D_{sJ} Spectroscopy

Two new charm-strange particles have been observed by *BABAR*, CLEO and Belle in 2003.

- DsJ Spectroscopy
- BaBar's Discovery of D_{sJ} (2317) -> $D_s\pi^0$
- CLEO's Discovery of D_{sJ} (2463)
  (left to Dr. Ecklund-CLEO talk)
- Belle's results on D_{sJ} (2317) , D_{sJ} (2457)
- BaBar Results on D_{sJ} (2458)

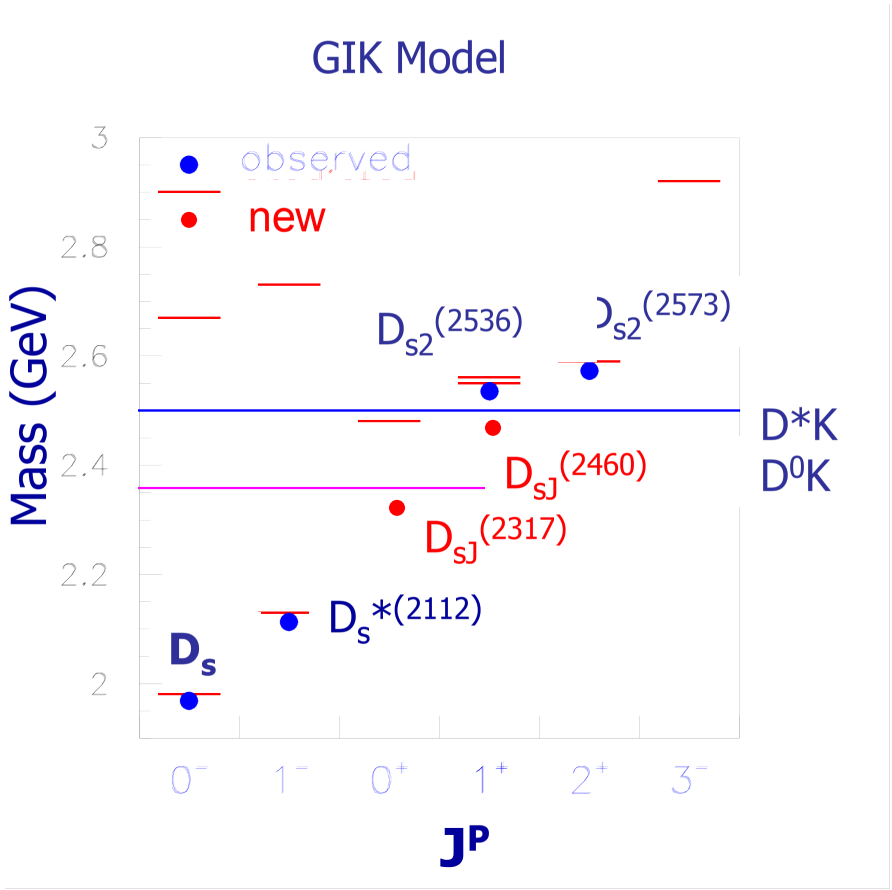
The New States

- The spectrum of D_s ($c\bar{s}$) states had gaps.

J^P	GIK [a] Model GeV/c^2	DP-E [b] Model GeV/c^2
0^+	2.48	2.487
1^+	2.55	2.535
1^+	2.56	2.605

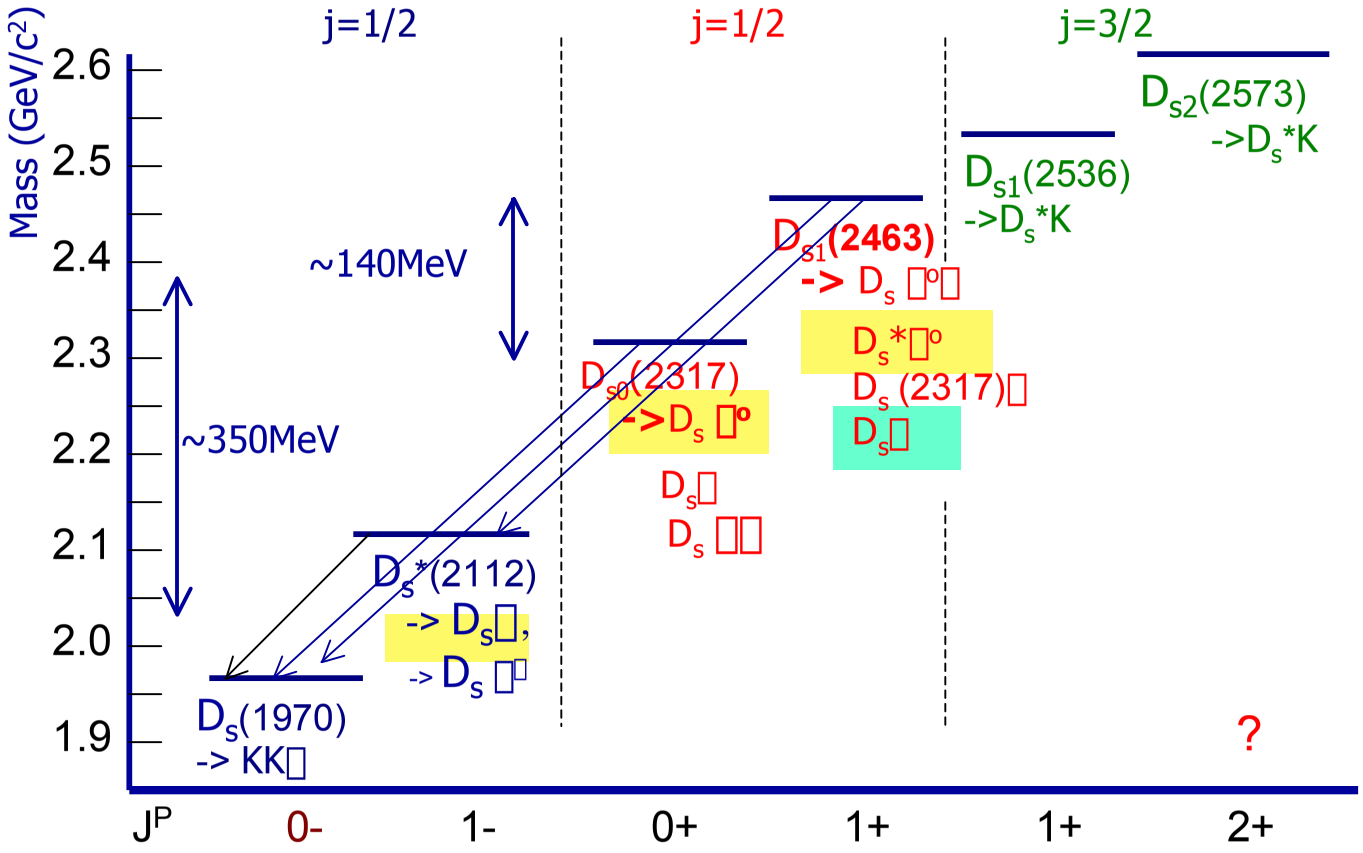
[a] S. Godfrey and R. Kokoski, Phys. Rev. D43, 1679 (1991). S. Godfrey and N. Isgur, Phys. Rev. D32, 189 (1985).
[b] M. Di Pierro and E. Eichten, Phys. Rev. D64, 114004 (2001).

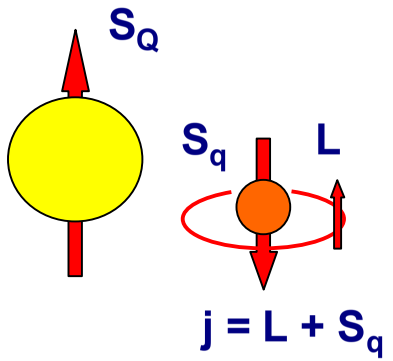
(a) **BardeenEichtenHill Model (HQET+chiral sym)**



- The states predicted could decay to **DK** so would be broad (Γ ~ 270-990 MeV/c^2).
- The states recently found lie below **DK** or **D*K** threshold and so are narrow.

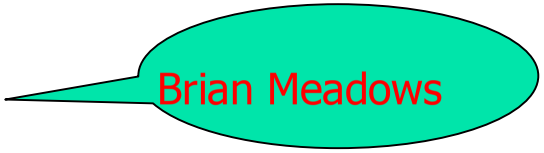
$c\bar{s}$ DOUBLET PICTURE





- D_sγ decays violate isospin conservation and are narrow.
- Radiative Decays D_sγ, D_s*γ give clues to J^P (0+ ⇏ 0-).
- Di-pion Decays (D_sππ) conserve isospin, OZI suppressed!
- Beware of Kinematical Reflections. D_sπ°/γ, or D_sπ° + γ [D_s* π°]

… the Fuss?



Each of the states:

- Are ~ 42 MeV/c^2 below **DK** (strong decay) threshold.
- Are narrow (width comparable to resolution).
- Decay in a $\Delta I = 1$ transition.

This seems to have everyone excited:

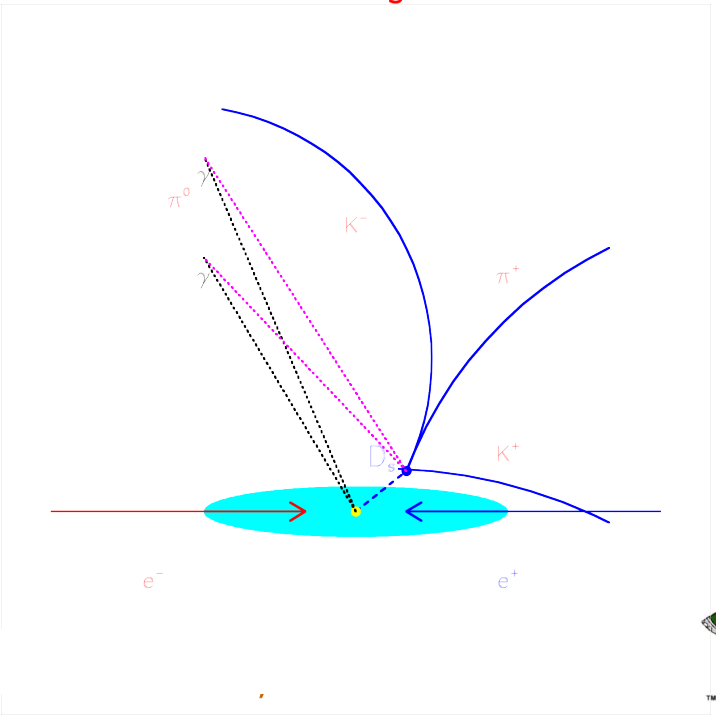
- Either something is wrong with the quark models.
- Perhaps there is a new quark phase for heavy hadrons.
- $c\bar{s}qq$ Molecules!

Data Selection

- Select good K K □ track candidates + particle id.
- All pairs of □s, each □having energy > 100 MeV, are fitted to a π^0 with mass constraint.
- Each π^0 is fitted twice:
  - To the production vertex to investigate the $D_s^+\pi^0$ mass.
  - To the $K^+K^-\pi^+$ vertex so that we can also use the D_s -> $K^+K^-\pi^+\pi^0$ mode.

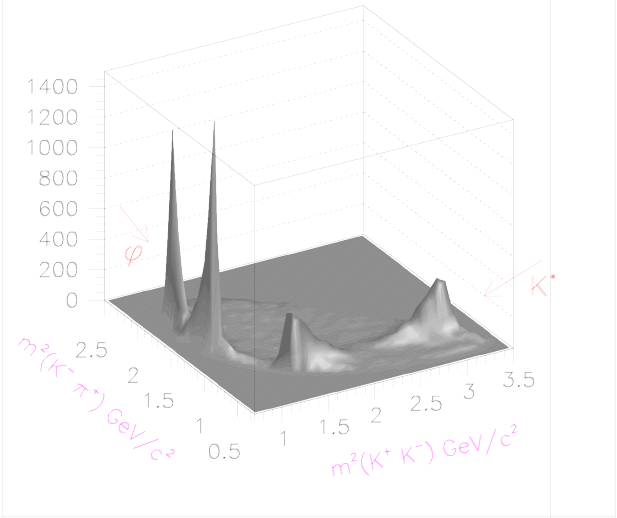
- Continuum-each event was required to have p_D^* > 2.5 GeV/c.

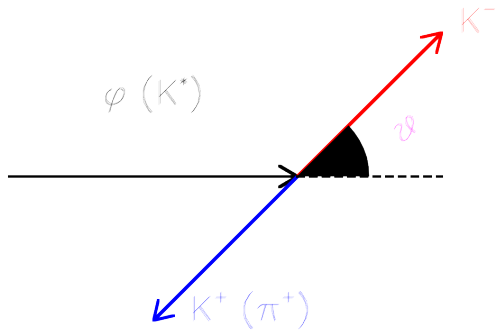
- DsJ from B decays are being studied now in BaBar.



The D_s^+ -> $K^+ K^- \pi^+$ Dalitz Plot

- Events in the $\mathbf{D_s^+}$ mass band:





- **K*** and ϕ bands do not cross (no double counting).
- $\cos^2\theta$ distributions evident in vector bands.
- Cuts select the ϕ and K* peaks in the plot.

Total $K^+K^-\pi^+$ Mass Spectrum

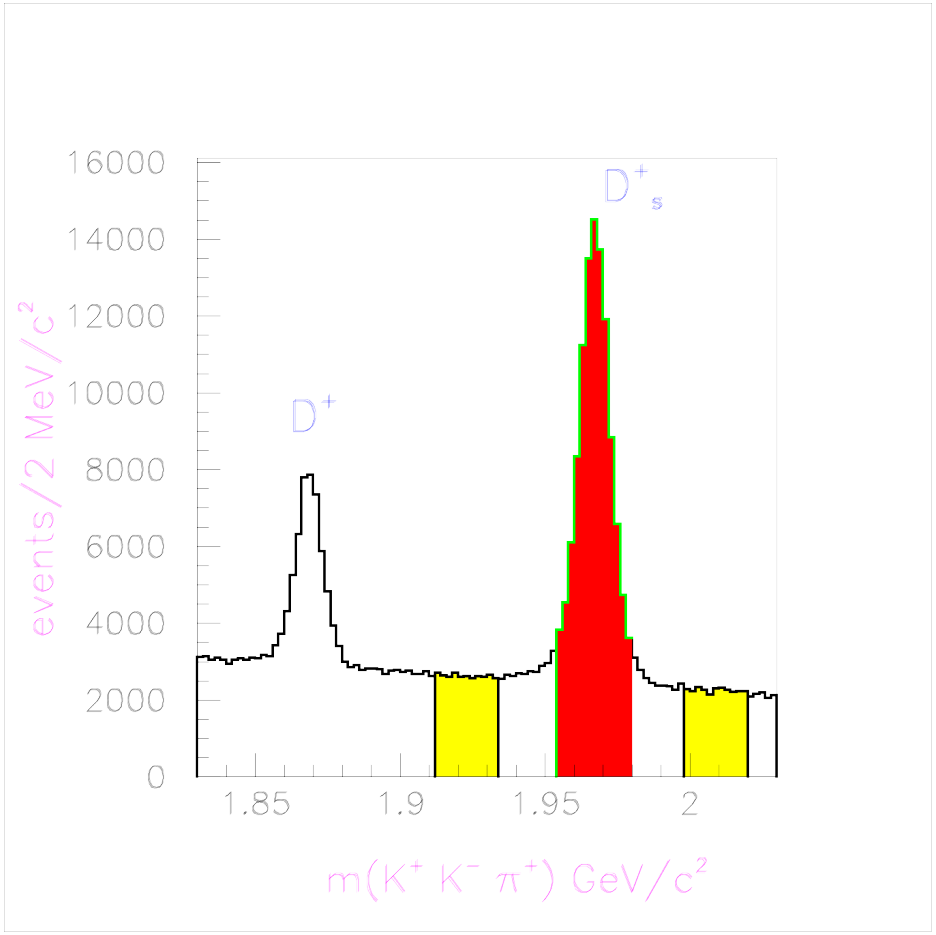
- Sum of $\phi\pi^+$ and $\overline{K}^{*0}K^+$ contributions is » 80,000 D_s^+ above background.
- We define
  - signal region:

$1.954 < m(K^+K^-\pi^+) < 1.980$ GeV/c^2

  - and two sideband regions:

$1.912 < m(K^+K^-\pi^+) < 1.934$ GeV/c^2

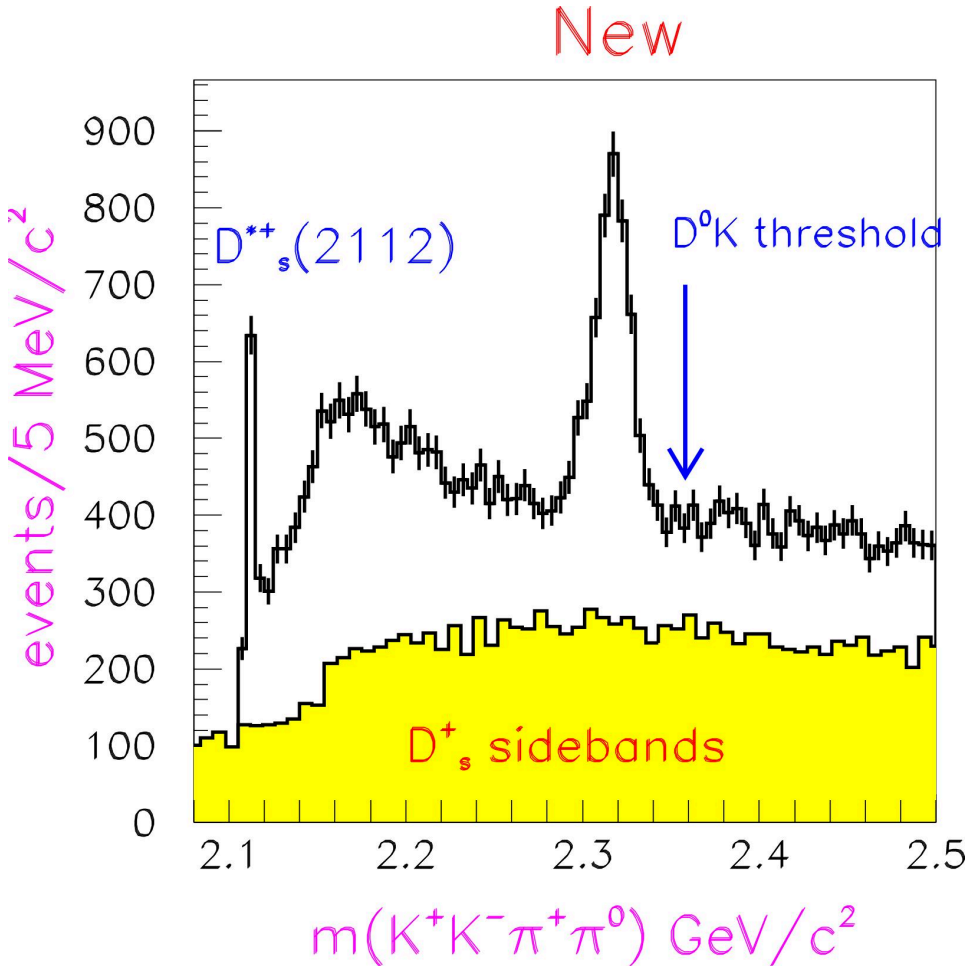
$1.998 < m(K^+K^-\pi^+) < 2.020$ GeV/c^2



Discovery of $D_{sJ}^{*}(2317)^{+}$

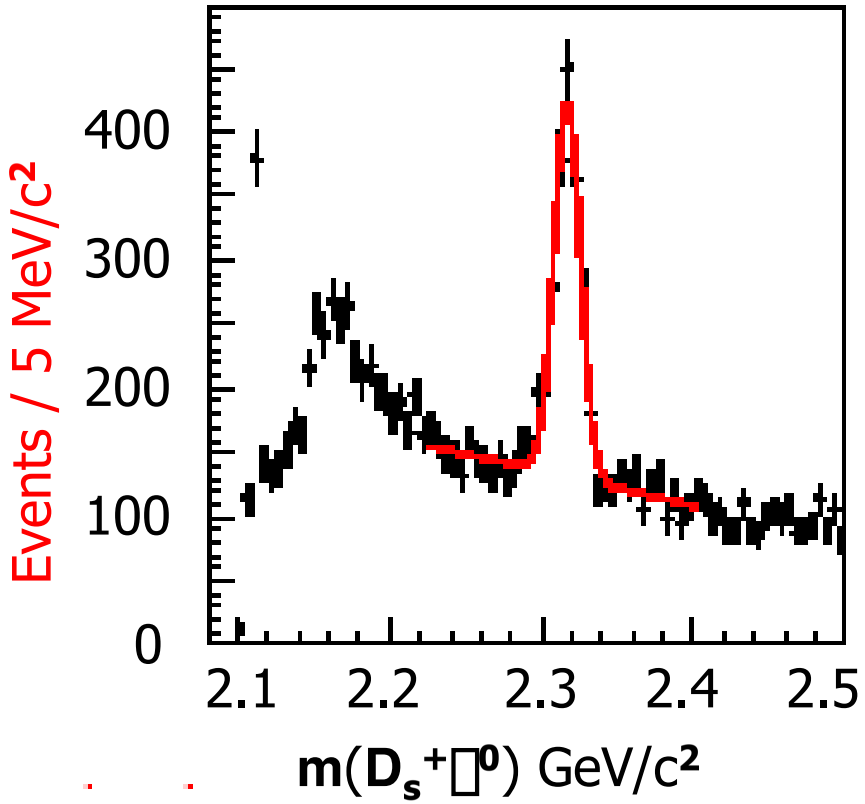
Unexpected large signal found in $D_s^+\pi^0$ mass

(by Antimo Palano)



Fit to the Signal

- Require **p*** **>** 3.5 GeV/c.



Fit to polynomial and a single Gaussian.

1267+-53 candidates (91fb^{-1})

m = 2316.8 +- 0.4 GeV/c^2

 = 8.6 +- 0.4 MeV/c^2

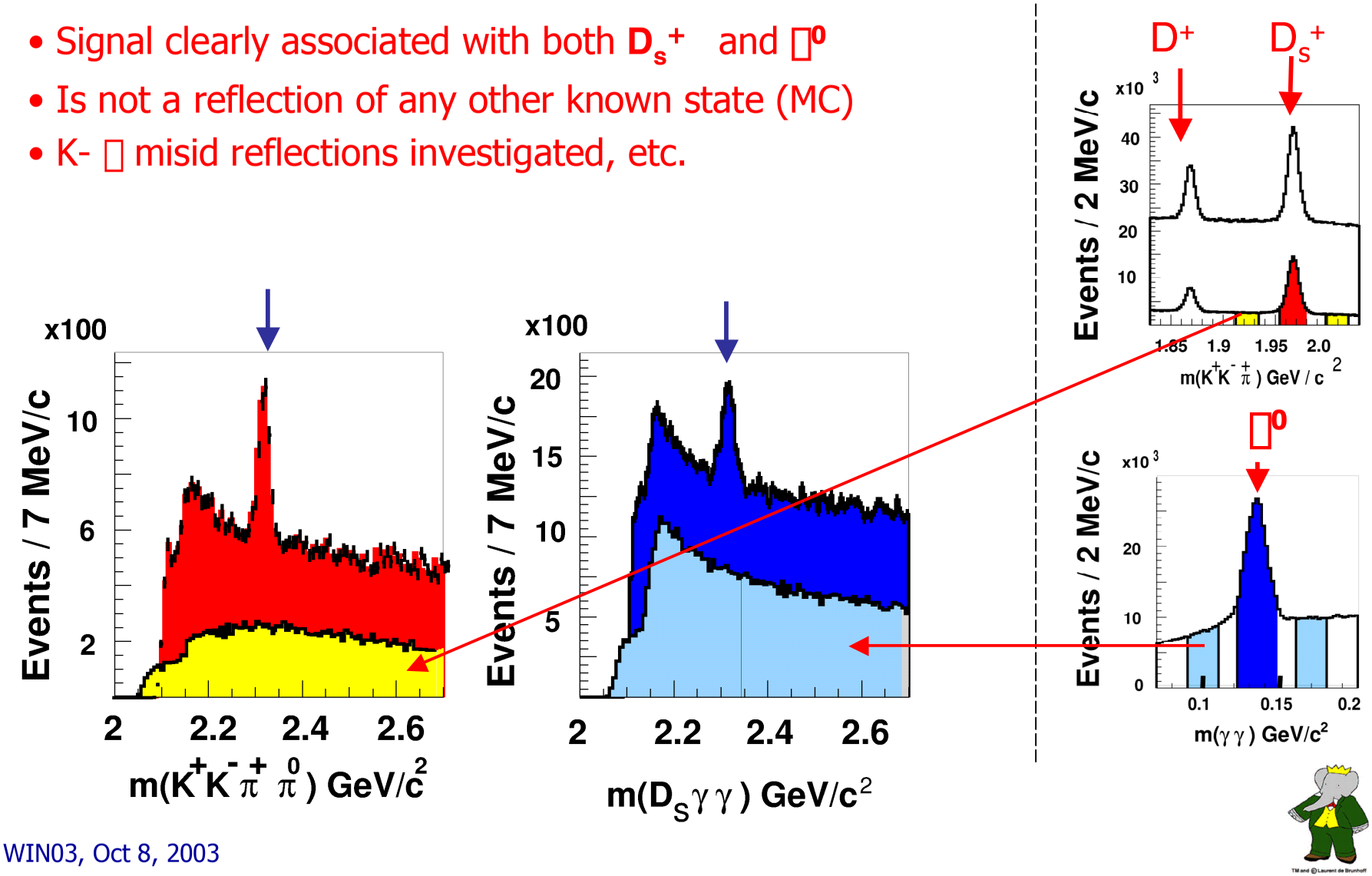
(*errors statistical only*).

Resolution from MC:
8.9 +- 0.2 MeV/c^2

$D_s^+\pi^0$ Mass Spectrum

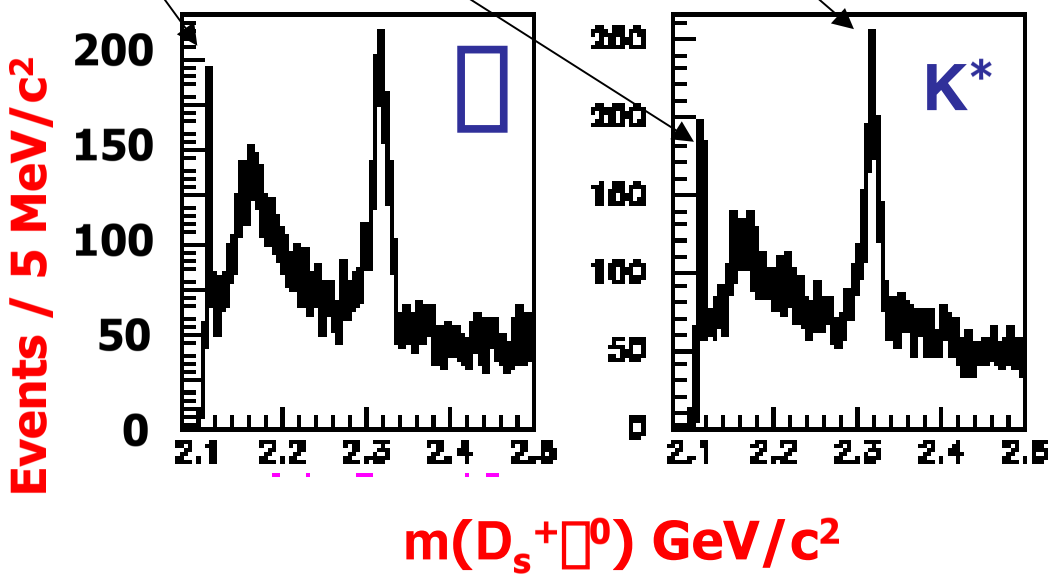
A striking signal observed in the $D_s^+\pi^0$ system.

- Signal clearly associated with both D_s^+ and π^0
- Is not a reflection of any other known state (MC)
- K- π misid reflections investigated, etc.



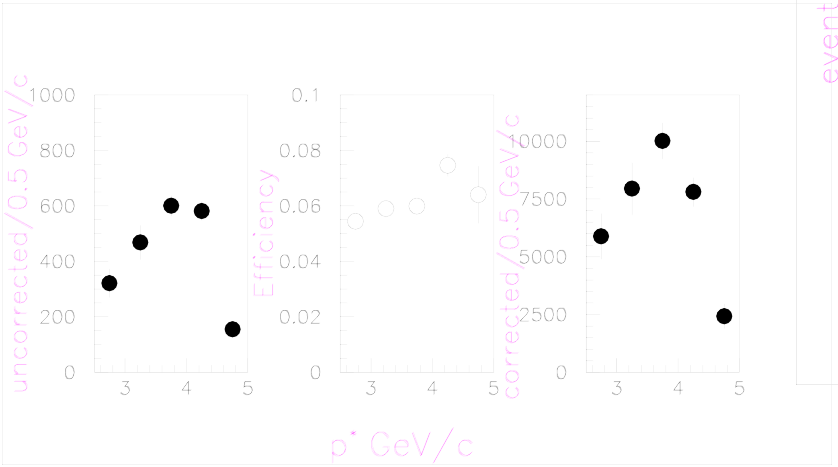
$D_s^+\pi^0$ Mass Spectra

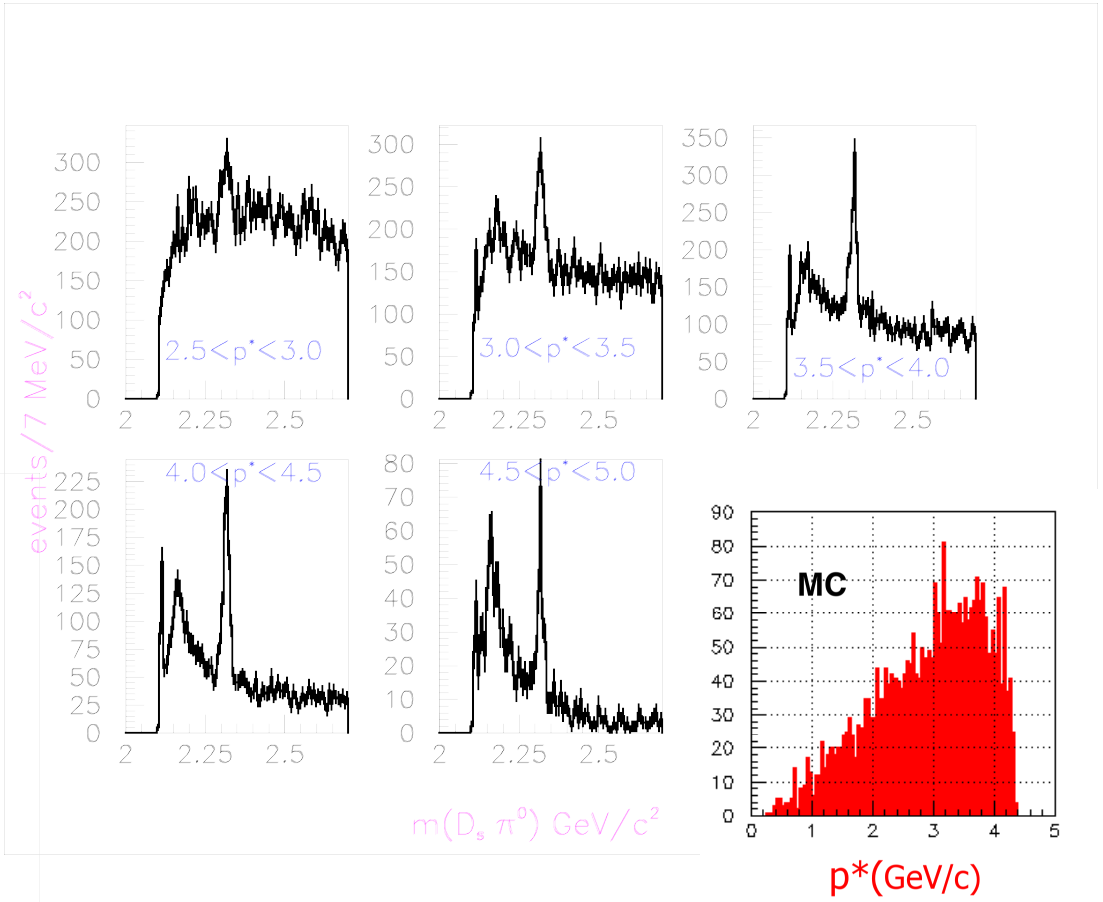
- Separate $\phi\pi^+$ and $K^{*0}K^+$ subsamples:
- $D_s^{*+}(2112)$ and signal at 2.32 GeV/c^2 present in both channels with roughly equal strength.



$D_s\pi^0$ CMS Momentum (p^*) Dependence

- Study $D_s^+\pi^0$ mass spectrum behavior in p^* intervals.
- Present in all intervals.
- Better signal to background at higher p^* values.
- Insures continuum production.
- Study dependence in Monte Carlo.

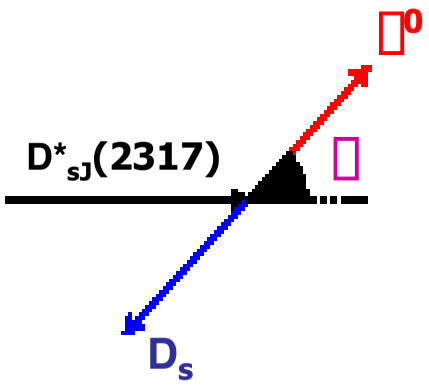


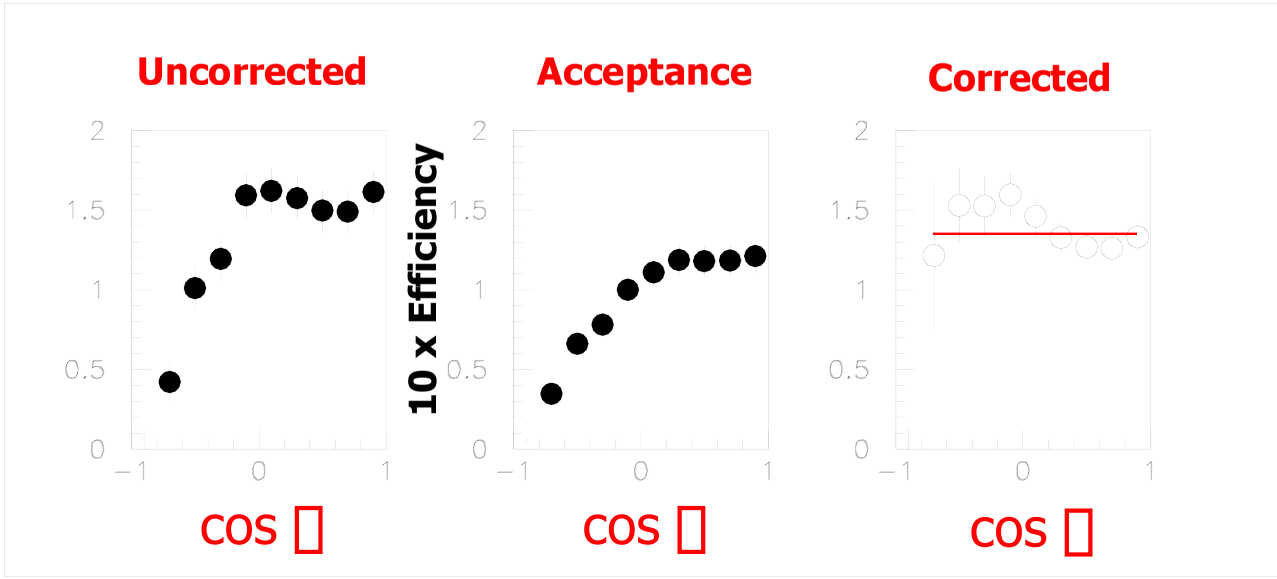


A p^* > 3.5 GeV/c cut Selected

$D_{sJ}^{+}(2317)$ Decay Angular Distribution

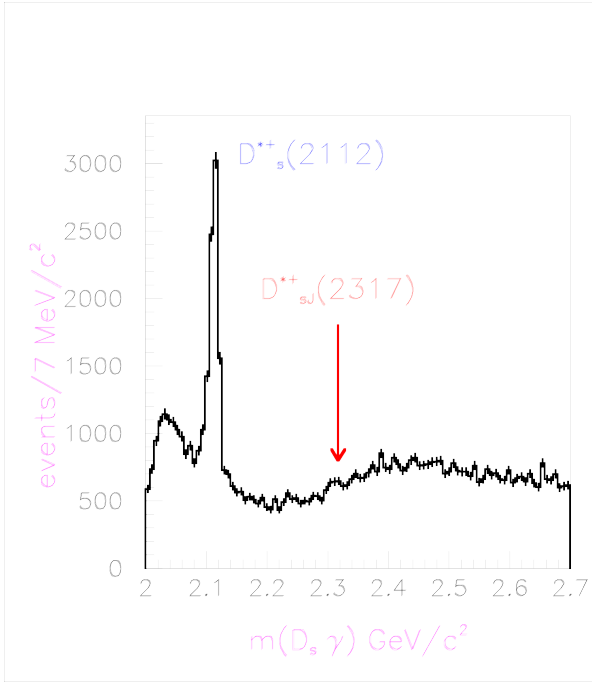
- Helicity angle distribution provides spin information.
- The $D_s^+\pi^0$ mass spectrum is fitted in 10 slices of $\cos(\theta)$.
- The corrected distribution in $\cos(\theta)$ is consistent with being flat - allowing for 0^+ - barring polarizing effects.

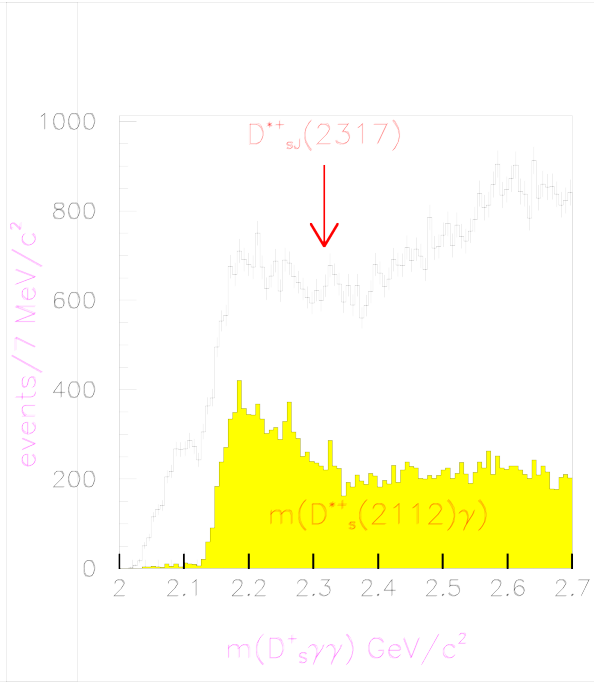


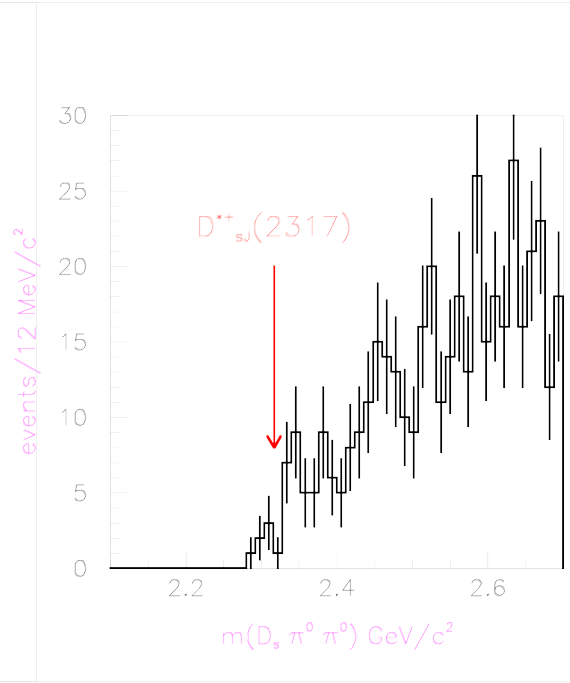


$D_s^+\gamma$, $D_s^+\pi^0$, $D_s^*(2112)\gamma$, $D_s^+\pi^0\pi^0$

- No evidence $D_{sJ}(2317)$ in any of these decays.





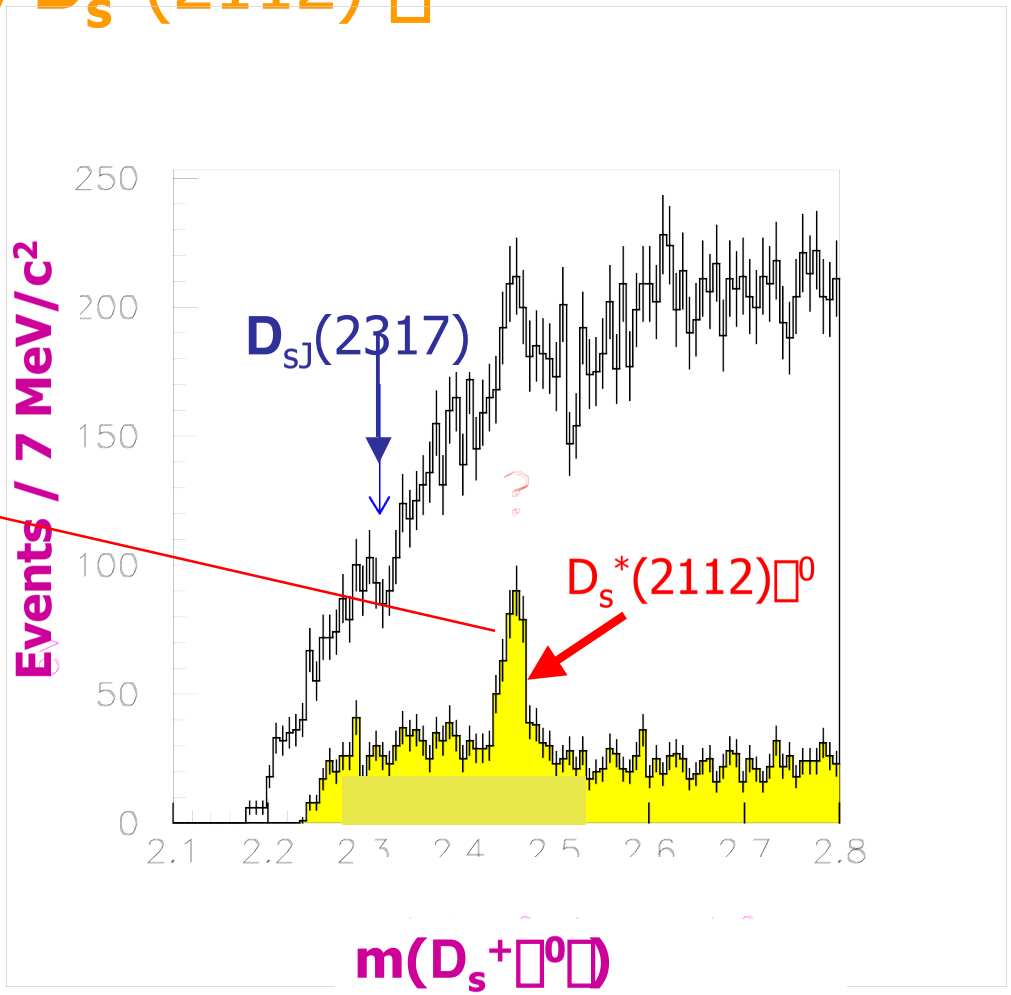


Missing Gammas from Higher Mass States - $D_s^+ \gamma^0 \gamma$, $D_s^*(2112)\gamma^0$

- No downfeed BUT …

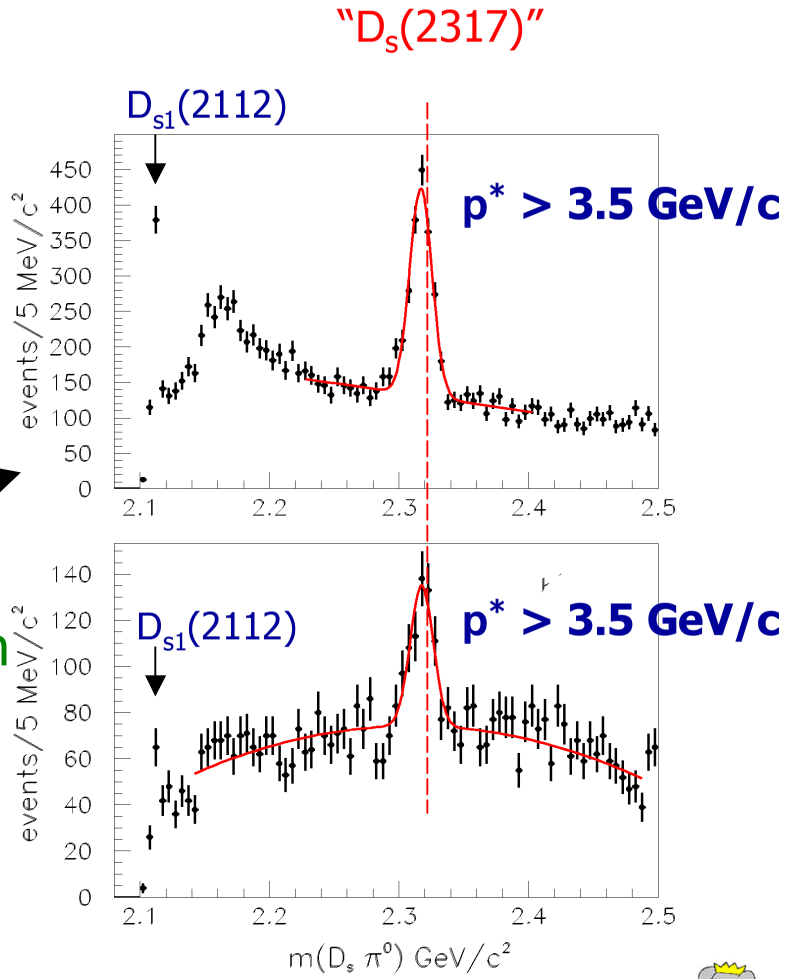
"Although we rule out the decay of a state of mass 2.46 GeV/c2 as the sole source of the $D_s^+\gamma^0$ mass peak corresponding to the $D_{sJ}(2317)^+$, such a state may be produced in addition to the $D_{sJ}(2317)^+$. However, the complexity of the overlapping kinematics of the $D_s(2112)^+ ! D_s^+\gamma$ and $D_{sJ}(2317)^+ ! D_s^+\gamma^0$ decays requires more detailed study, currently underway, in order to arrive at a definitive conclusion."

… from our PRL 90 (2003) 242001.



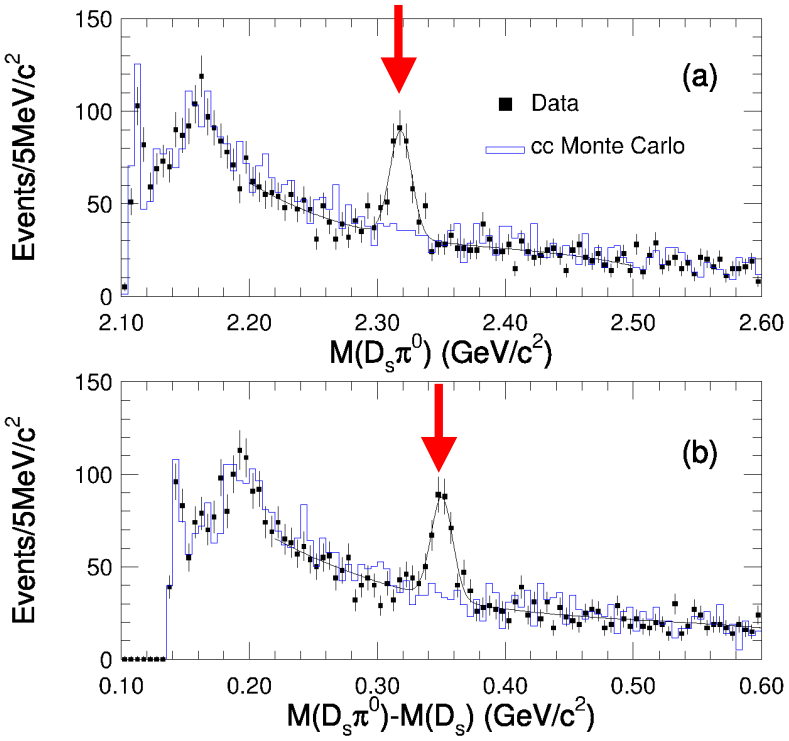
BaBaR Discovers New Narrow Resonance "$D_{sJ}(2317)$"

- Over 1500 events in the signal.
- The resonance has width comparable with the mass resolution in these systems.
- It is evident in two different topologies
  - **a) $D^+_s \to K^+K^-\pi^+$ (two modes)**
  - **b) $D^+_s \to K^+K^-\pi^+\pi^0$**
- Masses consistent in all channels – width ~ resolution.



PRL 90 (2003) 242001

CLEO Confirms the $D_s(2317)$



$m(D_s\pi^0) - m(D_s)$

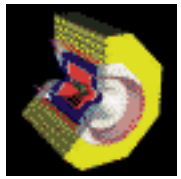
350.0 +- 1.2 (stat) +- 1.0 (syst)

(MeV/c^2)

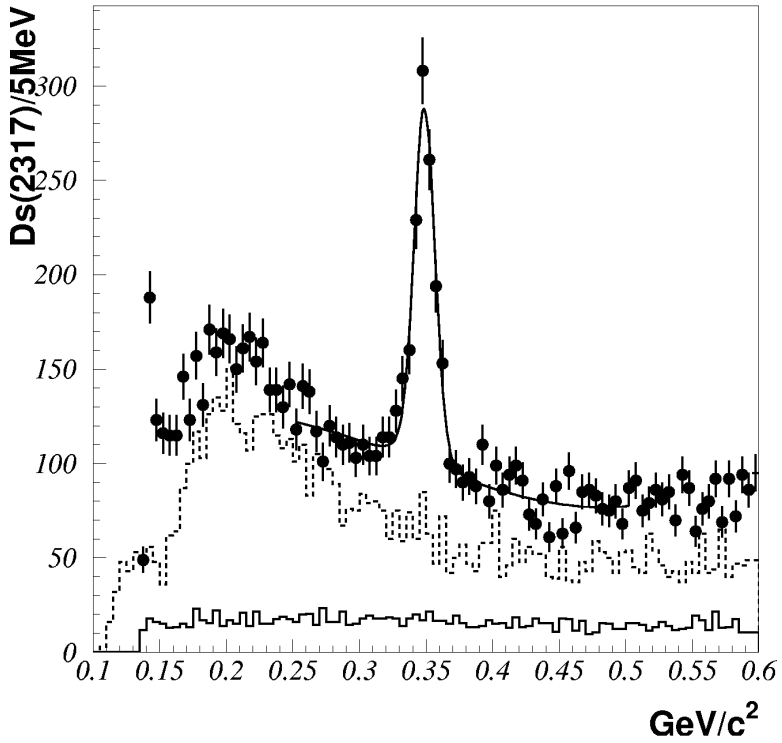
They use 13.5 fb^{-1} CLEO II

- Signal seen in $D_s\pi^0$
- Not seen in $D_s\pi^+\pi^-$, $D_s\gamma$, $D^*_{s1}(2112)\pi$

$$N = 231^{+31}_{-29}$$



So Does Belle (in continuum)



78 fb^{-1} sample

D_s -> □□, **p*** > 3.5 GeV/c

M = 2317 +- 0.5 MeV/c^2

□ = 8.1 +- 0.5 MeV/c^2

N = 770 +- 43 events

They also observe it in
B -> D D_{sJ} decays !

T. Browder, CIPANP 2003

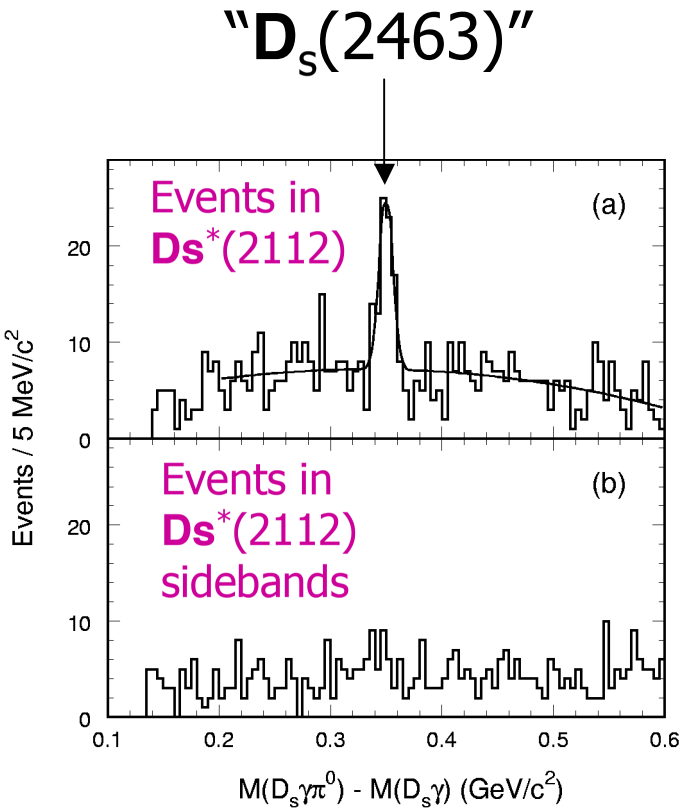
CLEO's Discovery of $D_s(2463)$ Signal

$D_{sJ}(2463) \to D_s^*(2112)\,\pi^0$

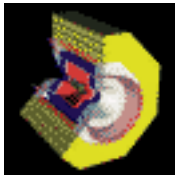
Surprise for Babar!

They used MC to estimate:

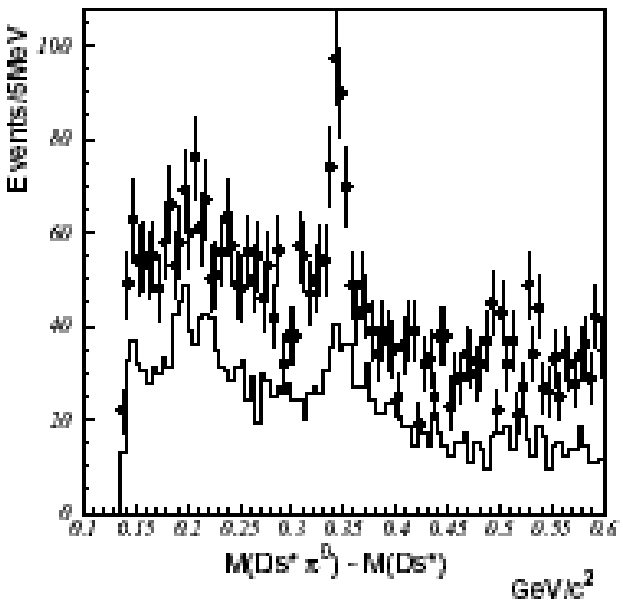
- "feed up" contribution from $D_s(2317)$ with random π^0 to be 9% of signal.
- "feed down" contribution of $D_s(2463)$ to the $D_s(2317)$ to be 84%.

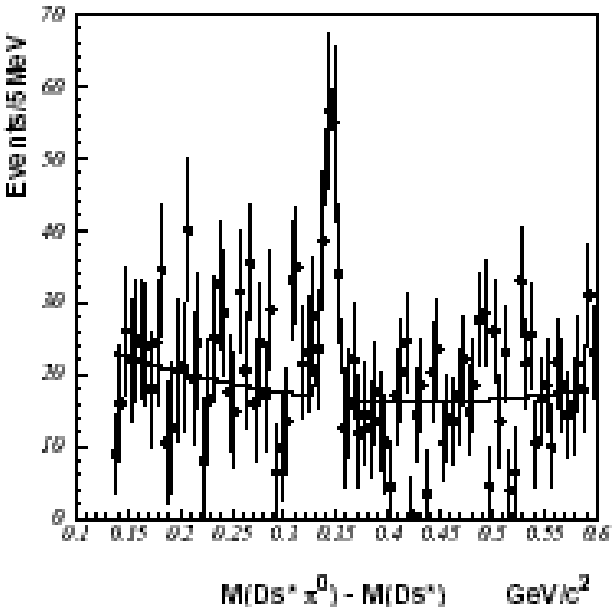


A signal of 41+- 12 events (>5σ)



Belle's Observation of the DsJ (2457) in the c $\bar{c}$ continuum





Side-band subtracted
M(Ds*□o) - M(Ds+* □o)

Signal:

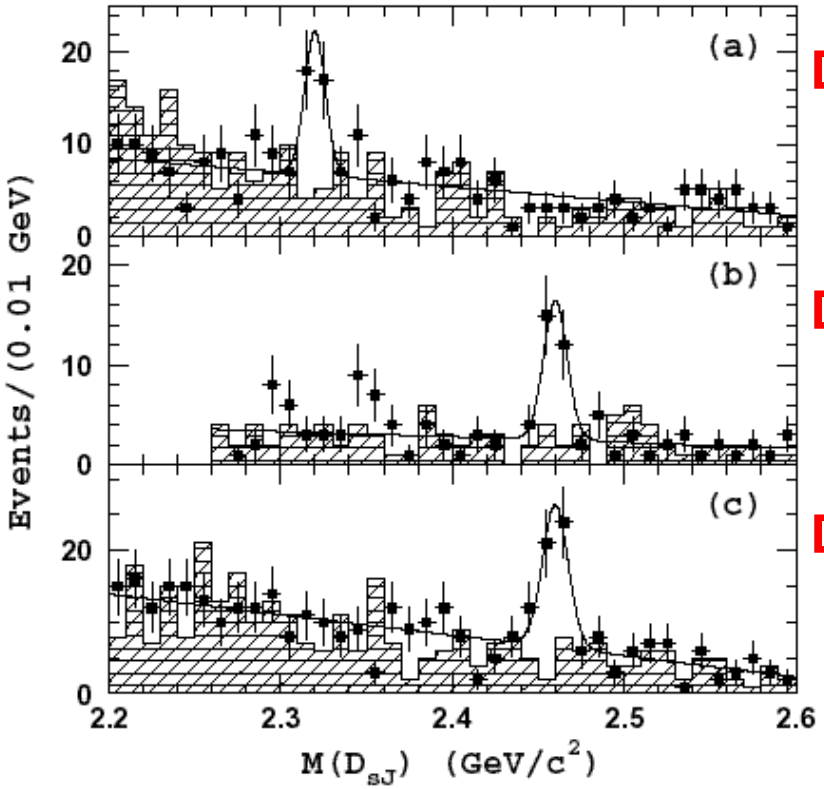
□m = 344.1+-1.3 MeV/c2

□ = 5.8+-1.3 MeV/c2

BELLE's First Observation of the B->$DD_{sJ}(2317)$ and B->$DD_{sJ}(2457)$ in B decays

hep-ex/0308019
Aug. 2003

- B->DDsj favored.
- Quantum #'s well known.



$D_{sJ}(2317)$-> $D_s\pi^0$

$D_{sJ}(2457)$->$D_s^*\pi^0$

$D_{sJ}(2457)$->$D_s\pi$!!!
(=> .not. 0^+)

Based on 123.7 x 10^6 B pairs:

D_s^+ -> $\phi\pi^+$, $K^{*0}K^+$, K^0K^+

D^0 > $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, D^+-> $K^-\pi^+\pi^+$

Production Branching Fractions for B->$DD_{sJ}(2317)$ and B->$DD_{sJ}(2457)$

BELLE COLLABORATION

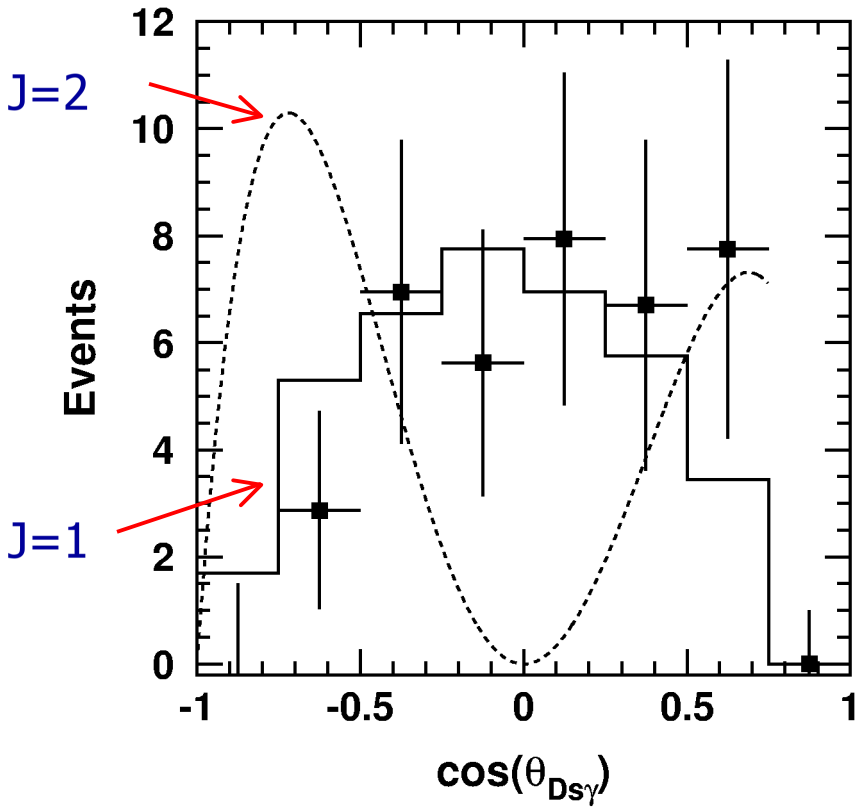
TABLE I: Product branching fractions for $B \to \bar{D} D_{sJ}$ decays.

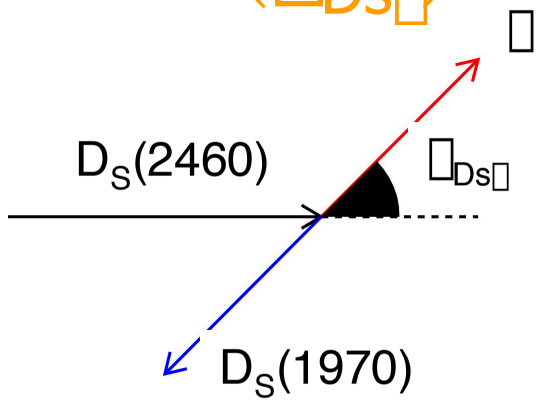
Decay channel	ΔE yield	$M(D_{sJ})$ yield	Efficiency, 10^{-4}	$\mathcal{B}$, 10^{-4}	Significance
$B^+ \to \bar{D}^0 D_{sJ}^+(2317)$ $[D_s^+\pi^0]$,	$13.7^{+5.1}_{-4.5}$	$13.4^{+6.2}_{-5.4}$	1.36	$8.1^{+3.0}_{-2.7} \pm 2.4$	5.0σ
$B^0 \to D^- D_{sJ}^+(2317)$ $[D_s^+\pi^0]$	$10.3^{+3.9}_{-3.1}$	$10.8^{+4.2}_{-3.6}$	0.97	$8.6^{+3.3}_{-2.6} \pm 2.6$	6.1σ
$B^+ \to \bar{D}^0 D_{sJ}^+(2317)$ $[D_s^{*+}\gamma]$	$3.4^{+2.8}_{-2.2}$	$2.1^{+4.1}_{-3.4}$	1.08	$2.5^{+2.1}_{-1.6} (< 7.6)$	—
$B^0 \to D^- D_{sJ}^+(2317)$ $[D_s^{*+}\gamma]$	$2.3^{+2.5}_{-1.9}$	$1.6^{+2.4}_{-1.9}$	0.69	$2.7^{+2.9}_{-2.2} (< 9.5)$	—
$B^+ \to \bar{D}^0 D_{sJ}^+(2457)$ $[D_s^{*+}\pi^0]$	$7.2^{+3.7}_{-3.0}$	$8.9^{+4.0}_{-3.3}$	0.49	$11.9^{+6.1}_{-4.9} \pm 3.6$	2.9σ
$B^0 \to D^- D_{sJ}^+(2457)$ $[D_s^{*+}\pi^0]$	$11.8^{+3.8}_{-3.2}$	$14.9^{+4.4}_{-3.9}$	0.42	$22.7^{+7.3}_{-6.2} \pm 6.8$	6.5σ
$B^+ \to \bar{D}^0 D_{sJ}^+(2457)$ $[D_s^+\gamma]$	$19.1^{+5.6}_{-5.0}$	$20.2^{+7.2}_{-6.9}$	2.75	$5.6^{+1.6}_{-1.5} \pm 1.7$	5.0σ
$B^0 \to D^- D_{sJ}^+(2457)$ $[D_s^+\gamma]$	$18.5^{+5.0}_{-4.3}$	$19.6^{+5.6}_{-4.9}$	1.83	$8.2^{+2.2}_{-1.9} \pm 2.5$	6.5σ
$B^+ \to \bar{D}^0 D_{sJ}^+(2457)$ $[D_s^{*+}\gamma]$	$4.4^{+3.8}_{-3.3}$	$8.2^{+4.0}_{-3.4}$	1.15	$3.1^{+2.7}_{-2.3} (< 9.8)$	—
$B^0 \to D^- D_{sJ}^+(2457)$ $[D_s^{*+}\gamma]$	$1.1^{+1.8}_{-1.2}$	$0.2^{+1.8}_{-1.2}$	0.71	$1.3^{+2.0}_{-1.4} (< 6.0)$	—
$B^+ \to \bar{D}^0 D_{sJ}^+(2457)$ $[D_s^+\pi^+\pi^-]$	< 4.0	$-2.2^{+2.0}_{-1.6}$	1.89	< 2.2	—
$B^0 \to D^- D_{sJ}^+(2457)$ $[D_s^+\pi^+\pi^-]$	< 2.5	$-1.2^{+2.7}_{-2.0}$	1.35	< 2.0	—
$B^+ \to \bar{D}^0 D_{sJ}^+(2457)$ $[D_s^+\pi^0]$	< 2.4	$1.0^{+2.7}_{-2.0}$	0.94	< 2.7	—
$B^0 \to D^- D_{sJ}^+(2457)$ $[D_s^+\pi^0]$	< 2.4	$0.3^{+1.8}_{-1.2}$	0.68	< 3.6	—

4 Modes of B-> $DD_{sJ}(2317)$

6 Modes of B-> $DD_{sJ}(2457)$

BELLE's Analysis of Cos(□Ds□)



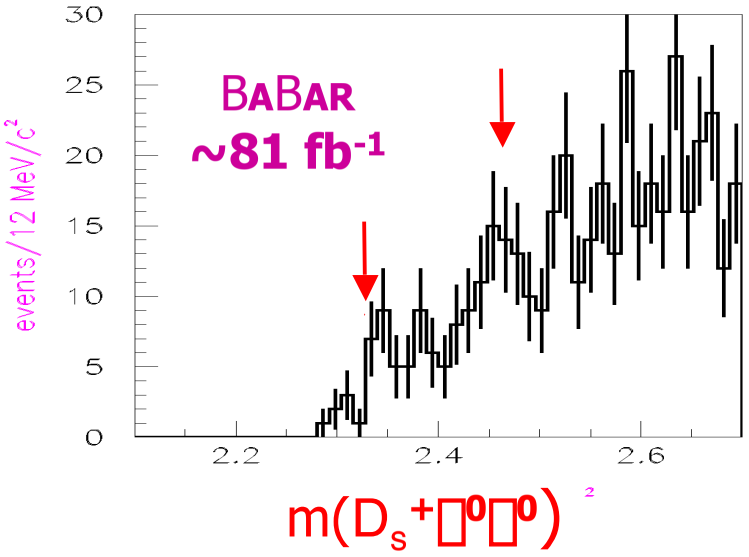


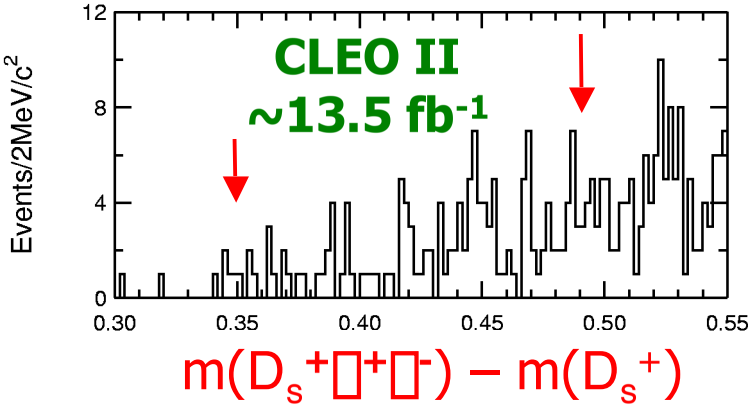
$D_{sJ}(2460)$:

→ $J^P = 1^+$ (χ^2/NDF = 5/6)

$J^P = 2^-$ (χ^2/NDF = 44/6)

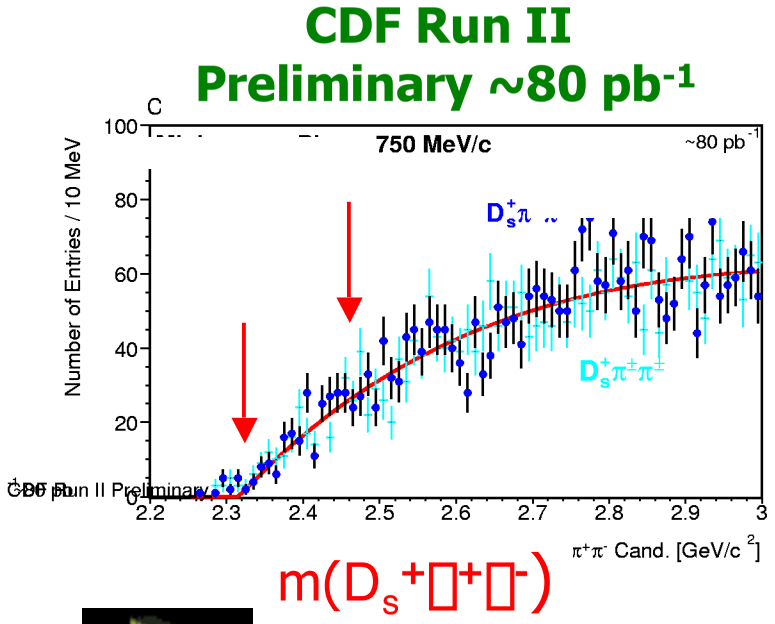
Decays to di-Pions

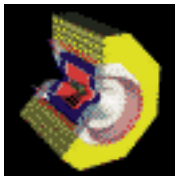


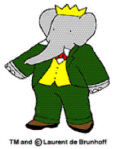


Modes conserve I-spin
But are OZI suppressed

No obvious signals (yet)



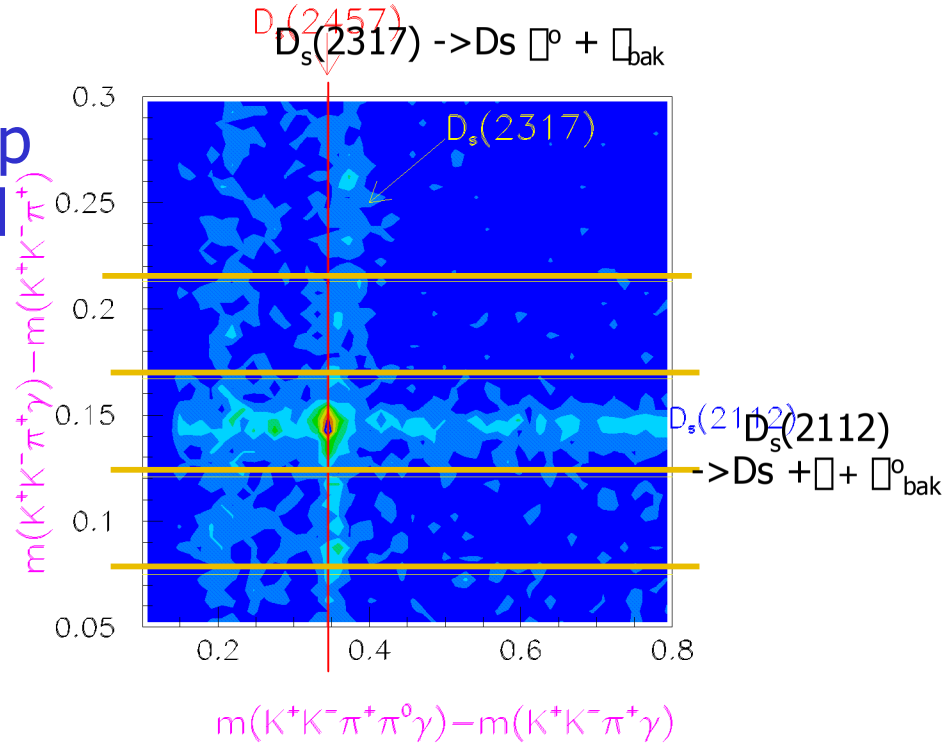




Kinematic Reflections

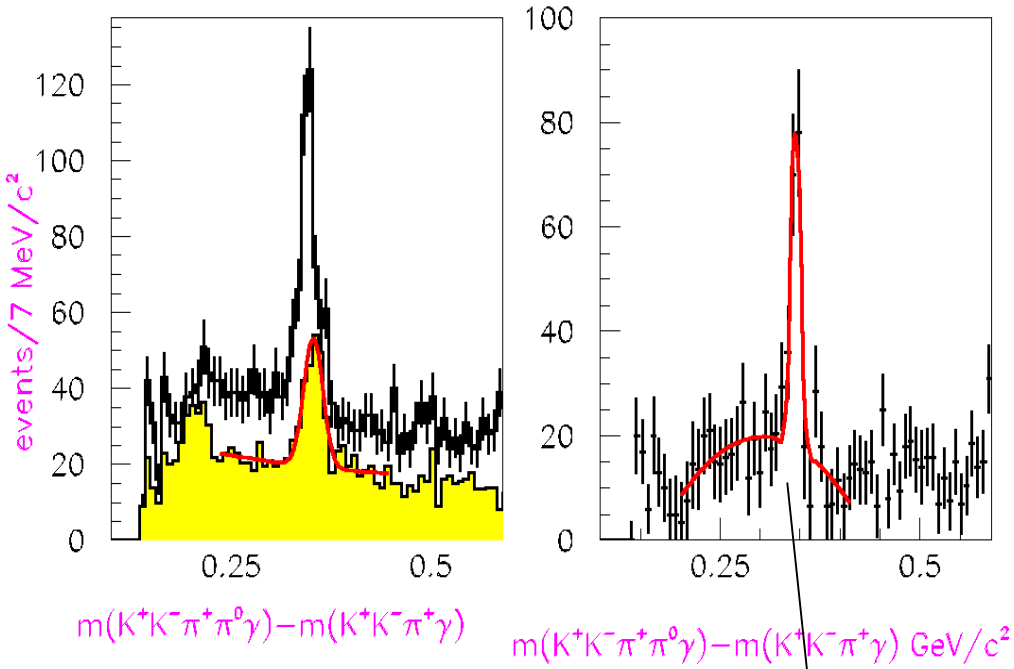
Enhancement at 2460 MeV/c^2 partly due to kinematic overlap between $\mathbf{D_{sJ}}(2317)\to\mathbf{D_s}\pi^0$ and $\mathbf{D^*}(2112)\to\mathbf{D_s}\pi$ bands.

It is important to separate such overlap from a possible signal from $\mathbf{D_s}(2460)\to\mathbf{D_s}\pi^0\pi$.



$D_s(2317)\to D_s\pi^0$ is seen as an almost vertical band.

Extract the $D_{sJ}^{+}(2458)$ Signal



Need New figures!!!

Subtract the Ds*(2112) sidebands and fit

Peaking background:

$\Delta m = 353.1 \pm 2.2$ MeV/c^2

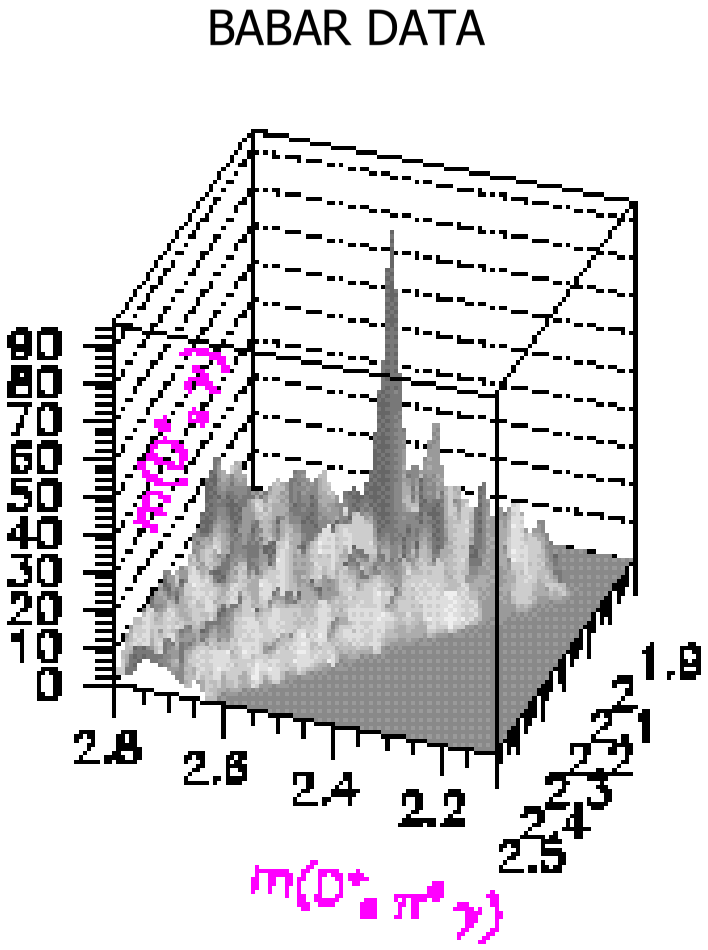
Signal:

$\Delta m = 344.6 \pm 1.2$ MeV/c^2

About 5 MeV/c^2 below CLEO

Multi-Dimensional $D_{sJ}^{+}(2458)$ Fit

- Channel Likelihood Fit *Condon and Cowl, PR D**9** 2558 (1974)
  - Signal-
    DsJ(2460) -->Ds π^0 γ
    - Ds*(2112) π^0 (interference ignored)
    - Dsj(2317) γ
  - Background-
    - Ds π^0 γ_{ran}
    - Ds* π^0_{ran}
    - Dsj(2317)γ_{ran}
    - D*s(2112) π^0_{ran}
      --> Ds γ_{ran}
- Refit of DsJ(2317)



$D_{sJ}^*(2317)^+$ $D_{sJ}^*(2458)^+$ Mass Comparison with CLEO and Belle

- $D_{sJ}^*(2317)^+$ mass: Seen $D_s^+ \pi^0$ Only : Consistent with $J^P = 0^+$
  - *BABAR* 2317.3 ± 0.4 ± 0.8 MeV/c^2 (prelim.)
  - Belle 2317.2 ± 0.5 ± 0.9 MeV/c^2 (*cc*, prelim.)
  - Belle 2319.8 ± 2.1 ± 2.0 MeV/c^2 (*B* decay)
  - CLEO 2318.5 ± 1.2 ± 1.1 MeV/c^2

- $D_{sJ}(2458)^+$ mass: Seen $D_s^+ \pi^0$ & $D_s^+ \gamma$: Consistent with $J^P = 1^+$
  - *BABAR* 2458.0 ± 1.0 ± 1.0 MeV/c^2 (prelim.)
  - Belle 2456.5 ± 1.3 ± 1.1 MeV/c^2 (*cc*, prelim.)
  - Belle 2459.2 ± 1.6 ± 2.0 MeV/c^2 (*B* decay)
  - CLEO 2463.1 ± 1.7 ± 1.2 MeV/c^2

SUMMARY

• DsJ(2317)and Dsj(2458) well established in B events and continuum.

•$J^P = O^+ 1^+$ assignments are compelling.

•Some mass refinements will come with the higher statistics samples of BaBar and BeLLe.

•BR measurements being published.

•Searches for new and rarer decays continue.