

# New Meson States.

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## Summary:

- Introduction.
- New Charm States.
- New Charmonium States.
- Conclusions.

Hadron 2007, October 8, 2007

## Introduction.

- Charm and Charmonium spectroscopy have made considerable and unexpected progress in the last few years.
- This is due to the large data sets being collected by several experiments, in particular:
  - $e^+e^-$  interactions at the  $\Upsilon(4S)$  energy:  
BaBar, BELLE, CLEO
  - Integrated luminosities. BaBar:  $477\text{ fb}^{-1}$ , BELLE:  $709\text{ fb}^{-1}$ .
- $e^+e^- \rightarrow \text{charmonium}$ :  
CLEO-c, BES-II
- $\bar{p}p$  colliders:  
CDF, D0

# Charm and Charmonium Spectroscopy.

□ Charm spectroscopy is studied in:

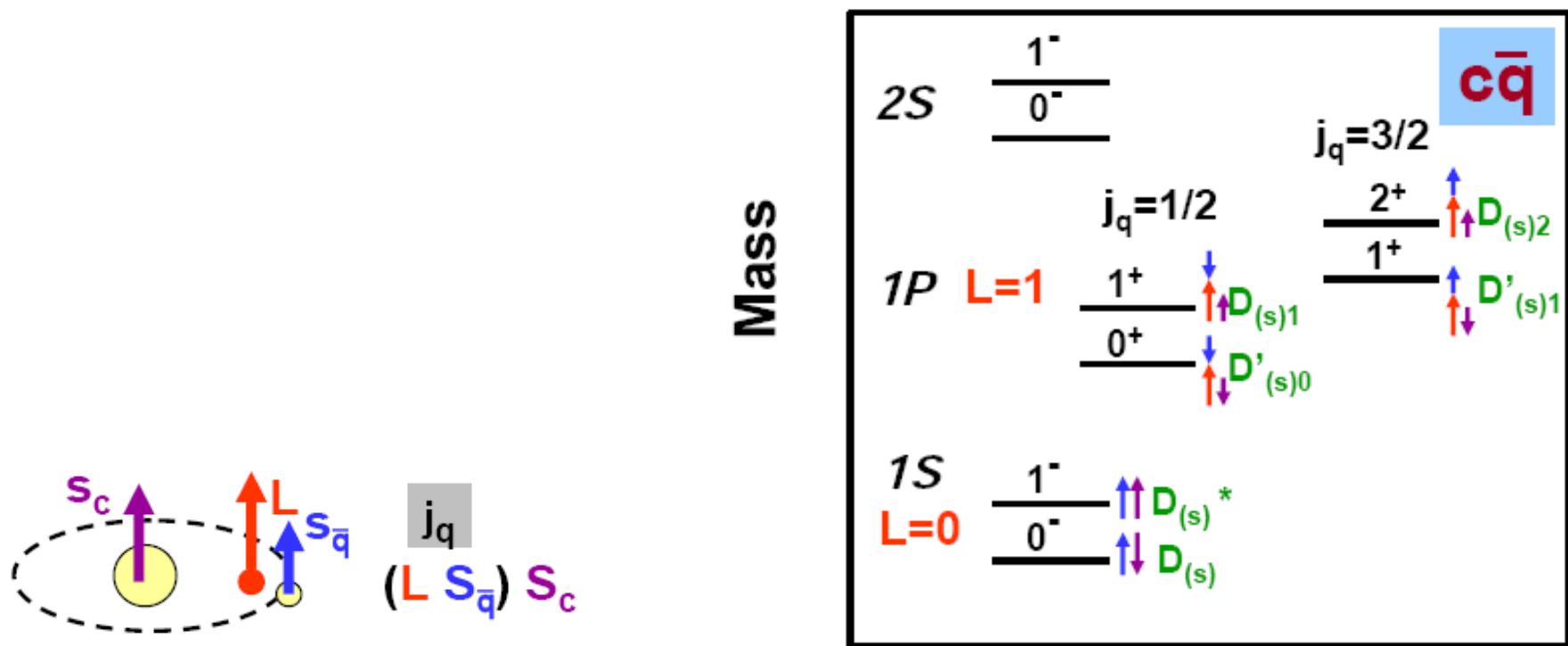
- inclusive  $e^+e^- \rightarrow \bar{c}c$  interactions (all spins allowed);
- B decays (higher spins suppressed).

□ Charmonium spectroscopy is studied in:

- B decays;
- Initial-State-Radiations reactions  $e^+e^- \rightarrow \gamma_{ISR}X$  (only  $J^{PC} = 1^{--}$ );
- Double  $c\bar{c}$  ( $e^+e^- \rightarrow J/\psi X$ ). C(X)=+;
- Two photon interactions  $\gamma\gamma \rightarrow X$ :  $J_X \neq 1$ ;

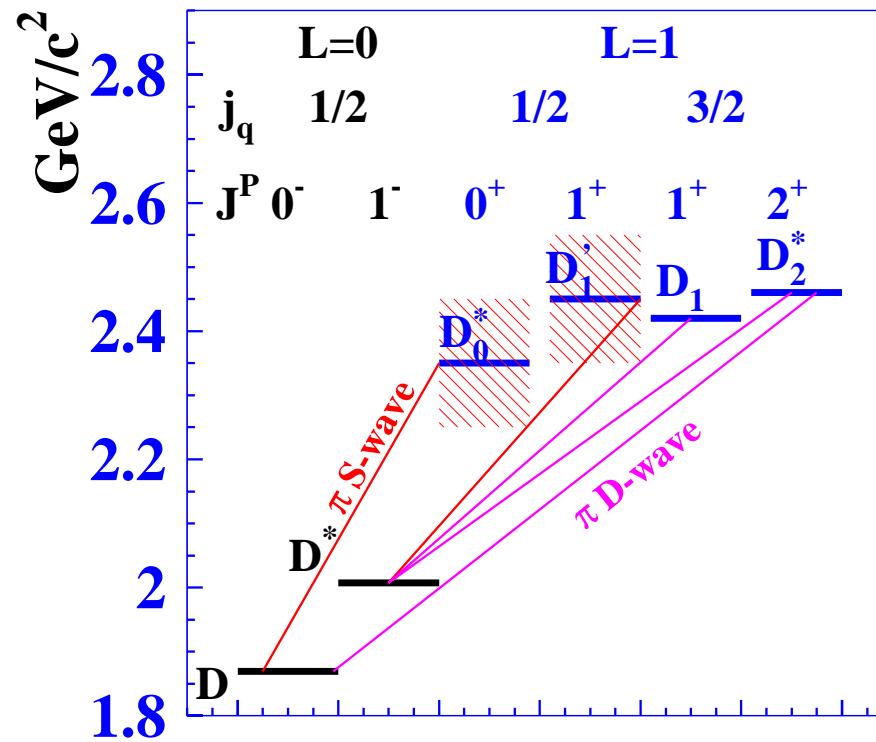
# The charm spectrum.

- Expected mass splitting.
- Separated  $D_{(s)}$  meson-spin doublets:  $(0^-, 1^-)$ ,  $(0^+, 1^+)$ ,  $(1^+, 2^+)$ .



## The spectroscopy of the $c(\bar{u}/\bar{d})$ states.

- Theory and experiment are in agreement.



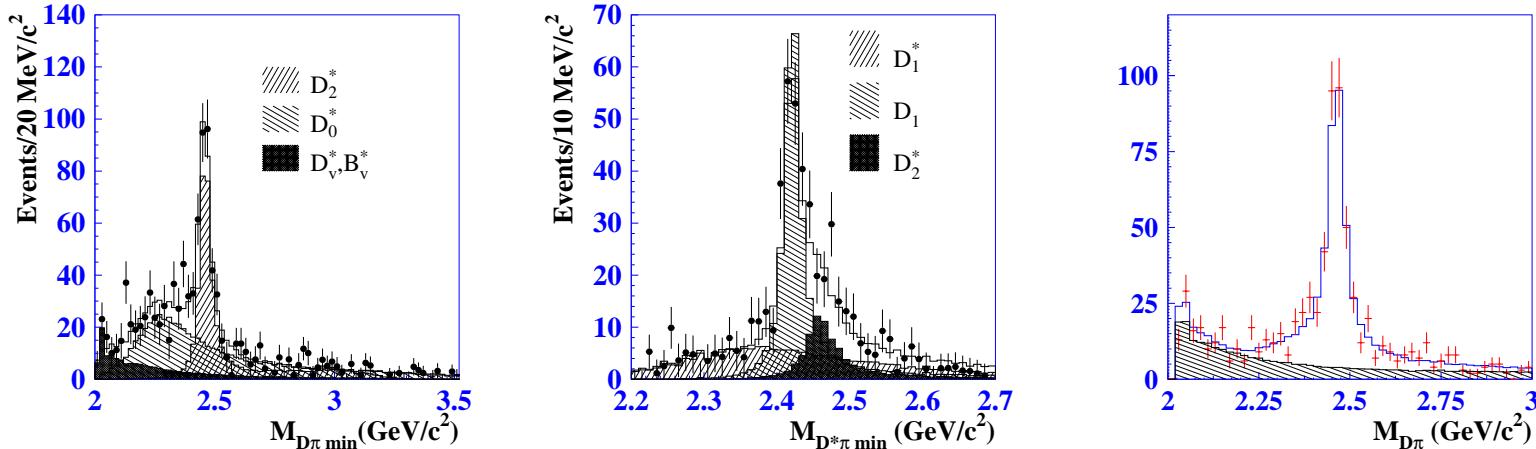
- Expect narrow and wide states. Wide resonances difficult to isolate.

## Recent results.

- BELLE experiment has studied the decays: hep-ex/0307021,hep-ex/0611054

$$B^- \rightarrow D^+ \pi^- \pi^-, \quad B^- \rightarrow D^{*+} \pi^- \pi^-, \quad \bar{B}^0 \rightarrow D^0 \pi^+ \pi^-$$

- Dalitz plot analysis of the B mesons three-body and four-body decays.  
Fitted projections on the  $D\pi$  and  $D^*\pi$  masses.



- Resulting parameters for the scalar and axial broad states:

$$D_0^{*0} : m = 2308 \pm 17 \pm 15 \pm 28 \text{ MeV}/c^2, \quad \Gamma = 276 \pm 21 \pm 18 \pm 60 \text{ MeV}$$

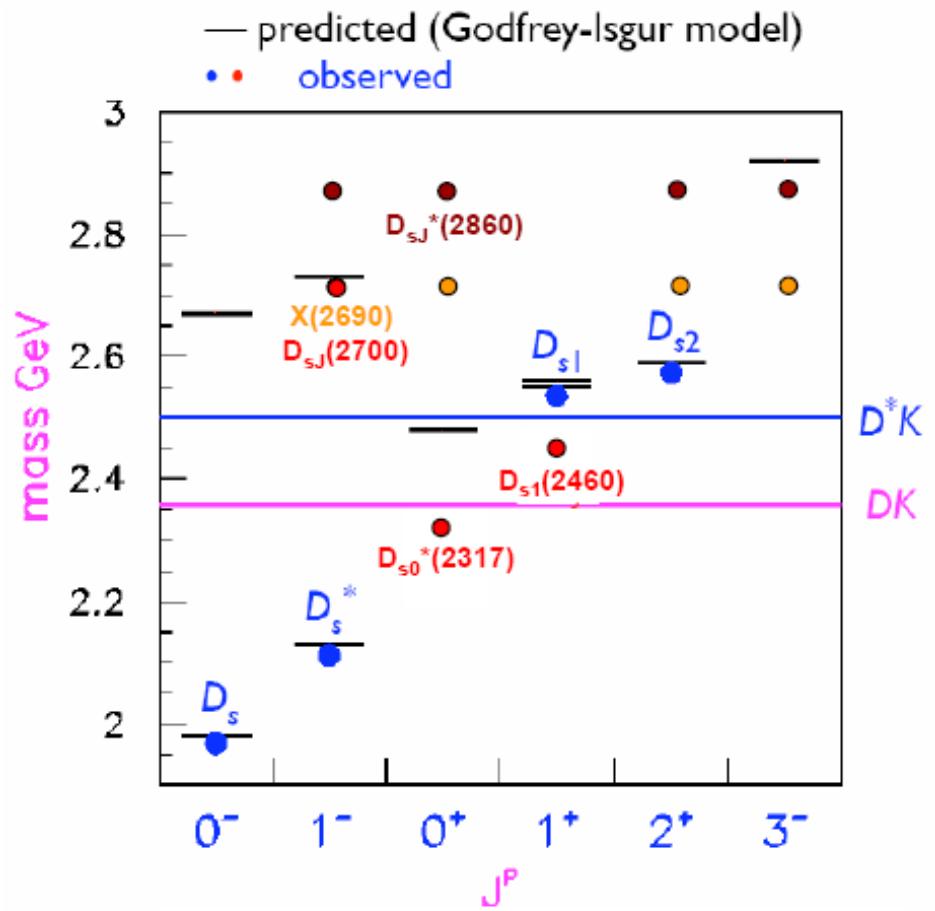
$$D_1 : m = 2427 \pm 26 \pm 20 \pm 15 \text{ MeV}/c^2, \quad \Gamma = 384_{-75}^{+107} \pm 24 \pm 70 \text{ MeV}$$

- Parameters of the  $D_2^{*0}$  state:

$$D_2^{*0} : m = 2465.7 \pm 1.8 \pm 0.8 \pm 4.7 \text{ MeV}/c^2, \quad \Gamma = 49.7 \pm 3.8 \pm 4.1 \pm 4.9 \text{ MeV}$$

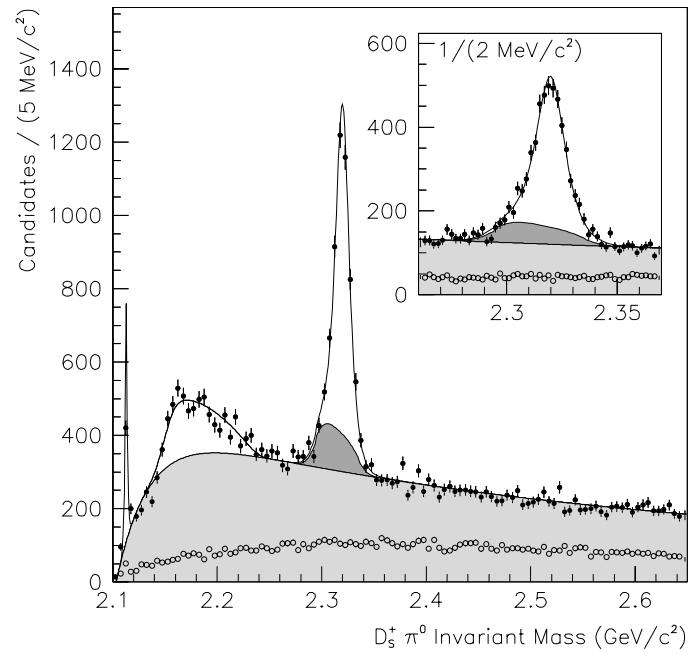
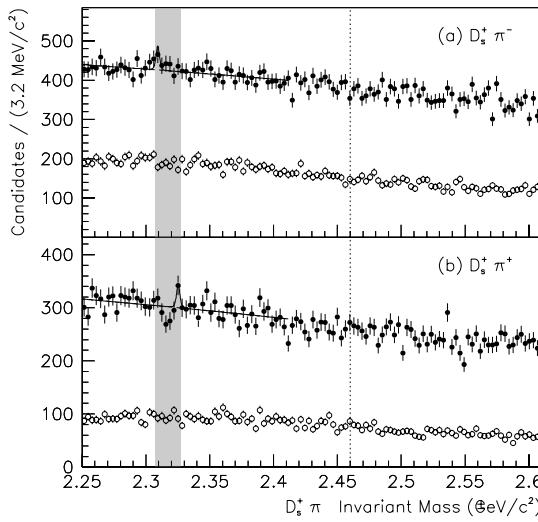
## Charm Spectroscopy: $D_{sJ}^+$ states.

- The discovery of the new  $D_{sJ}$  states has brought into question potential models.



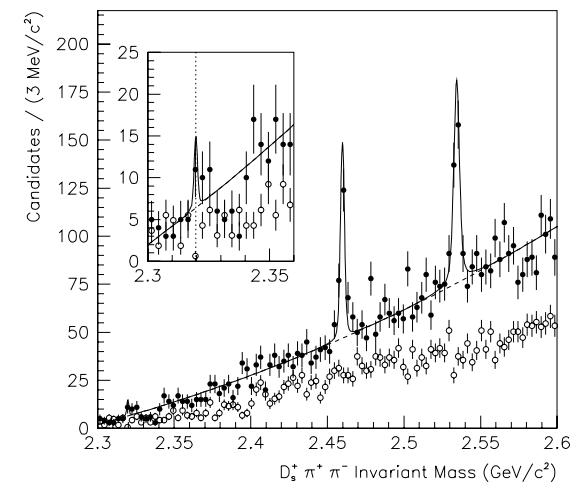
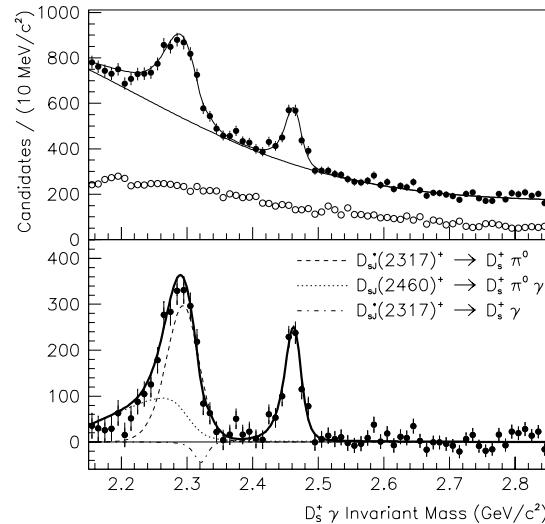
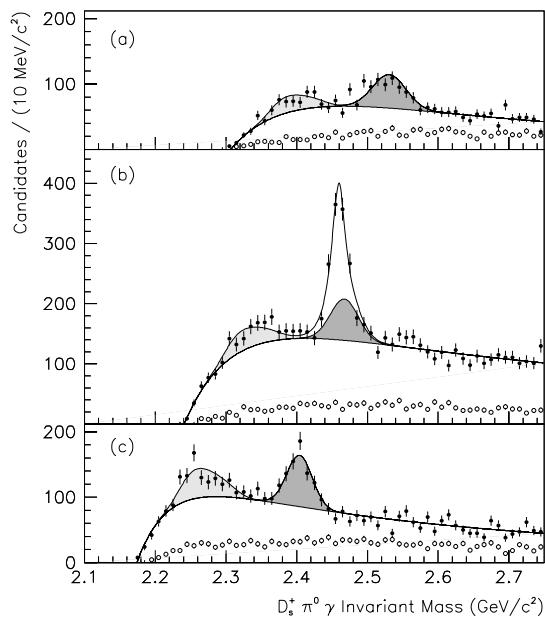
# Charm Spectroscopy: $D_{sJ}$ states.

- BaBar: upgrade of measurements with  $240 \text{ fb}^{-1}$ . [hep-ex/0604030](#)
- A new measurement of the  $D_{sJ}^*(2317)^+$  mass:  
 $m(D_{sJ}^*(2317)^+) = (2319.6 \pm 0.2 \pm 1.4) \text{ MeV}/c^2$
- Shaded is the reflection from  $D_{sJ}(2460)^+$ .
- Search for  $m(D_{sJ}^*(2317)^+) \rightarrow D_s^+ \pi^\pm$ :  
 No signal: probably not 4-quark states.



# Charm Spectroscopy: $D_{sJ}(2460)^+$ .

- BaBar: new measurements of the  $D_{sJ}(2460)^+$  has been obtained from  $D_s^+ \pi^0 \gamma$ ,  $D_s^+ \gamma$ , and  $D_s^+ \pi^+ \pi^-$  decays.



- The average of these results is:

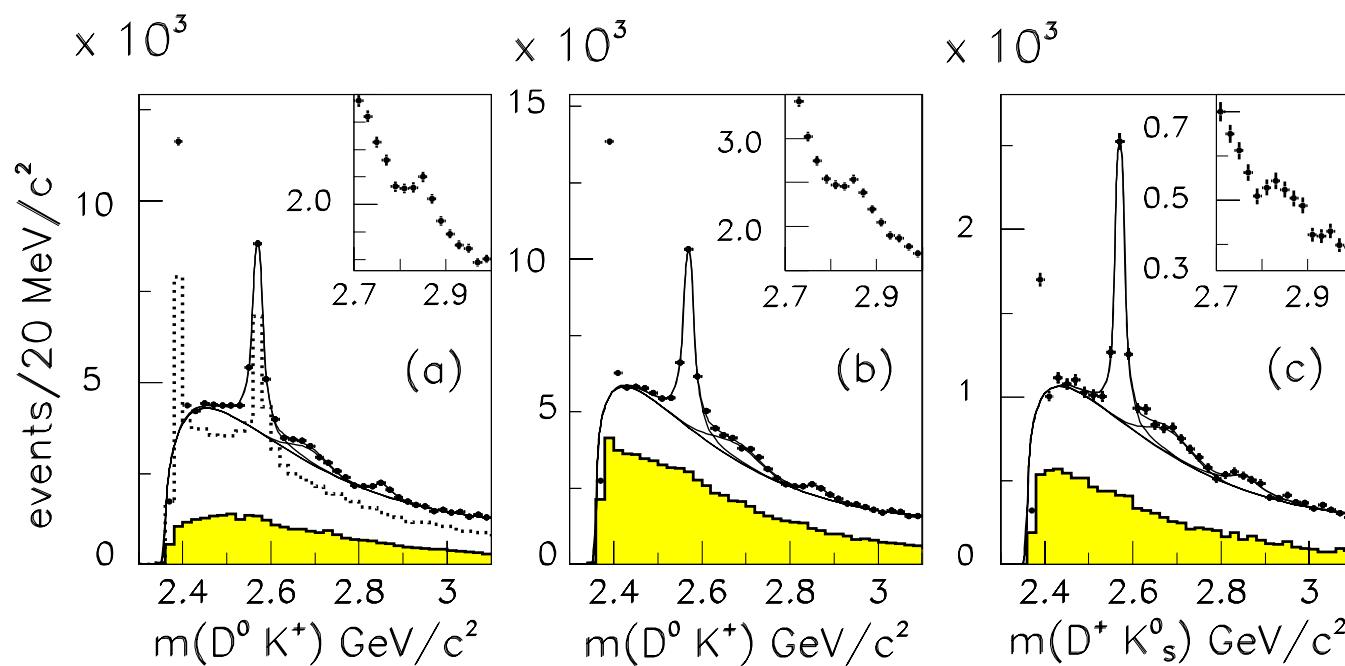
$$m(D_{sJ}(2460)^+) = (2460.1 \pm 0.2 \pm 0.8) \text{ MeV}/c^2 \quad (1)$$

## Summary on $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ .

- Discovered 4 years ago in  $e^+e^- \rightarrow c\bar{c}$  events, observed in B decays.
- $D_{sJ}^*(2317)^+$  and  $D_{sJ}(2460)^+$  very well established and known experimentally:
  - Mass and widths;
  - $J^P : 0^+$  for  $D_{sJ}^*(2317)^+$  and  $J^P : 1^+$  for  $D_{sJ}(2460)^+$ .
  - decay modes and branching fractions.
- Interpretation of these states still unclear.
  - Identification of these states as the  $0^+$  and  $1^+$   $c\bar{s}$  states: strong difficulties within the potential model
  - Other possibilities: 4-quark states?  $DK$  molecules?  $D\pi$  atom? Chiral symmetry?

## A new state: $D_{sJ}(2860)$ .

- BaBar. Study of continuum  $e^+e^- \rightarrow D^0(\rightarrow K^-\pi^+, K^-\pi^+\pi^0)X$  and  $e^+e^- \rightarrow D^+K_S^0X$ .



- New state at 2860 MeV/c<sup>2</sup>.
- Bump at 2690 MeV/c<sup>2</sup>.

## A new state: $D_{sJ}(2860)$ .

- Background subtracted sum of the three modes.
- Precision measurement of the  $D_{s2}^*(2573)$  parameters:

$$M(D_{s2}^*(2573)) = (2572.2 \pm 0.3 \pm 1.0) \text{ MeV}/c^2$$

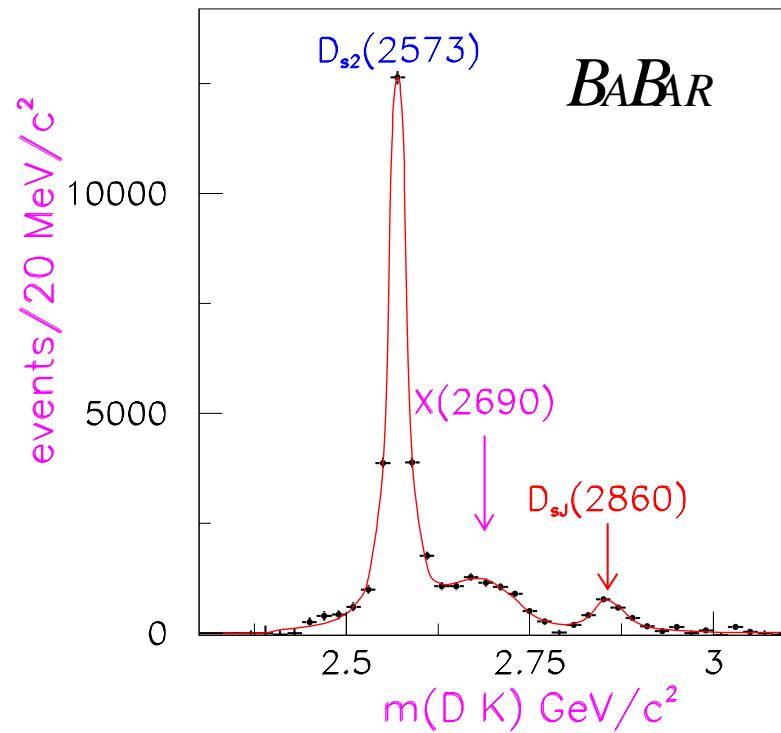
$$\Gamma(D_{s2}^*(2573)) = (27.1 \pm 0.6 \pm 5.6) \text{ MeV}$$

$$M(D_{sJ}^*(2860)) = (2856.6 \pm 1.5 \pm 5.0) \text{ MeV}/c^2$$

$$\Gamma(D_{sJ}^*(2860)) = (47 \pm 7 \pm 10) \text{ MeV}$$

- Final state is  $DK$ , i.e. two pseudoscalars. Therefore:

$$J^P = 0^+, 1^-, 2^+, 3^-, \dots$$



## Interpretation?

- Radial excitation of  $D_{s0}^*(2317)$ ? hep-ph/0606110
- $c\bar{s}$  with  $\text{JP} = 3^-$ ? hep-ph/0607245
- $c\bar{s}$  with  $\text{JP} = 0^+$ ? hep-ph/0608139
- Another structure at  $2690 \text{ MeV}/c^2$ ?

$$M(X(2690)) = (2688 \pm 4 \pm 3) \text{ MeV}/c^2$$

$$\Gamma(X(2690)) = (112 \pm 7 \pm 36) \text{ MeV}$$

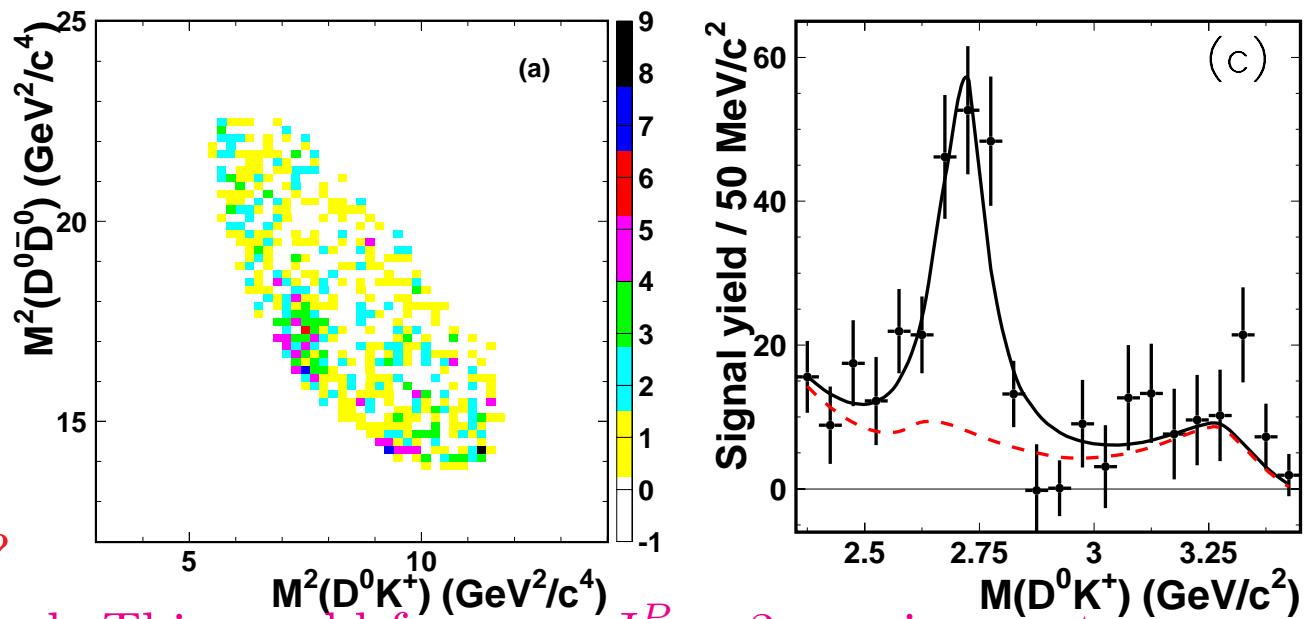
- Needs confirmation by other experiments.

## A new state: $D_{sJ}(2700)$ .

- BELLE: Study of  $B^+ \rightarrow D^0 \bar{D}^0 K^+$ . Observation of a new  $D_s$  meson with  $J^P = 1^-$ . Dalitz plot and  $D^0 K^+$  mass.

$$M = 2708 \pm 9^{+11}_{-10} \text{ MeV}/c^2$$

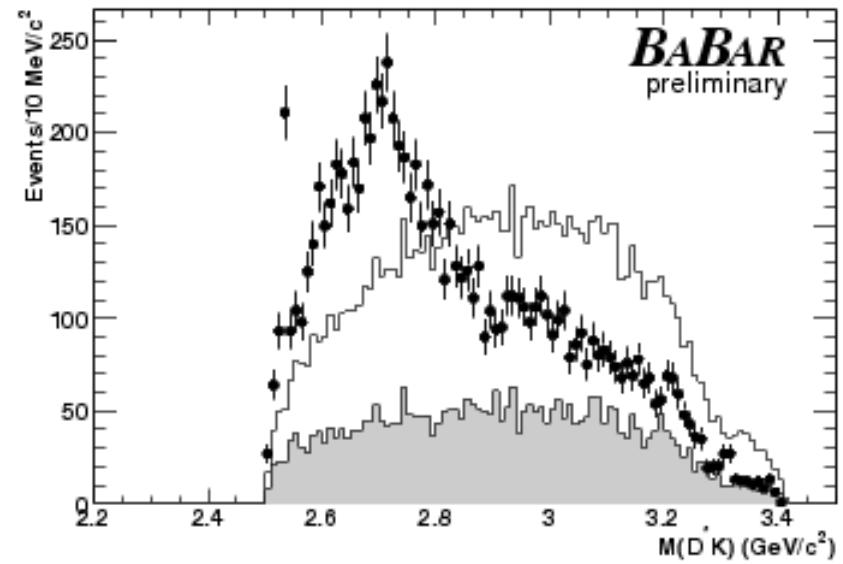
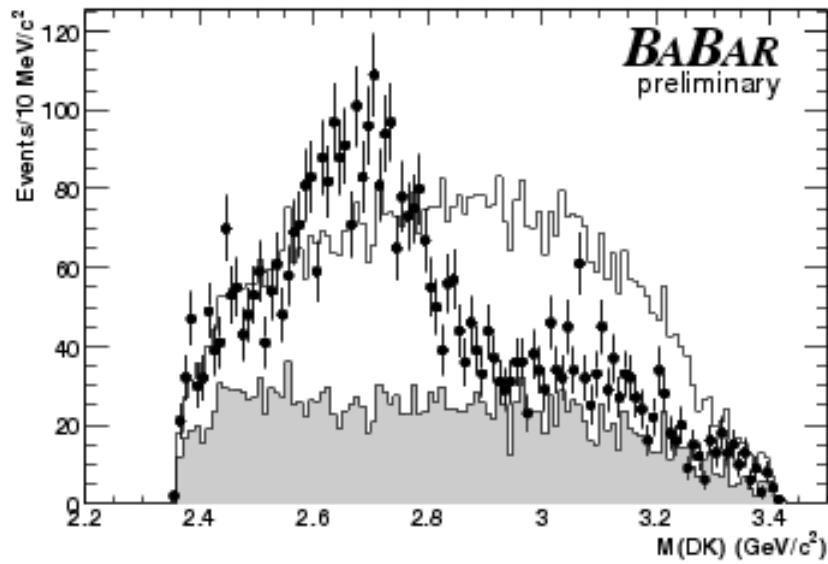
$$\Gamma = 108 \pm 23^{+36}_{-31} \text{ MeV}$$



- $X(2690)=D_{sJ}(2700)?$
- No  $D_{sJ}(2860)$  observed. This would favour a  $J^P = 3^-$  assignment (suppressed in B decays).

$D_{sJ}(2700)$ .

- BaBar: Study of  $B \rightarrow D^{(*)}\bar{D}^{(*)}K$  (22 modes).
- Observation of resonances in  $DK$  and  $D^*K$ . Dalitz analysis in progress.



## Charmonium spectroscopy: the new zoology.

- X(3872).
- The  $1^-$  family: Y(4260) and others.
- The 3940 family.
- Z(4430): an exotic charged state?

## X(3872).

- Decays:

$X(3872) \rightarrow J/\psi\pi\pi$  (original observation by BELLE), possibly  $J/\psi\rho$

$$\mathcal{B}(X(3872) \rightarrow J/\psi\rho) \approx \mathcal{B}(X(3872) \rightarrow J/\psi\omega)$$

$$X(3872) \rightarrow J/\psi\gamma, \frac{\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)} = 0.19 \pm 0.07$$

- $J^{PC} = 1^{++}$  favoured.

- Production in B decays only so far. BaBar:

$$\sigma(e^+e^- \rightarrow X(3872)X) \times \mathcal{B}(X(3872) \rightarrow \gamma J/\psi) \times \mathcal{B}(X \rightarrow (N_{ch} > 2)) < 5.1 fb$$

at 90% C.L.

- Not matching any predicted state.

- Above the  $D\bar{D}$  threshold. Should have large width but it is narrow.

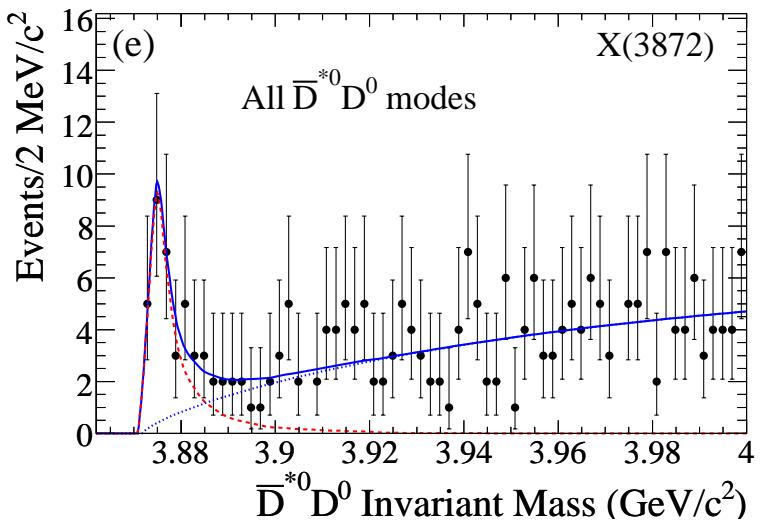
- Charmonium decay to  $J/\psi\rho$  highly suppressed because isospin violation.

$$X(3872) \rightarrow D^* \bar{D}.$$

- BELLE observes  $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$ .
- BABAR observes  $X(3872) \rightarrow D^* \bar{D}$ . (BABAR-PUB-07/049)

$$m = 3875.1 \pm 1.1 \pm 0.5 \quad MeV/c^2$$

$$\Gamma = 3.0^{+4.6}_{-2.3} \pm 0.9 \quad MeV$$

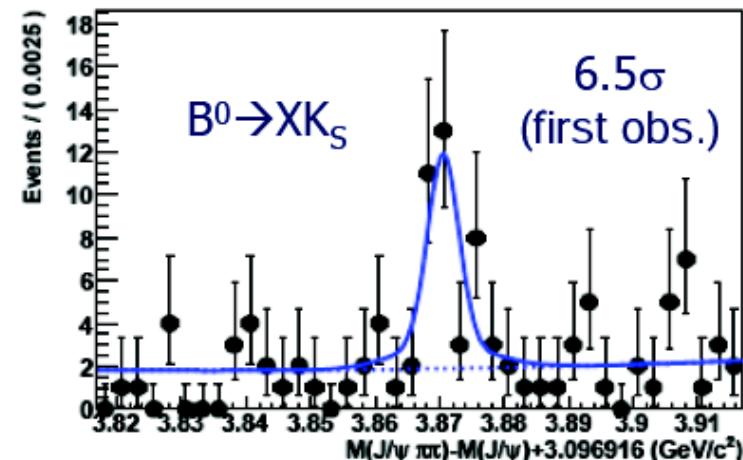
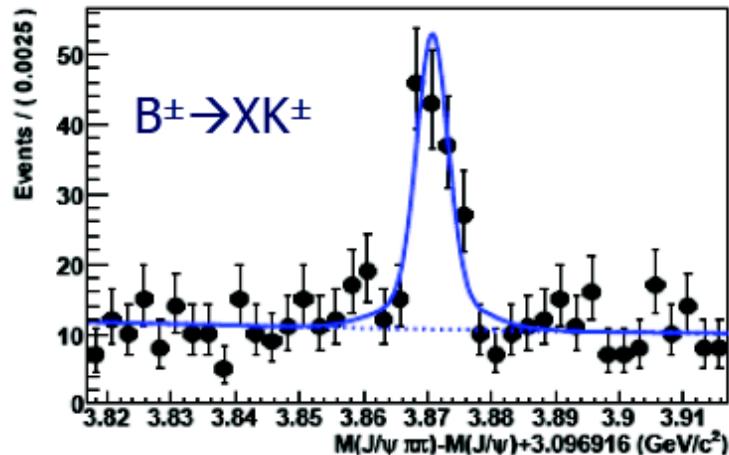


- Poor agreement in mass between  $J/\psi \pi\pi$  and  $D^* \bar{D}$  modes,  $\approx 3\sigma$ . However, presence of a threshold in  $D^* \bar{D}$ .

## X(3872) Production.

- New results from BELLE. Observation of  $X(3872)$  in  $B^+$  and  $B^0$  decays.

(BELLE-CONF-0711)



- Consistent with no mass difference:

$$\Delta m = (0.22 \pm 0.9 \pm 0.27) MeV/c^2$$

- Consistent with no rate difference:

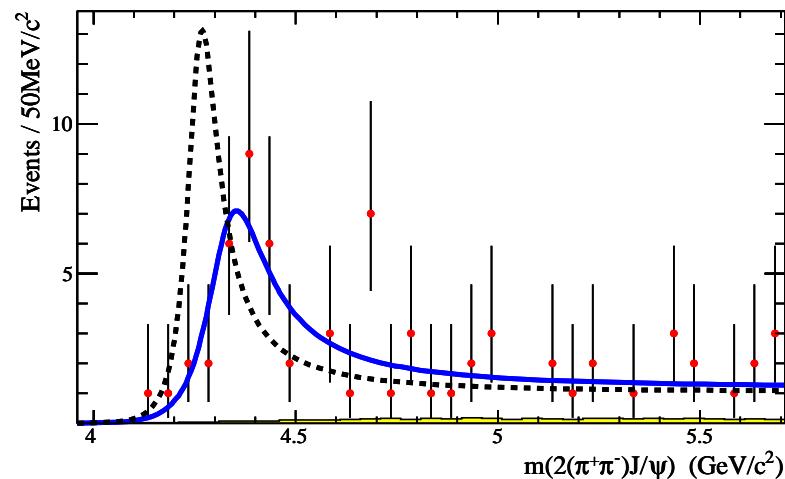
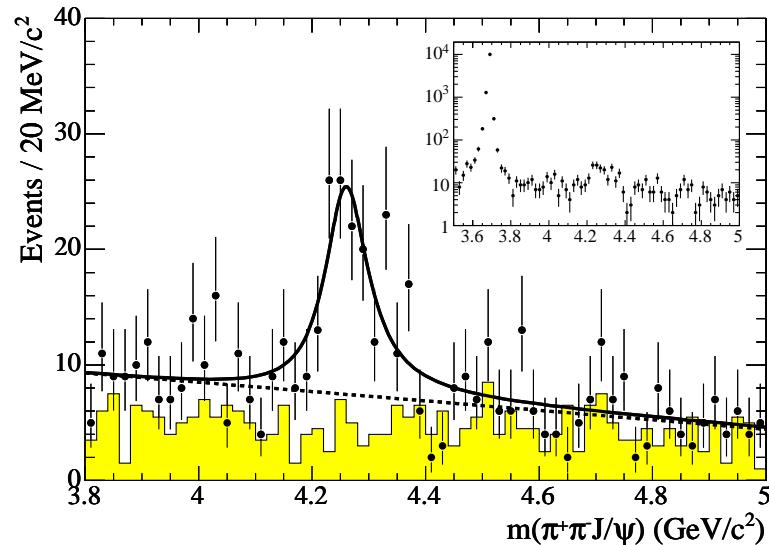
$$\frac{\mathcal{B}(B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow J/\psi\pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow X(3872)K_S^0, X(3872) \rightarrow J/\psi\pi^+\pi^-)} = 0.94 \pm 0.24 \pm 0.10$$

## The $J^P = 1^-$ family.

- BaBar: observation of  $Y(4260)$  in ISR events:  $J^P = 1^-$ .<sub>(PRL 95, 142001 (2005))</sub>

$$e^+ e^- \rightarrow \gamma_{ISR} Y(4260) (\rightarrow J/\psi \pi^+ \pi^-)$$

$$M(Y) = 4259 \pm 8^{+2}_{-6} \text{ MeV}/c^2, \quad \Gamma(Y) = 88 \pm 23^{+6}_{-4} \text{ MeV}$$



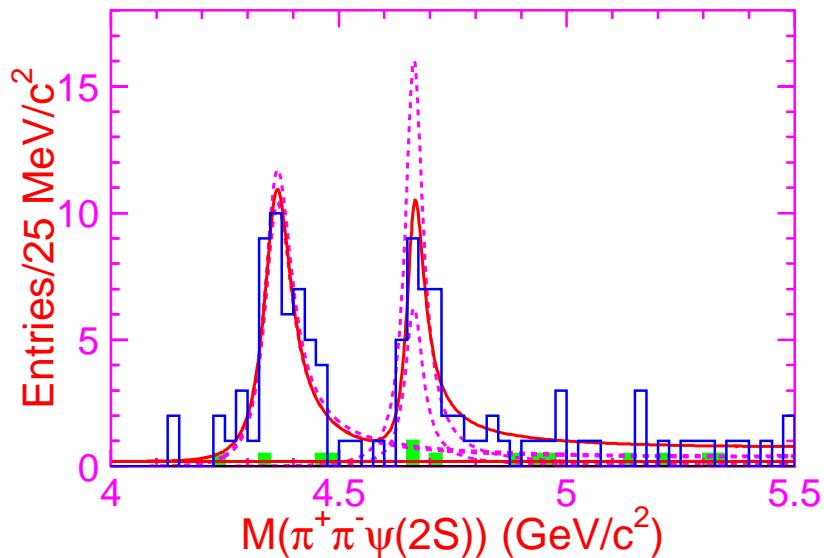
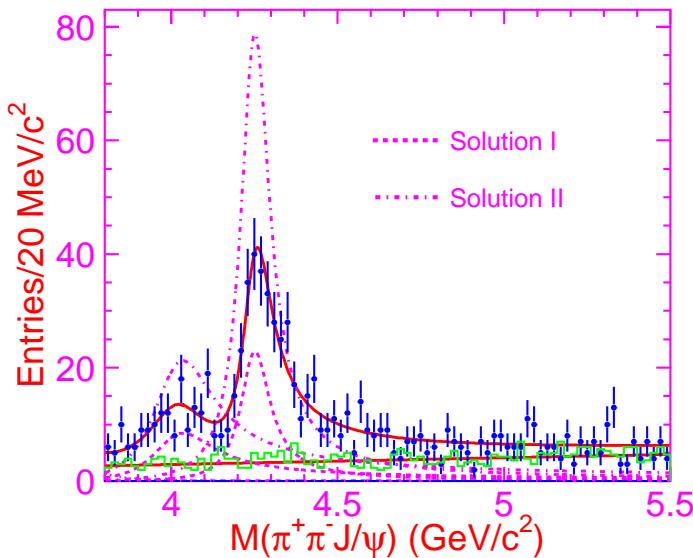
- BaBar, yet another state ( $Y(4350)$ ):<sub>(PRL 98, 1212001 (2007))</sub>

$$e^+ e^- \rightarrow \gamma_{ISR} Y(4350) (\rightarrow \psi(2S) \pi^+ \pi^-)$$

$$M(Y) = 4324 \pm 24 \text{ MeV}/c^2, \quad \Gamma(Y) = 172 \pm 33 \text{ MeV}$$

## The $J^P = 1^-$ family.

- New information from BELLE.



- Confirms BaBar findings.

$$M(Y) = 4247 \pm 12^{+17}_{-26} \text{ MeV}/c^2, \quad \Gamma(Y) = 108 \pm 19^{+8}_{-10} \text{ MeV}$$

$$M(Y) = 4361 \pm 9 \pm 9 \text{ MeV}/c^2, \quad \Gamma(Y) = 74 \pm 15 \pm 15 \text{ MeV}$$

- Claim/Evidence for further states:

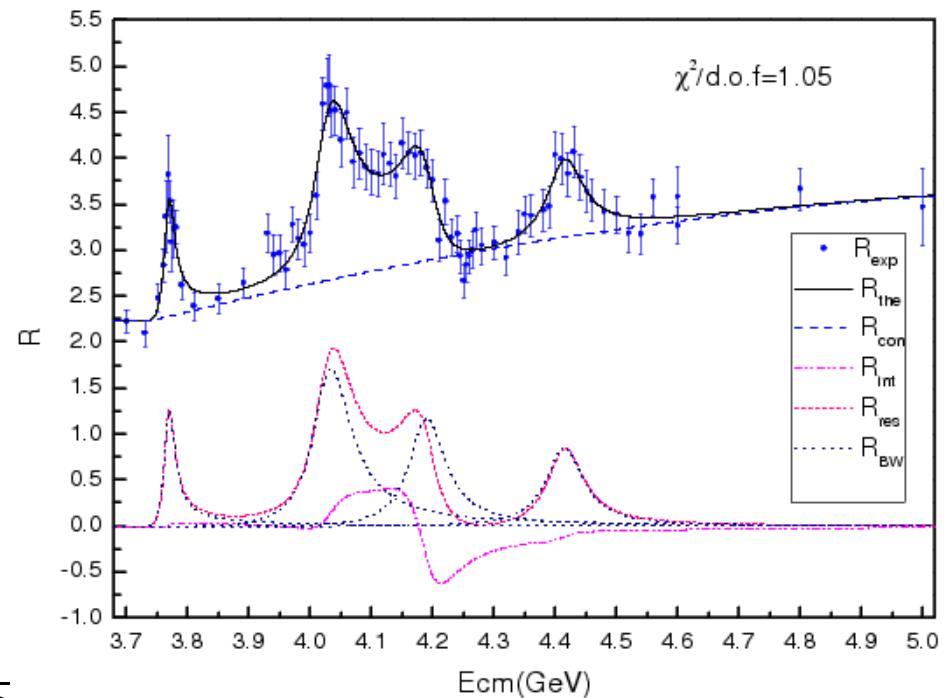
$$M(?) = 4008 \pm 40^{+72}_{-28} \text{ MeV}/c^2, \quad \Gamma = 226 \pm 44^{+87}_{-79} \text{ MeV}$$

$$M(Y) = 4664 \pm 11 \pm 5 \text{ MeV}/c^2, \quad \Gamma = 48 \pm 15 \pm 3 \text{ MeV}$$

## Search for $Y$ 's $D^{(*)}\bar{D}^{(*)}$ decays.

- BES fit of the R measurement. Include interferences among the different states.

$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
$3771.4 \pm 1.8$	$4038.5 \pm 4.6$	$4191.6 \pm 6.0$	$4415.2 \pm 7.5$
$25.4 \pm 6.5$	$81.2 \pm 14.4$	$72.7 \pm 15.1$	$73.3 \pm 21.2$

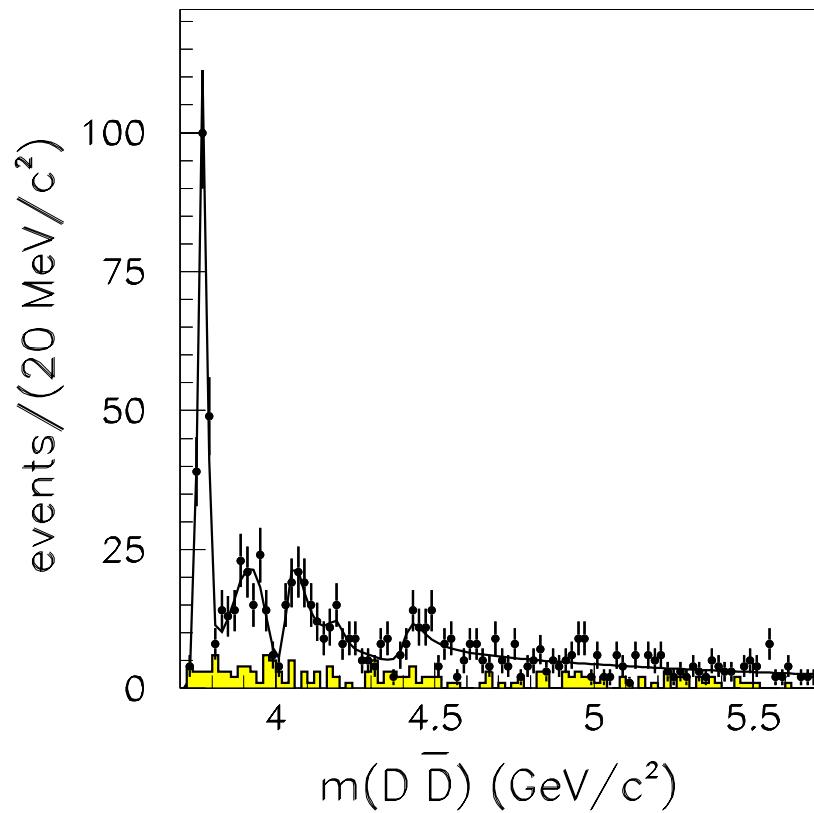


- No evidence for  $Y$ 's here.

## New information from ISR.

- BABAR (New Result): study of  $e^+e^- \rightarrow \gamma_{ISR} D\bar{D}$ .
- No evidence for  $Y(4260)$ .

$$\frac{\mathcal{B}(Y(4260) \rightarrow D\bar{D})}{\mathcal{B}(Y(4260) \rightarrow J/\psi \pi^+\pi^-)} < 1.0 \quad 90\% C.L.$$

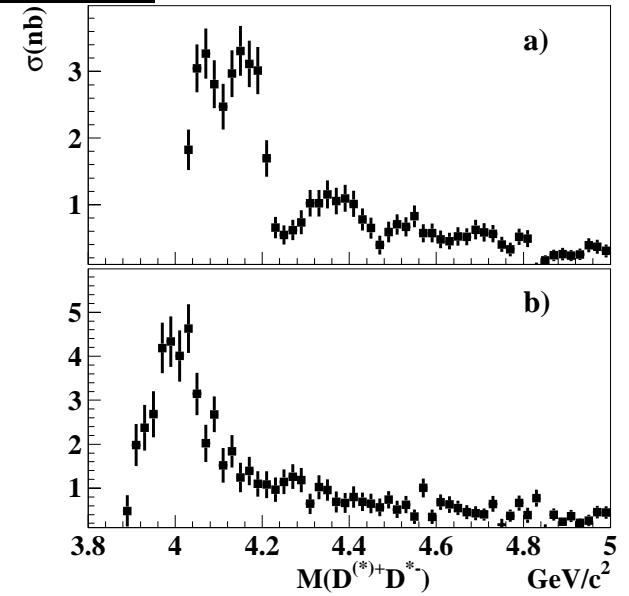


- Observation of structure in the 3.9 GeV region: expected from the coupled channel model of Eichten et al.

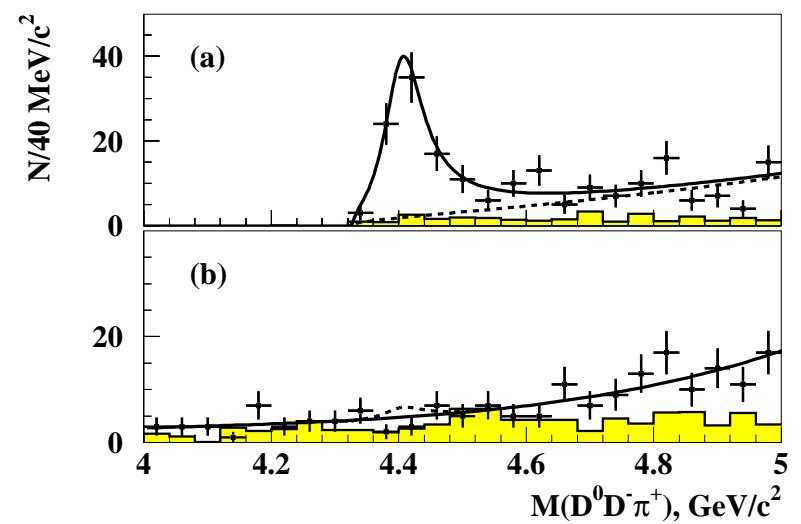
E. Eichten et al., Phys. Rev. **D21**, 203 (1980)

## New information from ISR.

- BELLE: study of  $e^+e^- \rightarrow \gamma_{ISR} D^{(*)}\bar{D}^{(*)}$ .

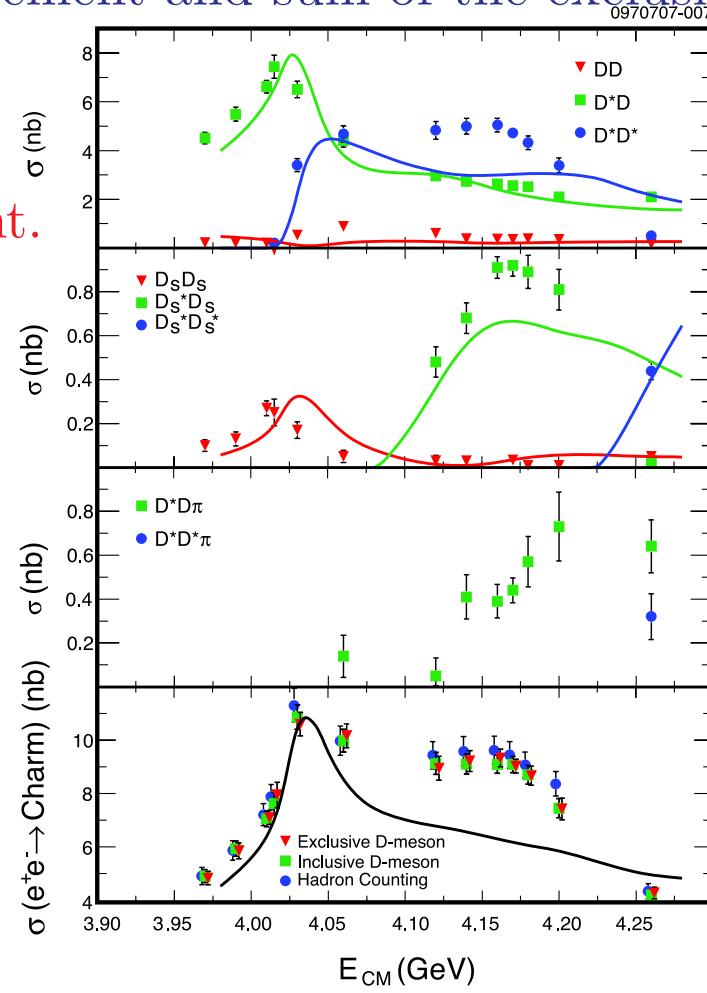
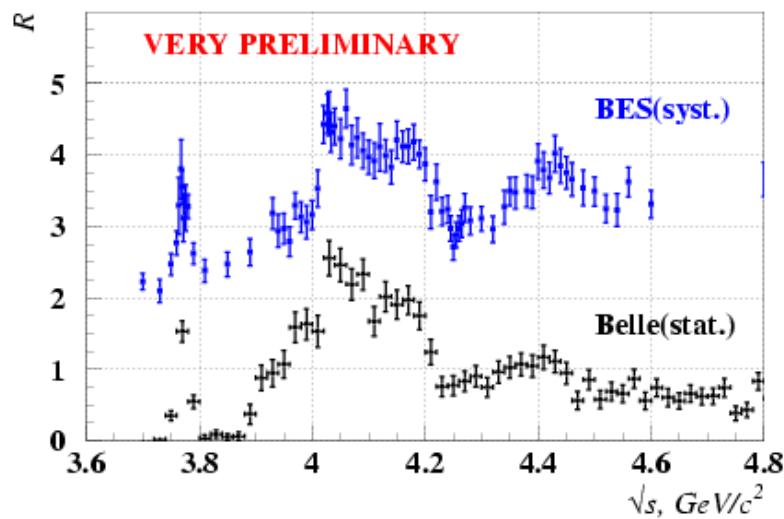


- BELLE: observation of  $\psi(4415) \rightarrow DD_2^*$ .



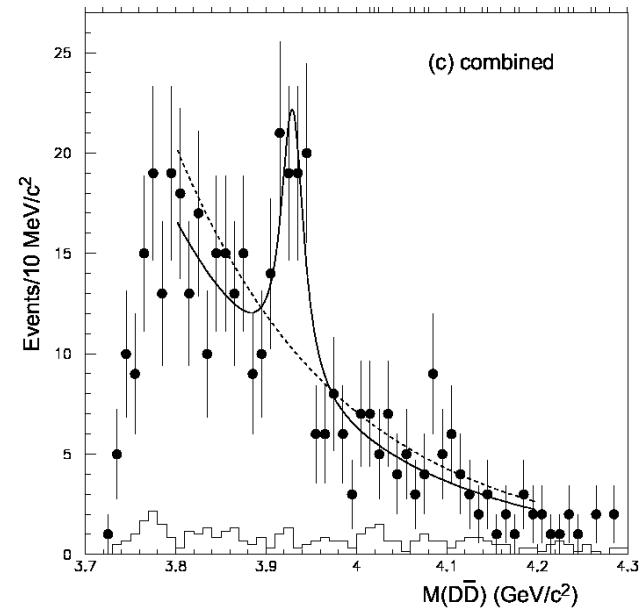
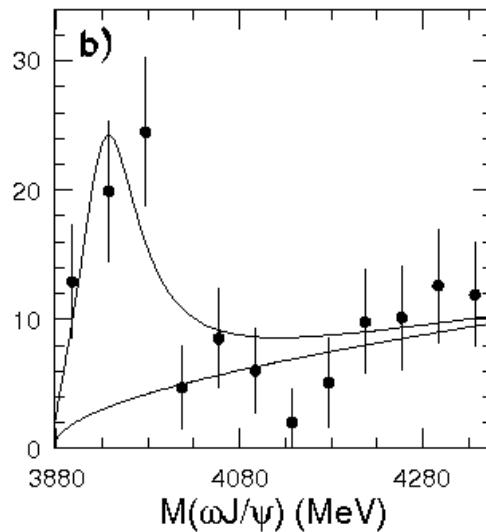
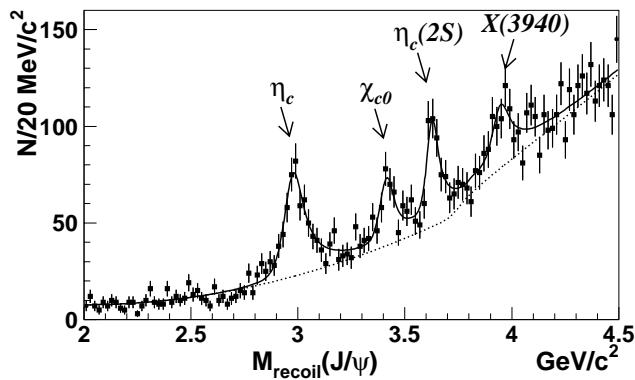
# New information from ISR.

- BELLE: Comparison between R measurement and sum of the exclusive measurements: good agreement.
- Upgraded coupled channel model on CLEO-c measurements: no good agreement.



# The X(3940) family.

□ Results from BELLE.



	Observed in	$J^{PC}?$	$M (MeV/c^2)$	$\Gamma (\text{MeV})$
X	$e^+e^- \rightarrow J/\psi X$	$0^{-+}, 1^{++}$	$3943 \pm 8$	$< 39$
Y	$B \rightarrow Y K (Y \rightarrow J/\psi \omega)$	$1^{++}, ..$	$3943 \pm 17$	$87 \pm 34$
Z	$\gamma\gamma \rightarrow Z (Z \rightarrow D\bar{D})$	$2^{++}$	$3929 \pm 5$	$29 \pm 10$

## More on $Y(3940)$ .

- BaBar: confirmation of  $Y(3940) \rightarrow J/\psi\omega$  in  $B \rightarrow J/\psi\omega K$ .

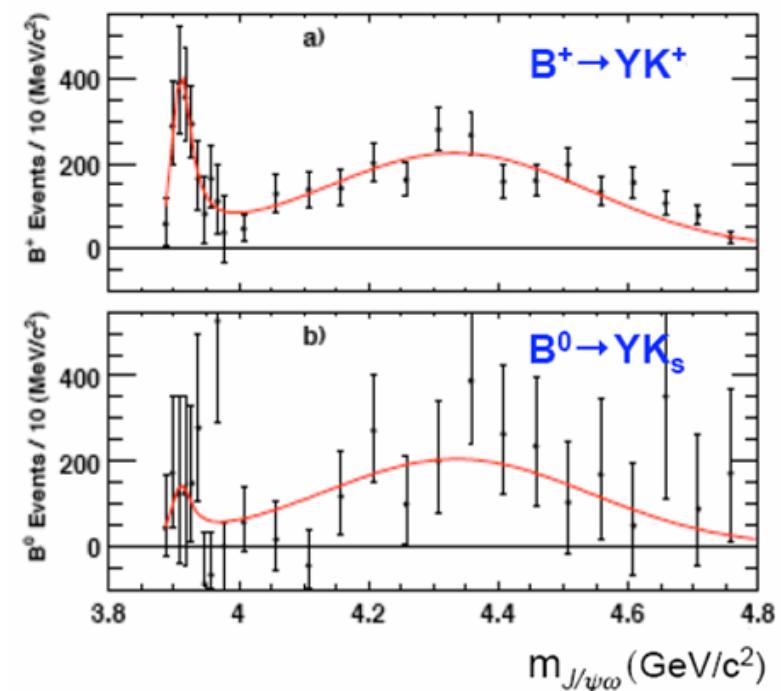
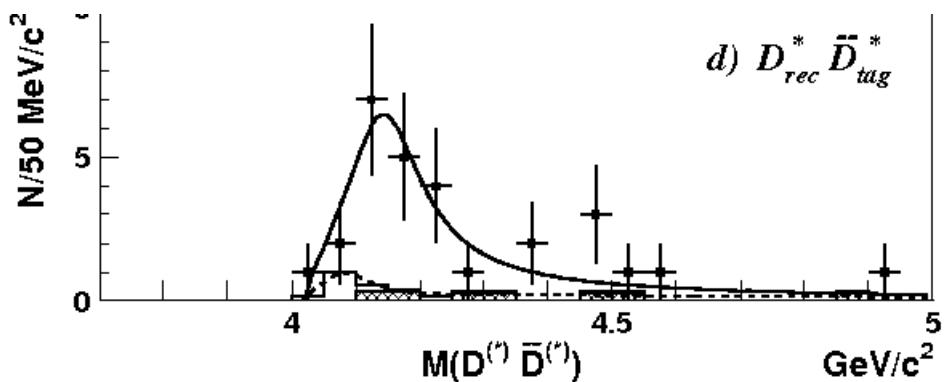
$$M = 3914.3^{+3.8}_{-3.4} \pm 1.6 \text{ MeV}/c^2, \quad \Gamma = 33^{+12}_{-8} \pm 6 \text{ MeV}$$

- $X(3940)$  the same as  $Y(3940)$ ?

- BELLE: Study of  $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ .

- Confirmation of  $X(3940) \rightarrow D^*\bar{D}$ .

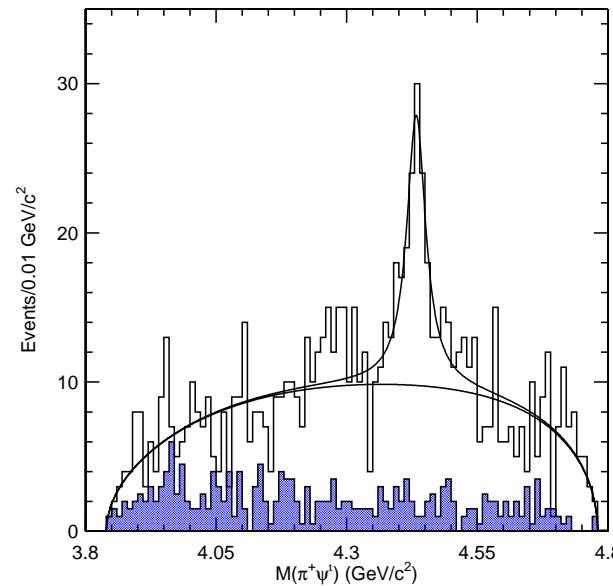
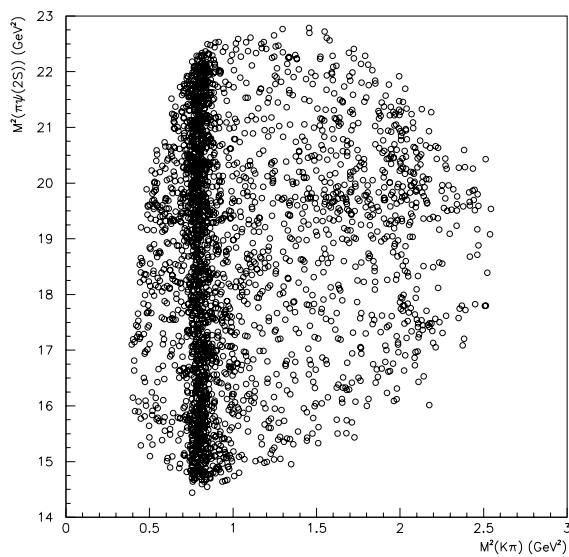
Further evidence for a new state  
in the  $D^*\bar{D}^*$  mass spectrum:  $\eta_c(3S)$ ?



$$M = 4156^{+25}_{-20} \pm 15 \text{ MeV}/c^2, \quad \Gamma = 37^{+111}_{-61} \pm 21 \text{ MeV}$$

# A new exotic charged state Z(4430)?

- BELLE: Study of  $B \rightarrow \psi(2S)K\pi$ . hep-ex/0708.1790



- $K^*$ 's removed. Narrow structure in  $\psi(2S)\pi^\pm$ .

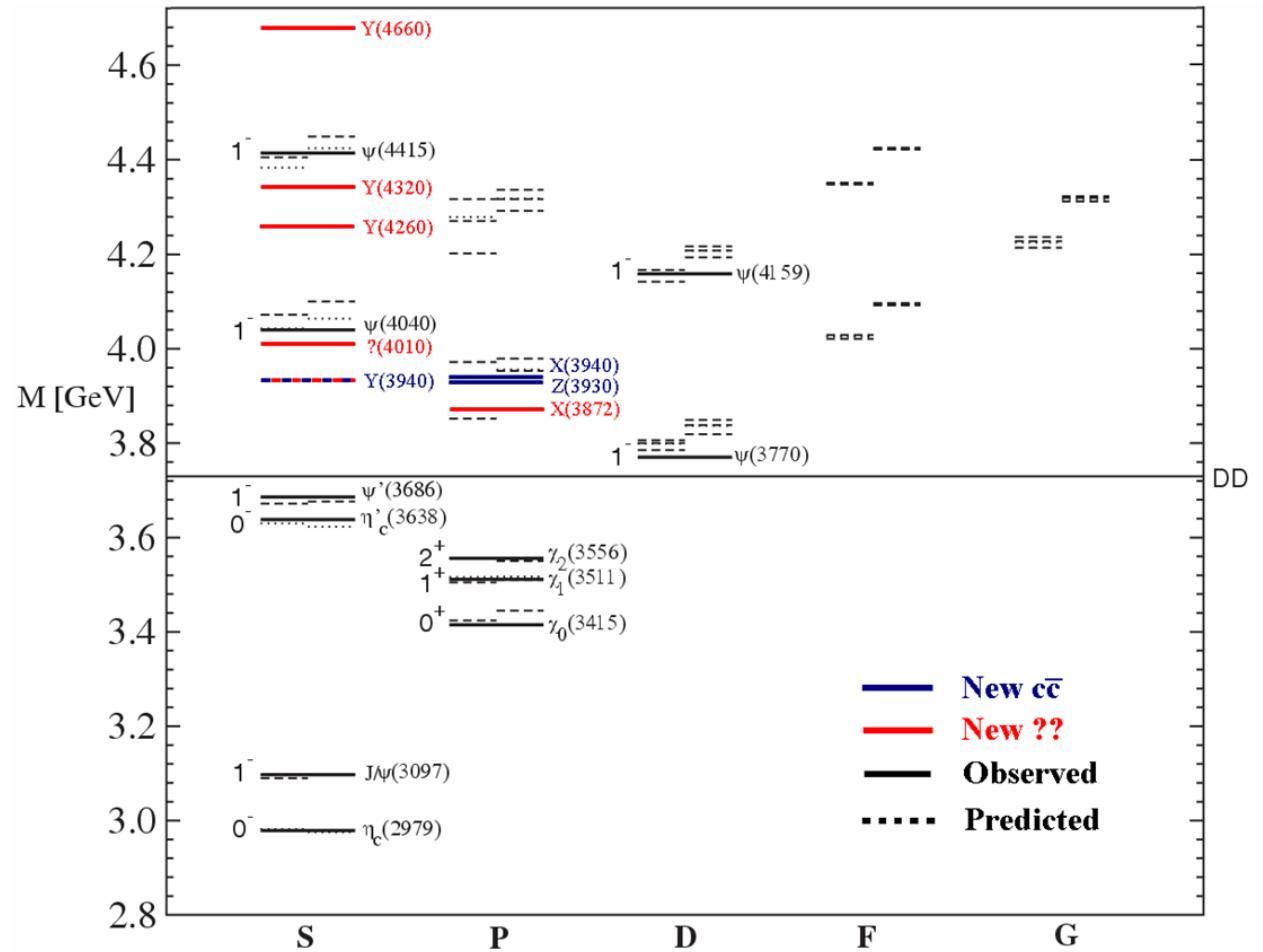
$$M = 4433 \pm 4 \pm 1 \text{ MeV}/c^2$$

$$\Gamma = 44^{+17+30}_{-13-11} \text{ MeV}$$

- If true: first observation of an exotic state.
- On an analysis of such a relevance: why not a full Dalitz analysis?

# Summary on the charmonium spectrum.

- Large number of new experimental results.
- Many states waiting for a classification.



## Conclusions.

- B-factories have produced a large mess of unexpected new states.
- Potential models are in troubles in trying to explain the available data.
- Are we close to the start of a new spectroscopy?
- Several possibilities:
  - Hybrids  $q\bar{q}g$ ;
  - Tetraquarks;  $(qq')\overline{(qq')}$
  - Molecules:  $(q\bar{q})(q'\bar{q}')$
- Need of new clean and high statistics data from many sources to clarify the situation.
- Super-B's,  $\tau - charm$  factories, LHCb?