Double Charm Baryons at SELEX
An Update

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Outline

- (very!)Brief Theory Review
- Present SELEX Double Charm Status
- Selex Single-Charm Baryon Review
- Observation of New High Mass States
- Are These States Double-Charm Baryons?

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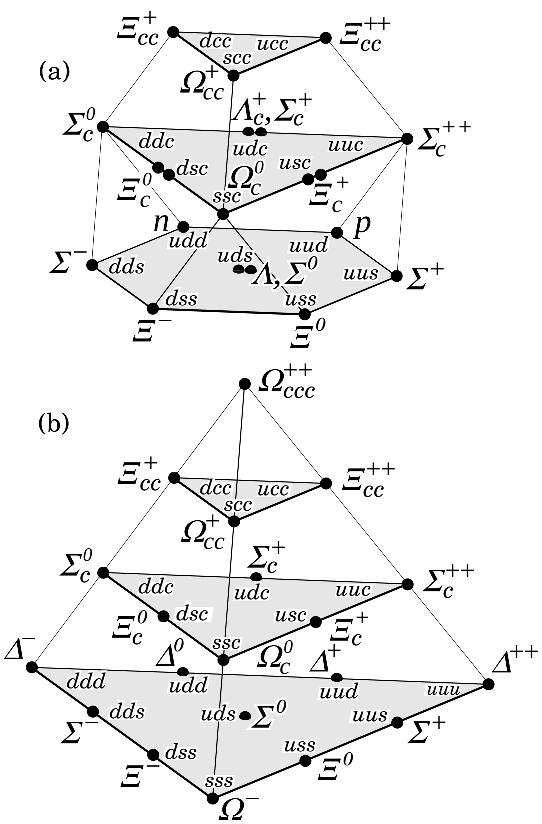
Flavor-Independent QCD Demands Double-Charm Baryons



SU(4) Baryon Multiplets

- Broken SU(4) classifies baryon states.
- States with $N_{ch} \leq 1$ all seen.
- Double- and Triple-Charm Baryons *must* exist.
- Characteristics ∼ charm meson spectra
  - cc binding potential ($\overline{\{3\}}$ state) 1/2 $\bar{c}$c potential ⇒ size of cc core ∼ J/ψ size
  - cc system in HQET approximation provides static color source to bind q, analogous to D-meson system.
  - finite $m_c \rightarrow$ 3-body effects (H_2^+ molecule)

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
Torii,*et al.*	2000	Born-Oppenheimer	3.649	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:

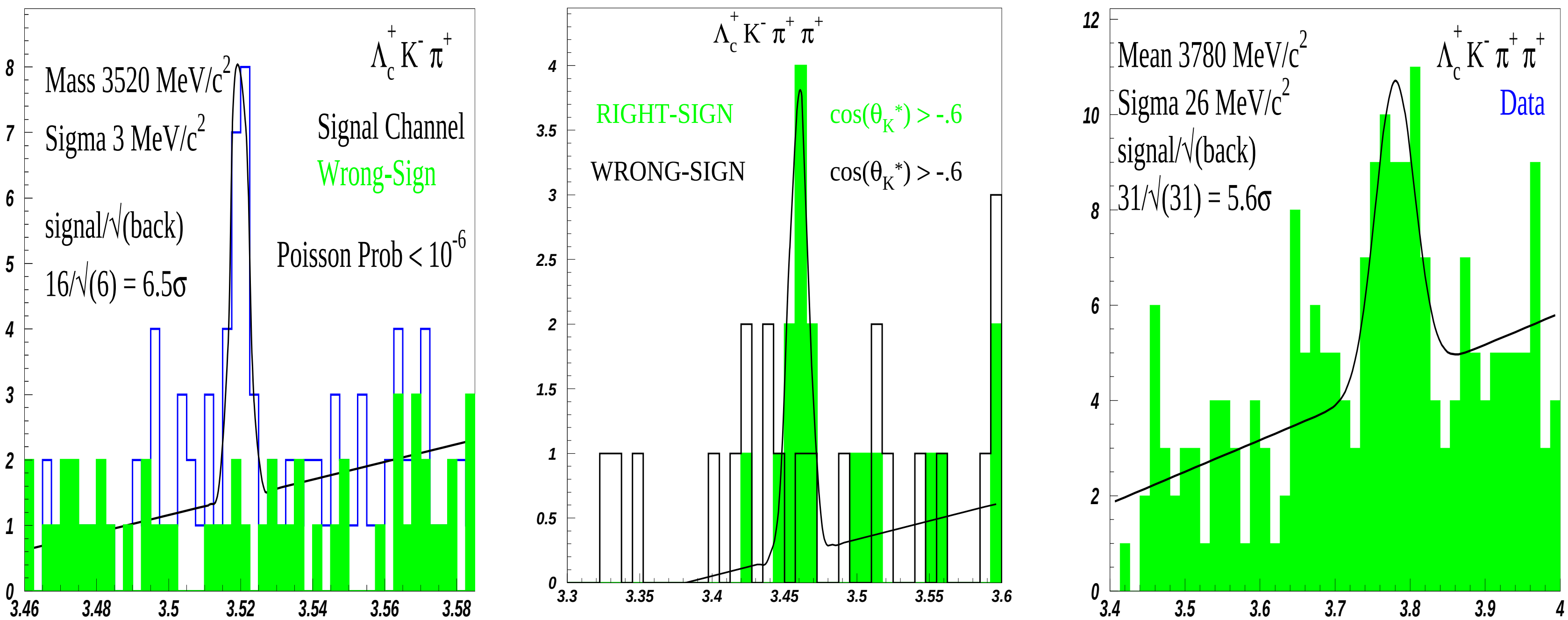
- ground state near 3.6 GeV/c^2
- ground state I=1/2 multiplet degenerate
- hyperfine splitting around 60-120 MeV/c^2

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

Experimental Evidence - 2002

Selex reported 3 significant high-mass peaks

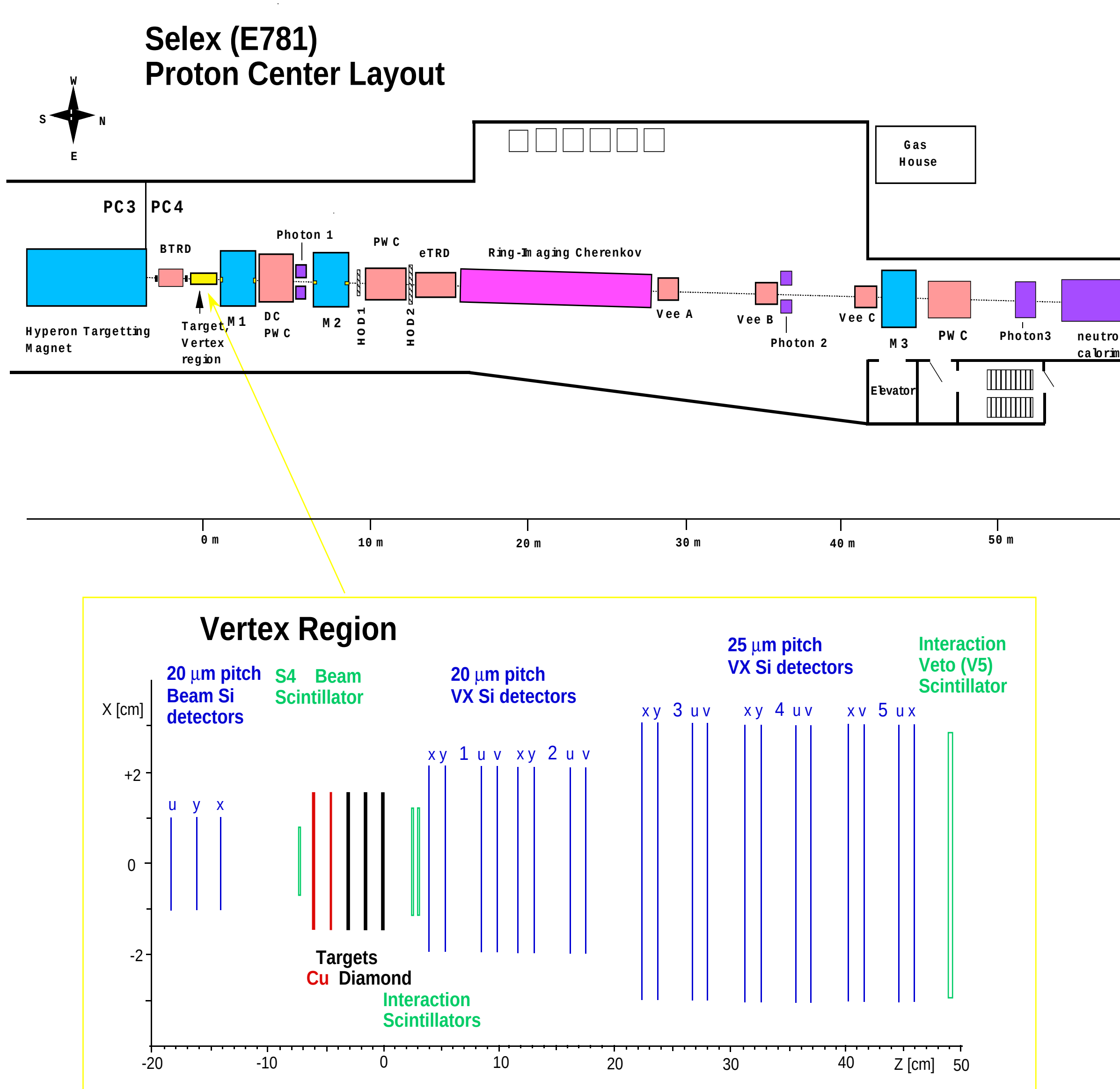
ccd^{+} ccu^{++} ccu^{*++}



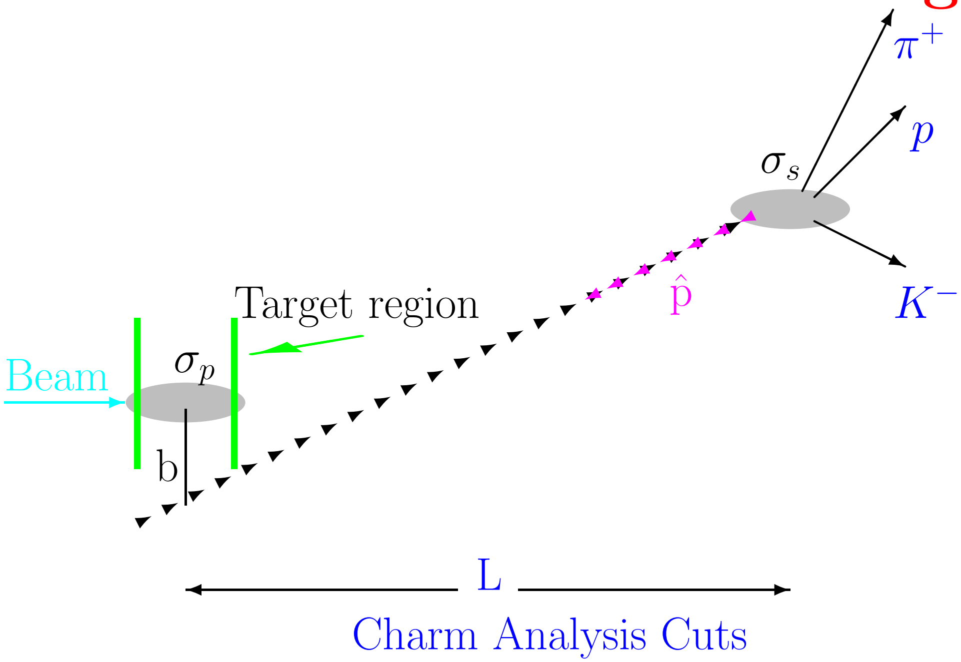
We will concentrate on the low-mass region in today's talk.

SELEX Apparatus Features

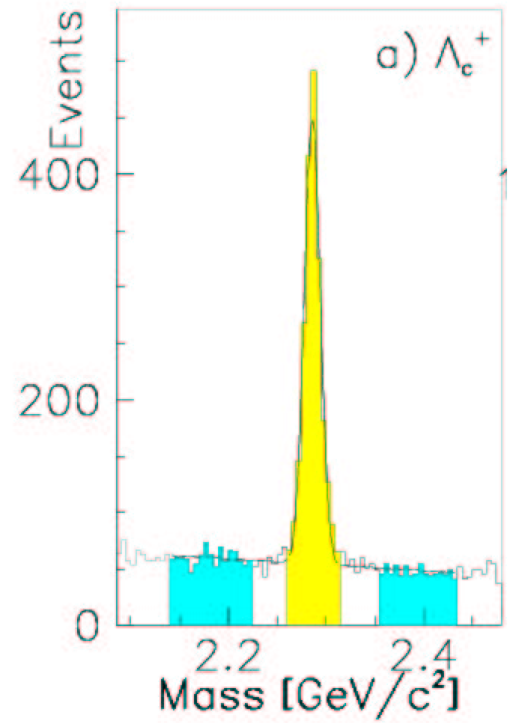
- Forward production
- π, Σ^-, p beams
- typical Lorentz Boost $\sim$ 100
- RICH identification above 25 GeV/c



SELEX Single Charm Analysis

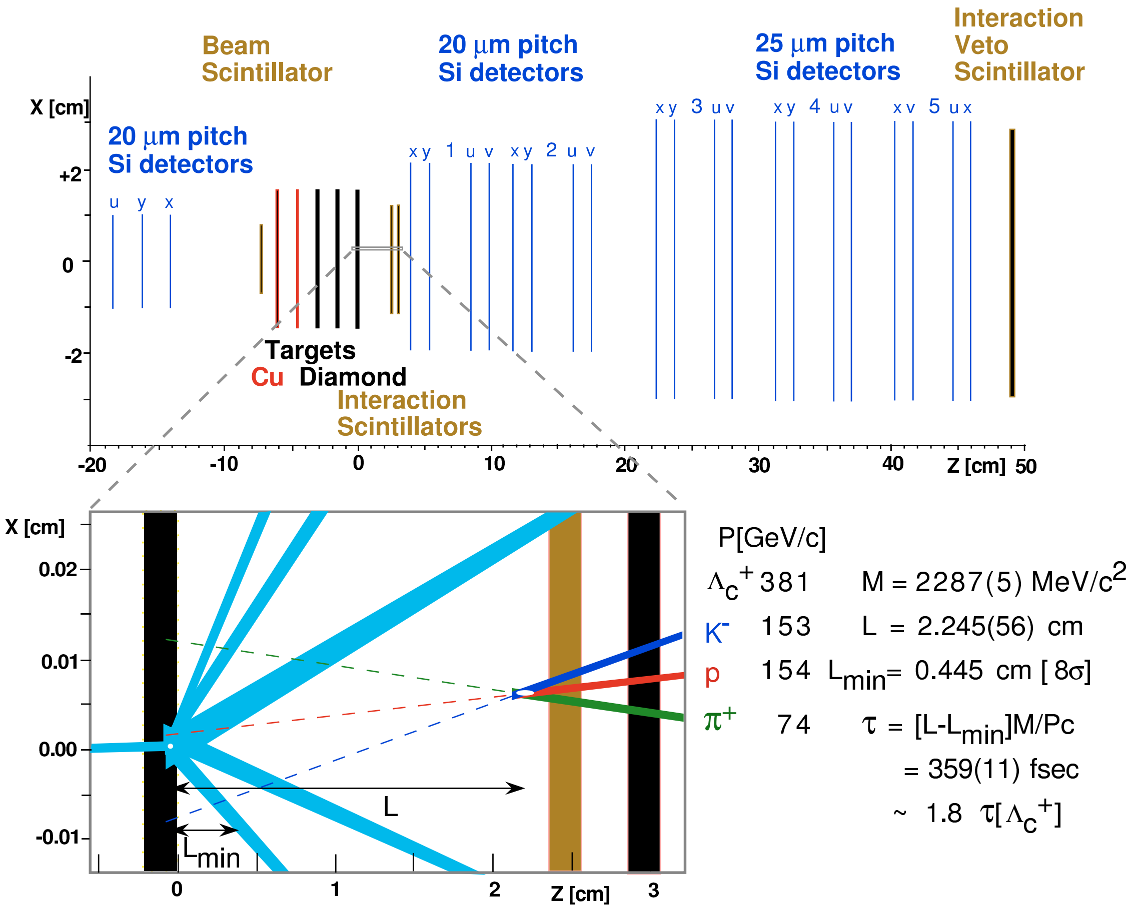


- Decay vertex separation significance L/σ
- Charm vector momentum points back to primary: cut on $(\text{b}/\sigma_\text{b})^2$ (point-back cut)
- Decay vertex lies outside target material (space cut)



- $\Lambda_c^+ \rightarrow p\text{K}^-\pi^+$ lifetime data sample used to search for double charm (1630 events)

SELEX Charm Selection Criteria



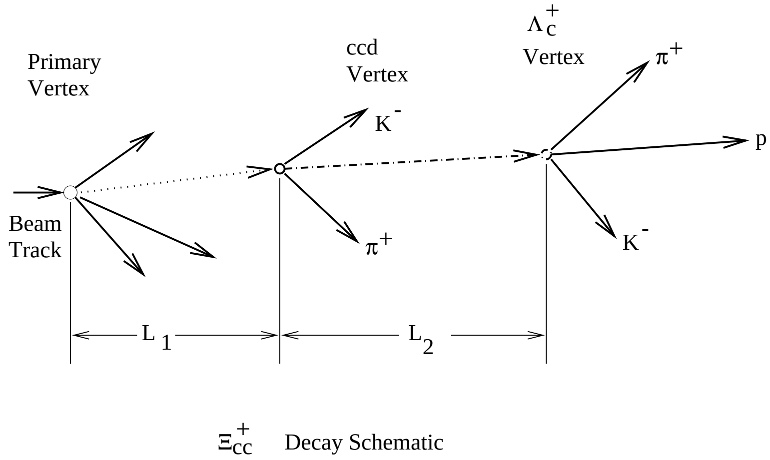
Λ_c^+ event

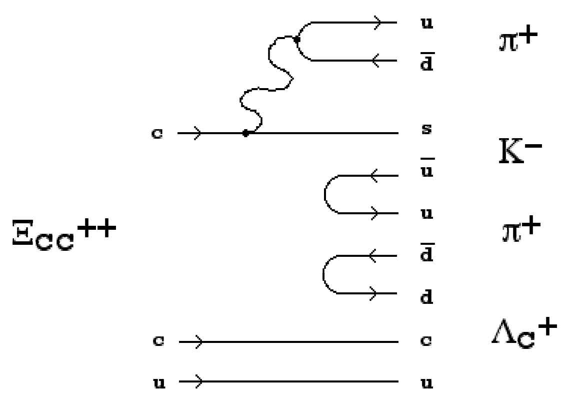
- primary vertex tagged by beam track
- secondary vertex must lie outside material

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: $c \rightarrow s + W^+ \Rightarrow$ **require K^- (not K^+) at second vertex**
- No RICH PID on tracks from second vertex.

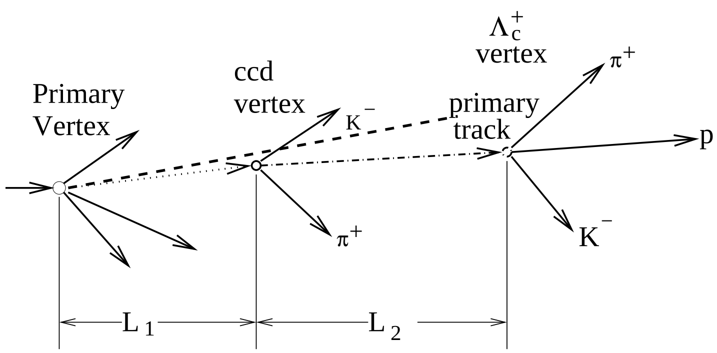
- Made independent data sets to search for ccu^{++} state and ccd^+ state
- Used SELEX $\Lambda_c^+ \rightarrow pK^-\pi^+$ sample with RICH identification required on p, K^-
- search for $K^-\pi^+\pi^+\Lambda_c^+$ vertex between primary vertex and Λ_c^+ decay point

ccu Backgrounds from ccd Candidates

$\Lambda_c^+ K^- \pi^+$ vertex can be boosted to $\Lambda_c^+ K^- \pi^+ \pi^+$ by accidental pickup of a primary-vertex pion

Typical primary vertex pions are 5-20 GeV/c

Typical charm is 150-300 GeV/c; slow pion lies in backward hemisphere in baryon rest frame.



ccd Accidental Boost

Cut on helicity angle in rest frame of decaying state to remove backward excess if seen.

Use Wrong-Sign Background Studies to reject topological accidents

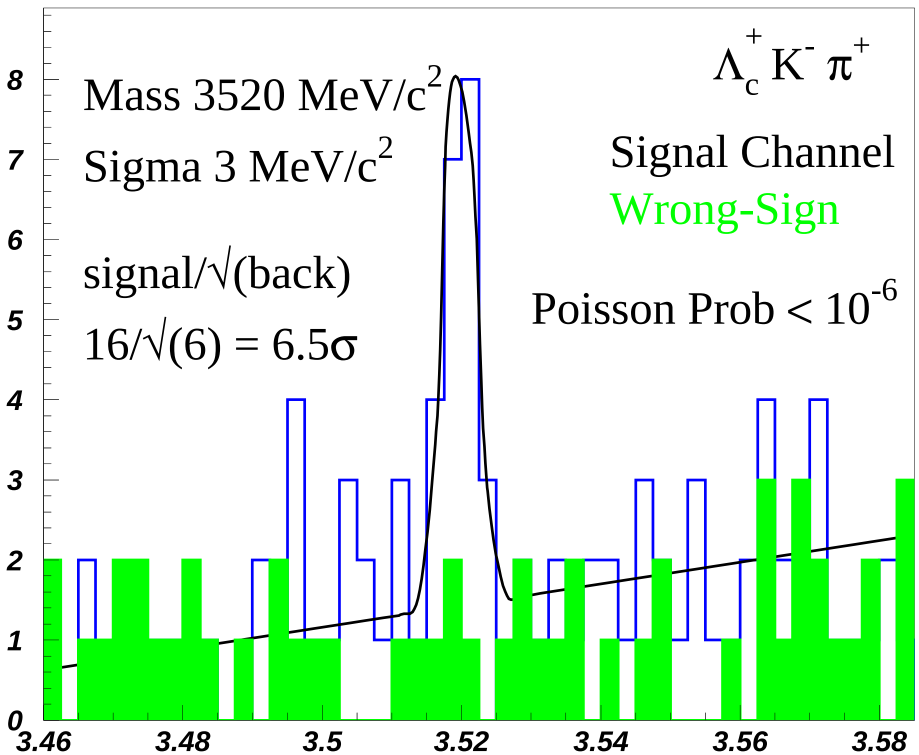
- At intermediate vertex, charge is defined but mass is not
- signal channel has negative track as K^-, positives as pions
- Wrong-Sign Background channel has highest-momentum positive track as K^+, negative track as π^-.
- SELEX data are consistent with charge symmetry for interaction trigger

$Q = +1$ state has one wrong-sign channel

$Q = +2$ state has wrong-sign background from one Q=2 and two Q=0 channels. We average them.

Results from ccd$^+$ Search

$K^-\pi^+\Lambda_c^+$: Phys. Rev. Lett **89**,112001(2002)



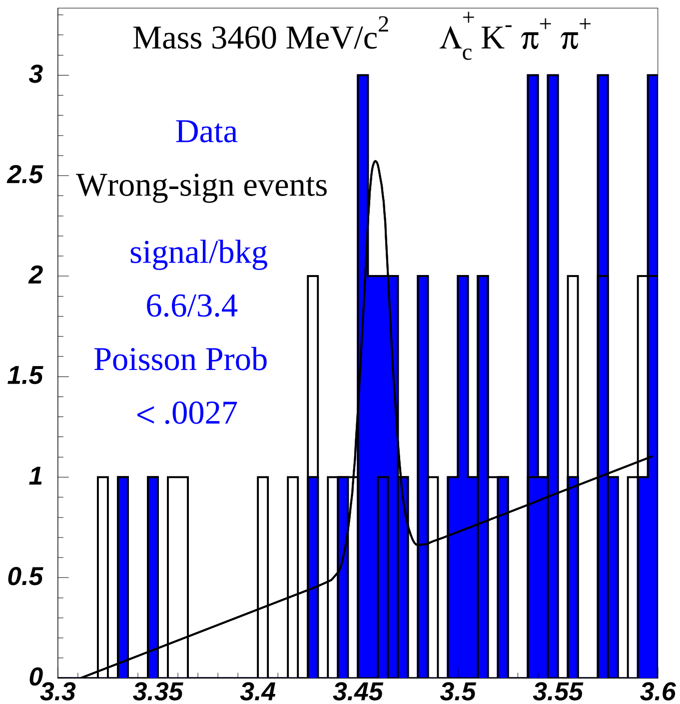
Calculate m(ccd$^+$) using m(Λ_c^+) = 2.2849 GeV/c^2 Poisson Probability for peak anywhere on plot: 1.1×10^{-4}

- Use a baryon to find a baryon: require Λ_c^+ daughter
- look for extra vertex between primary and Λ_c^+ with vertex significance ≥ 1.
- If it's double charm, ccq decay has to make a K^-

Right-sign channel has peak at 3520 MeV/c^2

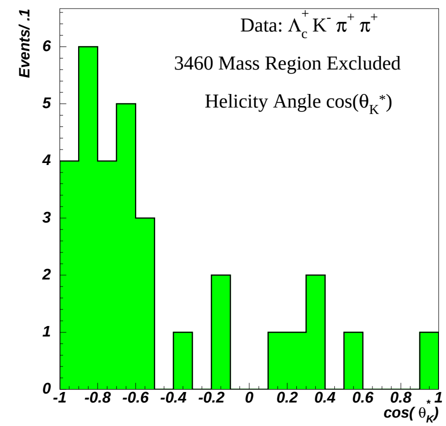
Wrong-sign channel has no significant structure

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



- Almost no events below 3.3 GeV/c^2
- Peak is barely significant and 60 MeV/c^2 from the $ccd^+(3520)$

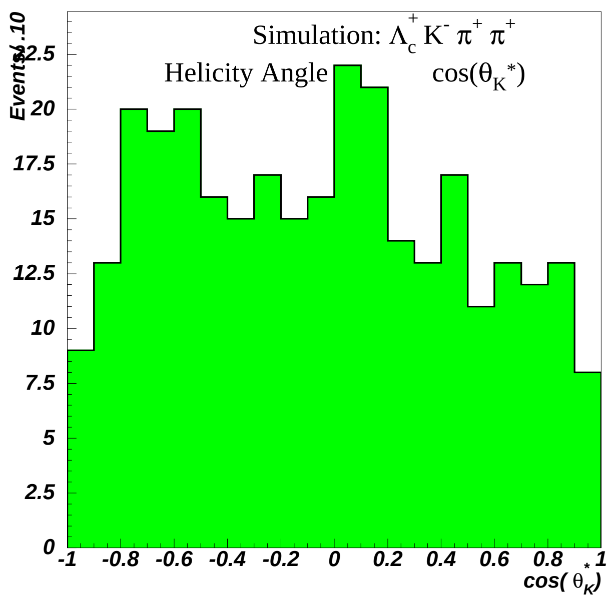
Angular character of SIDEBAND events

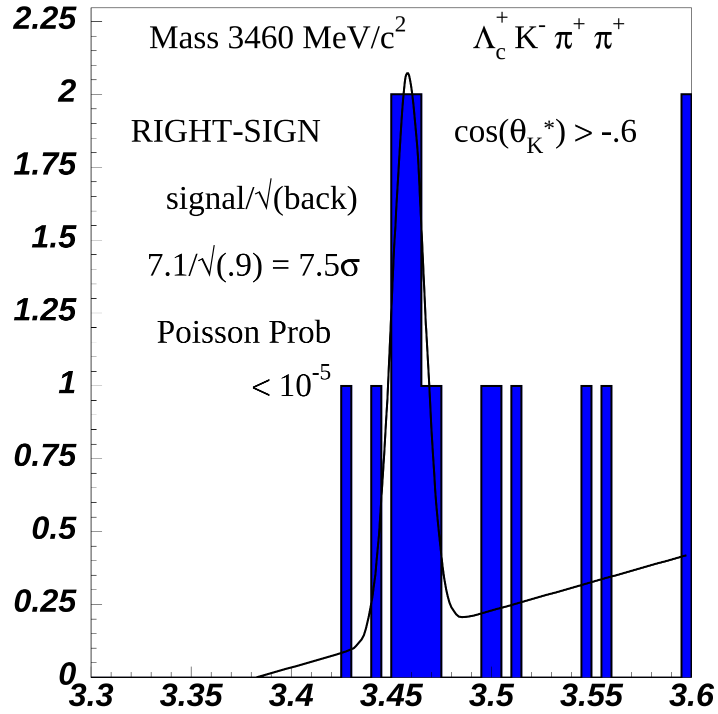


- **Plot K^- Helicity cosine for events outside peak region**
- See backward peak, reminiscent of slow pion accidentally attached to Q=1 vertex
- What is this distribution for the phase space decay of a ccu(3460)?

Phase Space Simulation and Data: $\Xi_{cc}^{++}(3460)$

- Use 4-body phase space to simulate $\Xi_{cc}^{++} \rightarrow K^-\pi^+\pi^+\Lambda_c^+$ signal (S_{MC})
- $B_{tot} \equiv$ total number of background events outside blind signal region
- optimize $\cos(\theta_K^*)$ cut on $S_{MC}/\sqrt{B_{tot}}$





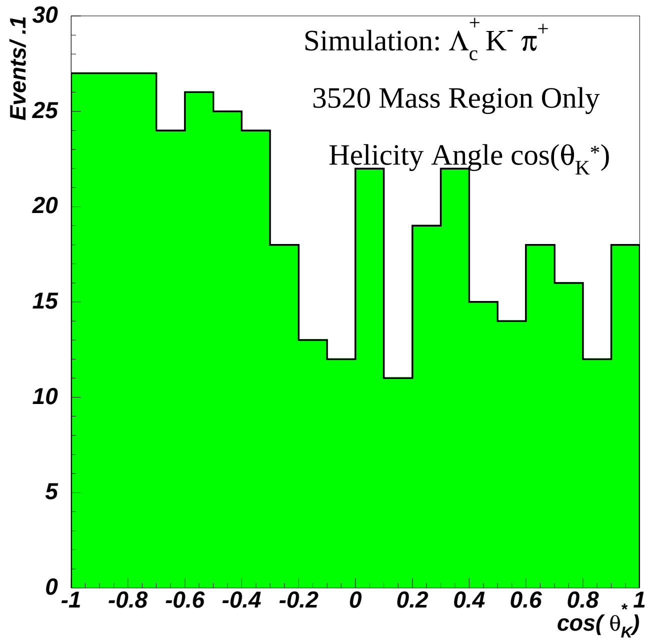
7.4 σ peak at 3460 MeV/c^2 with double-charm decay characteristics

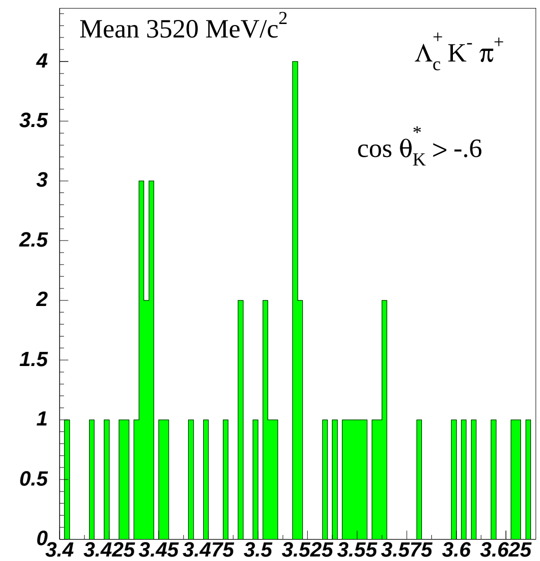
3460 state has angular characteristics consistent with L=0 decay

Can These Two State Be An Isodoublet?

Mass split is huge. Is ccd(3520) decay consistent with being isotropic?

Simulate phase space decay of ccd(3520)





The ccd(3520) peak is strongly attenuated by this angle cut! Signal/bkg: 16/6 (no cut) $\rightarrow$ 5/1

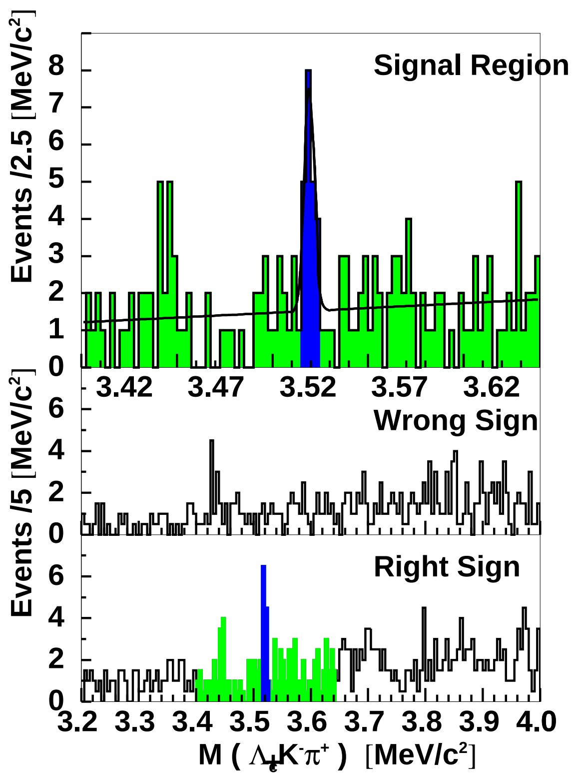
- 80% of simulated events have $\cos(\theta_K^* > -0.6)$

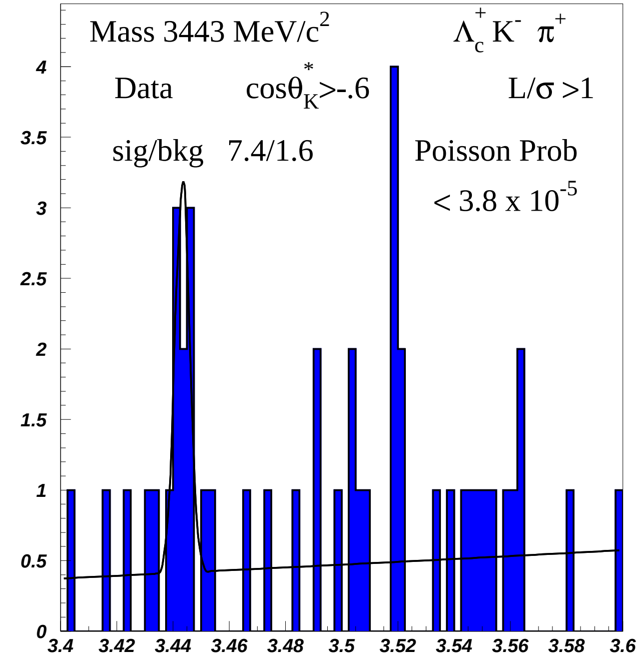
Q=+1 and Q=+2 states appear to have different angular decay characteristics $\Rightarrow$

Not Isodoublet!

A New ccd Candidate

Original ccd publication shows low-mass structure





- Make **same** angular cut that optimized ccu(3460).
- Look again at the ccd mass plot

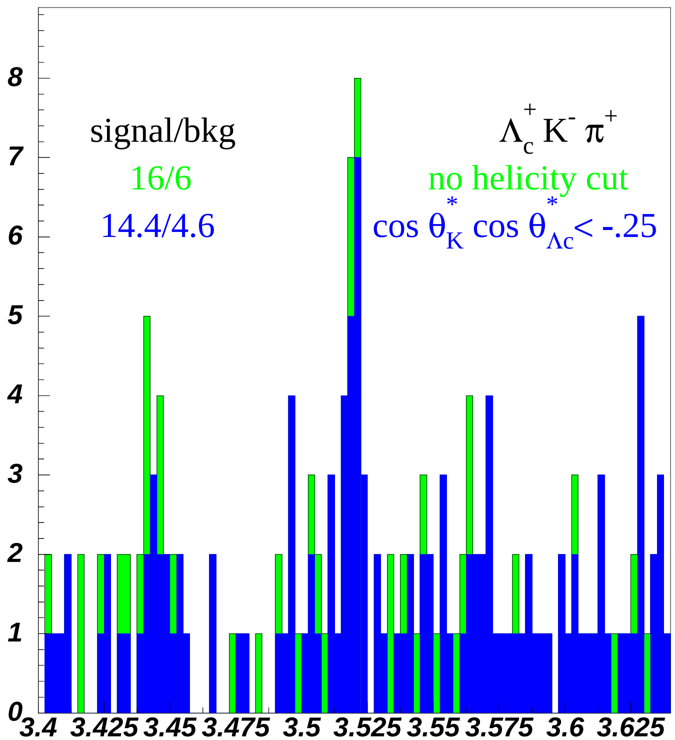
A new ccd(3443) peak with Poisson fluctuation probability $< 3.8 \times 10^{-5}$ stands out.

Q=+1(3443) and Q=+2(3460) states have same angular decay characteristics

Is *this* pair the ground state isodoublet?

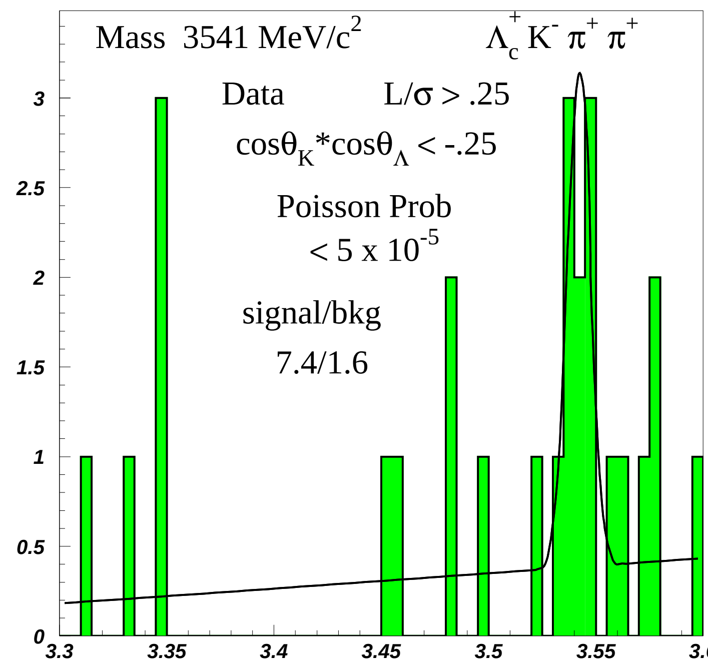
Where Does That Leave the Original ccd(3520)?

We saw that ccd(3520) emits K^- backward



- Cut keeps 90% of ccd(3520) signal

Apply ccd Cut to ccu Mass Distribution



New ccu(3540) peak with Poisson fluctuation probability $< 5 \times 10^{-5}$.

What Have We Just Seen?

The original Ξ_{cc}^{+} candidate now has 3 partners in the same mass region

The four states are arranged as two pairs (isodoublets?) having same mass splitting (20 MeV/c^2), with center of gravity separated by 78 MeV/c^2.

Kaon	Q = +1				Q = +2			
Angular	$\Lambda_c^+ K^- \pi^+$				$\Lambda_c^+ K^- \pi^+ \pi^+$			
Distribution	Mass	N_{signal}	N_{bkg}	Poisson Probability	Mass	N_{signal}	N_{bkg}	Poisson Probability
isotropic	3443	7.4	1.6	$< 3.8 \times 10^{-5}$	3460	7.1	0.9	$< 5 \times 10^{-6}$
backward	3520	16.9	6.1	5.2×10^{-7}	3540	7.4	1.6	$< 5 \times 10^{-5}$

Table 1: SELEX Candidates for Doubly Charmed Baryon States

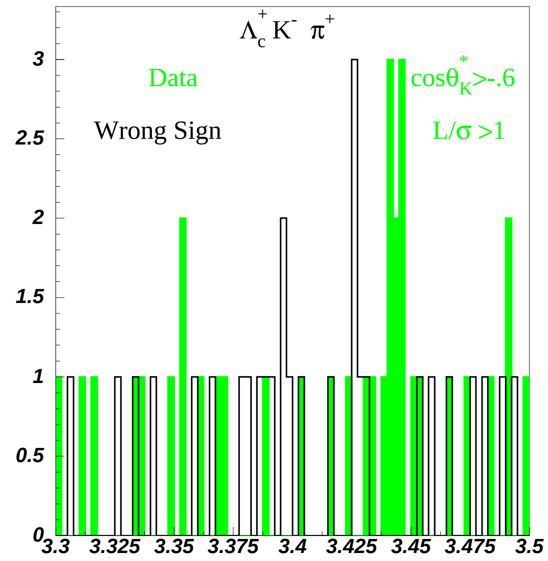
BUT

Both Doublets Decay into the Same Pair of Final States

NOT hyperfine pair - no photonic connection!

Is the New ccd(3443) an Accidental Peak?

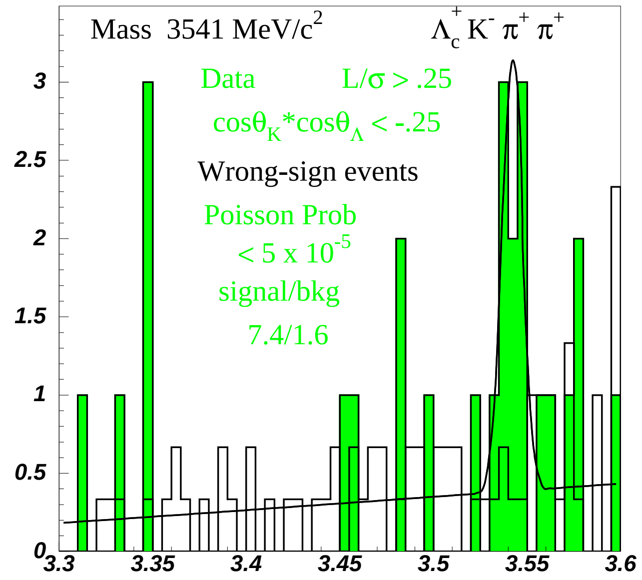
Use Wrong-Sign Events to Test Right-Sign Background Assumption



Wrong-sign background in left plot has 1-bin spike with Poisson fluctuation probability $< 0.8\%$ - we've looked at 300 bins.

Right-sign signal fluctuation probability is 400 times smaller

Is the New ccu(3540) an Accidental Peak?



- ccu(3540) only shows up for reduced L/σ requirement???
- statistical significance independent of L/σ in range 0.1-0.7
- reduced proper time distribution looks same as other channels

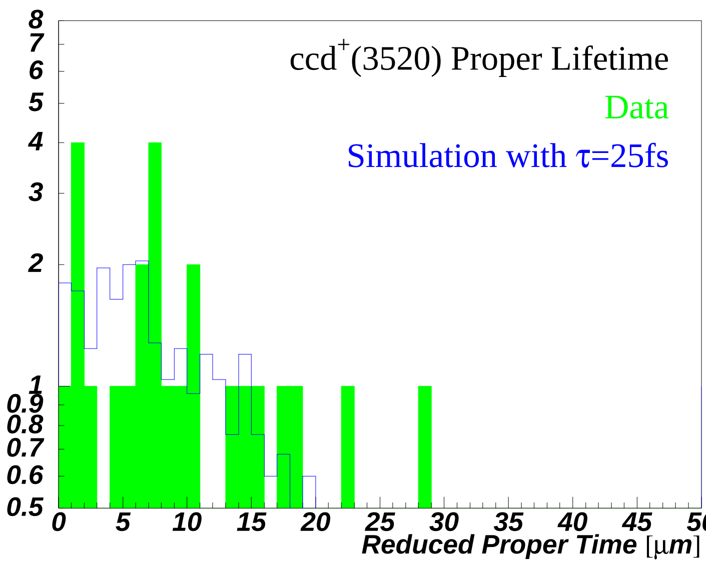
A Side-Step: ccq Lifetimes

SELEX analysis uses reduced proper length

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

l_{min} = sigma for this sample.

Make simulation templates for different lifetimes



ccd(3520) example: blue curve (normalized to 26 events) shows simulation results for 25 fs lifetime

For All 4 States, Average Raw Reduced Proper Time < 100 fs.

Guberina, et al.: Analysis Using HQET + $1/m_Q$ Expansion

- $\tau_{\Xi_{cc}^{+}} \sim 200$ fs
- $\tau_{\Xi_{cc}^{++}} \sim 1000$ fs

Double-charm lifetimes don't seem to follow predictions (low statistics?)

All lifetimes are similar to Ω_c^0 lifetime

In fact SELEX cannot guarantee that the lifetime is non-zero!

How Can the Decay Rate for ccq States Be So Large?

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	8	3	0
ccu(3460) sideband	9	0	0
ccd(3443) signal	6	2	0
ccd(3443) sideband	10	2	1
ccu(3540) signal	7	4	0
ccu(3540) sideband	10	1	1
ccd(3520) signal	18	4	0
ccd(3520) sideband	18	1	1

High-mass states dominantly produced by baryon beams.

Probability of seeing 0 pion events is at 4-5% level per channel - not impossible, but for 4 channels ?.

Production ratio Cu/C $\sim \Lambda_c^+$ data

Within statistics protons are at least as effective as Σ^- in producing these states.

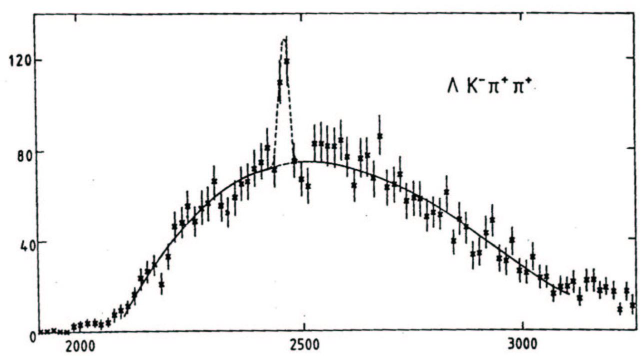
Why Does Only SELEX See These States?

FOCUS has $\sim 12\times$ more Λ_c^+ events and does not see Double Charm

E791 has 2/3 as many Λ_c^+ events and does not see Double Charm

but ... Only SELEX covers forward hemisphere with baryon beams

Recall that the Ξ_c^+ was discovered in a 135 GeV Σ^- beam (WA62) and not seen in photon or pion beams until much later.



Double-charm may not be *sooo* rare:

- Large 4-charm/2-charm production ratios seen in Hybrid Emulsion experiments (π^-, p beams)
- cc/$\bar{c}$c meson pairs $\sim$ 10% in NA32 (forward π^- at 230 GeV/c)

We don't understand ccq production!

ccq states supply $\sim 1/2$ of forward Λ_c^+

Are There Other Interpretations Than Double Charm?

Are ccd^+, ccu^{++} states isodoublets?

I=1/2 baryon isodoublet mass splittings:
$\Delta M = M(I_3{=}-1/2) - M(I_3{=}1/2)$

state	Δm (MeV)	core diquark charge
nucleon	+1.29	+1/3
Ξ	+6.48	-2/3
Ξ_c	$+5.5 \pm 1.8$	+1/3
Ξ_{cc}?	-20 ± 3	+4/3

SELEX states are massive and narrow - like $D_S{}^*$(2317)?

$\Lambda_c^+ K^- \pi^+$ final states have Ξ_c^{+*} quantum numbers ... but as narrow as the CLEO states and 1 GeV/c^2 heavier.

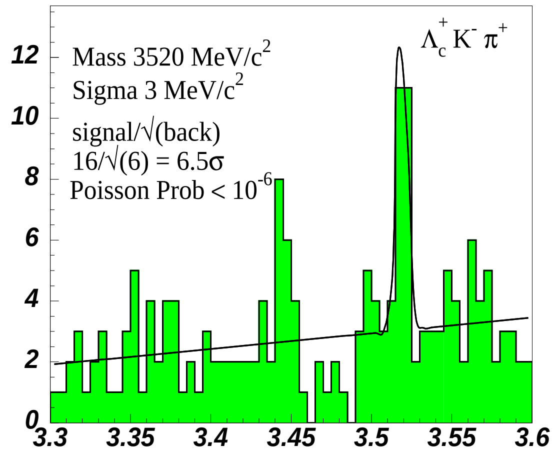
The $\Lambda_c^+ K^- \pi^+ \pi^+$ (Q = 2) final states don't share quantum numbers of any single-charm baryon.

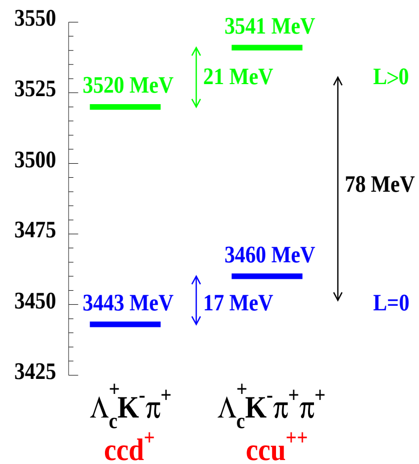
States are numerically weak, statistically strong. What are they if not double charm?

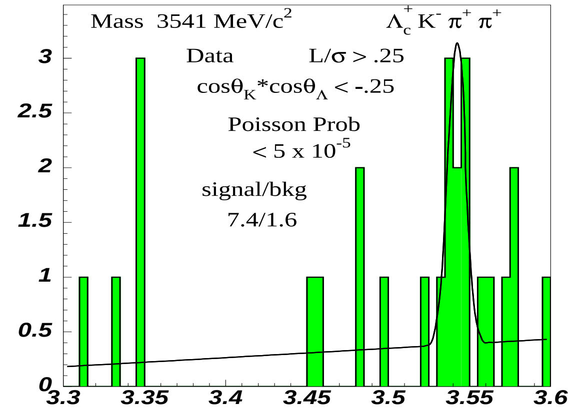
Anther possibility is ($csu\bar{d}q$) family
(Not the favored pentaquark structure!)

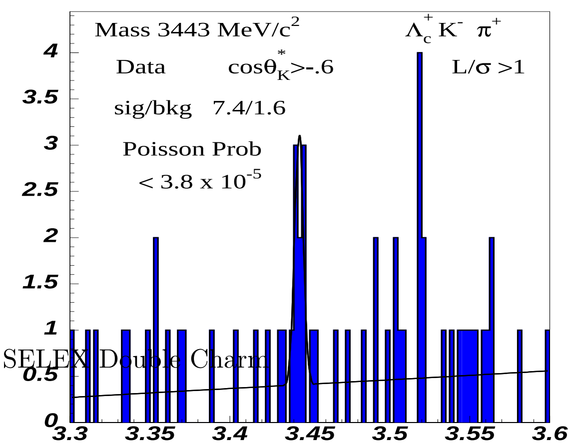
A Reprise

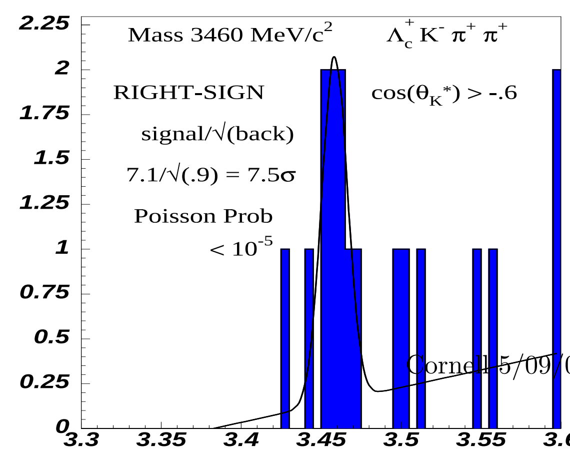
Selex has observed 4 narrow, high-mass peaks in the mass range expected for Double Charm Baryons









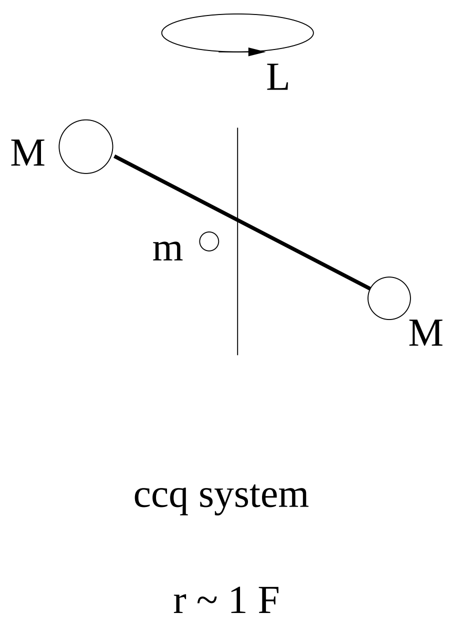


- The four SELEX high-mass states are a pair of pairs with 20 MeV/c^2 mass splitting.
  - lower-mass pair is consistent with L=0 decay
  - higher-mass pair is inconsistent with L=0 decay
- All 4 states decay like doubly-charmed baryons
- Lifetimes are very short for both Q=1 and Q=2 systems
- If pairs are isodoublets, isospin splitting is large

Where do these states fit into our theoretical framework?

Non-Relativistic QED Ideas and Recent QCD Analysis

Born-Oppenheimer L=0,1 Doublet



- Homopolar diatomic molecules have zero E1 moment (infrared impotent).
- By symmetry cc pair has no E1 moment ⇒ **NO L=1→0 EM TRANSITION**

Can B-O QCD treatment keep L=0,1 assignments for lowest two levels?

QCD View - QQq Hyperfine Doublet

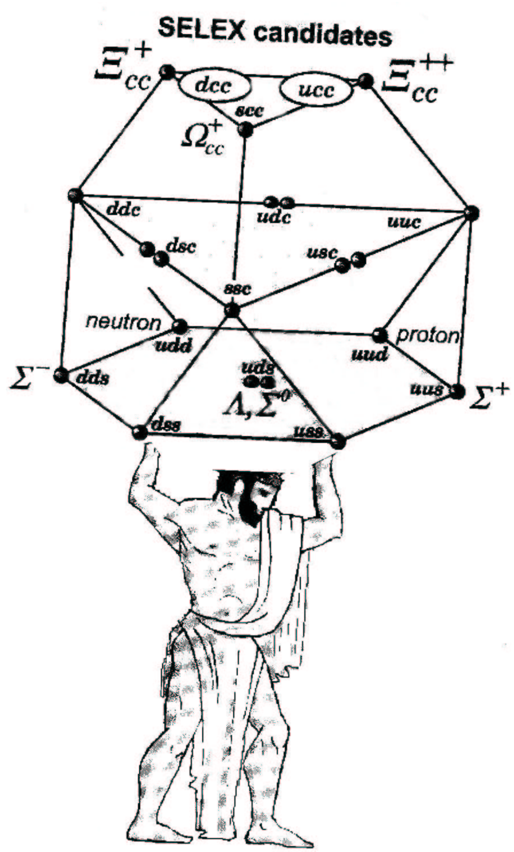
Bardeen, Eichten, and Hill (hep-ph/0305049) discuss QQq baryon multiplet levelss

- ccq hyperfine doublet $(1/2^+, 3/2^+)$ split by 78 MeV/c^2
- M1 EM transitions are strongly suppressed by chiral structure ⇒ weak decays from J=3/2 may be OK
- splittings match beautifully to SELEX data

In this picture SELEX data are the ground state hyperfine quartet of states of the ccu and ccd double charmed baryon family

The Final Word for Today

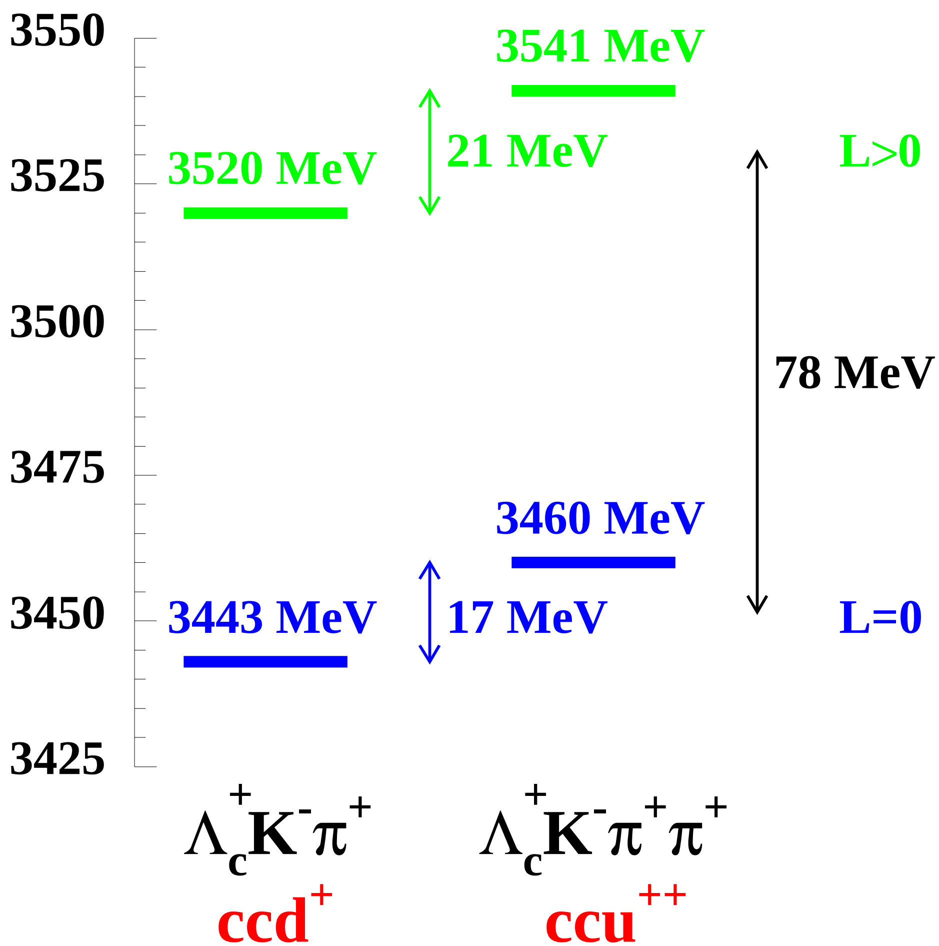
Additional support would be nice

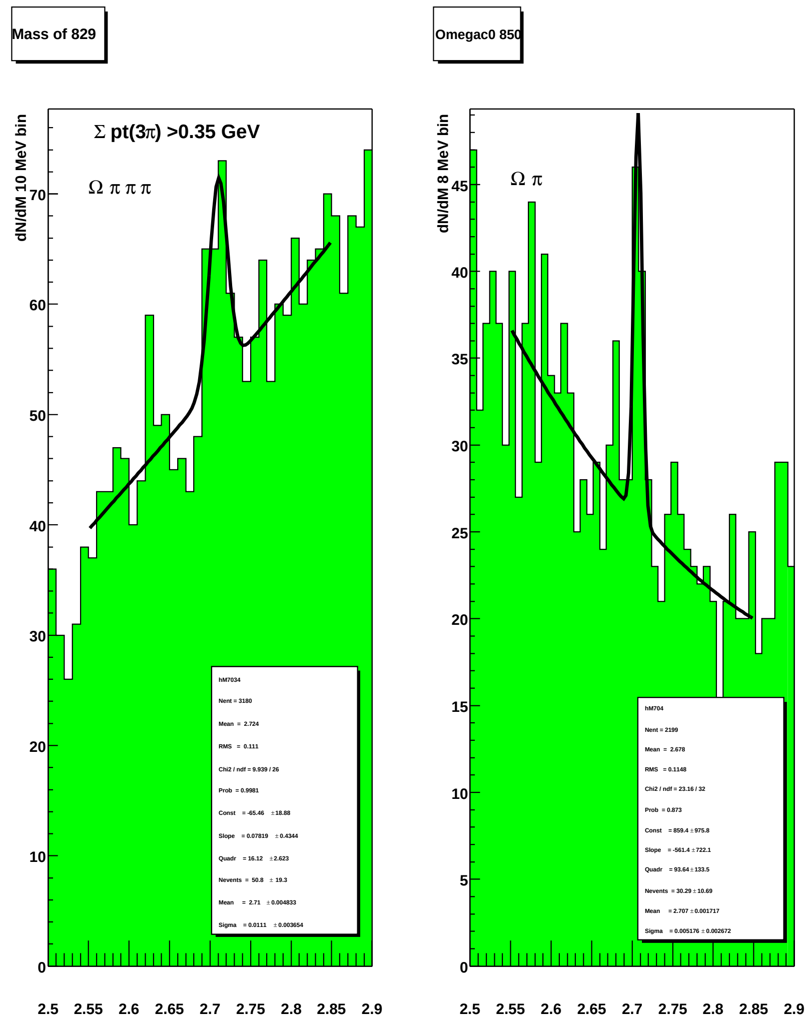


... but it may take awhile.

- FOCUS does not see double-charm baryons from photoproduction (12x more events)
- pion beams don't seem to be productive
- e^+e^- observation of Ξ_c^+ took 6 years after CERN publication
- There are not many places with 600 GeV proton beams these days

For now SELEX is looking at alternative modes: $D^+pK^-(\pi^+)$, $D^0pK^-\pi^+$, $\Xi_c^+\pi^+\pi^-(\pi^+)$


3550
3525
3500
3475
3450
3425
3541 MeV
3520 MeV
21 MeV
L>0
78 MeV
3460 MeV
3443 MeV
17 MeV
L=0
$\Lambda_c^+ K^- \pi^+$
$\Lambda_c^+ K^- \pi^+ \pi^+$
ccd$^+$
ccu^{++}


Mass of 829
Σ pt(3π) >0.35 GeV
Ω π π π
dN/dM 10 MeV bin
hM7034
Nent = 3180
Mean = 2.724
RMS = 0.111
Chi2 / ndf = 9.939 / 26
Prob = 0.9981
Const = -65.46 ± 18.88
Slope = 0.07819 ± 0.4344
Quadr = 16.12 ± 2.623
Nevents = 50.8 ± 19.3
Mean = 2.71 ± 0.004833
Sigma = 0.0111 ± 0.003654
Omegac0 850
Ω π
dN/dM 8 MeV bin
hM704
Nent = 2199
Mean = 2.678
RMS = 0.1148
Chi2 / ndf = 23.16 / 32
Prob = 0.873
Const = 859.4 ± 975.8
Slope = -561.4 ± 722.1
Quadr = 93.64 ± 133.5
Nevents = 30.29 ± 10.69
Mean = 2.707 ± 0.001717
Sigma = 0.005176 ± 0.002672