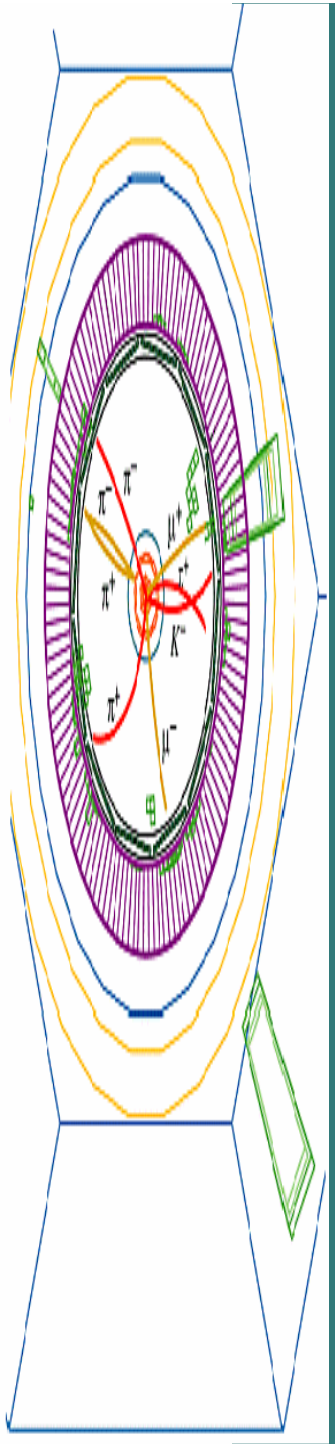


# Observation of two narrow mesons in the $D_s^+\pi^0$ and $D_s^+\pi^0\gamma$ final states

**Results from *BABAR*, CLEO & Belle**


**Alexis POMPILI**
**(University & I.N.F.N. of Bari)**
**[BABAR Collaboration]**


**QCD@Work 2003**
Conversano - 15 June 03

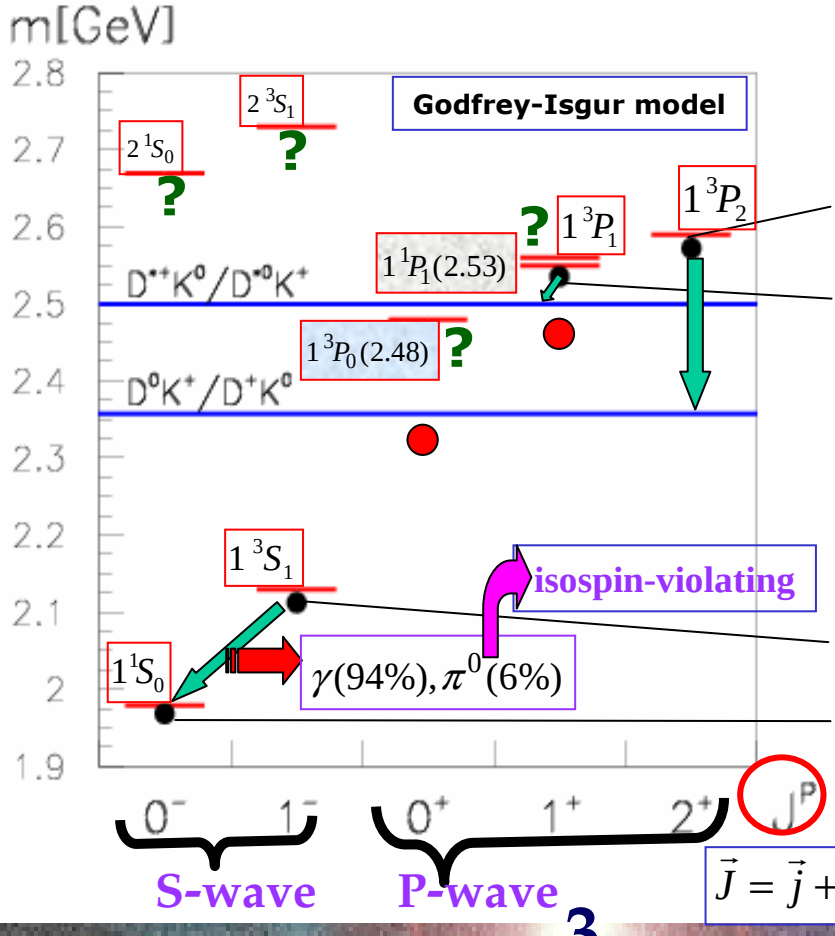
# Outline

- $c\bar{s}$ spectroscopy **before** new states observation
- Charm physics @ B-factories – reconstruction method issues
- **Observation of the first new state** - features
- Feedback/explanations by theorists
- **Evidence for a second new state** - features
- Summary and conclusions

# Spectroscopy of $c\bar{s}$ states

**Potential models** of **[heavy-quark | light-quark] mesons** have had so far **reasonable success** in describing the spectroscopy of the $D$, $D_s$, $B$, $B_s$ systems

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




$j = 3/2$ doublet

[narrow]

$D_{sJ}^*(2573)^+$

$D_{s1}(2535)^+$

(mix?) [narrow]

$j = 1/2$ doublet

**Predicted mass range:**

$\cong 2.4 \div 2.6\, GeV/c^2$

**Predicted large width range :**
**(for decay by *K*-emission)**

$\approx 270 \div 990\, MeV$

**Limited experimental information** ⟷ **NO experim. candidates (so far)**

**IF their masses were below $D^{(*)}K$ threshold, they would decay by isospin-violating π-emission and would be extremely narrow !**

$D_s^*(2112)^+$

$D_s^+(1969)$

$\vec{J} = \vec{j} + \vec{S}_{heavy}$, $\vec{j} = \vec{L} + \vec{S}_{light}$

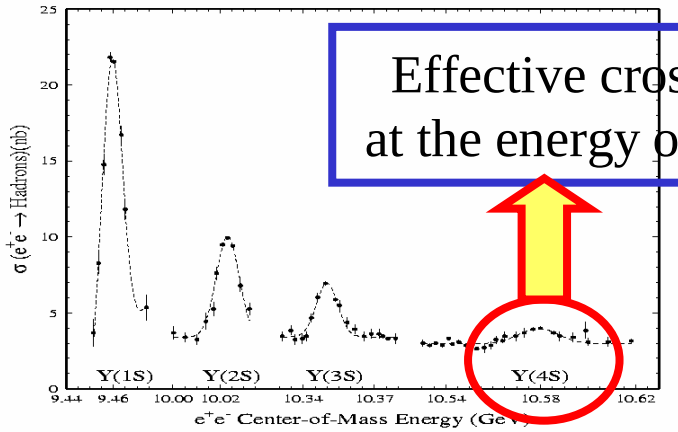
**The results presented here concern 2 states $[0^+, 1^+]$, below $DK$, $D^*K$ threshold, decaying to $D_s\pi^0$, $D_s^*\pi^0$ !**

# Charm Physics @ B-factories

| $e^+e^-$ colliders @ Y(4S) | Beams | Data taking | Det./Expt. | $\int Ldt$ [*] |
|---|---|---|---|---|
| CESR (Cornell) | Symmetric | 1990-1999 | **CLEO-II** | 13.5 $fb^{-1}$ |
| PEP-II (SLAC) | Asymmetric | Start: 1999 | BABAR | 91.5 $fb^{-1}$ |
| KEK-B (Tsukuba) | Asymmetric | Start: 1999 | **Belle** | 86.9 $fb^{-1}$ |

[*] *Integrated Luminosity* relative to the data sample **used** for the results presented **here**

**The Y(4S) resonance "lays" on a large continuum bkgd :**



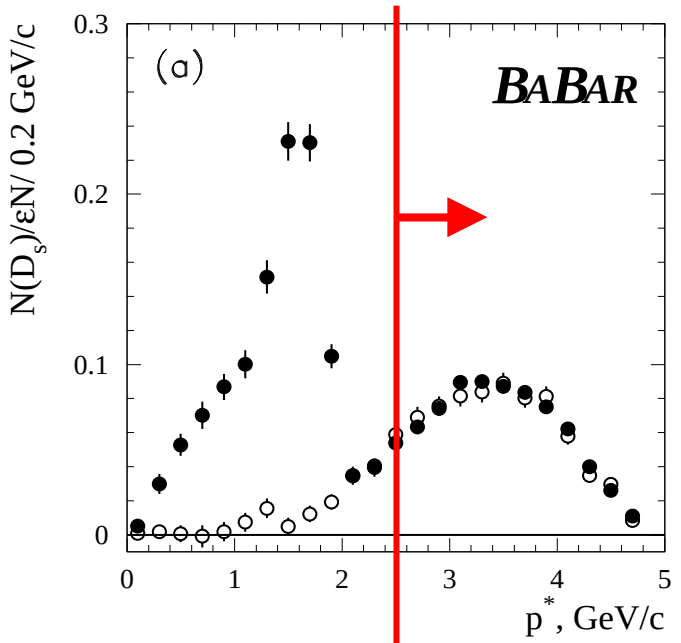

Effective cross sections at the energy of the Y(4S)

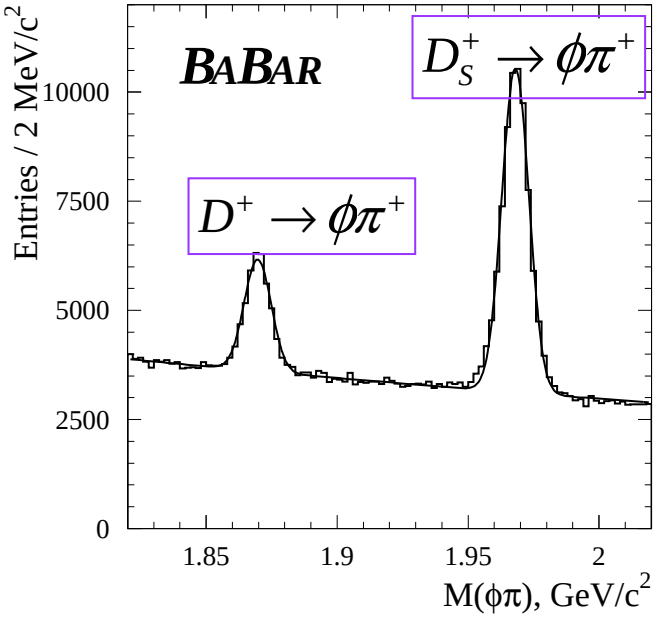
| $e^+e^- \rightarrow$ | σ (nb) |
|---|---|
| bb | 1.05 |
| cc | 1.30 |
| ss | 0.35 |
| uu | 1.39 |
| dd | 0.35 |
| $\tau^+\tau^-$ | 0.94 |
| $\mu^+\mu^-$ | 1.16 |
| $e^+e^-$ | ≈ 40 |

**Powerful tool for charm physics**

# Charm Physics from Continuum Production

**By using inclusive continuum events … combinatorial bkg is strongly reduced !**




**Solid (open) points: on (off) resonance data** [normalized]

**Kinematical selection: require cut on CMS momentum of charmed meson :** $p^*_D \geq 2.5\,GeV/c$

**It can be increased for cleaner samples (if statistics allows)**

# Reconstruction Method & Selection Criteria (from BABAR )

[charge-conjugate configurations are implied]

$D_s^+\pi^0$ ; $D_s^+ \to K^+K^-\pi^+$ , $K^+K^-\pi^+\pi^0$ ; $\pi^0 \to \gamma\gamma$

PID

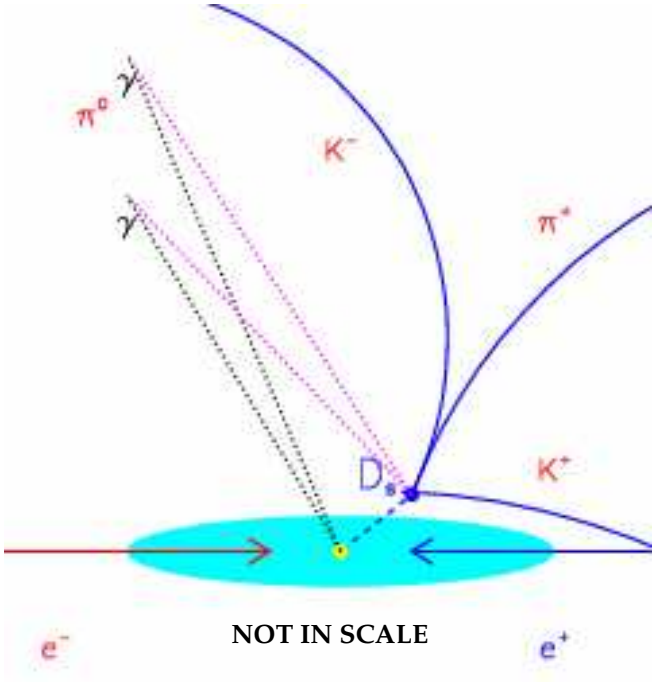
$E > 100\,MeV$

not sharing photons with others

geometric fit at a common vertex : $P(\chi^2) > 0.1\%$

consistent with production at the interaction region

$p^* > 2.5\,GeV/c$ (or tighter)



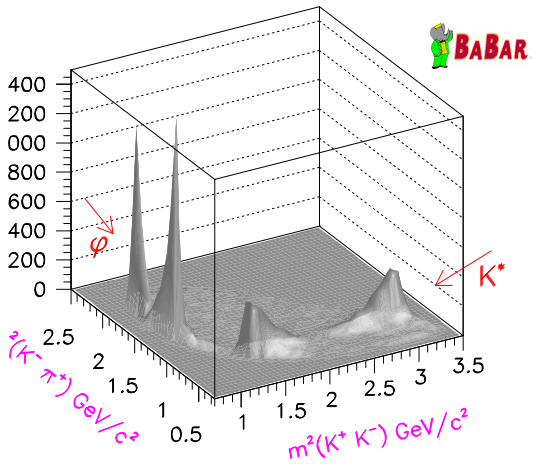

NOT IN SCALE

γγ couples (origin in track vertex) with kinematic fit [constraint : m(π⁰)] : $P(\chi^2) > 10\%$

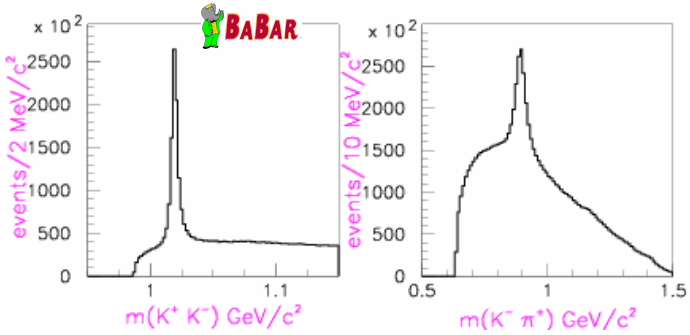
γγ couples (origin in production vertex) with kinematic fit [constraint : m(π⁰)] : $P(\chi^2) > 1\%$

# Further background rejection

## Select quasi-two body decay modes $[\phi\pi^+, \overline{K}^{*0}K^+]$



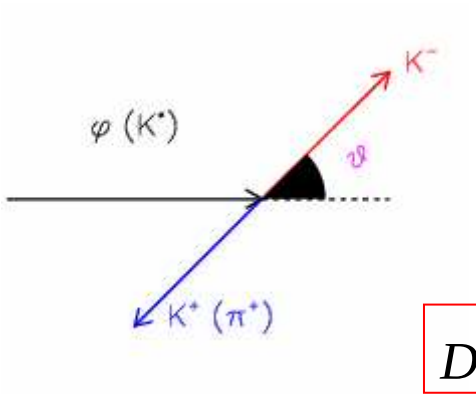

**2 disjoint sub-samples**

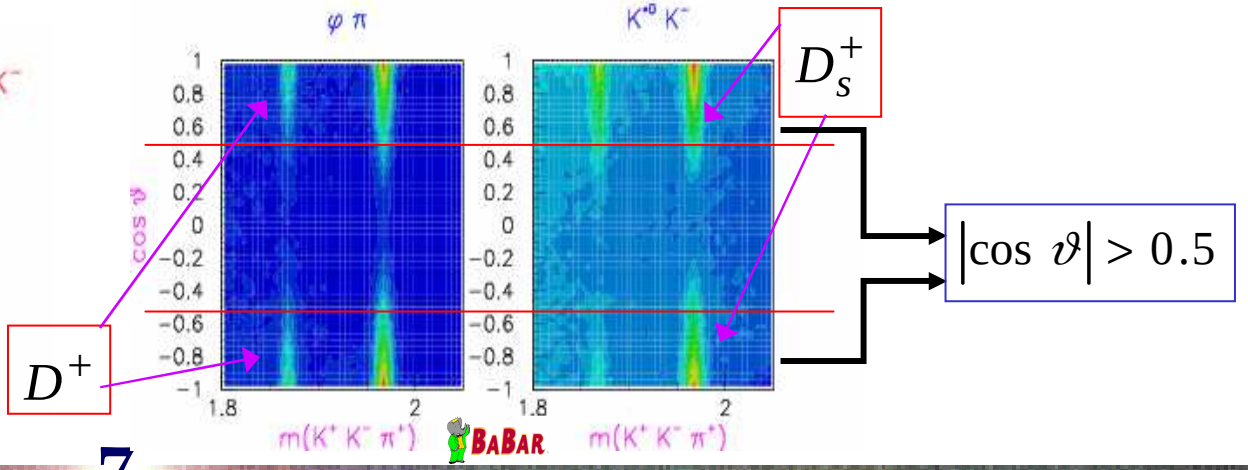



$\phi\pi^+$: $|m(K^+K^-) - m(\phi)| \leq 10$ MeV/$c^2$

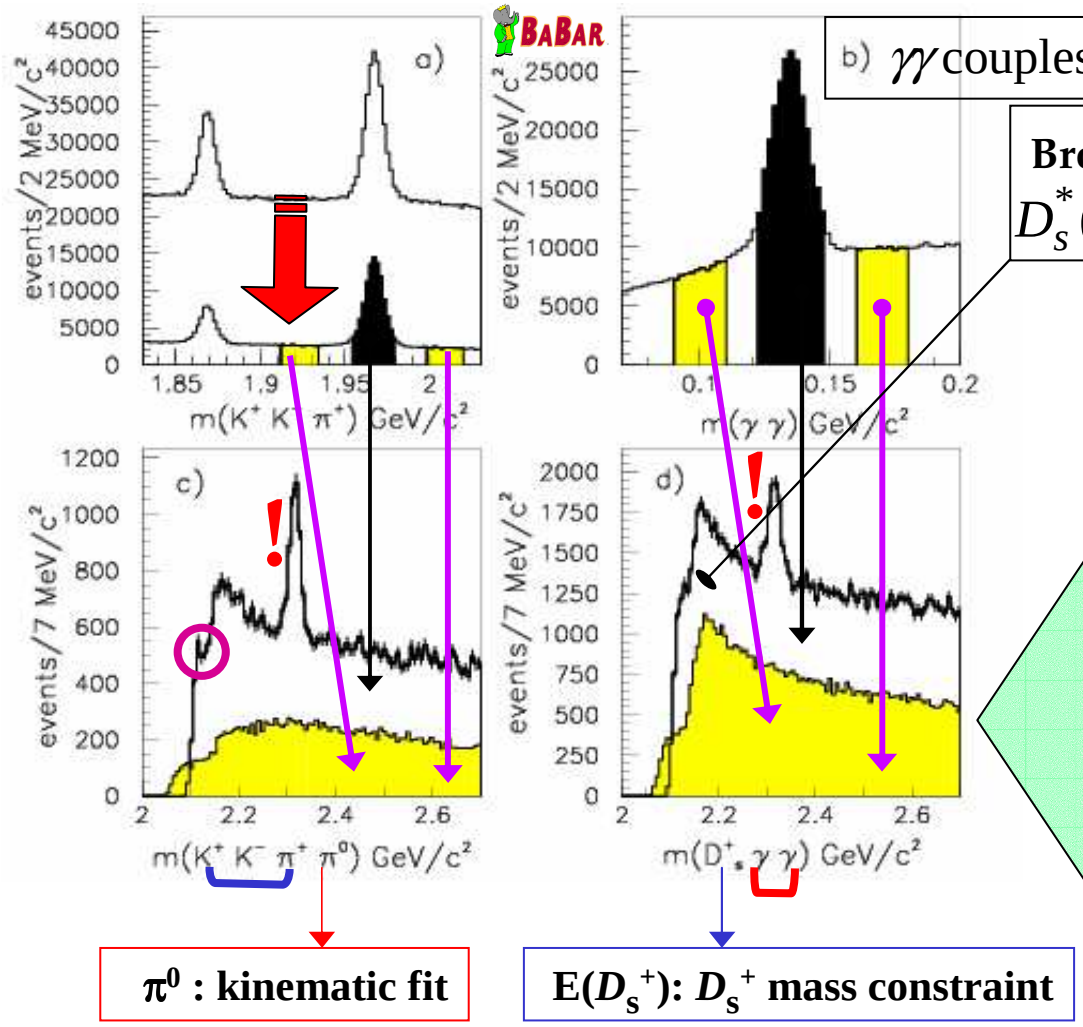
$\overline{K}^{*0}K^+$: $|m(K^+\pi^-) - m(\overline{K}^{*0})| \leq 50$ MeV/$c^2$

## Helicity angles cut [ 2-body decays of $(\phi, \overline{K}^{*0})$]



# Mass Spectra : $K^+K^-\pi^+$ , $\gamma\gamma$, $K^+K^-\pi^+\pi^0$ , $D_s^+\gamma\gamma$




b) $\gamma\gamma$ couples in events with $D_s^+\pi^0$ candidates

**Broad peak due to random combination** $D_s^*(2112)^+\gamma$ **where** $D_s^*(2112)^+ \to D_s^+\gamma$

**A signal @ 2.32 *GeV*/c² is missing in sidebands dist'ns : the peak is associated to the $D_s^+\pi^0$ system !**

**No other signal is evident up to 2.7 *GeV*/c² a part that associated with** $D_s^*(2112)^+ \to D_s^+\pi^0$

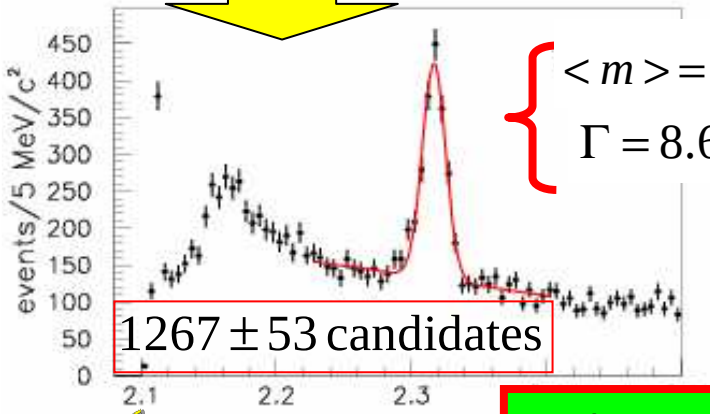
**$\pi^0$ : kinematic fit**

**E($D_s^+$): $D_s^+$ mass constraint**

# $D_s^+\pi^0$ mass spectra and fits [BABAR hep-ex/0304021, 12 April @ PRL]

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

$p^* > 3.5\,GeV/c$




$< m > = 2316.8 \pm 0.4\,(stat.)\ MeV/c^2$

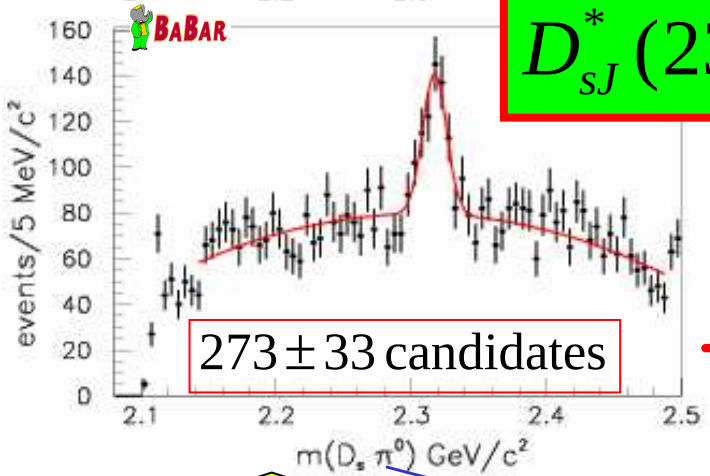
$\Gamma = 8.6 \pm 0.4\,(stat.)\ MeV/c^2$

**Mass systematic uncertainty estimated conservatively to be < 3 *MeV/c²***

**An estimate of the mass resolution for the system $K^+K^-\pi^+\pi^0$ can be provided directly from the data by fitting the mass dist'n for $D_s^+ \to K^+K^-\pi^+\pi^0$ characterized by a width consistent with that of the observed signal .**

**A similar mass resolution can be obtained from the simulation of $D_{sJ}^*(2317)^+[\Gamma \approx 0] \to D_s^+\pi^0$**

$D_{sJ}^*(2317)$




$< m > = 2317.6 \pm 1.3\,(stat.)\ MeV/c^2$

$\Gamma = 8.8 \pm 1.1\,(stat.)\ MeV/c^2$

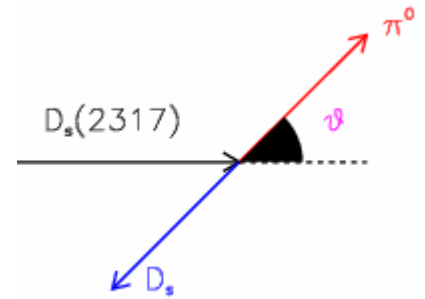
$p(\pi^0) > 300\,MeV/c$

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

**Observed width consistent with expt. resolution**
**Intrinsic width is smaller ($\Gamma$<10*MeV/c²*)[I-violation]**

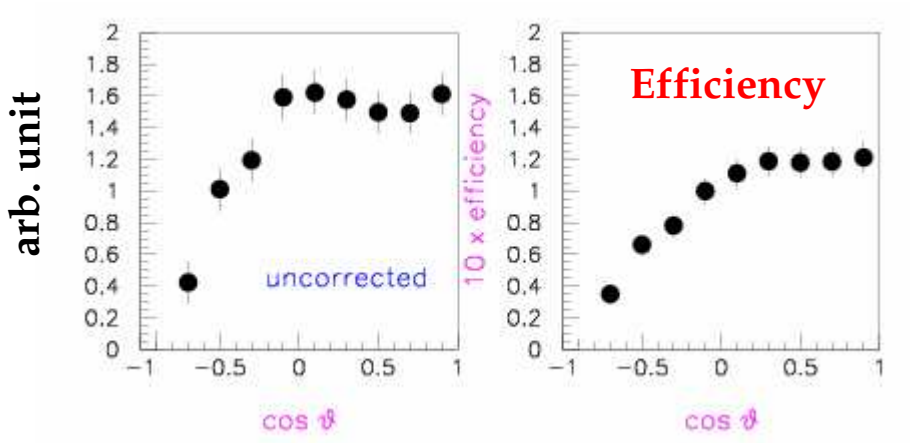
# $D_{sJ}^{*}(2317)$ Decay Angular Dist'n

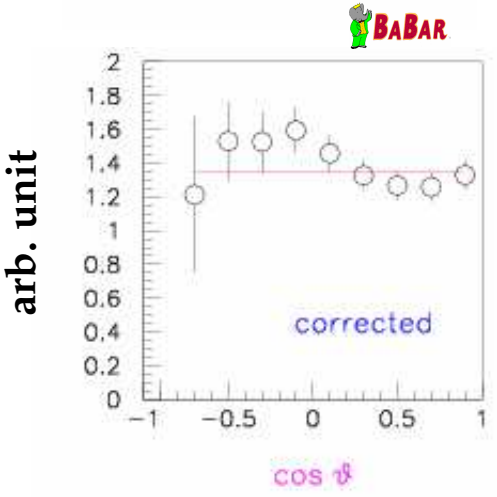
$\vartheta$ : $\pi^0$ angle in the $D_s^+\pi^0$ rest frame w.r.t the $D_{sJ}^{*}(2317)^+$ flight direction in the CMS




$D_{sJ}^{*}(2317)^+$ within bins of $\cos\vartheta$

[BKG subtracted]




**Angular dist'n consistent with being flat ( 43% probability )**

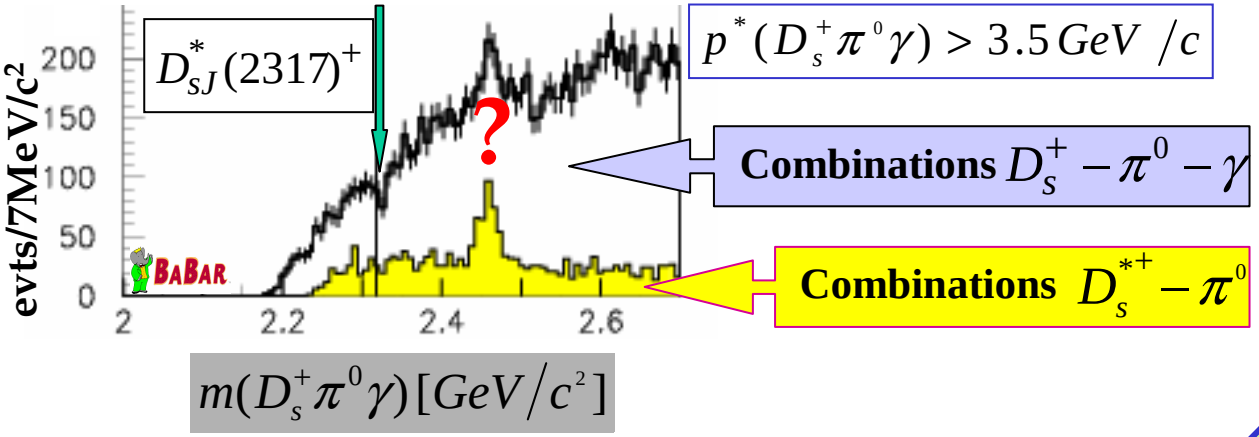
**This would be expected for:**
- **a spin J=0 state**
- **a higher-spin state produced unpolarized**

# Tests for Reflections

NO $D_{sJ}^{*}(2317)$ signal found using $e^+e^- \to c\bar{c}$ simulation of all known charmed states and decays

NO $D_{sJ}^{*}(2317)$ signal found when exchanging $\pi$-$K$ identification hypotheses [no $D^+$,$D^0$,$D^*$ seen]

Investigated decays involving known particles and generating a $D_{sJ}^{*}(2317)$ signal through the addition/omission/substitution of a $\pi$ or a $\gamma$. Nothing found ! However...




Is this peak @ 2.46$GeV/c^2$ a new narrow state kinematically feeding-down a $D_{sJ}^{*}(2317)$ signal:

$e^+e^- \to X(2460)^+ + X_{\text{recoil}}$

? $\quad D_s^{*+} \to D_s^+ \pi^0$ $\quad D_{sJ}^{*}(2317)$ $\quad \gamma$ lost/random

CHECK [MC UNFOLDING] : this feed down …

…1) would have a width $\Gamma$=15$MeV/c^2$ (smeared peak!)

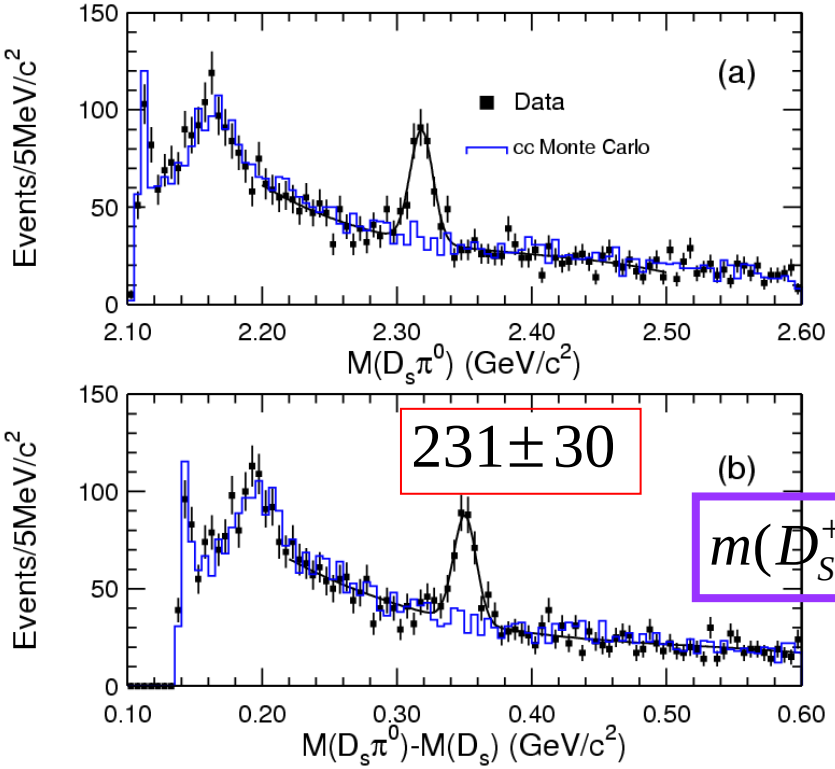
…2) can explain only 1/6 of the observed peak @ 2.32 $GeV/c^2$

This possible signal requires additional detailed study

# Confirmation of $D_{sJ}^{*}(2317)$ @ CLEO II & Belle

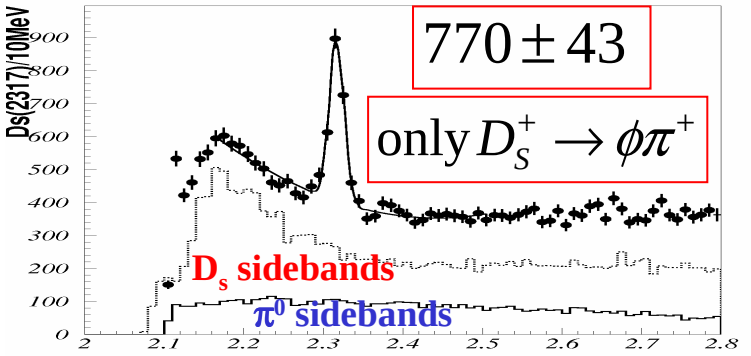
[ hep-ex/0305017 ]

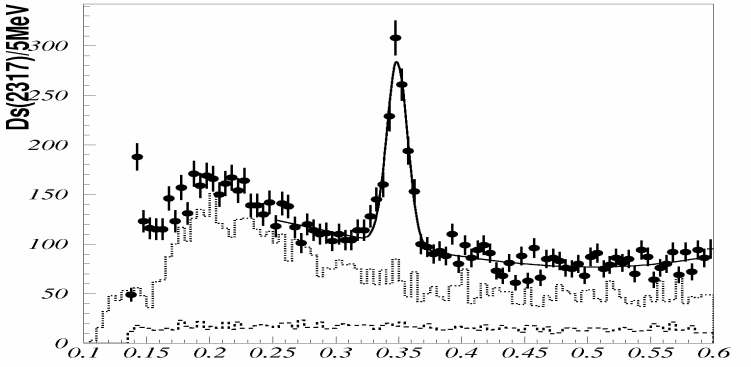
[@ CIPANP/03 – 20 May]




$m(D_S^+\pi^0)$

$m(D_S^+\pi^0) - m(D_S^+)$




$< \Delta m >= 350.3 \pm 1.0(stat.)\ MeV/c^2$

$\Gamma = 8.4^{+1.4}_{-1.2}(stat.)MeV/c^2$

$< m >= 2317.2 \pm 0.5(stat.)\ MeV/c^2$

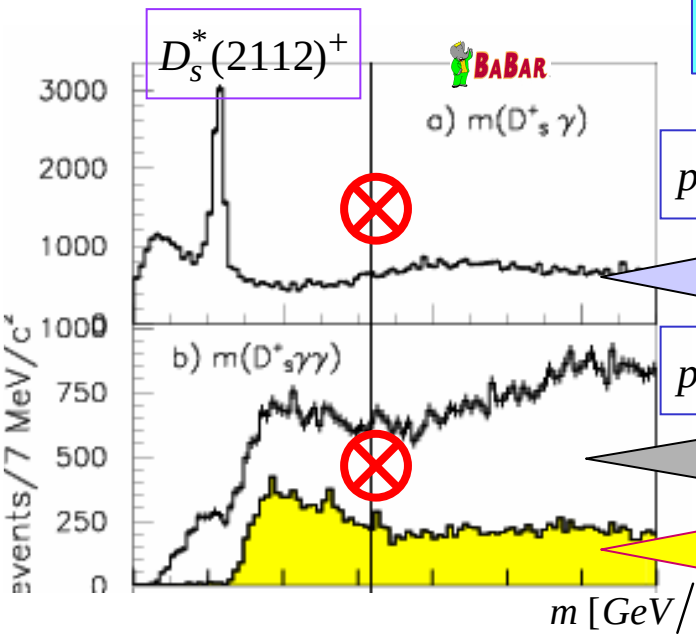
$\Gamma = 8.1 \pm 0.5(stat.)MeV/c^2$

**Consistent with experimental resolution**

# $J^P$ =? & Other $D_{sJ}^*(2317)$ Decay Modes

- For a parity conserving decay to $D_s^+[0^-]\pi^0$, only *natural* spin-parity series is allowed: $J^P = 0^+, 1^-, 2^+, \ldots$
- IF $J^P = 0^+$ (suggested by low mass & compatible with helicity dist'n)…
  … it cannot decay into $D_s^+[0^-]\gamma$
  … whereas… e.-m. decay into $D_s^{*+}[1^-]\gamma$ is allowed (by parity & angular momentum conservation)
- On the other hand, IF $J^P = 1^+$, it could strongly decay into $D_s^+\pi^+\pi^-$ [I-conserving, OZI-suppressed]
  IF $J^P = 0^+$, it cannot ($0^+ \not\to$ 3pseudoscalars)!

**Studied decay modes into:** $D_s^+\gamma, D_s^+\gamma\gamma, D_s^{*+}\gamma, D_s^+\pi^0\pi^0$ [*BABAR* & CLEO]; $D_s^+\pi^+\pi^-$ [CLEO]




**NO significant signals seen within current statistics**

$p^*(D_s^+\gamma) > 3.5\,GeV/c$

Combinations $D_s^+ - \gamma$

$p^*(D_s^+\gamma\gamma) > 3.5\,GeV/c$

Combinations $D_s^+ - \gamma - \gamma$

Combinations $D_s^{*+} - \gamma$

**CLEO B.R.** [w.r.t $D_s^+\pi^0$] **Upper Limits**

| MODE | 90%C.L. |
|---|---|
| $D_s^+\gamma$ | $< 0.054$ |
| $D_s^{*+}\gamma$ | $< 0.078$ |
| $D_s^+\pi^+\pi^-$ | $< 0.020$ |

## *"Theorists sent back to their drawing boards"* [from: SLAC Press Release]

**10 papers in May 1-20 !** ⇒ **2 main classes of interpretations :**

**a) Within a quark model representation** [$D_{sJ}^{*}(2317)$ still a $c\bar{s}$ state]

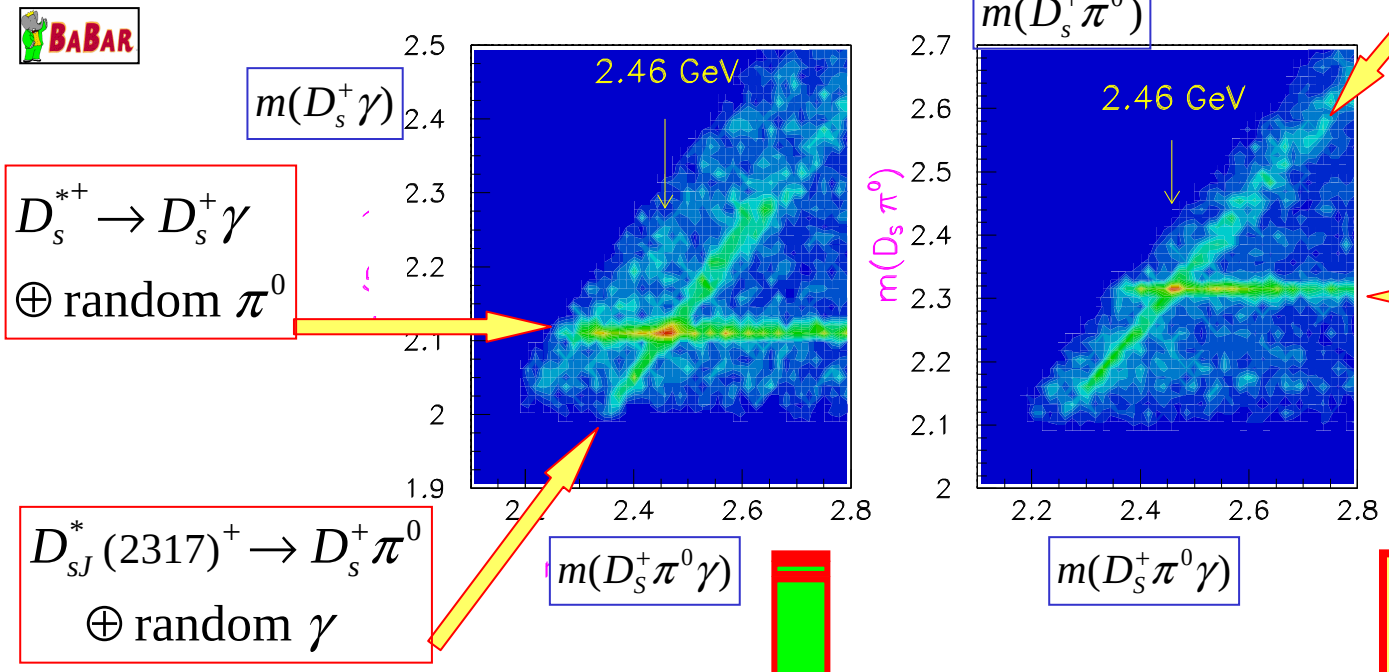
| | | |
|---|---|---|
| **Cahn & Jackson** | **hep-ph/0305012** | **Modified potential model in standard $c\bar{s}$ spectroscopy** |
| **van Beveren & Rupp** | **hep-ph/0305035** | **Quasi-bound $c\bar{s}$ in unitarized meson model** |
| **Bardeen, Eichten & Hill** | **hep-ph/0305049** | **Chiral Perturbation theory + HQET** |
| **Godfrey** | **hep-ph/0305122** | **Revision needed for masses! Crucial is the B.R. for decay $\to D_s^{*}\gamma$** |
| **Colangelo & De Fazio** | **hep-ph/0305140** | **Heavy quark spin-flavor sym.+ Vector Meson Dom. Ansatz** |

**b) quark model explanations unlikely: different type of state (*tetraquark*)**

| | | |
|---|---|---|
| **Barnes,Close & Lipkin** | **hep-ph/0305025** | ***molecular type* 4-quark state [DK molecule]** |
| **Cheng & Hou** | **hep-ph/0305038** | **4-quark state** $[c\bar{s}(n\bar{n})\,,\ n = u,d]$ |
| **Szczepaniak** | **hep-ph/0305060** | **Dπ atom** |
| **Bali** | **hep-ph/0305209** | **Lattice predictions on masses consistent with $c\bar{s}$ quark model** |

# $X(2460)^+ \to D_s^+ \pi^0 \gamma$ : is it really a new state?

**MC studies :** $e^+e^- \to c\bar{c}$ **including** $D_{sJ}^*(2317)$ Monte Carlo




$D_s^{*+} \to D_s^+ \gamma$ ⊕ random $\pi^0$

$D_s^{*+} \to D_s^+ \gamma$ ⊕ random $\pi^0$

$D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$ ⊕ random $\gamma$

$D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$ ⊕ random $\gamma$

**Kinematical CROSS-THROUGH**

**Concern: FEED-UP from** $D_{sJ}^*(2317)$ **: for** $D_s^{*+} \to D_s^+ \gamma$ **signal band there is a …**
**… peaking BKG associated with the crossing band produced by** $D_{sJ}^*(2317)^+ \to D_s^+ \pi^0$

**This can be addressed with different techniques! For istance:**
**a) MC-based unfolding method: feed-up probability & lineshape distortion [CLEO]**
**b) Sidebands from data used to estimate peaking BKG [CLEO & BELLE]**

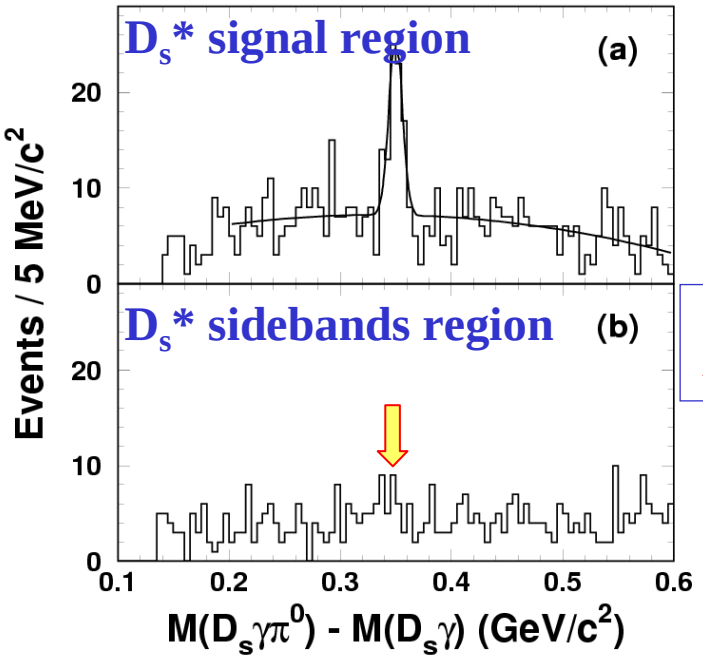
BABAR will release results soon

# … YES! Evidence of a new state @ 2.46 GeV/c² into $D_s^{*+}\pi^0$

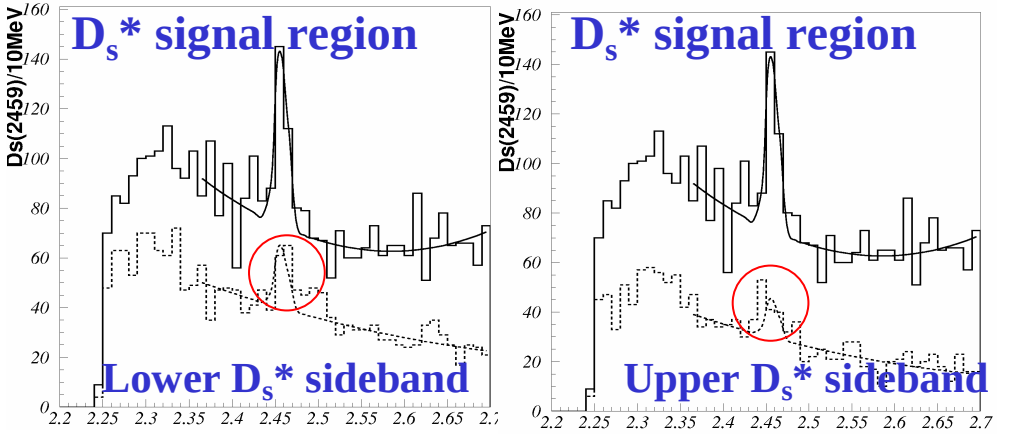
CLEO

[@ CIPANP/03 – 20 May]

BELLE




Feed-up: 9%




$D_{sJ}^{*}(2460)$

**Raw yield :131±21 candidates**

**Peaking BKG : 38±8 candidates**

**BKG-subtracted yield: 93±22 cand.**

**Statistical significance ~ 4.2σ**

| $D_s^*(2463)$ à $D_s^*\pi^0$ | Sideband subtraction | Unfolding method |
|---|---|---|
| Number of candidates | 40.8 ±11.3 | 40.7 ± 10.6 |
| $M(D_s^*\pi^0) - M(D_s^*)$ [MeV] | 351.6 ±1.7 | 350.6 ± 1.2 |
| σ [MeV] | 5.3 ± 1.2 | 6.1 ± 1.0 |

**Statistical significance ~ 5.3σ**

$\Gamma \approx 7\,MeV/c^2$

$< m >= 2459.0 \pm 1.4(stat.)\ MeV/c^2$

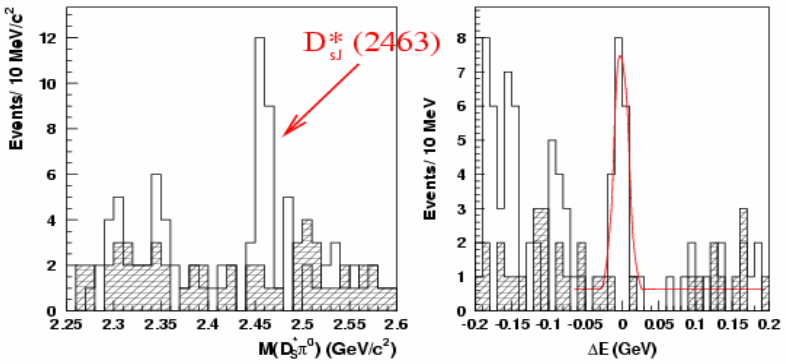
$\Gamma \approx 7\,MeV/c^2$

# $D_{sJ}^{*}$ states in exclusive decays of B mesons [byBELLE]

(@ FPCP/03 – 5 June)

**Dominant exclusive process for the two $D_{sJ}$* production in *B* decays is :** $B \to DD_{sJ}^{*}$

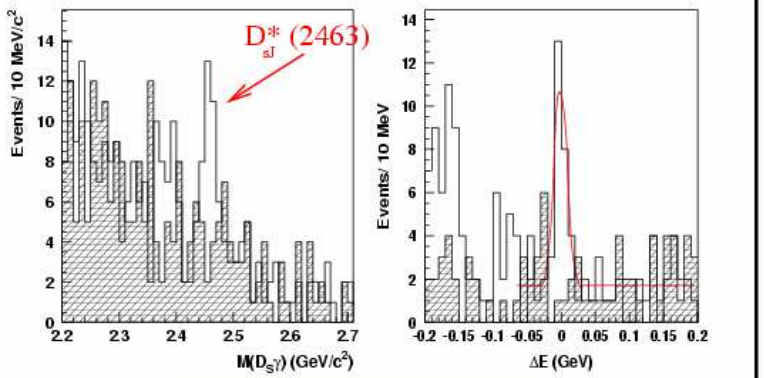
$DD_s^*\pi^0$ *decay mode (Belle, preliminary)*




$DD_S^*\pi^0$

$M = 2460 \pm 3 MeV/c^2$
$N = 16.7^{+4.8}_{-4.1}$ events $(6.0\,\sigma)$

$DD_s\gamma$ *decay mode (Belle, preliminary)*




$M = 2460 \pm 2\ MeV/c^2$
$N = 21.8^{+5.8}_{-5.1}$ events $(5.9\,\sigma)$

$DD_s\gamma$

**CLEO B.R.**
**[w.r.t $D_s^{*+}\pi^0$]**
**Upper Limits**

**13*fb*$^{-1}$**

| MODE | 90%C.L. |
|---|---|
| $D_s^+\gamma$ | < 0.49 |
| $D_s^{*+}\gamma$ | < 0.16 |
| $D_s^+\pi^+\pi^-$ | < 0.08 |

$$\frac{B(D_{sJ}^{*}(2460)^+ \to D_S^+\gamma)}{B(D_{sJ}^{*}(2460)^+ \to D_S^{*+}\pi^0)} = 0.21 \pm 0.07 \pm 0.03$$

**90*fb*$^{-1}$**

$D_{sJ}^{*}(2460) \to D_S^+\gamma \Rightarrow J^P \neq 0^+$

**A preliminary helicity dist'n shows to be consistent with $1^+$ state**

# Summary & Conclusions

- Two narrow states have been observed, in the inclusive $D_s\pi^0$ & $D_s^*\pi^0$ invariant mass distributions, near $2.317 GeV/c^2$ & $2.460 GeV/c^2$.
  The widths [$\Gamma < 10 MeV/c^2$] are consistent with experimental resolution.
  The smaller intrinsic widths are due to isospin-violation in their decay.
  The most likely assignment for their spin-parity is $0^+$ & $1^+$.

- They do not fit well into the existing potential models for $c\bar{s}$ spectroscopy.

- The mass splittings m[$D_{sJ}^*(2317)$]-m[$D_s(1969)$] & m[$D_{sJ}^*(2460)$]-m[$D_s^*(2112)$] are consistent with being equal as predicted by *Bardeen et al.* (BEH) if these are $0^+$ & $1^+$ states.

- The B.R. Upper Limit for the decay of $D_s^*(2317)$ into $D_s^*\gamma$, $D_s\gamma$ and $D_s\pi^+\pi^-$ [w.r.t. $D_s\pi^0$] and the preliminary B.R. measurement for the decay of $D_s^*(2460)$ into $D_s\gamma$ [w.r.t. $D_s^*\pi^0$] are consistent with BEH predictions.

- Most results are compatible with models based on HQET and chiral symmetry, which predict that $0^+$ & $1^+$ are the chiral partners of the $0^-$ & $1^-$ states, with same mass splitting.

- Interesting times ahead both for experimentalists & theorists.

# Few more numbers...

$$\frac{B(D_{sJ}^{*}(2317)^{+} \to \text{final mode})}{B(D_{sJ}^{*}(2317)^{+} \to D_S^{+}\pi^0)}$$

| MODE | 90%C.L. | BEH |
|---|---|---|
| $D_s^{+}\gamma$ | < 0.054 | 0 |
| $D_s^{*+}\gamma$ | < 0.078 | 0.08 |
| $D_s^{+}\pi^{+}\pi^{-}$ | < 0.020 | 0 |

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$$\frac{B(D_{sJ}^{*}(2460)^{+} \to \text{final mode})}{B(D_{sJ}^{*}(2460)^{+} \to D_S^{*+}\pi^0)}$$

| MODE | 90%C.L. (BELLE) | BEH |
|---|---|---|
| $D_s^{+}\gamma$ | < 0.49 / $0.21 \pm 0.07 \pm 0.03$ | 0.24 |
| $D_s^{*+}\gamma$ | < 0.16 | 0.22 |
| $D_s^{+}\pi^{+}\pi^{-}$ | < 0.08 | 0.20 |