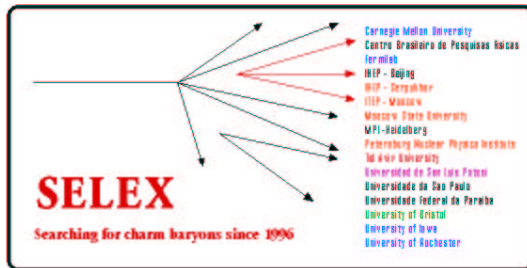


High Mass States in SELEX

Have Doubly-charmed Baryons Been Discovered?



Fermilab Wine and Cheese

May 31, 2002

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for the SELEX Collaboration

Outline

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

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High Mass States in SELEX

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High Mass States in SELEX

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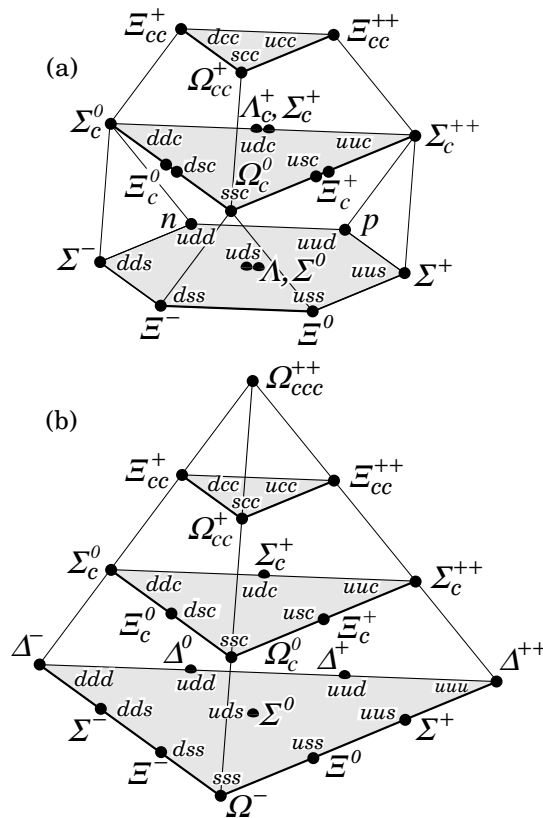
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Flavor-Independent QCD Demands Double-Charm Baryons



- 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

SU(4) Baryon Multiplets

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 <i>et al.</i>	1995	Feynmann/Hellman	3.81	3.66
Ellis	2002	phenom	3.711	3.651

Sampling of ccq mass predictions

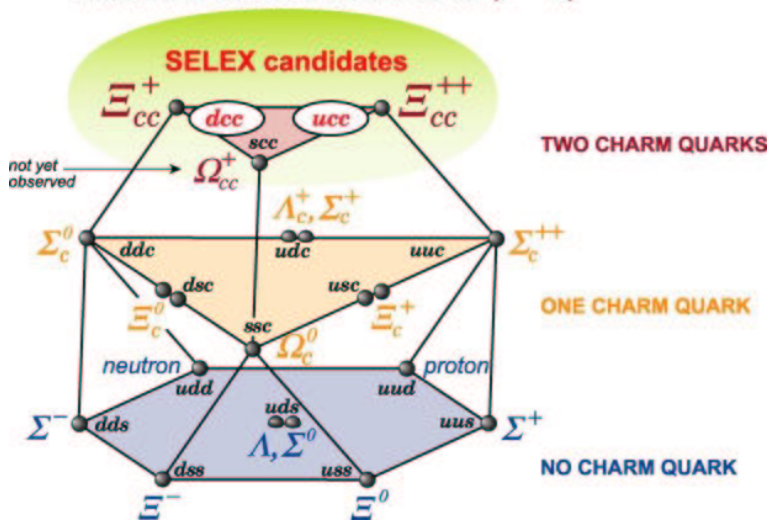
Overall features of models:

- ground state near 3.6 GeV/c²
- hyperfine splitting around 60-120 MeV/c²
- some models predict pionic transitions for 3/2 → 1/2
- most potential model calculations based on non-charmed decuplet-octet splits predict only electromagnetic transitions.
- Model-dependent predictions for orbital, radial excitations

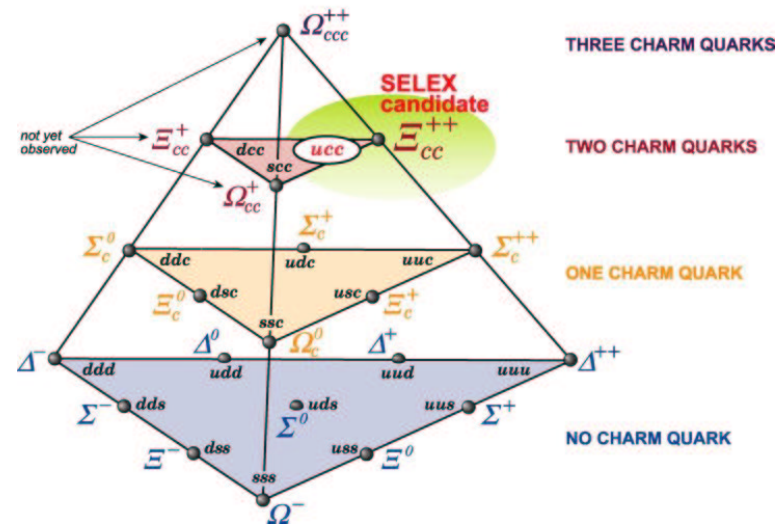
Some Nomenclature

In this talk we replace PDG names by suggestive labels.

BARYONS WITH LOWEST SPIN ($J = 1/2$)



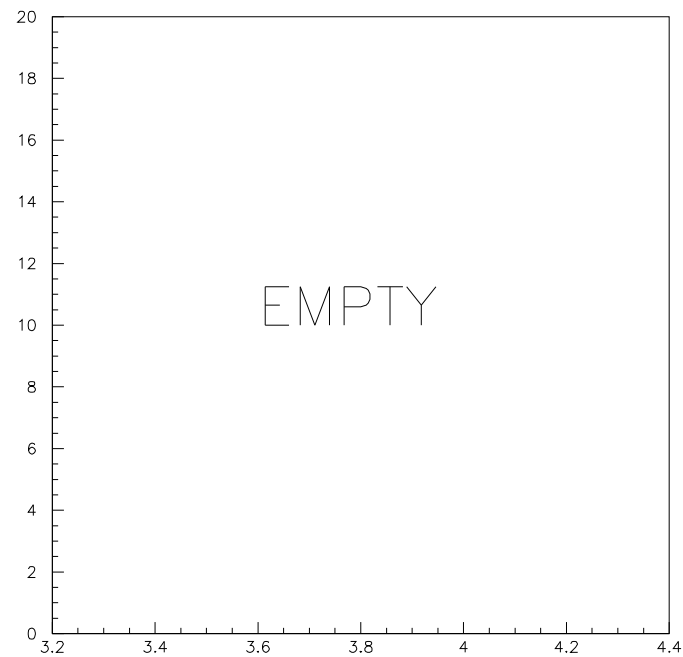
BARYONS WITH HIGHEST SPIN ($J = 3/2$)



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

- $\Xi_{cc}^{*++}(J=3/2) \equiv ccu^{*++}$
- decays :
 $ccu^{*++} \rightarrow K^- \pi^+ \pi^+ \Lambda_c^+$
and $ccu^{*++} \rightarrow ccd^+ \pi^+$

Previous Experimental Evidence



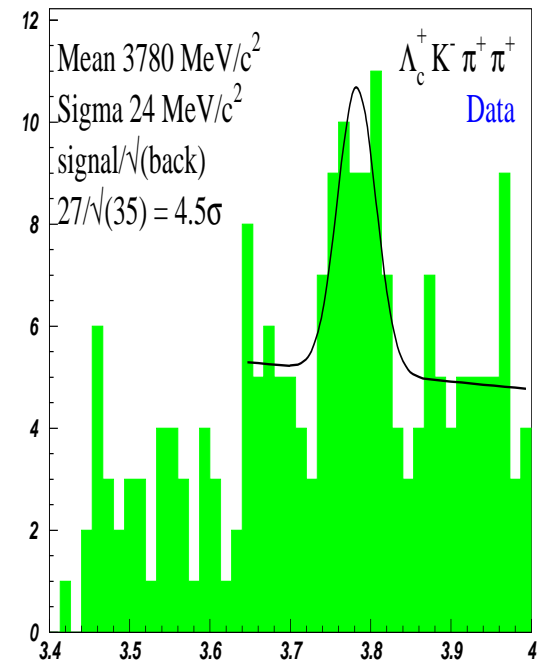
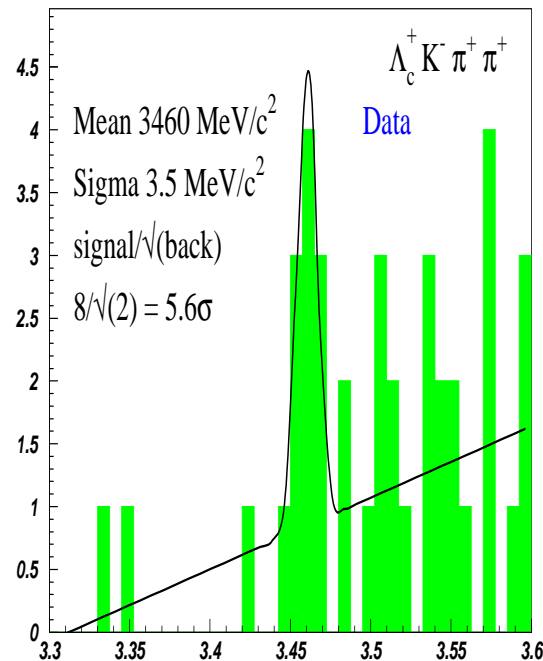
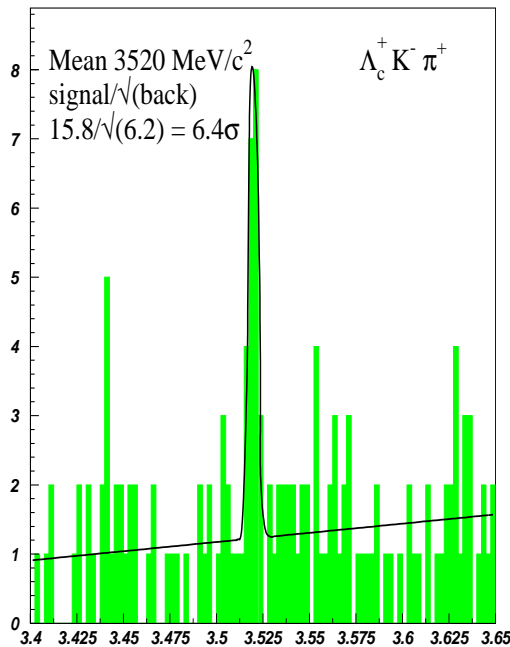
Experimental Evidence Today - a Preview

Selex reports 3 significant high-mass peaks

ccd^+

ccu^{++}

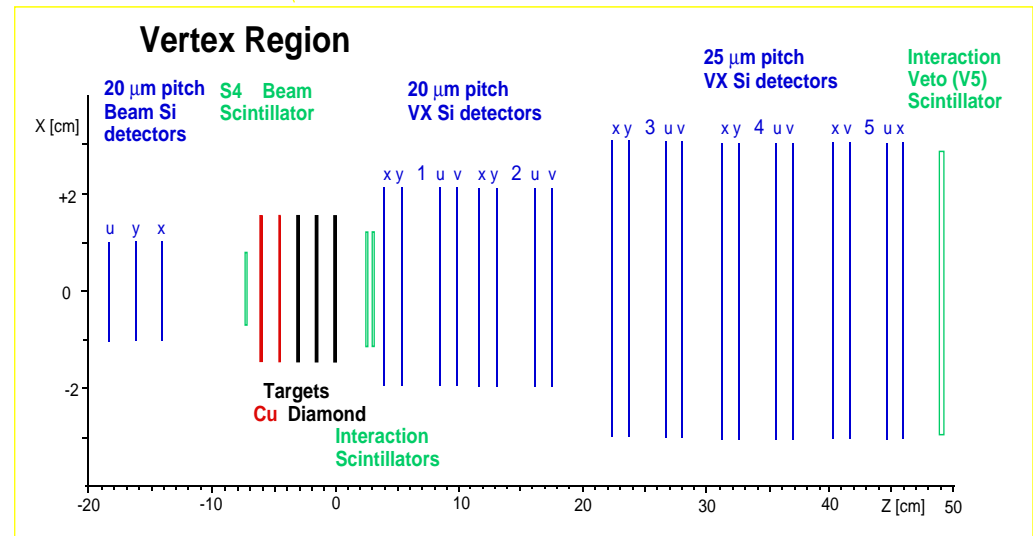
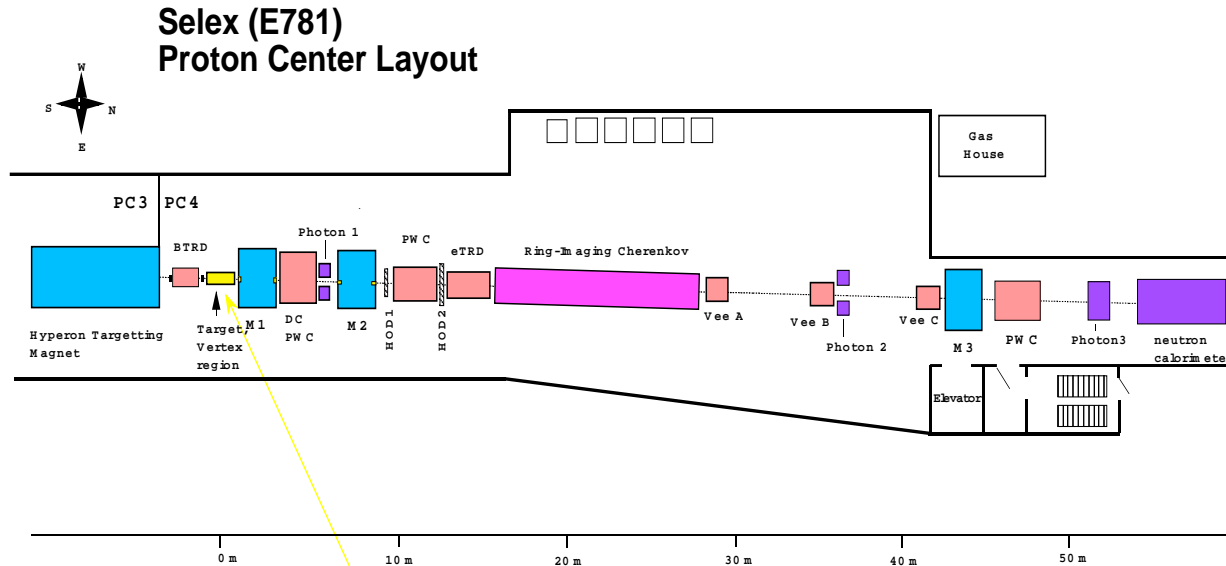
ccu^{*++}



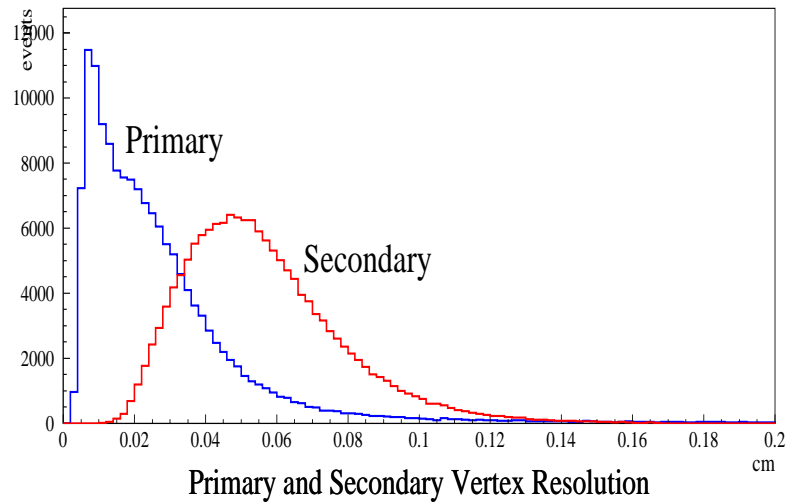
We will argue that these states are doubly-charmed baryons.

SELEX Apparatus Features

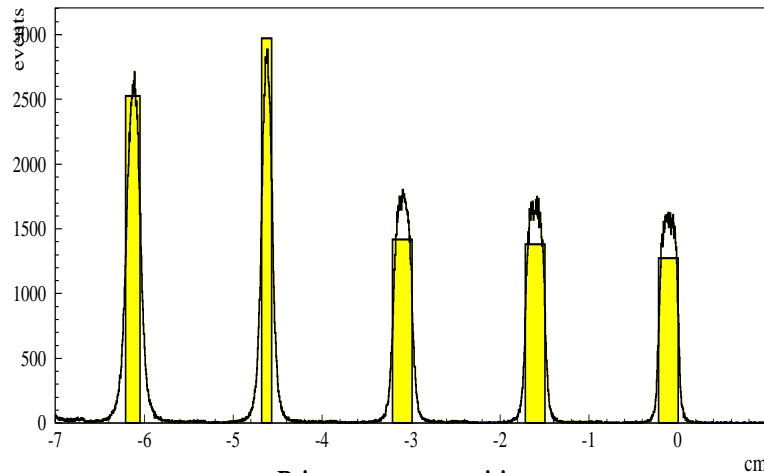
- Forward production
- π , Σ^- , p beams
- typical Lorentz Boost ~ 100
- RICH identification above 25 GeV/c



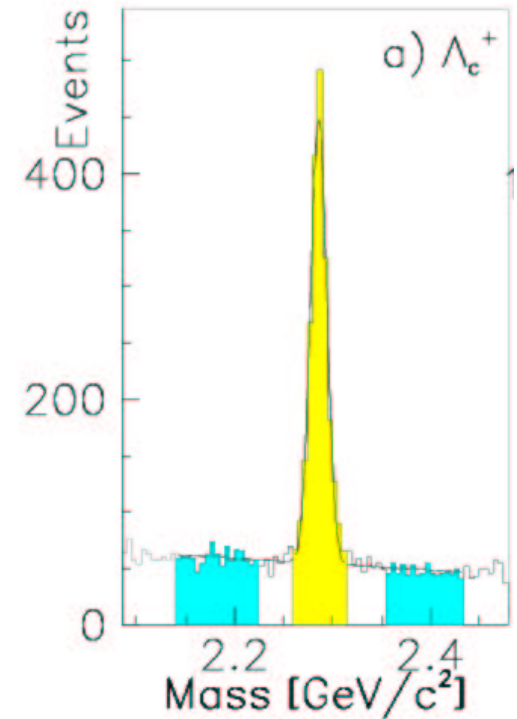
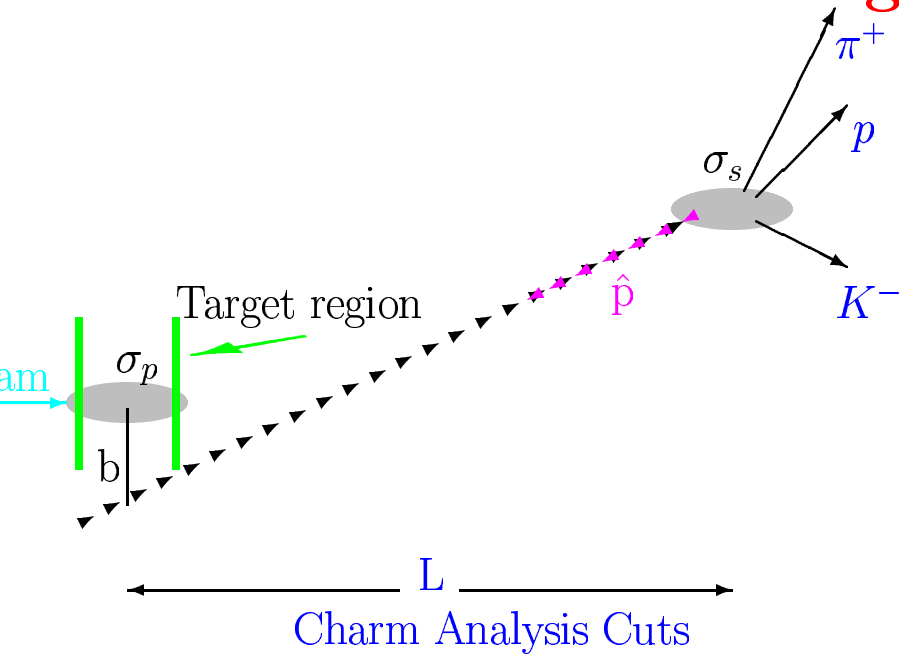
Vertex Spectrometer Performance



- 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



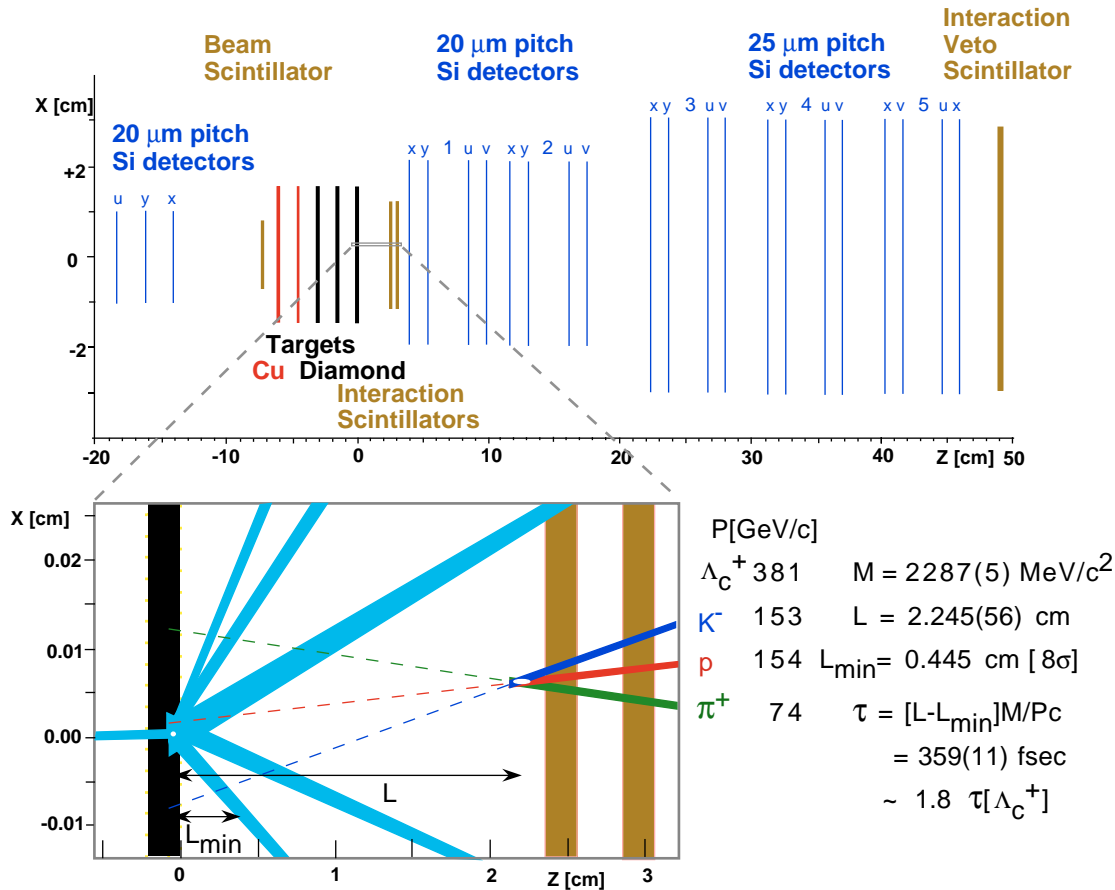
SELEX Single Charm Analysis



- 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)

- $\Lambda_c^+ \rightarrow pK^-\pi^+$ sample used to search for double charm

SELEX Charm Selection Criteria



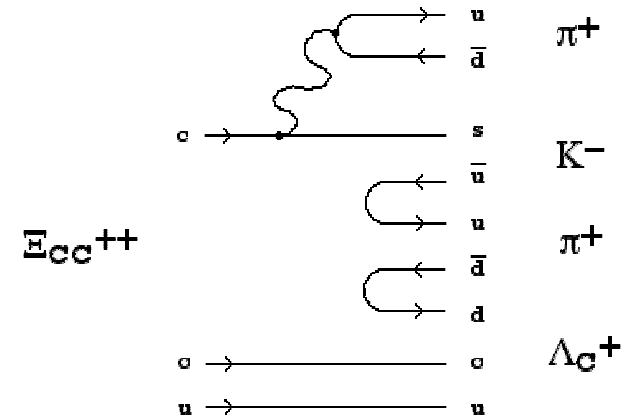
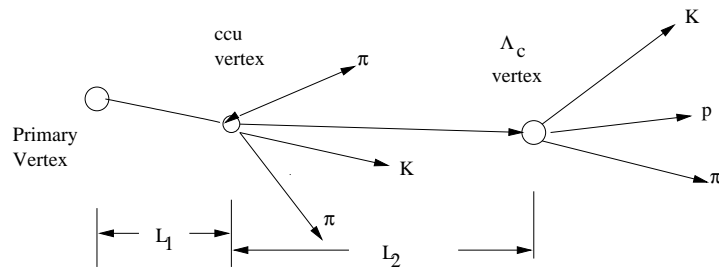
Λ_c^+ event

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 (Λ_c^+, \dots)
- Pointback ≤ 4 ($2 \sigma_b$)
- *second*-largest miss significance among decay trks ≥ 4 .

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

SELEX Double Charm Baryon Search Strategy



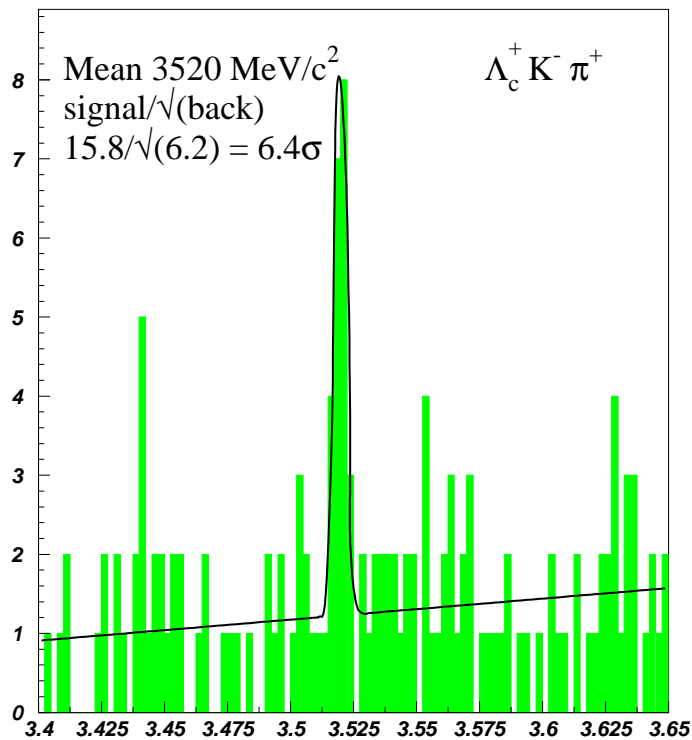
2 vertices to consider, L/σ cuts

- ccq baryons can decay to cqq baryon;
look for Λ_c^+ plus extra vertex
- Cabibbo-allowed modes: $c \rightarrow s + W^+ \Rightarrow$
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 $\Lambda_c^+ \rightarrow pK^-\pi^+$ 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



- 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
 $3520 \text{ MeV}/c^2$

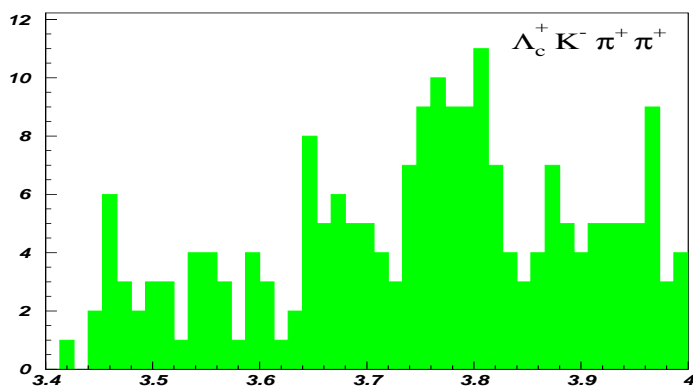
This looks like a ccd^+ Decay!

Mass calculated using constrained Λ_c^+ mass

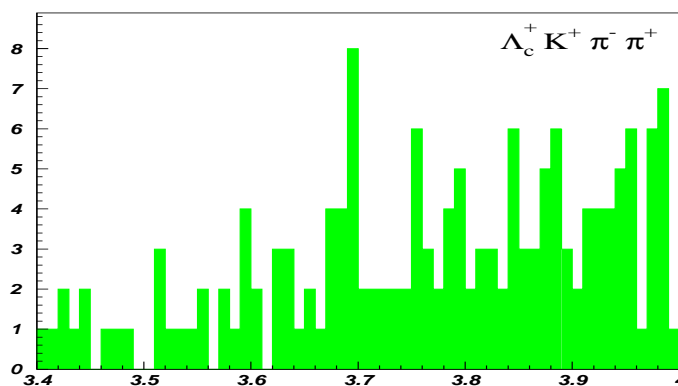
SELEX ccu^{++} Baryon Data

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

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



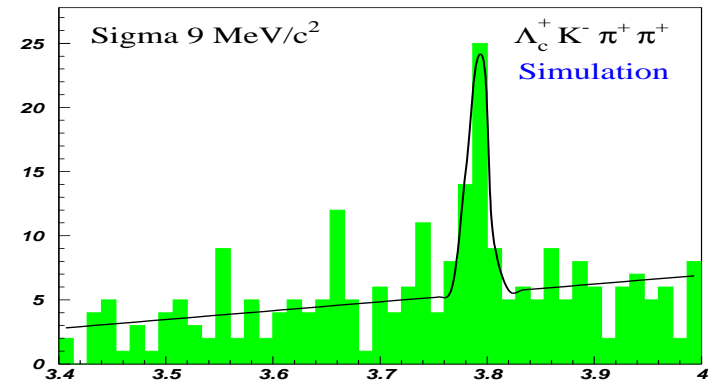
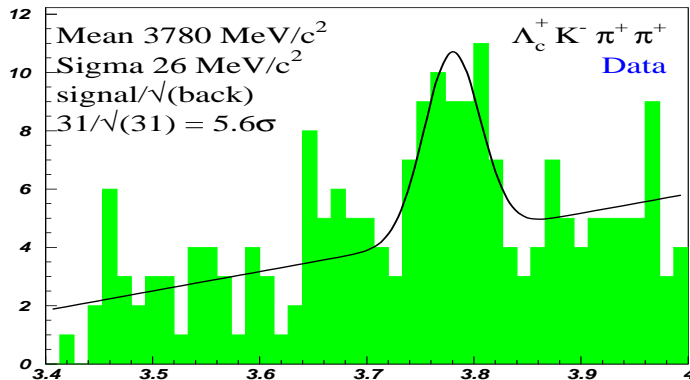
ccu^{++} wrong-sign backgnd channel $K^+ \pi^- \pi^+ \Lambda_c^+$



- 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

Monte Carlo: Simulate weakly-decaying $\text{ccu}(3780)$

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

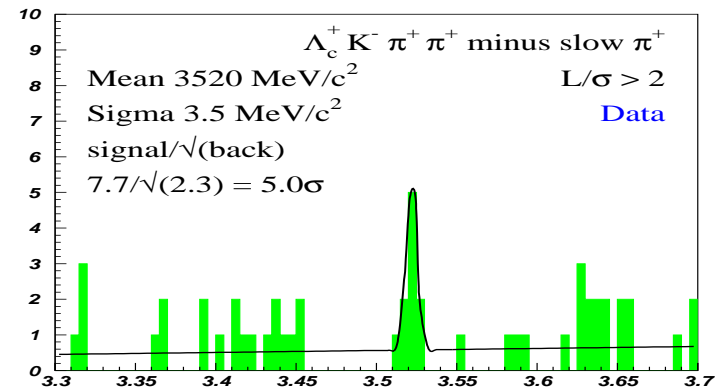
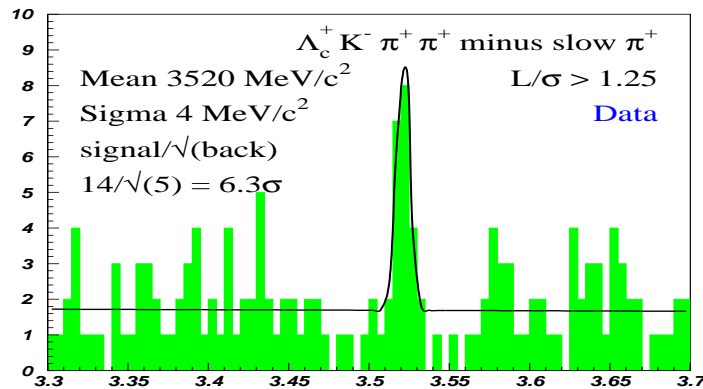
- resolution is $1/3$ the width of the data

Is the $3.78 \text{ GeV}/c^2$ 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



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

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

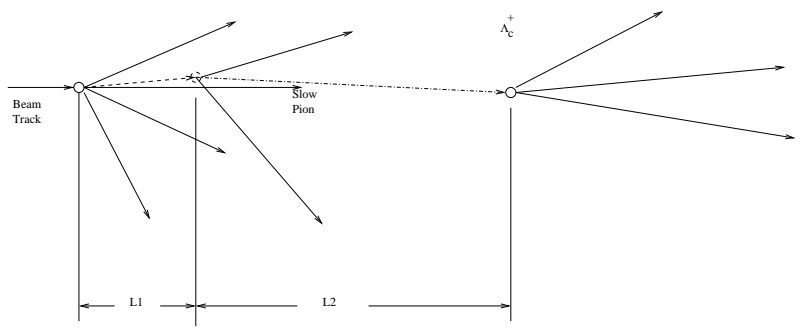
- Poisson significance of signal peak is 6.3σ .
- position, width are same as in ccd^+ sample

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

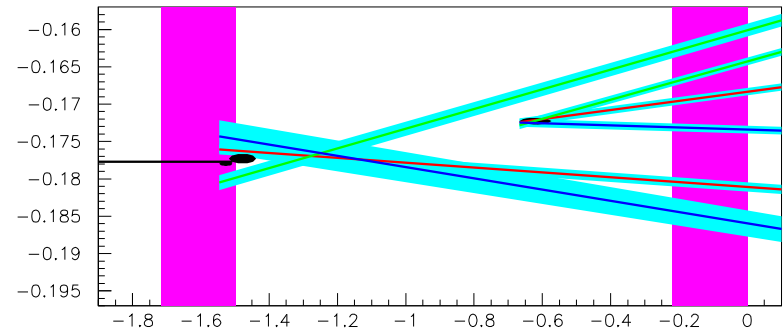
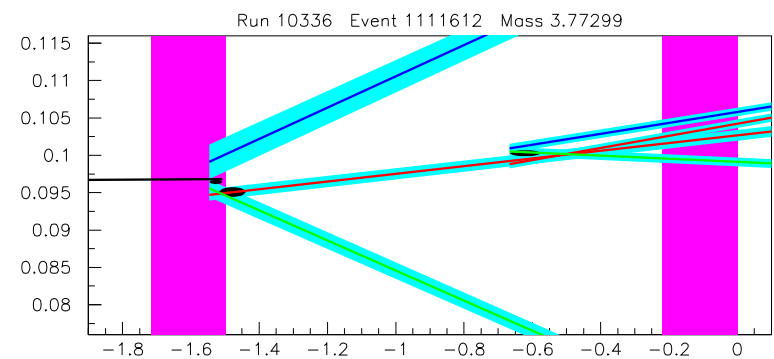
This state does NOT originate from accidental overlap of primary tracks.

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

2002/04/16 14:52



- 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

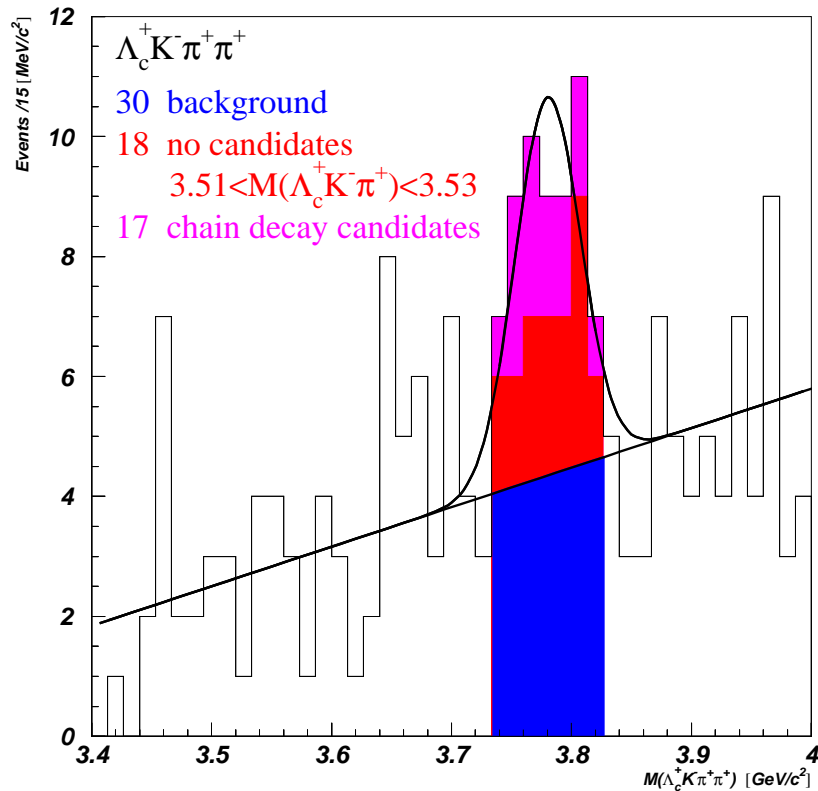


- track trajectories are colored lines
- track errors are colored bands

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.

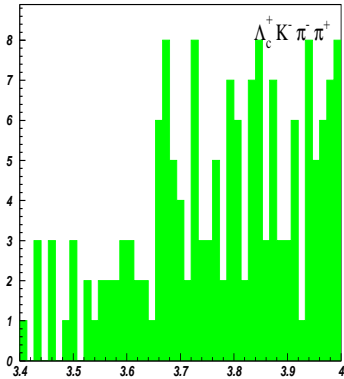
- The solid line is the fit from the previous page
- The background extrapolation is in blue.
- The $ccu^{*++}(3780)$ has *some* decays via π^+ emission to ccd^+ . The area shown in *magenta* represents events like this.
- The area shown in *red* represents *direct* decays to $K^- \pi^+ \pi^+ \Lambda_c^+$

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

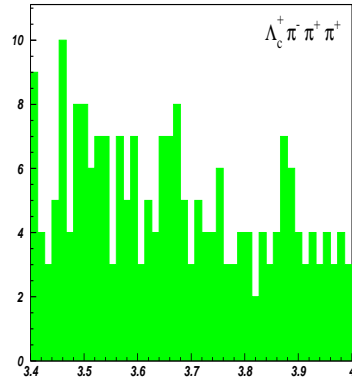
Any Other Explanation for These Data?

Look at the Wrong-Sign Plots

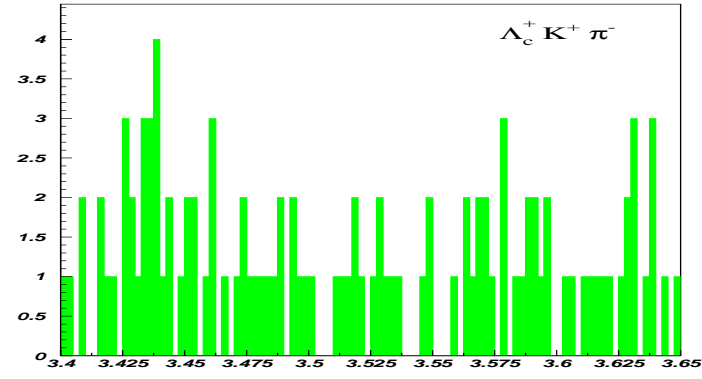
$K^- \pi^- \pi^+ \Lambda_c^+$



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



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



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

The ccu^{++} (3780) 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

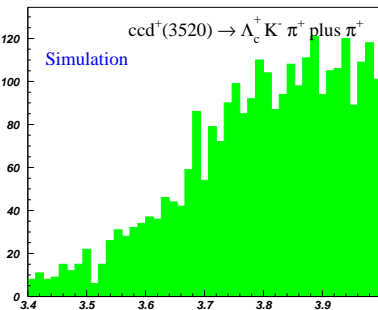
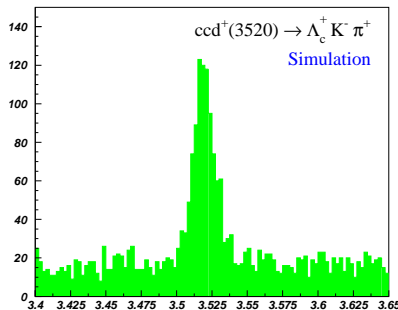
Simulation

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

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

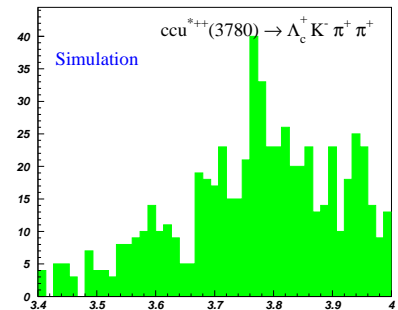
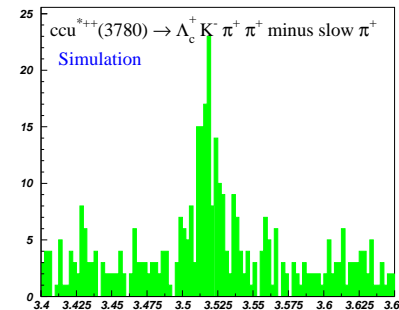
ccd^+ plot

ccu^{++} plot



ccd^+ plot

ccu^{++} plot



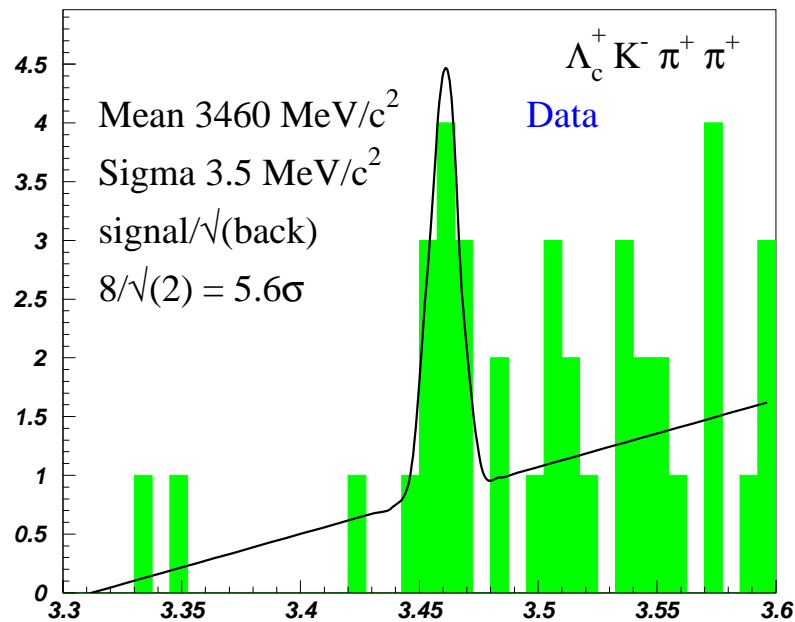
- ccu^{++} reconstruction forces random extra pion to be included along with tracks from $ccd^+(3520)$
- see clean $ccd^+(3520)$ peak after removing slow π^+ . (left plot)
- ccu^{++} mass distribution (right plot) rises sharply above $3.64 \text{ GeV}/c^2$

- Simulate ccu^{*++} with width $\Gamma = 30 \text{ MeV}/c^2$
- 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 $K^-\pi^+\pi^+\Lambda_c^+$



Data show 5.6 σ peak at 3460 MeV/c².

- State on edge of acceptance \Rightarrow only 2 evts below 3.4 GeV/c²
- acceptance changes much faster for 4-prong ccu^{++} than 3-prong ccd^+
- simulation: $\epsilon(ccu^{++}(3460))/\epsilon(ccd^+(3520)) \sim 1/2$.

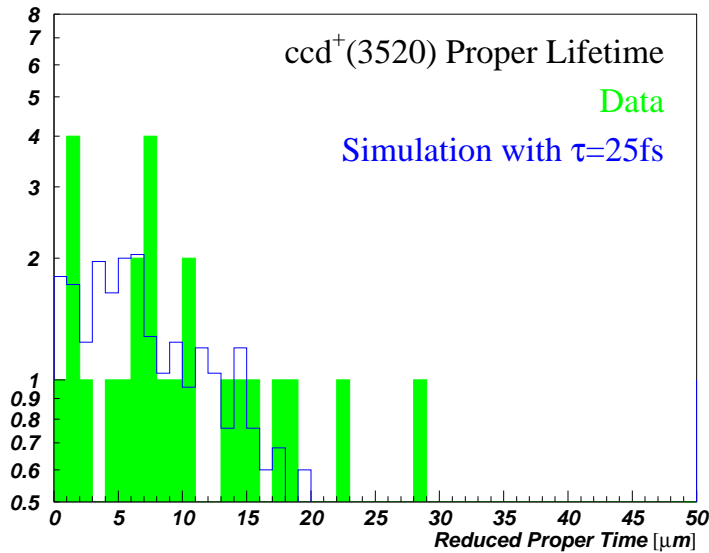
Have a third high-mass peak with double-charm decay characteristics

ccd⁺(3520) Lifetime

Plot reduced proper length

$$ct_r = m/pz^*(1-l_{\min})$$

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



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

For each event $\sigma(ct_r) \sim ct_r$

- 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 $\sim 5\%$.

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

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

ccq 's take $\sim 40\%$ 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, $D^0 - \bar{D}^0$ 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 $y_{CP} = (1.4 \pm 1.0_{-0.7}^{+0.6}) \%$ with D^{*+} tag.
 - Belle updated $D^0 \rightarrow K^+ \pi^-$: $R_{WS} = (0.38 \pm 0.03) \%$.
 - FOCUS: new measurement of D^0 and D^+ lifetimes:
 $\tau_{D^0} = (409.6 \pm 1.1 \pm 1.5) \text{ fs}$ and
 $\tau_{D^+} = (1039.4 \pm 4.3 \pm 7.0) \text{ fs}$.
- Belle observed $e^+e^- \rightarrow 2(c\bar{c})$:
 - $\sigma(e^+e^- \rightarrow J/\psi \eta_c(\gamma)) \times \mathcal{B}(\eta_c \rightarrow \geq 4 \text{ charged}) = (0.033_{-0.006}^{+0.007} \pm 0.009) \text{ pb}$
 - $\sigma(e^+e^- \rightarrow J/\psi c\bar{c}) = 0.89_{-0.19}^{+0.21} \pm 0.21$ and
 $\sigma(e^+e^- \rightarrow J/\psi c\bar{c}) / \sigma(e^+e^- \rightarrow J/\psi X) = 0.61_{-0.13}^{+0.15} \pm 0.12$
- 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 $cc\bar{d}^+(3520)$ 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.

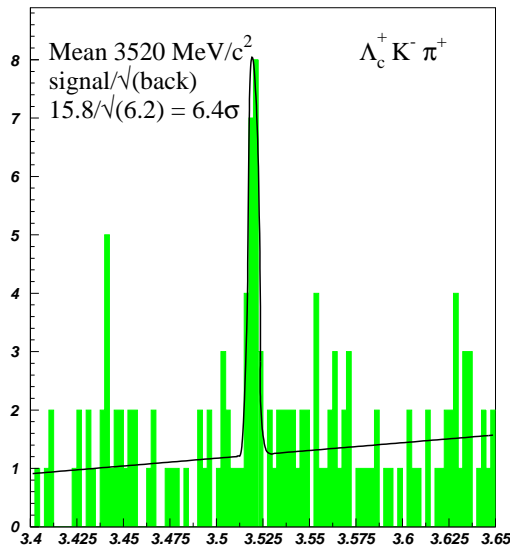
There are other hints that double-charm may not be so rare

- Large 4-charm/2-charm production ratios seen in Hybrid Emulsion experiments
- BELLE: huge $[J/\psi c\bar{c}]/[J/\psi]$ 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 $3520 \text{ MeV}/c^2$

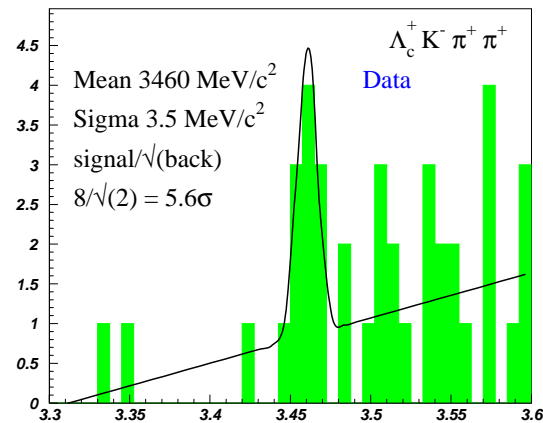


- This state decays like a doubly-charmed baryon
- Its mass falls nicely within range of doubly-charmed baryon predictions
- Its lifetime appears to be in the 30 fs range
- The $ccd^+(3520)$ candidate fits all expectations for double charm.

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

Summary-2

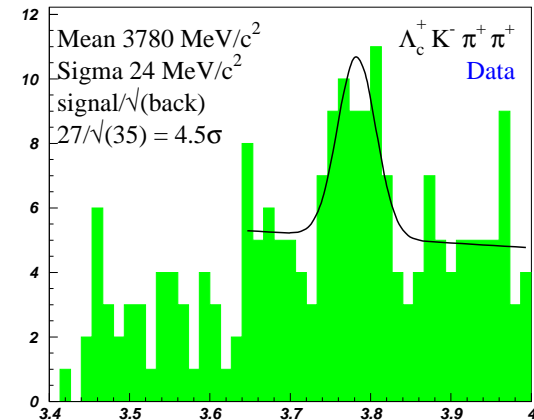
Selex has a high-mass ccu^{++} candidate at $3460 \text{ MeV}/c^2$



- 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 $3780 \text{ MeV}/c^2$



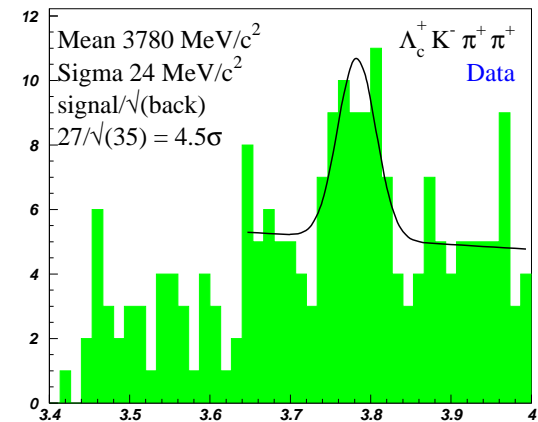
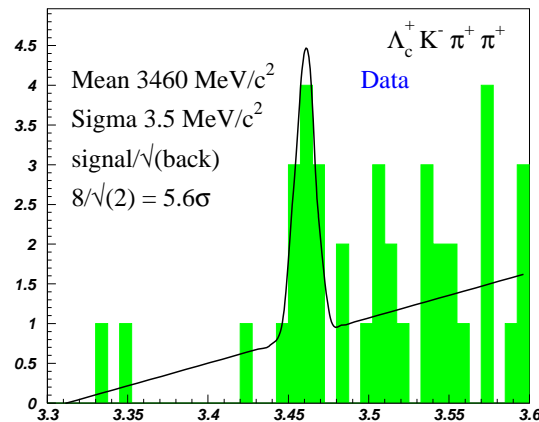
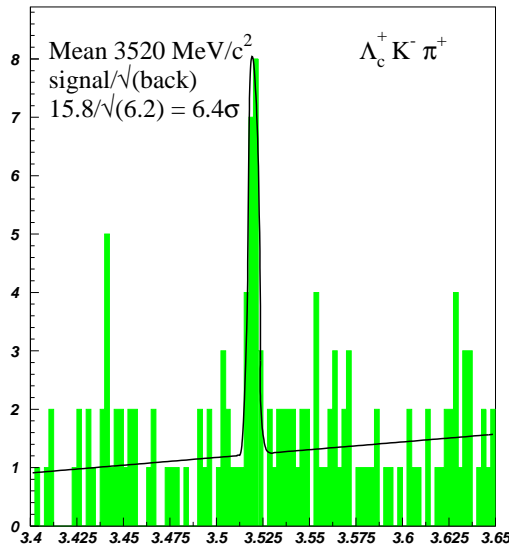
- The $ccu^{*++}(3780)$ decay scheme is confusing
- The mass splitting from the lower-lying narrow states is large.

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.