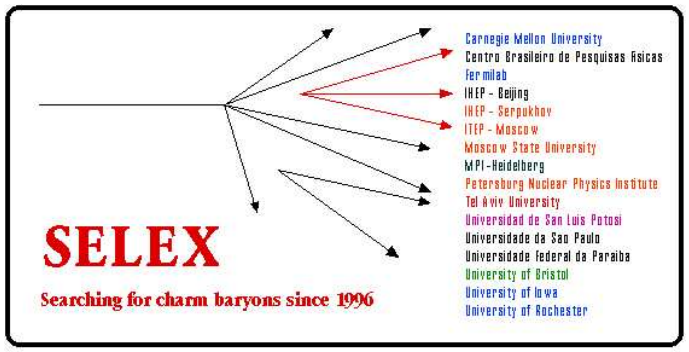


Recent SELEX Results on the Properties of Charmed Hadrons

Jürgen Engelfried, Instituto de Física, Universidad Autónoma de San Luis Potosí, Mexico
For the SELEX (Fermilab E781) Collaboration

Outline

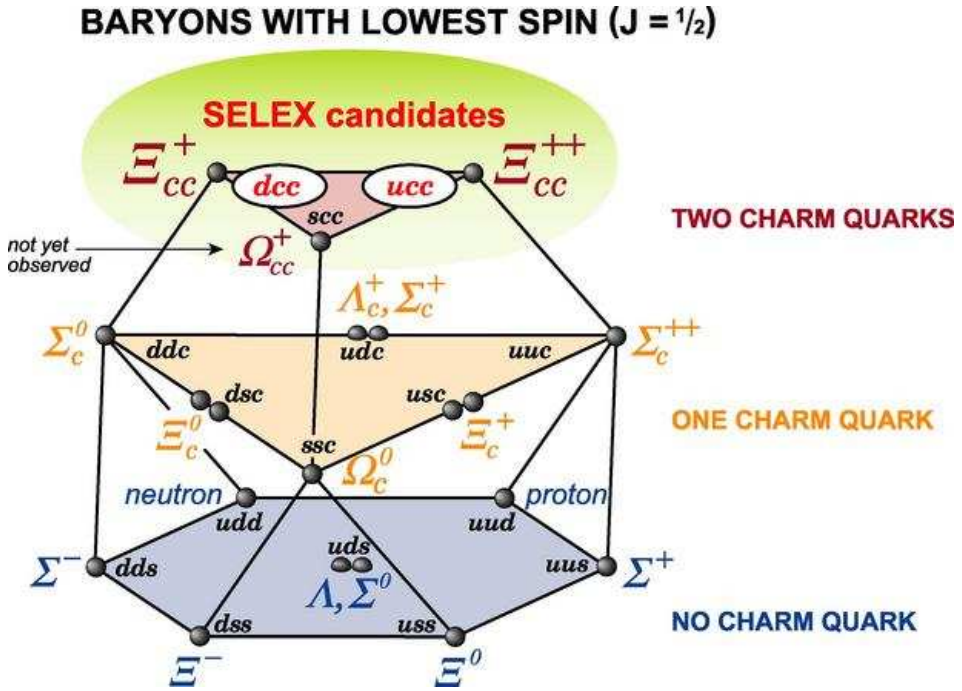
- Introduction
- The SELEX Experiment
- Double-Charm Baryons
- $D_s(2632)$
- Summary and Outlook

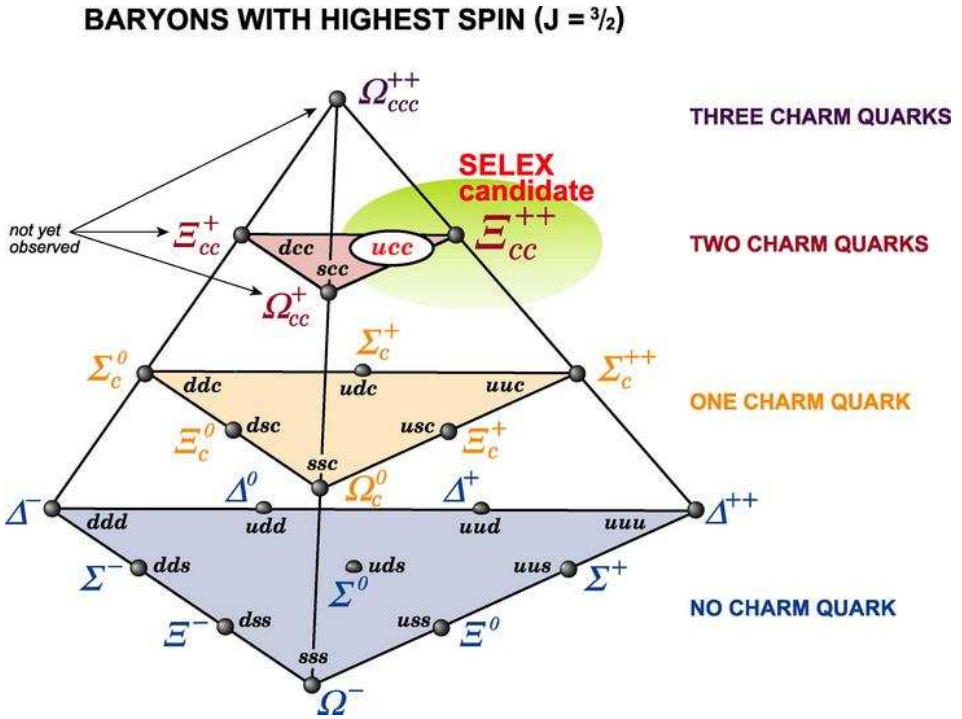
[0]jurgen@ifisica.uaslp.mx, http://www.ifisica.uaslp.mx/~jurgen

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.

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





Model Predictions for Doubly Charmed Baryon Masses

author	year	model	$\Xi_{cc}(J=3/2)$	$\Xi_{cc}(J=1/2)$
Bjorken	1986	phenom	$3.70\,\mathrm{GeV}/c^2$	$3.64\,\mathrm{GeV}/c^2$
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??

The SELEX (Fermilab E781) 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[2], D. Mao[3], P. Mathew[4], M. Mattson, M. Procario[5], J. Russ, J. You[1]
Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

A.M.F. Endler
Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

P.S. Cooper, J. Kilmer, S. Kwan, J. Lach, E. Ramberg, D. Skow, L. Stutte
Fermi National Accelerator Laboratory, 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.V. 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[6], 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[7], I. Eschrich[8], I. Konorov[9], H. Krüger[10], J. Simon[11], K. Vorwalter[12]
Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

I.S. Filimonov[6], E.M. Leikin, A.V. Nemitkin, V.I. Rud
Moscow State University, Moscow, Russia

A.G. Atamantchouk[6], G. Alkhazov, N.F. Bondar, V.L. Golovtsov, V.T. Kim, L.M. Kochenda, A.G. Krivshich, N.P. Kuropatkin[1], V.P. Maleev, P.V. Neoustroev, B.V. Razmyslovich[13], V. Stepanov[13], M. Svoiski[13], N.K. Terentyev[14], L.N. Uvarov, A.A. Vorobyov
Petersburg Nuclear Physics Institute, St. Petersburg, Russia

I. Giller, M.A. Moinester, A. Ocherashvili[15], V. Steiner
Tel Aviv University, 69978 Ramat Aviv, Israel

J. Amaro-Reyes, A. Blanco C., J. Engelfried[1], A. Morelos, I. Torres, E. Vázquez-Jáuregui
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

U. Akgun, A.S. Ayan, M. Kaya[16], E. McCliment, K.D. Nelson[17], C. Newsom, Y. Onel, E. Ozel, S. Ozkorucuklu[18], P. Pogodin
University of Iowa, Iowa City, IA 52242, U.S.A.

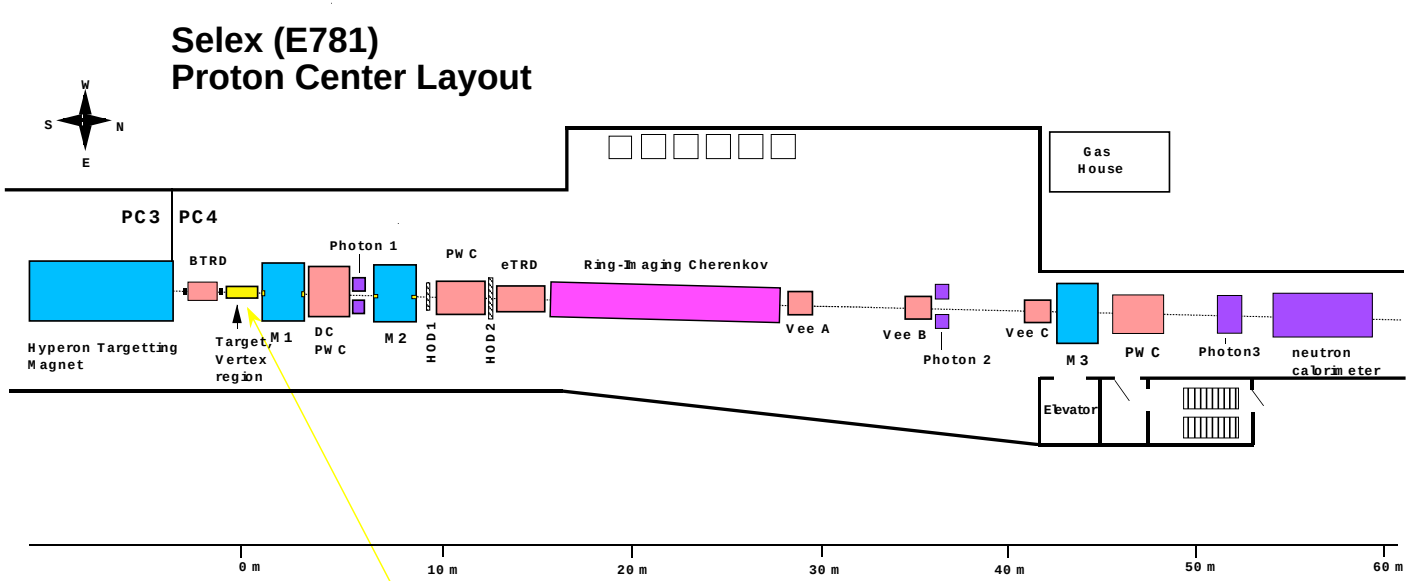
L.J. Dauwe
University of Michigan-Flint, Flint, MI 48502, U.S.A.

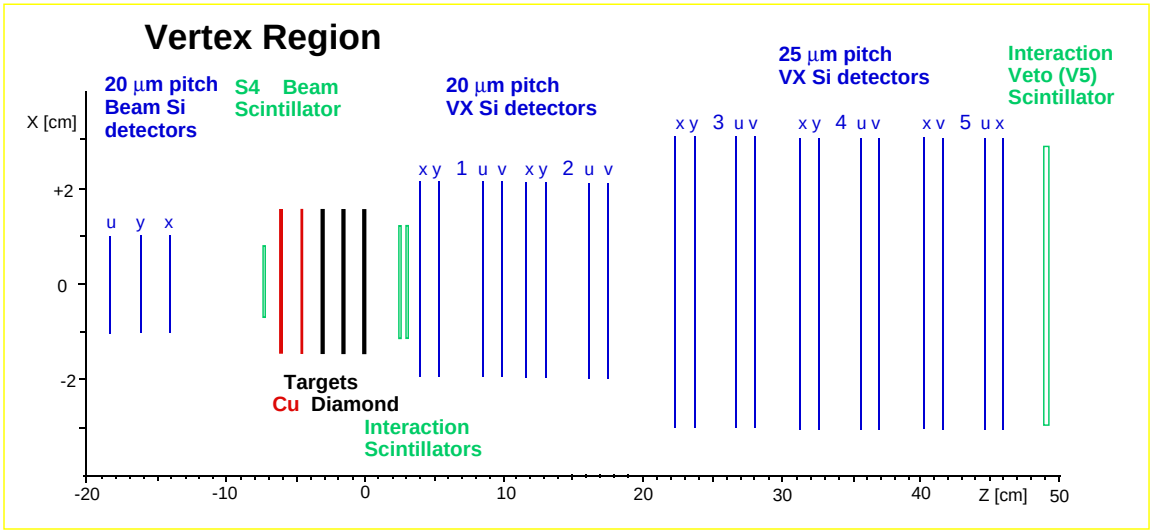
M. Gaspero, M. Iori
University of Rome "La Sapienza" and INFN, Rome, Italy

L. Emediato, C.O. Escobar[19], F.G. Garcia[1], P. Gouffon, T. Lungov, 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

The SELEX Experiment at Fermilab

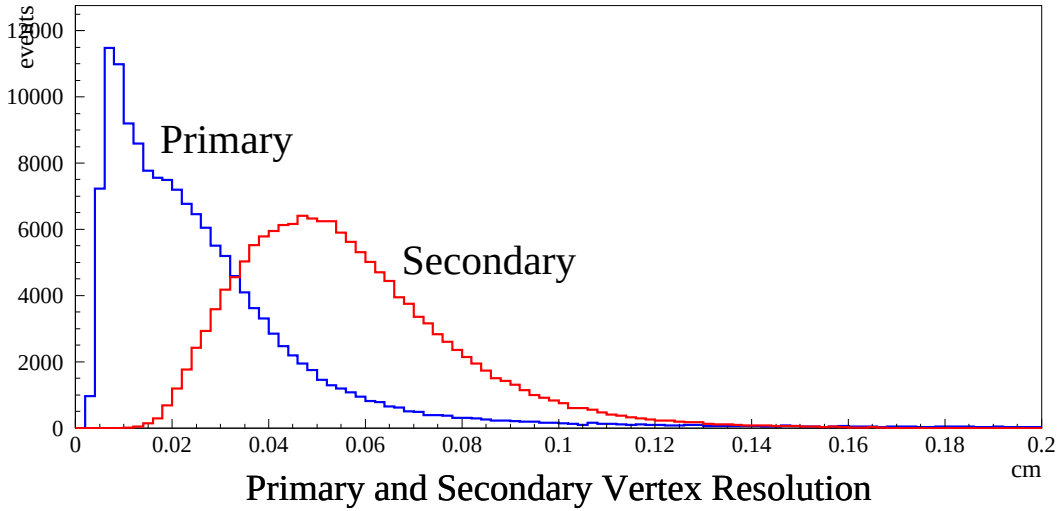


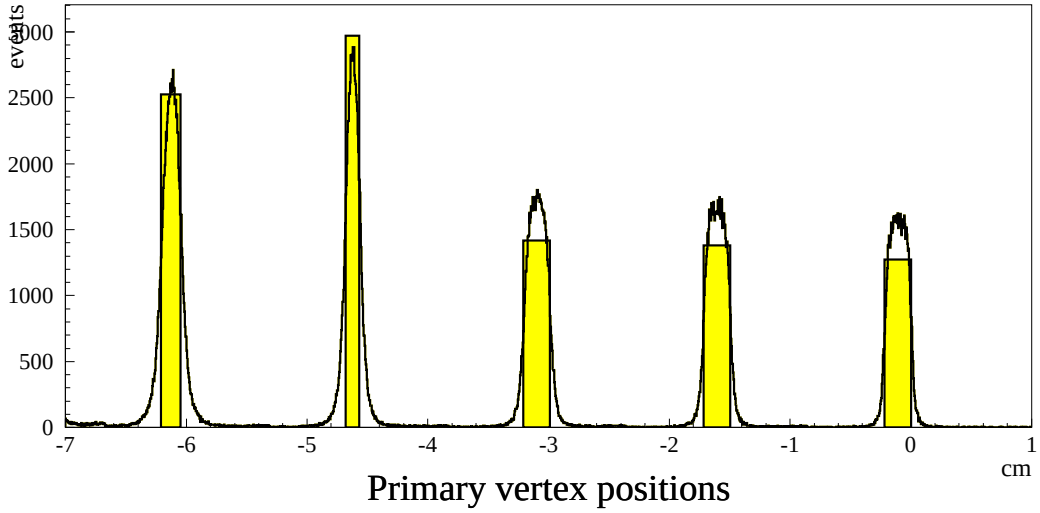


SELEX experiment

- 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

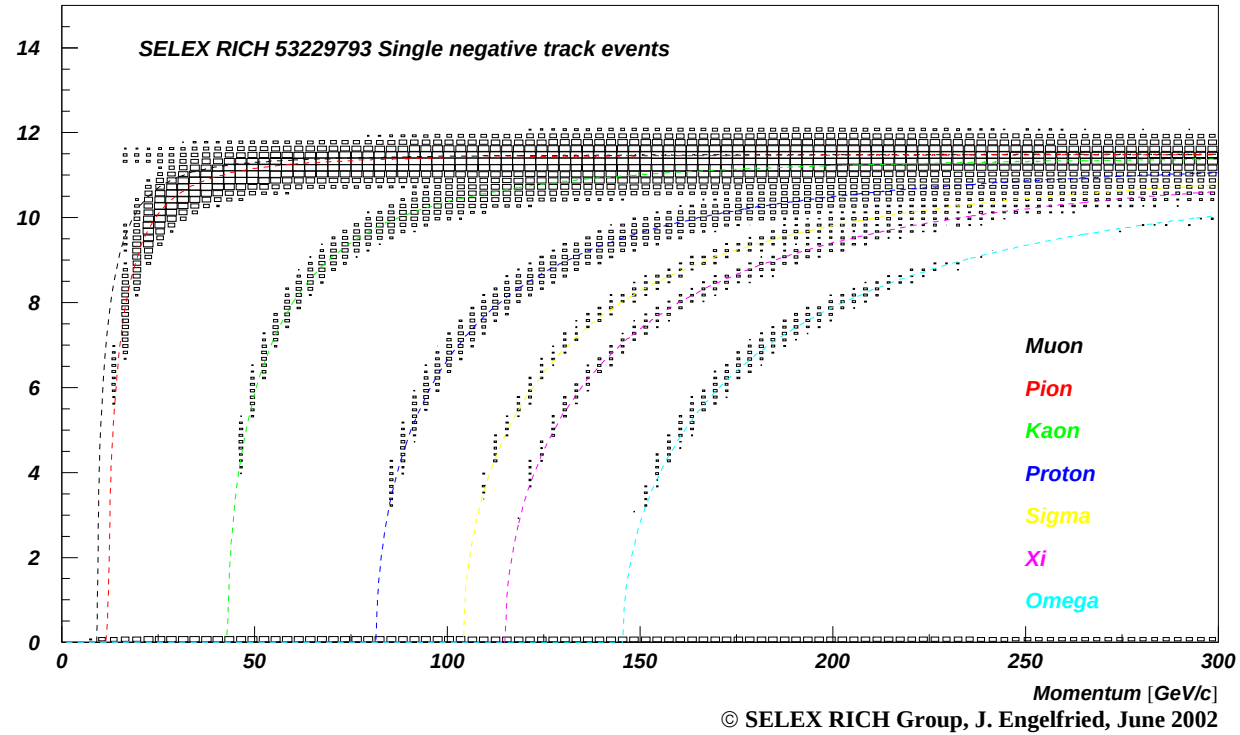
Vertex Spectrometer Performance

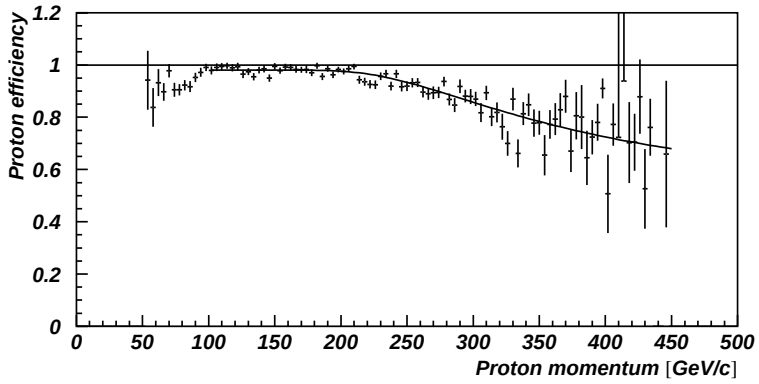


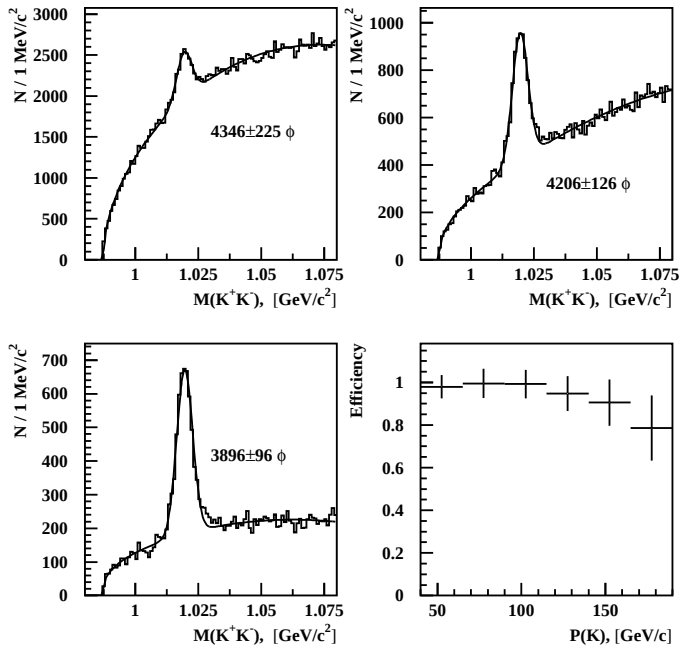


- **transverse vtx resolution $8 - 15\,\mu$m**
- **20 highly-efficient vertex planes over-determine tracks, reduce tracking confusion in high-multiplicity events**
- **target foils 0.8-2.2 mm thick with 1.5 cm spacing to localize primary interaction**
- **Lifetime resolution ~ 20 fs (slightly depending on particle and decay mode)**

Ring Imaging Cherenkov Counter Performance





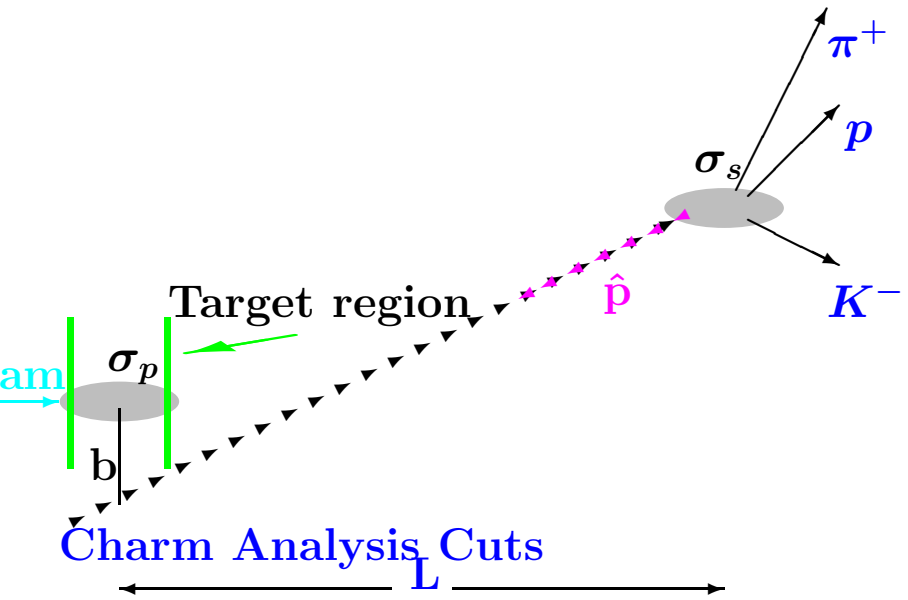


Selex publications

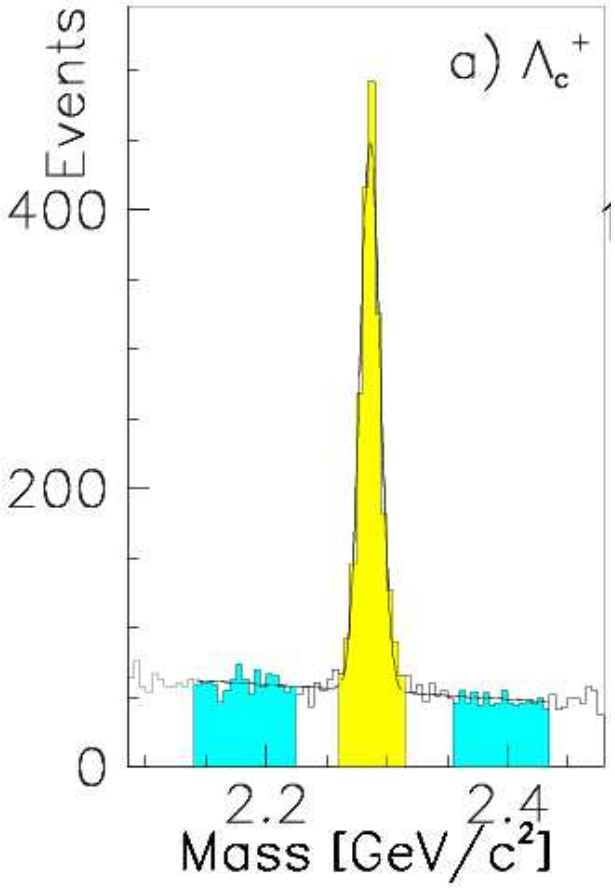
1. Observation of the Cabibbo-suppressed decay $\Xi_c^+ \to pK^-\pi^+$. Phys. Rev. Letter 84 (2000) 1857-1861.
2. Total Cross Section Measurements with π^-, Σ^- and Protons on Nuclei and Nucleons around 600 GeV/c. Nucl. Phys. B 579 (2000) 277-312.
3. Measurement of the Σ^- Charge Radius by Σ^-– Electron 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

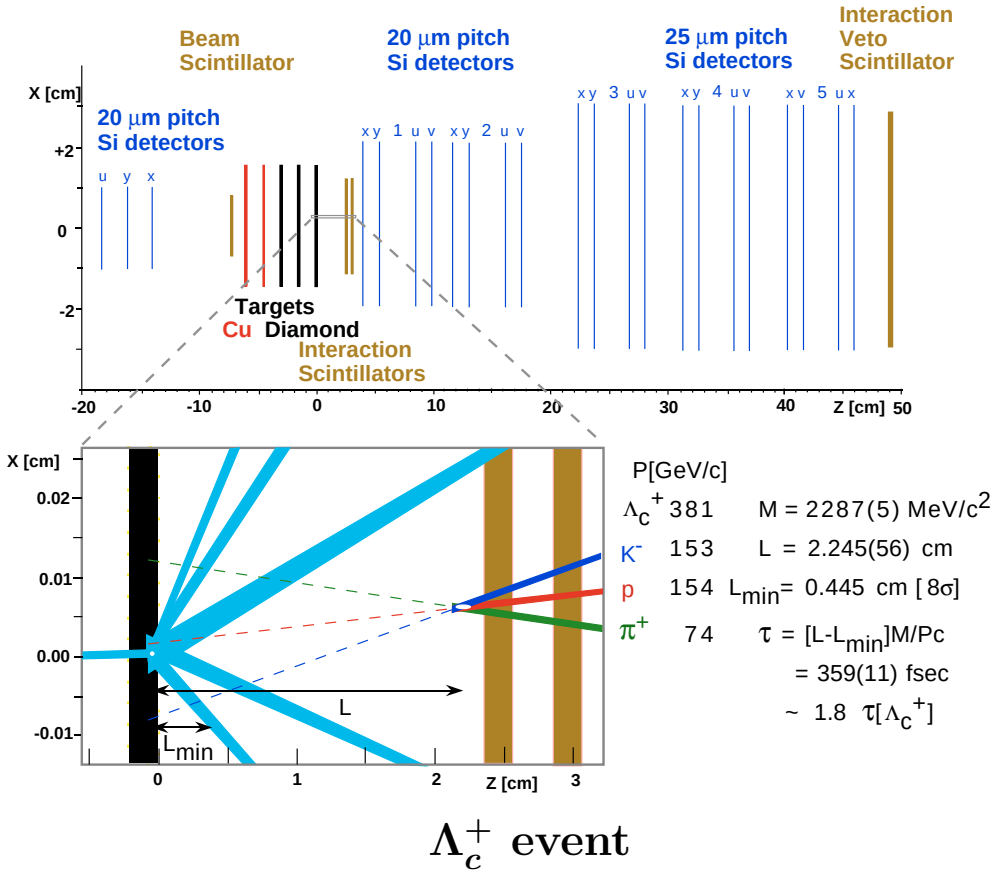


- Decay vertex separation significance L/σ
- Charm vector momentum points back to primary: cut on $(b/\sigma_b)^2$ (point-back cut)
- Decay vertex lies outside target material (space cut)
- Proton and Kaon identified in RICH detector



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

SELEX Charm Selection Criteria



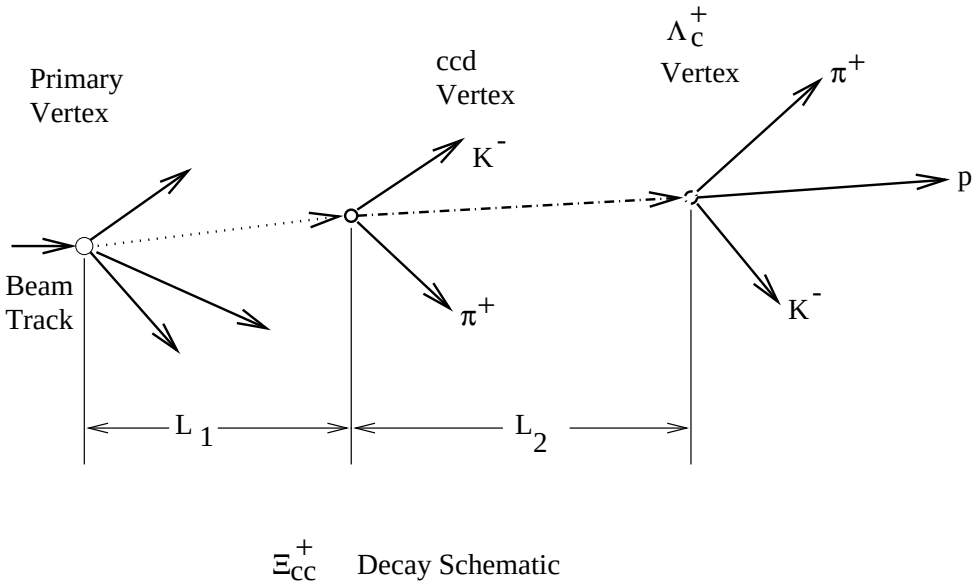
Λ_c^+ event

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

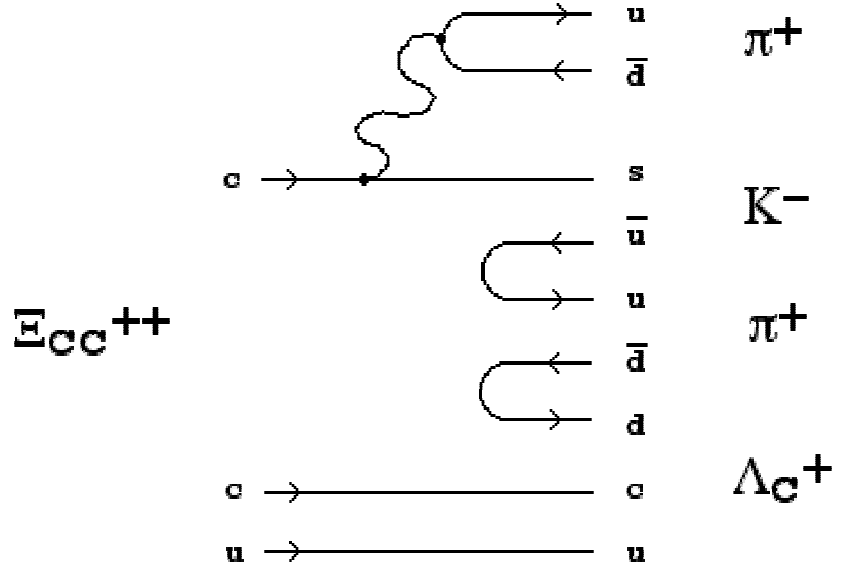
Charm Selection Cuts for single charm studies:

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

SELEX Search Strategy for Doubly-Charmed Baryons



Ξ_{cc}^+ Decay Schematic

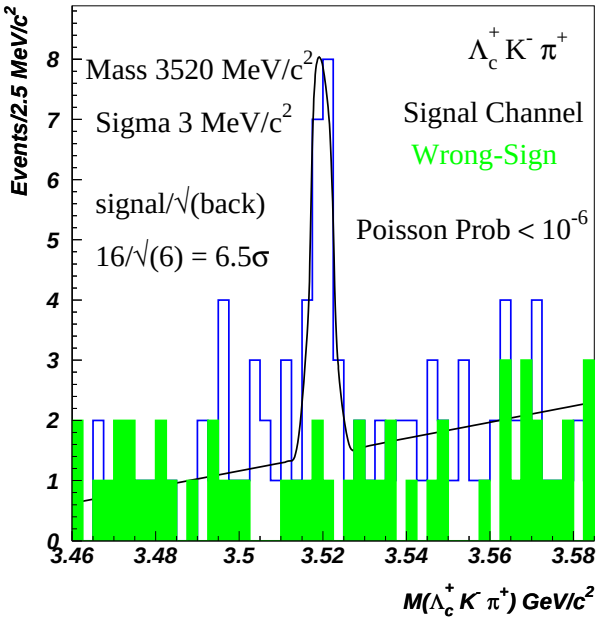


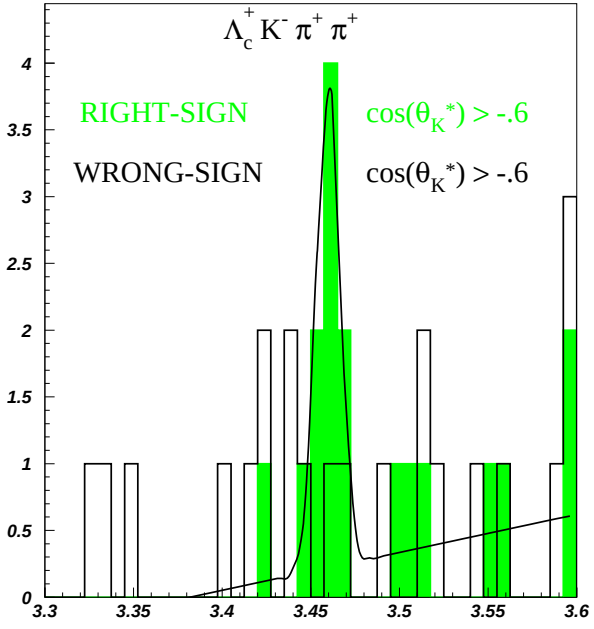
- ***ccq*** **decays to** ***csqu$\bar{d}$*****. Look for charm, strange and baryon in final state. SELEX started with** $\Lambda_c^+ K^- \pi^+ (\pi^+)$**.**
- **Look for new secondary vertex between primary and** Λ_c^+
- **no RICH PID on new** $K^- \pi^+$ **tracks (too soft)**
- **All other cuts fixed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

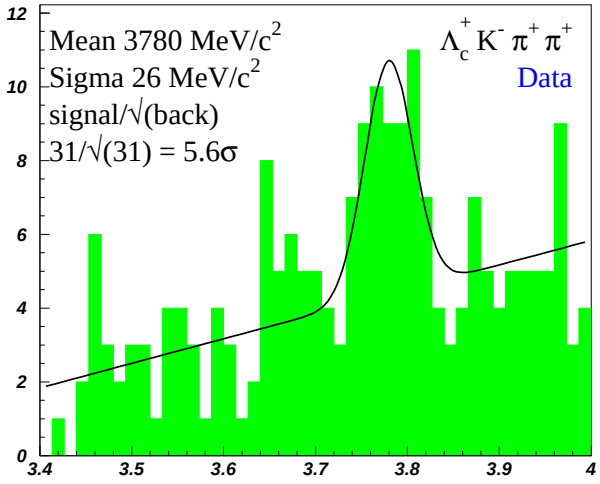
SELEX: Experimental Evidence from 2002

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 $3780\,\mathrm{MeV}/c^2$**





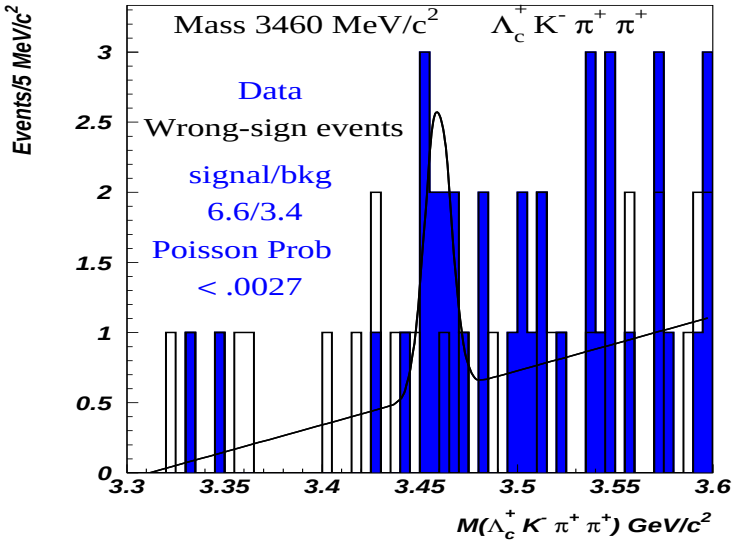


SELEX argued that these states are doubly-charmed baryons

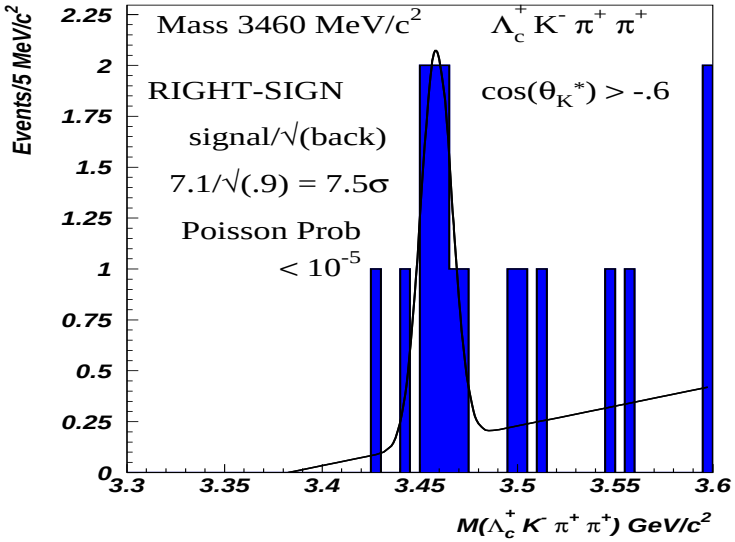
First Observation of the Doubly Charmed Baryon $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$. Phys. Rev. Letters 89 (2002) 112002.

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??

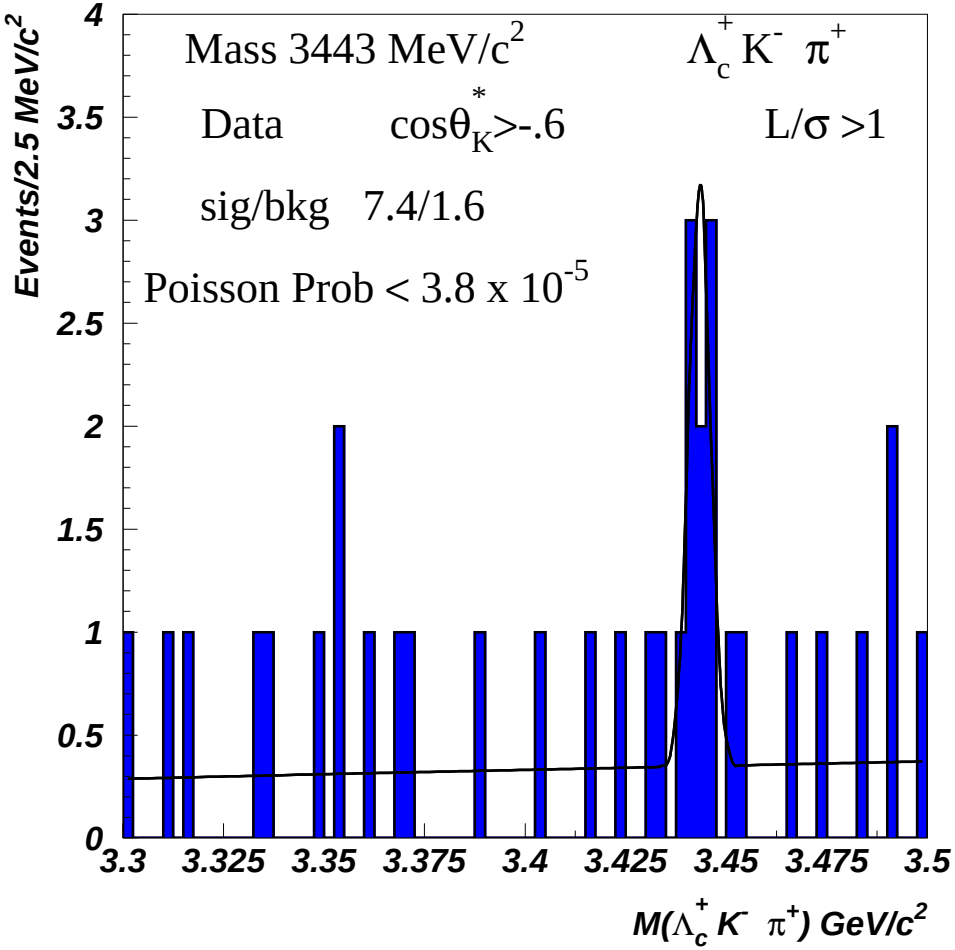
SELEX: Where is the Isopartner to $\Xi_{cc}^{++}(3460)$?

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

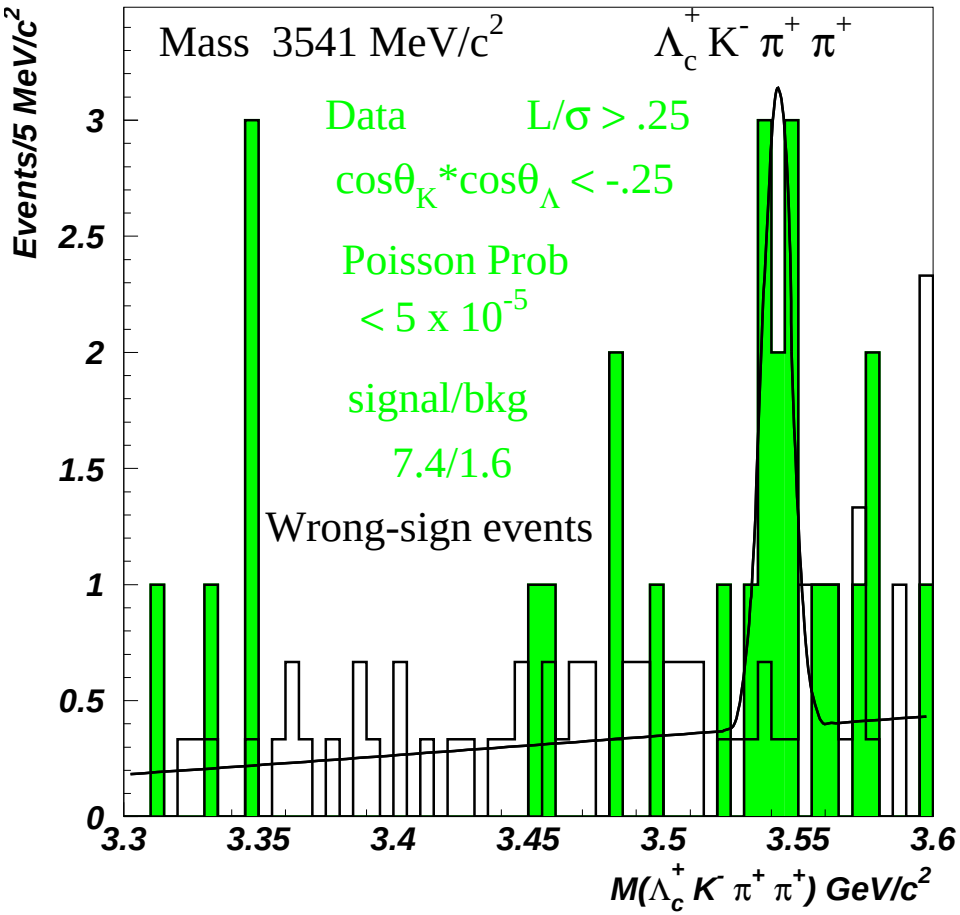
- $ccd^{+}(3520)$ not phase space ($\cos\Theta^{*}_{K}$ cut)
- Λ_c^{+} and K^{-} are back-to-back: $\cos\Theta^{*}_{K}\cos\Theta^{*}_{\Lambda_c} < -0.25$ keeps most of signal
- Apply also to $\Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ sample: Nothing

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

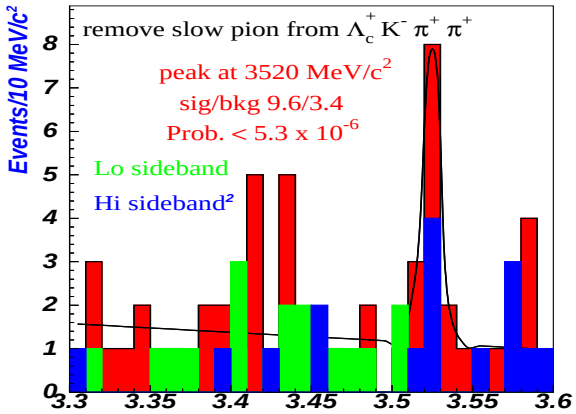
New $ccu^{++}(3541)$ now very significant

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

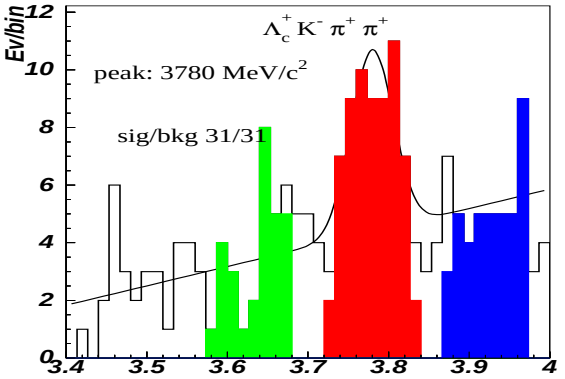
- $ccu^{++}(3541)$ is partner to $ccd^{+}(3520)$

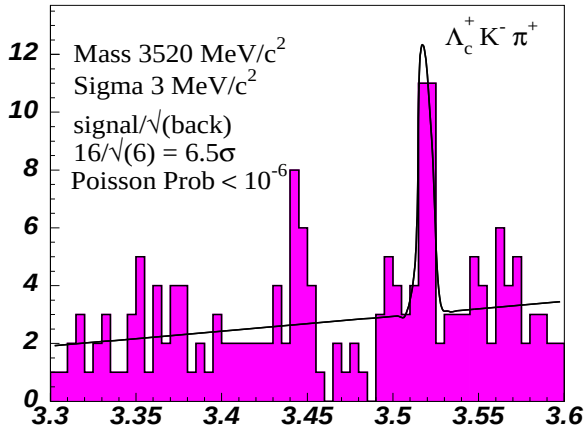


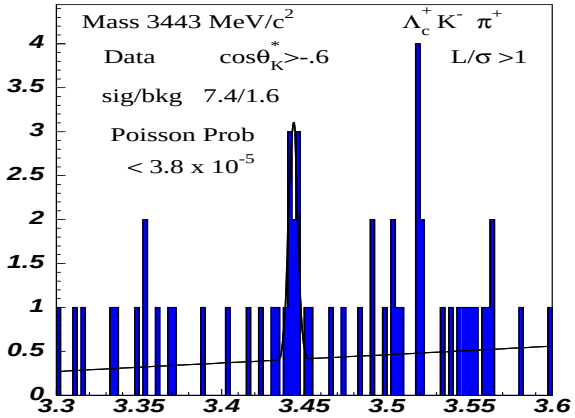
SELEX Double Charmed Baryon States

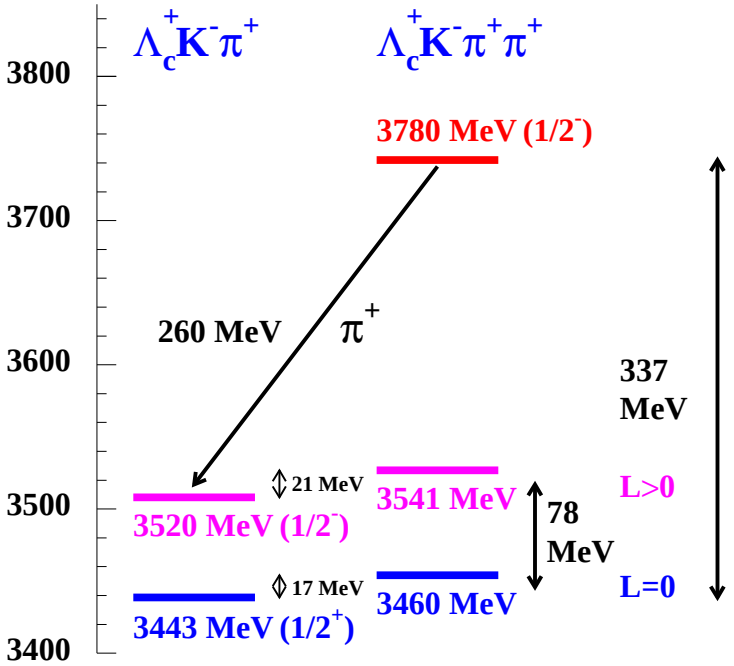


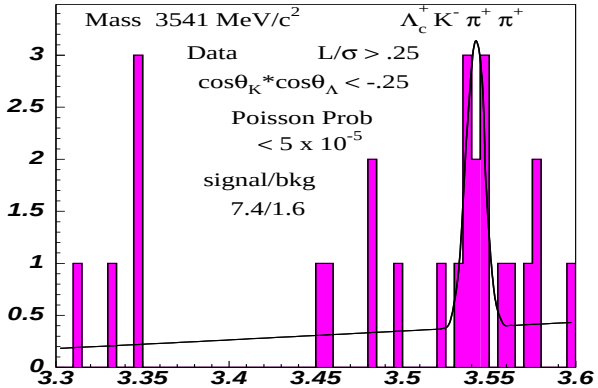
An exited state and a pair of isodoublets?

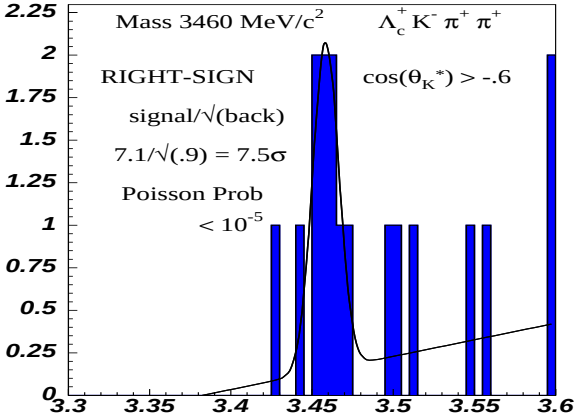






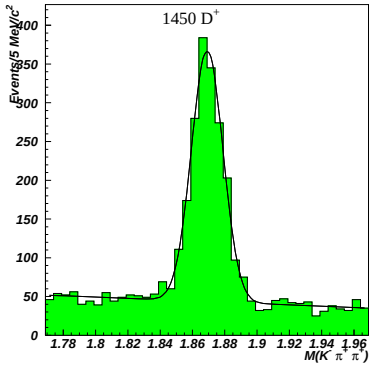


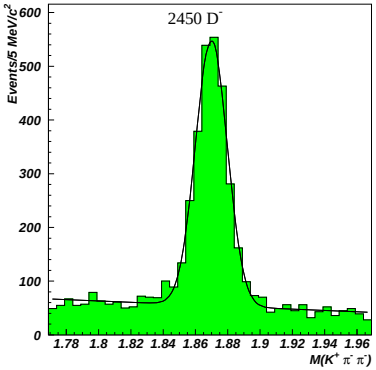




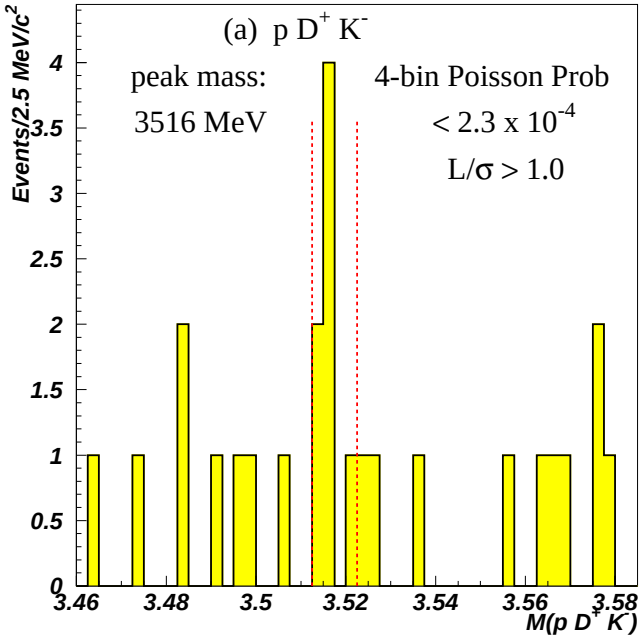
Other Double Charm Baryon Decay Modes?

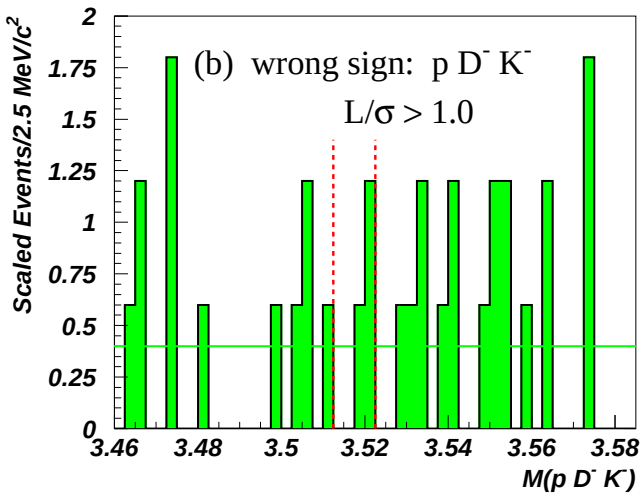
New SELEX result on $\Xi_{cc}^{+} \to pD^{+}K^{-}$: hep-ex/0406033, submitted to PRL



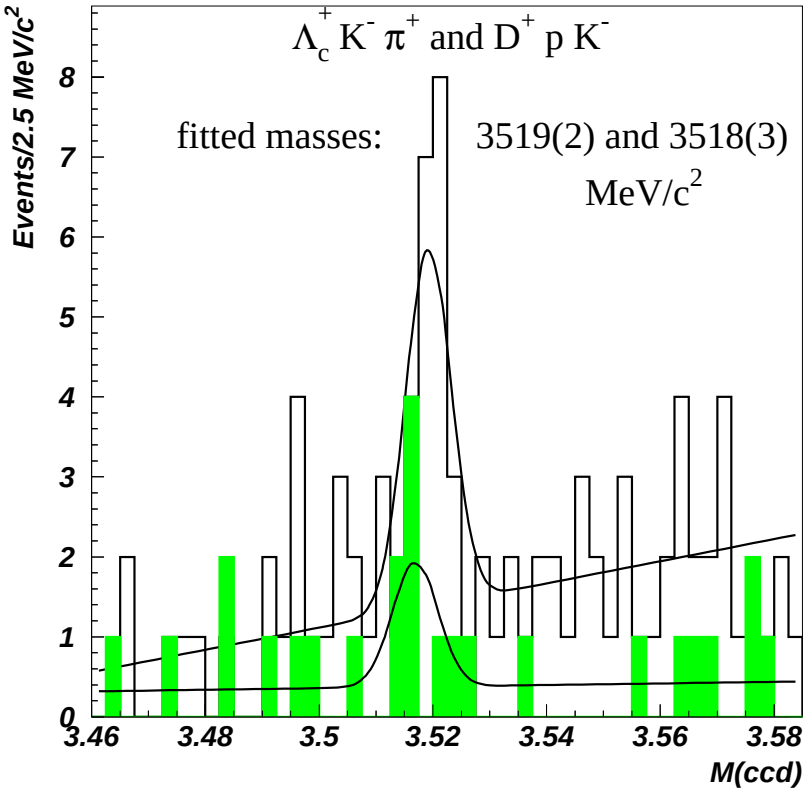


SELEX D^{+} and D^{-} Sample





Both Ξ_{cc}^{+} Decay Modes combined



$$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+ : \quad (3519 \pm 2)\,\mathrm{MeV}/c^2$$
$$\Xi_{cc}^{+} \to p D^+ K^- : \quad (3518 \pm 3)\,\mathrm{MeV}/c^2$$

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

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

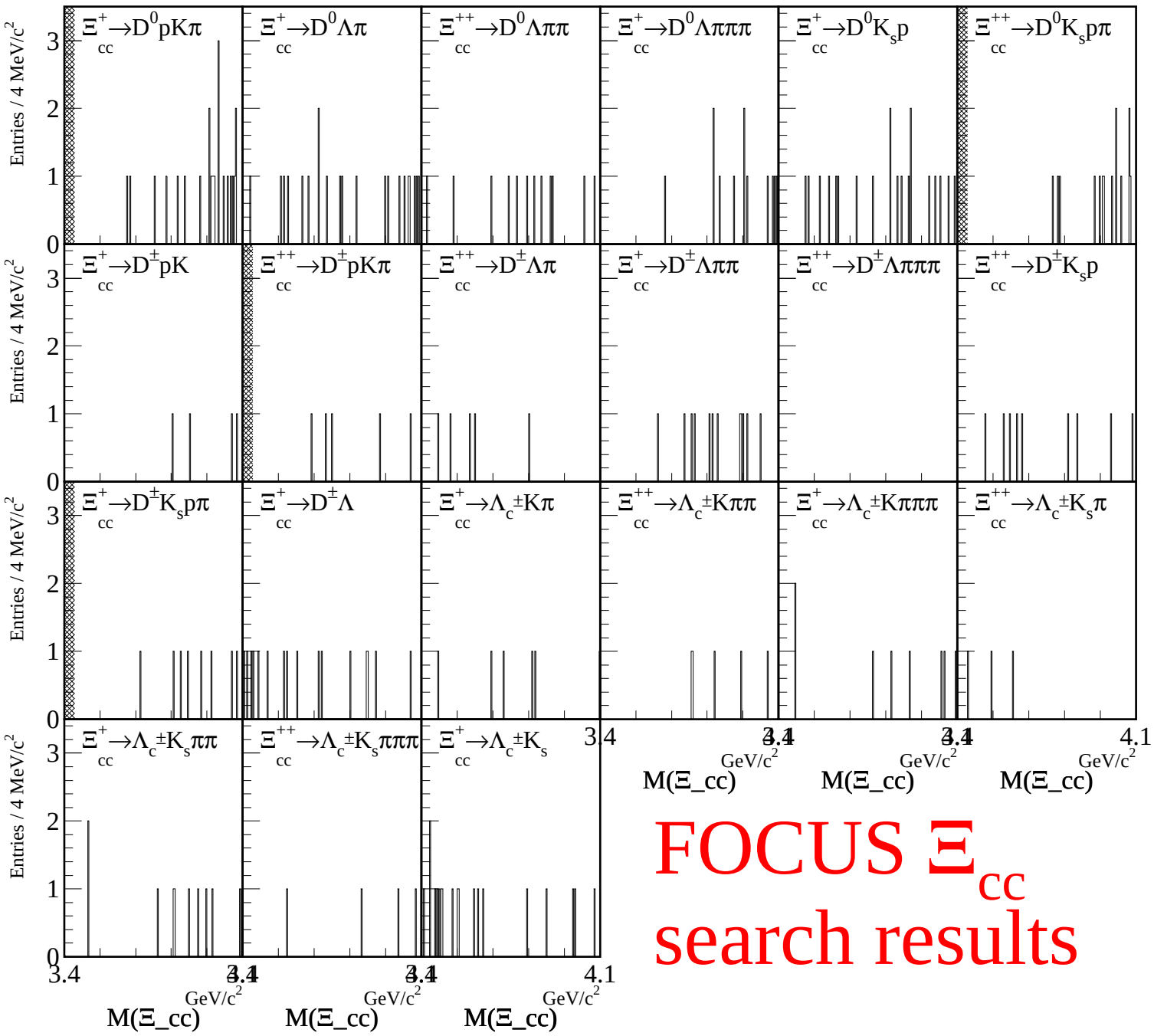
Doubly Charmed Baryons Properties

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 GeV/c π^- production** no signal
- **FOCUS looked in 250 GeV/c photo-production** no signal



FOCUS Ξ_{cc} search results

Why weakly decaying Doublet?

- **Observed Excitation is $\sim 78\,\mathrm{MeV}/c^2$:**
- **If Excitation is Chromomagnetic:**
  - **Expect dominant M1 Dipole Transition (like in $D^\star \rightarrow D\gamma$)**
  - **Weak decay of Chromomagnetic Excited State Suppressed by ~ 6 orders of magnitude**

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

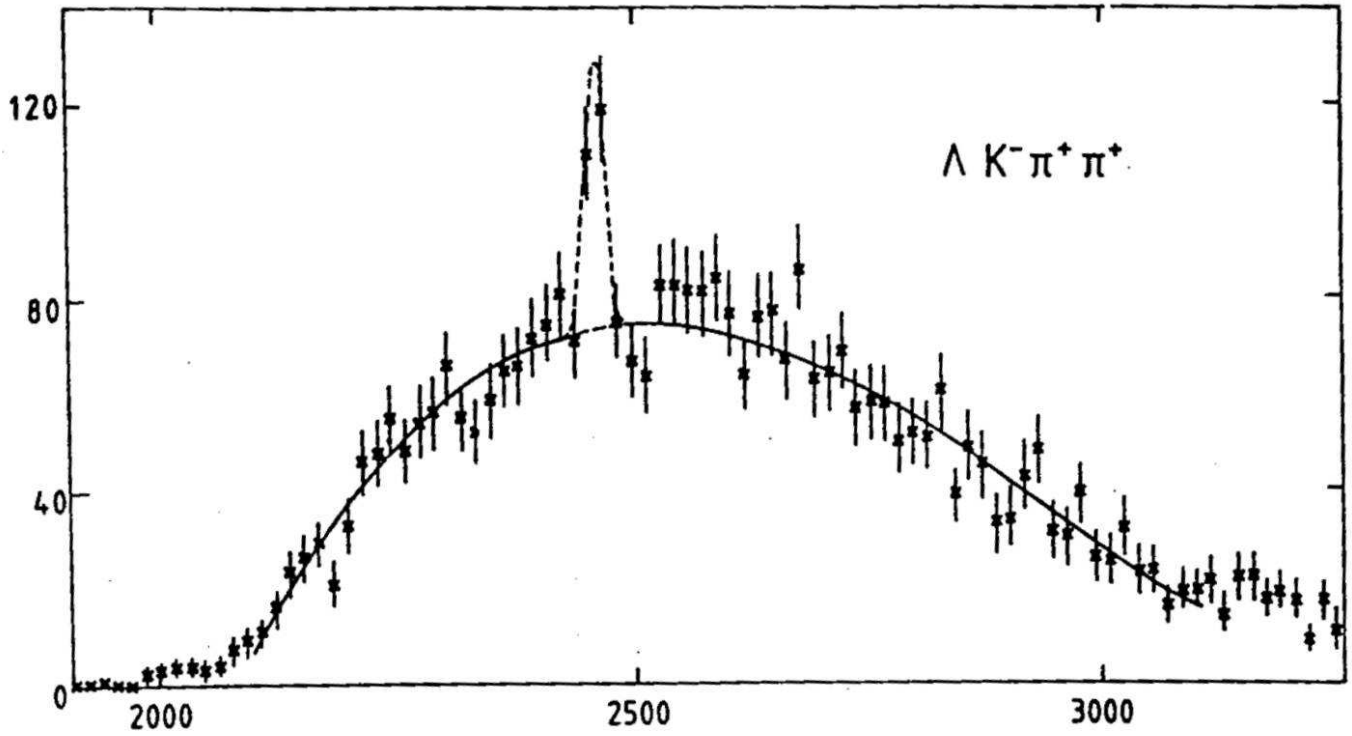
$$\textbf{Ground State:} \quad J^P = \frac{1}{2}^+ \, [c\uparrow \; c\uparrow \; L=0, J^P = 1^+]\, q\downarrow$$

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

- **First excited state is $L = 1$ of heavy (cc) di-quark**
- **In at least one version of the model splitting is consistent with observed $78\,\mathrm{MeV}/c^2$**
- **First EM transition is M2.**

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

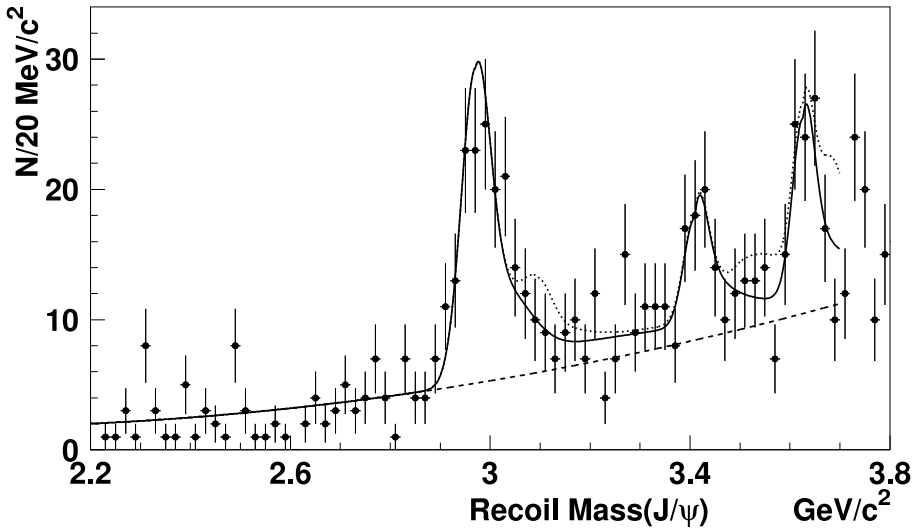
CERN WA62 (1983)



- **Beam: 135 GeV/c Σ^-**
- **3 weeks of running**
- **no silicon detectors**

- **83 events $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$**
- **measured Ξ_c^+ lifetime correctly**

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

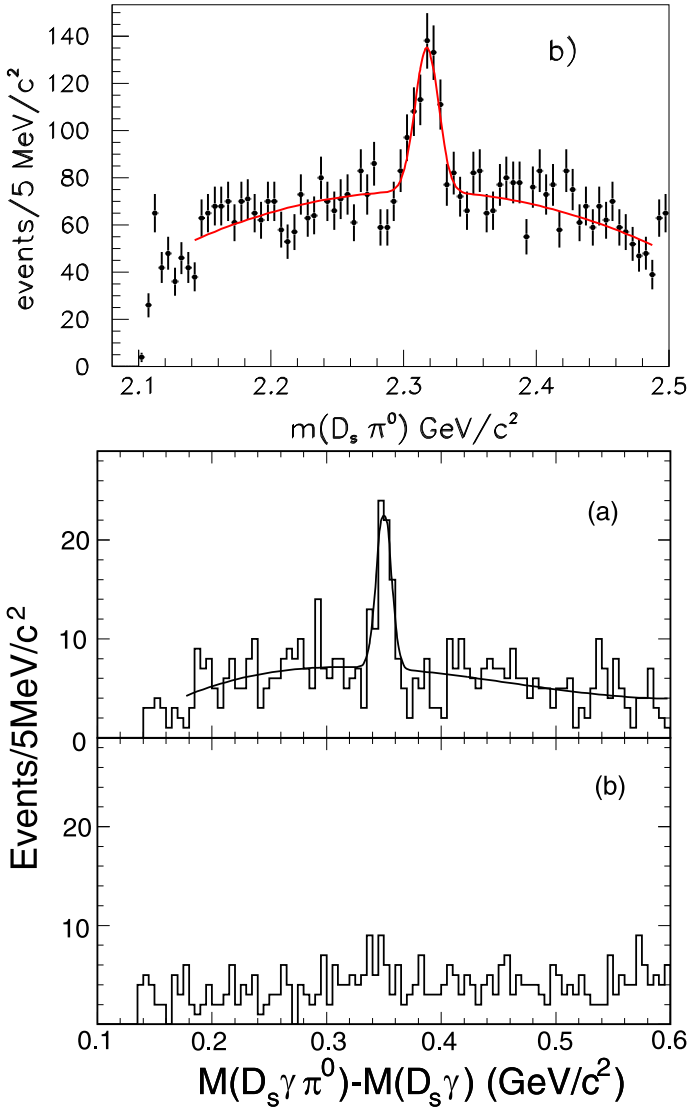


- Belle observed high double charm production in $e^+e^- \rightarrow J/\Psi\,c\bar{c}$, $e^+e^- \rightarrow J/\Psi\,\eta_c$ (Phys. Rev. Lett. 89 (2002) 142001, hep-ex/0205104)
- Belle does not see $e^+e^- \rightarrow J/\Psi\,J/\Psi$ (hep-ex/0306015)
- At publication, factor x40 higher cross section than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

Charm Mysteries (3) – Narrow D_s Resonances

BaBar, CLEO, Belle (2003)

$D^{\star}_{sJ}(2315) \to D_s\pi^0$, $D_{sJ}(2463) \to D_s\gamma\pi^0$



PRL90 (hep-ex/0304021); PRD68;

PRL91 (hep-ex/0308019)

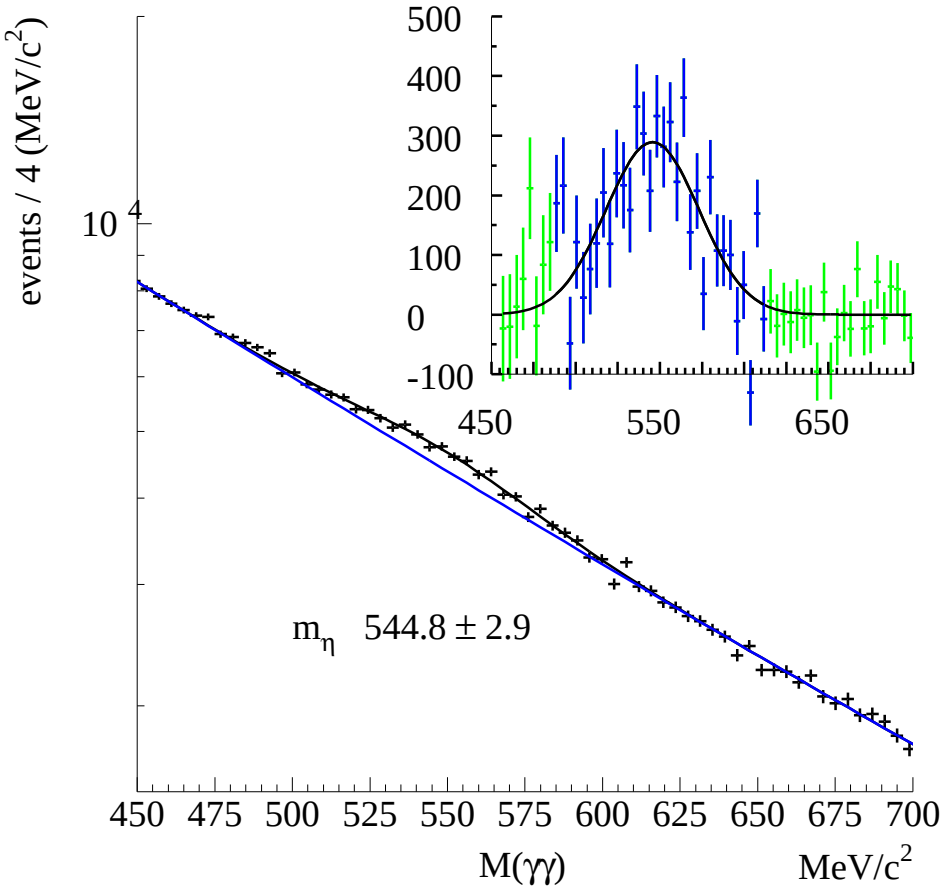
SELEX Search: η Signal in Charm trigger

SELEX Photon detection (Leadclass):

- **Energy scale verified on π^0, Σ^0: Good to $< 2\,\%$ over full energy range**
- **Also on D^*.**

$\eta \to \gamma\gamma$

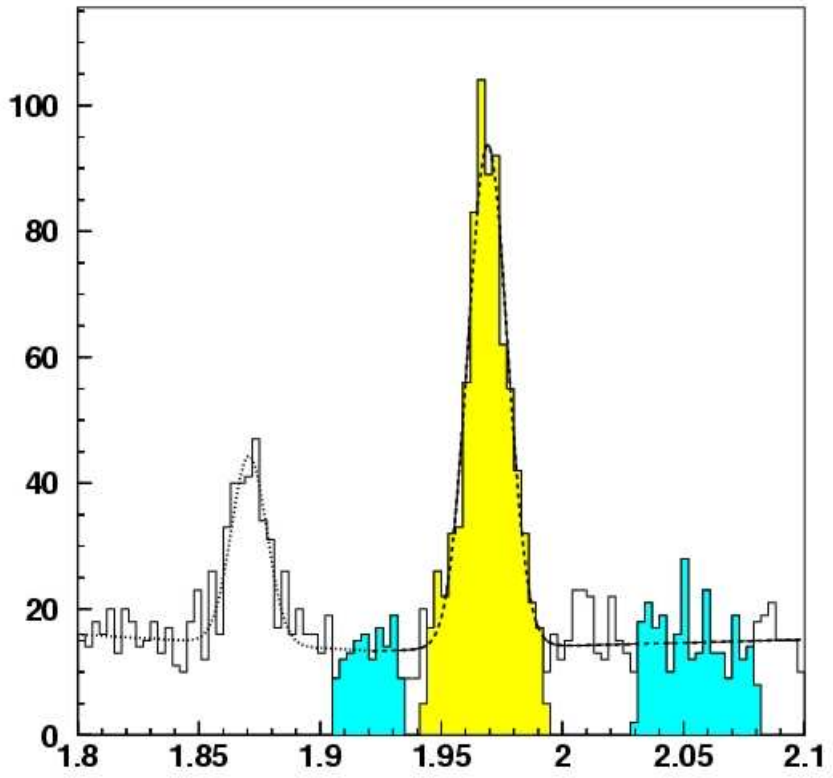
- $E_\gamma > 2\,\mathrm{GeV}$
- $E_{\gamma\gamma} > 15\,\mathrm{GeV}$
- **Good fit to: exponential + Gauss**
  - **Fit $M(\eta) = 544.9 \pm 2.9$**
  - **PDG $M(\eta) = 547.3 \pm 0.12$**
  - **Fit Width: 27.8 ± 4.3**
  - **MC resolution: 30.2 ± 1.2**



η-yield per interaction: 0.05

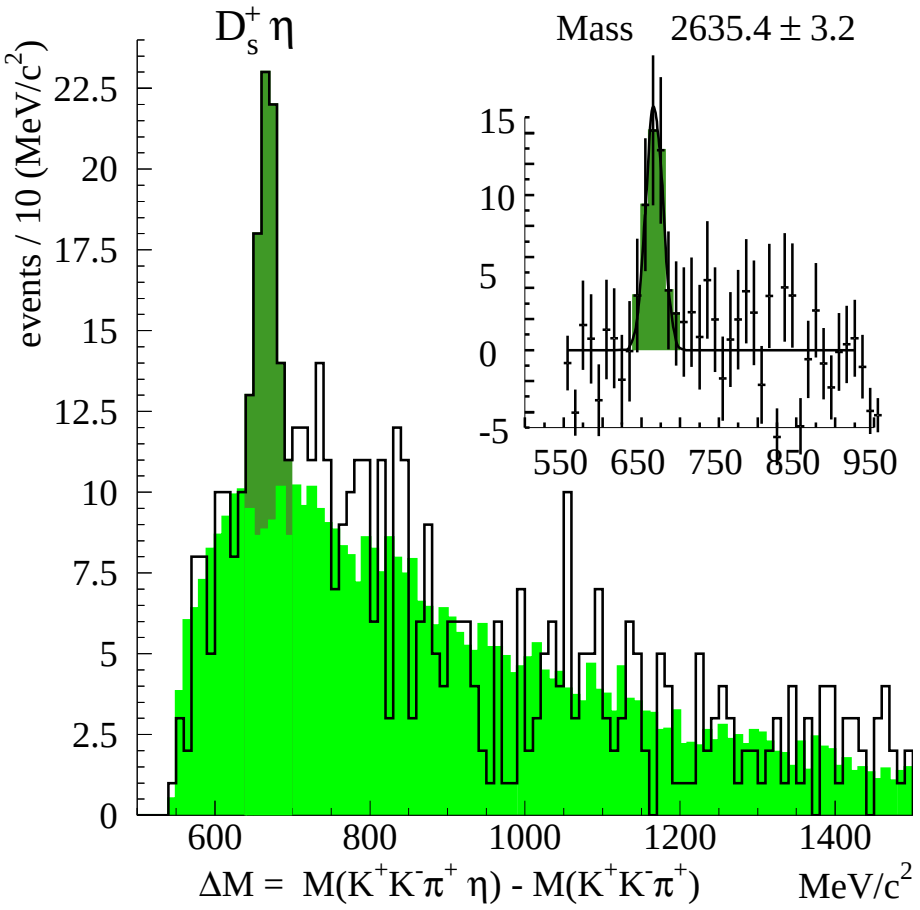
SELEX Search: D_s Signal in Charm trigger

$$D_s \to K^- K^+ \pi^-$$



SELEX: $D_{sJ}^{\star}(2632) \rightarrow D_s^+\eta$

- Combine D_s events with η candidates
- Reject events with $N_\eta > 5$ (loss: 18/554)
- Background: mix η from 25 other events with each D_s and rescale
- 43.4 ± 9.1 signal events for Gaussian fit to substracted data; $\chi^2 = 0.9$
- $6.2\,\sigma$ peak at $2635.4\,\mathrm{MeV}/c^2$

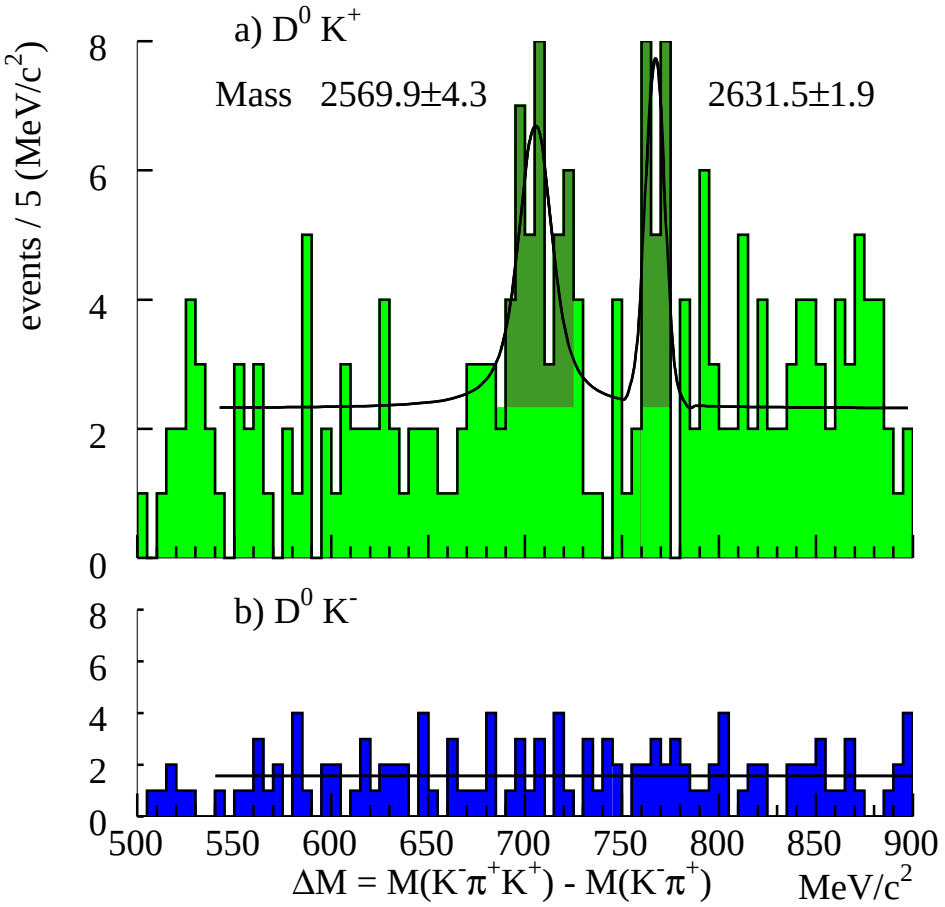


η-yield:

- in signal band: 0.18 per interaction with D_s
- Remove Signal: $.12 \pm 0.05$

hep-ex/0406045, submitted to PRL

SELEX: $D_{sJ}^{\star}(2632) \to D^0 K^+$



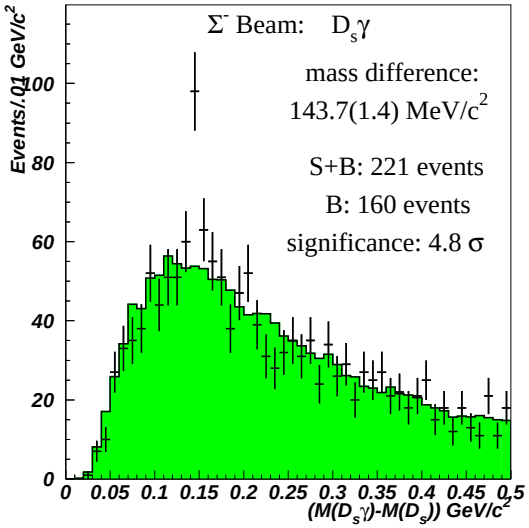
- Well identified D^0, K^+
  - $D^0 \to K^-\pi^+$ only (S/N 4/1)
  - Prob(K^+) > 10 Prob(any other)
- Wrong sign background constant
- Fit to 2 Breit-Wigner with Gaussians, and constant background
- Width of Gaussians fixed from MC

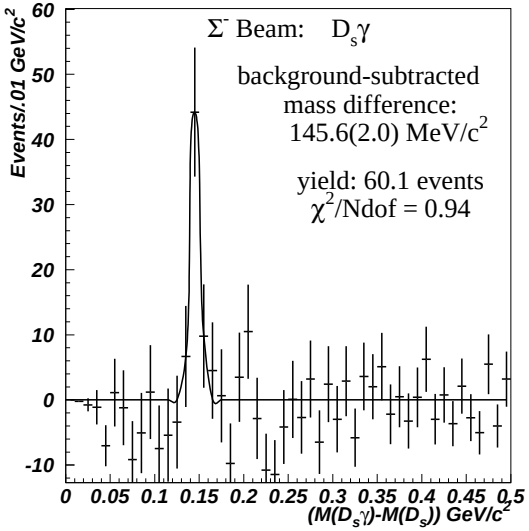
$D_{sJ}(2573)$	Mass	Width Γ
PDG	2573 ± 1.7	15^{+5}_{-4}
SELEX	2569 ± 4.3	14^{+9}_{-6}

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

14 ± 4.5 Events at $2631.5 \pm 1.9\,\mathrm{MeV}/c^2$
Poisson excess prob. 10^-4
90% CL upper limit: $\Gamma < 17\,\mathrm{MeV}/c^2$
ABOVE THRESHOLD! WHY NARROW?

Look at $D_s(2112) \rightarrow D_s\gamma$





- **CLEO: $D_s(2112)/D_s$: $0.59 \pm 0.03 \pm 0.01$**
- **SELEX: $D_s(2112)/D_s$: 0.24 ± 0.06**
- **BUT: A lot of D_s come from $D_s(2632)$! Corrected SELEX Yield: $D_s(2112)/D_s$: 0.53 ± 0.13**
- **$D_s(2632)$ has different production mechanism**
- **What is it?**

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 compatible 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 $\Xi_{cc}^{+(+)} \to \Xi_{c}^{+} \pi^{+} \pi^{-} (\pi^{+})$
  - Eventually also go to the Ω_{cc}^{++}
- SELEX observes new excited D_s Meson in two decay modes: $D_{sJ}(2632) \to D_s^{+} \eta$ and $D^0 K^{+}$, with small width, and mostly decaying to $D_s^{+} \eta$
- SELEX is working on charmed baryon properties:
  - Ω_c lifetime
  - Ξ_c lifetimes
  - $D^{\pm}$, D^0 production