BEAUTY 2003

Review of Recent Results in Charm Physics

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Introduction

Open Charm in the previous ~ 5 years:

- The "Traditional" Charm Experiments: E791, FOCUS, SELEX, (WA89, WA92), CLEO, H1/ZEUS
- "Traditional" Topics: Production, Lifetime, rare decays, resonances in decay, $D^0 - \overline{D^0}$ mixing
- Small number of theory and phenomenology papers

In the last year or so:

- New players: BaBar and Belle, CDF
- New charm states: double charm baryons, hidden double charm $(J/\Psi\, c\overline{c})$, D_s^*, $X(3872)$
- New particles: Z^+ (Θ^+), triggered Θ_c^0 predictions
- Large number of "theory" papers: spectroscopy, production
- Shift of used words in papers: di-quark

Outline

- $D^0 - \overline{D^0}$ Mixing
- Decays of D^0, D^+, D_s^+ Mesons
- New D_s states
- Charmed Baryons: New Modes in Λ_c^+, Ξ_c^+, Ξ_c^0, Ω_c^0
- Charmed Baryons: Mass of Σ_c, Ω_c^0
- Doubly Charmed Baryons: Update on SELEX Observations

More talks about charm:

- Chunhui Chen: Heavy Flavour Production at the Tevatron (today 11:30)
- J.C. Wang: Review of New D_S States (today 2pm)
- Karim Trabelsi: Charm Physics at Belle (today 2:45pm)
- Robert Harr: Recent Heavy Flavor Results from CDF (yesterday 9:30) (Belle $X(3872)$)
- David Asner: CLEO$_c$

$D^0 - \overline{D^0}$ Mixing

usually measured: Lifetime difference between $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$

$$y_{\mathcal{CP}} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \qquad \text{Standard Model: } y_{\mathcal{CP}} \sim 10^{-3}$$

Recent Results:

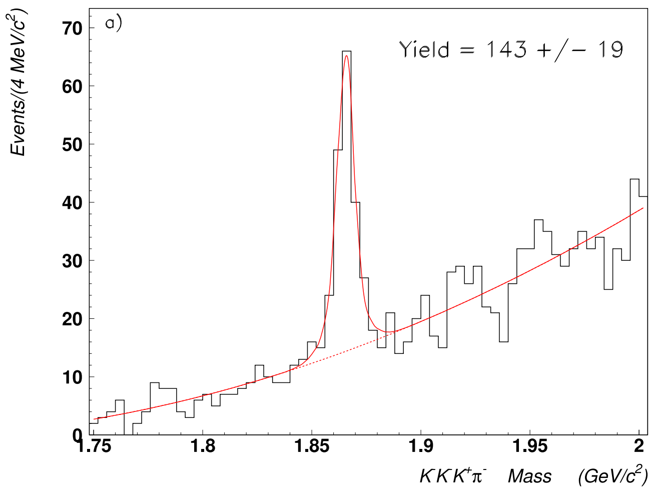
Belle:	$y_{\mathcal{CP}} = (+1.15 \pm 0.69 \pm 0.38)\,\%$	(hep-ex/0308034)	
BaBar:	$y_{\mathcal{CP}} = (-0.8 \pm 0.4\,^{+0.5}_{-0.4})\,\%$	(hep-ex/0306003)	also includes $D^0 \to \pi^+\pi^-$
CLEO:	$y_{\mathcal{CP}} = (-1.2 \pm 2.5 \pm 1.4)\,\%$	(PRD65, 2002)	also includes $D^0 \to \pi^+\pi^-$
FOCUS:	$y_{\mathcal{CP}} = (3.42 \pm 1.39 \pm 0.74)\,\%$	(PLB485, 2000)	
E791:	$y_{\mathcal{CP}} = (0.8 \pm 2.9 \pm 1.0)\,\%$	(PRL83, 1999)	Measured $\Delta\Gamma = (0.04 \pm 0.14 \pm 0.05)\,\text{ps}^{-1}$

Also: Analyze “wrong sign” Double Cabibbo Suppressed $D^0 \to K^+\pi^-$

BaBar:	$-0.056 < y' < 0.039$ (95% C.L.)	(hep-ex/0304007)
CLEO:	$-0.058 < y' < 0.01$ (95% C.L.)	(PRL84, 2000)

Rare Decays of D Mesons: D^0

FOCUS: $D^0 \to K^- K^- K^+ \pi^+$

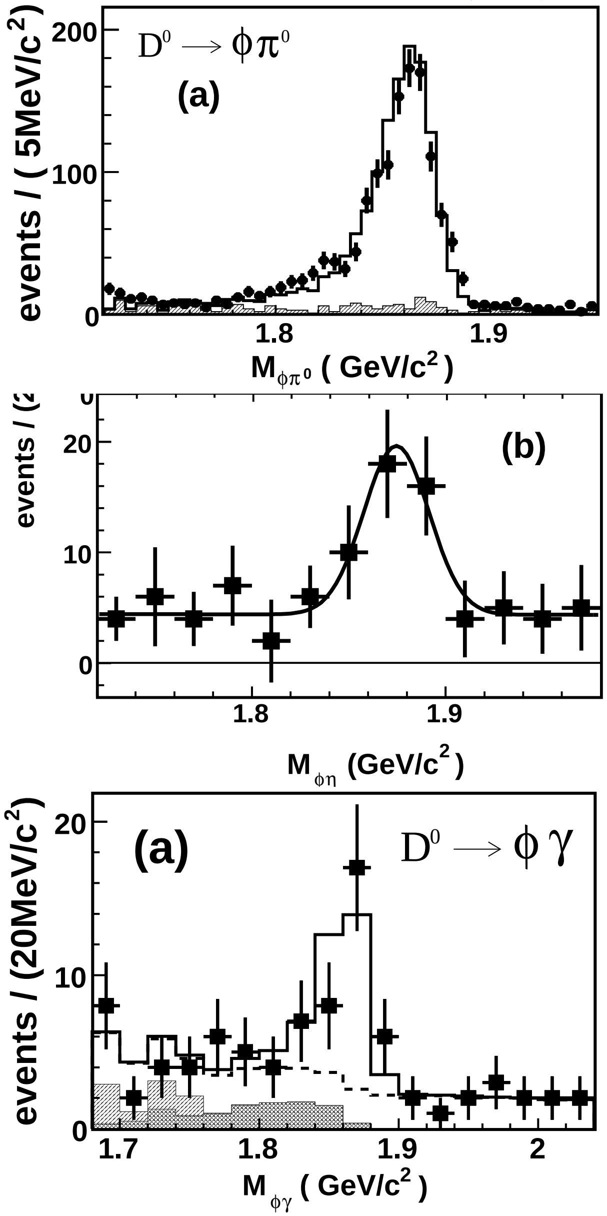


$$\frac{\Gamma(D^0 \to K^- K^- K^+ \pi^+)}{\Gamma(D^0 \to K^- \pi^- \pi^+ \pi^+)} =$$

$$0.00257 \pm 0.00034 \pm 0.00024$$

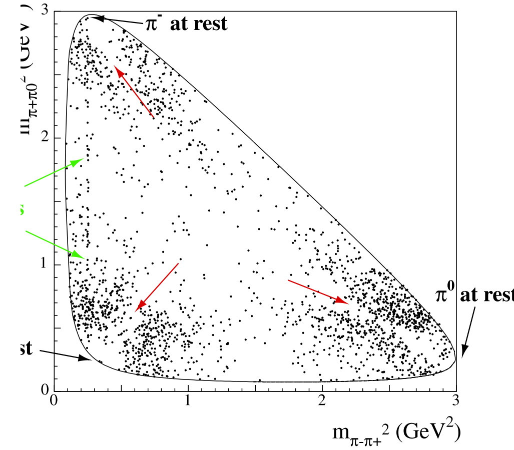
Resonant substructures with Φ and $\overline{K^*(892)^0}$ dominant.
(hep-ex/0308054)

Belle: $D^0 \to \phi\pi^0, \phi\eta, \phi\gamma$

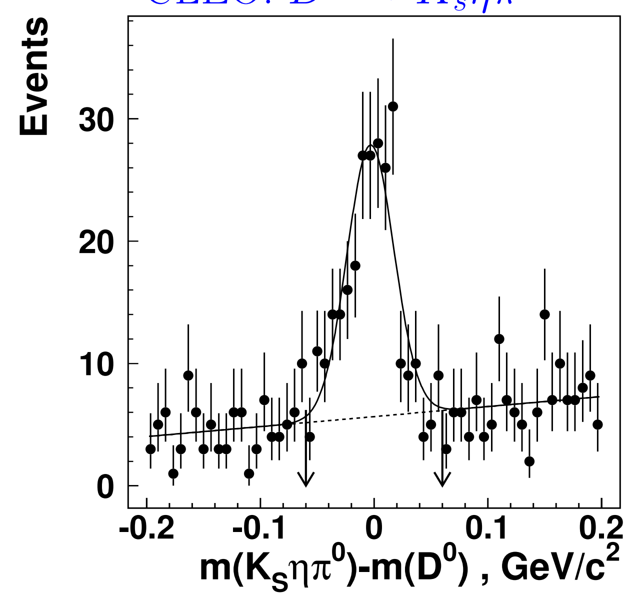


(hep-ex/0308037)

CLEO: $D^0 \to \pi^- \pi^+ \pi^0$



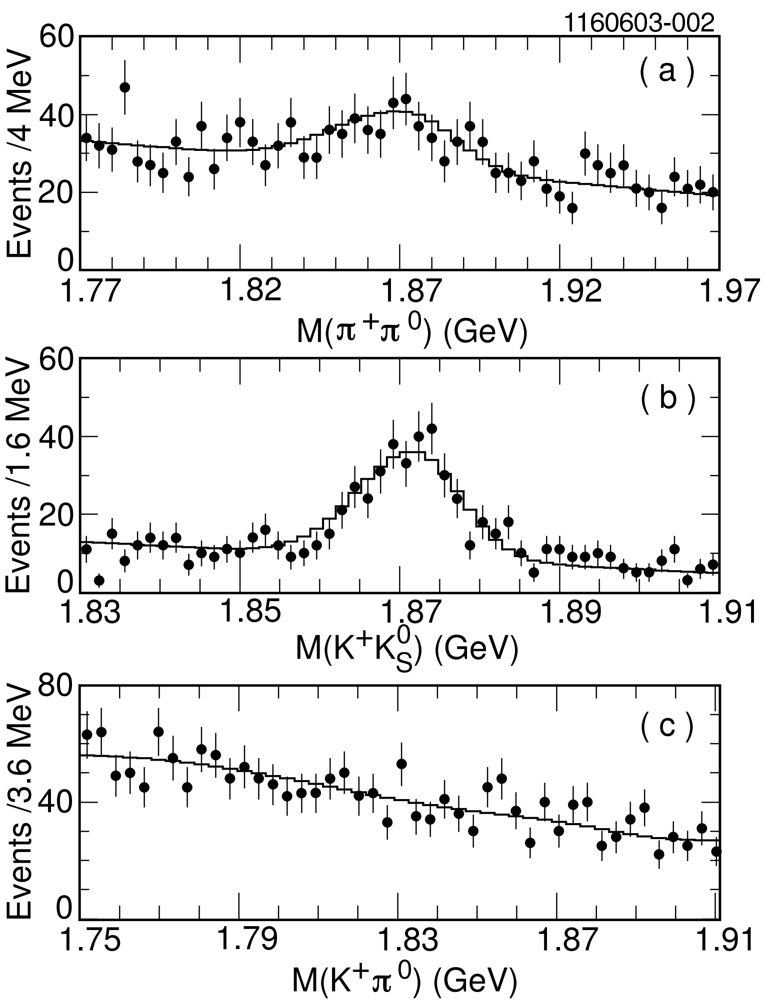
CLEO: $D^0 \to K_s \eta \pi^0$



(hep-ex/0305006)

Rare Decays of D Mesons: D^+, D_s^+

: CLEO: $D^+ \to \pi^+\pi^0, K^+\overline{K^0}, K^+\pi^0$



(hep-ex/0309065)

$$\mathcal{B}(D^+ \to \pi^+\pi^0) = (1.31 \pm 0.17 \pm 0.09 \pm 0.09) \cdot 10^{-3}$$
$$\mathcal{B}(D^+ \to K^+\overline{K^0}) = (5.24 \pm 0.43 \pm 0.20 \pm 0.34) \cdot 10^{-3}$$
$$\mathcal{B}(D^+ \to K^+\pi^0) < 4.2 \cdot 10^{-4} \quad (90\% \text{ C.L.})$$

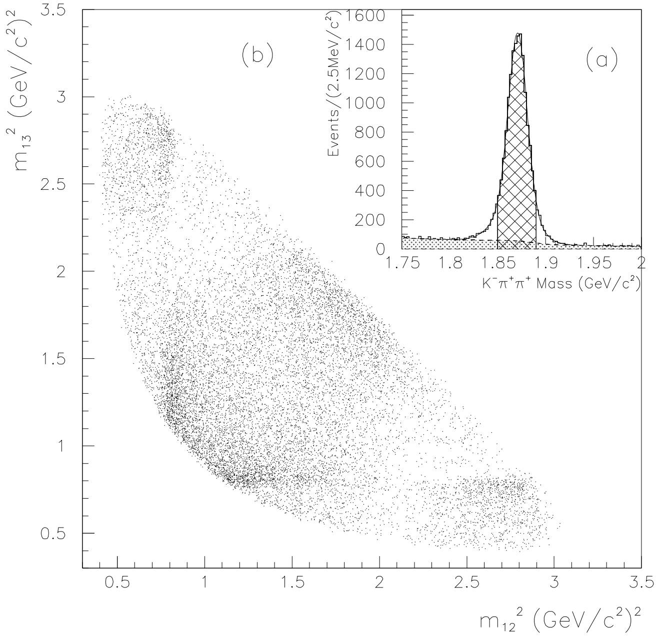
FOCUS: Limits on Rare and SM-Forbidden Di-Muon Decays for D^+ and D_s^+

Decay Mode	FOCUS Limit	Previous Best
$D^+ \to K^+\mu^-\mu^+$	$9.2 \cdot 10^{-6}$	$44 \cdot 10^{-6}$
$D^+ \to K^-\mu^+\mu^+$	$13 \cdot 10^{-6}$	$120 \cdot 10^{-6}$
$D^+ \to \pi^+\mu^-\mu^+$	$8.8 \cdot 10^{-6}$	$15 \cdot 10^{-6}$
$D^+ \to \pi^-\mu^+\mu^+$	$4.8 \cdot 10^{-6}$	$17 \cdot 10^{-6}$
$D_s^+ \to K^+\mu^-\mu^+$	$36 \cdot 10^{-6}$	$140 \cdot 10^{-6}$
$D_s^+ \to K^-\mu^+\mu^+$	$13 \cdot 10^{-6}$	$180 \cdot 10^{-6}$
$D_s^+ \to \pi^+\mu^-\mu^+$	$26 \cdot 10^{-6}$	$140 \cdot 10^{-6}$
$D_s^+ \to \pi^-\mu^+\mu^+$	$29 \cdot 10^{-6}$	$82 \cdot 10^{-6}$

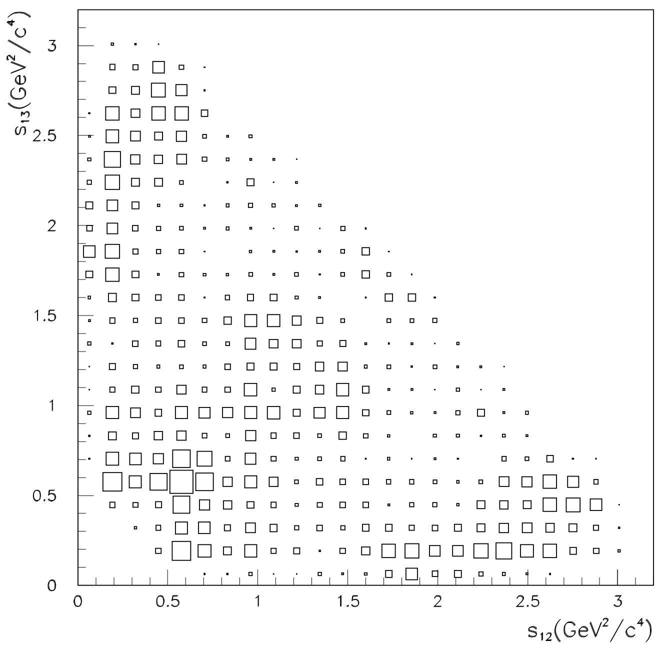
(hep-ex/0306049)

CDF: $D^0 \to \mu^+\mu^- < 2.5 \cdot 10^{-6}$ (hep-ex/0308059)

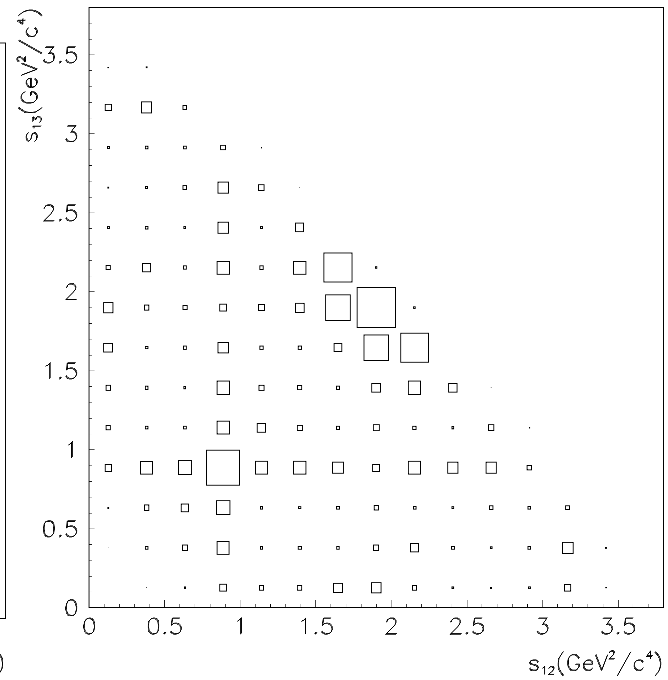
E791: Scalar Resonances in D^+ and D_s^+ Decays



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



$D^+ \to \pi^-\pi^+\pi^+$



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

Need to include two Scaler Resonance:

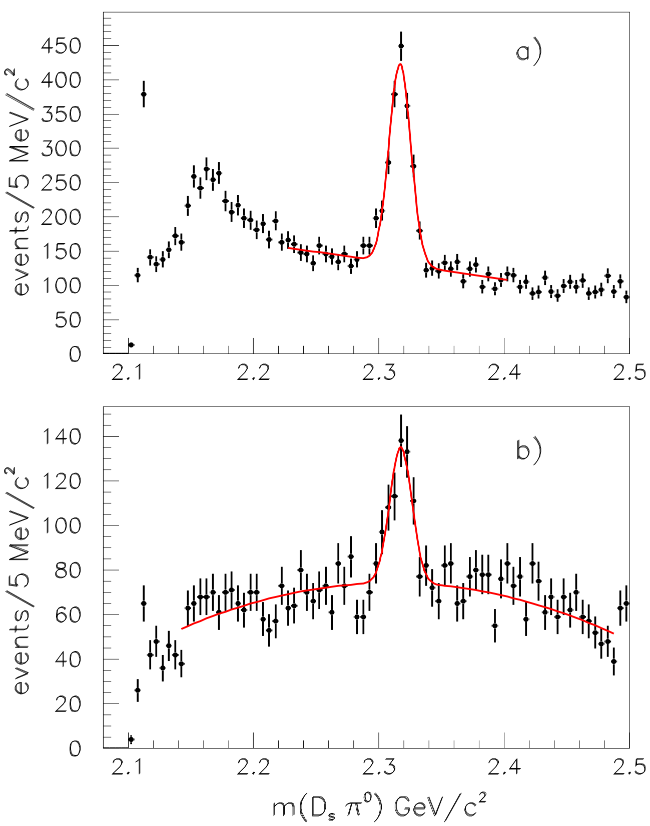
$K\pi$ with mass $(797 \pm 19 \pm 43)$ MeV$/c^2$, width $(410 \pm 43 \pm 87)$ MeV$/c^2$

$\pi\pi$ with mass $(478^{+24}_{-23} \pm 17)$ MeV$/c^2$, width $(324^{+42}_{-40} \pm 21)$ MeV$/c^2$

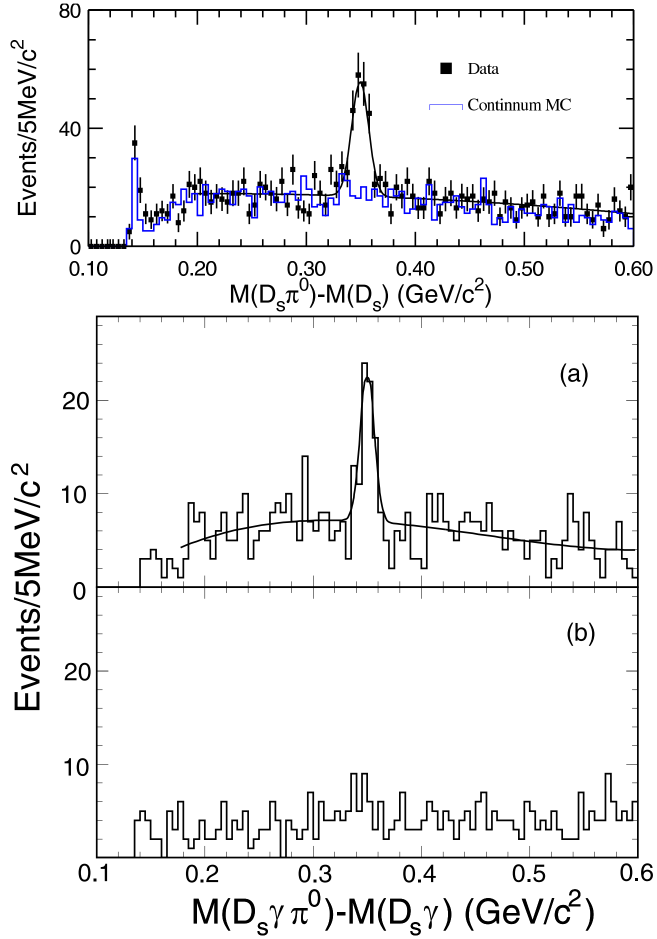
(PRL89, 2002; hep-ex/0307008; PRL86, 2001)

The D_s System

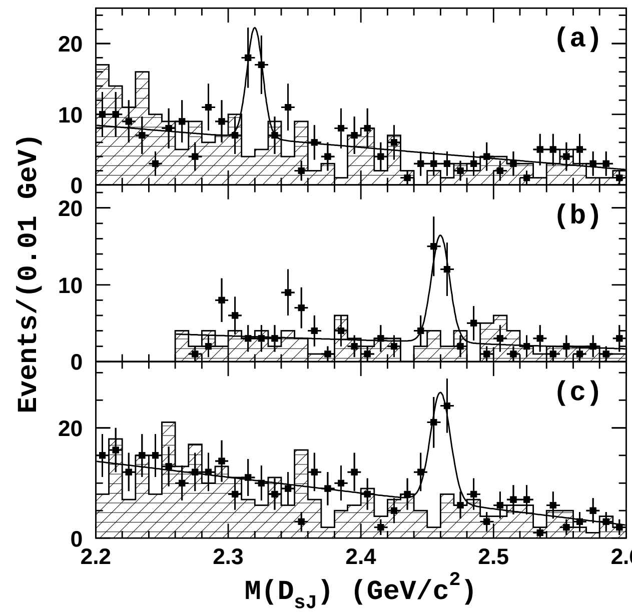
April 12, 2003: BaBar announced Observation of a Narrow Resonance, decaying to $D_s\pi^0$, at 2.32 GeV/c^2



BaBar:
(hep-ex/0304021; PRL90, 2003)



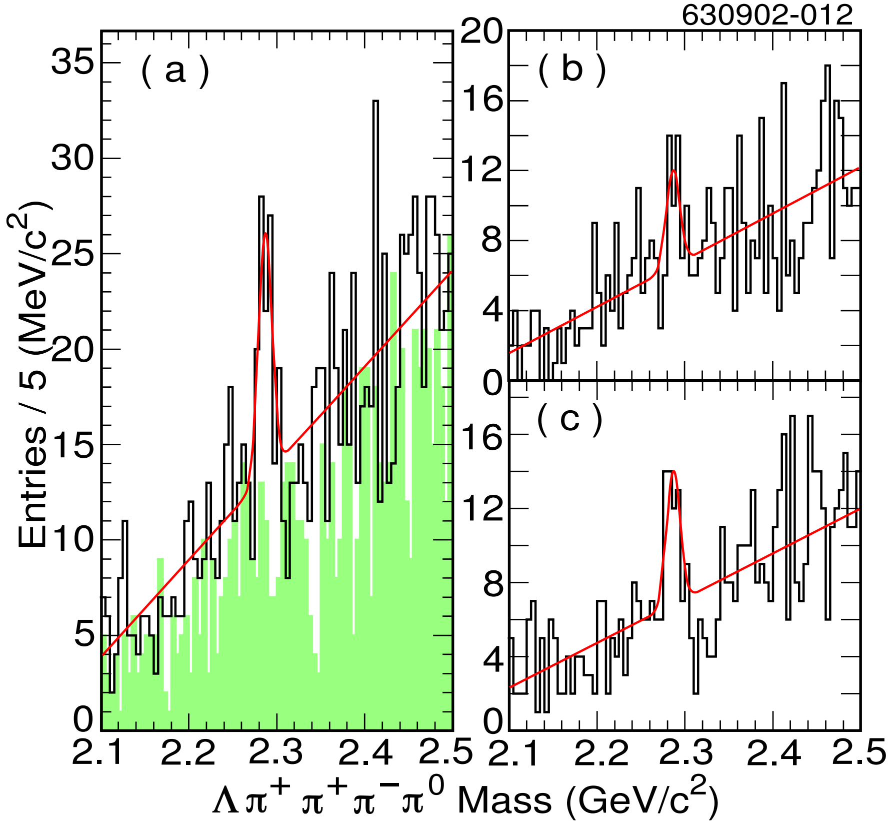
CLEO:
(PRD68, 2003; hep-ph/0308166)



BELLE:
(hep-ex/0308019; hep-ex/0307052)

Charmed Baryons: Λ_c^+, $\Sigma_c^{0,++}$

CLEO: $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-\pi^0$

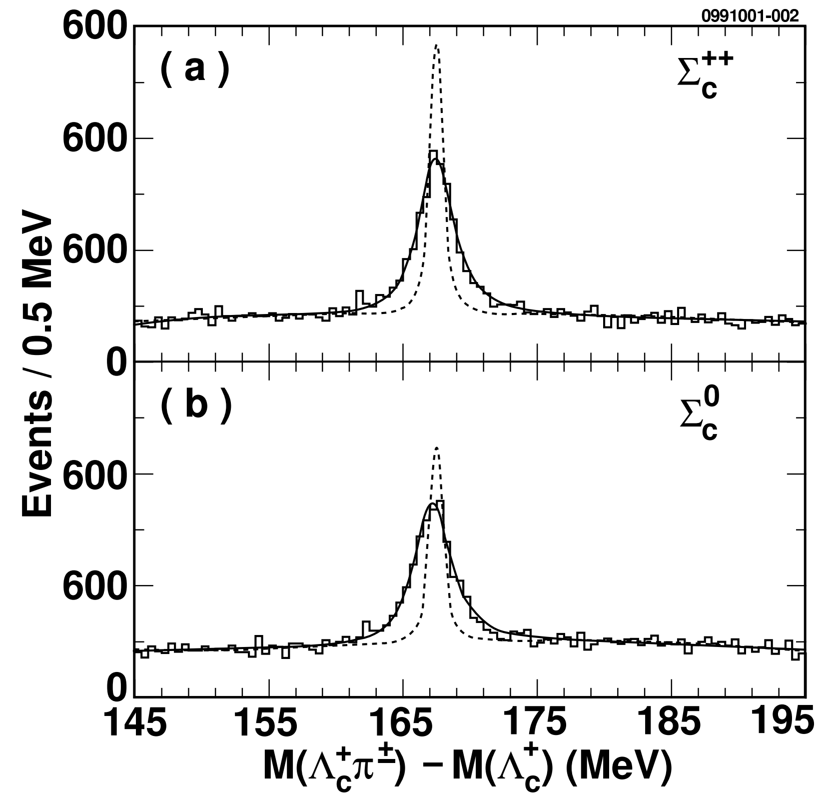


$\mathcal{B} = (1.79 \pm 0.47 \pm 0.43)\,\%$

Most of resonant into $\Lambda_c^+ \to \Lambda\omega\pi^+$

(PRD67, 2003)

CLEO: Masses and Widths of Σ_c^{++} and Σ_c^0



$M(\Sigma_c^{++}) - M(\Lambda_c^+) = (167.4 \pm 0.1 \pm 0.2)\,\mathrm{MeV}/c^2$

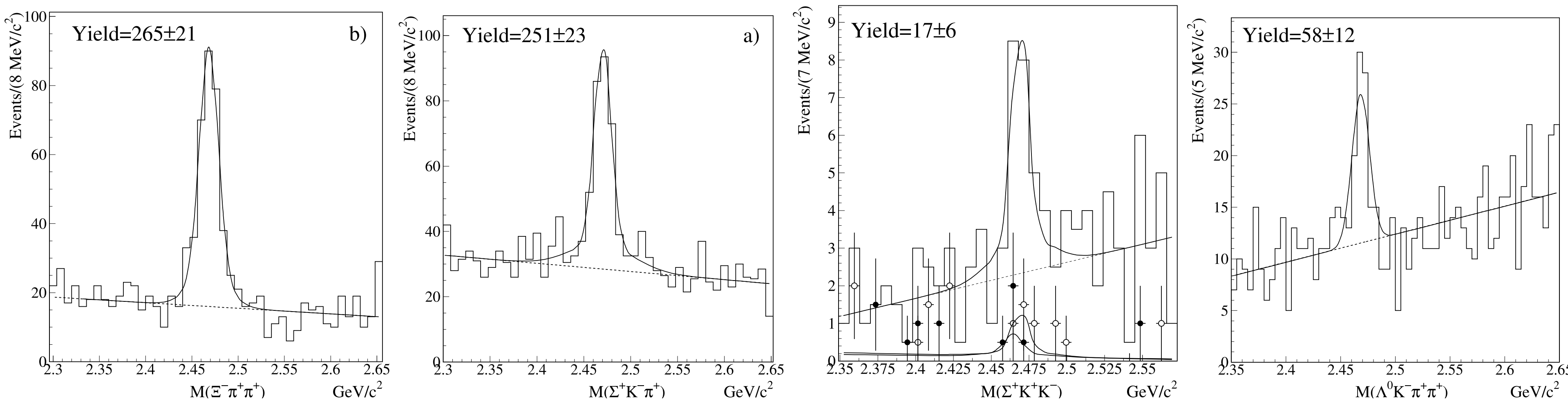
$M(\Sigma_c^{0}) - M(\Lambda_c^+) = (167.2 \pm 0.1 \pm 0.2)\,\mathrm{MeV}/c^2$

$\Gamma(\Sigma_c^{++}) = (2.3 \pm 0.2 \pm 0.3)\,\mathrm{MeV}/c^2$

$\Gamma(\Sigma_c^{0}) = (2.5 \pm 0.2 \pm 0.3)\,\mathrm{MeV}/c^2$

(PRD65, 2002)

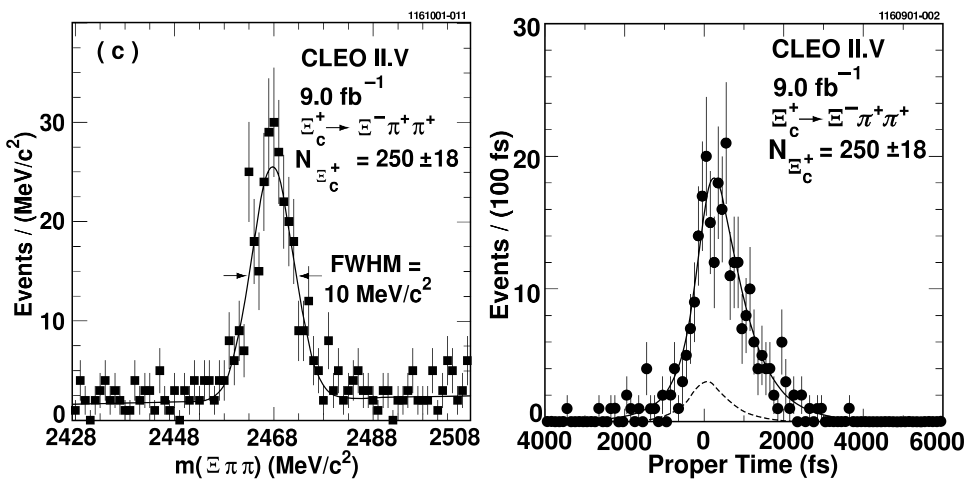
Charmed Baryons: FOCUS: Ξ_c^+ Branching Ratios

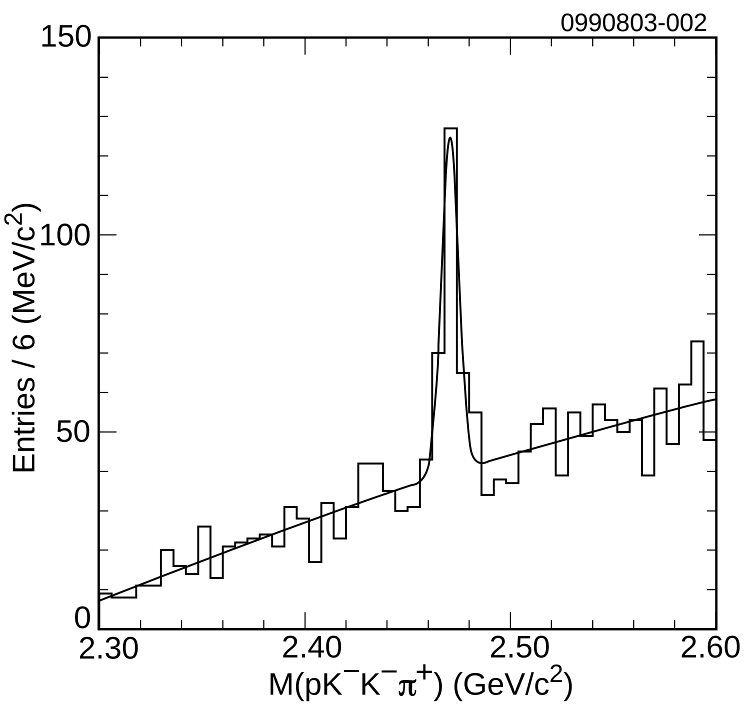


Decay Mode	FOCUS (hep-ex/0305038)	CLEO (PLB365, 1996)	SELEX (PRL84, 2000)
$\frac{\Gamma(\Xi_c^+ \to \Sigma^+ K^- \pi^+)}{\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)}$	$0.91 \pm 0.11 \pm 0.04$	$1.18 \pm 0.26 \pm 0.17$	$0.92 \pm 0.20 \pm 0.07$
$\frac{\Gamma(\Xi_c^+ \to \Sigma^+ K^+ K^-)}{\Gamma(\Xi_c^+ \to \Sigma^+ K^- \pi^+)}$	$0.16 \pm 0.06 \pm 0.01$		
$\frac{\Gamma(\Xi_c^+ \to \Lambda^0 K^- \pi^+ \pi^+)}{\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi +)}$	$0.28 \pm 0.06 \pm 0.06$	$0.58 \pm 0.16 \pm 0.07$	
$\frac{\Gamma(\Xi_c^+ \to \Omega^- K^+ \pi^+)}{\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi +)}$	$0.07 \pm 0.03 \pm 0.03$		
$\frac{\Gamma(\Xi_c^+ \to \Sigma^*(1385)^+ \overline{K^0})}{\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi +)}$	$1.00 \pm 0.49 \pm 0.24$		

Also have upper limits for other resonance modes.

Charmed Baryons: CLEO: Ξ_c^+ Lifetime, $\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+)$





$$\tau(\Xi_c^+) = (503 \pm 47 \pm 18)\,\mathrm{fs}$$

(PRD65, 2002)

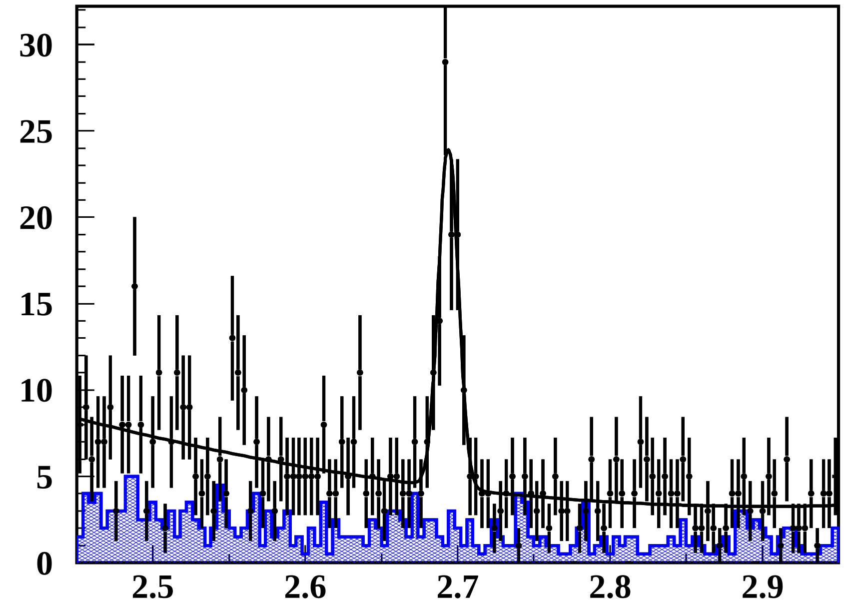
$$\frac{\mathcal{B}(\Xi_c^0 \to pK^-K^-\pi^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)} = 0.35 \pm 0.08 \pm 0.05$$

Also see evidence for resonant $\overline{K^*(892)^0}$ substructure.

(hep-ex/0309020)

Charmed Baryons: Mass and semileptonic decays of Ω_c^0

Belle: $M(\Omega^-\pi^+) - M(\Omega^-) + 1.6725\,\mathrm{GeV}/c^2$

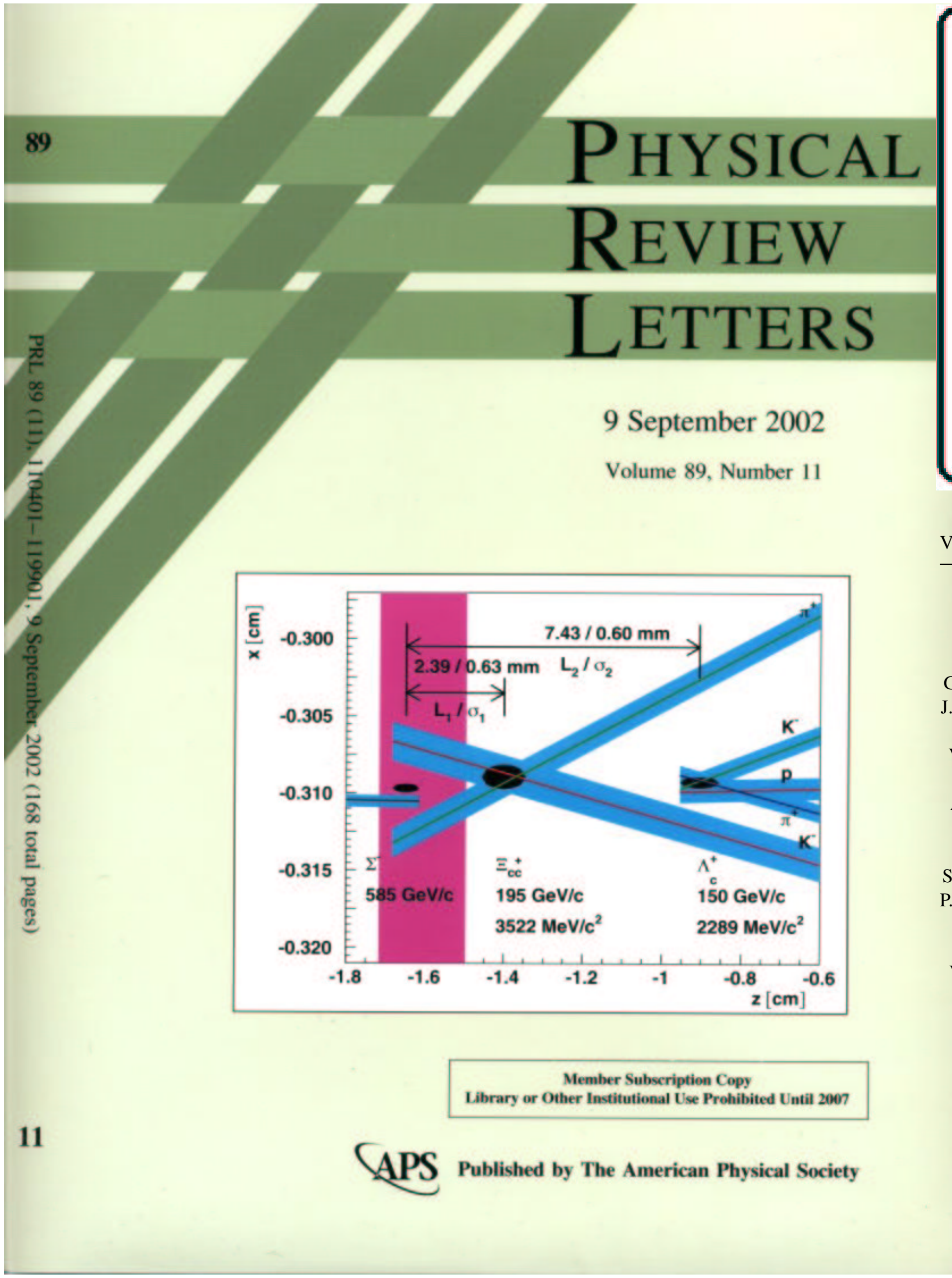


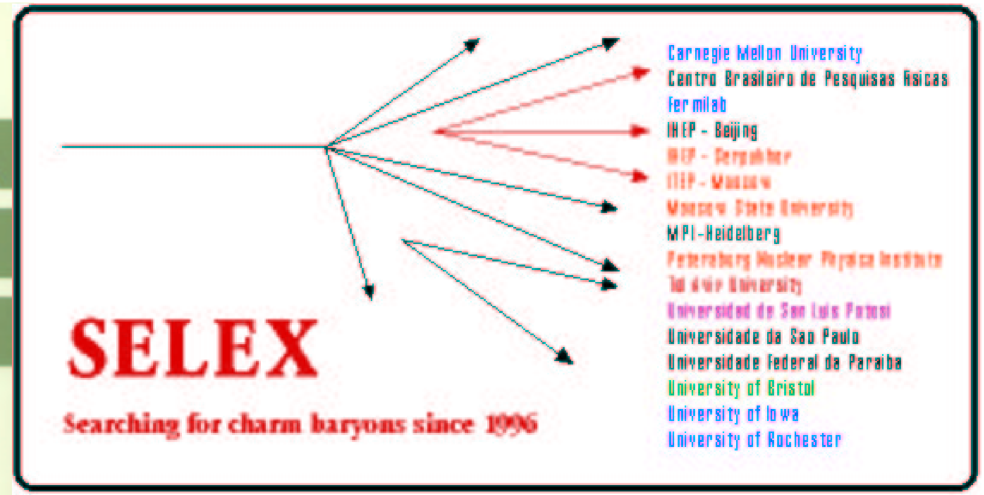
Mass measurements:

Belle:	$(2693.9 \pm 1.1 \pm 1.4)\,\mathrm{MeV}/c^2$	(LP2003)
CLEO:	$(2694.6 \pm 2.6 \pm 1.9)\,\mathrm{MeV}/c^2$	(PRL86, 2001)
PDG2000:	$(2704 \pm 4)\,\mathrm{MeV}/c^2$	

Semileptonic decays:

Experiment	$\Omega_c^0 \to \Omega^-\mu^+\nu$	$\Omega_c^0 \to \Omega^-e^+\nu$	$\frac{\mathcal{B}(\Omega_c^0\to\Omega^-\pi^+)}{\mathcal{B}(\Omega_c^0\to\Omega^-l^+\nu)}$
Belle (LP2003)	33.1 ± 8.2	31.9 ± 7.1	$0.8 \pm 0.2 \pm 0.1$
CLEO (PRL89, 2002)		11.4 ± 3.8	$0.41 \pm 0.19 \pm 0.04$





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First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+}

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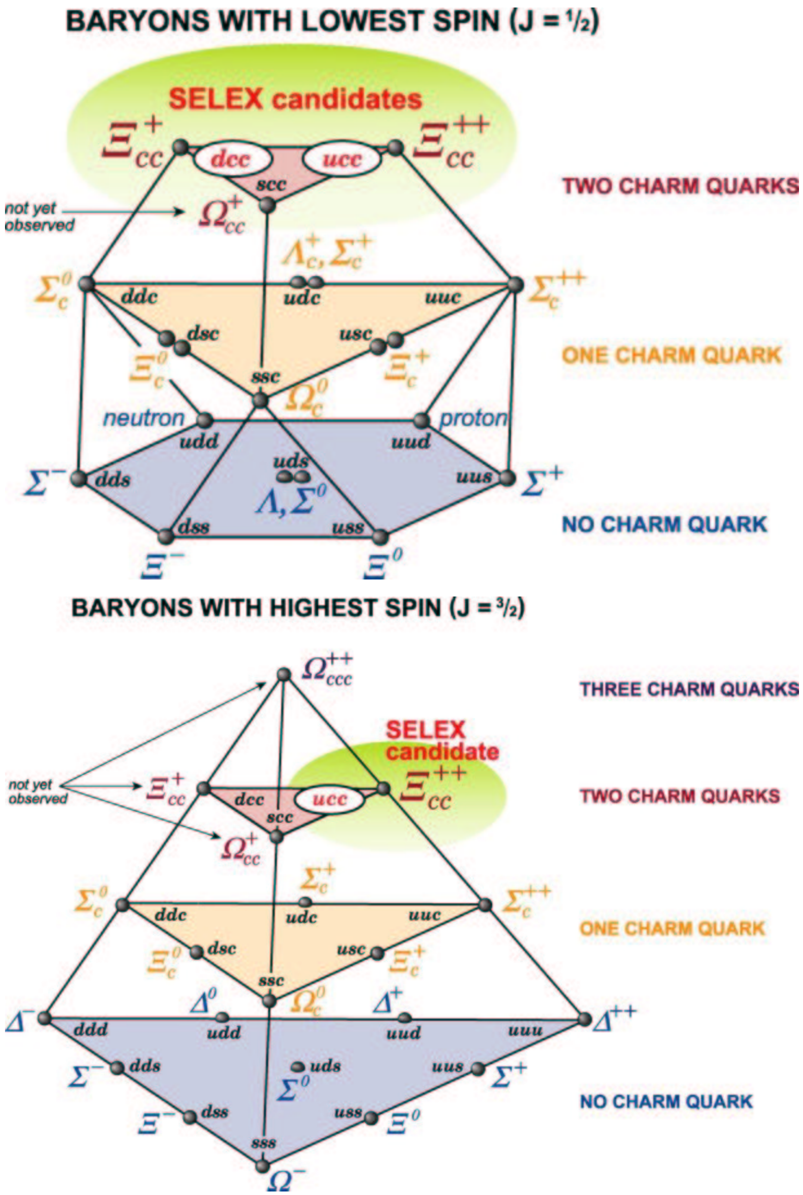
(SELEX Collaboration)

Model Predictions for Doubly Charmed Baryon Masses

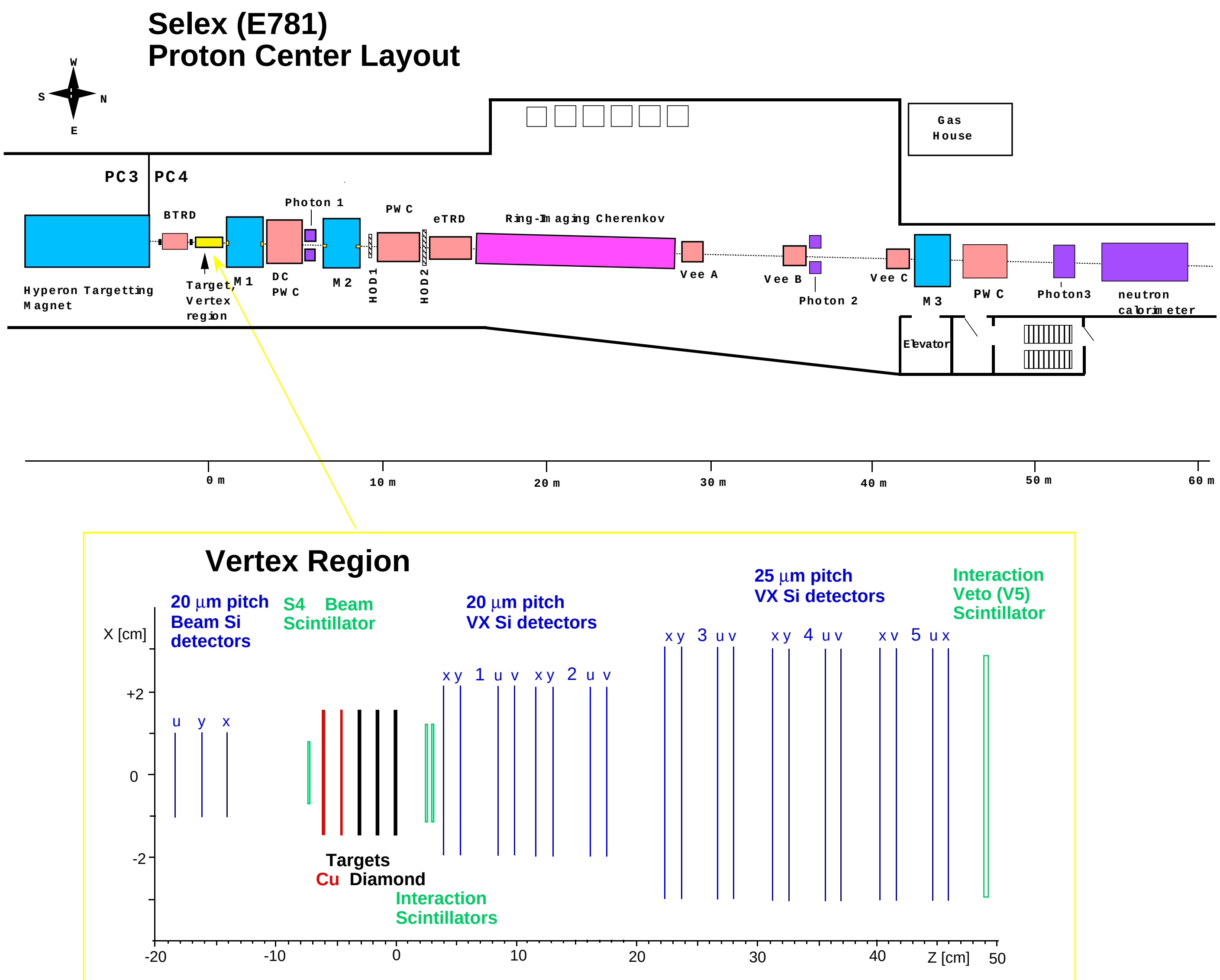


- Several Authors (Bjorken 1986, Fleck&Richard 1989, Roncaglia 1995, Ellis 2002)
- Different models (Phenomenology, Bag, Quarkonium)
- Masses (J=1/2): $3.516 - 3.66\,\text{GeV}/c^2$
- Masses (J=3/2): $3.636 - 3.81\,\text{GeV}/c^2$

Overall Features

- ground states near $3.6\,\text{GeV}/c^2$
- ground states Isospin=1/2 multiplets degenerate
- Hyperfine splitting around $60 - 120\,\text{MeV}/c^2$
- Most predict electromagnetic hyperfine transition (but some pionic)
- Model dependent predictions for orbital and radial excitations

The SELEX Experiment at Fermilab

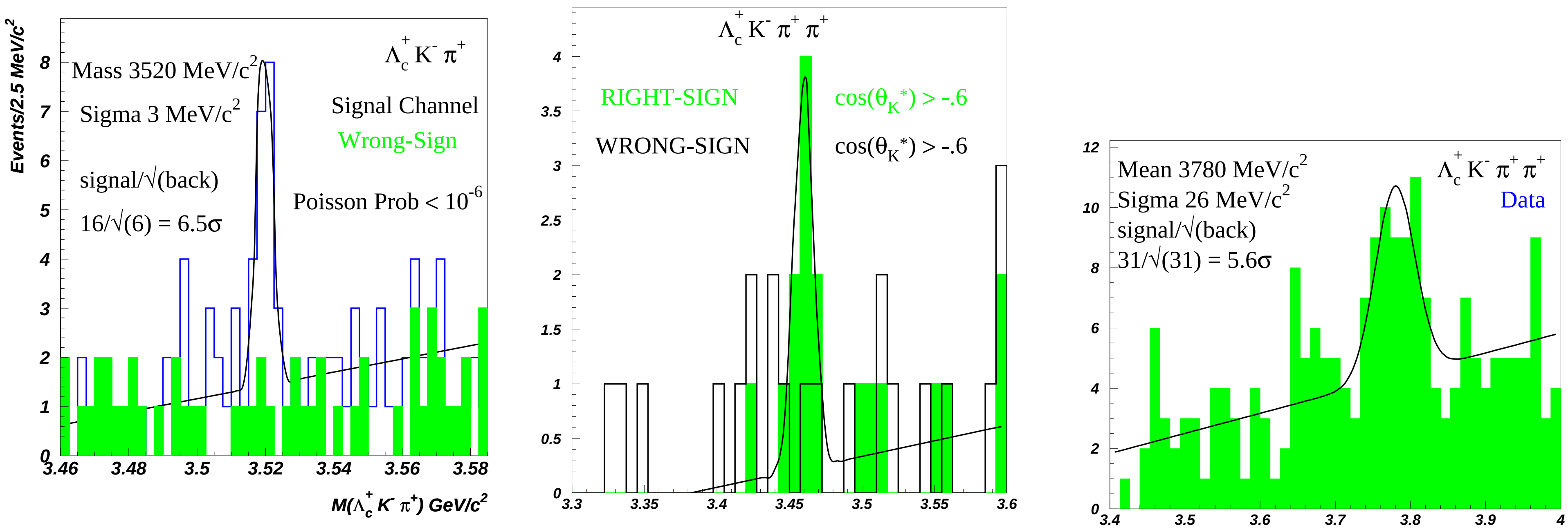


SELEX experiment

- 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

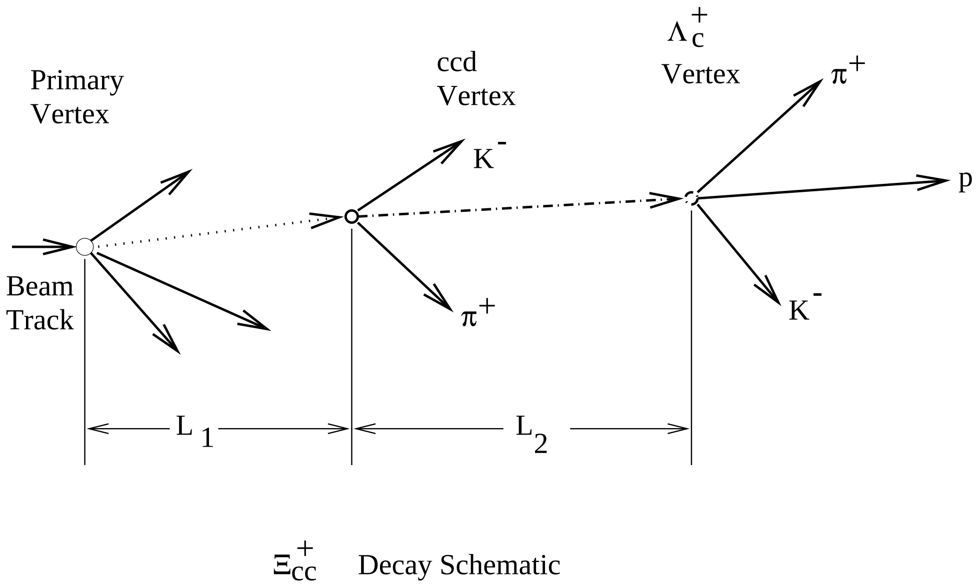
SELEX: Experimental Evidence from 2002

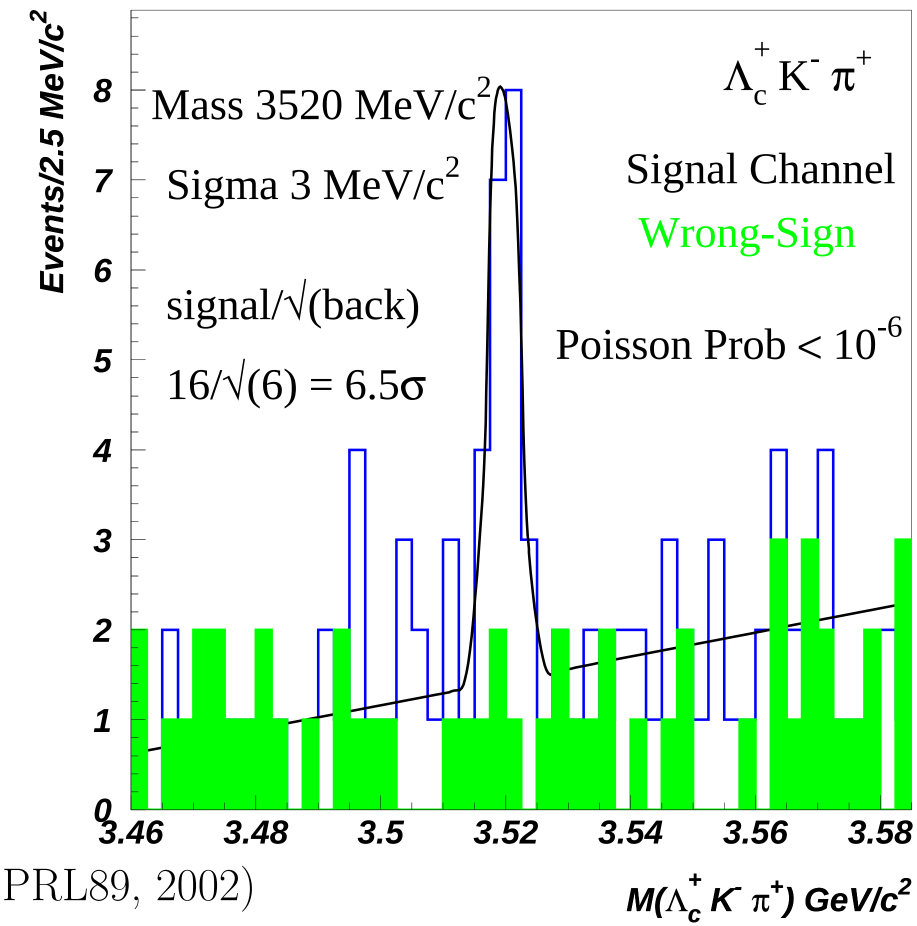
SELEX reported 3 significant high mass peaks



SELEX argued that these states are doubly-charmed baryons

SELEX Search Strategy for Doubly-Charmed Baryons





(PRL89, 2002)

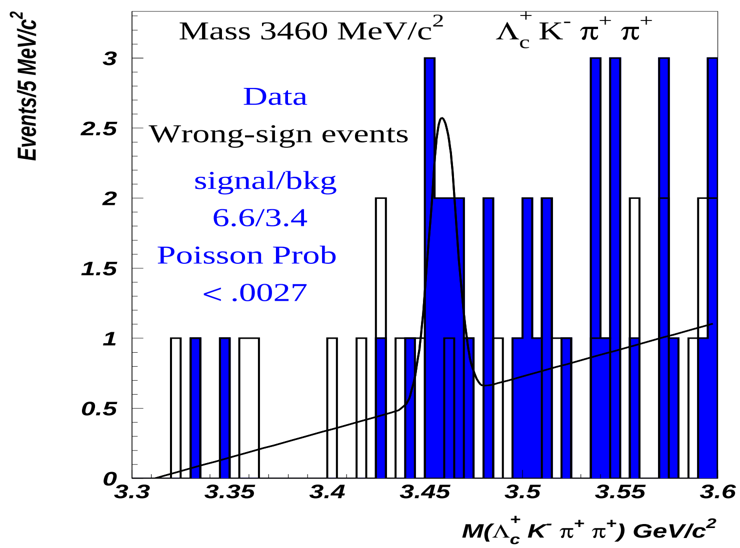
- ccq decays to $csqu\bar{d}$. Look for charm, strange and baryon in final state.
  SELEX started with $\Lambda_c^+ K^- \pi^+ (\pi^+)$.
- Look for new secondary vertex between primary and Λ_c^+
- no RICH PID on new $K^- \pi^+$ tracks (too soft)
- All other cuts fixed from previous searches

$ccd^+(3520)$

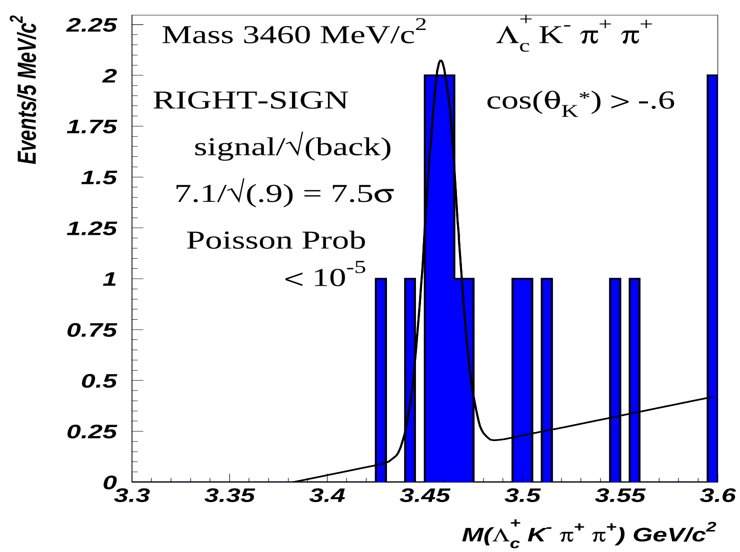
- $L/\sigma > 1$.
- Right sign has peak at 3520.
  15.8 signal, 6.2 background. 6.3 σ
- Wrong sign has no structure

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



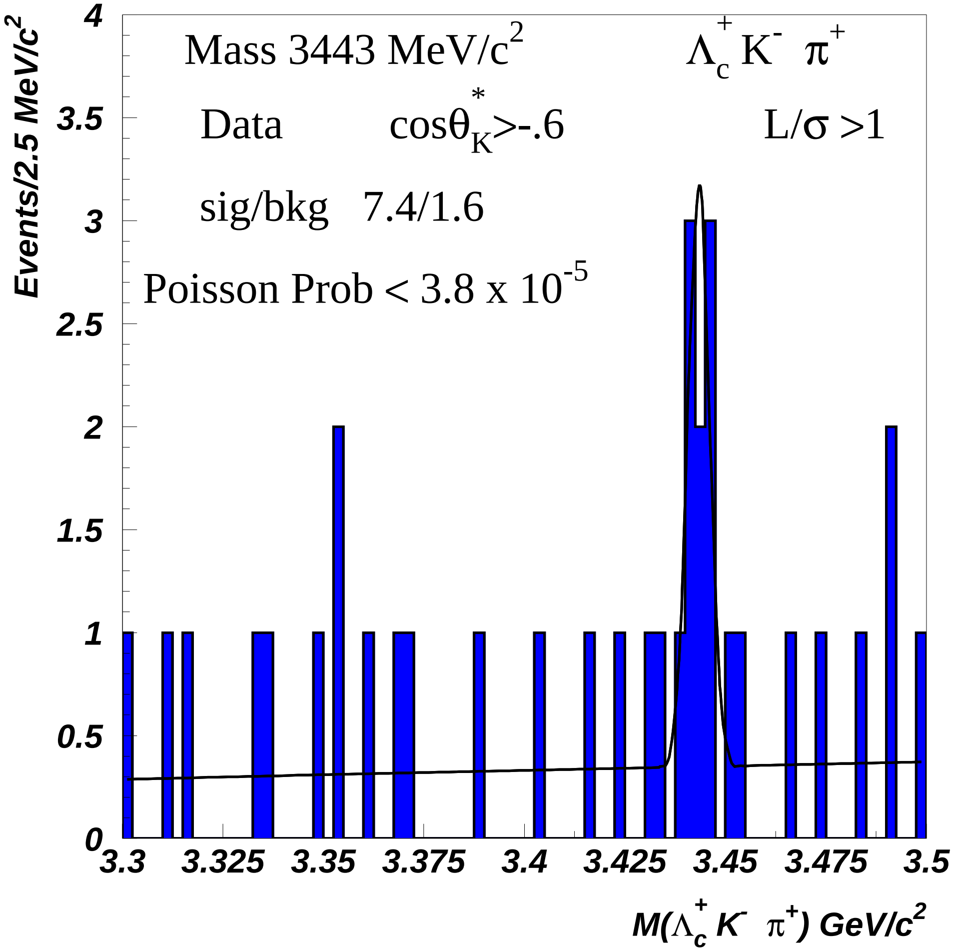
- Mass peak at 3460.
  7.1 signal, 0.9 background. $7.5\,\sigma$
- Loss of signal consistent with phase space $(L = 0)$



- $\Xi_{cc}^{++}(3460)$, $\Xi_{cc}^{+}(3520)$ 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 $L = 0$

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

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

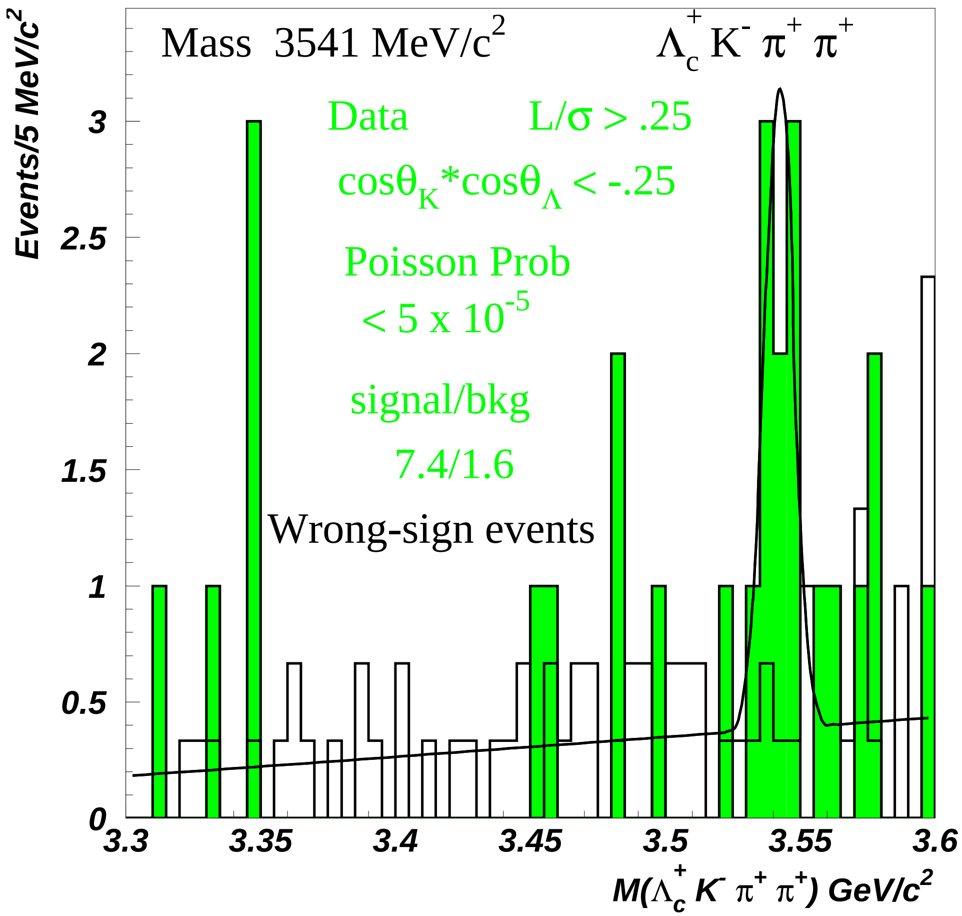
- $ccd^{+}(3520)$ not phase space $(\cos\Theta_K^* < 0.6)$
- Λ_c^+ and K^- are back-to-back: $\cos\Theta_K^* \cos\Theta_{\Lambda_c}^* < -0.25$ keeps most of signal
- Apply also to $\Lambda_c^+ K^- \pi^+ \pi^+$ sample: Nothing

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

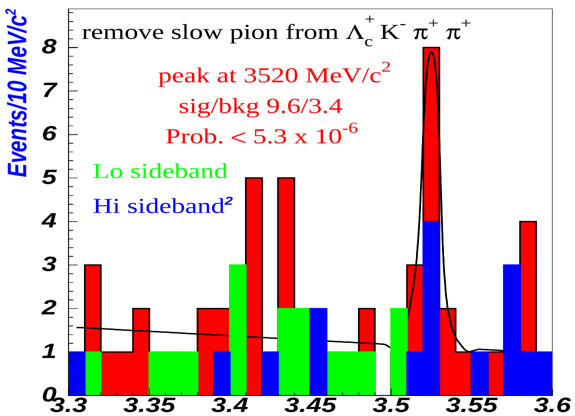
New $ccu^{++}(3541)$ now very significant

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

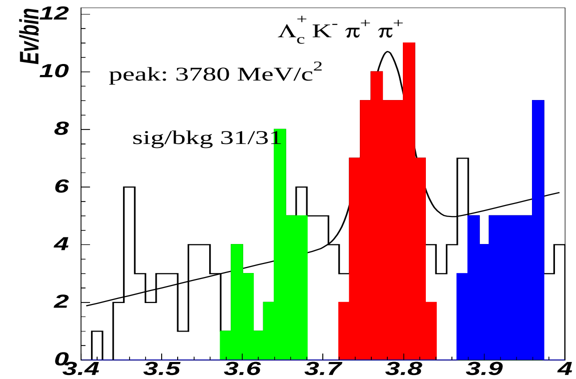
- $ccu^{++}(3541)$ is partner to $ccd^{+}(3520)$

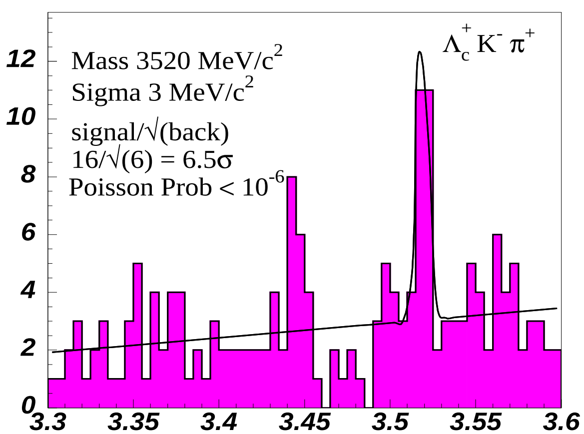


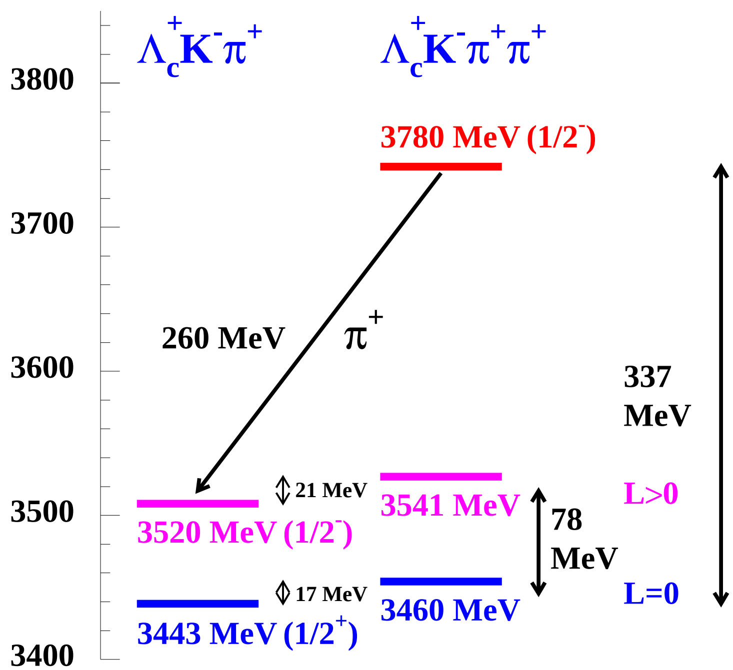
SELEX Double Charmed Baryon States

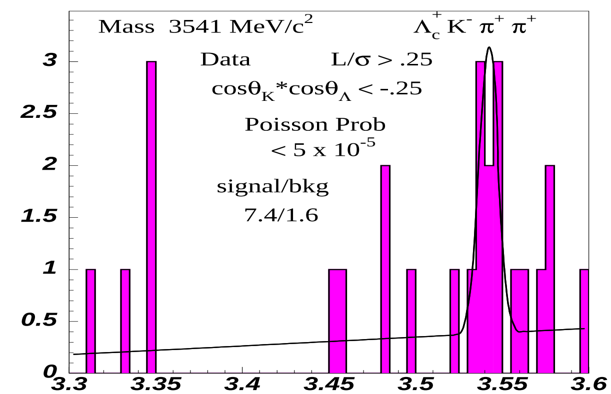


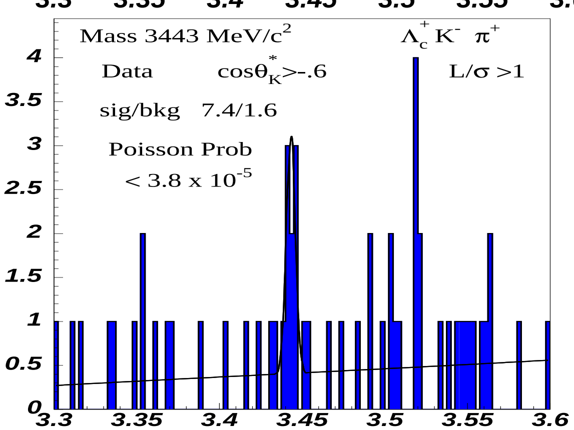
An exited state and a pair of isodoublets?

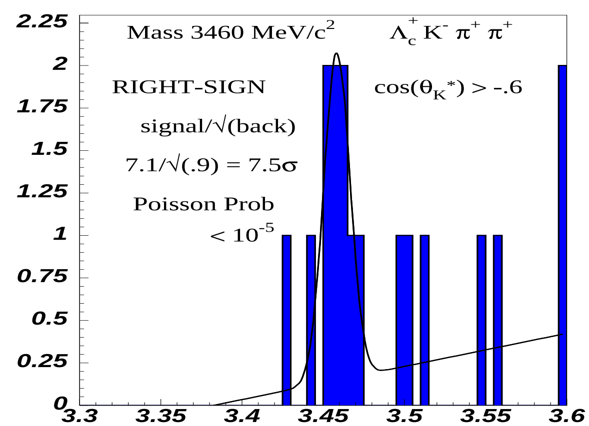












Doubly Charmed Baryons

Lifetimes

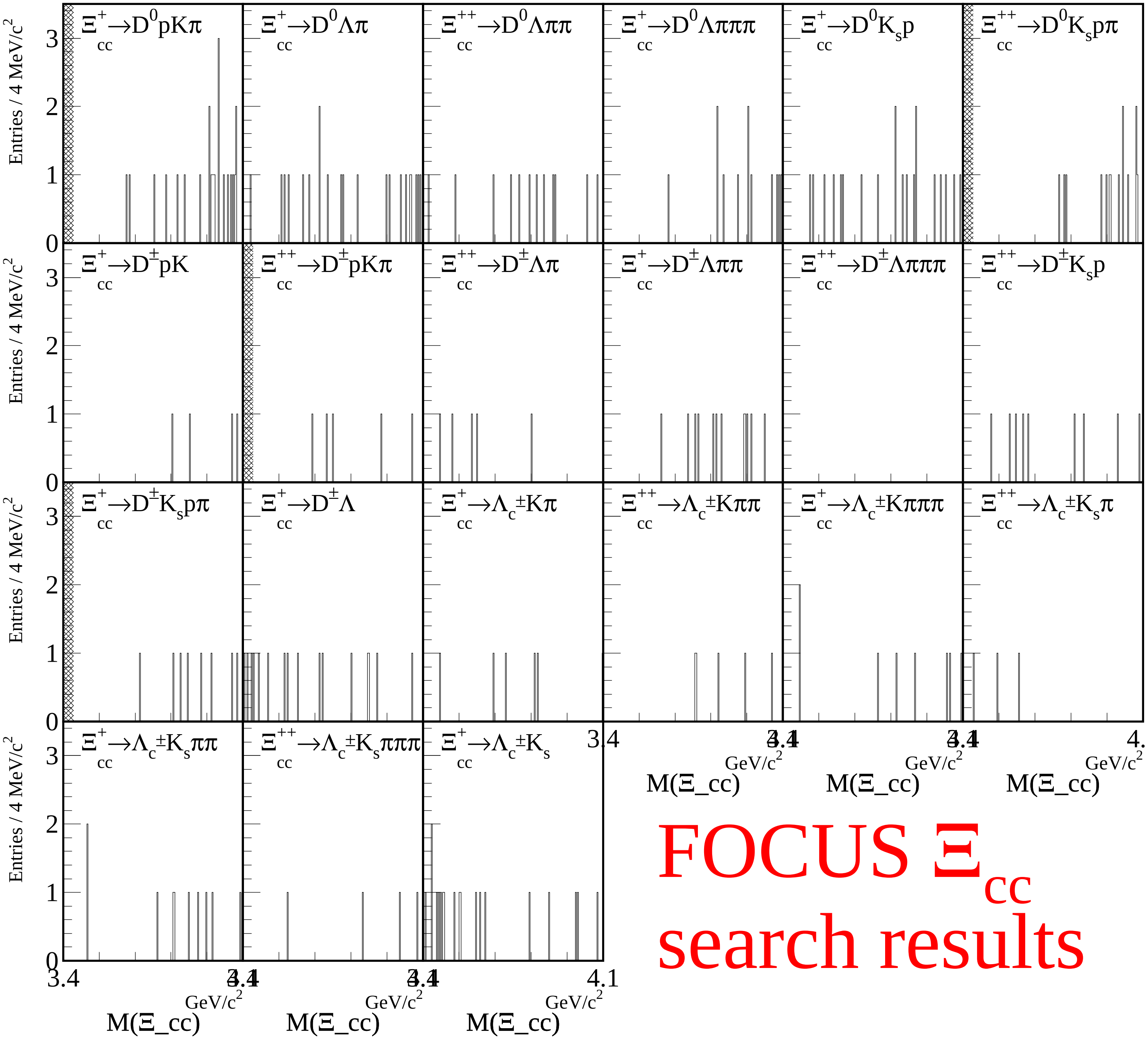
- SELEX tried to measure lifetime
  All lifetimes near resolution limit $< 30\,\mathrm{fs}$
- Model predictions: several hundreds of fs.
- Bardeen, Eichten and Hill: spectroscopy of cc

$$J^P = \frac{1}{2}^+ [c\uparrow\ c\uparrow\ L=0, J^P=1^+]\, q\downarrow$$
$$J^P = \frac{1}{2}^- [c\uparrow\ c\downarrow\ L=1, J^P=1^-]\, q\downarrow$$

- Predicted splitting consistent with observed $78\,\mathrm{MeV}/c^2$
- First EM transition is M2.

Production

- SELEX: Dominantly produced by baryon 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

Conclusions

- Charm Physics is more exciting than ever
- New Results on Mixing, (rare) decays, and masses of Mesons and Baryons
- New States in the D_s system
- Doubly Charmed Baryons