

# New Results in Charm Meson Spectroscopy from FOCUS and SELEX

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## Outline

FOCUS (thanks to Rob Kutschke and Eric Vaandering)

Masses and Widths of  $D_2^{*+}$   $D_2^{*0}$  mesons

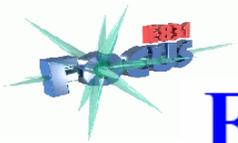
Evidence for  $D_0^{*+}$  and  $D_0^{*0}$  broad states

Confirmation of  $D_s^+(2317)$  and others

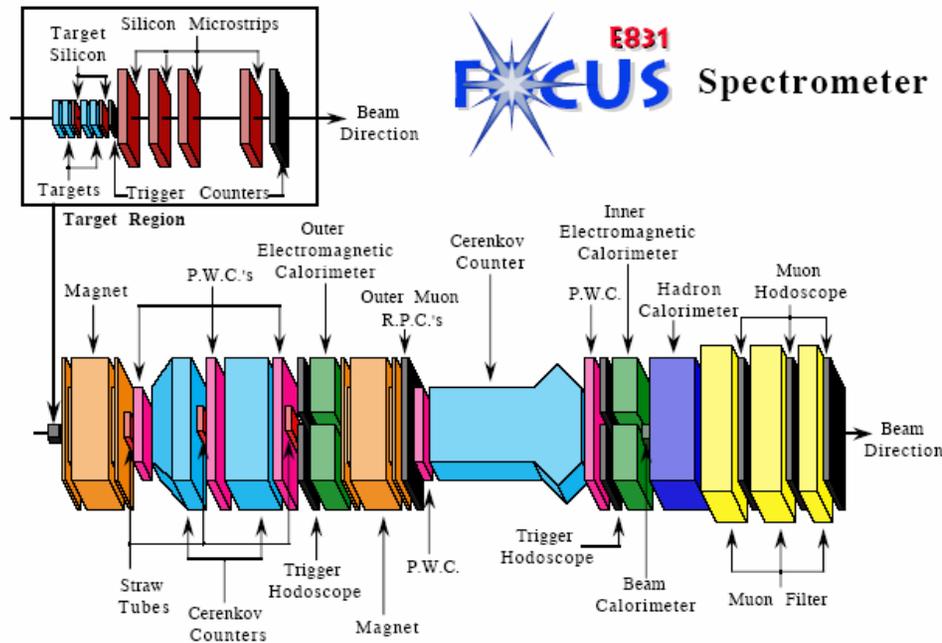
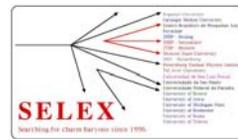
SELEX

Evidence for  $D_{sJ}^+(2632)$  in  $D_s^+\eta$  and  $D^0K^+$





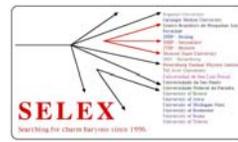
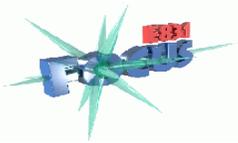
# FOCUS Spectrometer



## Highlights:

- Segmented target
- Silicon vertexing
- MWPC tracking
- ~200 GeV Photon Beam
- Threshold Čerenkov
- EM/hadronic calorimeters
- Muon detectors
- Charm Photo-production

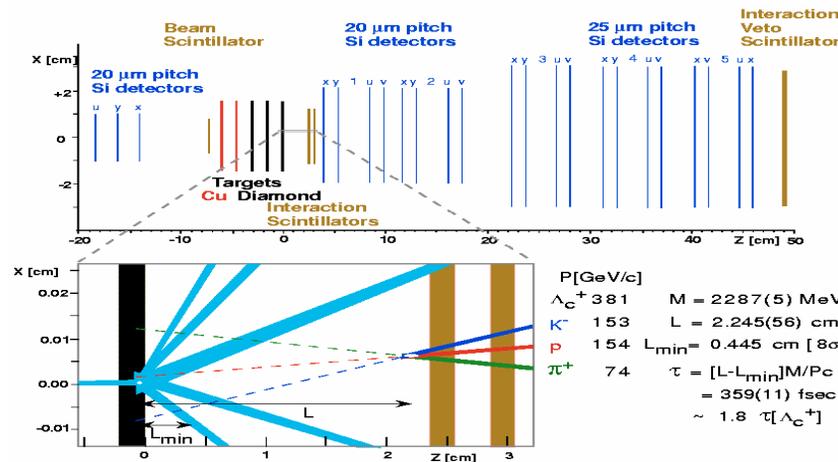
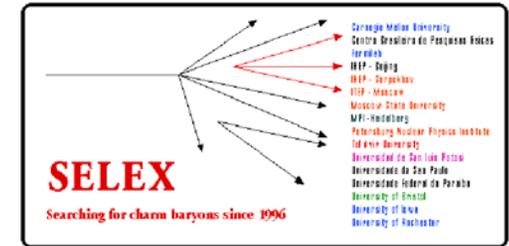
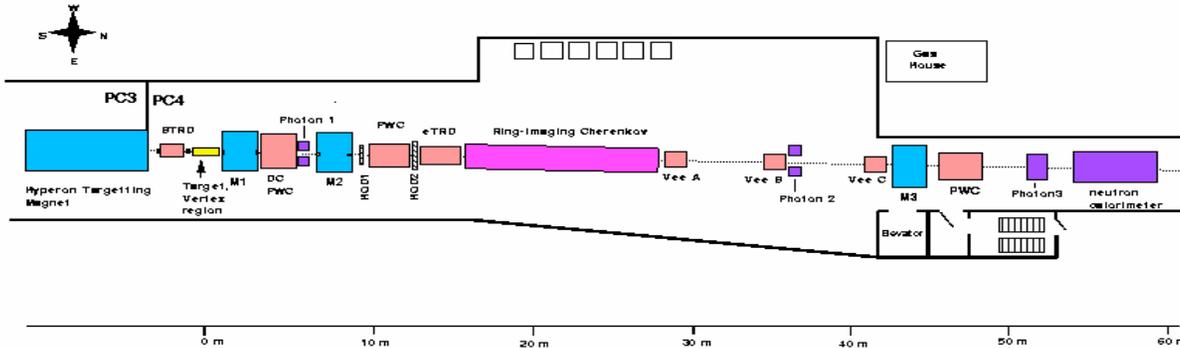




# Selex Experiment at Fermilab

## Charmed Hadroproduction with $\pi^-$ , $p$ and $\Sigma^-$ beams

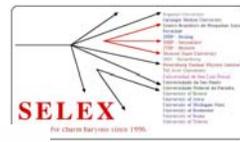
SELEX (E781)  
Proton Center Layout



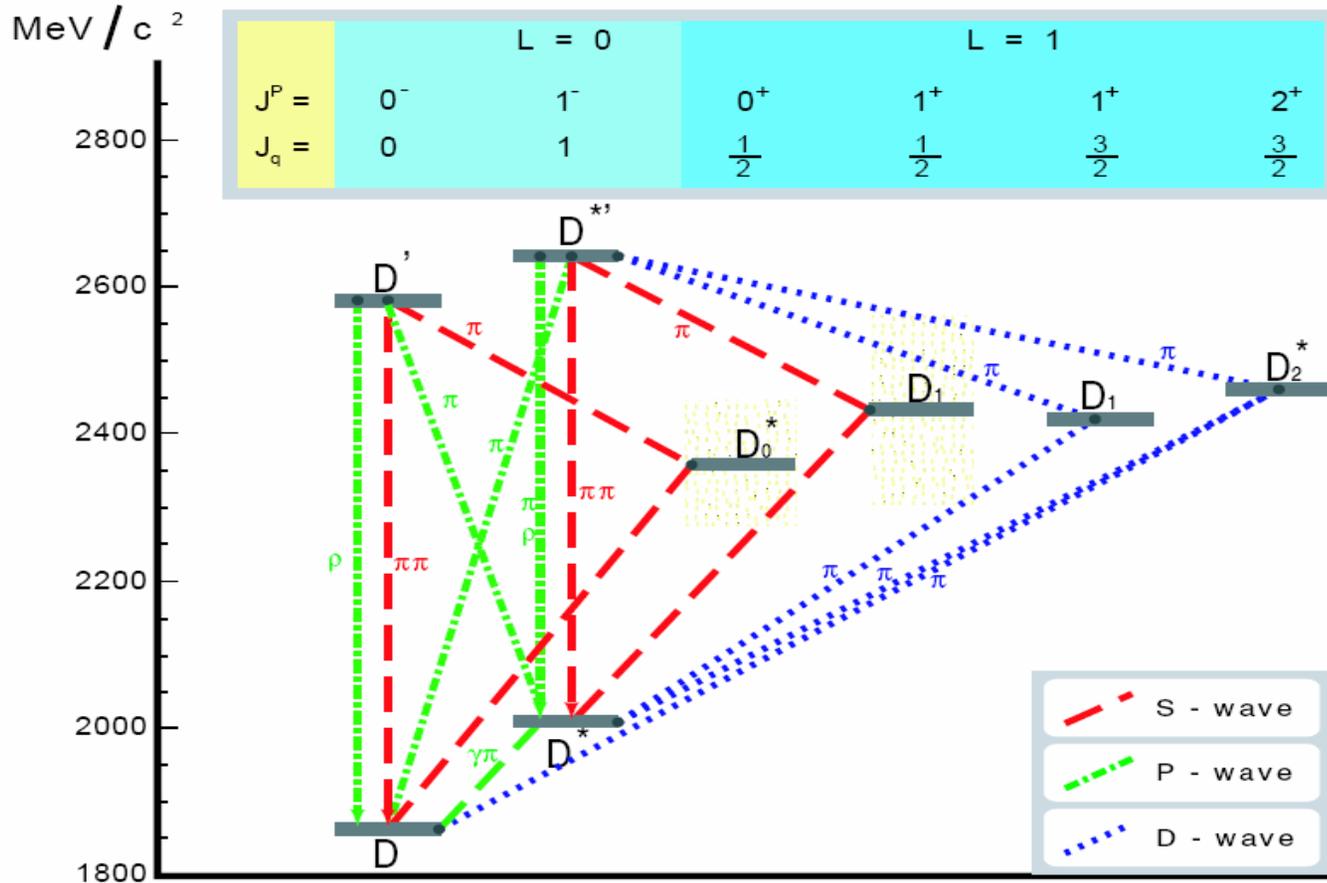
### SELEX Experiment

- Forward charm hadro-production  $x_F > 0.1$
- $\pi^-$ ,  $p$  and  $\Sigma^-$  beams @ 600 GeV/c
- Typical boost  $\sim 100$
- RICH PID above 22 GeV/c
- 20 plane – 4 view SVX  $\sigma > 4 \mu\text{m}$
- data taken in 1996-7



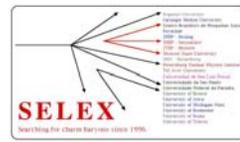


# $L = 1$ Charm Decays



3 Hydrogenic (heavy-light) systems:  $D^0(c\bar{u})$   $D^+(c\bar{d})$   $D_s^+(c\bar{s})$





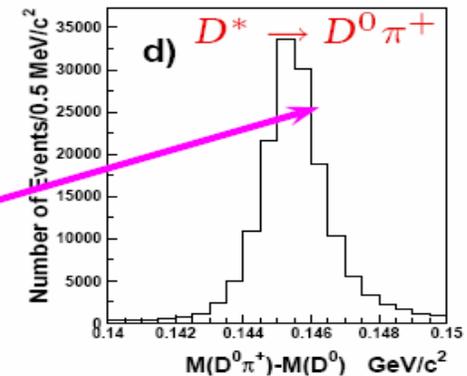
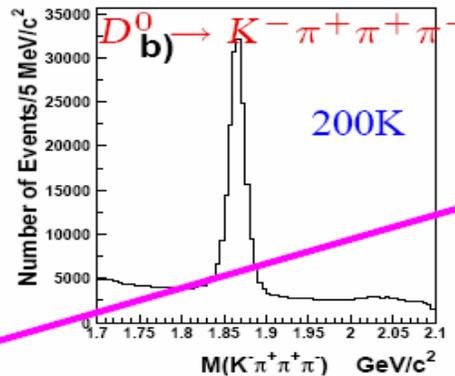
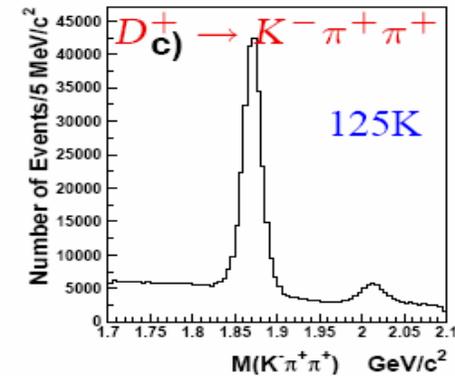
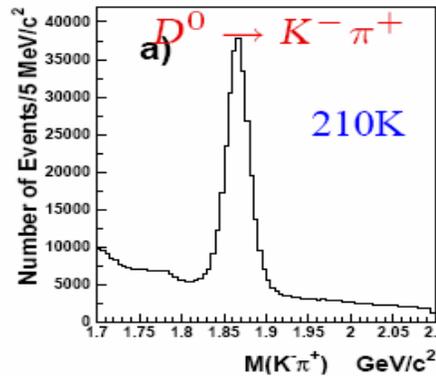
# D Samples for $D_2$ Measurement

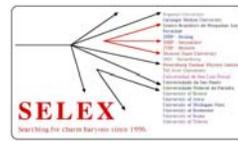
Photoproduction gives sizable yields with low multiplicity

Processes studied:

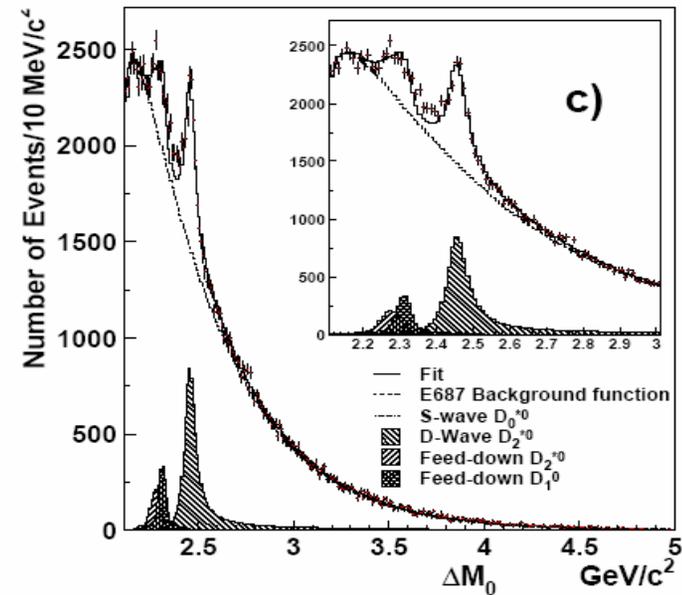
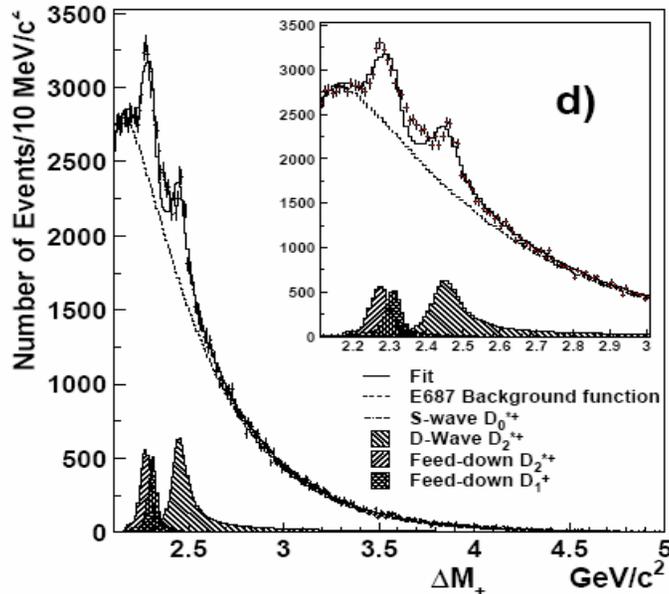
- $\gamma N \rightarrow D^0 \pi^+ + X$ 
  - $D^0 \rightarrow K^- \pi^+$
  - $D^0 \rightarrow K \pi \pi \pi$
- $\gamma N \rightarrow D^+ \pi^- + X$ 
  - $D^+ \rightarrow K \pi \pi$

Remove any  $D^0$  candidate with  $D^* < 3\sigma$ .  
(Cleans up  $D^0 \pi^+$ .)



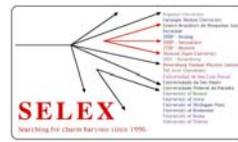
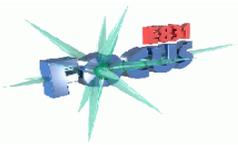


# Fitting without $D_0^*$ Broad States

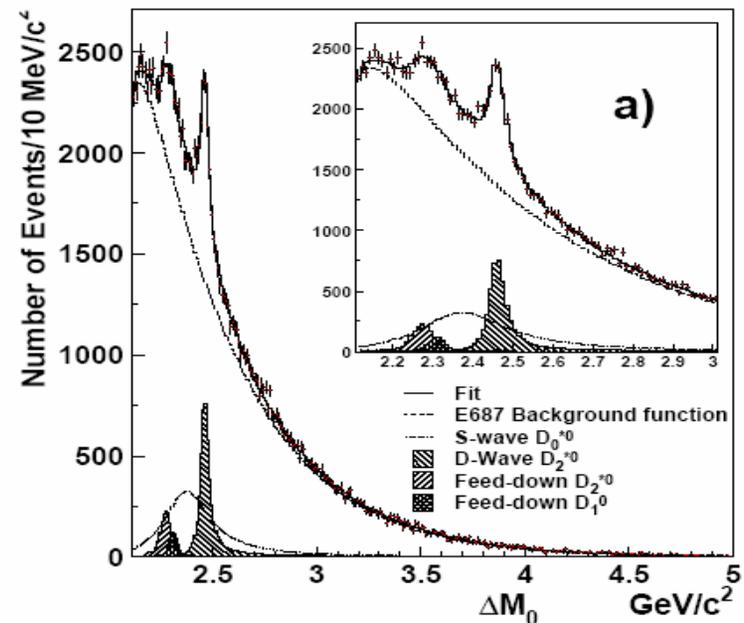
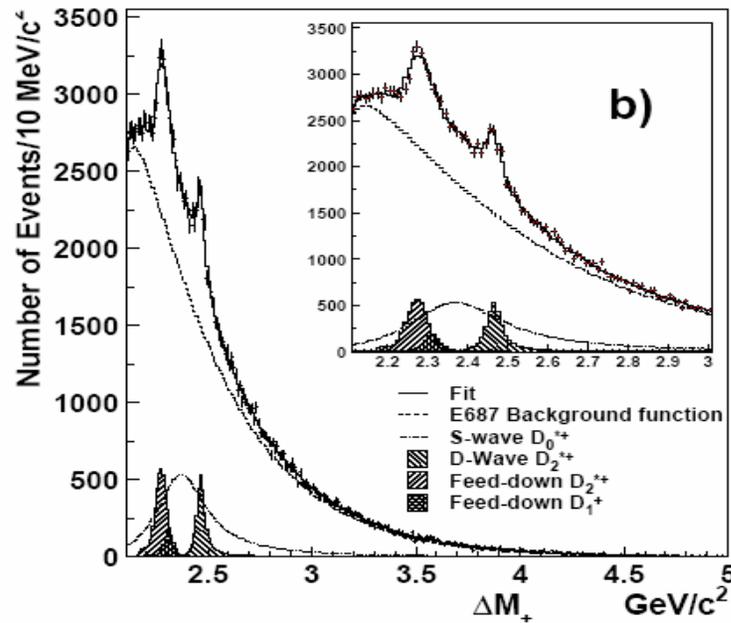


Perform a free fit just of  $D_2^*$  parameters. Feed-downs are calculated from PDG values. Still very poor agreement ( $\chi^2/\text{d.o.f} \approx 3$ ) between  $D_2^*$  signal region and the feed-down region.  $D_2^*$  parameters are far from expected values.



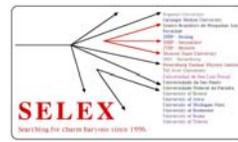


# Adding $D_0^*$ Broad States



Add  $S$ -wave contribution for  $D_0^*$  state ( $j\ell = \frac{1}{2}$ ). Fit is much improved, especially problem region before. CL = 22%. Also could be  $D_1^*$  ( $j\ell = \frac{1}{2}$ )  $\rightarrow D^*\pi$  with an unreconstructed  $\pi^0$ .





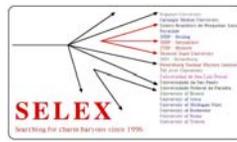
# FOCUS $D_J^*$ Fit Results

	$D_2^{*0}$	$D_2^{*+}$	$D_2^{*+} - D_2^{*0}$
Yield	$5776 \pm 869 \pm 696$	$3474 \pm 670 \pm 656$	—
Mass	$2464.5 \pm 1.1 \pm 1.9$	$2467.6 \pm 1.5 \pm 0.8$	$3.1 \pm 1.9 \pm 0.9$
PDG03	$2458.9 \pm 2.0$	$2459 \pm 4$	$0.0 \pm 3.3$
Belle03	$2461.6 \pm 3.9$		
Width	$38.7 \pm 5.3 \pm 2.9$	$34.1 \pm 6.5 \pm 4.2$	
PDG03	$23 \pm 5$	$25^{+8}_{-7}$	
Belle03	$45.6 \pm 8.0$		

	“ $D_0^{*0}(j_\ell = \frac{1}{2})$ ”	“ $D_0^{*+}(j_\ell = \frac{1}{2})$ ”
Yield	$9810 \pm 2657$	$18754 \pm 2189$
Mass	$2407 \pm 21 \pm 35$	$2403 \pm 14 \pm 35$
Belle03	$2308 \pm 36$	
Width	$240 \pm 55 \pm 59$	$283 \pm 24 \pm 34$
Belle03	$276 \pm 66$	

Errors on  $D_2^*$  masses and widths smaller than or same as PDG03 and agree with recent Belle report (hep-ex/0307021).





# Excited $D_s$ Mesons

Until spring 2003, this pattern was expected to be repeated in the  $D_s$  sector. Two relatively narrow  $j_{\text{light}} = 3/2$  states had been observed and broad  $j_{\text{light}} = 1/2$  were expected to be there too.

Instead, two new, very narrow states have been observed by the  $B$  factories decaying to  $D_s^{(*)}\pi^0$ .

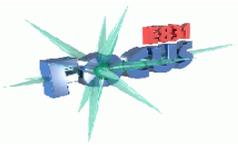
The first, dubbed  $D_{sJ}^*(2317)$ , was discovered by BABAR and later confirmed by CLEO and Belle.

The second,  $D_{sJ}^*(2463)$ , was discovered by CLEO and confirmed by BABAR and Belle.

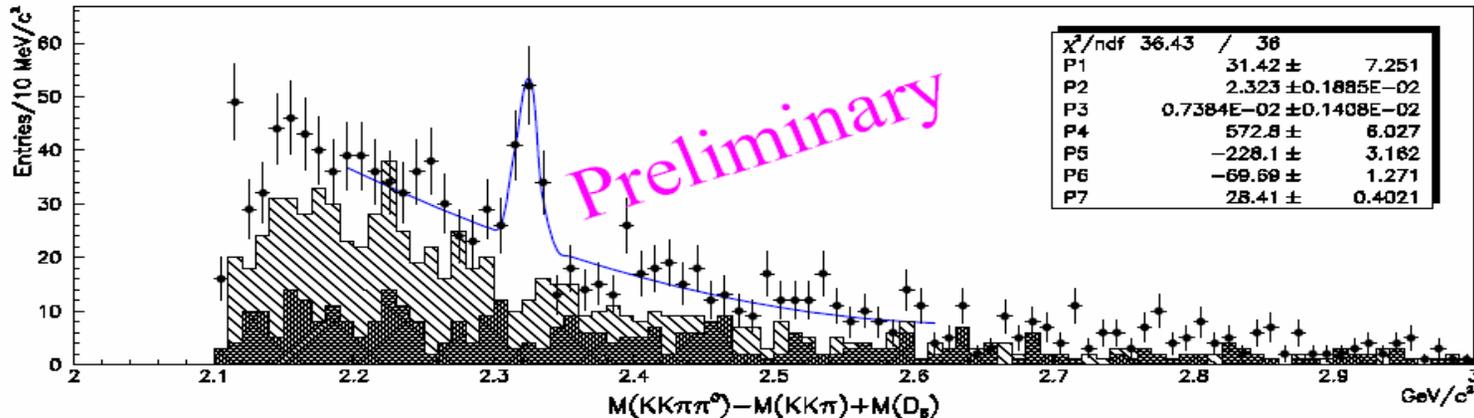
$D_{sJ}^*(2317)$  also seen by FOCUS

For  $j_\ell = 3/2$  states, analysis is very similar to  $D$  sector; replace  $\pi$  with  $K^+/K_S^0$ .



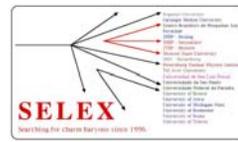


# $D_s^+(2317)$ Observation

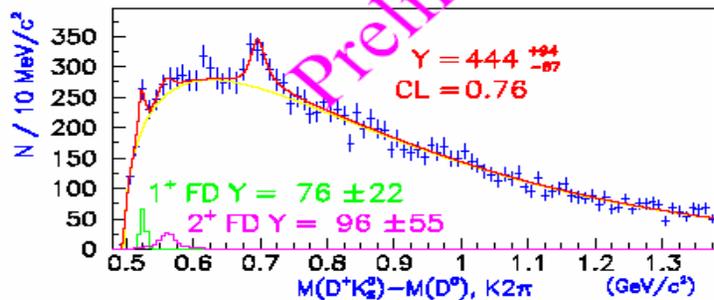
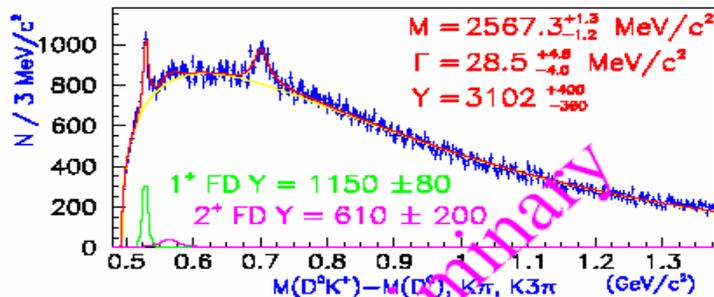


- Reconstructed in  $D_s^+ (\rightarrow K^- K^+ \pi^+) \pi^0$  (58 events, inner EM Cal only)
- Correction to  $\pi^0$  energy based on  $D_s^* \rightarrow D_s^+ \pi^0$  and  $D^0 \rightarrow K^- \pi^+ \pi^0$ .
- Mass (using PDG  $D_s^+$  value) found to be  $2323 \pm 2 \text{ MeV}/c^2$ . BABAR/Belle/CLEO avg.  $\sim 2317$





# $D_{sJ}^+(2573) \rightarrow D^0 K^+$ and $D^+ K_S^0$



Simultaneous fit to  $D^0 K^+$  and  $D^+ K_S^0$ . Terms:

- $D_{s2}^*$  signal: D-wave Rel. BW
- Smooth BG shape
- $D_{s1}$  &  $D_{s2}^*$  feed-down shapes

Common  $M$  and  $\Gamma$ , stat. only.

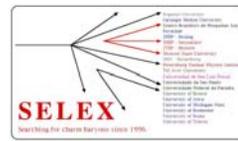
- $M = 2567.3^{+1.3}_{-1.2} \text{ MeV}/c^2$
- $\Gamma = 28.5^{+4.8}_{-4.0} \text{ MeV}/c^2$

PDG values are:

- $M = 2572.4 \pm 1.5 \text{ MeV}/c^2$
- $\Gamma = 15 \pm 5 \text{ MeV}/c^2$

First observation of  $D^+ K_S^0$  decay mode.  
 Comparable errors to PDG averages

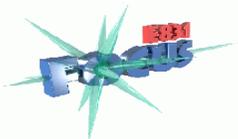




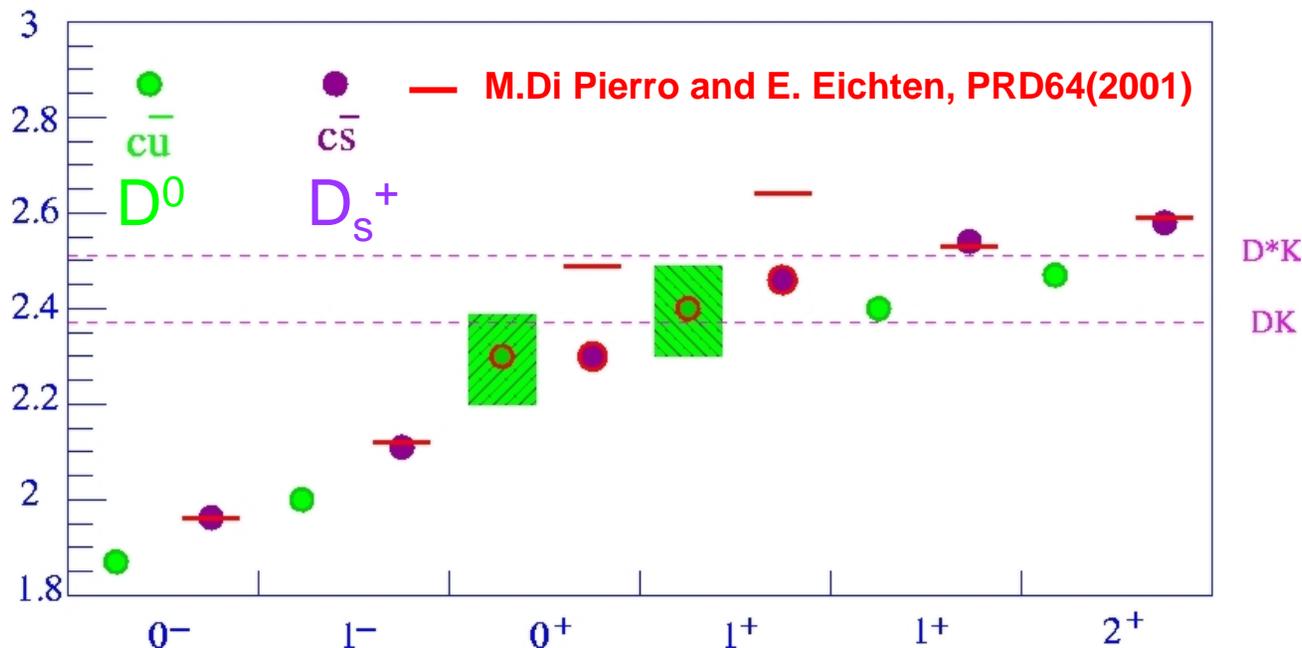
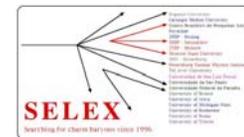
# Summary Of FOCUS Results

- New precise measurements of  $D_2^{*+}$  and  $D_2^{*0}$  masses and widths. Errors comparable to PDG averages. Published as PLB 586 (2004) 11–20.
- Same paper presents evidence for broad ( $D_0^{*0}$ ) states in  $D^+\pi^-$  and  $D^0\pi^+$  final states (first evidence in  $D^0\pi^+$ ).
- Combined paper on excited  $D_s$  states in preparation.
- $D^*\pi^\pm$  under study for other  $L = 1$  states.
- Renewed interest in sector due to “strange” charmed mesons



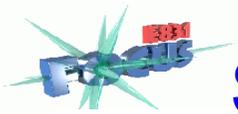


# Heavy-light spectroscopy

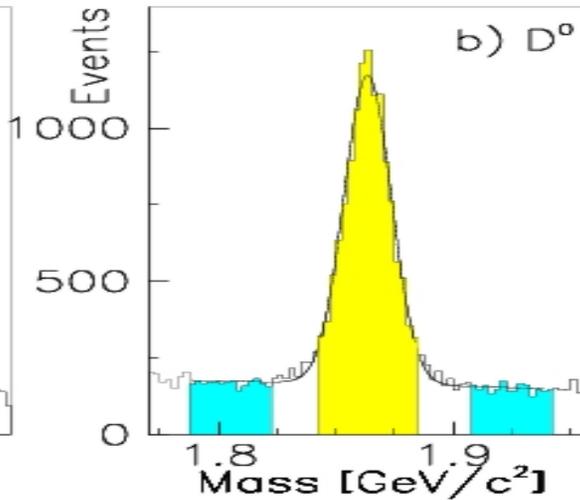
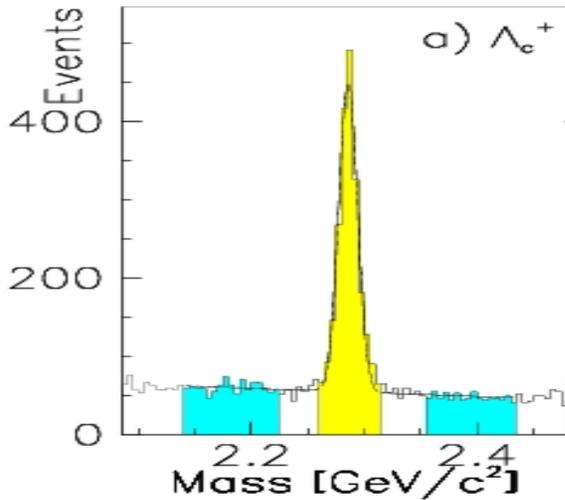
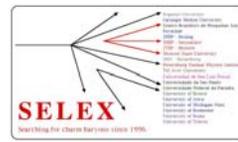


- Model predicts mass and widths – works well for  $D(c\bar{d})$ , but not for all  $D_s(c\bar{s})$
- 2003 –  $e^+e^-$  found  $D_s(2317)$ ,  $D_s(2463)$  – below DK threshold, inconsistent with model
- Higher states – expected above  $D^{(*)}K$  threshold – therefore broad and hard to observe

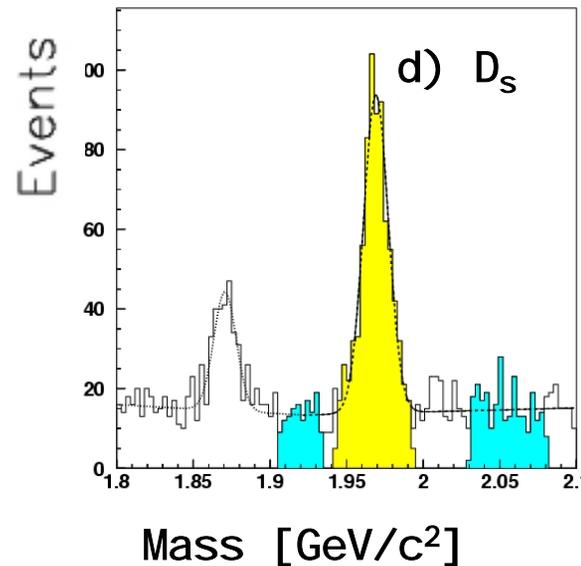
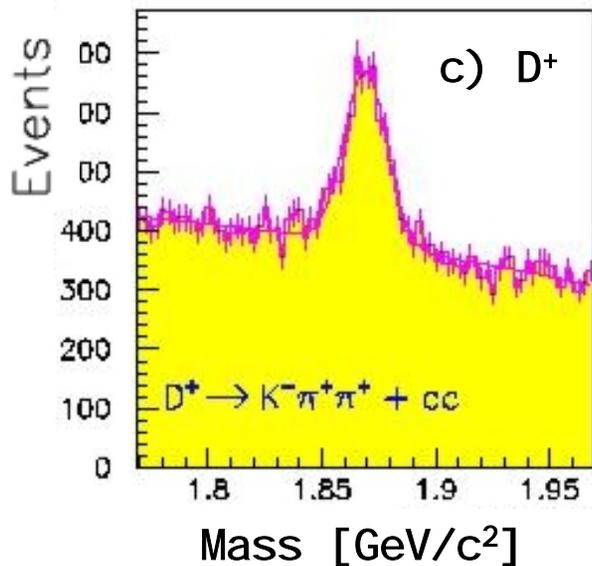




# SELEX search for $D_{sJ}^+ \rightarrow D_s^+ \eta^0, D^0 K^+$



SELEX single charm samples (few % FOCUS)

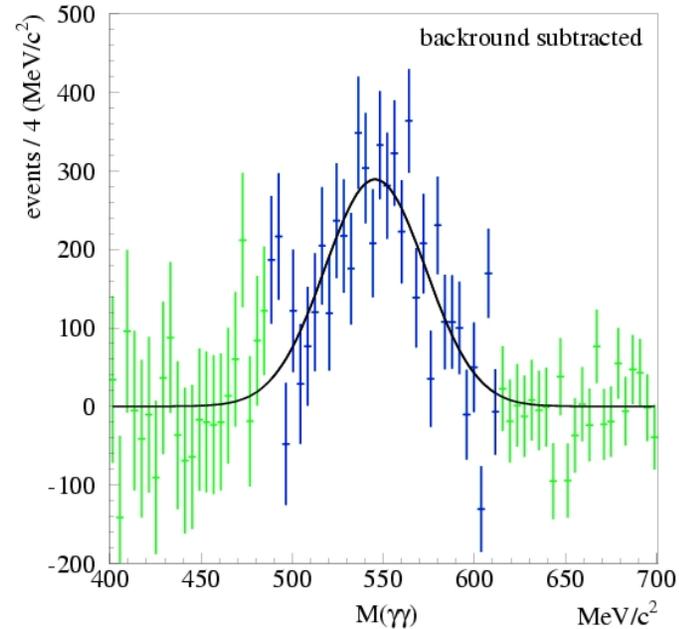
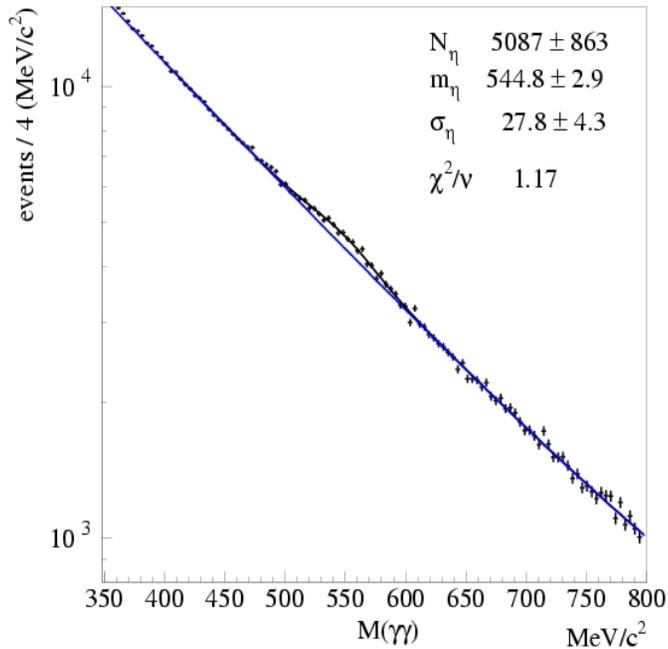
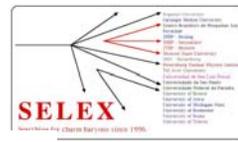


This analysis uses  $D^0$  and  $D_s$  data





# $\eta^0$ signal in CHARM trigger

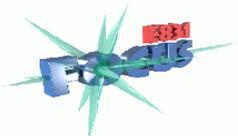


- ✓  $E_\gamma > 2$  GeV,
- ✓  $E_{\gamma\gamma} > 10$  GeV,
- ✓  $N_\gamma < 10$
- ✓ Fit to: exp + Gaussian + constant
- ✓ good fit

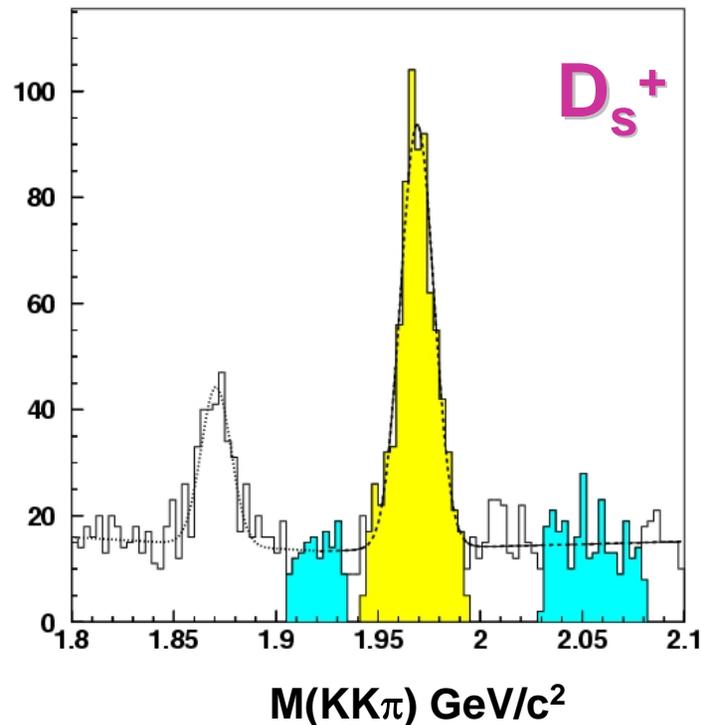
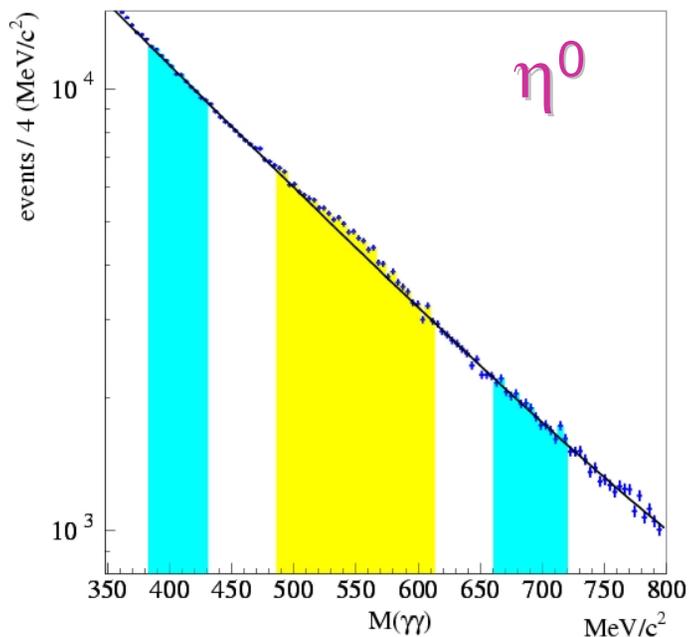
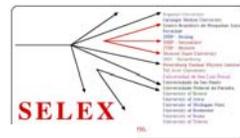
Fit $M(\eta^0)$	$544.8 \pm 2.9$
PDG $M(\eta^0)$	$547.3 \pm 0.12$
Fit resolution	$27.8 \pm 4.3$
MC resolution	$30.2 \pm 1.2$

- ✓  $\eta^0$  mass agrees with PDG value.
- ✓ MC represents resolution well.





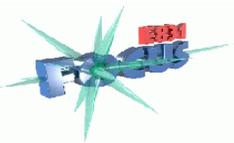
# $\eta$ and $D_s$ selection



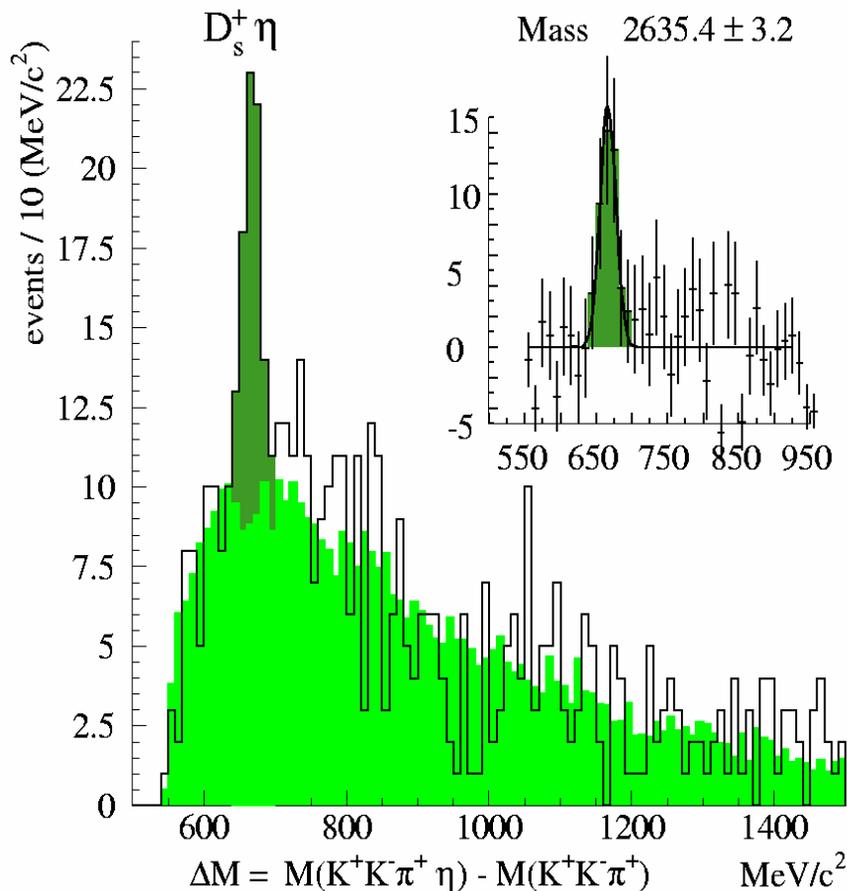
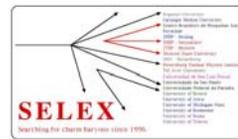
- ✓  $E_\gamma > 2 \text{ GeV}$ ,  $E_{\gamma\gamma} > 15 \text{ GeV}$
- ✓  $\eta^0$  mass region:  $M_{\text{PDG}}(\eta^0) \pm 60 \text{ MeV}$
- ✓  $5\text{M } \eta^0$  in  $150\text{M}$  candidates  
S/N  $\sim 1/30$
- ✓  $0.15 \eta^0$  candidates / event

- ✓  $L/\sigma > 8$ ,  $p_{\text{vtx}} < 8$
- ✓  $|M(\text{KK}\pi) - 1968.5| < 25 \text{ MeV}$
- ✓  $\sim 1.2 \eta^0$  candidate /  $D_s$  candidate





# New charm-strange meson



✓ Combined clean sample of  $D_s$  with  $\eta^0$  candidates

$\eta$  mass constrained  $\vec{p}_\eta = [M_{\text{PDG}}(\eta), \vec{p}]$

✓ 615  $\eta^0$  cand in 554  $D_s$  cand

✓  $103 \pm 27$   $\eta^0$  signal events

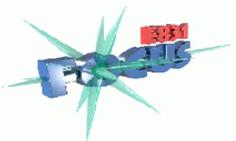
Clear peak near  $2635 \text{ MeV}/c^2$

Event mixed background technique

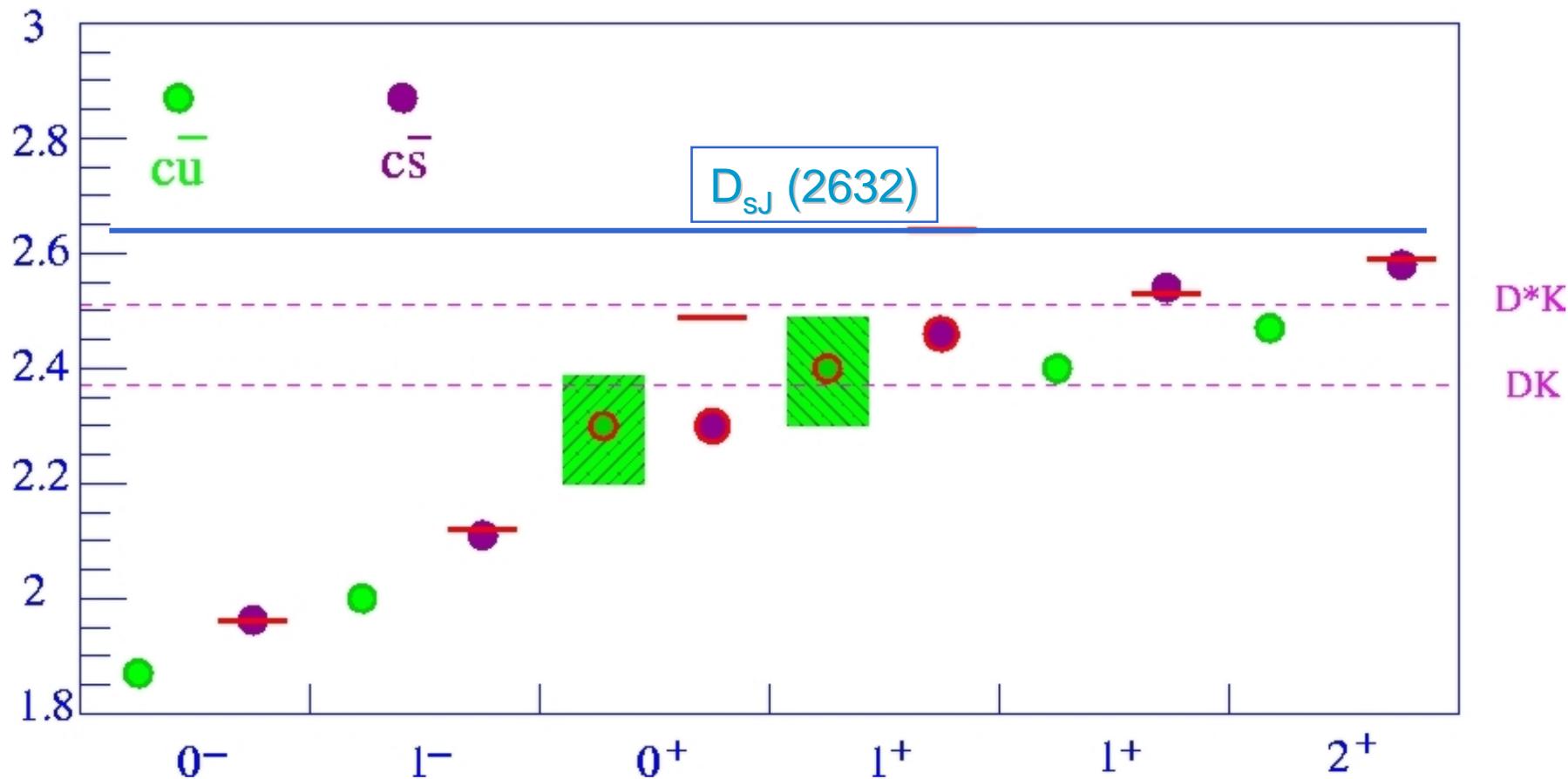
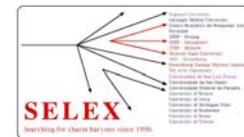
$\eta^0$ s from previous 25 events +  $D_s$  candidates

Background consistent with just combinatorics – all sidebands flat.





# Heavy-light spectroscopy now



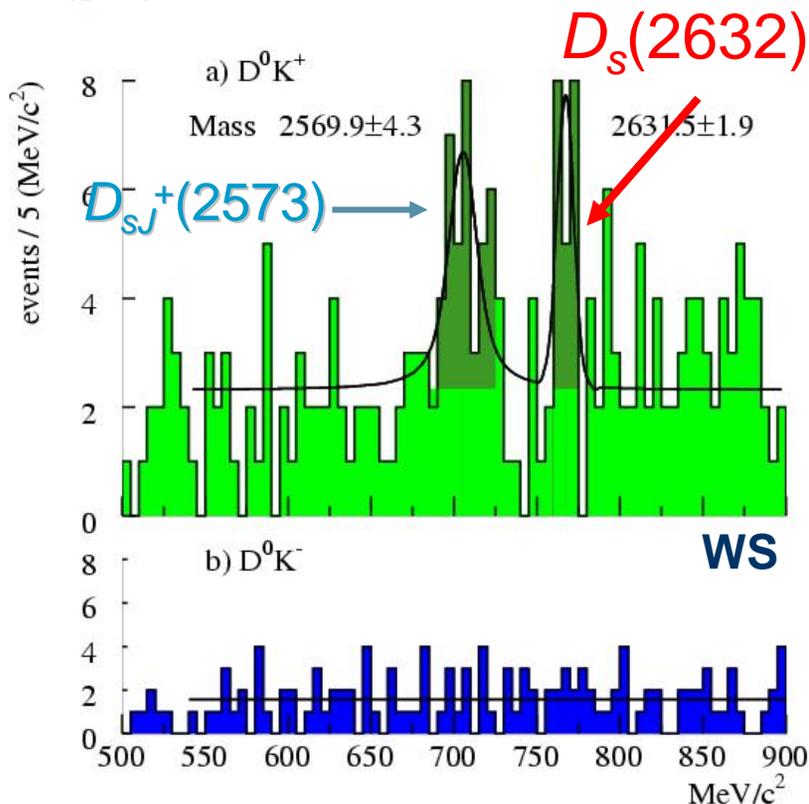
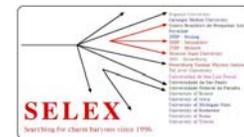
New state lies above  $D^{(0)}$  K threshold

Look for  $D_s(2632) \Rightarrow D^0 K^+$





# Fitting $D_s (2632) \rightarrow D^0 K^+$



- ✓ Strong selection criteria on  $D^0$  &  $K^+$ 
  - ✓  $D^0 \rightarrow K^- \pi^+$  only (S/N 4/1)
  - ✓  $L/\sigma > 6$ , svtx  $\chi^2 < 3$ , pointback  $\chi^2 < 5$
  - ✓ Prob( $K^+$ )  $> 10$  Prob(any other)

- ✓ Wrong sign background constant
- ✓ Fit with 2 [ BW convolved with Gaussian ] + constant background
- ✓ Fix resolution from MC (4.9 MeV)

*New state is narrow (resolution only)*

Count  $S = 21$ ,  $B = 7.0 \pm 0.6$ ,  $(S-B)/\sqrt{B} = 5.3 \sigma$

3 bin Poisson excess probability =  $2.5 \times 10^{-5}$

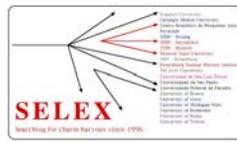
Fit events:  $13.2 \pm 4.9$ , Mass  $2631.5 \pm 2.0$  MeV/c<sup>2</sup>

- ✓ A 90% CL upper limit  $\Gamma < 17$  MeV/c<sup>2</sup>

<b>DsJ(2573) PDG</b>	<b><math>2573.5 \pm 1.7</math> MeV/c<sup>2</sup></b>	<b><math>15^{+5}_{-4}</math> MeV/c<sup>2</sup></b>
<b>DsJ(2573) SELEX</b>	<b><math>2569.9 \pm 4.3</math> MeV/c<sup>2</sup></b>	<b><math>14^{+9}_{-6}</math> MeV/c<sup>2</sup></b>



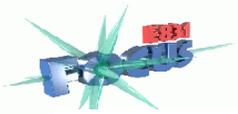
# $D_{sJ}(2632)$ Branching Ratios



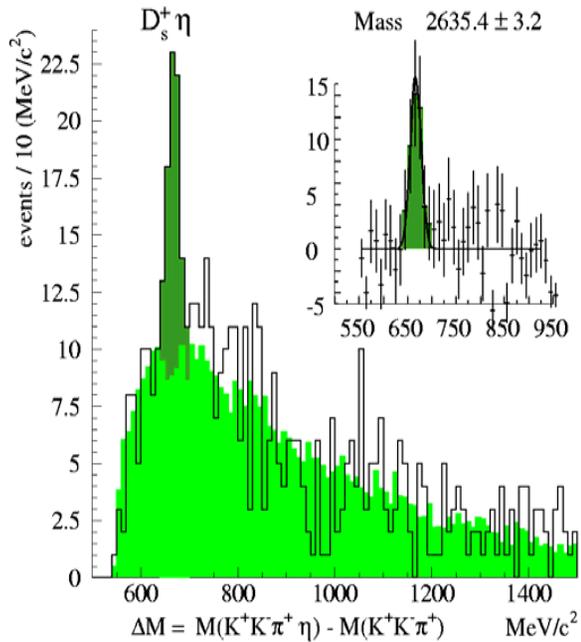
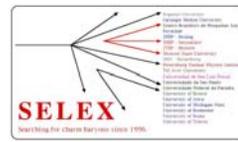
- Most models say that  $D^0 K^+$  coupling should be much bigger than  $D_s^+ \eta^0$
- Phase space favors  $D^0 K^+$  mode by 2.3x
- Acceptances given a detected  $D(s)$  meson are comparable
- We see 3x as many  $D_s^+ \eta^0$  decays as  $D^0 K^+$

**SURPRISE:**  $\Gamma(D^0 K^+)/\Gamma(D_s^+ \eta^0) = 0.14 \pm 0.06$

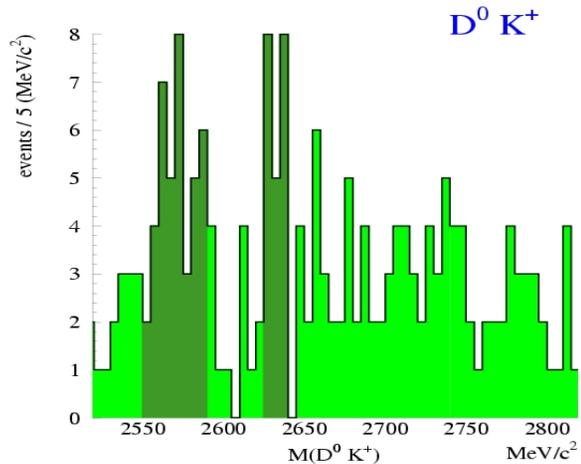




# D<sub>s</sub> (2632) summary



State	D <sub>s</sub> (2632) → D <sub>s</sub> η	D <sub>s</sub> (2632) → D <sup>0</sup> K
mass	$2635.4 \pm 3.3$	$2631.5 \pm 2.0$
Sign.	$6.2 \sigma$	$5.3 \sigma$
Events	$43.4 \pm 9.1$	$13.2 \pm 4.9$
$\chi^2 / n_d$	1.10	0.77

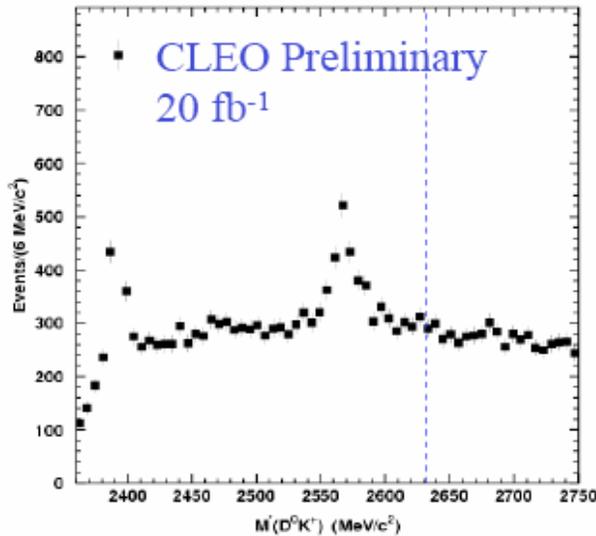
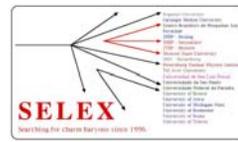


- ✓ Average D<sub>sJ</sub><sup>+</sup>(2632) mass  $2632.5 \pm 1.7 \text{ MeV}/c^2$
- ✓  $\Gamma < 17 \text{ MeV}/c^2$  @ 90% CL(D<sup>0</sup>K<sup>+</sup>)
- ✓  $\Gamma(D^0K^+) / \Gamma(D_s^+\eta^0) = 0.14 \pm 0.06$





# Not seen in $e^+e^-$ or photoproduction



CLEO: shown at PIC2004 (6/28/2004)  
Thanks to Rich Galik (Cornell)

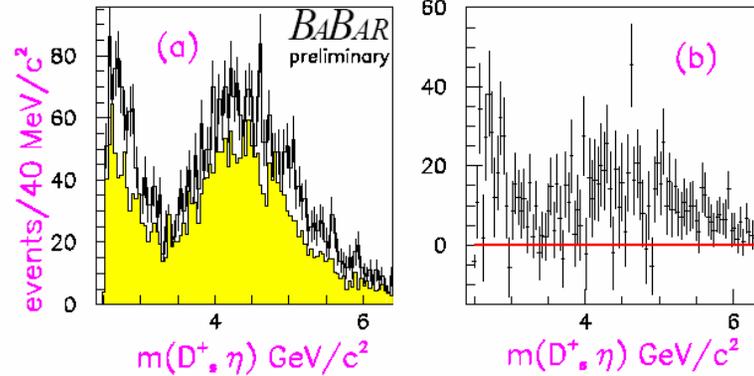
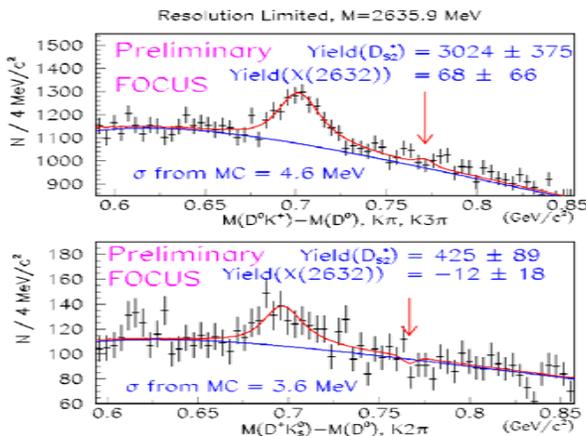


Figure 4: (a) The  $D_s^+ \eta$  invariant mass distribution. The unshaded distribution ( $m_5$ ) corresponds to the central region of Fig. 3a while the shaded distribution is obtained using Eq. 4. (b) The  $D_s^+ \eta$  mass distribution obtained by subtracting the distributions of (a).

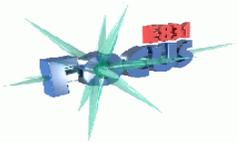
Babar hep-ex/04080087

- Not Made?
- Not there?
- Babar only sees  $\sim 0.4\%$   $D_s \eta / D_s$   
Are any of the higher mass  $D_s$  states being produced in  $e^+e^-$  ?

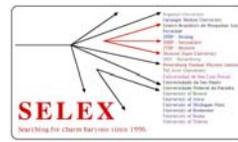


FOCUS (unpub) Thanks to Rob Kutschke (FNAL)





# Summary of Selex Result



$D_s^+ \eta^0$  Observed a clear peak of  $43.4 \pm 9.1$  events with a significance of  $6.2 \sigma$  at a mass difference  $666.9 \pm 3.3 \text{ MeV}/c^2$  above ground state

$D^0 K^+$  Observed a clear peak of  $13.2 \pm 4.9$  events with a significance of  $5.3 \sigma$  at a mass difference  $767.0 \pm 2.0 \text{ MeV}/c^2$  above ground state

Clear evidence for a new state  $D_{sJ}^+(2632)$  at  $2632.5 \pm 1.7 \text{ MeV}/c^2$  with  $\Gamma < 17 \text{ MeV}/c^2$ !

Result accepted for publication in PRL (after much hand-wringing on both sides)

This state is definitely NOT seen in  $e^+e^-$  (CLEO, Babar) or in photo-production (FOCUS) ?

## CONCLUSIONS

Heavy-Light systems still require exploration and explanation

Can  $D_{sJ}^+(2632)$  be confirmed?

Are there other states to be found; wide or narrow?

Who are these guys ( $I^G J^P$ , etc.)?

Exotica? (21 cites for the  $D_s^+(2632)$  preprint include some eclectic explanations)

Will we have a descriptive “post-diction” of this spectroscopy to build on the relatively successful predictions?

