5 \cdot 10^{5}$/sec at charm target

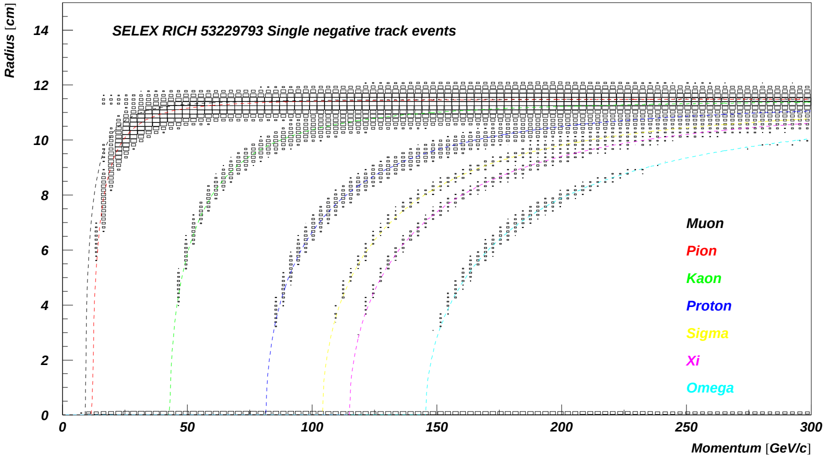
Vertex Spectrometer Performance



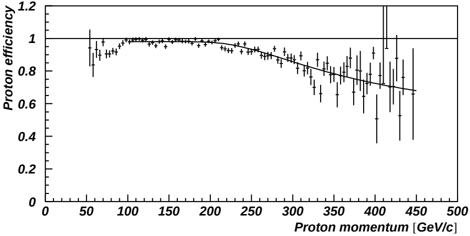


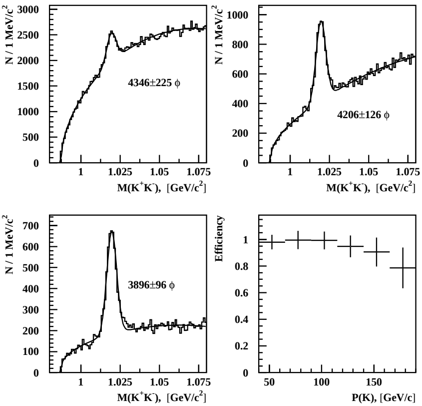
- transverse vtx resolution 8-15 μm
- 20 highly-efficient vertex planes over-determine tracks, reduce tracking confusion in high-multiplicity events
- target foils 0.8-2.2 mm thick with 1.5 cm spacing to localize primary interaction
- Lifetime resolution 20 – 40 fs depending on particle/mode

Ring Imaging Cherenkov Counter Performance (1)

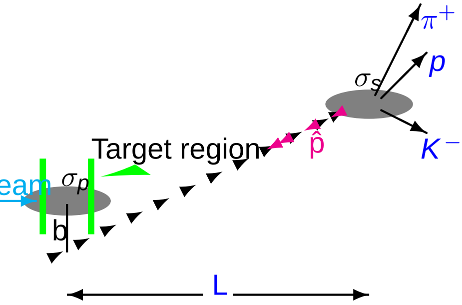


Ring Imaging Cherenkov Counter Performance (2)





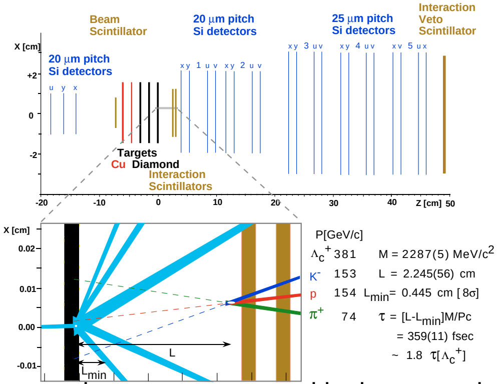
SELEX Single Charm Analysis



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

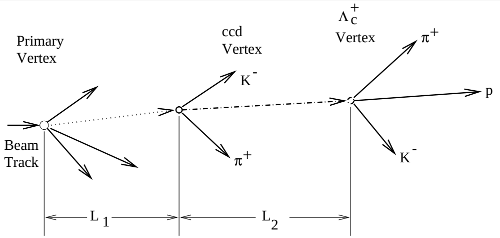


- primary vertex tagged by beam track
- secondary vertex must lie outside material

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

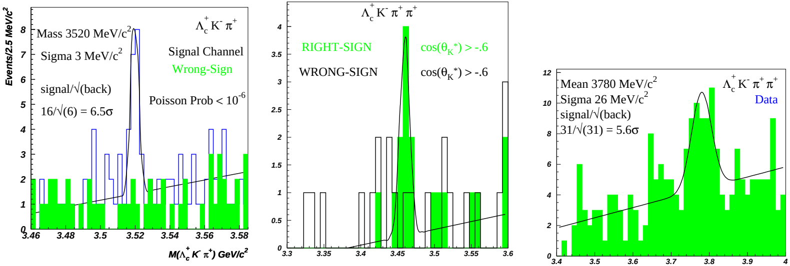


Ξ_{cc}^+ Decay Schematic

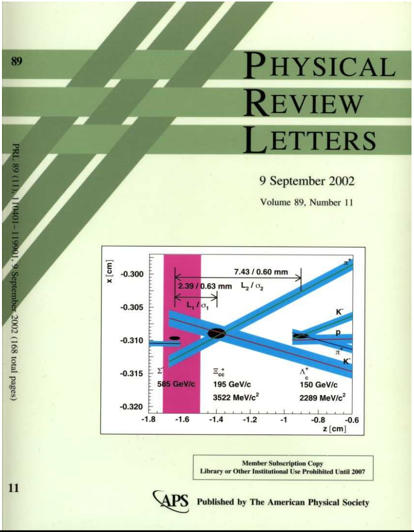
- *ccq* decays to $csqu\bar{d}$. Look for charm, strange and baryon in final state. SELEX started with $\Lambda_c^+ K^- \pi^+ (\pi^+)$.
- Look for new secondary vertex between primary and Λ_c^+
- no RICH PID on new $K^- \pi^+$ tracks (too soft)
- All other cuts fixed from previous searches

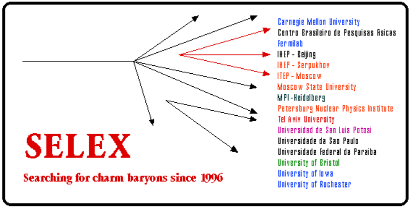
SELEX: Experimental Evidence from 2002

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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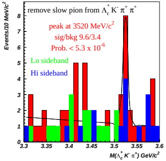
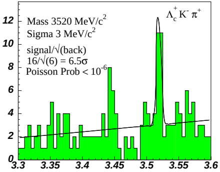
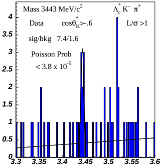
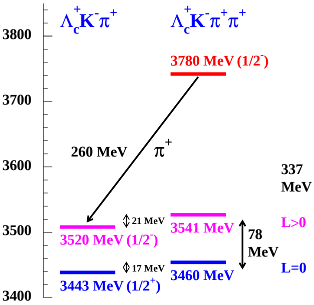
SELEX Double Charmed Baryon States – 2003

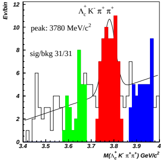


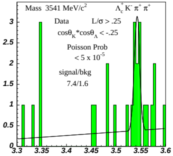


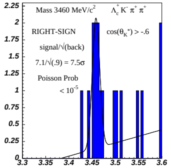


An exited state and a pair of isodoublets?









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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... 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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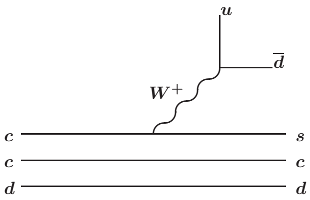
Other Decay Modes of Double Charm Baryons

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:

$\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$
$\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}\pi^{-}$
$\Xi_{cc}^{+} \to pD^{+}K^{-}$
$\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$

$\Xi_{cc}^{++} \to \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$
$\Xi_{cc}^{++} \to pD^{+}K^{-}\pi^{+}$ (?)
$\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$
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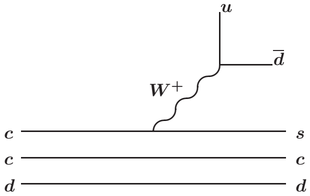

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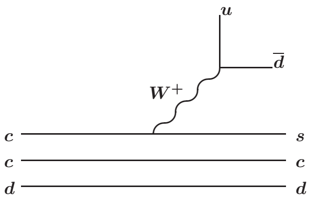

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$\Omega_{cc}^{+} \to \Xi_c^{+}K^{-}\pi^{+}$
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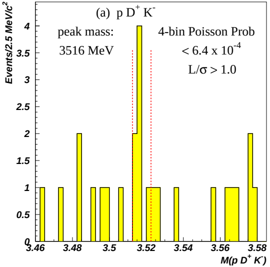
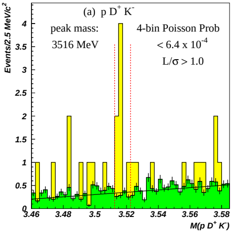
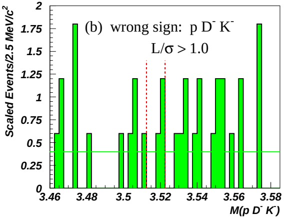
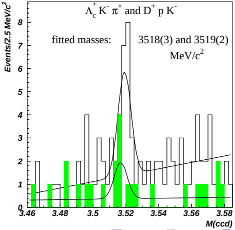
$\Xi_{cc}^+ \to pD^+K^-$ (PLB628 (2005) 18)

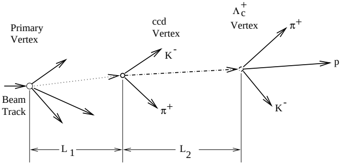








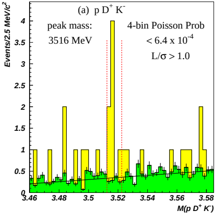
Background Determination: Event Mixing



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



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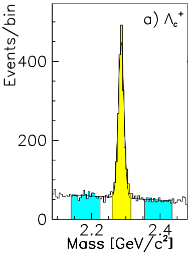
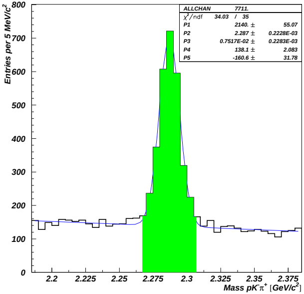
$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ – New Analysis

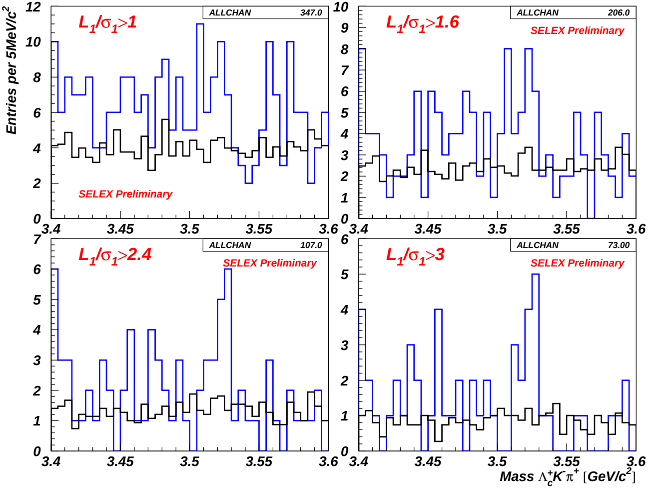
Re-analysis of full data set $\Rightarrow$ More Λ_c cands (1630 $\to$ 2450)





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

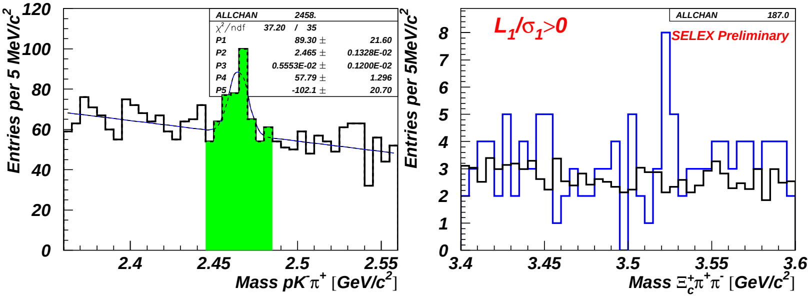
$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$, $\Lambda_c^+ \to p K^- \pi^+$ – New Analysis



Features of new Analysis

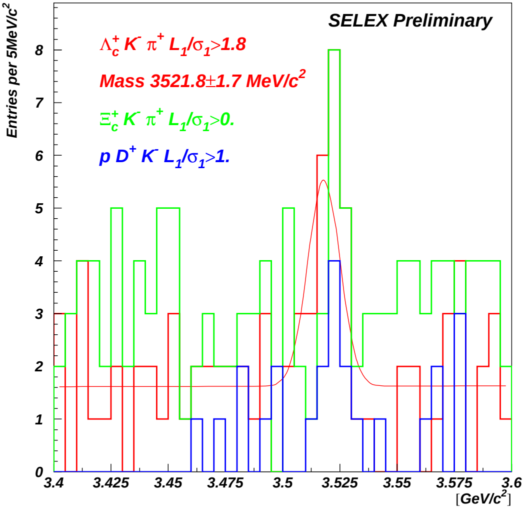
- Re-Analysis and Relaxing Cuts on Single Charm:
  - some more background, but shape is well understood from combinatoric analysis
  - more signal
- Improved sec. vertex resolution:
  - Cleaner Signals, access to other modes
  - Possibility (but challenging) to measure lifetime (is around 1 σ)

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



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

Comparing the Mass of the Three Decay Modes

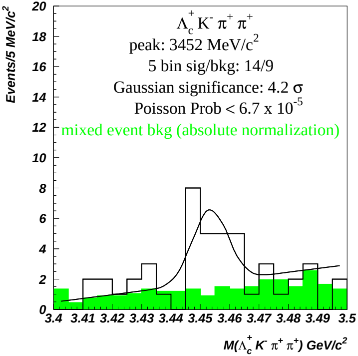


Observation of $\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$

- 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

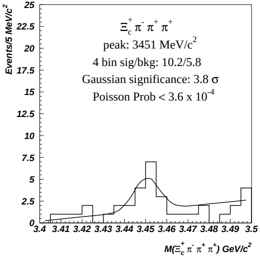
Gaussian with fixed width (MC)



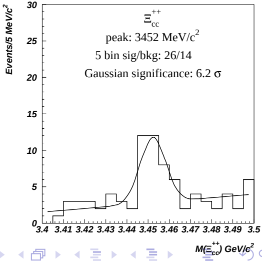
New Ξ_{cc}^{++} at 3452!

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 $\Xi_c^{+} \to pK^{-}\pi^{+}$

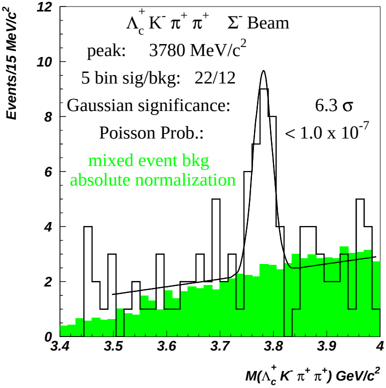


- Add data from both modes
- Significance 6.5 σ
- Mixed event background describes sidebands



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

- 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 M1 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

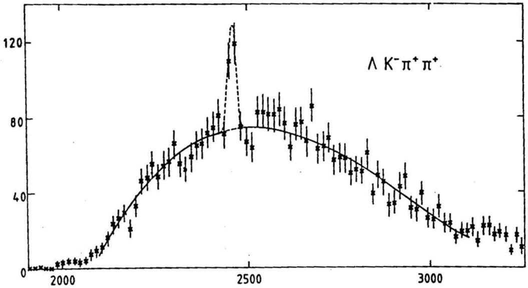
- SELEX: Dominantly produced by baryon beam.
- E791 has looked in 250 GeV/c π^- production
  no signal
- FOCUS looked in 250 GeV/c photo-production
  no signal
- BaBar looked:
  no signal
- Waiting for LHCb upgrade. . . or *After*?
- Hadro-Production Theory/Phenomenology:
  - Most just assume independent 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)

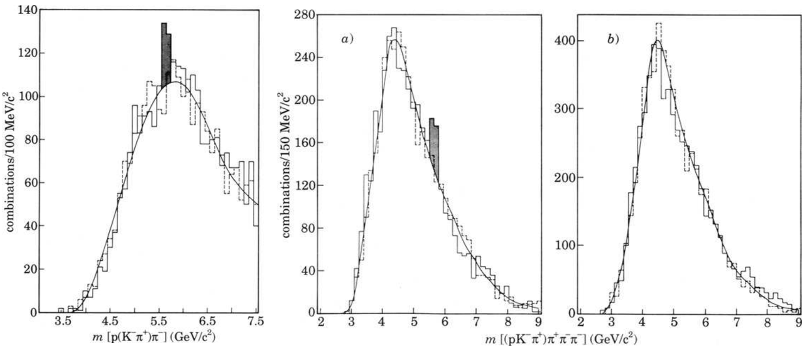


- Beam: 135 GeV/c Σ^-
- 3 weeks of running
- no silicon detectors

- 83 events $\Xi_c^+ \rightarrow \Lambda K^- \pi^+ \pi^+$
- measured Ξ_c^+ lifetime correctly

Beauty Mysteries – Λ_b at ISR

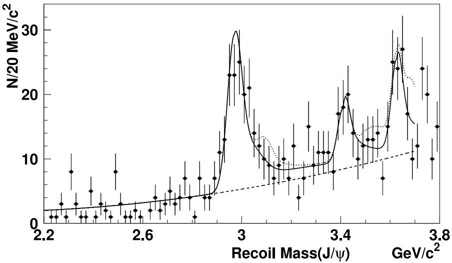
CERN-ISR R422 (Split Field Magnet), 1988/1991



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

Il Nuovo Cimento 104, 1787

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

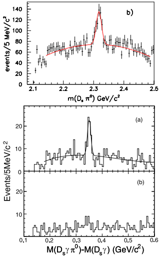


- Belle observed high double charm production in $e^+e^- \to J/\Psi\, c\bar{c}$, $e^+e^- \to J/\Psi\,\eta_c$ (PRL 89 (2002) 142001)
- At publication, $\times 40$ higher cross section than theory
- BaBar confirms a few years later
- Today still x10 higher
- From Vato: In LHCb double-J/Ψ also not understood

Charm Mysteries (3) – Narrow D_s Resonances

BaBar, CLEO, Belle (2003)

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

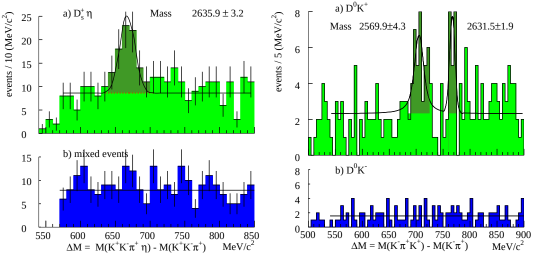


PRL90 (hep-ex/0304021); PRD68;

PRL91 (hep-ex/0308019)

SELEX 2004

$D^{\star}_{sJ}(2632) \rightarrow D_s^+\eta$ 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)

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

Ongoing Analyses in SELEX:

- 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 Theorists and Phenomenologists

- 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}?
- I do not care how you calculate it (HQET, Lattice, . . .), JUST DO IT
- In this field, Experiments are Ahead!