Observation of New Narrow D_s states.

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Outline.

- **Introduction.**
- **Events selection.**
- **Observation of** $D_{sJ}^{*+}(2317) \to D_s^+ \pi^0$
- **Observation of** $D_{sJ}^{+}(2457) \to D_s^{*+} \pi^0$
- **Comparison with other experiments.**
- **Theoretical work in progress.**
- **Conclusions and Outlook.**

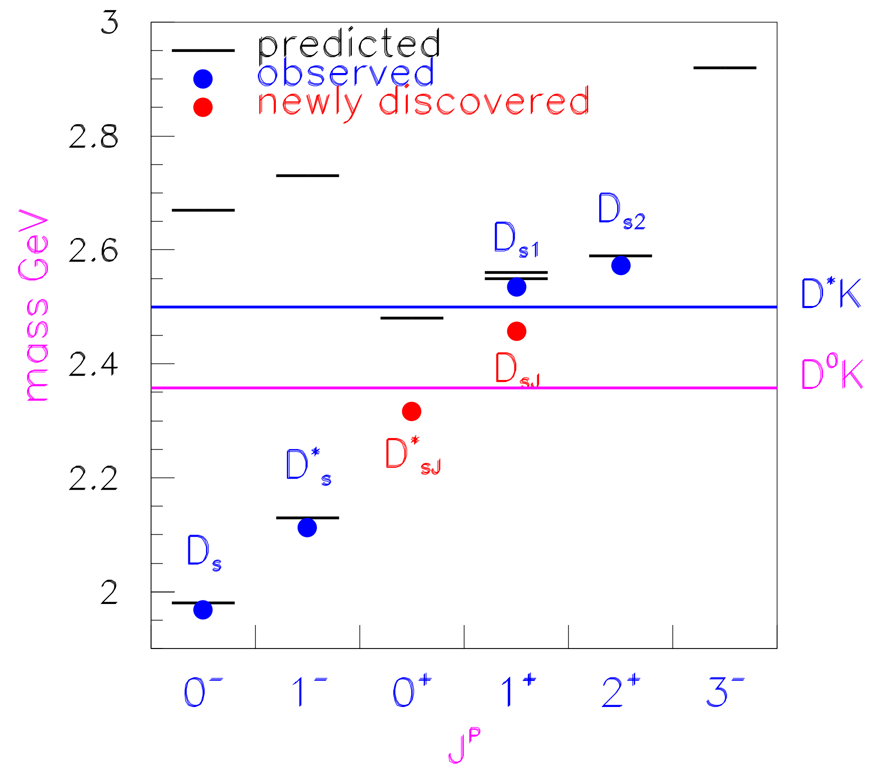
(Charge conjugation is implied through all this work.)

Introduction.

□ The expected spectrum of the $c\bar{s}$ D_s mesons still contains empty slots.

□ For example, the Godfrey-Isgur-Kokoski potential model predicts the $J^P = 0^+$ member at a mass of 2.48 GeV/c^2, with a width 270–990 MeV decaying mainly to D^0K. The large width would make it difficult to observe.

□ The model also predicts two 1^+ states at masses of 2.55 and 2.56 GeV/c^2.



□ Potential model expectations and experimental status for D_s mesons.

□ Remarkably good agreement up to now.

□ Exception: the newly discovered states at 2.317 and 2.457 GeV/c^2.

Data selection.

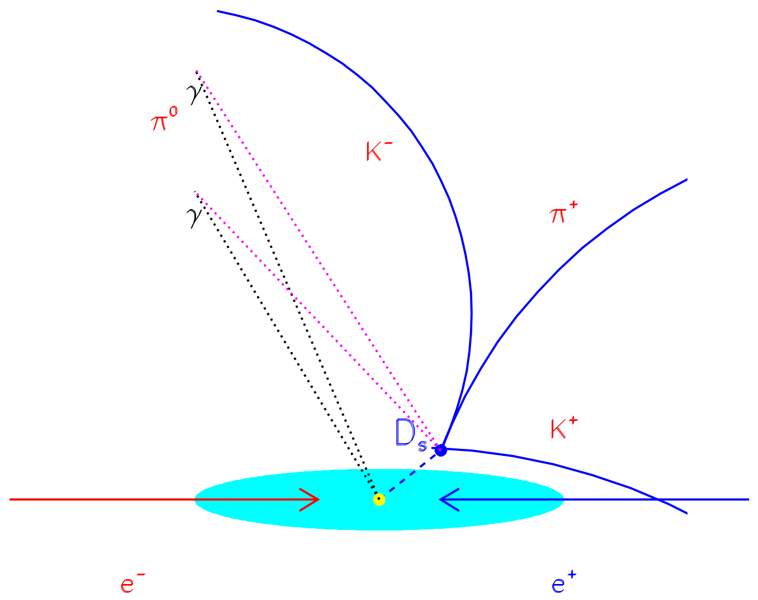
- Charm Analyses are performed on data selected from continuum $\bar{c}c$ production.

$$e^+e^- \to c\bar{c}$$

- In this work we search for resonances decaying to:

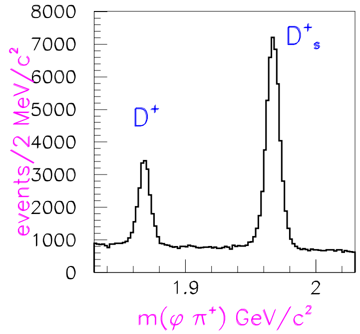
$$D_s^+\pi^0 \quad and \quad D_s^+\pi^0\gamma \qquad \to K^+K^-\pi^+\gamma\gamma(\gamma)$$

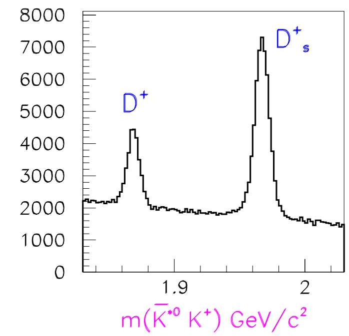
- Qualitative sketch, not to scale, of one event.
- Data sample: 91.5 fb^{-1}.



$K^+K^-\pi^+$ mass spectrum.

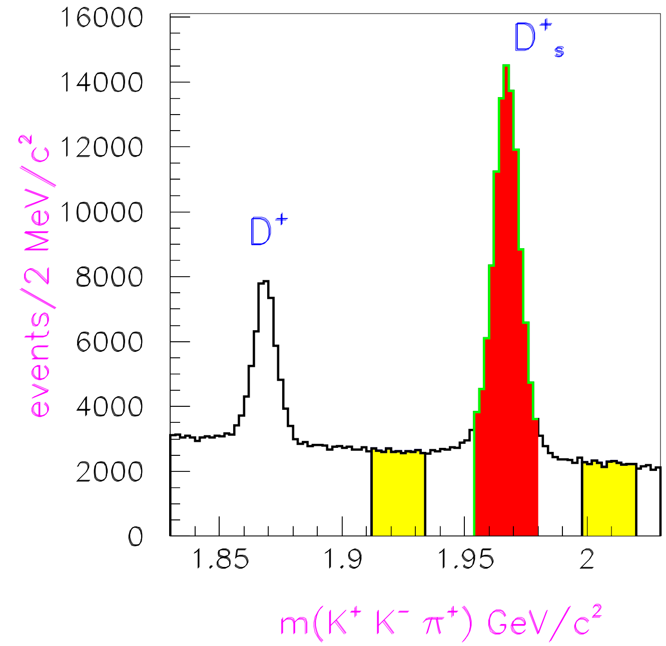
- D_s^+ mesons are selected through the $\phi\pi^+$ and $\overline{K}^{*0}K^+$ decay modes.
- Require $\mid cos\theta \mid > 0.5$ to enhance the D_s^+ signal (θ, helicity angle).
- Resulting $\phi\pi^+$ and $\overline{K}^{*0}K^+$ mass spectra:





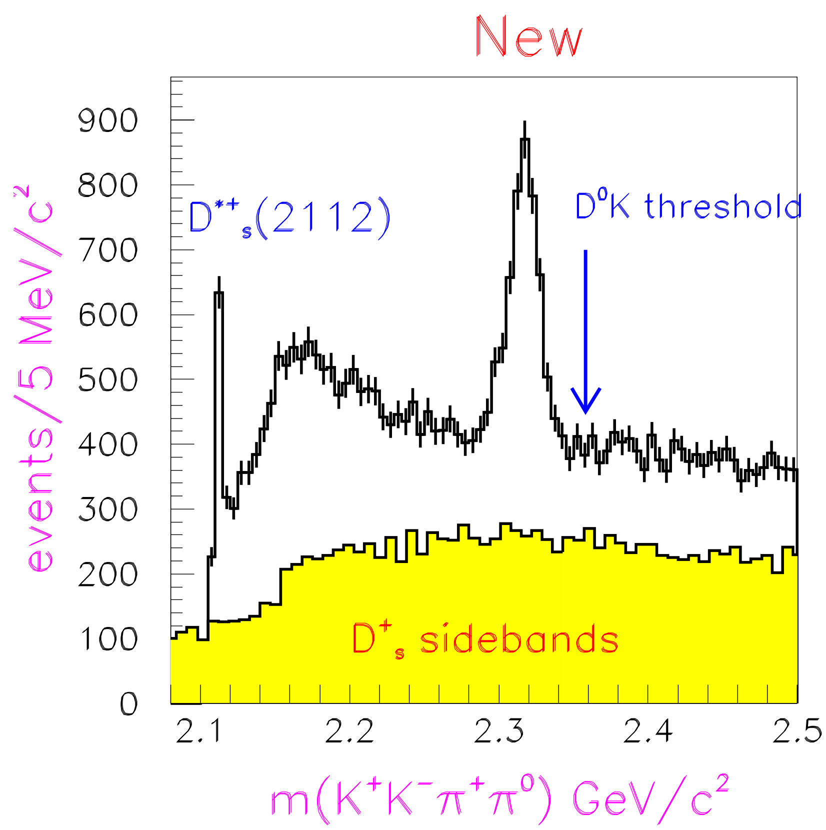
- The two samples have similar sizes.
- Sum of the $\phi\pi^+$ and $\overline{K}^{*0}K^+$ contributions

($\approx$ 80 000 D_s^+ events above background):



$D_s^+\pi^0$ mass spectrum.

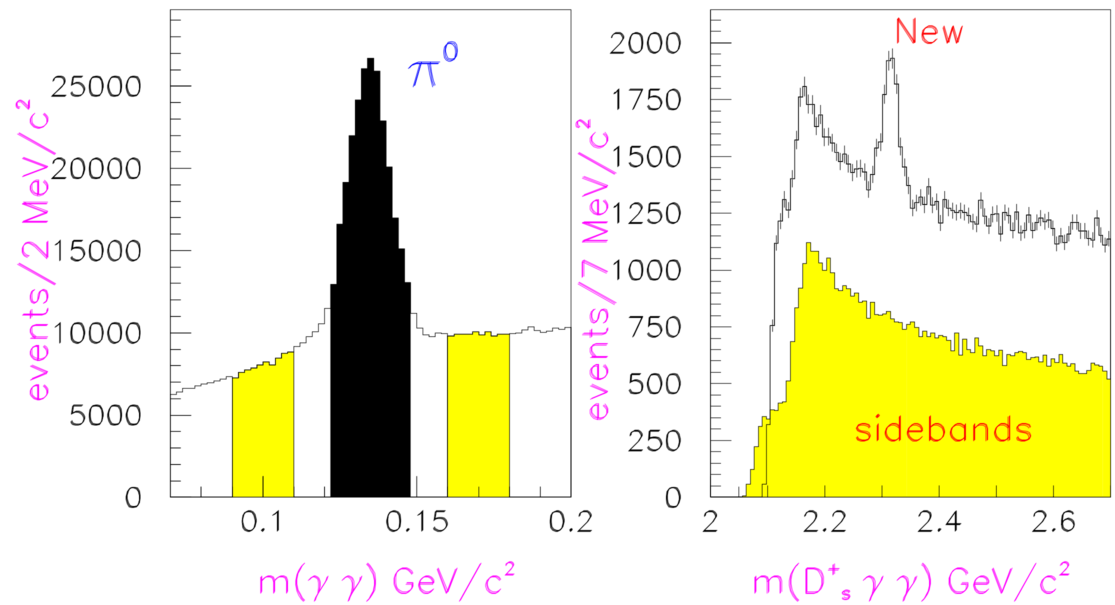
- Compare $(K^+K^-\pi^+)\pi^0$ mass spectra for the D_s^+ signal region and sidebands.
- We observe the known decay: $D_s^{*+}(2112) \to D_s^+\pi^0$.
- **Totally unexpected large signal ($\approx$ 2200 events) at 2.32 GeV/c^2.**



- No signals for the D_s^+ sidebands.

$D_s^+\gamma\gamma$ mass for π^0 signal and sidebands.

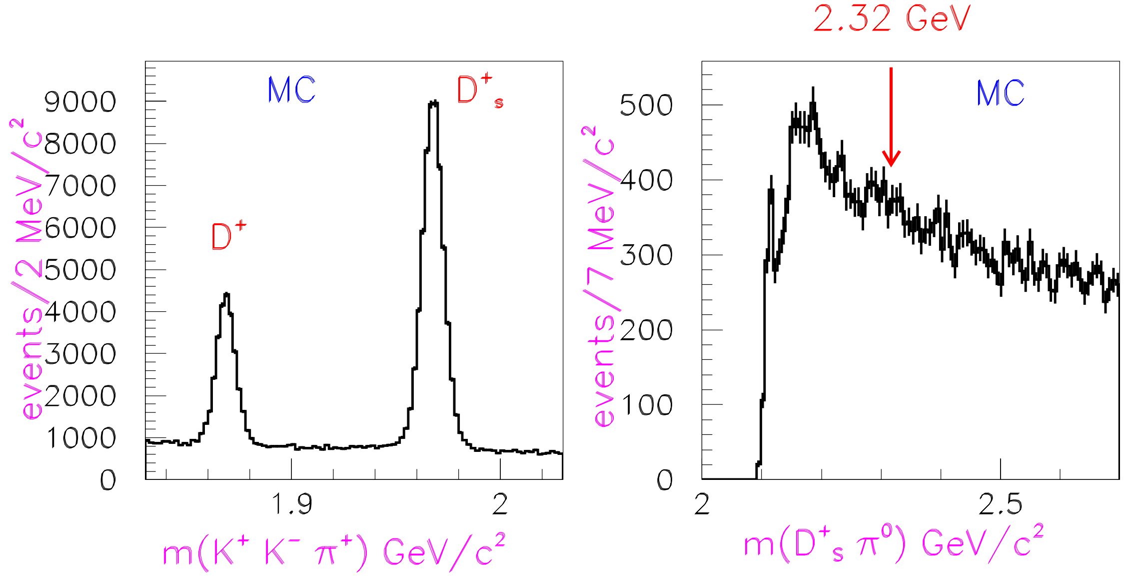
- Plot of the $\gamma\gamma$ effective mass defining π^0 signal and sideband regions.
- $D_s^+\gamma\gamma$ mass spectrum for the π^0 signal region.
- We make no use of the fitted π^0, use the 4-momentum of the γ pair.
- Same large signal at 2.32 GeV/c^2.
- $D_s^{*+}(2112)$ signal washed out because of "π^0" resolution.



- π^0 sidebands: no signals.

Test for reflections using Monte Carlo simulation.

□ Sum of $\phi\pi^+$ and $\overline{K}^{*0}K^+$ mass distributions and $D_s^+\pi^0$ mass spectrum.



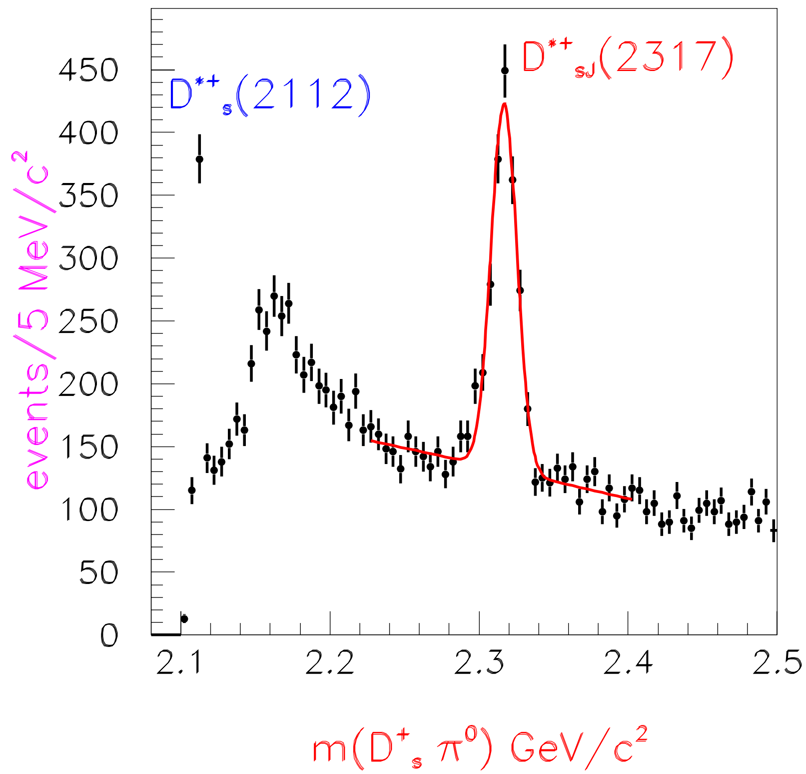
□ We observe the known decay: $D_s^{*+}(2112) \rightarrow D_s^+\pi^0$.

□ The $D_s^+\pi^0$ mass spectrum shows no significant signal in the 2.32 GeV/c^2 mass region. We would expect $\approx$ 1400 events.

□ We conclude that the 2.32 GeV/c^2 structure is not due to reflections from known states.

Fit to the $D_s^+\pi^0$ mass spectrum in the 2.32 GeV/c^2 region.

□ In order to select e^+e^- continuum events, require the $D_s^+\pi^0$ center of mass momentum $p^* > 3.5$ GeV/c.

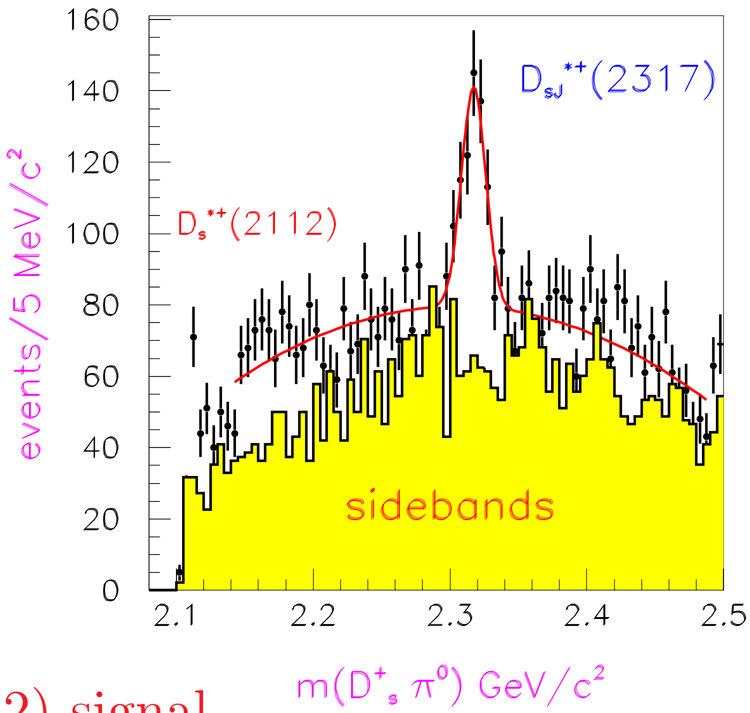


□ Fit with a polynomial and a single Gaussian (statistical errors only).

$$m = 2316.8 \pm 0.4 \text{ MeV}/c^2 \qquad \sigma = 8.6 \pm 0.4 \text{ MeV}/c^2$$

The $D_s^+\pi^0$ effective mass for $D_s^+ \to K^+K^-\pi^+\pi^0$.

- $D_s^+\pi^0$ spectrum for the D_s^+ signal region and sidebands.



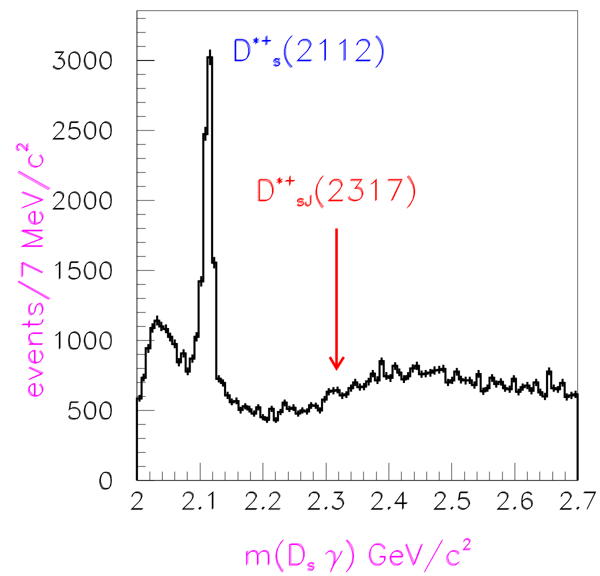
- There is a $D_s^{*+}(2112)$ signal.
- No signals for the D_s^+ sideband regions.
- There is a clear $D_{sJ}^{*+}(2317)$ signal with the following parameters:

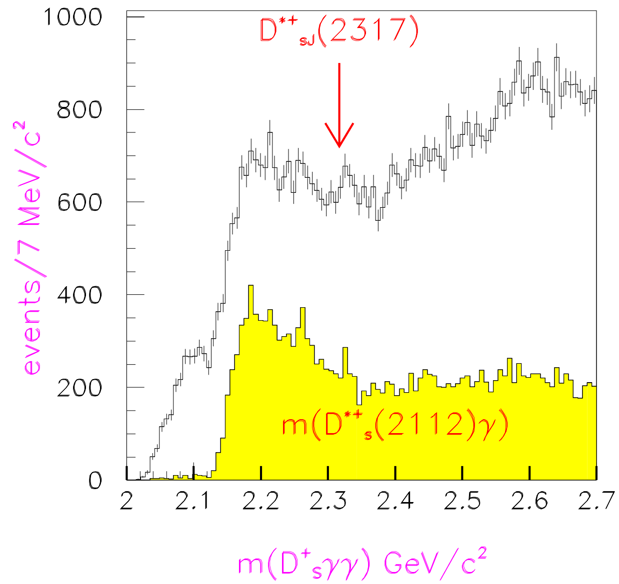
$$m = 2317.6 \pm 1.3 \ \text{MeV}/c^2 \qquad \sigma = 8.8 \pm 1.1 \ \text{MeV}/c^2$$

- Consistent with the values obtained using the $D_s^+ \to K^+K^-\pi^+$ decay mode.

Search for other $D_{sJ}^{*+}(2317)$ decay modes.

- ☐ Require that the γ is not part of any π^0 candidate.
- ☐ Require $p^*_{D_s\gamma} > 3.5$ and $p^*_{D_s\gamma\gamma} > 3.5$ GeV/c respectively.

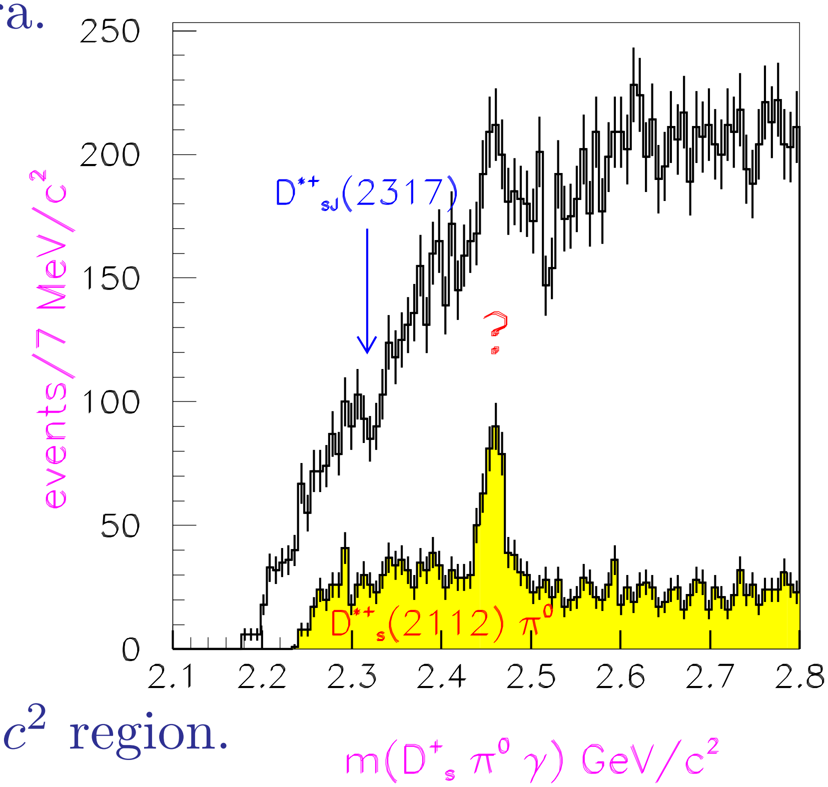




- ☐ At the present level of statistics.
  - No significant $D_{sJ}^{*+}(2317)$ signal in the $D_s^+\gamma$ mass spectrum.
  - No significant $D_{sJ}^{*+}(2317) \rightarrow D_s^+\gamma\gamma$ decay.
  - No significant $D_{sJ}^{*+}(2317) \rightarrow D_s^{*+}(2112)\gamma$ decay.

Search for $D_{sJ}^{*+}(2317)$ decay to $D_s^+\pi^0\gamma$.

- Require $p^*_{D_s\pi^0\gamma} > 3.5$ GeV/c.
- Require the π^0 lab. momentum > 300 MeV/c.
- Neither γ from a π^0 can be part of any other π^0.
- The bachelor γ cannot belong to any π^0 candidate.
- $D_s^+\pi^0\gamma$ and $D_s^{*+}(2112)\pi^0$ mass spectra.



- No significant signal in the 2.32 GeV/c^2 region.
- Possible structure at ≈ 2.46 GeV/c^2.

Could the $D_{sJ}^{*+}(2317)$ signal be due to the decay of a narrow state at 2.46 GeV/c^2 in $D_s^+\pi^0\gamma$?

□ If we assume the existence of a narrow state, the $X^+(2460)$ which decays to $D_s^{*+}(2112)\pi^0$, the kinematic cross-over would result in a narrow signal in $m(D_s^+\pi^0)$ near 2.32 GeV/c^2.

□ Two ways to test this hypothesis:

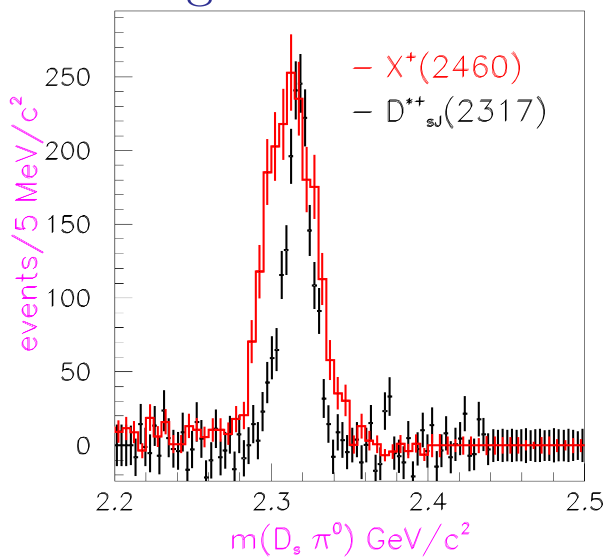
- The $D_{sJ}^{*+}(2317)$ lineshape.
- Comparison of the $D_{sJ}^{*+}(2317)/X^+(2460)$ relative rates for data and $X^+(2460)$ Monte Carlo simulation.

The $D_{sJ}^{*+}(2317)$ lineshape.

□ Use of Monte Carlo simulation of:

$$e^+e^- \to X^+(2460) \qquad\qquad + X_{recoil}$$
$$\qquad\to D_s^{*+}(2112)\pi^0$$

□ Comparison between the $X^+(2460)$ reflection from Monte Carlo and the $D_{sJ}^{*+}(2317)$ data signal after background subtraction.



□ Conclusion: the $D_{sJ}^{*+}(2317)$ lineshape does not agree with that expected from $X^+(2460)$ reflection.

$D_{sJ}^{*+}(2317)/X^+(2460)$ **ratio.**

□ The second test is to compute the ratio $D_{sJ}^{*+}(2317)/X^+(2460)$ for data and Monte Carlo for $X^+(2460) \to D_s^{*+}(2112)\pi^0$ with no $D_{sJ}^{*+}(2317)$ generated.

□ For $p^* > 3.0$ GeV/c:

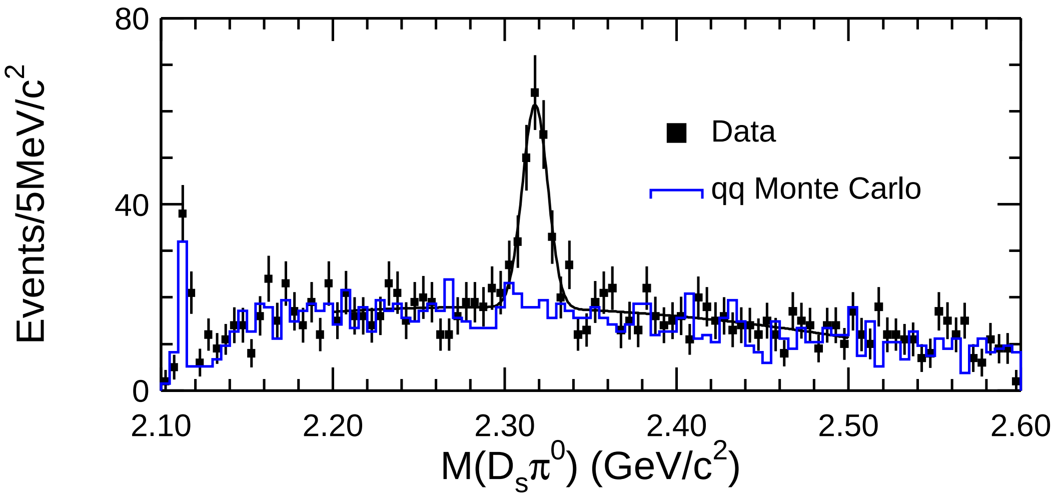
$$\frac{N(D_{sJ}^{*+}(2317))/N(X^+(2460))(Data)}{N(D_{sJ}^{*+}(2317))/N(X^+(2460))(MC)} = 5.4 \pm 0.3$$

□ In the data we find ≈ 5 times more $D_{sJ}^{*+}(2317)$ events than expected from a Monte Carlo simulation with only $X^+(2460)$ production.

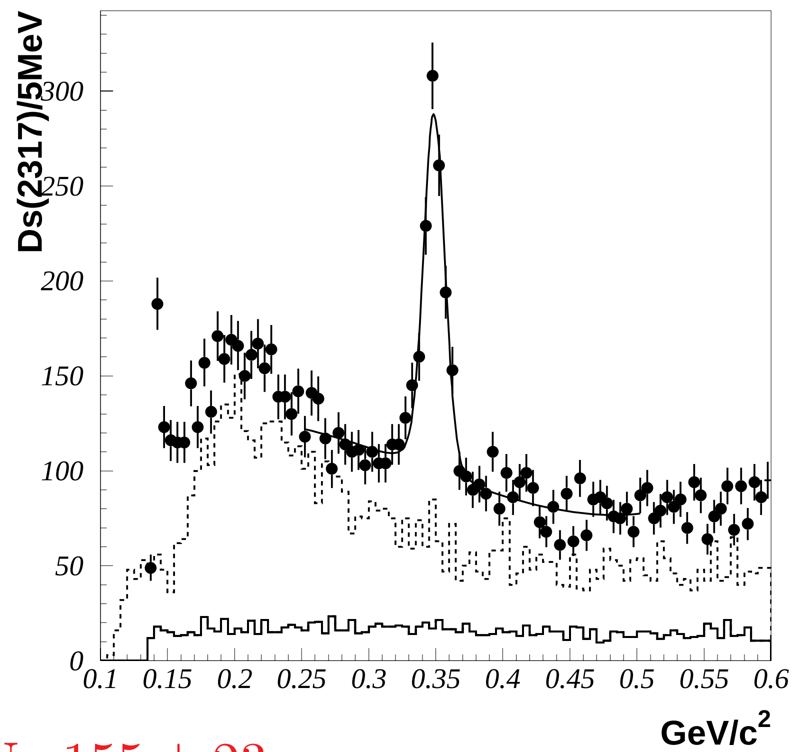
□ Conclusion: the relative rates disagree with the hypothesis that the $D_{sJ}^{*+}(2317)$ signal is due entirely to production of a state at ≈ 2.46 GeV/c^2 which decays to $D_s^{*+}(2112)\pi^0$.

Confirmation of $D_{sJ}^{+}(2317)$ by other experiments.

CLEO 13.5 fb^{-1}



BELLE Preliminary 78 fb^{-1}



□ Confirmation by CLEO:

$\Delta m = 350.0 \pm 1.2\,(\text{stat}) \pm 1.0\,(\text{syst})\ \text{MeV}/c^2$, N=155 $\pm$ 23 hep-ex/0305017

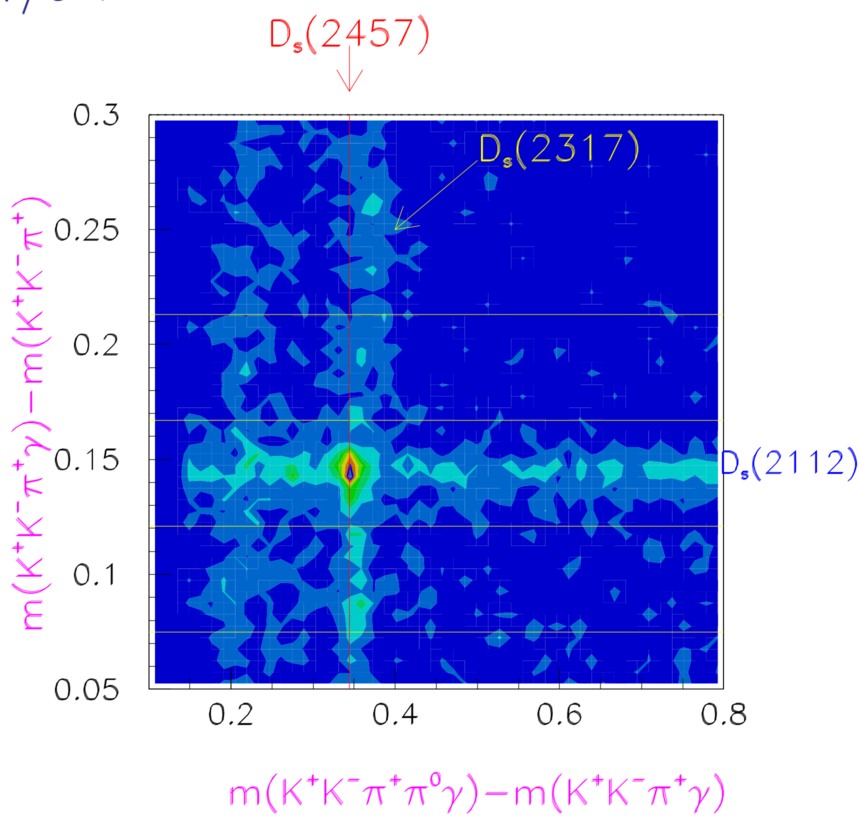
□ Confirmation by BELLE: $\Delta m = 348.9 \pm 0.5\,(\text{stat})\ \text{MeV}/c^2,\ N = 643 \pm 50$

□ In good agreement with BaBar (91.5 fb^{-1}):

$\Delta m = 348.4 \pm 0.4\,(\text{stat})\ \text{MeV}/c^2,\ N = 1948 \pm 104$.

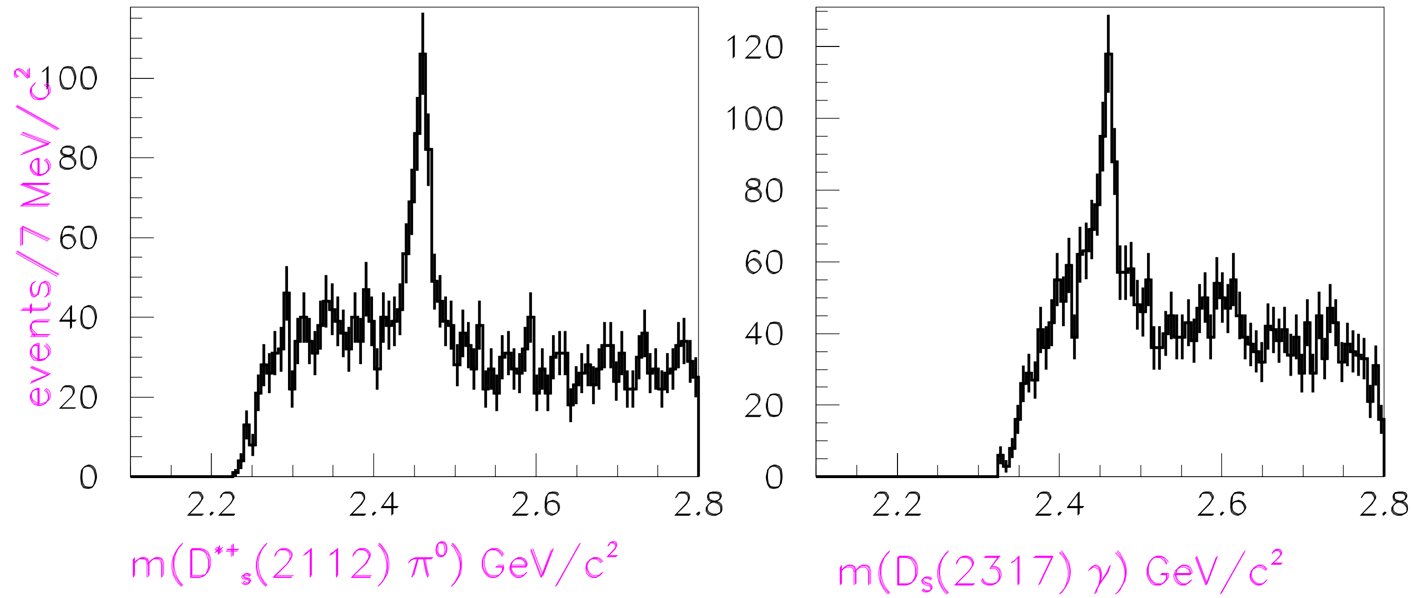
The 2.46 GeV/c^2 region of $m(D_s^+\pi^0\gamma)$: a new particle or an artifact of kinematics?

□ In an inclusive environment, the scatter diagrams of $\Delta m(D_s^+\gamma)$ vs $\Delta m(D_s^*\pi^0)$ exhibit bands due to $D_s^{*+}(2112)$ and $D_{sJ}^{*+}(2317)$ which cross near $m(D_s^+\pi^0\gamma)$= 2.46 GeV/c^2.



Mass distributions.

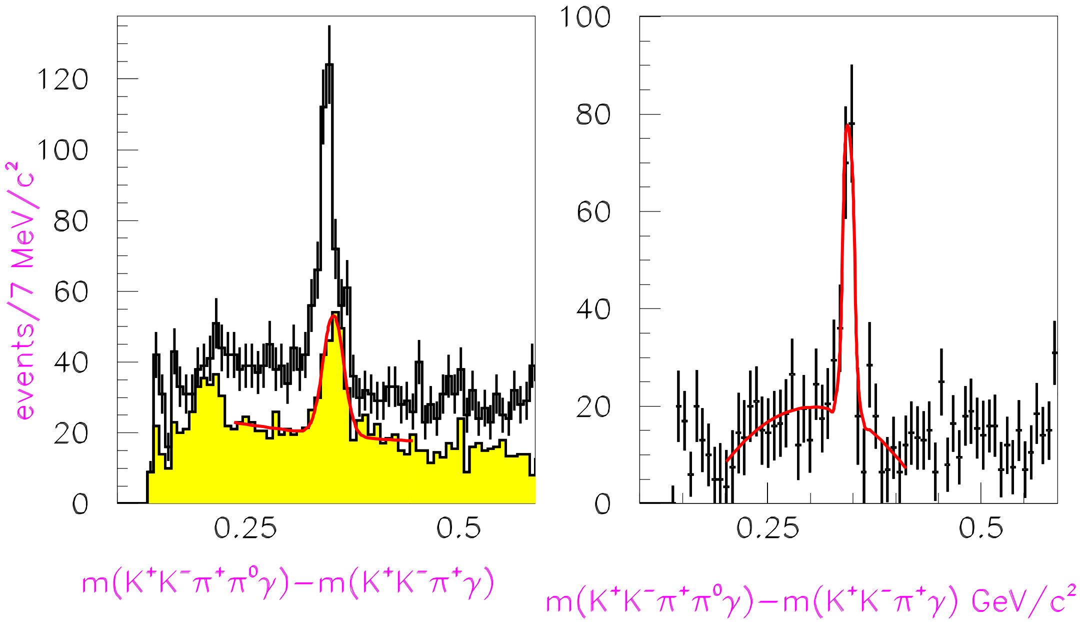
□ $D_s^{*+}(2112)\pi^0$ and $D_{sJ}^{*+}(2317)\gamma$ mass distributions.



□ Structures at ≈ 2.46 GeV/c^2 in both $D_s^{*+}(2112)\pi^0$ and $D_{sJ}^{*+}(2317)\gamma$. At this level, not possible to separate them.

Extraction of the $D_{sJ}^{+}(2457)$ signal.

- Subtract directly the sidebands in the Δm scatterplot (slide 17):



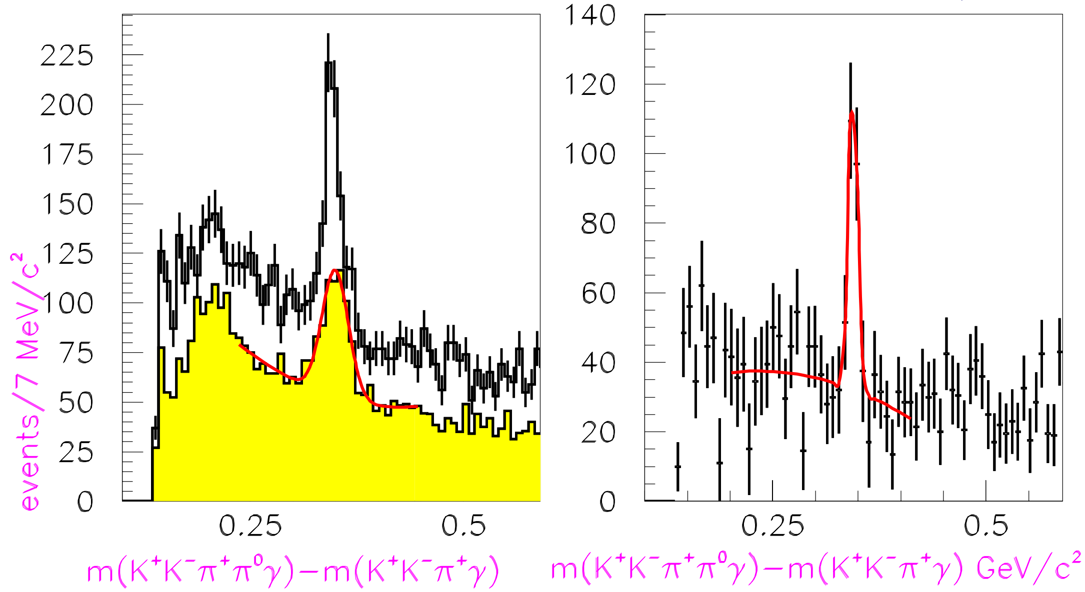
- Fitted parameters (preliminary, statistical errors only):

$$\Delta m(D_s^{*+}(2112)\pi^0) = 344.6 \pm 1.2 \qquad \sigma = 5.5 \pm 1.4 \ \mathrm{MeV/c^2}$$

- Events: $N = 140 \pm 22$
- Peaking background at $\Delta m = 353.1 \pm 2.2$ MeV/c^2 (≈ 50 % of the signal.)

Extraction of the $D_{sJ}^+(2457)$ signal.

☐ Relaxing the condition of γ's not shared within π^0's (like CLEO analysis):



☐ Signal parameters:

$$\Delta m = 344.2 \pm 0.9 \ \text{MeV}/c^2 \qquad \sigma = 5.3 \pm 1.2 \ \text{MeV}$$

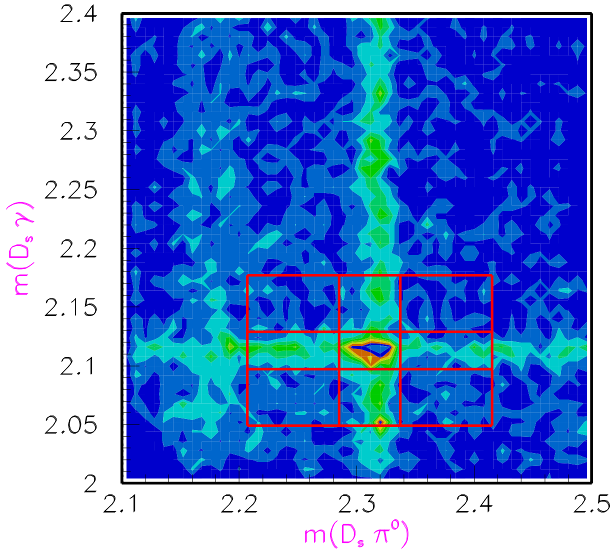
☐ Peaking background parameters:

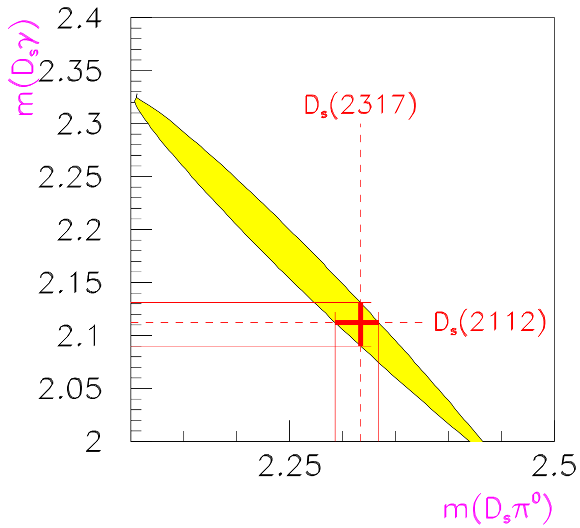
$$\Delta m = 349.4 \pm 1.7 \ \text{MeV}/c^2$$

☐ ≈ 69 % of the signal is due to peaking background.

The method of the 9 tiles.

□ Consider the $m(D_s^+\gamma)$ vs. $m(D_s^+\pi^0)$ scatter diagram:





□ Subtracting the adjacent tiles, the $D_{sJ}^+(2457)$ "Dalitz plot" projections on the two axes can be extracted.

□ Predicted events from sidebands (assuming linear behavior): $N_p = 312 \pm 12$

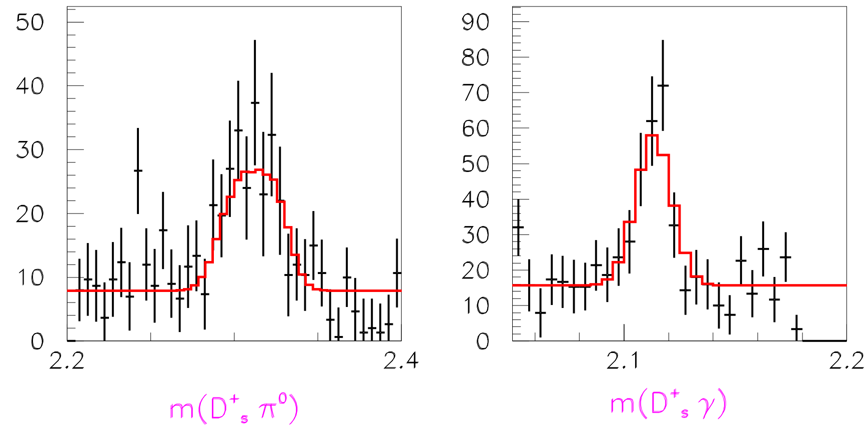
□ Observed events: $N_o = 472$

□ Excess: $N_e = 160 \pm 25$. A better than 6σ effect.

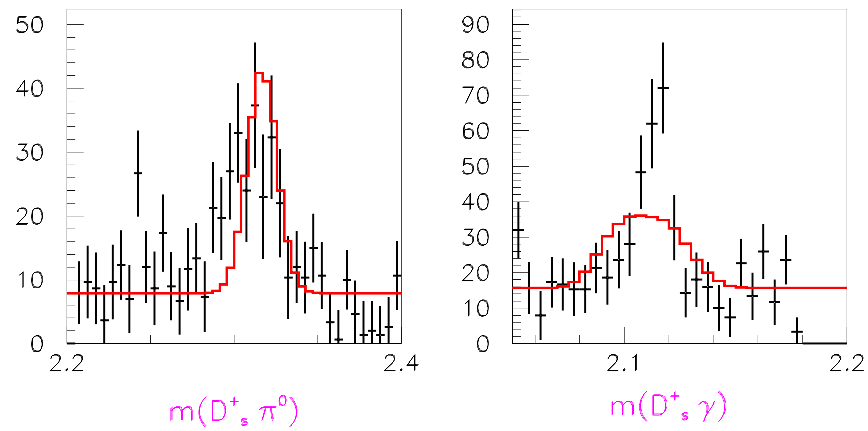
$D^+_{sJ}(2457)$ **projections.**

□ $D^+_{sJ}(2457)$ projections compared with Monte Carlo simulations for:

$$D^+_{sJ}(2457) \rightarrow D^{*+}_s(2112)\pi^0$$



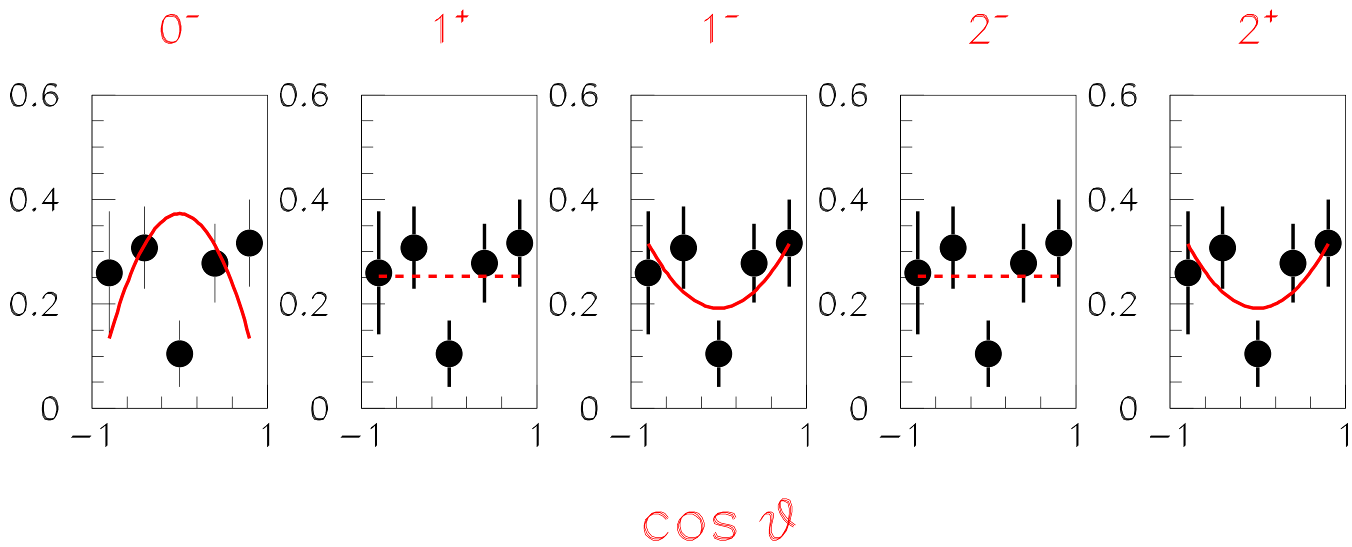
$$D^+_{sJ}(2457) \rightarrow D^{*+}_{sJ}(2317)\gamma$$



□ $D^+_{sJ}(2457) \rightarrow D^{*+}_s(2112)\pi^0$ decay clearly favoured.

Angular analysis.

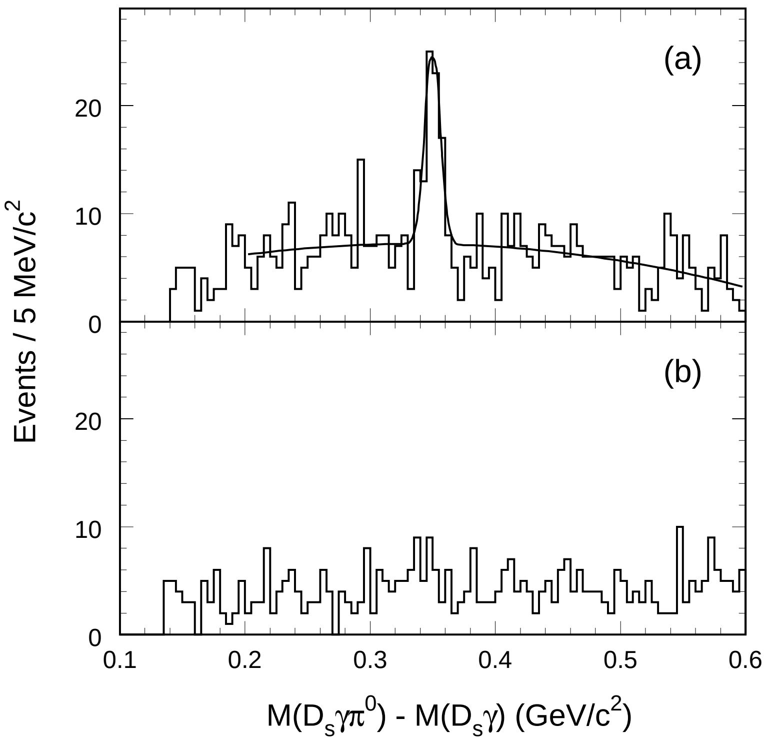
□ Distribution of the helicity angle θ of the γ with respect to the $D_s^{*+}(2112)$ direction in the $D_{sJ}^+(2457)$ rest frame (preliminary).



□ Inconsistent with $J^P = 0^-$.

$D_{sJ}^{+}(2457)$: results from other experiments.

CLEO 13.5 fb^{-1}

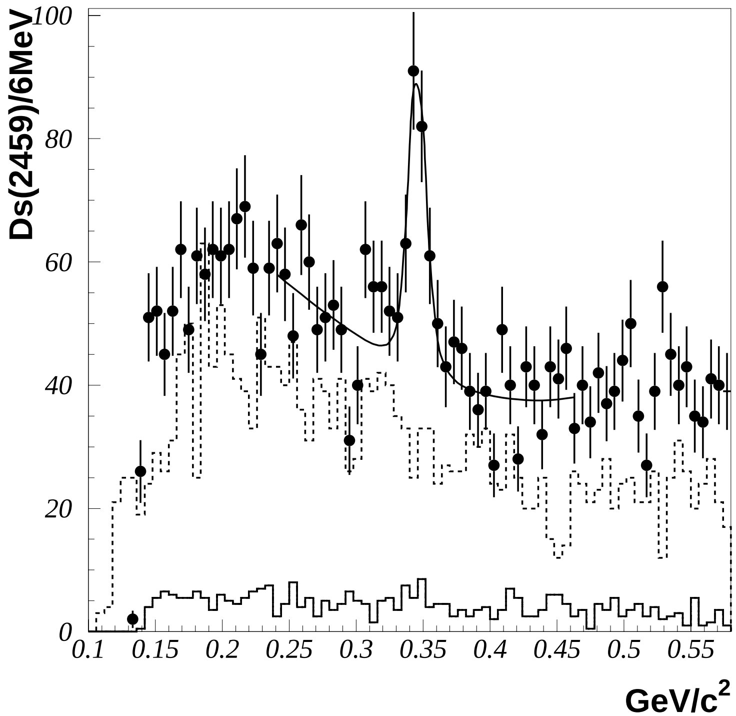


$\Delta m = 351.0 \pm 1.7 \pm 1.0$ MeV$/c^2$

$N = 41 \pm 12$

No peaking background

BELLE preliminary 78 fb^{-1}



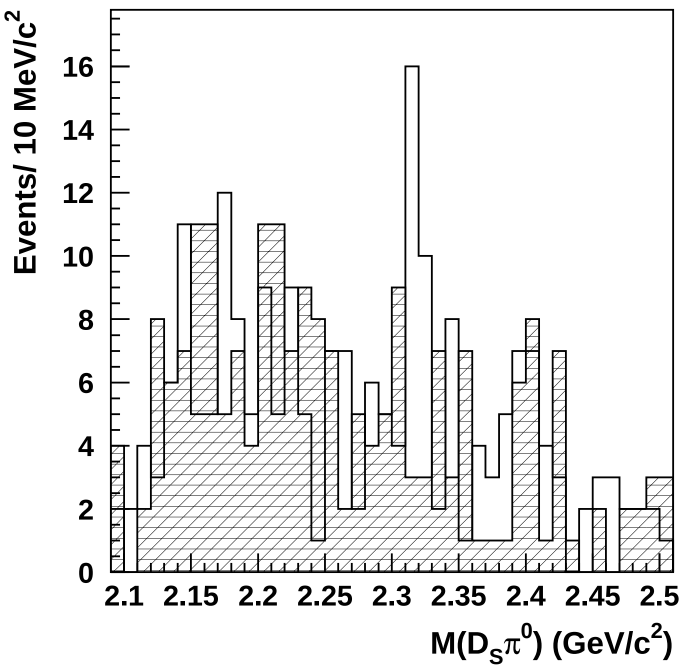
$\Delta m = 345.4 \pm 1.3$ MeV$/c^2$

$N = 79 \pm 18$

B decays from BELLE.

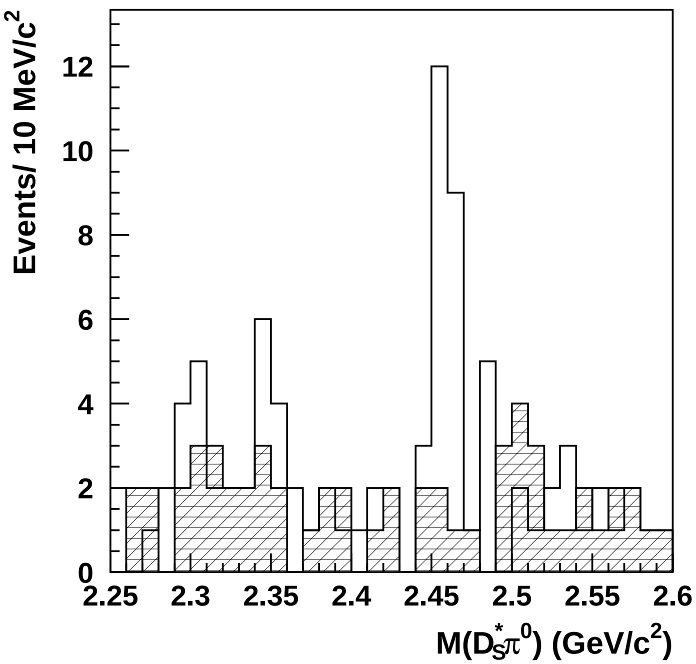
□ Evidence for:

$B \to D D_{sJ}^{*+}(2317)$



$m = 2318 \pm 4 \ \ \text{MeV}/c^2$
$N = 18.6^{+5.4}_{-4.8}$

$B \to D D_{sJ}^{+}(2457)$

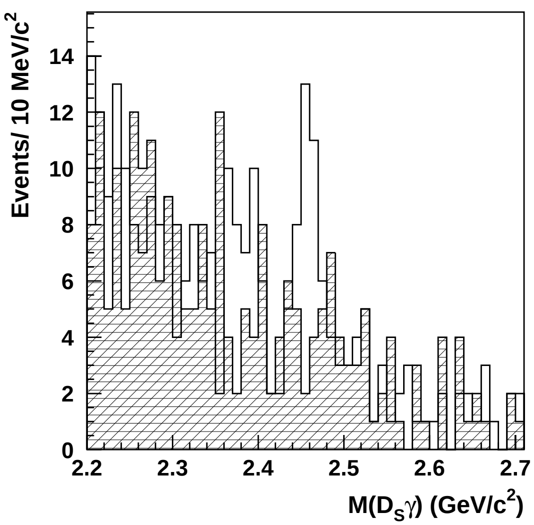


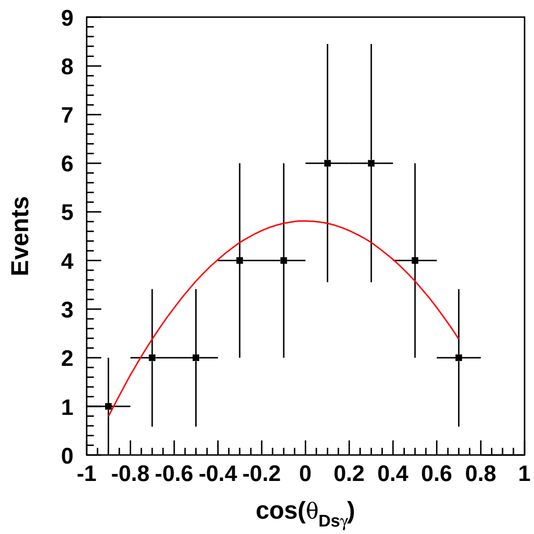
$m = 2460 \pm 3 \ \ \text{MeV}/c^2$
$N = 16.7^{+7.0}_{-6.0}$

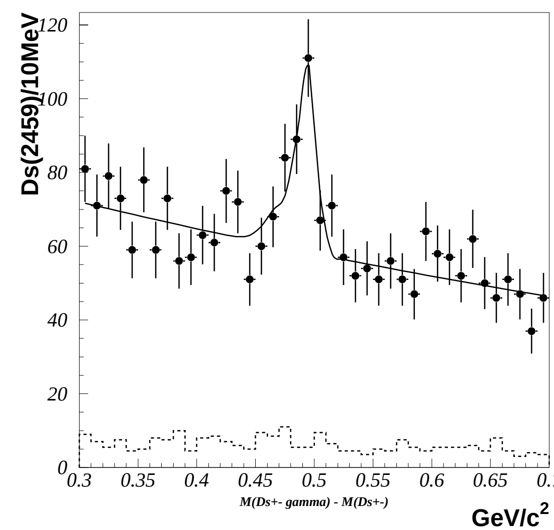
$D_{sJ}^{+}(2457) \to D_s^{+}\gamma$ from BELLE.

□ From both B decays and continuum (preliminary):

$B \to D D_{sJ}^{+}(2457)$ $c\bar{c} \to D_{sJ}^{+}(2457)\ X$







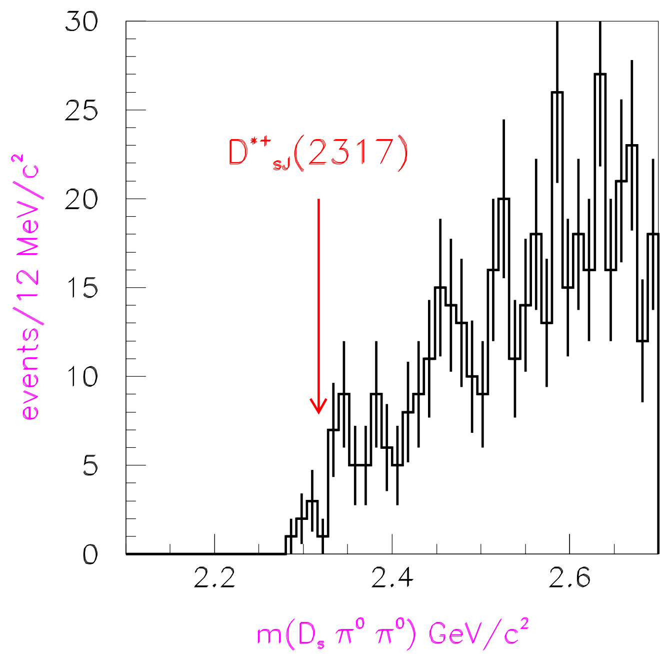
$m = 2460 \pm 2\ \mathrm{MeV}/c^2$ Consistent with $J = 1$ $N = 128 \pm 20$

$N = 21.8^{+5.8}_{-5.1}$

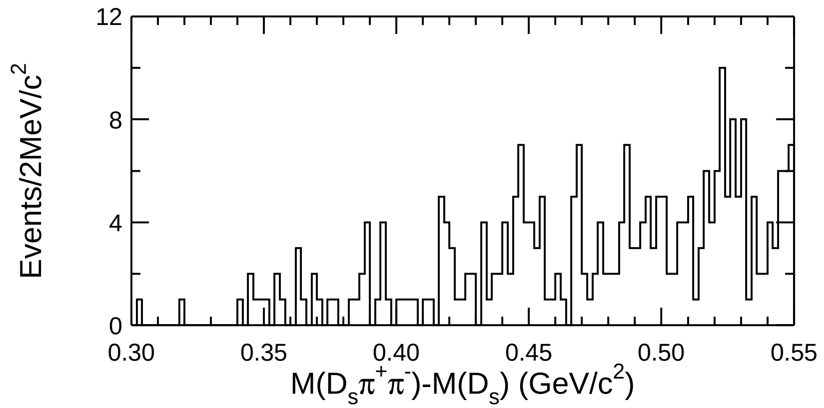
□ Evidence for $D_{sJ}^{+}(2457) \to D_s^{+}\gamma$: $J = 0$ excluded.

Search for structure in $D_s^+\pi\pi$.

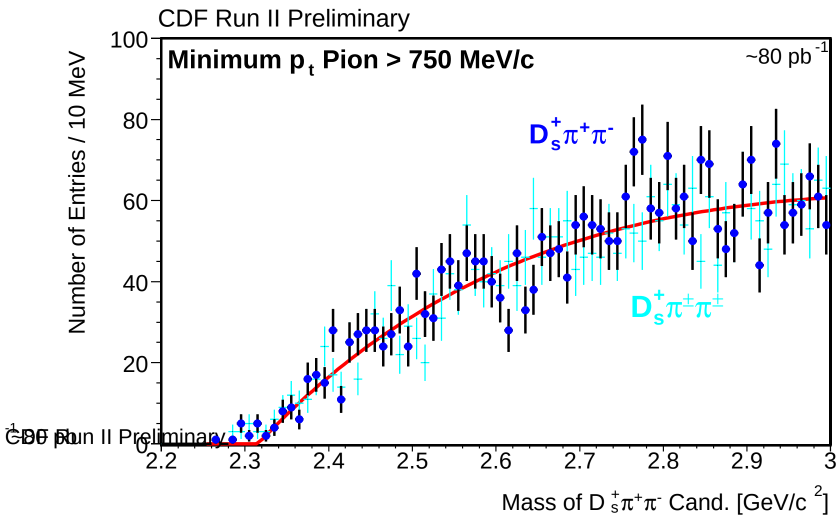
BABAR $D^0\pi^0\pi^0$



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



CDF II $D^0\pi^+\pi^-$



- No structures seen in $D_s^+\pi\pi$.

Experimental Summary ($D_{sJ}^{*+}(2317)$).

□ A large ($\approx$ 2200 events), narrow signal has been discovered by BaBar experiment in the inclusively-produced $D_s^+\pi^0$ mass distribution for the D_s^+ decay modes:

$$D_s^+ \to K^+K^-\pi^+, \qquad D_s^+ \to K^+K^-\pi^+\pi^0$$

□ The fitted mass value is:

$$m = 2316.8 \pm 0.4 \ \mathrm{MeV/c^2} \qquad (\textit{statistical error only})$$

□ The measured width is consistent with the experimental resolution, which implies a small intrinsic width ($\Gamma < 10$ MeV).

□ The structure is not observed in the $D_s^+\gamma$, $D_s^+\gamma\gamma$, $D_s^{*+}(2112)\gamma$, $D_s^+\pi^0\pi^0$, $D_s^+\pi^+\pi^-$ nor $D_s^+\pi^0\gamma$ mass distributions.

□ The quantum numbers are consistent with being $J^P = 0^+$, but other natural spin-parity assignments cannot be excluded.

□ This observation has been confirmed by CLEO in continuum and by BELLE in both continuum and B decays.

Experimental Summary ($D_{sJ}^+(2457)$).

□ BaBar has first shown evidence of structure in the $D_s^+\pi^0\gamma$ mass distribution at ≈ 2.46 GeV/c^2. "However, the complexity of the overlapping kinematics of the $D_s^{*+}(2112) \to D_s^+\gamma$ and $D_{sJ}^{*+}(2317) \to D_s^+\pi^0$ requires more detailed study ... in order to arrive at a definitive conclusion." Phys.Rev.Lett. 90 (2003) 242001

□ CLEO experiment observes $D_s^+(2463)$ state (hep-ex/0305100)

□ Confirmed by Belle, including $D_s^+\gamma$ decay mode

□ The preliminary analysis reported here by the BaBar experiment reports the observation of a state at 2.457 GeV/c^2 decaying to $D_s^{*+}(2112)\pi^0$. The parameters of this state are the following (statistical errors only):

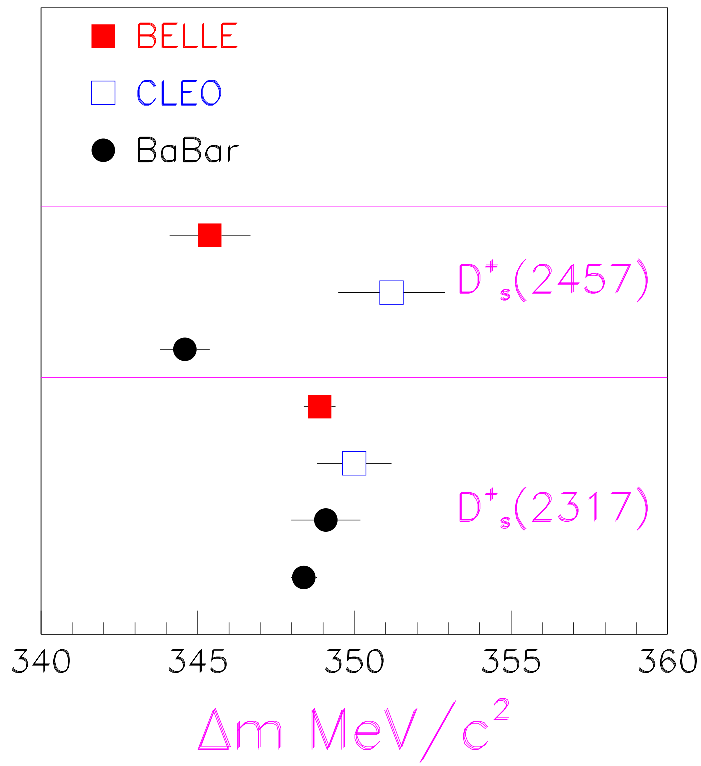
$$\Delta m = 344.6 \pm 0.8, \qquad \sigma = 7.0 \pm 1.5 \ \text{MeV/c}^2$$

$$m(D_{sJ}^+(2457)) = 2.457 \pm 0.001 \ \text{GeV}/c^2$$

□ The width is consistent with experimental resolution.

Experimental Summary.

□ Comparison of Δm from BELLE, CLEO, and BaBar:



□ The spin analyses support the possibility that $D_{sJ}^+(2457)$ has $J^P = 1^+$.

□ This is also supported by the BELLE observation of $D_{sJ}^+(2457) \to D_s^+\gamma$ which rules out all J^P except 1^- or 1^+

Experimental Summary.

□ The mass of the $D_{sJ}^{*+}(2317)$ is 40 MeV/c^2 below D^0K threshold.

□ The mass of the $D_{sJ}^{+}(2457)$ is 44 MeV/c^2 below $D^{0*}K$ threshold.

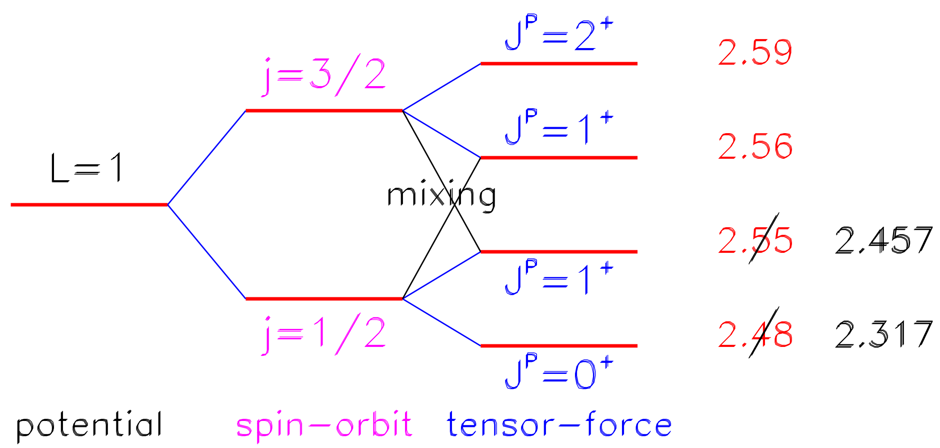
□ If the isospin of these states is I=0, since the $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ systems have isospin I=1, these decays violate isospin conservation. This would explain the small widths.

□ In this case it is possible that this isospin violating decay proceeds via $\eta - \pi^0$ mixing, as proposed by Cho and Wise. Phys.Rev. D49 (1994) 6228.

What can these states be?

□ Potential Models before $D_{sJ}^{*+}(2317)$ predicted masses too high.

S. Godfrey and N. Isgur, Phys. Rev. D32 (1985) 189, S. Godfrey and R. Kokoski, Phys. Rev. D43 (1991) 1679.



□ After discovery of $D_{sJ}^{+}(2317)$ a class of potential models has some difficulty fitting all states and getting decay patterns right.

R. Cahn and J. Jackson, hep-ph/0305012, S. Godfrey, hep-ph/0305012, P. Colangelo and F. De Fazio, hep-ph/0305140.

□ Perhaps with new potentials all charm, non-charm mesons can be fit.

☐ Also QCD Lattice calculations are in trouble: the mass for a scalar $c\bar{s}$ is expected to be higher than that measured.
G. Bali,hep-ph/0305209.

☐ Chiral symmetry models predict observed pattern: splitting of $D_{sJ}^{*+}(2317)$ and $D_{sJ}^{+}(2457)$ is about the same as $D_s^+(1969) - D_s^{*+}(2112)$. Predict many decay modes, including radiative decay of $D_{sJ}^{+}(2457)$.
W. Bardeen et al., hep-ph/0305049.

What can these states be?

☐ Four-quark states or molecules:

T.Barnes, F. Close, H. Lipkin (hep-ph/0305025), Cheng and Hou hep-ph/0305038,K. Terasaki hep-ph/0305213, A. Szczepaniak hep-ph/0305060

☐ Ordinary $c\bar{s}$ states still there to be found.

☐ Expect in this case a large variety of new states with I=0 and I=1.

How can we decide?

☐ Measure radiative decays.

☐ Measure transitions with di-pion emission.

☐ Find still more states.

☐ Look for other charge states.

Conclusions and Outlook.

□ The BaBar discovery of a narrow D_s^+ state has opened a new window in particle physics.

□ This, and related discoveries, will have a large impact on the theory of charmed and beauty meson spectroscopy.

□ Lots of activity, both experimental and theoretical.