The Double Charm Baryon Family at SELEX
An Update

James S. Russ
Physics Department
Carnegie Mellon University
Pittsburgh, PA
for the SELEX Collaboration

Outline

- Last Year's SELEX Double Charm Status
- (very!)Brief Theory Review
- Selex Single-Charm Baryon Review
- Observation of New High Mass States
- Double-Charm Baryon Spectroscopy

The SELEX Collaboration

G.P. Thomas
Ball State University, Muncie, IN 47306, U.S.A.
E. Gülmez
Bogazici University, Bebek 80815 Istanbul, Turkey
R. Edelstein, S.Y. Jun, A.I. Kulyavtsev[1], A. Kushnirenko, D. Mao[1], P. Mathew[2], M. Mattson, M. Procario[3], J. Russ, J. You[4]
Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.
A.M.F. Endler
Centro Brasiliero de Pesquisas Físicas, Rio de Janeiro, Brazil
P.S. Cooper, J. Kilmer, S. Kwan, J. Lach, E. Ramberg, D. Skow, L. Stutte
Fermilab, Batavia, IL 60510, U.S.A.
V.P. Kubarovsky, V.F. Kurshetsov, A.P. Kozhevnikov, L.G. Landsberg, V.V. Molchanov, S.B. Nurushev, S.I. Petrenko, A.N. Vasiliev, D.V. Vavilov, V.A. Victorov
Institute for High Energy Physics, Protvino, Russia
Li Yunshan, Mao Chensheng, Zhao Wenheng, He Kangling, Zheng Shuchen, Mao Zhenlin
Institute of High Energy Physics, Beijing, P.R. China
M.Y. Balatz[5], G.V. Davidenko, A.G. Dolgolenko, G.B. Dzyubenko, A.V. Evdokimov, M.A. Kubantsev, I. Larin, V. Matveev, A.P. Nilov, V.A. Prutskoi, A.I. Sitnikov, V.S. Verebryusov, V.E. Vishnyakov
Institute of Theoretical and Experimental Physics, Moscow, Russia
U. Dersch[6], I. Eschrich[7], I. Konorov[8], H. Krüger[9], J. Simon[10], K. Vorwalter[11]
Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
I.S. Filimonov[5], E.M. Leikin, A.V. Nemitkin, V.I. Rud
Moscow State University, Moscow, Russia
A.G. Atamantchouk, G. Alkhazov, N.F. Bondar, V.L. Golovtsov, V.T. Kim, L.M. Kochenda, A.G. Krivshich, N.P. Kuropatkin, V.P. Maleev, P.V. Neoustroev, B.V. Razmyslovich, V. Stepanov, M. Svoiski, N.K. Terentyev[12], L.N. Uvarov, A.A. Vorobyov
Petersburg Nuclear Physics Institute, St. Petersburg, Russia

I. Giller, M.A. Moinester, A. Ocherashvili, V. Steiner
Tel Aviv University, 69978 Ramat Aviv, Israel

J. Engelfried[4], A. Morelos
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

M. Luksys
Universidade Federal da Paraíba, Paraíba, Brazil

V.J. Smith
University of Bristol, Bristol BS8 1TL, United Kingdom

M. Kaya, E. McCliment, K.D. Nelson[13], C. Newsom, Y. Onel, E. Ozel, S. Ozkorucuklu, P. Pogodin
University of Iowa, Iowa City, IA 52242, U.S.A.

L.J. Dauwe
University of Michigan-Flint, Flint, MI 48502, U.S.A.

M. Gaspero, M. Iori
University of Rome "La Sapienza" and INFN, Rome, Italy

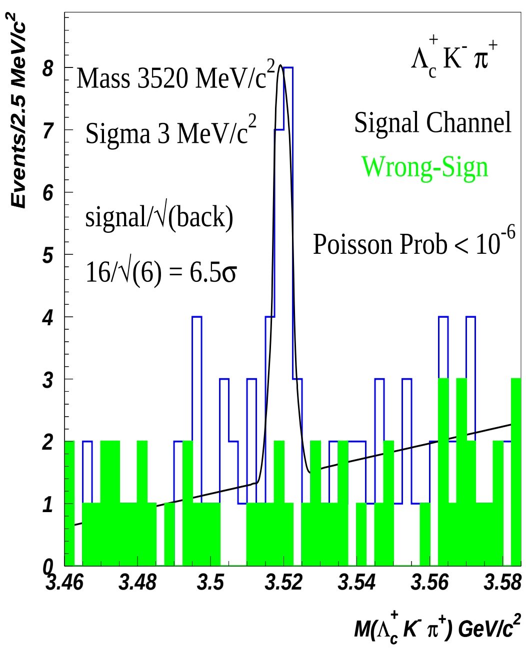
L. Emediato, C.O. Escobar[14], F.G. Garcia[4], P. Gouffon, T. Lungov[15], M. Srivastava, R. Zukanovich-Funchal
University of São Paulo, São Paulo, Brazil

A. Lamberto, A. Penzo, G.F. Rappazzo, P. Schiavon
University of Trieste and INFN, Trieste, Italy

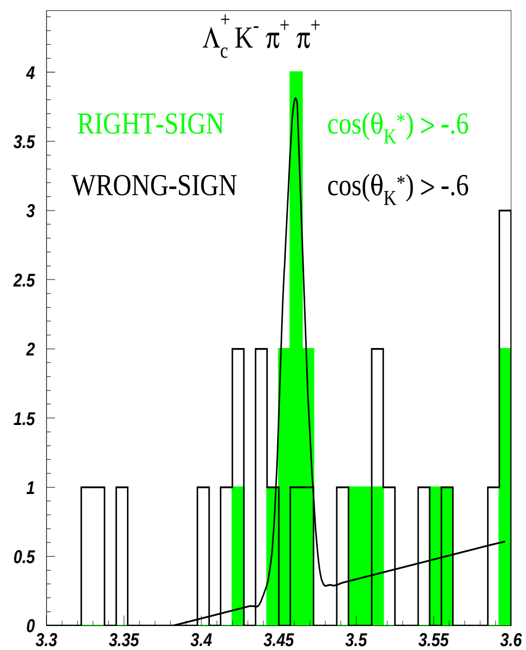
Experimental Evidence - Wine and Cheese, May, 2002

Selex reported 3 significant high-mass peaks

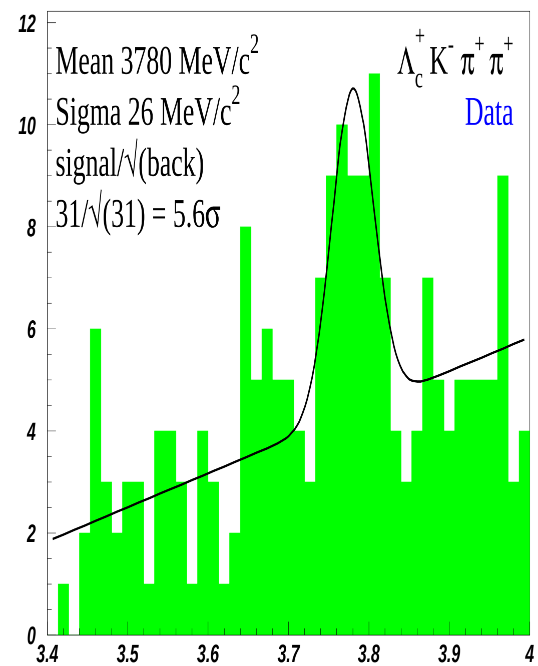
ccd^+



ccu^{++}

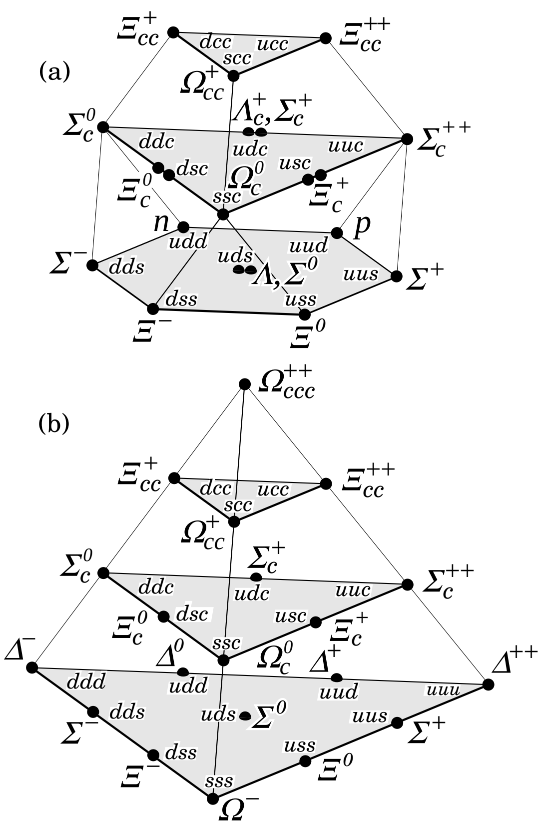


ccu^{*++}



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

Flavor-Independent QCD Demands Double-Charm Baryons

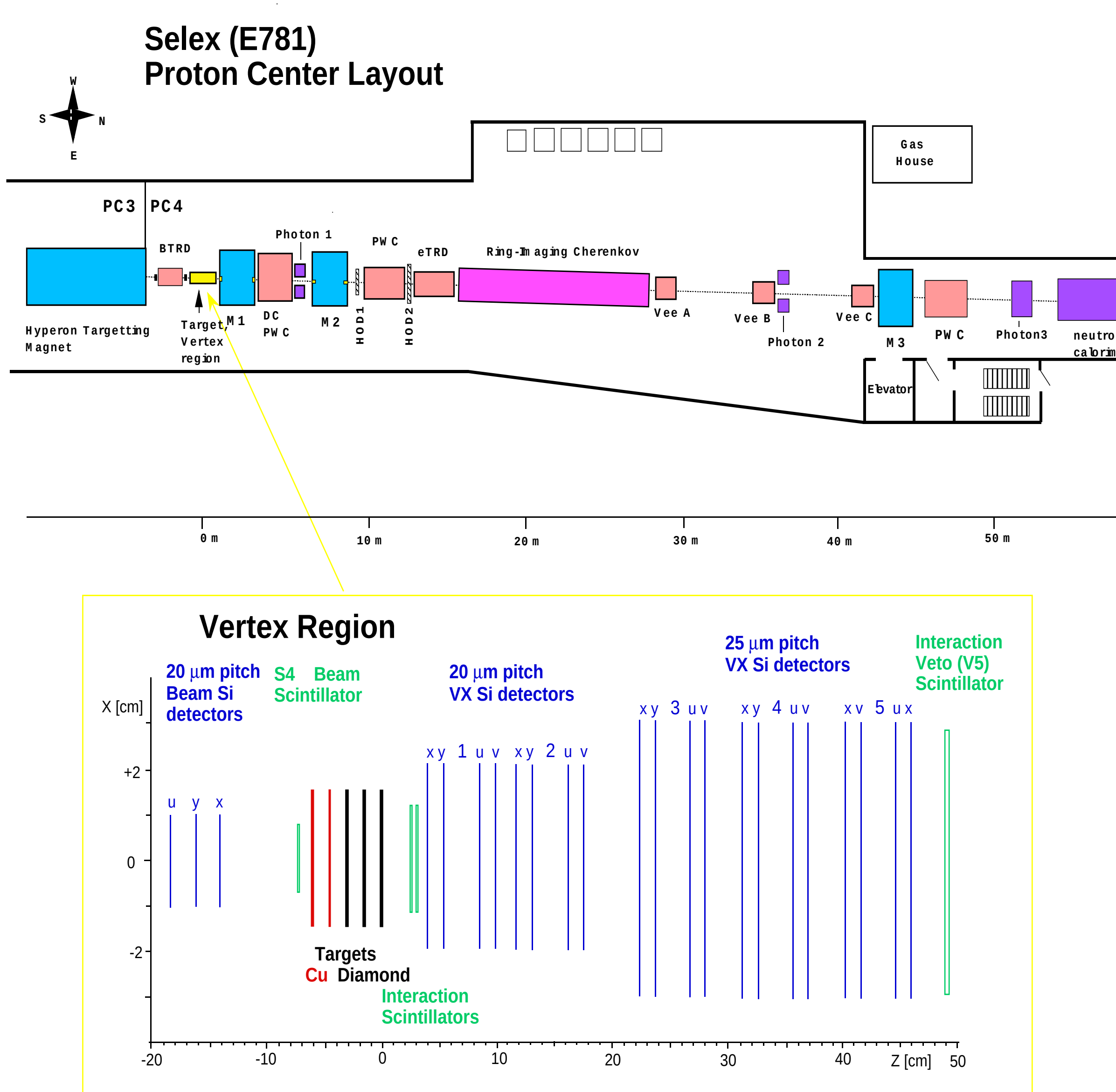


SU(4) Baryon Multiplets

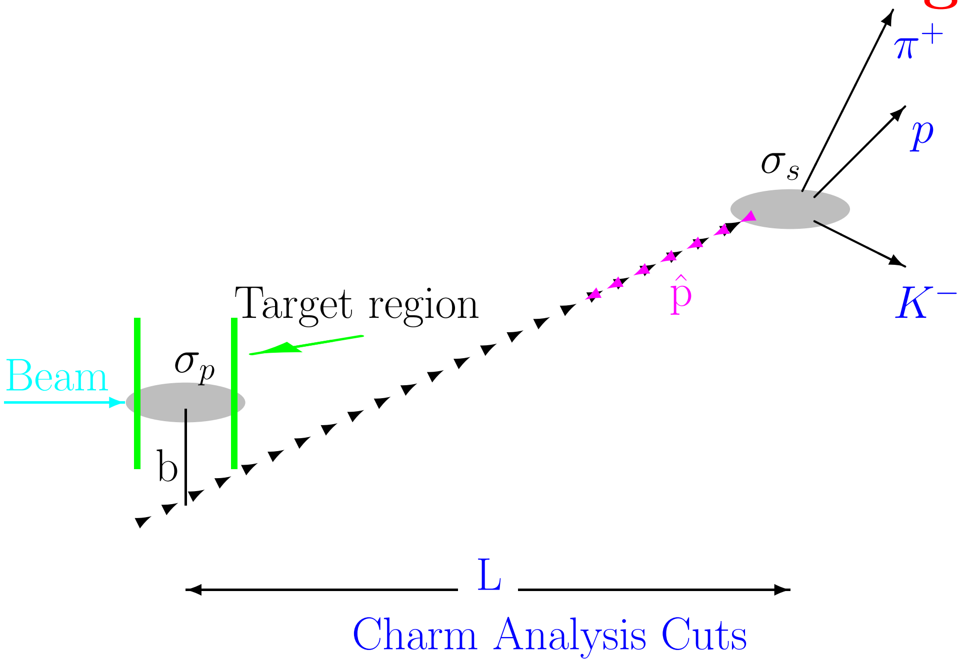
- Broken SU(4) classifies baryon states.
- Potential model calculations - ground states $\sim$ 3.5-3.6 GeV/c^2
- Potential Models: Hyperfine splits $\sim$ 70 MeV
- Savage and Wise: Light Quark Excitation Characteristics $\sim$ meson spectra
- finite $m_c \rightarrow$ 3-body effects (H_2^+ molecule)

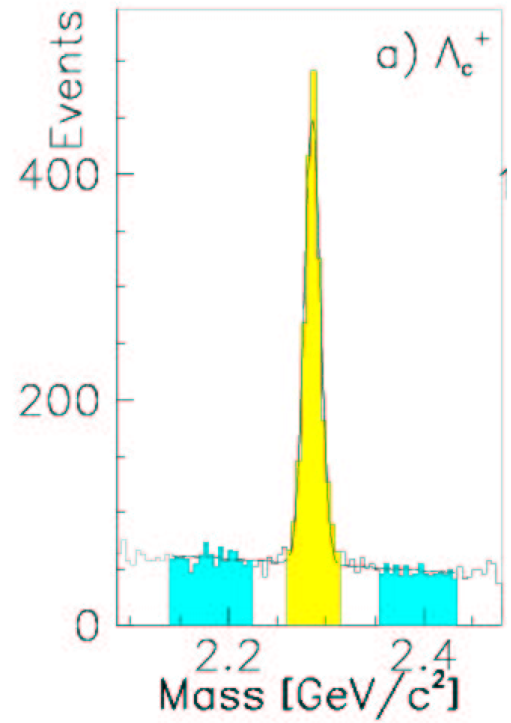
SELEX Apparatus Features

- Forward production: $p_t < 3$ GeV/c
- typical Lorentz Boost ~ 100
- π, Σ^-, p beams
- RICH identification above 25 GeV/c
- decay proper time resolution ~ 18 fs



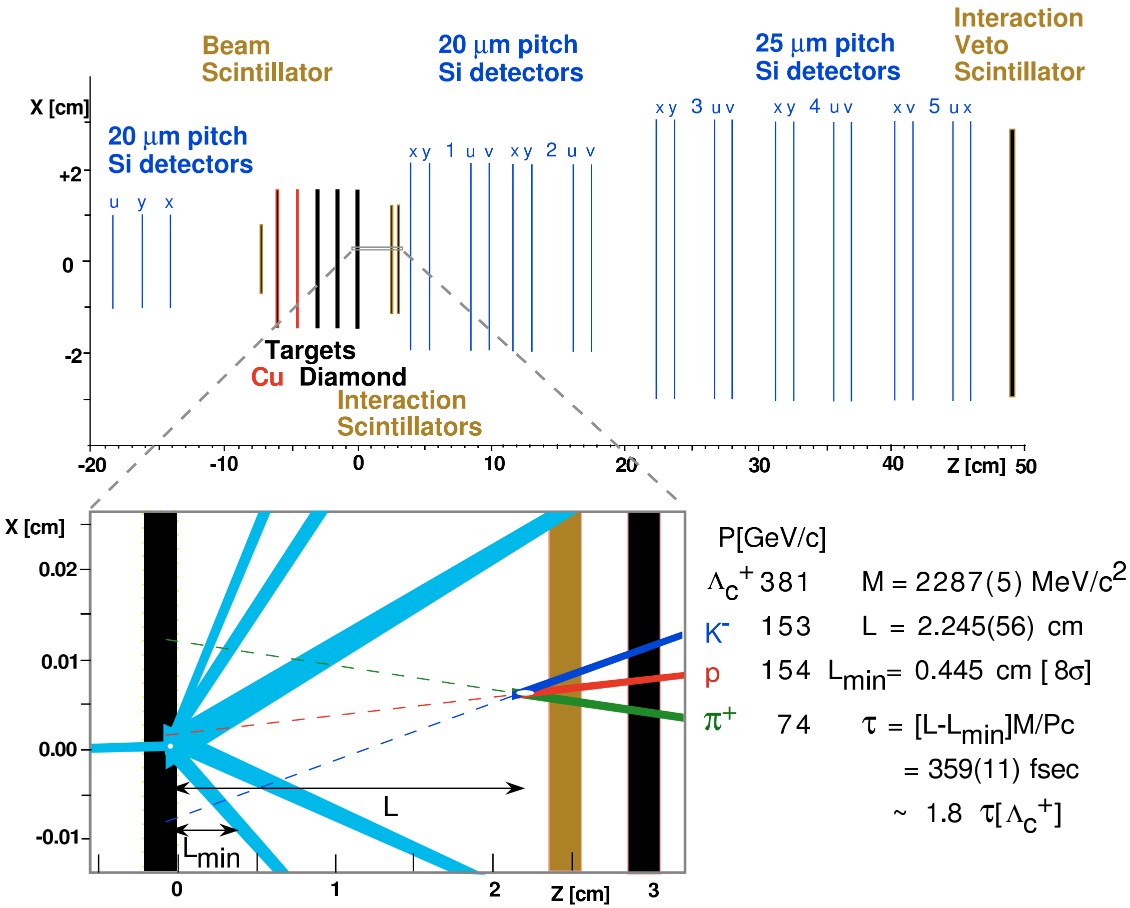
SELEX Single Charm Analysis





- Decay vertex separation significance L/σ
- Charm vector momentum points back to primary: cut on $(\mathrm{b}/\sigma_{\mathrm{b}})^2$ (point-back cut)
- Decay vertex lies outside target material (space cut)
- $\Lambda_c^+ \rightarrow p\mathrm{K}^-\pi^+$ lifetime data sample used to search for double charm (1630 events)

SELEX Charm Selection Criteria



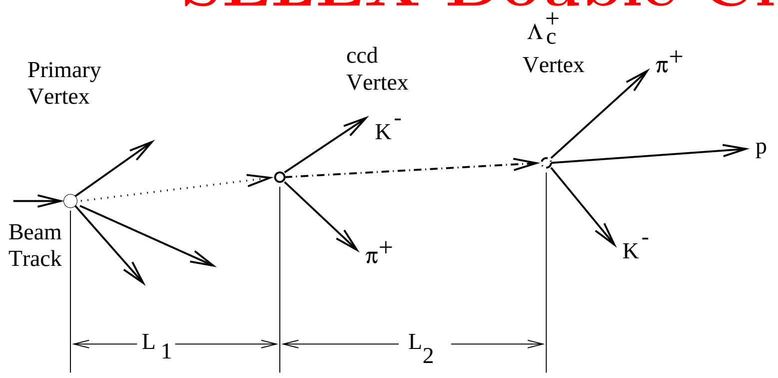
Λ_c^+ event

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

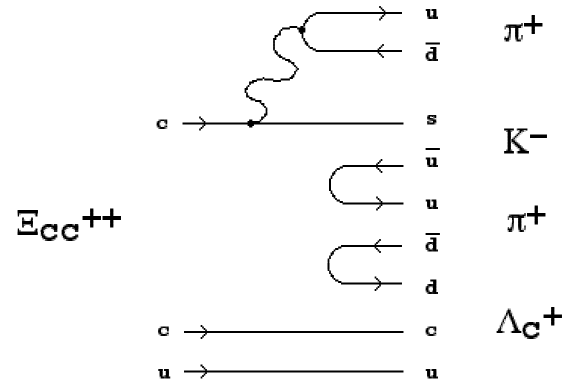
Charm Selection Cuts for single charm studies:

- 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



Ξ_{cc}^+ Decay Schematic



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.

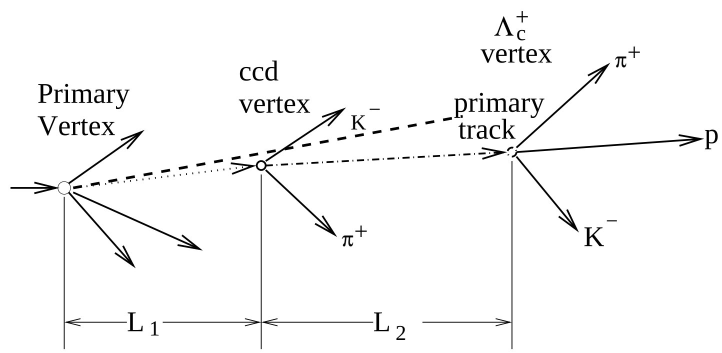
- Made independent data sets to search for ccu^{++} state and ccd^+ state
- Used SELEX $\Lambda_c^+ \rightarrow pK^-\pi^+$ sample with RICH identification required on p, K^-
- search for $K^-\pi^+\pi^+\Lambda_c^+$ vertex between primary vertex and Λ_c^+ decay point

ccu Backgrounds from ccd Candidates

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

Typical primary vertex tracks are 5-20 GeV/c

Typical charm is 150-300 GeV/c; slow track 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

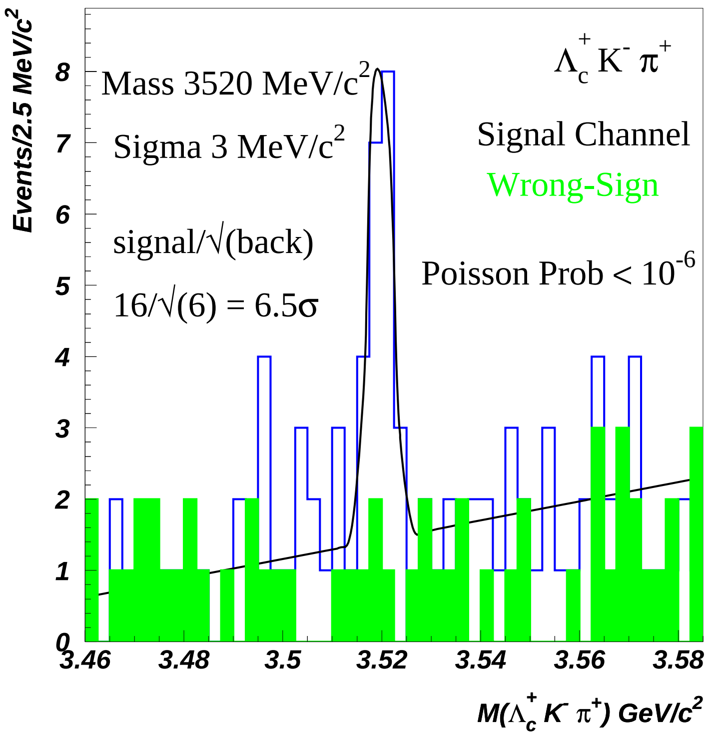
- At intermediate vertex, charge is defined but mass is not
- signal channel has negative track as K^-, positives as pions
- Wrong-Sign Background channel has highest-momentum positive track as K^+, negative track as π^-.
- SELEX data are consistent with charge symmetry for interaction trigger

$Q = +1$ 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)



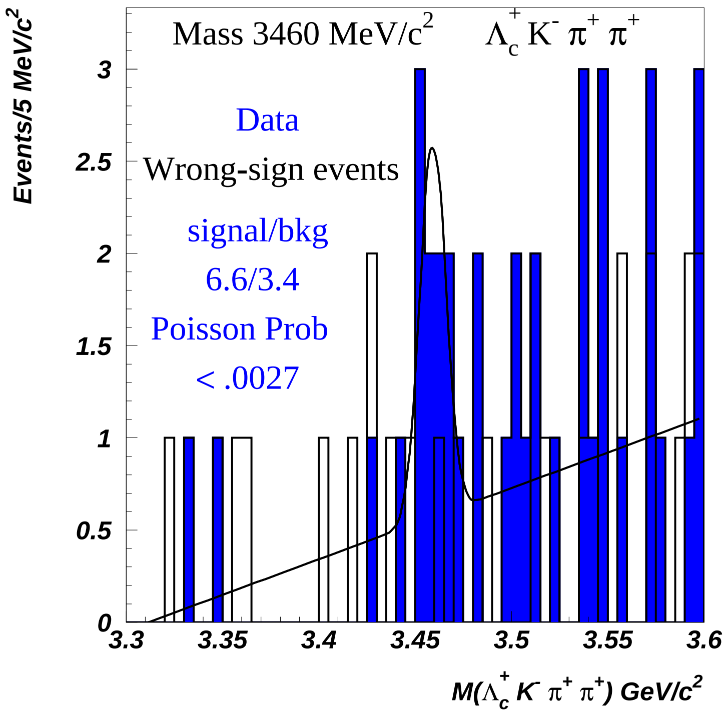
Calculate m(ccd$^+$) using m(Λ_c^+) = 2.2849 GeV/c^2 Poisson Probability for peak anywhere on plot: 1.1×10^{-4}

- 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^-
- Results confirmed by two independent, different analysis methods

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

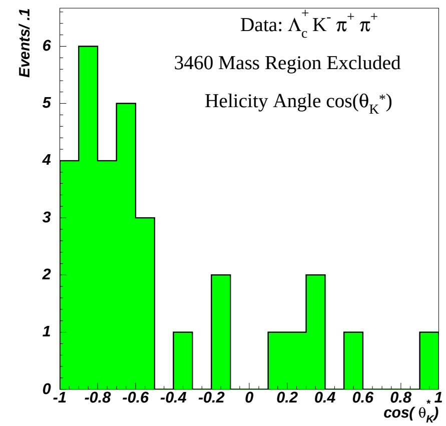
Wrong-sign channel has no significant structure

Where is the Partner ccu^{++} State?



- Look in mass window around 3.5 GeV/c^2
- Barely significant peak 60 MeV/c^2 from the $ccd^+(3520)$

Check angular character of SIDEBAND events

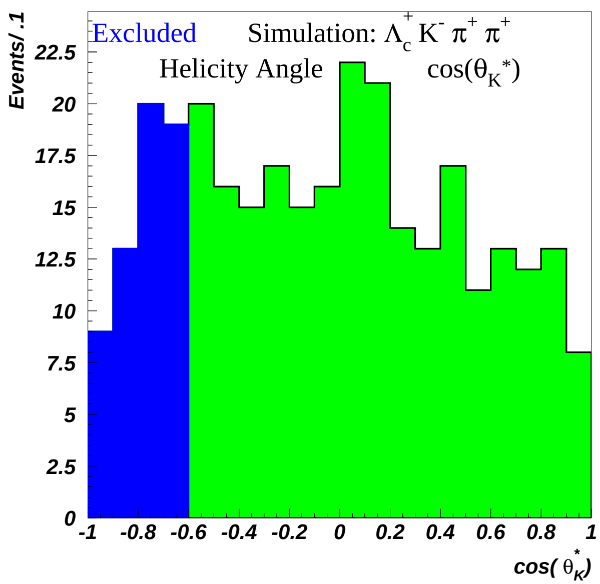


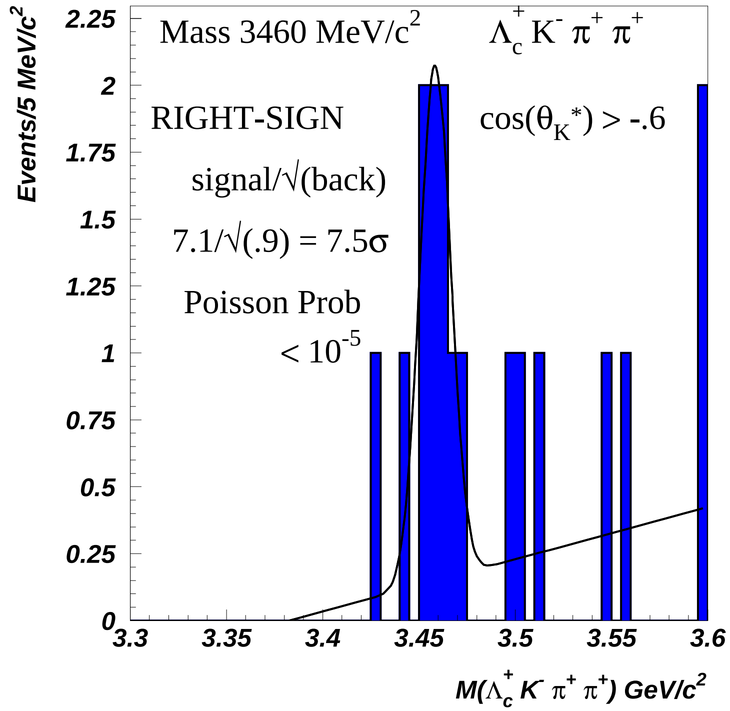
- **Plot K^- Helicity cosine for events outside peak region**
- See backward peak, reminiscent of slow pion accidentally attached to Q=1 vertex

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





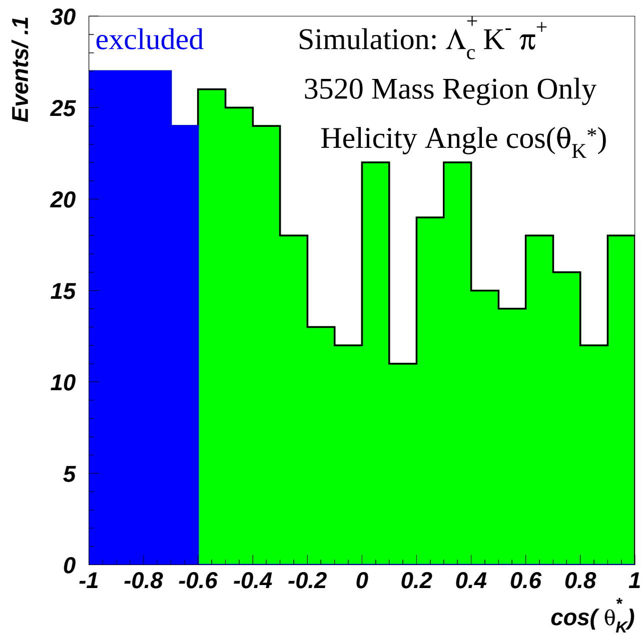
7.4 σ peak at 3460 MeV/c^2 with double-charm decay characteristics

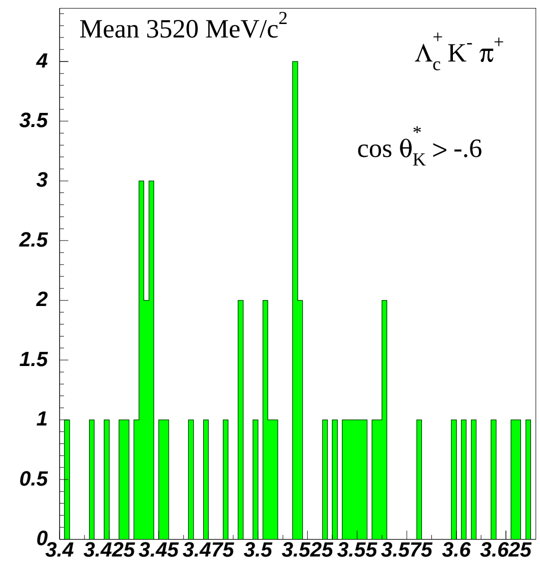
3460 state has angular characteristics consistent with phase space (L=0) decay

Can These Two States Be An Isodoublet?

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

Simulate phase space decay of ccd(3520)





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

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

Q=+1 and Q=+2 states appear to have different angular decay characteristics $\Rightarrow$
Not Isodoublet!

Are These States ccq Baryons?

- 3460 MeV/c^2 state decays isotropically - consistent with L=0 and consistent with decay of unpolarized baryon ground state. (Recall production has small p_t.)

- 3520 MeV/c^2 state appears to have non-zero angular momentum in its decay

There must be more states in this mass region if these are ccq systems

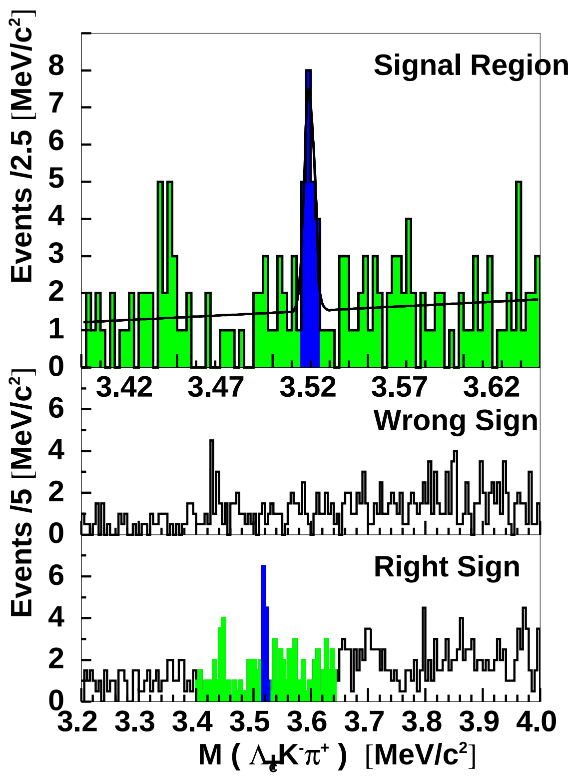
- Use angular asymmetry cuts to re-examine mass spectrum

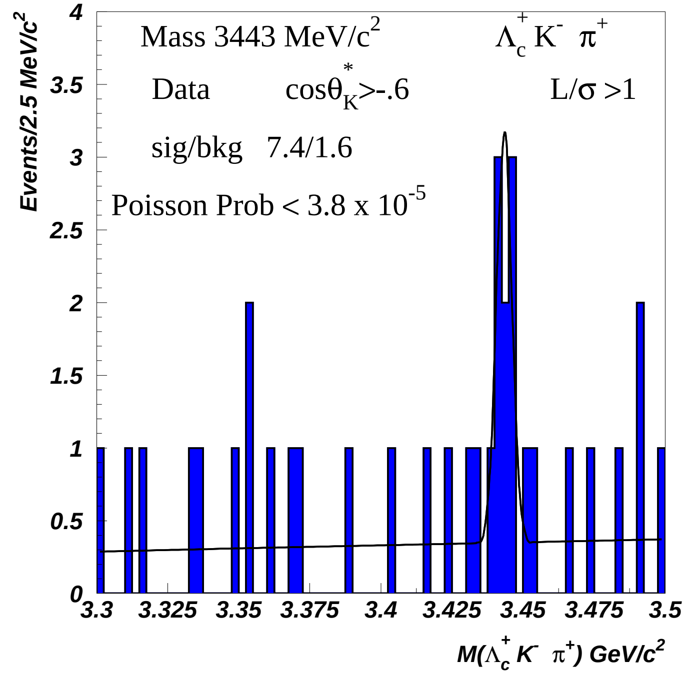
- Use simulation to demonstrate behavior of isotropic decays with phase space distribution

- **Look in small mass window around existing pair of states**

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

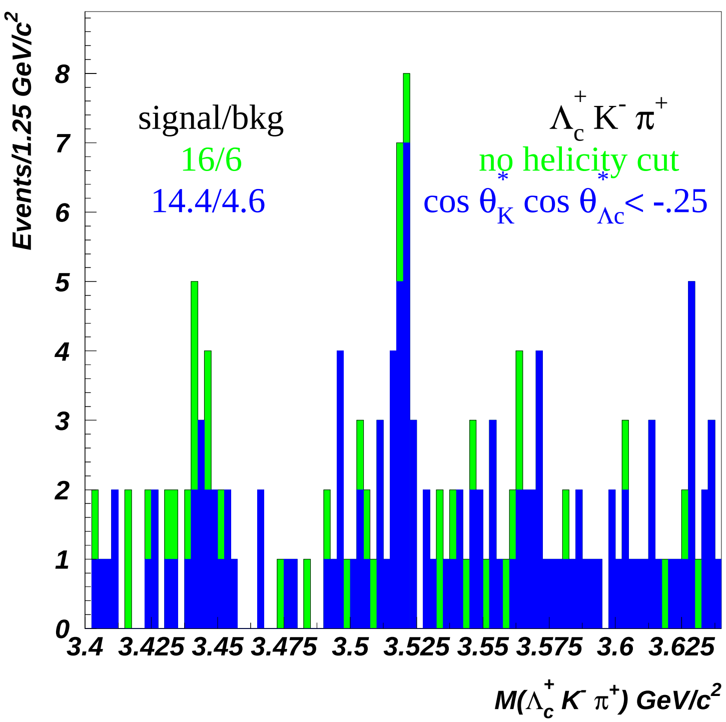
A new ccd(3443) peak with Poisson fluctuation probability $< 3.8 \times 10^{-5}$ stands out.

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

this pair is consistent with being the ground state isodoublet . . . but split is still big.

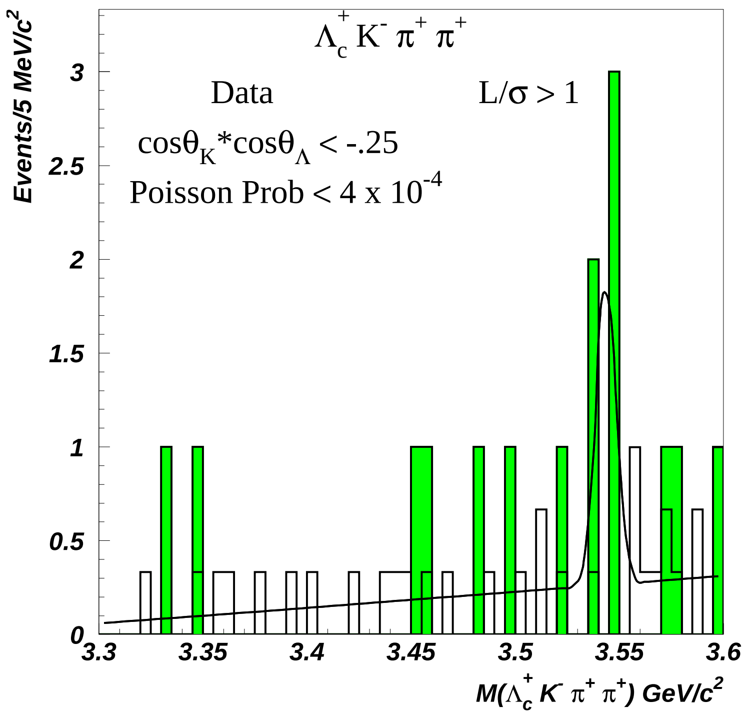
Where Does That Leave the Original ccd(3520)?

We saw that ccd(3520) does not emit its K^- forward. Try front-back helicity selection on data.



- Cut on $\cos(\theta^*_K)$ x $\cos(\theta^*_{\Lambda_c^+}) <$ -0.25 keeps 90% of ccd(3520) signal

Apply ccd Cut to ccu Mass Distribution



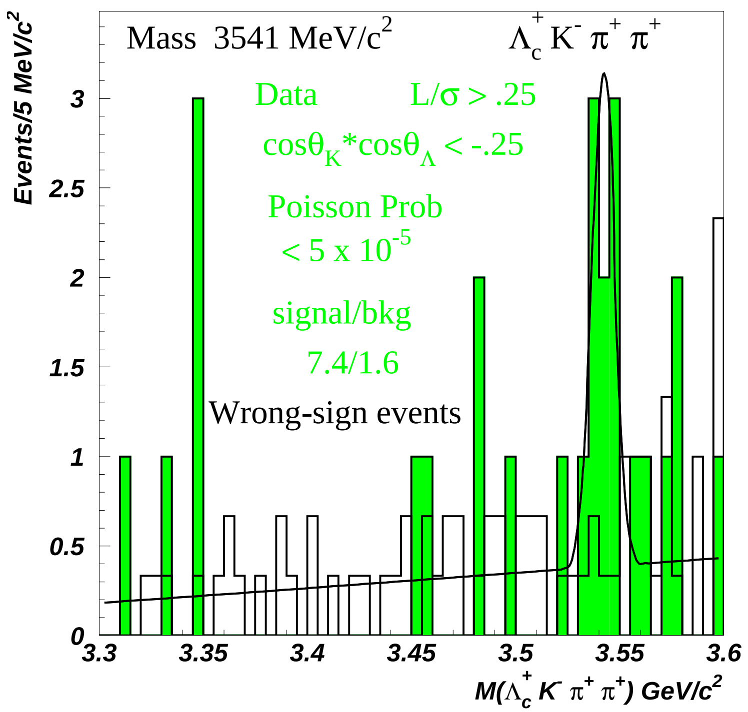
Very few events, either wrong-sign or right-sign.

Reduce L/σ requirement to allow more entries

New ccu partner for ccd(3520)

- minimum L/σ cut driven by background
- background very low in this channel
- compare right-sign and wrong-sign mass distributions for different L/σ cuts

Apply ccd(3520) front-back helicity selection.



New ccu(3540) peak with Poisson fluctuation probability $< 5 \times 10^{-5}$ and same angular dependence as the ccd(3520).

- Poisson significance stable as L/σ cuts is varied from 1 to 0
- Simulation shows smooth reconstruction efficiency variation with L/σ
- wrong-sign background gives good interpolation of combinatoric background for all L/σ cuts

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.

These are all distinct events. In signal regions only ccd(3520) has one event with two entries in peak region (one signal, one compatible with combinatoric bkg).

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	$< 5 \times 10^{-6}$
front-back	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

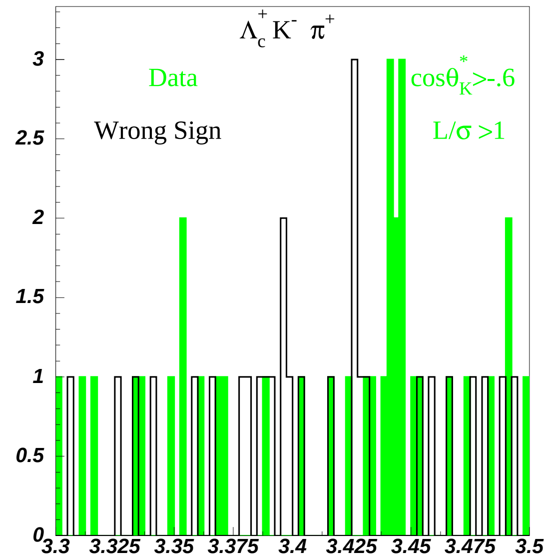
BUT

Both Doublets Decay (weakly?) into the Same Pair of Final States

NOT $3/2 \rightarrow 1/2$ coupling - no photonic connection!

Is the New ccd(3443) an Accidental Peak?

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



Wrong-sign background 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

A Side-Step: ccq Lifetimes

SELEX uses reduced proper decay length

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

l_{min} = sigma for this sample.

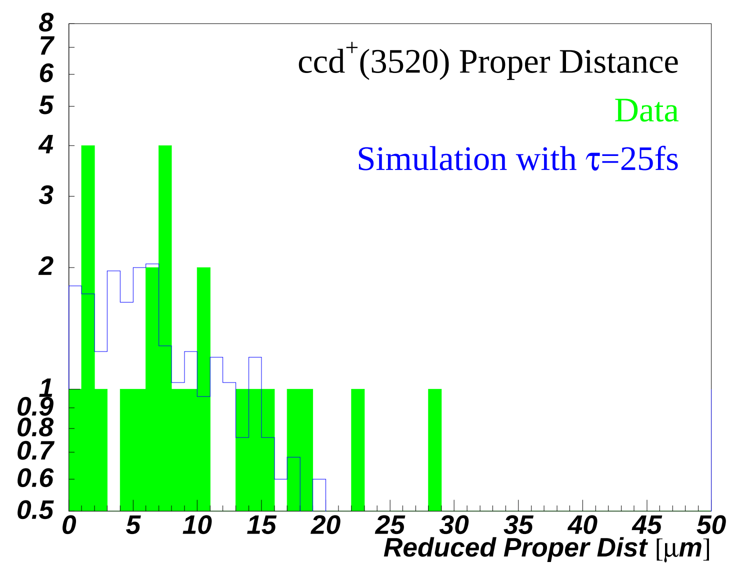
$\tau_{\Lambda_c^+} \sim 200$ fs $\Rightarrow$ proper mean decay length $c\tau \sim 60\ \mu$m

SELEX proper resolution $\sim 5.5\ \mu$m.

No ccq candidate has a reduced proper distance as long as 60 μm.

To estimate ccq lifetime make simulation templates for different lifetimes

Take specific case of ccd(3520):



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

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.

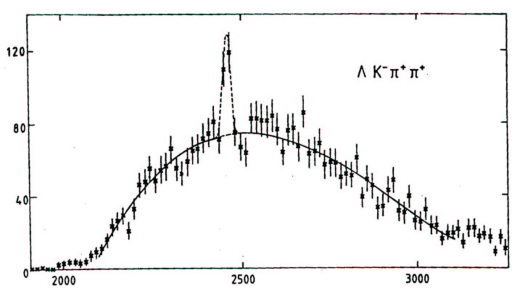
Why Does Only SELEX See These States?

FOCUS has $\sim 12\times$ more Λ_c^+ events at $\sqrt{s} \sim \frac{1}{2}$ that for SELEX. Focus does not see Double Charm in a wide range of decay modes.

E791(500 GeV/c) has 5x as many Λ_c^+ events from pions as SELEX pion sample and does not see Double Charm. ... consistent with SELEX non-observation from pions.

Only SELEX covers forward hemisphere with baryon beams and that's where the double charm events are observed.

Ξ_c^+ discovered in 135 GeV Σ^- beam (WA62) with huge yield relative to D mesons:



- 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:
ΔM = 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 $\pm$ 3	+4/3

Note that the ccq splittings reverse the order of lighter I=1/2 baryons; $I_3 = 1/2$ is heavier

SELEX states are massive and narrow - like $\mathrm{D_S}^{*}$(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.

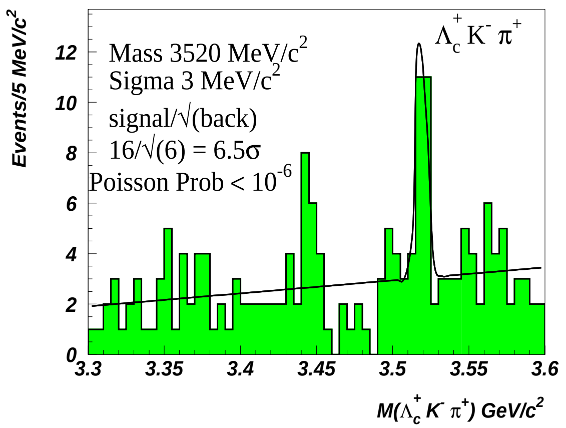
The $\Lambda_c^+ K^- \pi^+ \pi^+$ ($Q = 2$) final states don't share quantum numbers of any single-charm baryon.

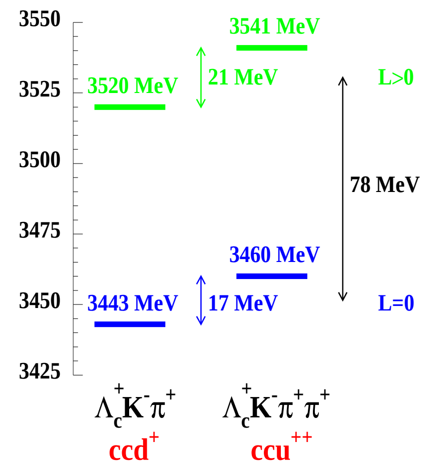
States are numerically weak, statistically strong. What are they if not double charm?

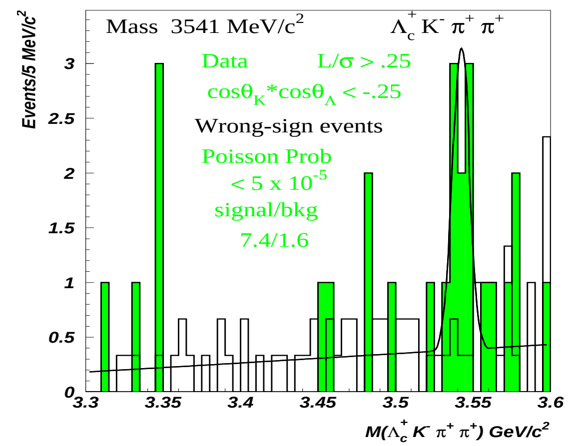
Another possibility is (csu$\bar{\mathrm{d}}$q) family
(Not the favored pentaquark structure!)

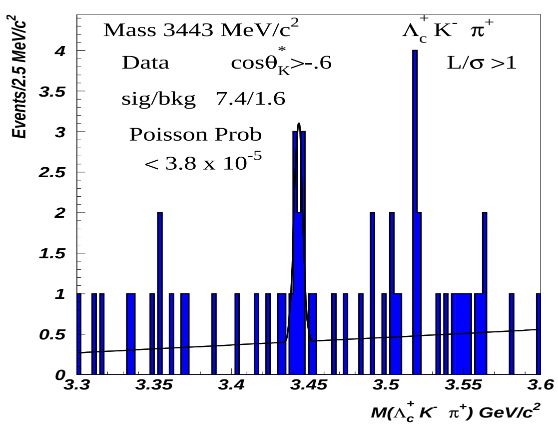
A Reprise

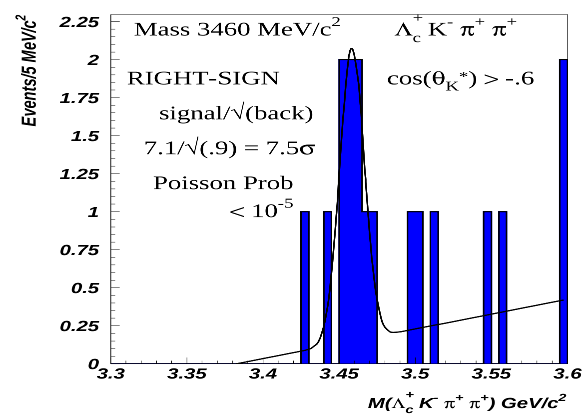
Selex has observed 4 narrow, high-mass peaks in the mass range expected for Double Charm Baryons











- 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?

ccq Doublet Picture and Lifetimes

Average reduced proper time is lifetime estimator

NO acceptance corrections applied to these data

(Acceptance favors longer-lived decays)

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 follow HQET predictions

All lifetimes $\leq \Omega_c^0$ lifetime

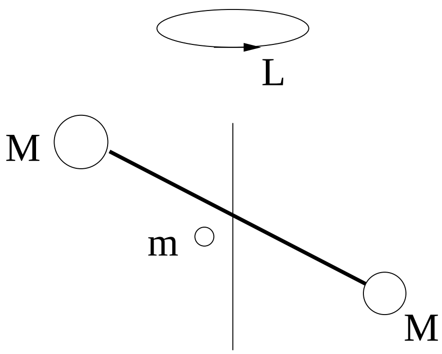
SELEX resolution is good, BUT lower lifetime limit includes zero!

The two-doublet picture requires weak decay rate to dominate EM decays from upper to lower doublet!

What Is Weak Decay Mechanism for ccq States?

Non-Relativistic QED Ideas and Recent QCD Analysis

Born-Oppenheimer L=0,1 Doublet



ccq system

r ~ 1 F

- numerically, rigid rotator L=0,1 levels have 80 MeVsplit for cc separation of 1/2 F, $m_c \sim 1.5$ GeV/c^2
- By symmetry cc pair has no E1 moment ⇒ **NO L=1→0 E1 TRANSITION**

QCD View - QQq p-waveDoublet

Bardeen, Eichten, and Hill (private comm) discuss QQq baryon multiplet levels in chiral Lagrangian picture

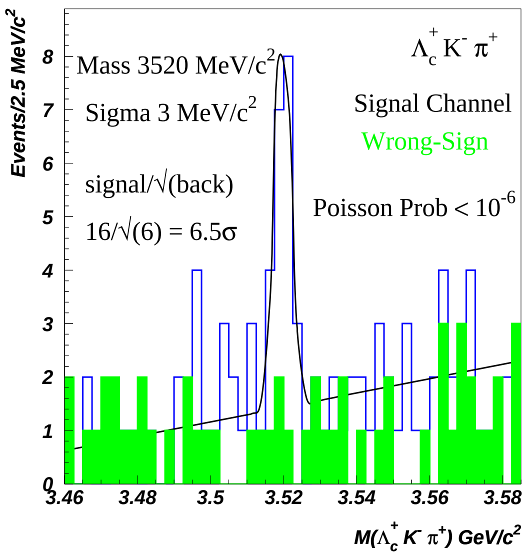
- ccq gnd state $(1/2^+)$ split first by cc orbital excitation
- lowest excitation involves cc L=1 system $(1/2^-)$
- M2 EM transition ⇒ $\tau \sim \mathcal{O}(1\ \mathrm{fs})$
- model calculations have M(ccu) > M(ccd).
- Potential model limits ⇒ lattice calculation needed

The SELEX data illustrate excitation hierarchy of double charmed baryons

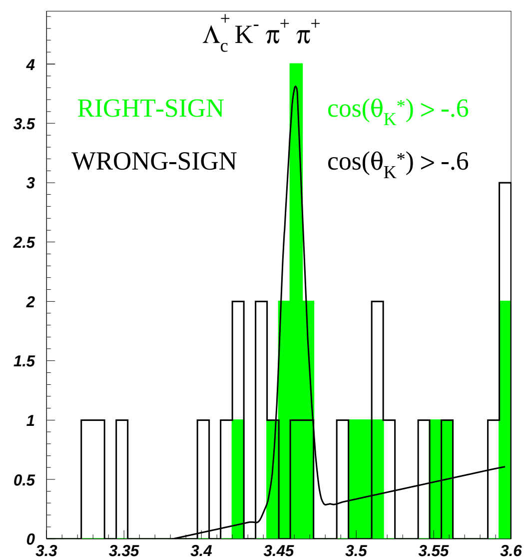
Experimental Evidence - Wine and Cheese, May, 2002

Selex reported 3 significant high-mass peaks

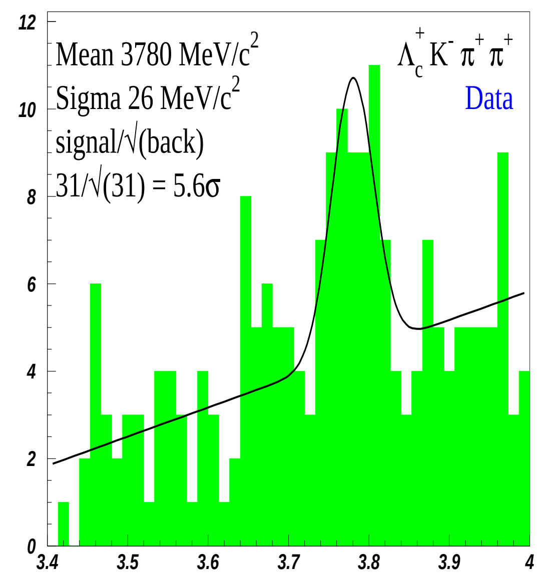
ccd^{+}



ccu^{++}



ccu^{*++}



PRELIMINARY: pi decay from ccu(3780)

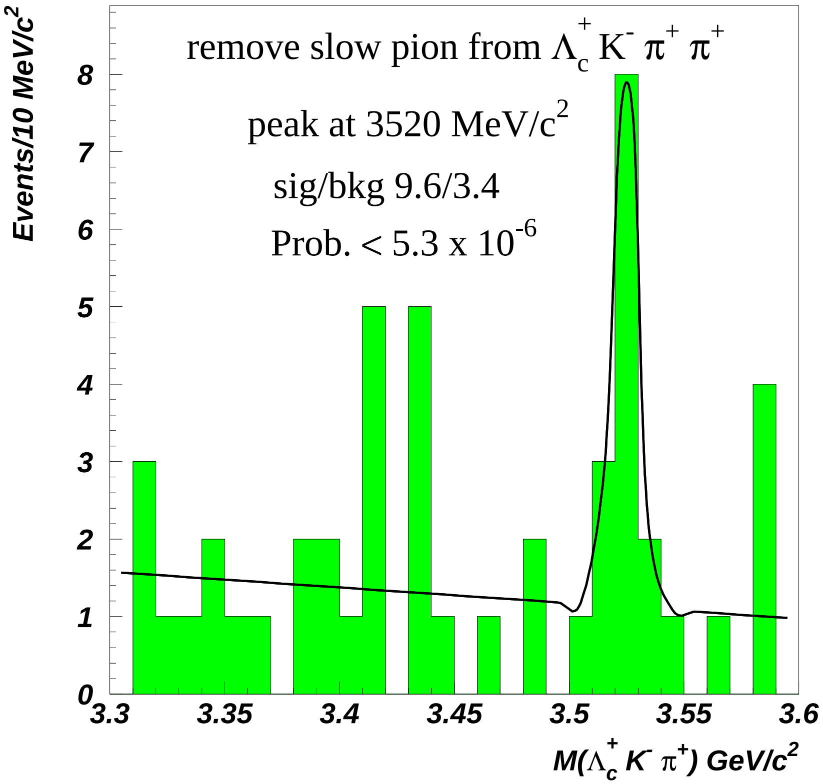


Figure 1: $M(\Lambda_c^+ K^- \pi^+)$ Distribution after removing slow π^+

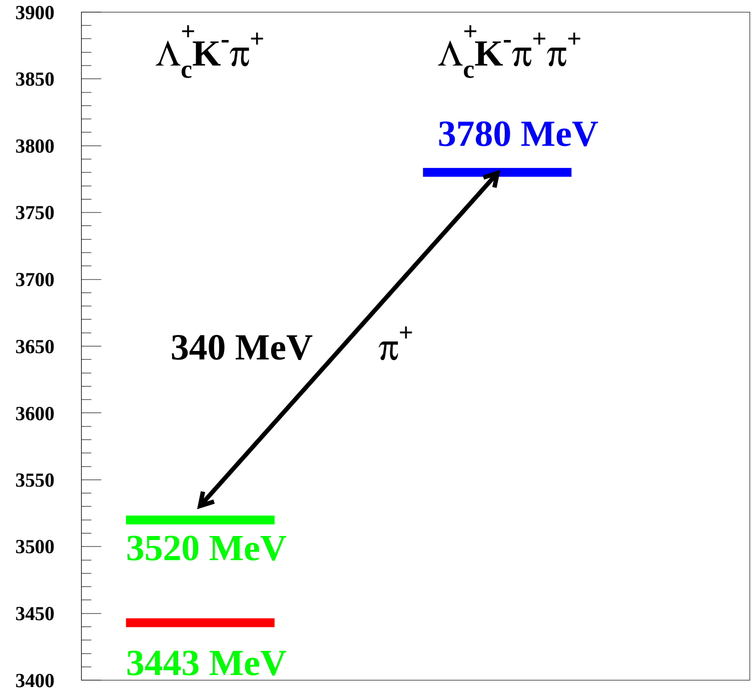


Figure 2: Level Diagram with π^+ Transition

Dominant transition to excited ccd state!

PRELIMINARY: pi decay from ccu(3780)

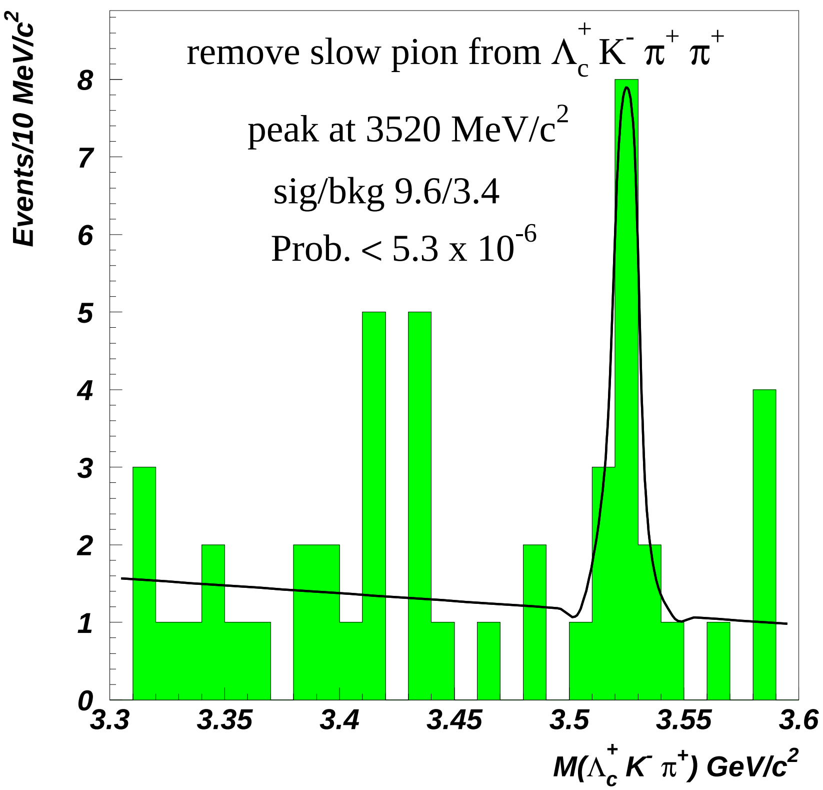


Figure 3: $M(\Lambda_c^+ K^- \pi^+)$ Distribution after removing slow π^+

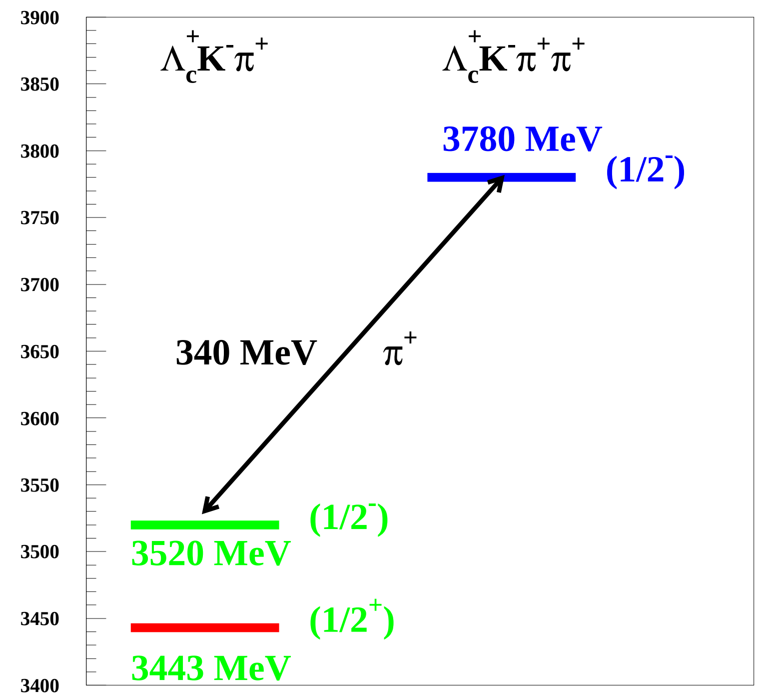


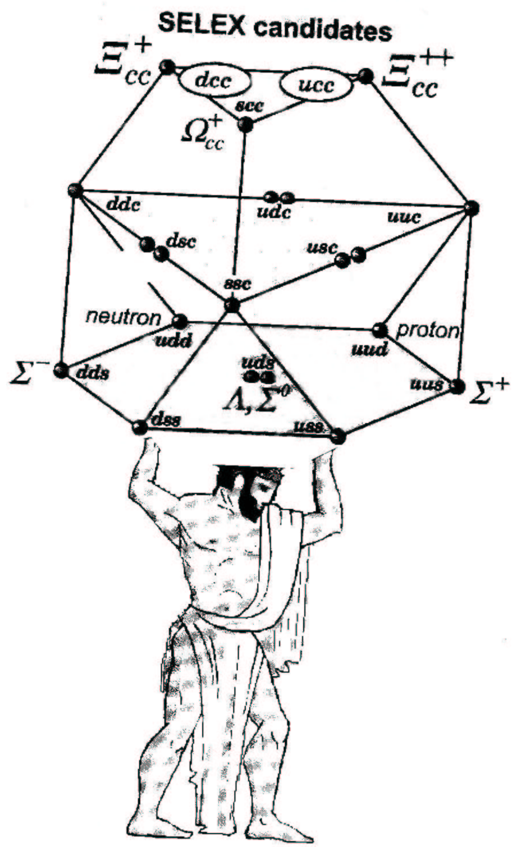
Figure 4: Level Diagram with π^+ Transition

SPECULATE: 3780 state is light-quark p-wave excitation

p-wave pion decay ONLY to negative-parity ccd state!

The Final Word for Today

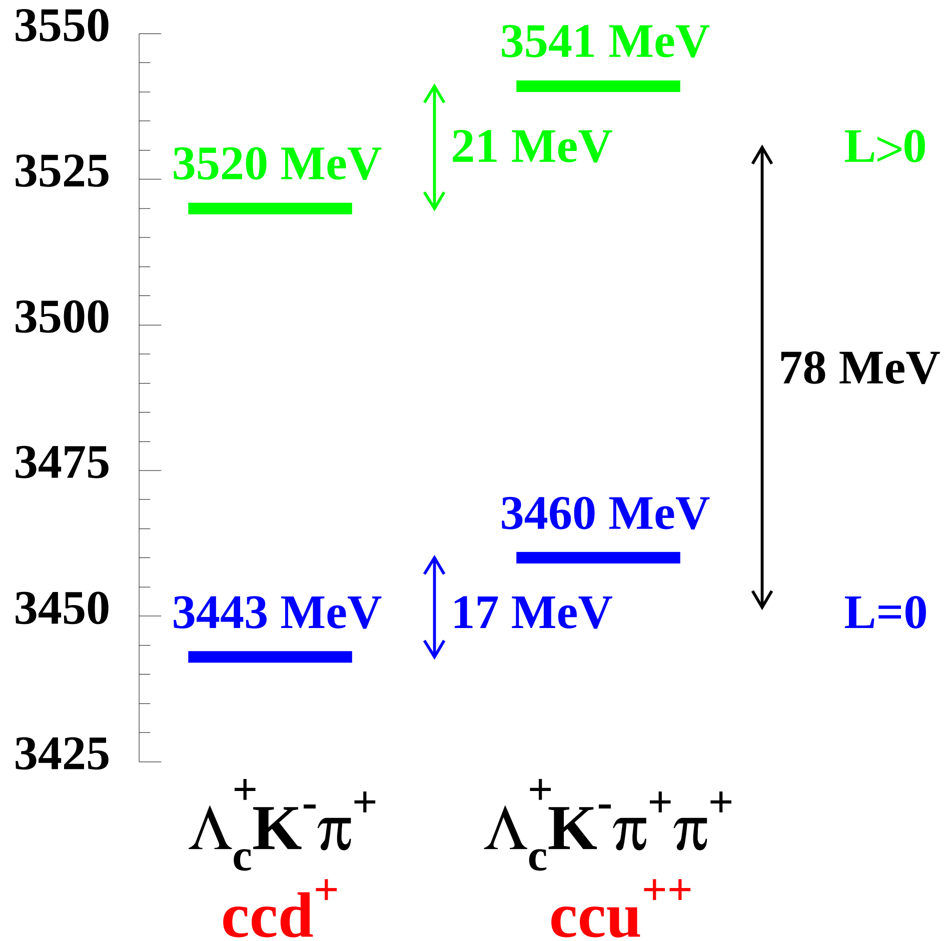
Additional support would be nice

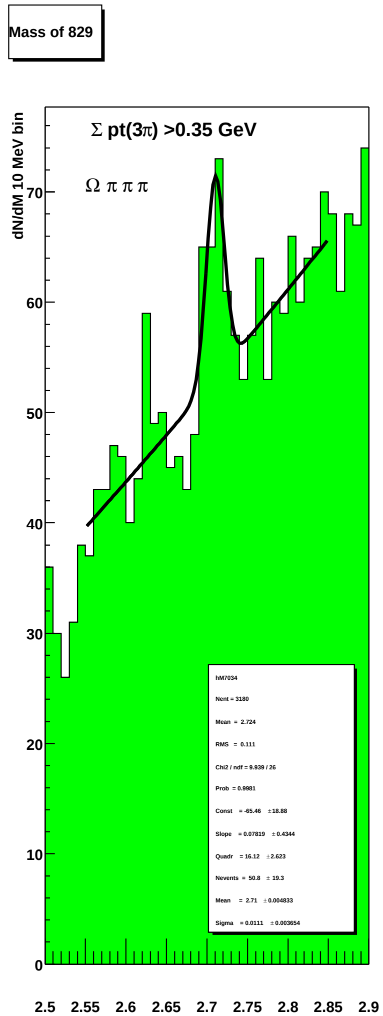


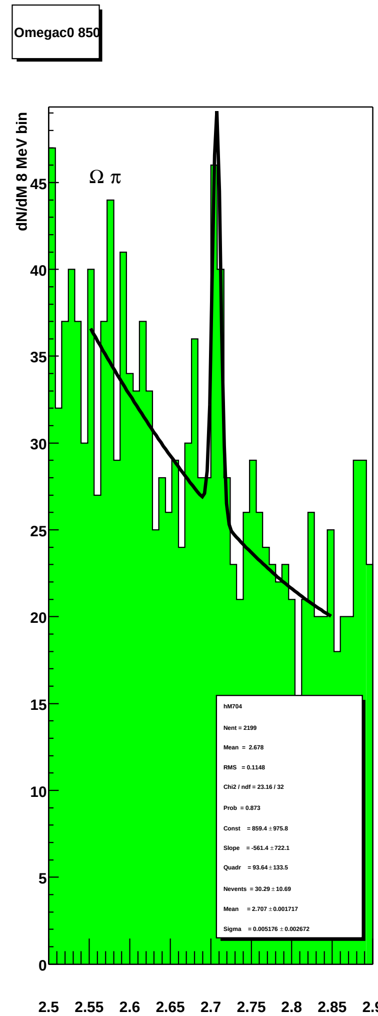
. . . but it may take awhile.

- FOCUS does not see double-charm baryons from photoproduction (12x more events at half the CM energy)
- 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
0
10
20
30
40
50
60
70
2.5
2.55
2.6
2.65
2.7
2.75
2.8
2.85
2.9


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
0
5
10
15
20
25
30
35
40
45
2.5
2.55
2.6
2.65
2.7
2.75
2.8
2.85
2.9