High Mass States in SELEX
Have Doubly-charmed Baryons Been Discovered?

Fermilab Wine and Cheese
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Outline

- (very!)Brief Theory Review
- Results from Previous Experiments
- Selex Preview
- Selex Single-Charm Baryon Review
- Observation of High Mass States
- Are These States Double-Charm Baryons?

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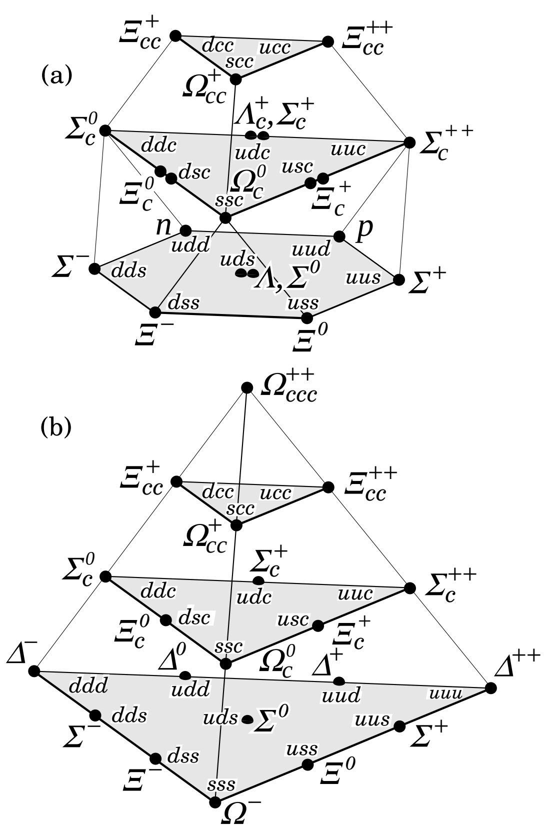
Flavor-Independent QCD Demands Double-Charm Baryons



SU(4) Baryon Multiplets

- Broken SU(4) provides accurate classification of baryon states.
- All predicted states with $N_{ch} \leq 1$ have been observed.
- Double- and Triple-Charm Baryons *must* exist.
- Characteristics $\sim$ charm meson spectra
  - ccq potential for cc in $\overline{\{3\}}$ state is 1/2 $\bar{c}$q potential
  - cc system in HQET approximation provides static color source to bind q, analogous to D-meson system.
  - finite m_c leads to 3-body effects in binding

Many Models, Many Predictions

author	year	model	$\Xi_{cc}(J = 3/2)$	$\Xi_{cc}(J = 1/2)$
Bjorken	1986	phenom	3.70 GeV/c^2	3.64 GeV/c^2
Fleck & Richard	1989	bag	3.636	3.516
Fleck & Richard	1989	quarkonium	3.741	3.613
Roncaglia *et al.*	1995	Feynmann/Hellman	3.81	3.66
Ellis	2002	phenom	3.711	3.651

Sampling of ccq mass predictions

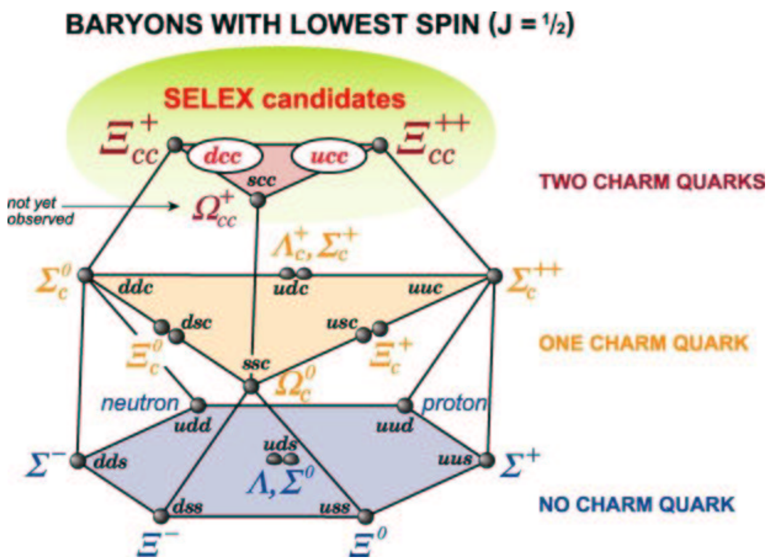
Overall features of models:

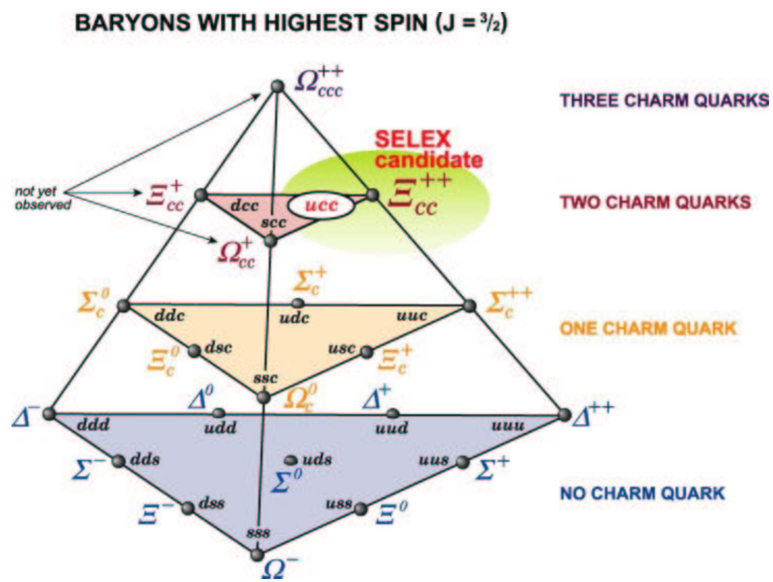
- ground state near 3.6 GeV/c^2
- hyperfine splitting around 60-120 MeV/c^2

- some models predict pionic transitions for $3/2 \rightarrow 1/2$
- most potential model calculations based on non-charmed decuplet-octet splits predict only electromagnetic transitions.
- Model-dependent predictions for orbital, radial excitations

Some Nomenclature

In this talk we replace PDG names by suggestive labels.





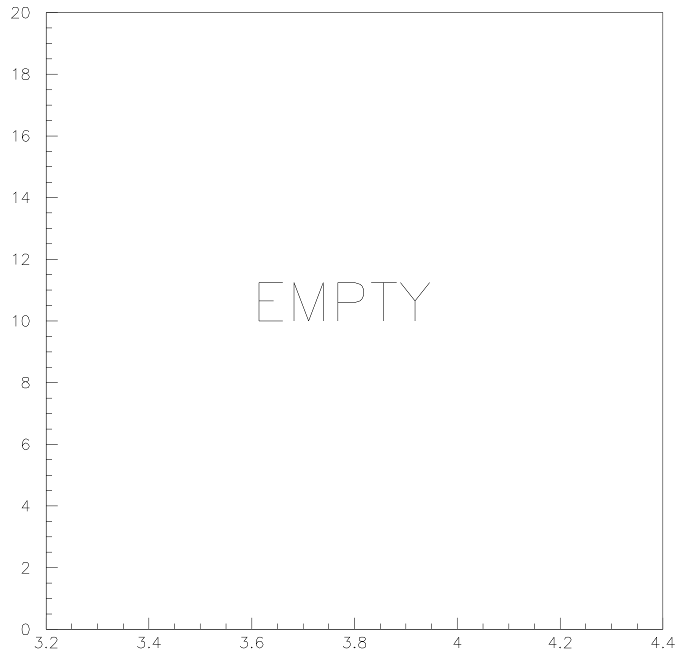
- Ξ_{cc}^{++}(J=1/2) $\equiv$ ccu^{++}
  decay: ccu$^{++} \rightarrow$ K$^-\pi^+\pi^+\Lambda_c^+$

- Ξ_{cc}^{+}(J=1/2) $\equiv$ ccd^{+}
  decay: ccd$^{+} \rightarrow$ K$^-\pi^+\Lambda_c^+$

- Ξ_{cc}^{++}(J=3/2) $\equiv$ ccu^{*++}

- decays :
  ccu$^{*++} \rightarrow$ K$^-\pi^+\pi^+\Lambda_c^+$
  and ccu$^{*++} \rightarrow$ ccd$^+\pi^+$

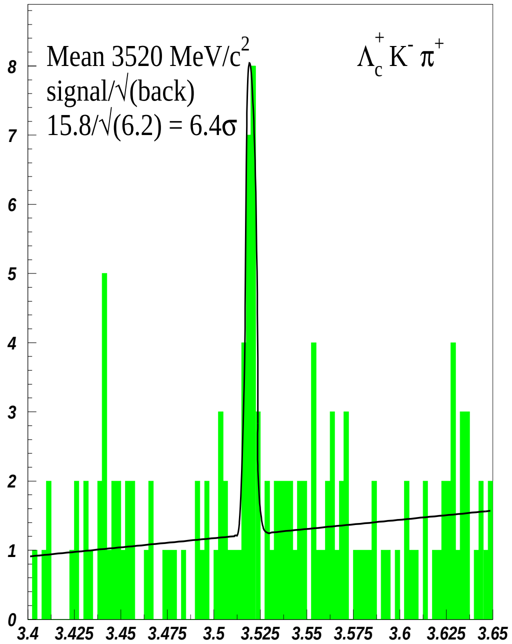
Previous Experimental Evidence



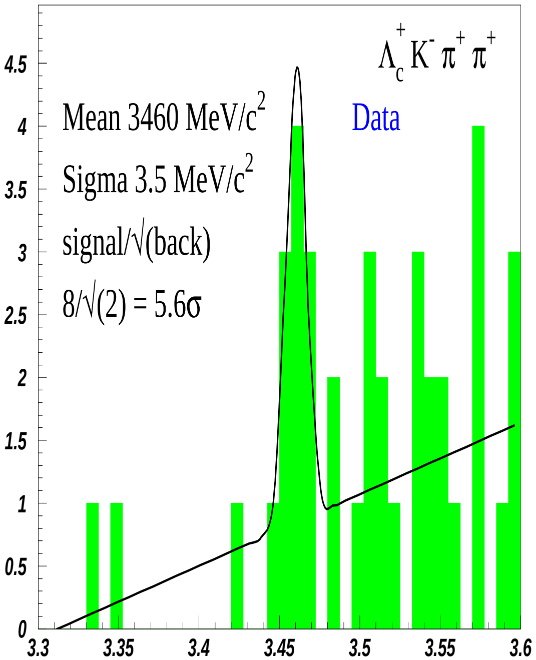
Experimental Evidence Today - a Preview

Selex reports 3 significant high-mass peaks

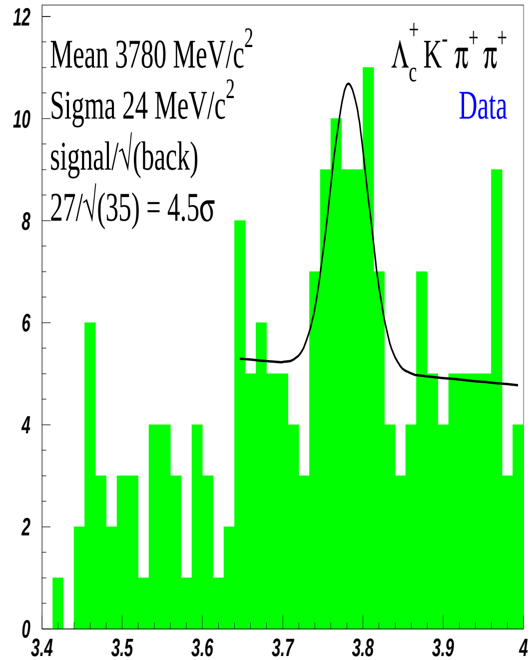
ccd$^+$



ccu^{++}



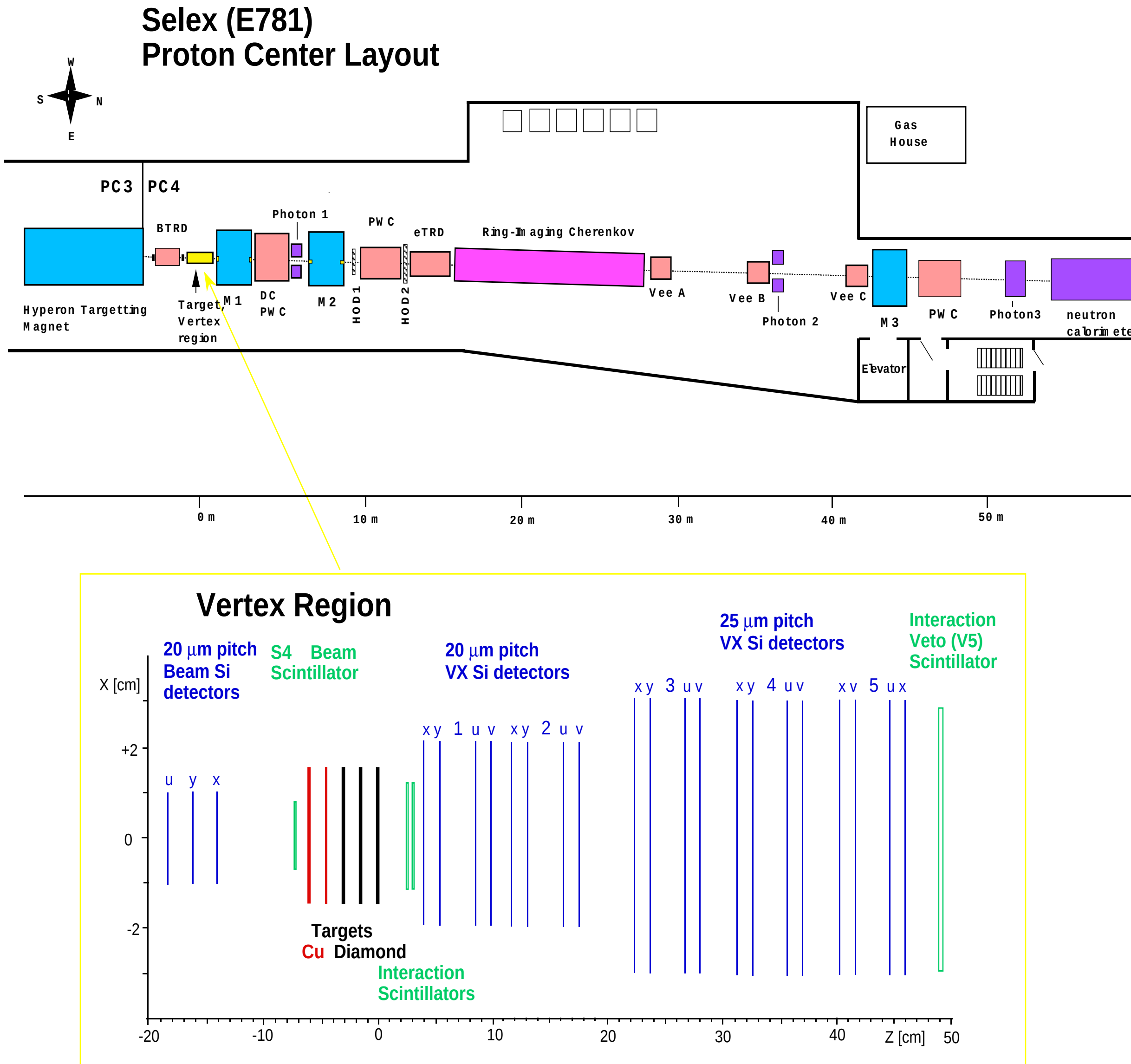
ccu^{*++}



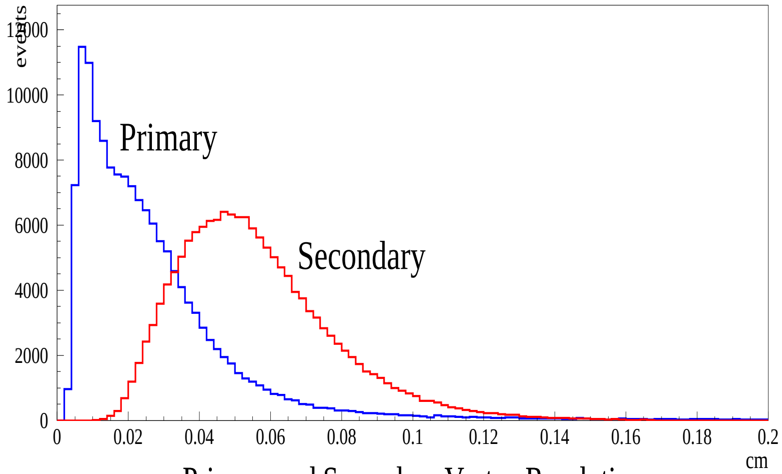
We will argue that these states are doubly-charmed baryons.

SELEX Apparatus Features

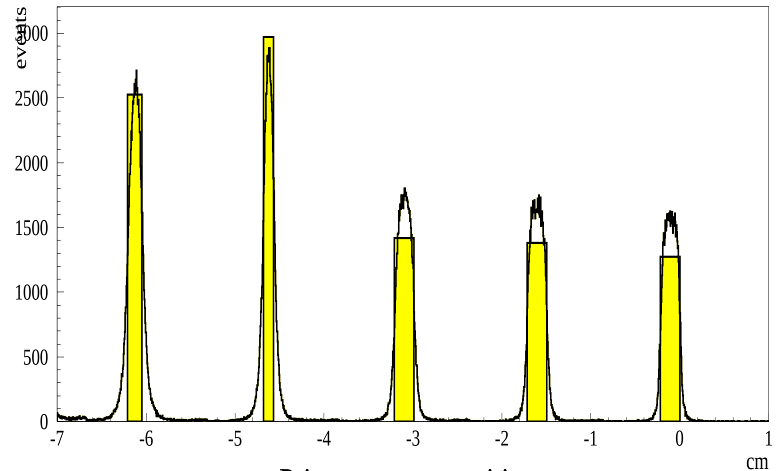
- Forward production
- π, Σ^-, p beams
- typical Lorentz Boost $\sim$ 100
- RICH identification above 25 GeV/c



Vertex Spectrometer Performance



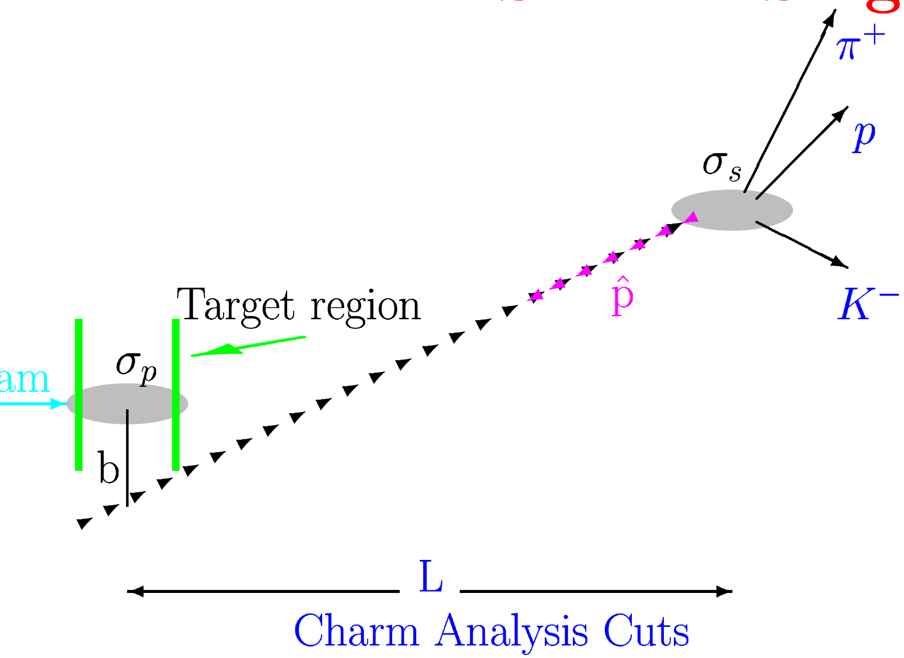
Primary and Secondary Vertex Resolution

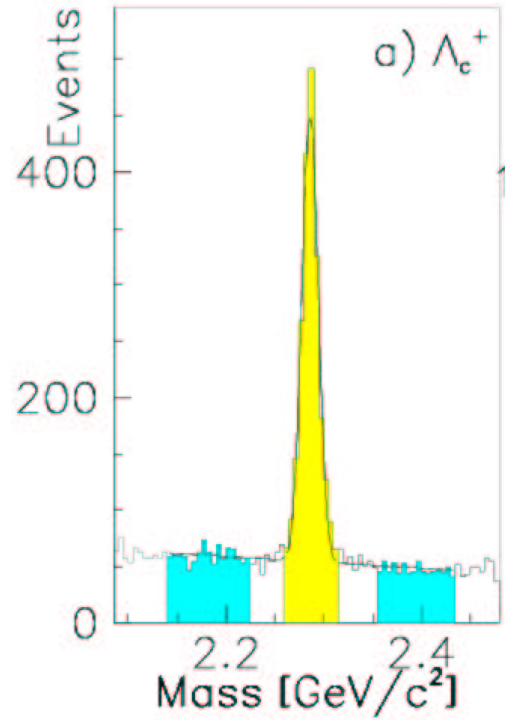


Primary vertex positions

- transverse vtx resolution 8-15 μm
- 20 highly-efficient vertex planes overdetermine tracks, reduce tracking confusion in high-multiplicity events
- target foils 0.8-2.2 mm thick with 1.5 cm period to localize primary int

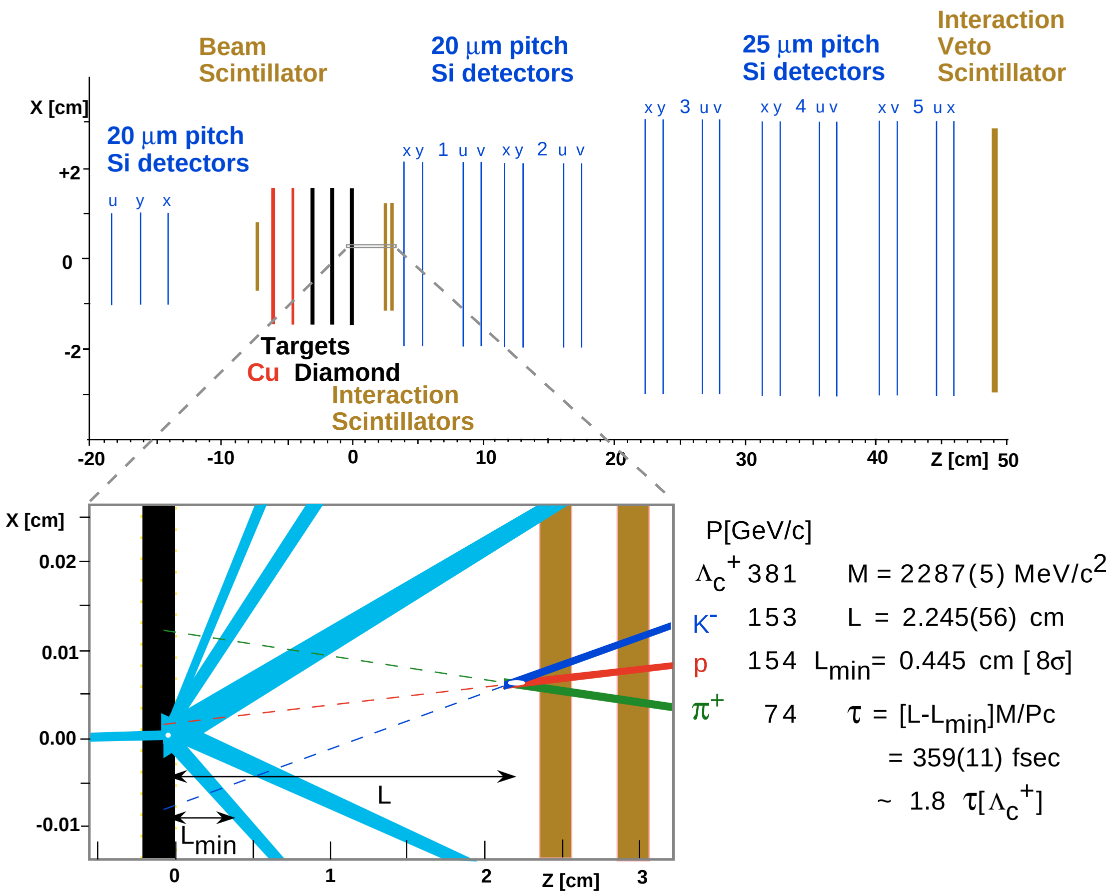
SELEX Single Charm Analysis





- 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 (space cut)
- $\Lambda_c^+ \to pK^-\pi^+$ sample used to search for double charm

SELEX Charm Selection Criteria



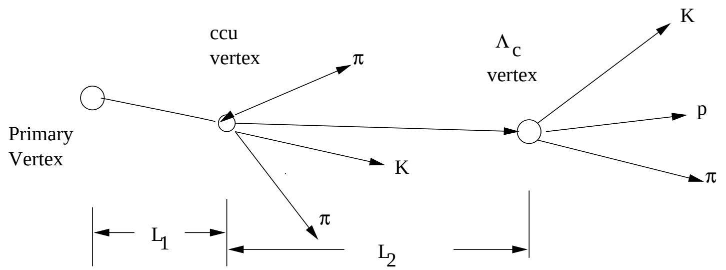
Λ_c^+ event

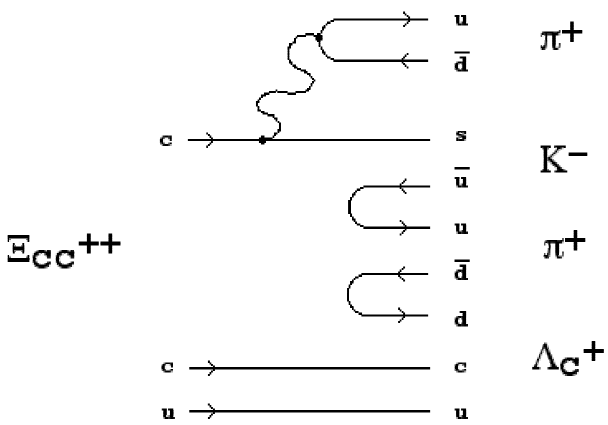
- primary vertex tagged by beam track
- secondary vertex must lie outside material

Charm Selection Cuts for single charm studies:

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

SELEX Double Charm Baryon Search Strategy





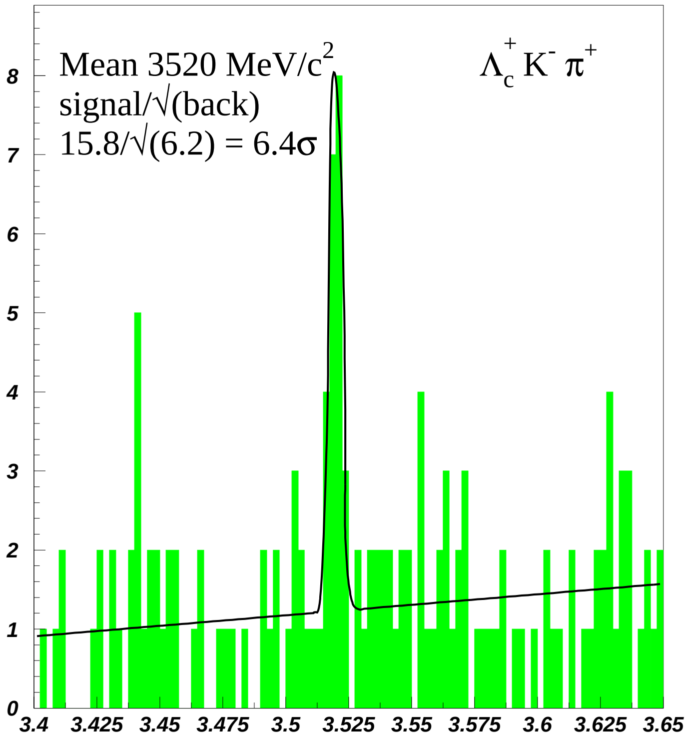
2 vertices to consider, L/σ cuts

- ccq baryons can decay to cqq baryon; **look for Λ_c^+ plus extra vertex**
- Cabibbo-allowed modes: $c \to s + W^+ \Rightarrow$ **require K^- (not K^+) at second vertex**
- No RICH PID on tracks from second vertex.

- Made independent data sets to search for ccu^{++} state and ccd^+ state
- Used SELEX $\Lambda_c^+ \to pK^-\pi^+$ sample with RICH identification required on p, K^-
- search for $K^-\pi^+\pi^+\Lambda_c^+$ vertex between primary vertex and Λ_c^+ decay point

PRELIMINARY Results from ccd$^+$ Search

$K^-\pi^+\Lambda_c^+$ Mass Plot



Mass calculated using constrained Λ_c^+ mass

- Use a baryon to find a baryon: require Λ_c^+ daughter
- look for extra vertex between primary and Λ_c^+
- If it's double charm, ccq decay has to make a K^-

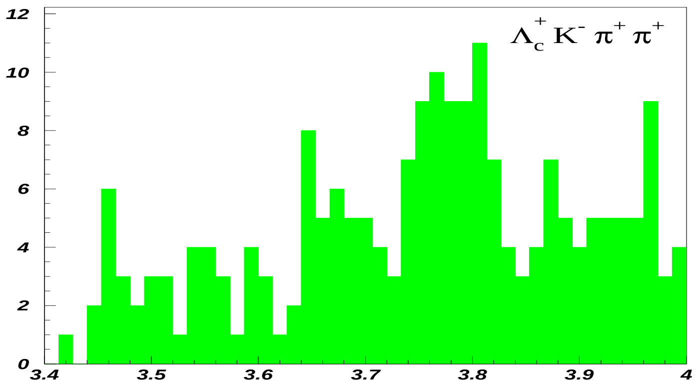
All requirements are met by the peak at 3520 MeV/c^2

This looks like a ccd$^+$ Decay!

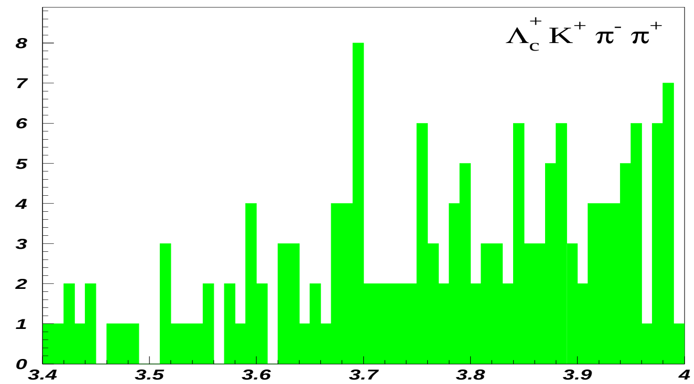
SELEX ccu^{++} Baryon Data

Is there a ccu^{++} partner to the ccd^{+} Candidate?

ccu^{++} candidate channel $K^-\pi^+\pi^+\Lambda_c^+$



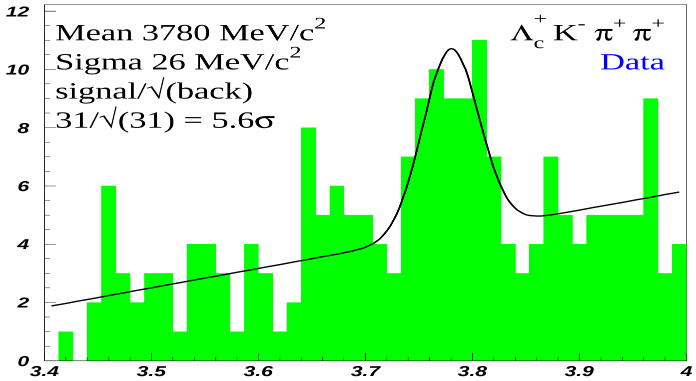
ccu^{++} wrong-sign backgnd channel $K^+\pi^-\pi^+\Lambda_c^+$

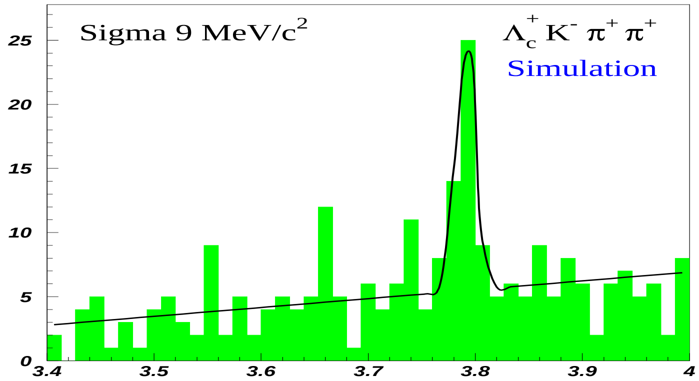


- NO RICH PID except on Λ_c^+ tracks
- cuts on data from single-charm analysis
- large mass peak at 3.78 GeV/c^2

- in wrong-sign (K^+) combination, no equivalent large peak
- $\Rightarrow$ right-sign ccu candidate is not random combinatoric vertex from only primary tracks

Do These Data Match Double Charm?





Data: Fit with Gaussian + Linear Background

- Signal Poisson significance is 5.6 σ.
- The peak is broad.
- peak mass is at high end of expected range.

Monte Carlo: Simulate weakly-decaying ccu(3780)

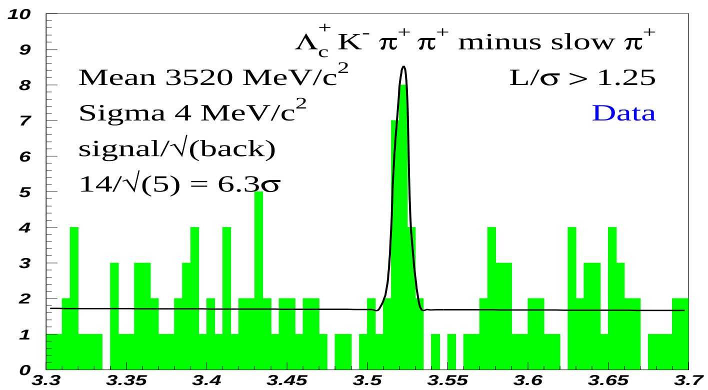
- resolution is 1/3 the width of the data

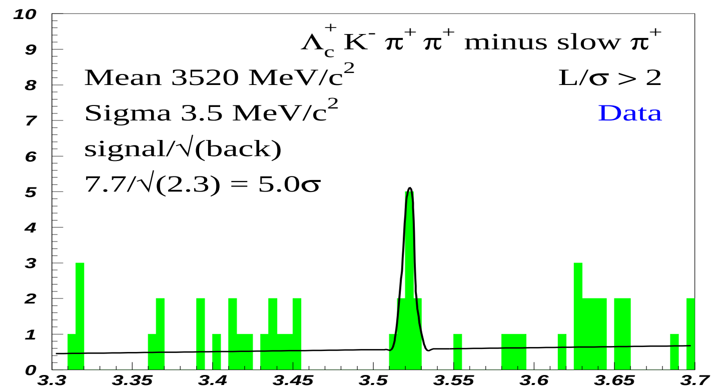
Is the 3.78 GeV/c^2 object a ccu excited state?

Remove Slow π^+ from ccu^{++} Sample and ... Voila!

Choosing only slow pion costs some signal but minimizes background

ccd$^+$ Mass Spectrum from ccu^{++} Sample





Rediscover ccd$^+$(3520) in independent sample

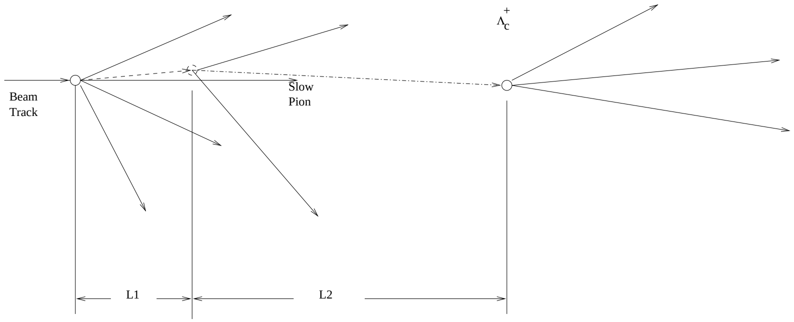
- Poisson significance of signal peak is 6.3 σ.
- position, width are same as in ccd$^+$ sample

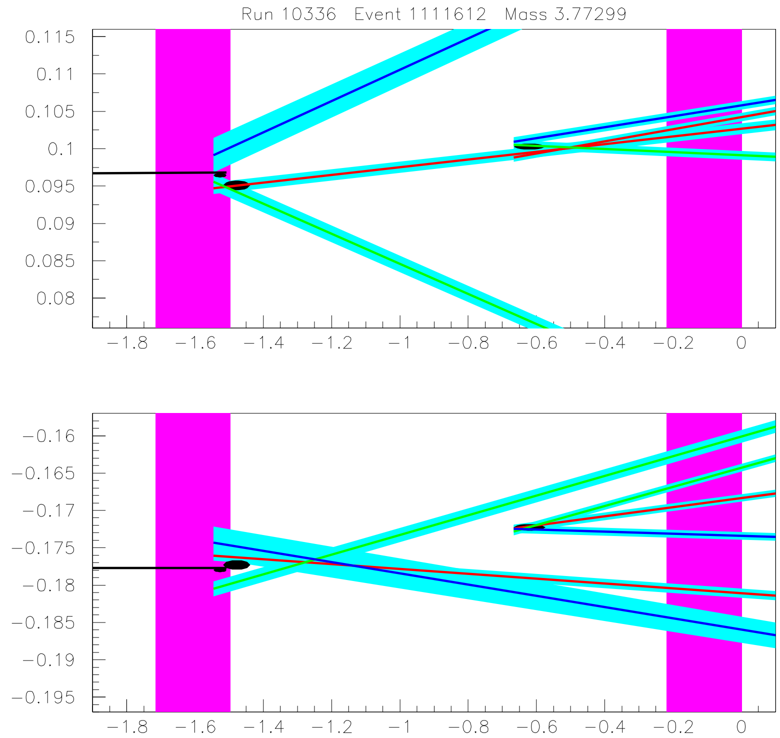
Check fakes: Increase L/σ cut from 1.25 to 2

- Now have 5.0 σ peak
- sideband background falls faster than signal as L/σ is increased.

This state does NOT originate from accidental overlap of primary tracks.

How Did the ccd$^+$State Appear in the ccu$^+$+ Reconstruction?





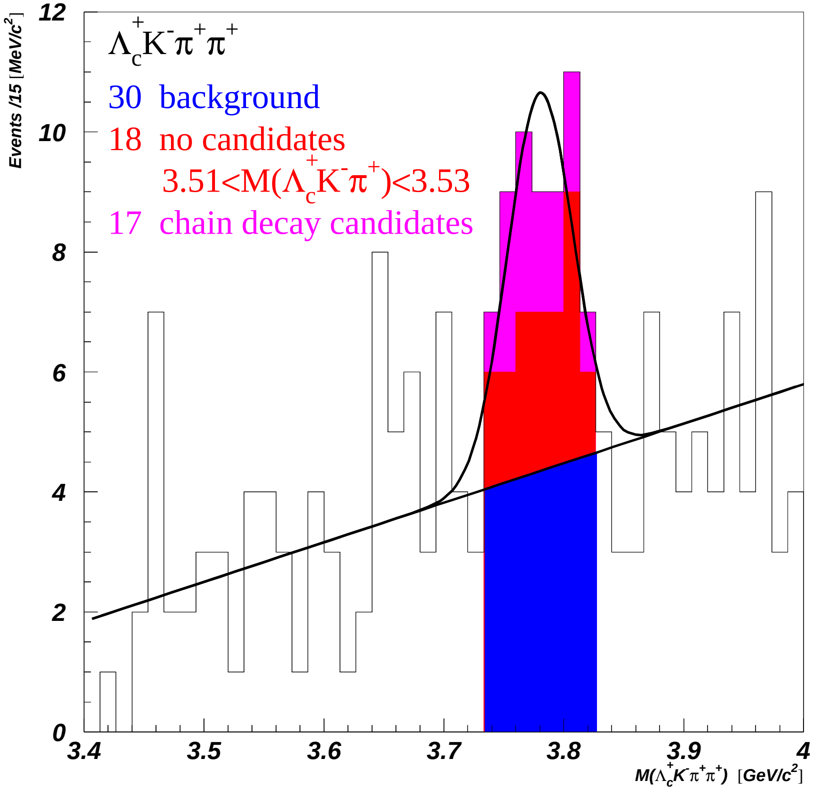
- slow pions have sizeable track errors
- track is allowed to be consistent with two vertices
- primary pion can overlap with true $K^-\pi^+\Lambda_c^+$ vertex to simulate ccu^{*++} state

- track trajectories are colored lines
- track errors are colored bands

Event contributes to both ccu^{*++} peak at 3.78 and ccd$^+$ peak at 3.52 when slow pion is removed

Candidate for ccu$^{++}(3780) \rightarrow \pi^+ + $ ccd$^+(3520)$

Are the ccd$^+$ and ccu^{++} States Related?



The ccu^{++} Decay is Complicated.

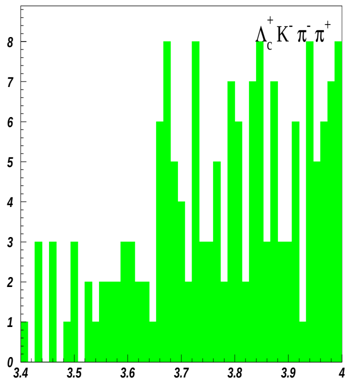
- The solid line is the fit from the previous page
- The background extrapolation is in blue.
- The ccu^{*++}(3780) has some decays via π^+ emission to ccd$^+$. The area shown in magenta represents events like this.
- The area shown in red represents direct decays to $K^- \pi^+ \pi^+ \Lambda_c^+$

There appear to be two independent decay modes of the ccu^{*++}(3780) (??)

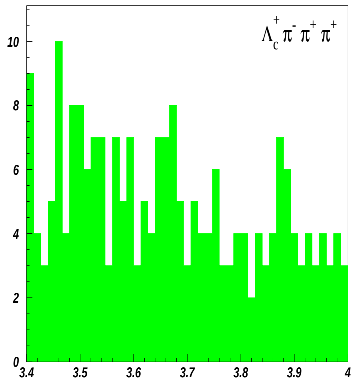
Any Other Explanation for These Data?

Look at the Wrong-Sign Plots

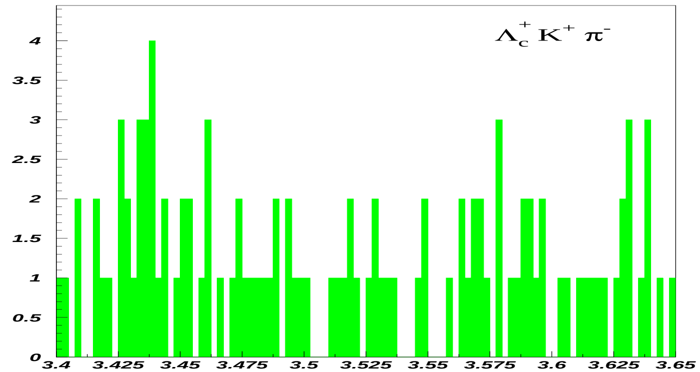
$K^-\pi^-\pi^+\Lambda_c^+$



$\pi^-\pi^-\pi^+\Lambda_c^+$



$K^+\pi^-\Lambda_c^+$



- No peaks seen in $K^-\pi^-\pi^+\Lambda_c^+$.
- No peaks seen in $\pi^-\pi^-\pi^+\Lambda_c^+$
- Previously showed no peaks in $K^+\pi^-\pi^+\Lambda_c^+$.

The ccu^{++}(3780)is not a reconstruction artifact.

- The Wrong-Sign plot for the ccd$^+$ shows no peaks
- **The ccd$^+$(3520) is not a reconstruction artifact.**

Where Are We?

We have shown two new high-mass peaks with high statistical significance

Decays are consistent with coming from doubly-charmed baryons .

ccd$^+$(3520) seen two ways

- 6.4σ peak in direct search for ccd$^+$ states
- 6.3σ peak in restricted search from sample of ccu^{++} candidates
- $\approx$ 60% overlap of samples

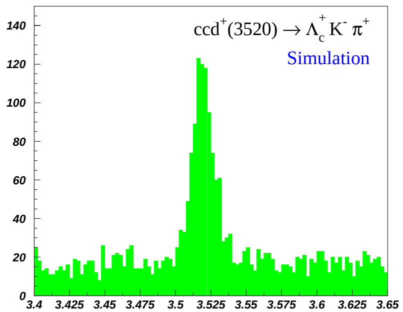
broad ccu^{++} seen in direct search

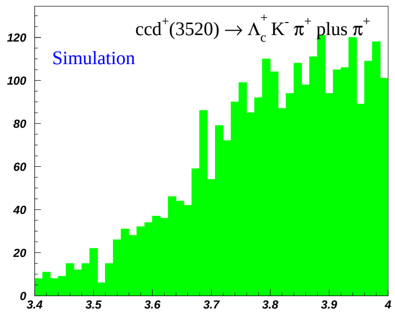
- decay analysis suggests that this state may have more than one decay
- statistics are too low to do much more investigation

Simulation

only ccd$^+$(3520)decaying to $K^-\pi^+\Lambda_c^+$

ccd$^+$ plot   ccu^{++} plot

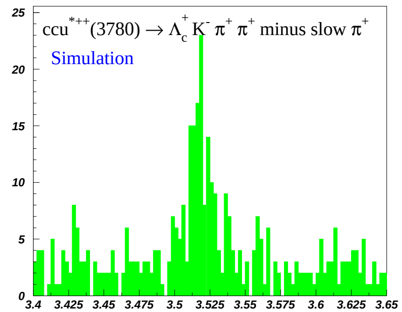


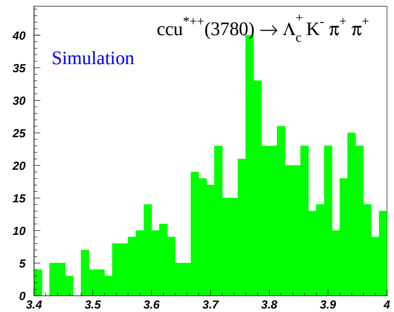


- ccu^{++} reconstruction forces random extra pion to be included along with tracks from ccd$^+$(3520)
- see clean ccd$^+$(3520)peak after removing slow π^+.(left plot)
- ccu^{++} mass distribution (right plot) rises sharply above 3.64 GeV/c^2

chain decay of ccu$*^{++}$(3780) to ccd$^+\pi^+$

ccd$^+$ plot   ccu^{++} plot



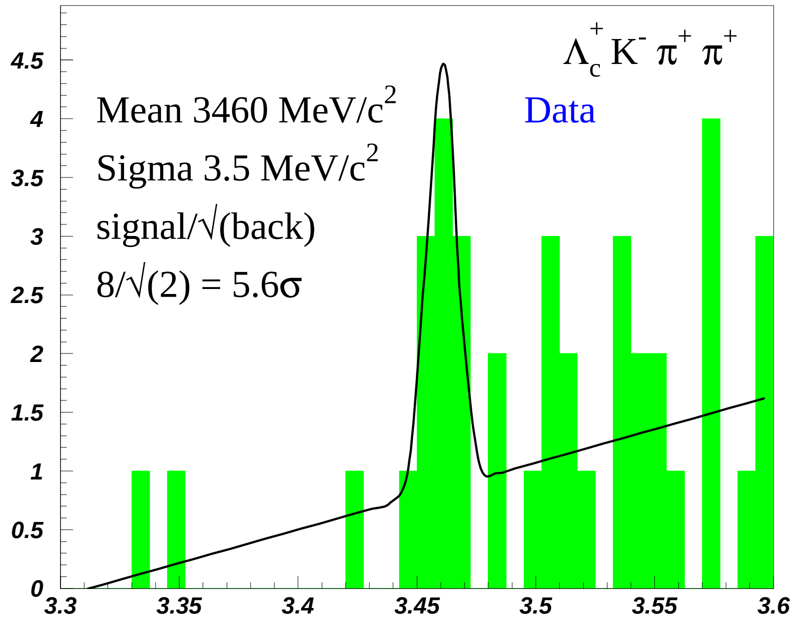


- Simulate ccu^{*++} with width $\Gamma = 30$ MeV/c^2
- see background step and broad ccu^{++}(3780) peak.(right plot)
- Drop slower π^+; see narrow ccd peak. (left)

data and simulation agree on peaks, other features

Is There a Narrow ccu^{++} State in SELEX Data?

Look in vicinity of ccd^{+}(3520) for narrow ccu^{++} state decaying to $\mathrm{K}^{-}\pi^{+}\pi^{+}\Lambda_c^{+}$



Data show 5.6 σ peak at 3460 MeV/c^2.

- State on edge of acceptance ⇒ only 2 evts below 3.4 GeV/c^2
- acceptance changes much faster for 4-prong ccu^{++} than 3-prong ccd^{+}
- simulation: $\epsilon(\mathrm{ccu}^{++}(3460))/\epsilon(\mathrm{ccd}^{+}(3520)) \sim 1/2.$

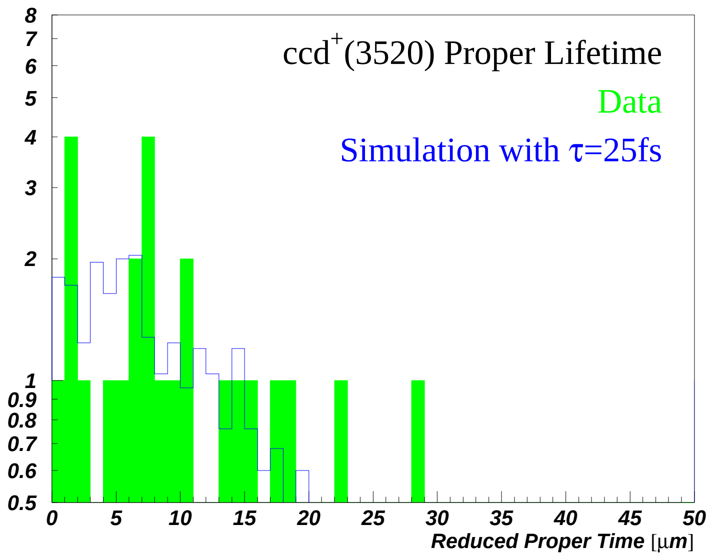
Have a third high-mass peak with double-charm decay characteristics

ccd^{+}(3520) Lifetime

Plot reduced proper length

$\mathrm{ct_r} = \mathrm{m/pz}*(\mathrm{l}-\mathrm{l_{min}})$

$\mathrm{l_{min}} = 1.25\sigma$ for this sample.



- mean l/σ is 1.94
- Average l is 1.8 mm
- average boost is 62

For each event $\sigma(\mathrm{ct_r}) \sim \mathrm{ct_r}$

- blue curve (normalized to 26 events) shows simulation results for 25 fs lifetime - about right!
- ccd^{+}**(3520) looks like weakly-decaying state with** $\tau_{ccd} \sim 0.5 \times \tau_{\Omega_c}$ **(60 fs)**

Λ_c^+ Economics

How many Λ_c^+s are associated with double-charm states?

The short answer - about half

How did we get this?

- simulation: 10% ccd$^+$(3520) detection efficiency if Λ_c^+ is reconstructed
- ccu^{++}(3460) detection efficiency ∼5%.

16 ccd$^+$ and 7 ccu^{++} ⇒ 30 efficiency-corrected events ⇒ 300 Λ_c^+s out of 1650

- BR into $\overline{\mathrm{K}}^0\pi^0$ is 1/2 that into $\overline{\mathrm{K}}^-\pi^+$ ⇒ 15 Λ_c^+/observed event
- Handwave over modes with more pions:overall estimate 25 Λ_c^+/observed event

ccq's take ∼40% of the SELEX Λ_c^+'s

- non-chain ccu^{*++}(3780) decays raise Λ_c^+ consumption to about half
- The observed signals don't violate Λ_c^+ conservation

This sounds enormous, but consider BELLE: double charm there is half single charm.

Charm Lifetimes, $D^0 - \overline{D}^0$ Mixing and Double $c\bar{c}$ Production

P. Pakhlov
(ITEP, BELLE Collaboration)

FPCP, University of Pennsylvania, May 17, 2002 – p.1

Summary

- Charm physics is not abandoned: all experiments show their interest in this field.
- At present:
  - BaBar measured $y_{CP} = (1.4 \pm 1.0^{+0.6}_{-0.7})\,\%$ with D^{*+} tag.
  - Belle updated $D^0 \to K^+\pi^-$: $R_{WS} = (0.38 \pm 0.03)\,\%$.
  - FOCUS: new measurement of D^0 and D^+ lifetimes: $\tau_{D^0} = (409.6 \pm 1.1 \pm 1.5)\,\mathrm{fs}$ and $\tau_{D^+} = (1039.4 \pm 4.3 \pm 7.0)\,\mathrm{fs}$.
- Belle observed $e^+e^- \to 2(c\bar{c})$:
  - $\sigma(e^+e^- \to J/\psi\,\eta_c\,(\gamma)) \times \mathcal{B}(\eta_c \to \geq 4\,\mathrm{charged}) = (0.033\,^{+0.007}_{-0.006} \pm 0.009)\,\mathrm{pb}$
  - $\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.89^{+0.21}_{-0.19} \pm 0.21$ and $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.61^{+0.15}_{-0.13} \pm 0.12$
- Many new results are coming, and come soon.

What About Production?

Which beam hadrons(Σ^-, π^-, p) make these states?

state	Σ^-	proton	π^-
luminosity fraction	0.77	0.13	0.10
ccu(3460) signal	9	0	0
ccu(3460) sideband	9	0	0
ccu(3780) signal	43	12	1
ccu(3780) sideband	30	10	3
ccd(3520) signal	18	4	0
ccd(3520) sideband	18	1	1

The high-mass states dominantly produced by baryon beams.

Why Does SELEX See These States?

They're produced in a corner of phase space:

Take ccd$^+$(3520) for example.

- mean $x_F \sim 0.35$ (200 GeV/c)
- mean $p_T \sim 1$ GeV/c
- they make leading Λ_c^+'s, which have to be reconstructed fully

Other particle production puzzles in this corner of phase space

- Why does the Hyperon beam work? Leading strange baryon production at Fermilab
- The discovery experiment for the Ξ_c^+ (135 GeV Σ^- beam: WA62)

Cross section calculations for small p_T, large x_F processes are very unreliable. Experiment must lead, and there are surprises.

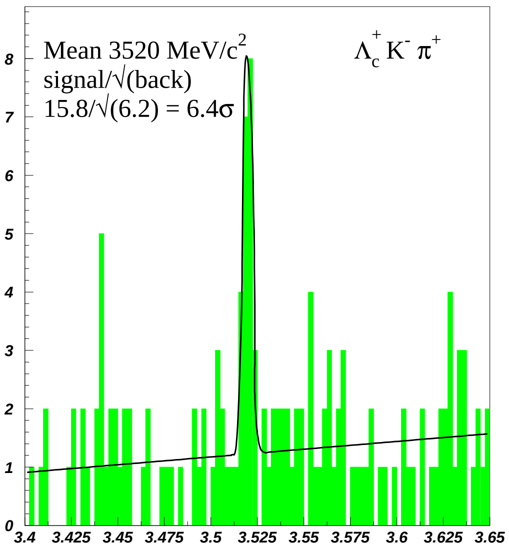
There are other hints that double-charm may not be so rare

- Large 4-charm/2-charm production ratios seen in Hybrid Emulsion experiments
- BELLE: huge [J/ψc$\bar{\text{c}}$]/[J/ψ] ratio in continuum e^+e^- collisions.

  We don't understand the production mechanism, but we see the states

Summary-1

Selex has a high-mass ccd^+ candidate at 3520 MeV/c^2

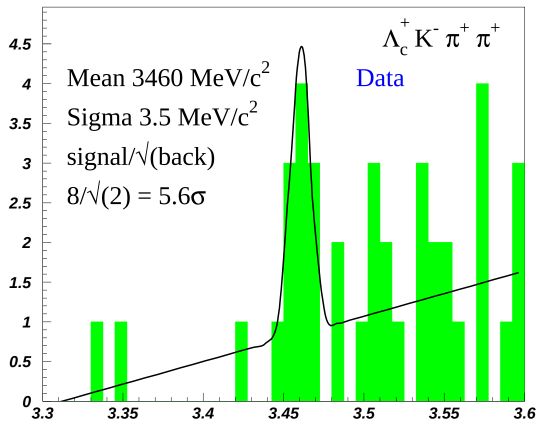


- This state decays like a doubly-charmed baryon
- Its mass falls nicely within range of doubly-charmed baryon predictions
- Its lifetime appears to be in the 30 fs range
- The $ccd^+(3520)$ candidate fits all expectations for double charm.

Based on this state, it's time to remove the question mark.
SELEX has discovered a doubly-charmed baryon.

Summary-2

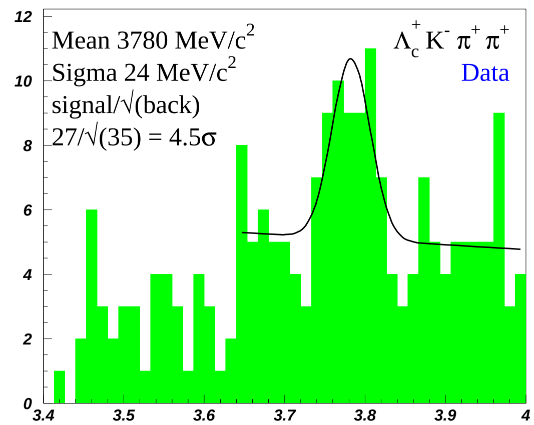
Selex has a high-mass ccu^{++} candidate at 3460 MeV/c^2



- The $ccu^{++}(3460)$ candidate decays like a doubly-charmed baryon.
- Its mass is low end of the range expected.
- It lies far from the $ccd^{+}(3520)$ state to be an isospin partner (60 MeV).

Summary-3

Selex has a broad high-mass ccu^{*++} candidate at 3780 MeV/c^2



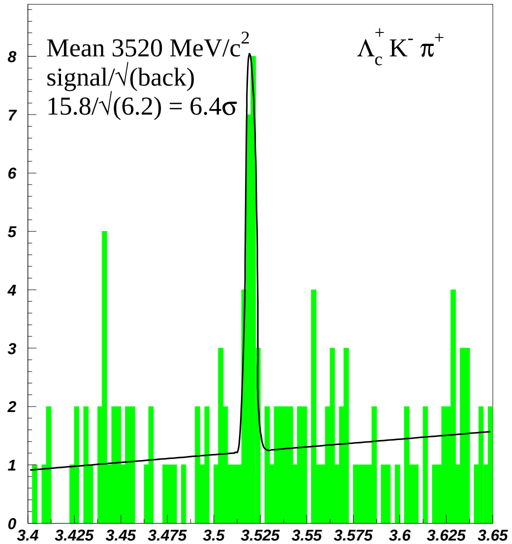
- The ccu^{*++}(3780) decay scheme is confusing
- The mass splitting from the lower-lying narrow states is large.

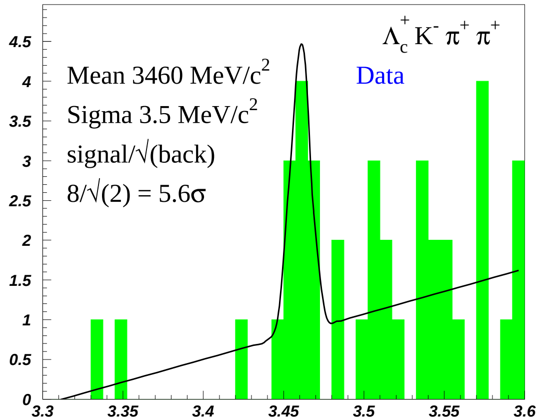
The ccu^{*++}(3780) state doesn't fit neatly into the basic scheme.

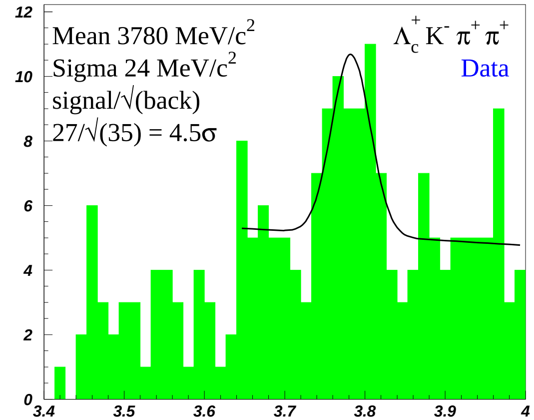
but it's there.

The Final Word for Today

Selex has observed 3 significant high-mass peaks







- SELEX has preliminary but strong evidence for a family of high-mass states
- These states decay like doubly-charmed baryons
- The spectroscopy is not easy to understand
- The production rate is astoundingly high, but the double-charm world has seen a partner surprise from e^+e^- collisions.

It's difficult to avoid calling these states doubly-charmed baryons.