The Experimental Discovery of Double-Charm Baryons

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For the SELEX (Fermilab E781) Collaboration

Outline

- Introduction
- The SELEX Experiment
- Double-Charm Baryons Search Strategy
- Results
- Summary and Outlook

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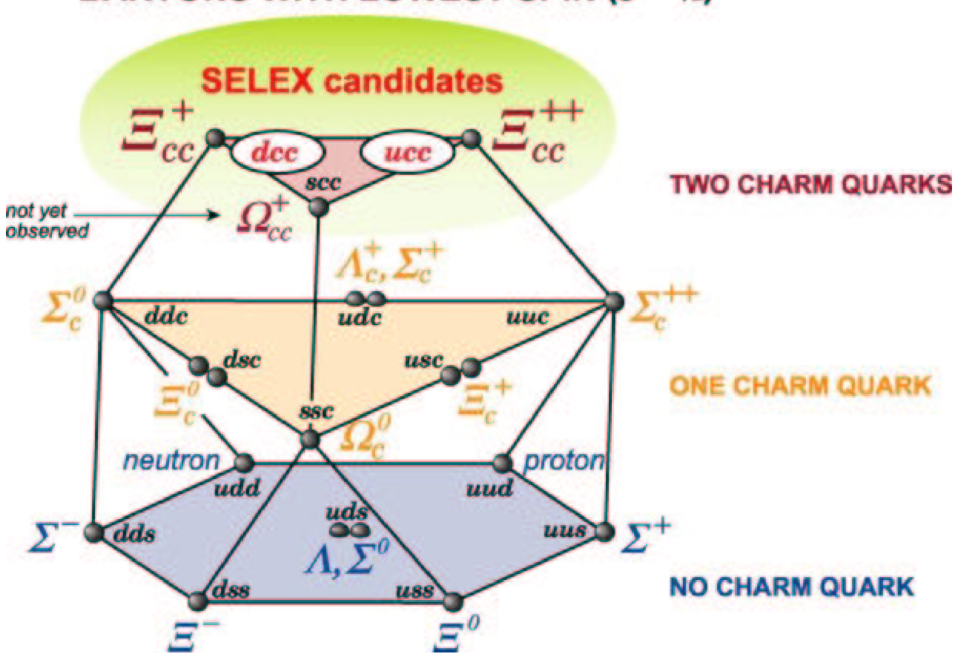
Introduction

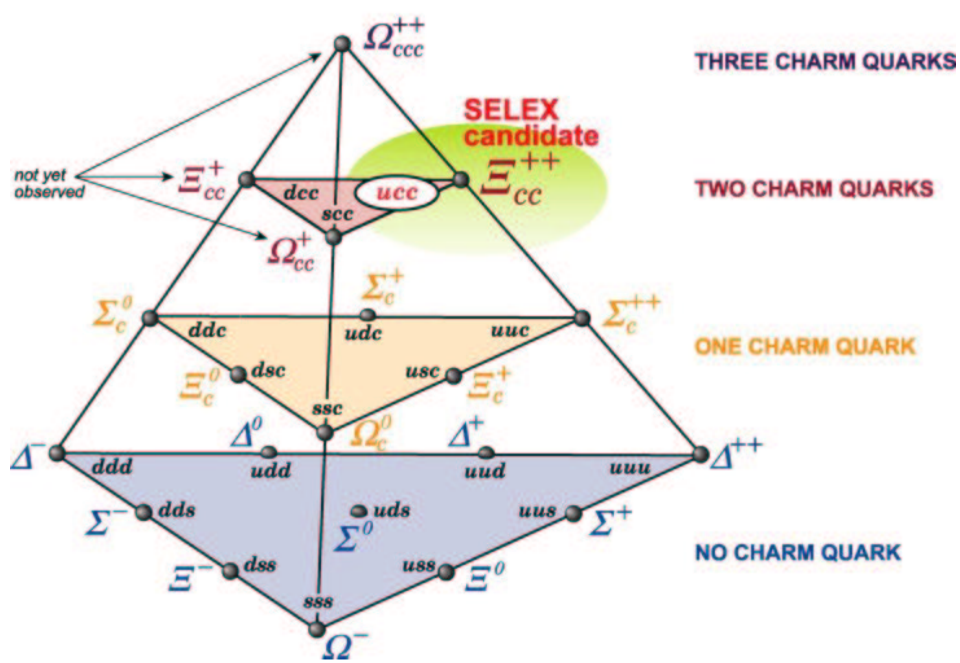
- Mesons consist of 2 valence quarks
- Baryons consist of 3 valence quarks
- 4, 5, and 6 quark systems not yet unambiguously confirmed
- there are 6 different types of quarks
- only 5 of them form hadrons.

BARYONS WITH LOWEST SPIN (J = ½)



- A lot of possible baryons states
- All ground states and first excited states with one charm quark have been observed:
  Mesons: D^0 $(c\bar{u})$, D^+ $(c\bar{d})$, D_s^+ $(c\bar{s})$, Ψ $(c\bar{c})$
  Baryons (cqq): Λ_c^+, Σ_c^0, Σ_c^+, Σ_c^{++}
  Baryons (csq): Ξ_c^0, Ξ_c^+, $\Xi_c^{\prime 0}$, $\Xi_c^{\prime +}$
  Baryon (css): Ω_c^0

BARYONS WITH HIGHEST SPIN (J = 3/2)



Model Predictions for Doubly Charmed Baryons Masses

author	year	model	Ξ_{cc}(J = 3/2)	Ξ_{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

- 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
- Some Models: Light Quark excitation characteristics similar to heavy-light meson spectra (heavy (cc) diquark)

Production

- Basically no models (except independent production)
- Expect small production cross section
- But why not look anyway??

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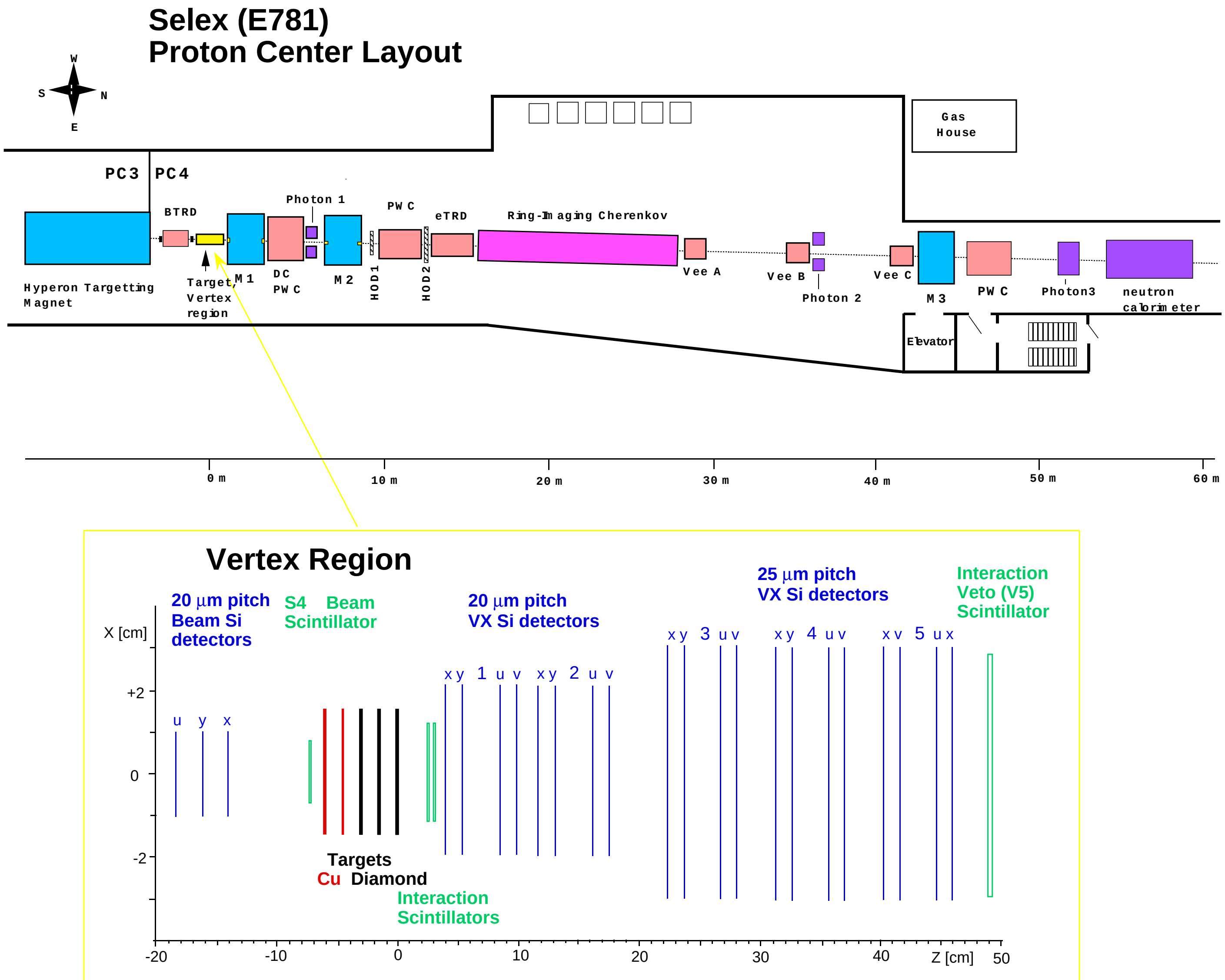
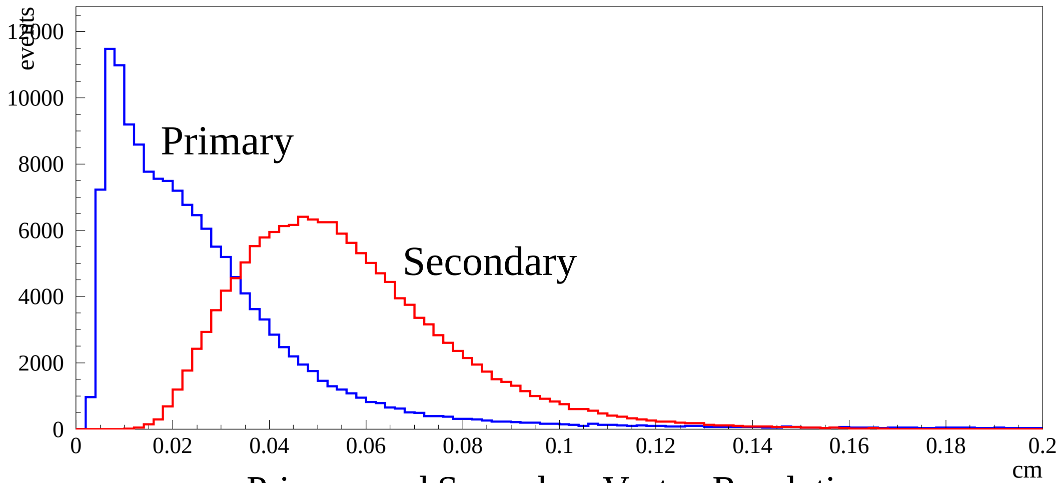
The SELEX Experiment at Fermilab



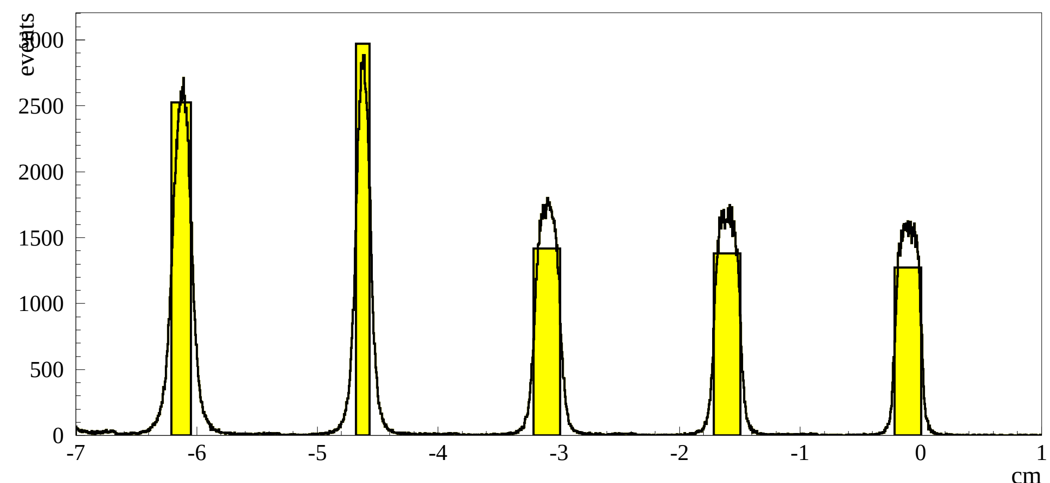
SELEX experiment

- Forward ($x_F > 0.1$) charm production
- Σ^-, π, p beam at 600 GeV$/c$
- RICH PID above ~ 22 GeV$/c$
- 20 plane Si-Vertex.
- Data taken 1996/7

Vertex Spectrometer Performance



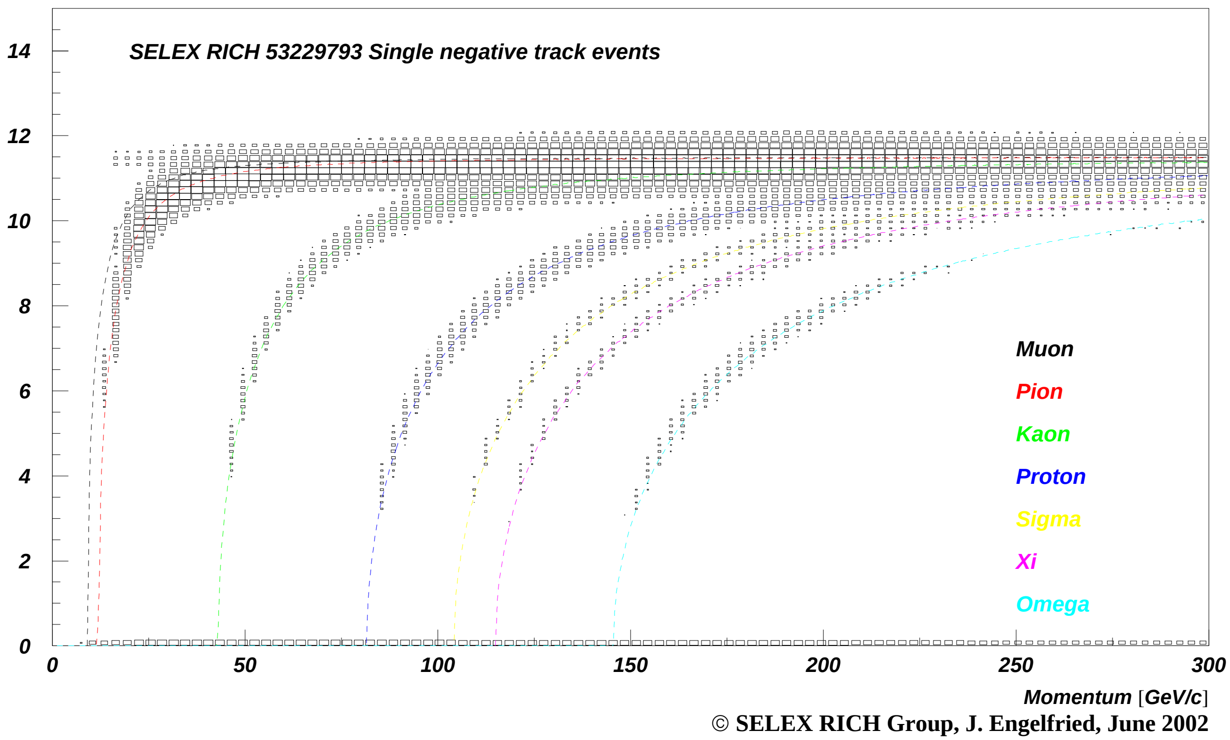
Primary and Secondary Vertex Resolution

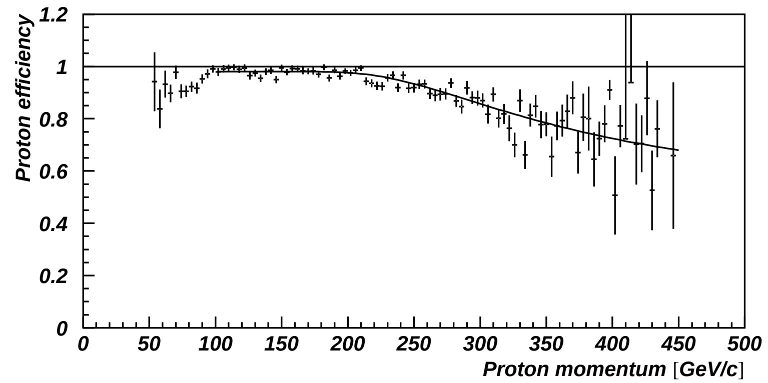


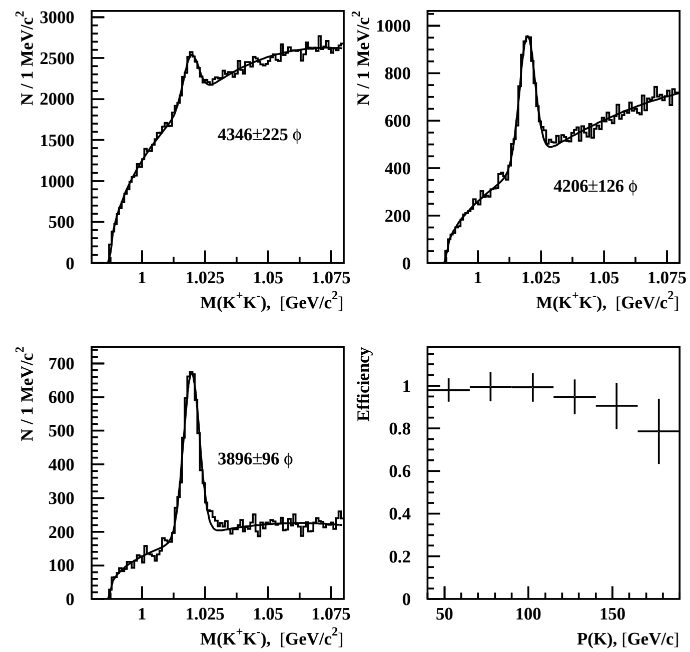
Primary vertex positions

- 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 spacing to localize primary interaction
- Lifetime resolution $\sim$ 20 fs (slightly depending on particle and decay mode)

Ring Imgaging Cherenkov Counter Performance





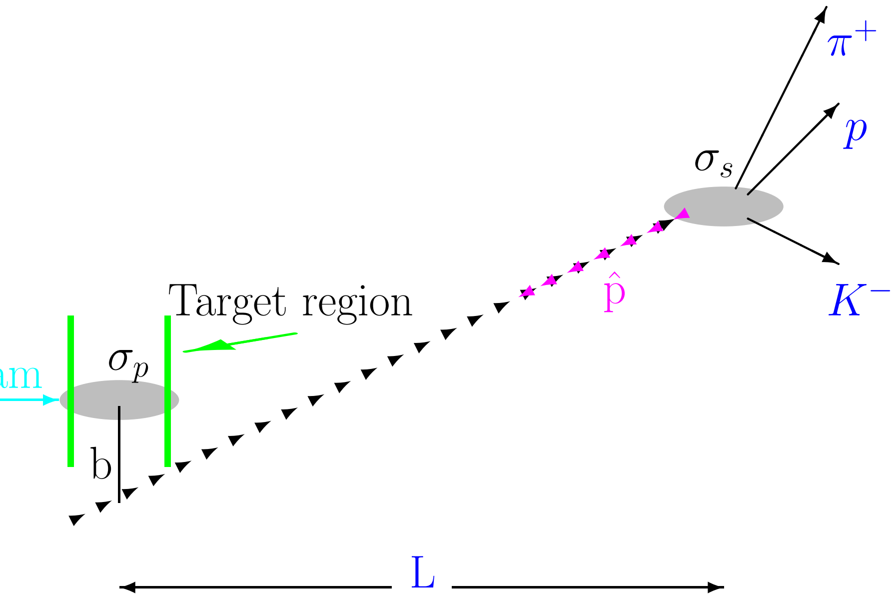


Selex publications

1. *Observation of the Cabibbo-suppressed decay $\Xi_c^+ \to pK^-\pi^+$.* Phys. Rev. Letter **84** (2000) 1857-1861.
2. *Total Cross Section Measurements with π^-, Σ^- and Protons on Nuclei and Nucleons around 600 GeV/c.* Nucl. Phys. B 579 (2000) 277-312.
3. *Measurement of the Σ^- Charge Radius by Σ^-–Electron Elastic Scattering.* Physics Letters **B522** (2001) 233-239.
4. *Precision measurements of the Λ_c^+ and D^0 lifetimes.* Phys. Rev. Letter **86** (2001) 5243-5246.
5. *Radiative decay width of the $a_2(1320)^-$ meson.* Physics Letters **B521** (2001) 171-180.
6. *Measurement of the D_s lifetime.* Physics Letters **B523** (2001) 22-28.
7. *Hadronic Production of Λ_c from 600 GeV/c π^-, Σ^- and p beams.* Physics Letters **B528** (2002), 49-57.
8. *First Measurement of $\pi^- e \to \pi^- e\gamma$ Pion Virtual Compton Scattering.* Phys. Rev. C **66**, 034613 (2002).
9. *First Observation of the Doubly Charmed Baryon Ξ_{cc}^+.* Phys. Rev. Letters **89** 112001 (2002).
10. *Production Asymmetry for D_s for 600 GeV/c Σ^- and π^- beam.* Physics Letters **B558** (2003) 34-40.
11. *Upper limit on the decay $\Sigma(1385)^- \to \Sigma^-\gamma$ and cross section for $\gamma\Sigma^- \to \Lambda\pi^-$.* Physics Letters **B590**, 161-169 (2004).
12. *Polarization of Σ^+ Hyperons produced by 800 GeV/c Protons on Cu and Be.* Submitted to PRD.
13. *Confirmation of the Double Charm Baryon Ξ_{cc}^+ via its Decay to pD^+K^-.* Submitted to PRL, hep-ex/0406033.
14. *First Observation of a Narrow Charm-Strange Meson $D_{sJ}^+ \to D_s^+\eta$ and D^0K^+.* Submitted to PRL, hep-ex/0406045.

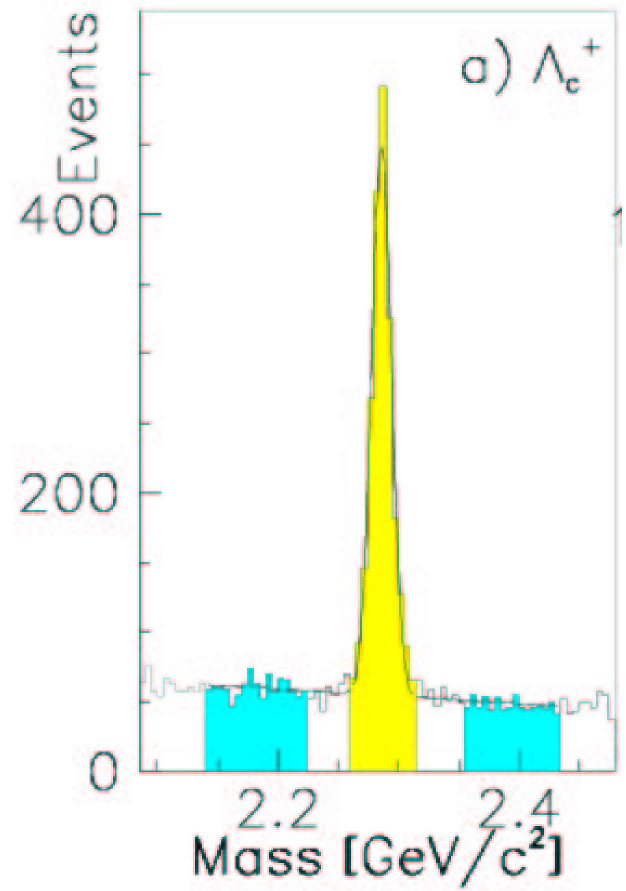
Charm Topics Non-Charm Topics

SELEX Single Charm Analysis



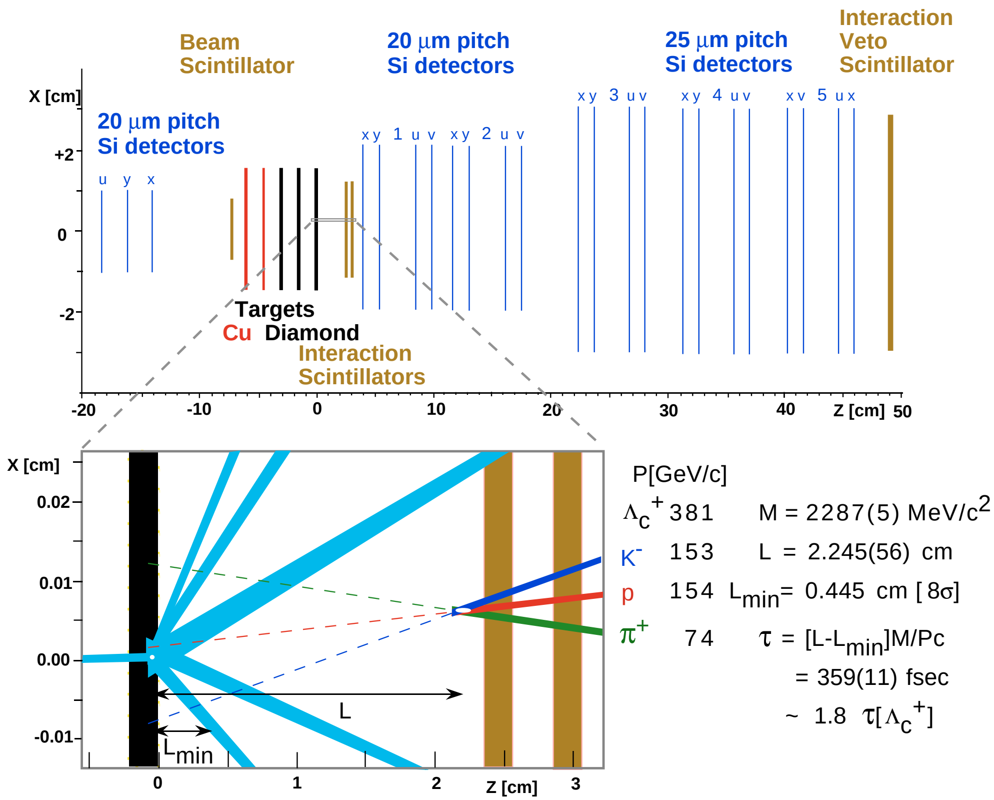
Charm Analysis Cuts

- 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 (space cut)
- Proton and Kaon identified in RICH detector



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

SELEX Charm Selection Criteria



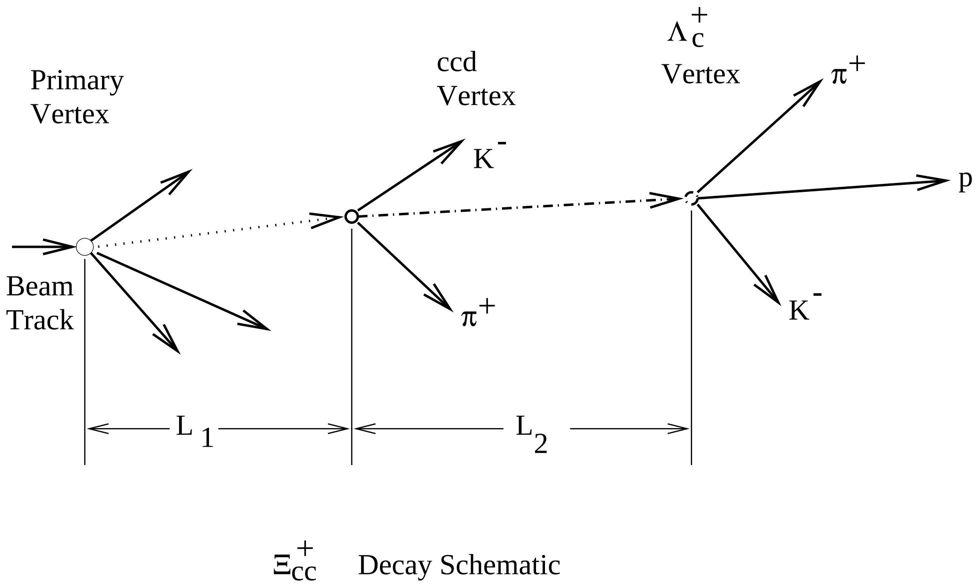
Λ_c^+ event

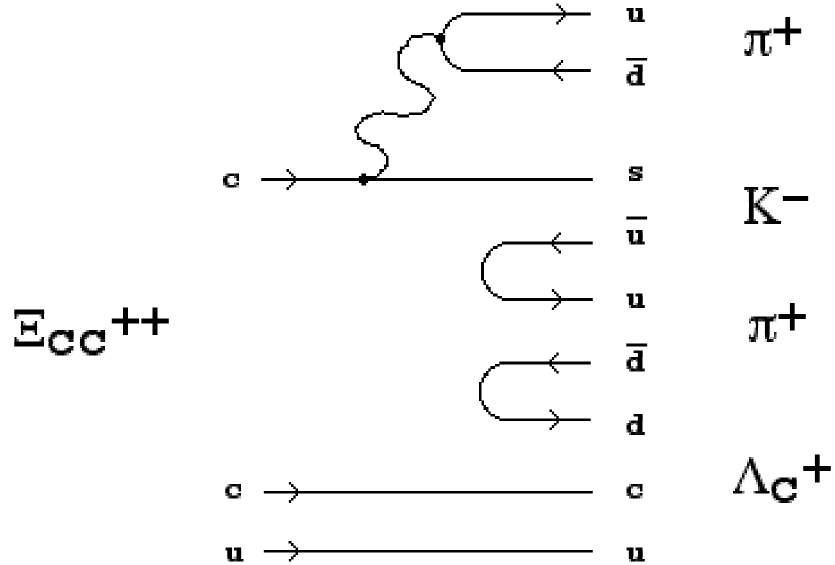
- primary vertex tagged by beam track
- secondary vertex must lie outside material

Charm Selection Cuts for single charm studies:

- secondary vertex significance:
  - $L/\sigma \geq 1$ 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



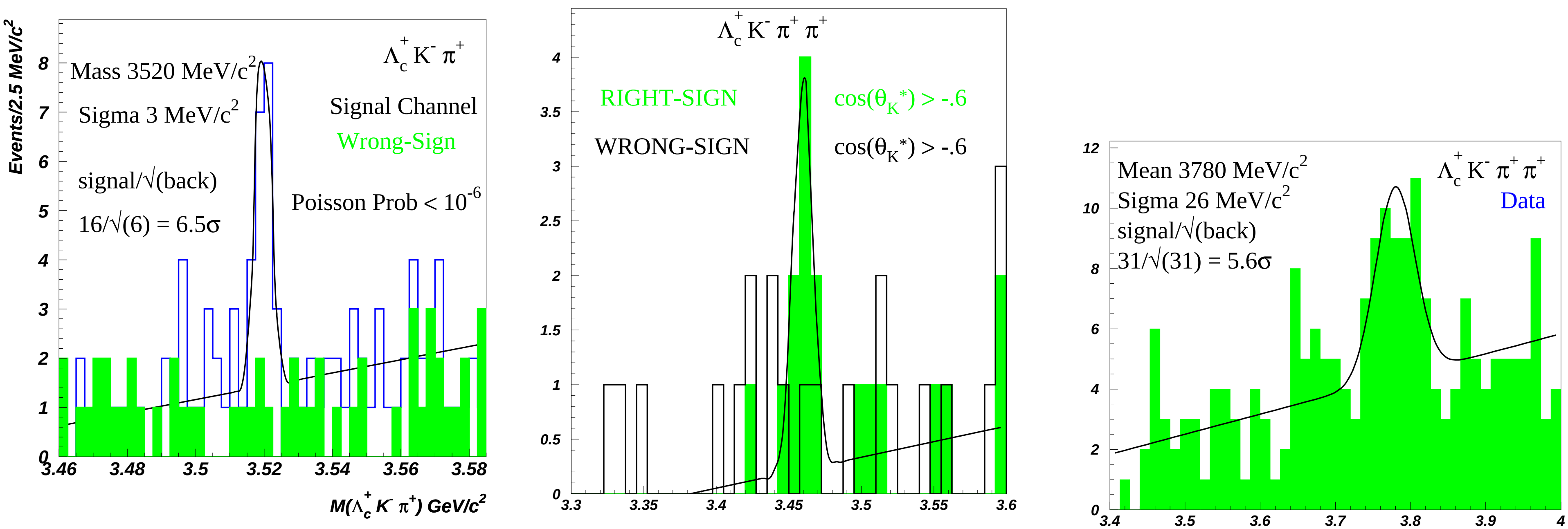


- ccq decays to $csqu\bar{d}$. Look for charm, strange and baryon in final state.
  SELEX started with $\Lambda_c^+ K^- \pi^+ (\pi^+)$.
- Look for new secondary vertex between primary and Λ_c^+
- no RICH PID on new $K^- \pi^+$ tracks (too soft)
- All other cuts fixed from previous searches

SELEX: Experimental Evidence from 2002

SELEX reported 3 significant high mass peaks

- in $\Lambda_c^+ K^- \pi^+$ at $3520\,\mathrm{MeV}/c^2$
- in $\Lambda_c^+ K^- \pi^+ \pi^+$ at $3460\,\mathrm{MeV}/c^2$ and $3780\,\mathrm{MeV}/c^2$

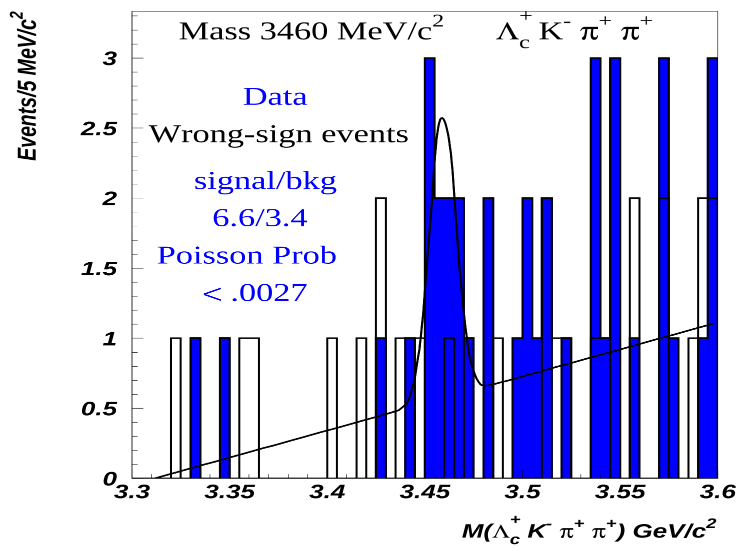


SELEX argued that these states are doubly-charmed baryons

First Observation of the Doubly Charmed Baryon $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$. Phys. Rev. Letters 89 (2002) 112002.

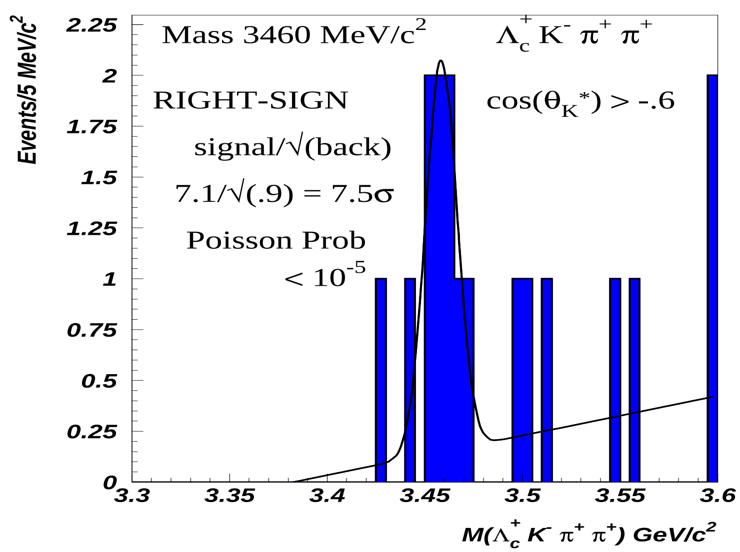
SELEX: Search for $ccd^{+}(3520)$ Isopartner: ccu^{++}

- same cuts as before:
  $3.5\,\sigma$ hint in $\Lambda_c^+ K^- \pi^+ \pi^+$.
- No peak in wrong sign ($\Lambda_c^+ K^+ \pi^- \pi^+$).
- Try additional cut: $\cos\Theta_K^* > -0.6$ to remove soft vertex tracks



- Mass peak at $3460\,\mathrm{MeV}/c^2$
  7.1 signal, 0.9 background. $7.5\,\sigma$
- Loss of signal consistent with phase space ($L = 0$)

- $\Xi_{cc}^{++}(3460)$, $\Xi_{cc}^{+}(3520)$ Isodoublet??



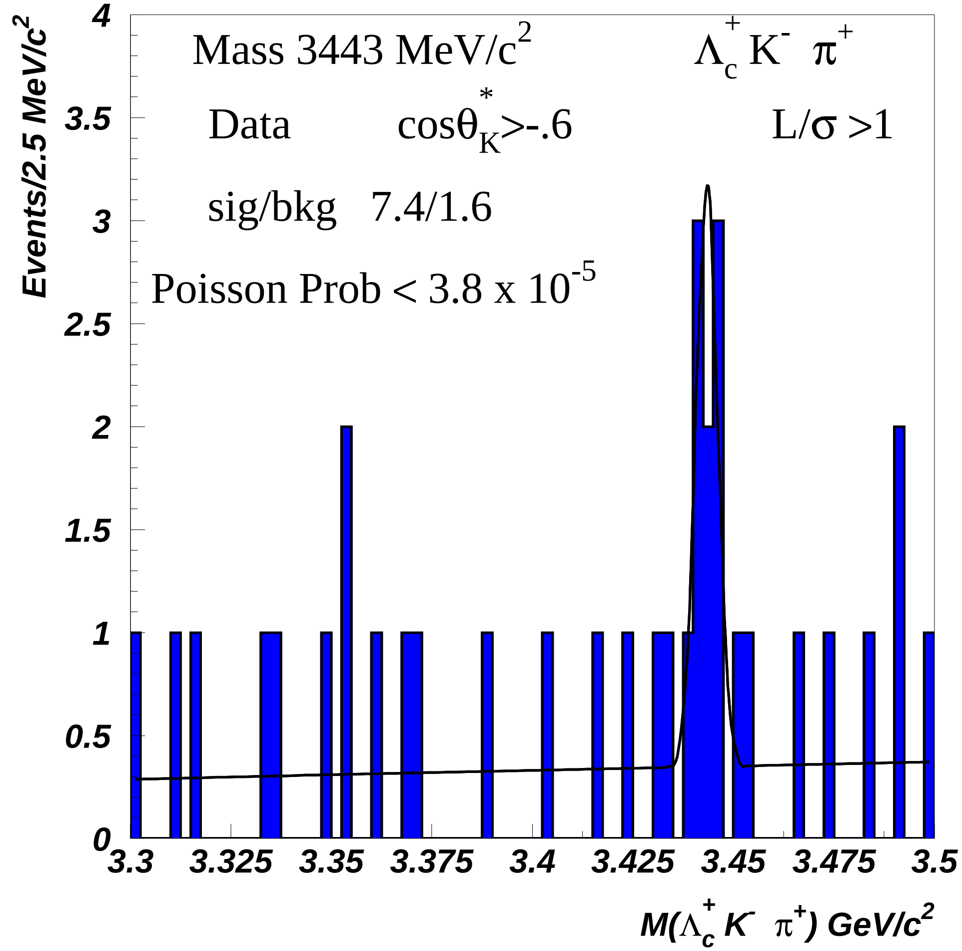
SELEX: Where is the Isopartner to $\Xi_{cc}^{++}(3460)$?

- apply $\cos\Theta_K^* > -0.6$ also to $\Lambda_c^+ K^- \pi^+$
- $ccd^+(3520)$ strongly attenuated:
  $\Rightarrow$ not phase space
- $\Rightarrow$ NOT isopartner to $ccu^{++}(3460)$

New $ccd^+(3443)$ now very significant

- there was a "bump" before – was ignored
- Now: 7.4 signal, 1.6 background. $5.8\,\sigma$
- Consistent with phase space decay

- $ccd^+(3443)$ is partner to $ccu^{++}(3460)$



SELEX: Where is the Isopartner to $\Xi_{cc}^{+}(3520)$?

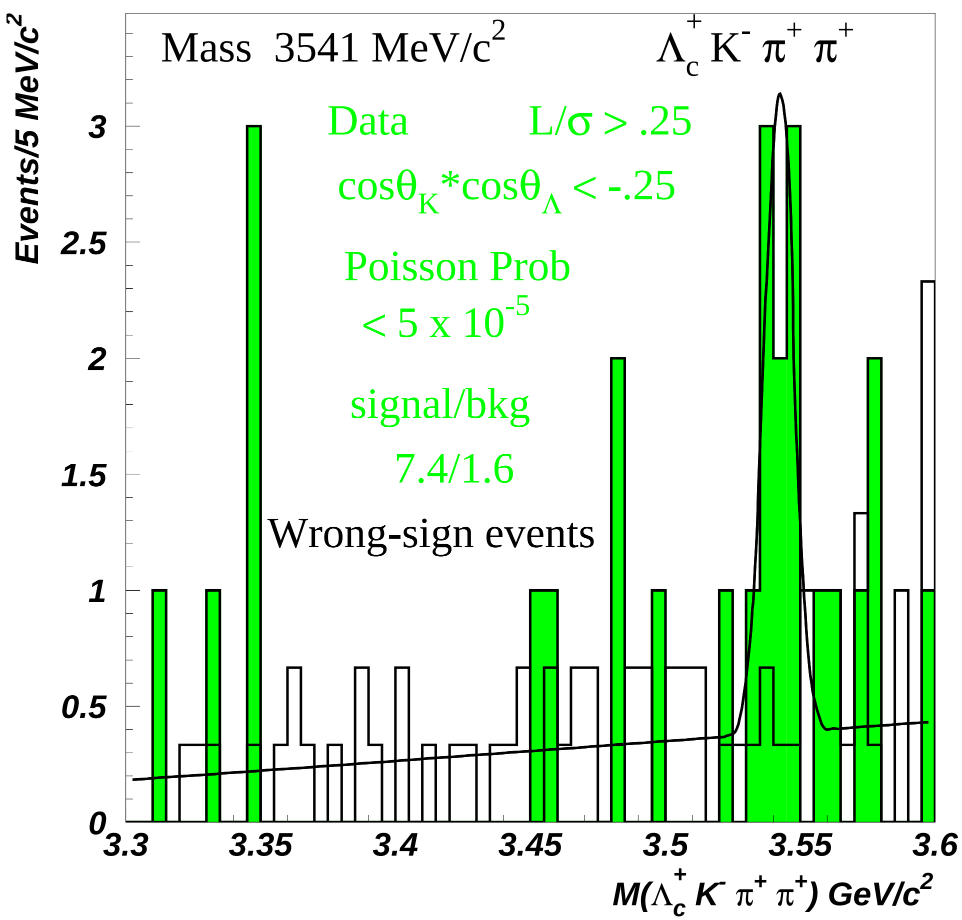
- $ccd^{+}(3520)$ not phase space ($\cos\Theta_K^*$ cut)
- Λ_c^+ and K^- are back-to-back: $\cos\Theta_K^* \cos\Theta_{\Lambda_c}^* < -0.25$ keeps most of signal
- Apply also to $\Lambda_c^+ K^- \pi^+ \pi^+$ sample: Nothing

- Reduce cut to $L/\sigma > 0.25$

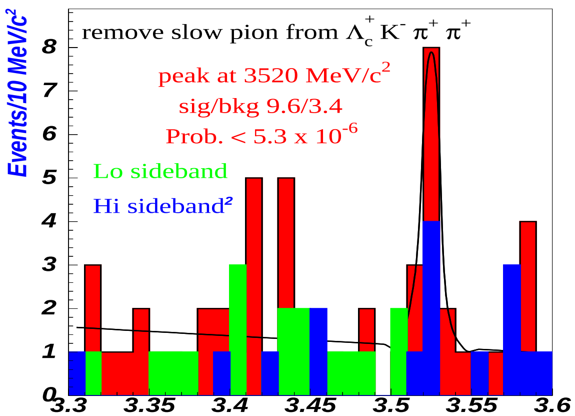
New $ccu^{++}(3541)$ now very significant

- 7.4 signal, 1.6 background. $5.8\,\sigma$
- Consistent with $L > 0$

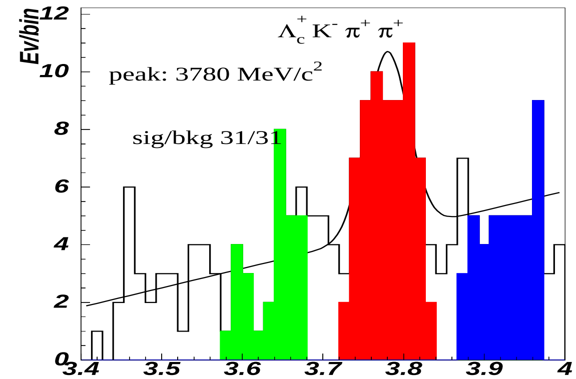
- $ccu^{++}(3541)$ is partner to $ccd^{+}(3520)$

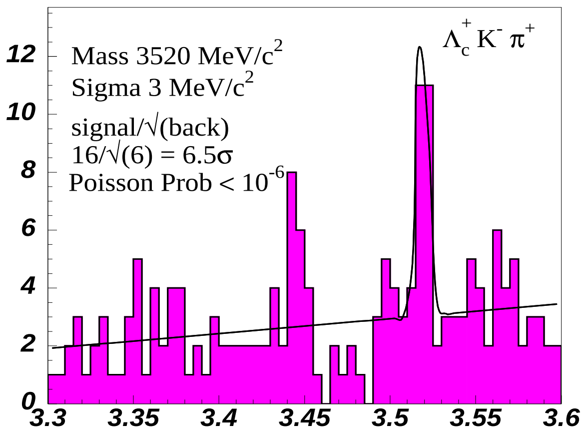


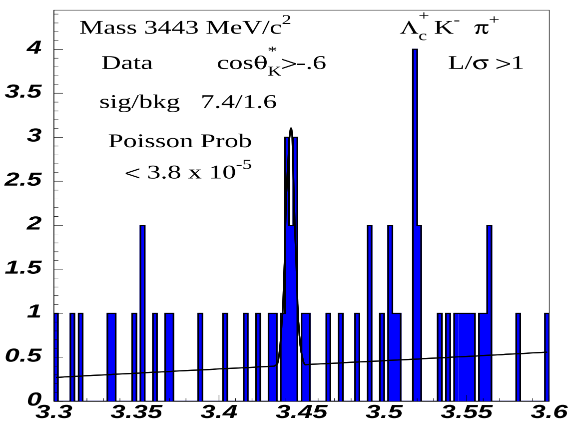
SELEX Double Charmed Baryon States

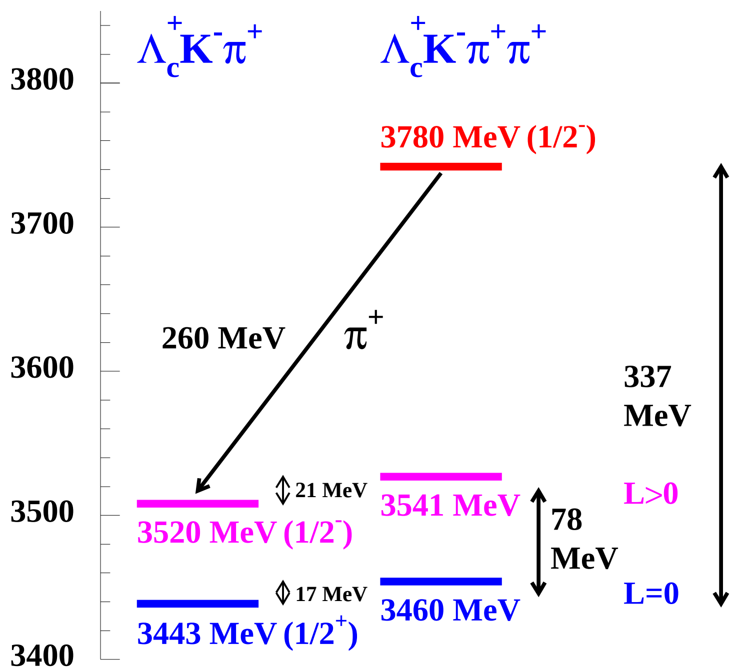


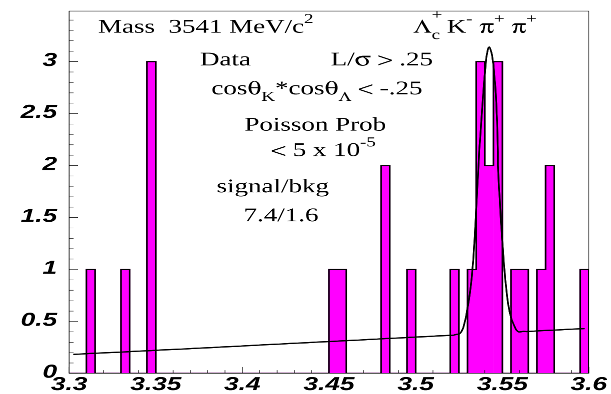
An exited state and a pair of isodoublets?

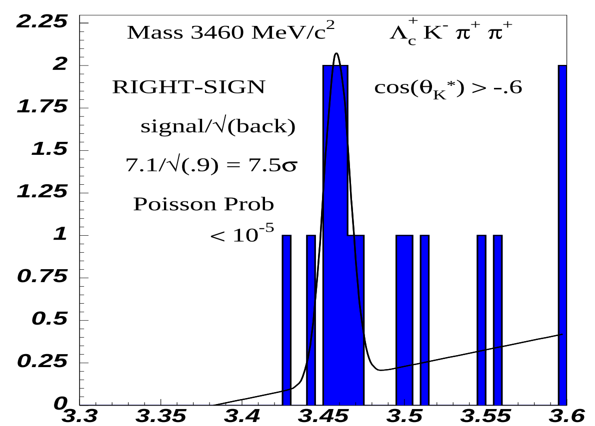






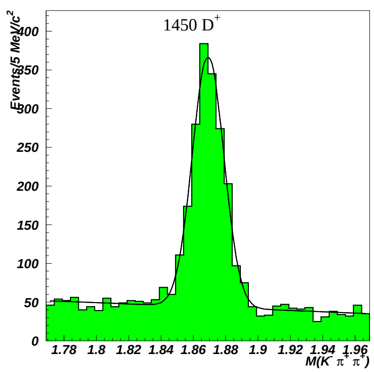


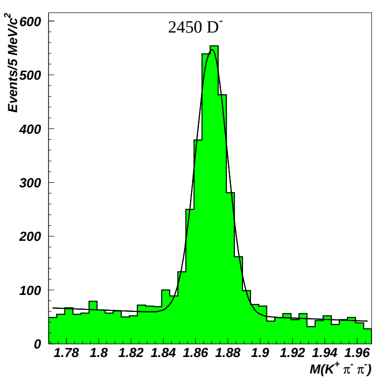




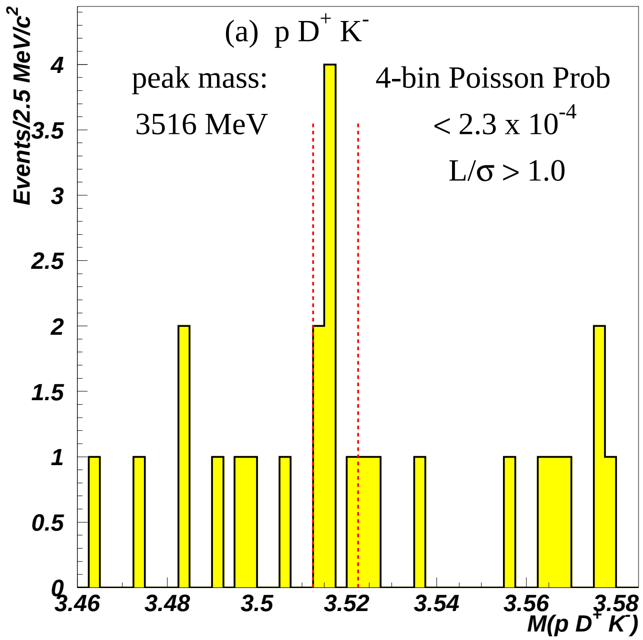
Other Double Charm Baryon Decay Modes?

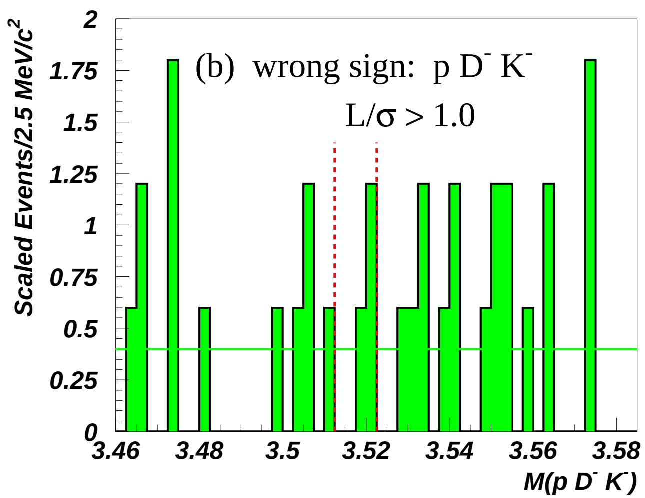
New SELEX result on $\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$: hep-ex/0406033, submitted to PRL

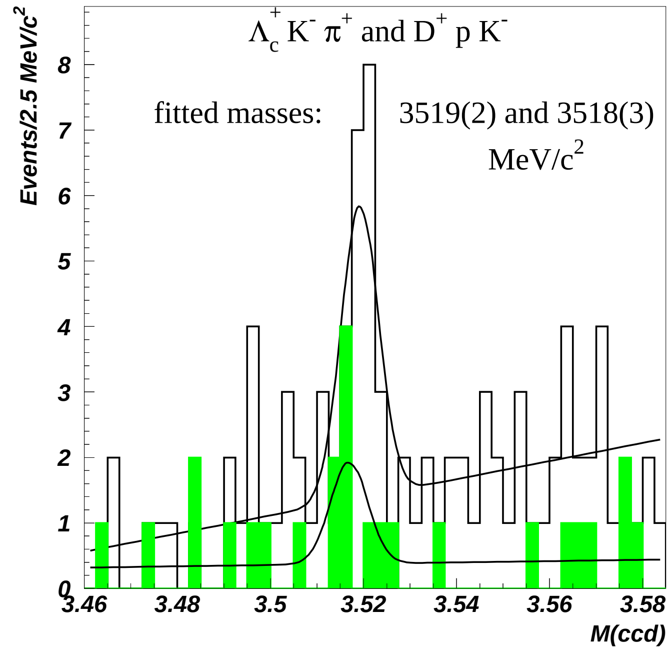




SELEX D^{+} and D^{-} Sample







$\Xi_{cc}^{+} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}$: (3519 ± 2) MeV$/c^2$

$\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$: (3518 ± 3) MeV$/c^2$

$$\frac{\Gamma(\Xi_{cc}^{+} \rightarrow \Lambda_c^{+}K^{-}\pi^{+})}{\Gamma(\Xi_{cc}^{+} \rightarrow pD^{+}K^{-})} = 0.078 \pm 0.045$$

Not possible to access $ccd(3443)$, $ccu(3460)$, $ccu(3541)$ with D modes

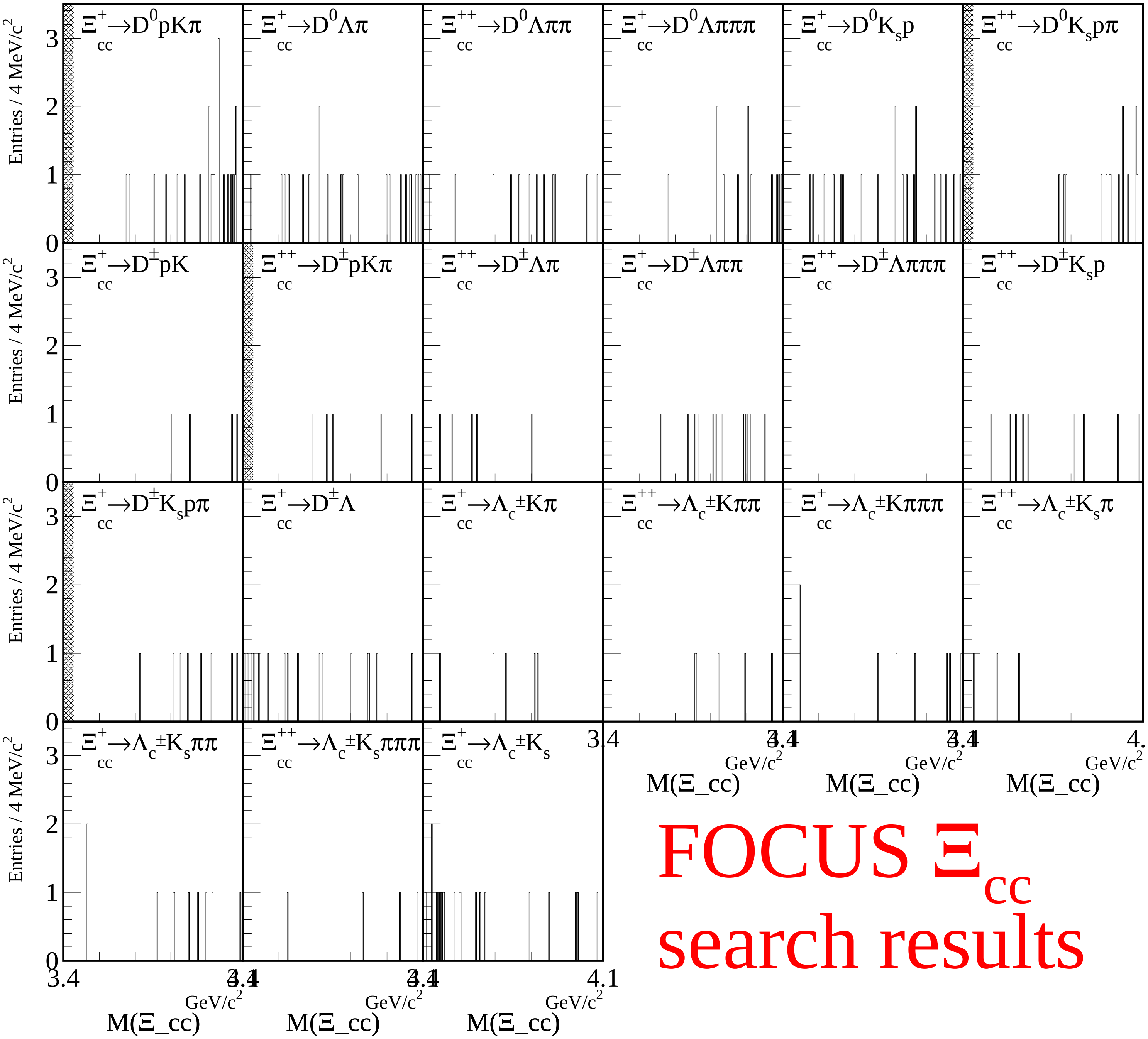
Doubly Charmed Baryons Properties

Lifetimes

- SELEX tried to measure lifetime: All lifetimes near resolution limit: $\tau_{cc} < 30\,\mathrm{fs}$
- Decays are via weak interaction
- Model predictions: several hundreds of fs.

Production

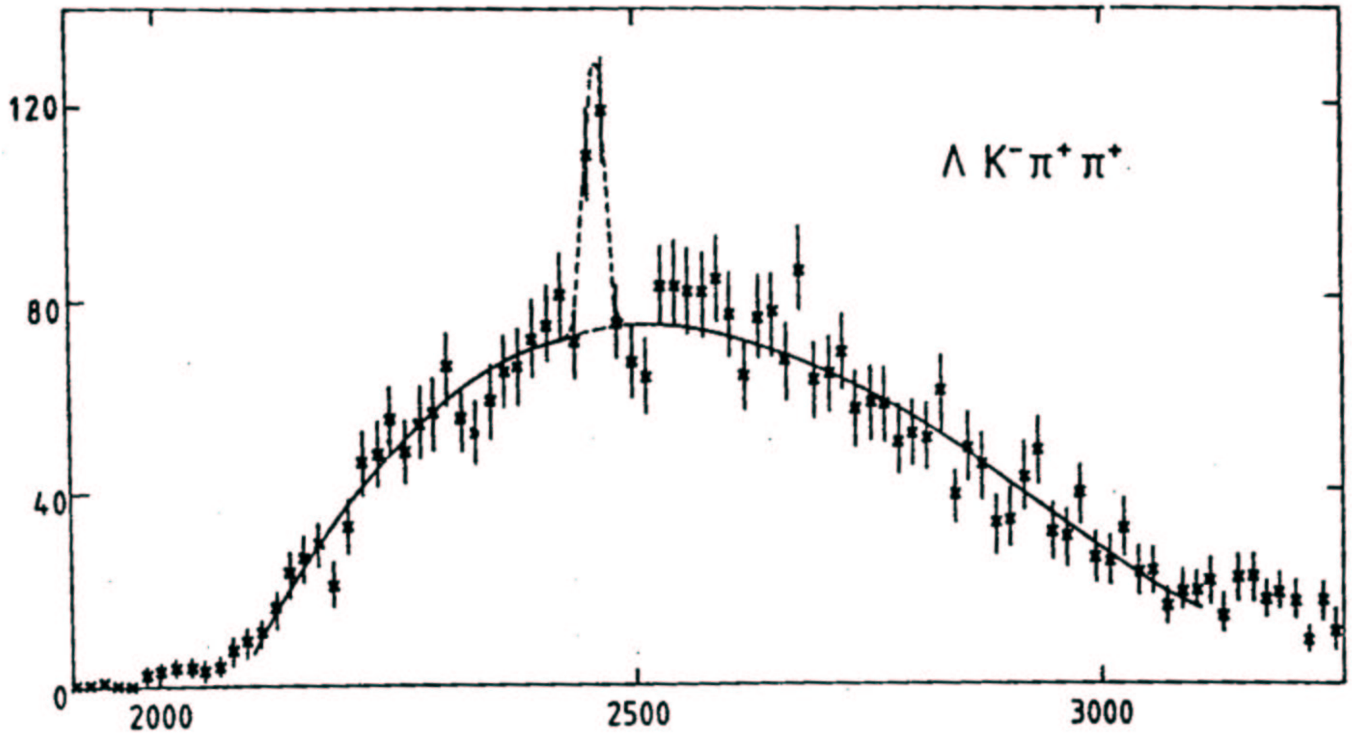
- SELEX: Dominantly produced by baryon (Σ^-, p) beam
- E791 has looked in $250\,\mathrm{GeV}/c$ π^- production   no signal
- FOCUS looked in $250\,\mathrm{GeV}/c$ photo-production   no signal



FOCUS Ξ_{cc} search results

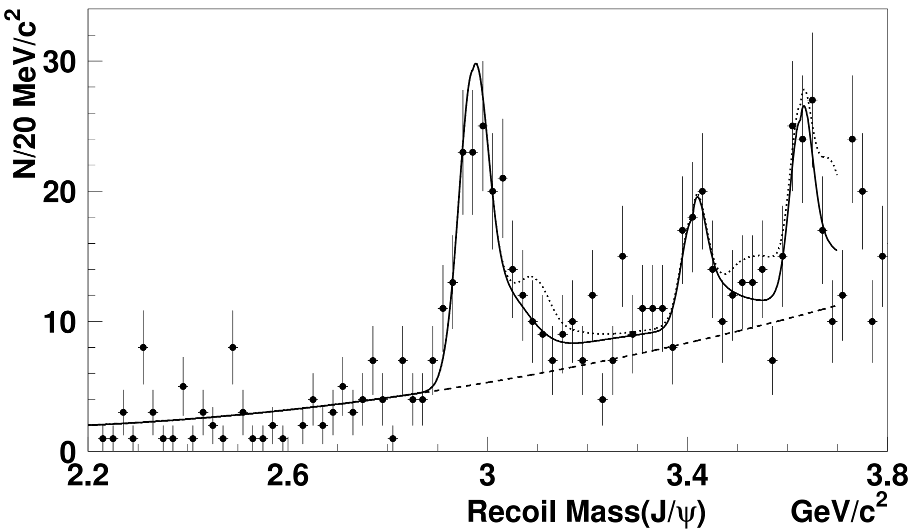
Charm Mysteries (1) – Discovery of the Ξ_c^+

CERN WA62 (1983)



- Beam: 135 GeV/c Σ^-
- 3 weeks of running
- no silicon detectors
- 83 events $\Xi_c^+ \longrightarrow \Lambda K^- \pi^+ \pi^+$
- measured Ξ_c^+ lifetime correctly

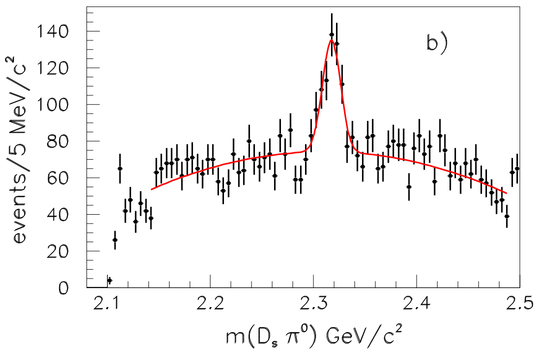
(Double)-Charm Mysteries (2) – $J/\Psi\,\eta_c$ Production

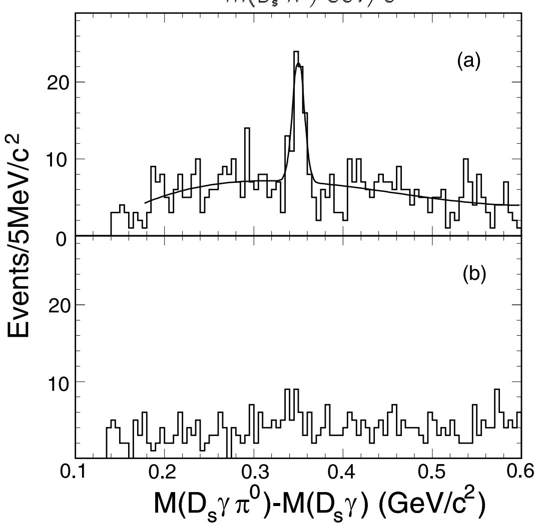


- Belle observed high double charm production in $e^+e^- \longrightarrow J/\Psi\, c\bar{c}$, $e^+e^- \longrightarrow J/\Psi\, \eta_c$
  (Phys. Rev. Lett. 89 (2002) 142001, hep-ex/0205104)
- Belle does not see $e^+e^- \longrightarrow J/\Psi\; J/\Psi$ (hep-ex/0306015)
- At publication, factor x40 higher cross section than theory.
- revised models still x10 too low.
- No confirmation from BaBar yet

Charm Mysteries (3) – Narrow D_s Resonances

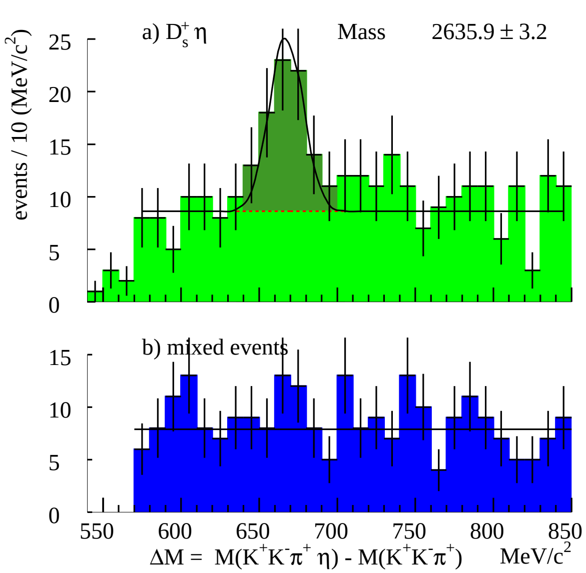
BaBar, CLEO, Belle (2003)
$D^{\star}_{sJ}(2315) \rightarrow D_s\pi^0$,
$D_{sJ}(2463) \rightarrow D_s\gamma\pi^0$

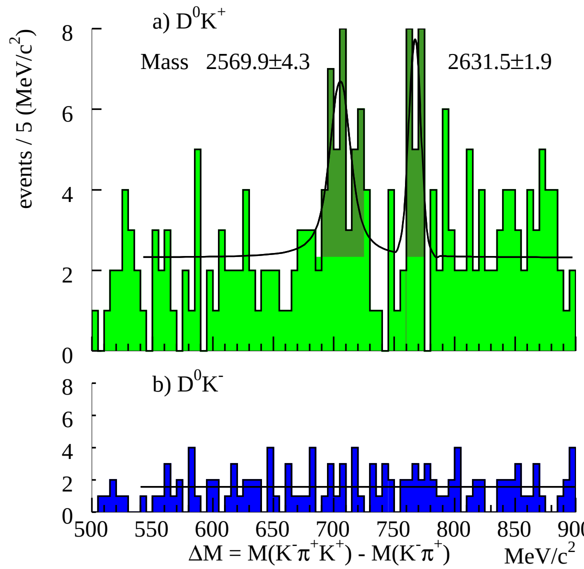




PRL90 (hep-ex/0304021); PRD68;
PRL91 (hep-ex/0308019)

SELEX 2004
$D^{\star}_{sJ}(2632) \rightarrow D^+_s\eta$ and D^0K^+





$$\frac{\Gamma(D^0K^+)}{\Gamma(D^+_s\eta)} = 0.16 \pm 0.06$$

hep-ex/0406045, submitted to PRL

Why weakly decaying Doublet?

- Excitation is $\sim 78\,\mathrm{MeV}/c^2$:
- Expect Electro-Magnetic De-Excitation (Emission of γ)
- About 6 orders of magnitud more probable as weak decay

- Bardeen, Eichten and Hill: spectroscopy of cc compared to $c\bar{s}$ (PRD68 054024, hep-ph/0305049)

$$\text{Ground State:} \quad J^P = \frac{1}{2}^+ [c\uparrow\ c\uparrow\ L=0, J^P=1^+]\, q\downarrow$$

$$\text{Excited State:} \quad J^P = \frac{1}{2}^- [c\uparrow\ c\downarrow\ L=1, J^P=1^-]\, q\downarrow$$

- First excited state is $L=1$ of heavy (cc) di-quark
- Predicted splitting consistent with observed $78\,\mathrm{MeV}/c^2$
- First EM transition is M2.

Summary and Outlook

- SELEX observes the $\Xi_{cc}^{+}(3520)$ in two decay modes: $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^{+} \to p D^+ K^-$
- SELEX observes two doublet of weakly decaying Double Charm Baryons:
  - $\Xi_{cc}^{+}\ (3443) \to \Lambda_c^+ K^- \pi^+$, $\Xi_{cc}^{+}\ (3520) \to \Lambda_c^+ K^- \pi^+$
  - $\Xi_{cc}^{++}(3460) \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_{cc}^{++}(3541) \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - Isospin splitting $\sim 19\,\mathrm{MeV}/c^2$
  - Excitation $\sim 78\,\mathrm{MeV}/c^2$
  - decay of lower states combatible with phase space, higher states not
- SELEX observes an excited Double Charm Baryon: $\Xi_{cc}^{\star++} \to \Xi_{cc}^{+} \pi^+$
- Double Charm Baryons produced by baryons (Σ^-, p)
- Lifetime at resolution limit: $\tau_{cc} < 30\,\mathrm{fs}$

- SELEX is working on other decay modes: Most promising $\Xi_{cc}^{+(+)} \to \Xi_c^+ \pi^+ \pi^- (\pi^+)$

- SELEX observed new excited D_s Meson in two decay modes: $D_{sJ}(2632) \to D_s^+ \eta$ and $D^0 K^+$