Charm Spectroscopy

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on behalf of the **Belle Collaboration**

Outline

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- **New Results on Charmonia (Belle, BaBar, CLEO, BES)**
- Ω_c^0 **Mass and** Ω_c^0 **Semileptonic Decay (Belle)**
- **Observation of New Charmed Mesons**
  - **New** $c\bar{u}$ **states:** D^{**0} **with Belle**
  - **New** $c\bar{s}$ **states:** D_{sJ}^{**+} **with BaBar, CLEO, Belle**
- **Summary**

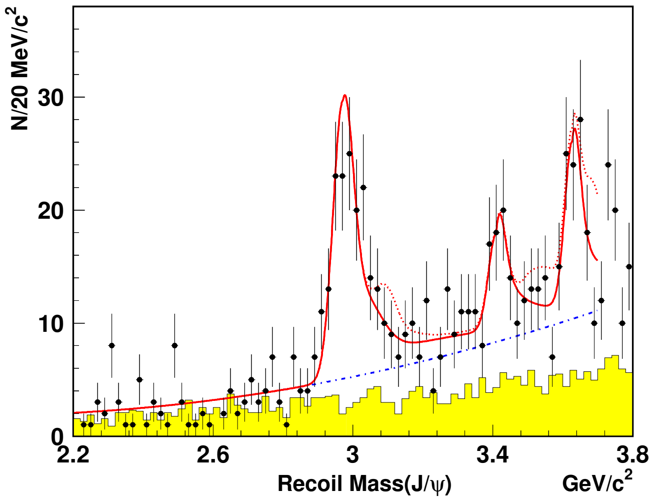
Introduction

- **Charm Spectroscopy provides information about QCD:**
  - **new resonances (masses and widths) - check model predictions for their properties**
  - **decay channels of charmonia are used to search for new light quark states (σ, κ etc.)**
- **Understanding of charm - insight to B physics**
- **B-factories proved to be rich source of new results on charm hadrons**

New Results on $\eta_c(2S)$ (Belle)

In 2002 Belle observed $\eta_c(2S)$ in B decays using 45 fb^{-1} of data:
$M(\eta_c(2S)) = 3654 \pm 6 \pm 8$ **MeV** (PRL 89, 102001 (2002)) **which is higher than previous evidence from Crystal Ball** ($M(\eta_c(2S)) = 3594 \pm 5$ **MeV).**

This year using 100 fb^{-1} of data Belle observed $\eta_c(2S)$ signal ($N = 108 \pm 24$ **events) in double $c\bar{c}$ process $e^+e^- \to J/\psi\eta_c(2S)$**



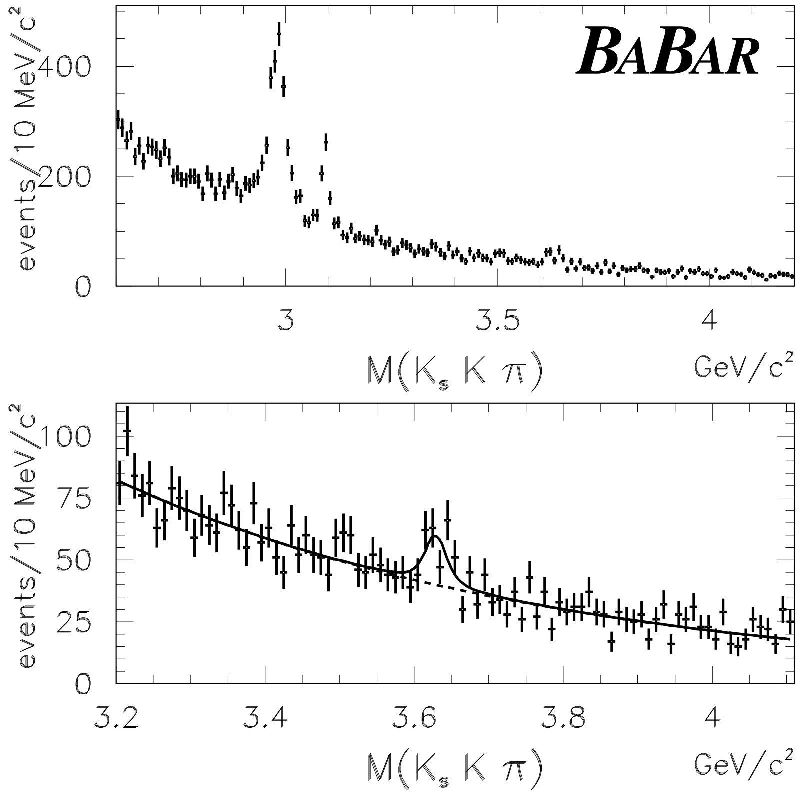
Belle preliminary:
$M(\eta_c(2S)) = 3630 \pm 8$ **MeV**

New Results on $\eta_c(2S)$ (BaBar)

Recently BaBar observed significant signal for $\eta_c(2S)$ production in $\gamma\gamma$ collisions.

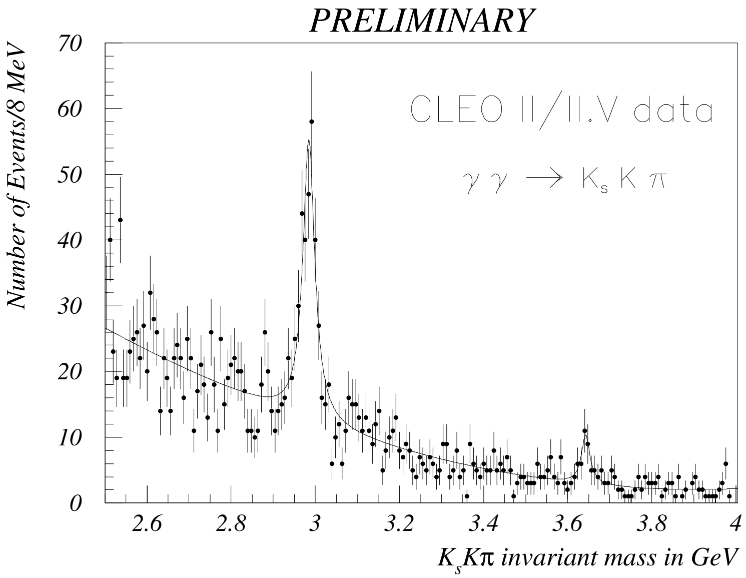
$$\gamma\gamma \to \eta_c \to K_s K \pi, \ \gamma\gamma \to \eta_c(2S) \to K_s K \pi$$

$N = 86 \pm 23$ **events at** $M(\eta_c(2S)) = 3632.2 \pm 5.0 \pm 1.8$ **MeV with total width** $\Gamma(\eta_c(2S)) = 20 \pm 10 \pm 4$ **MeV.**



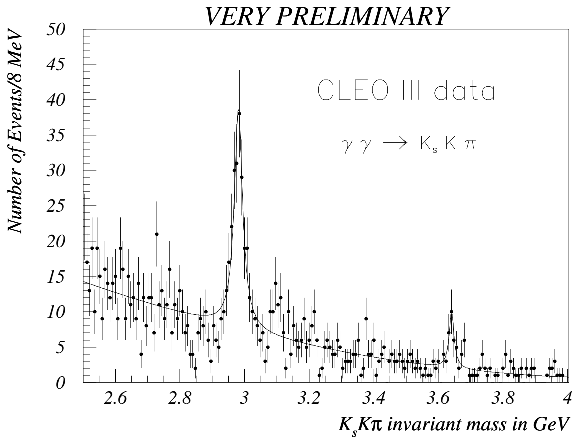
New Results on $\eta_c(2S)$ (CLEO)

CLEO also sees significant signals for $\eta_c(2S)$ production in $\gamma\gamma$ for both CLEO II/II.V and CLEO III data sets.



$\gamma\gamma \to \eta_c \to K_s K\pi$, $\gamma\gamma \to \eta_c(2S) \to K_s K\pi$

- $N = 36^{+15}_{-11}$ **events at** $M(\eta_c(2S)) = 3642.7 \pm 4.0 \pm 4.0$ **MeV**
- **signif.** $= 5.7\sigma$



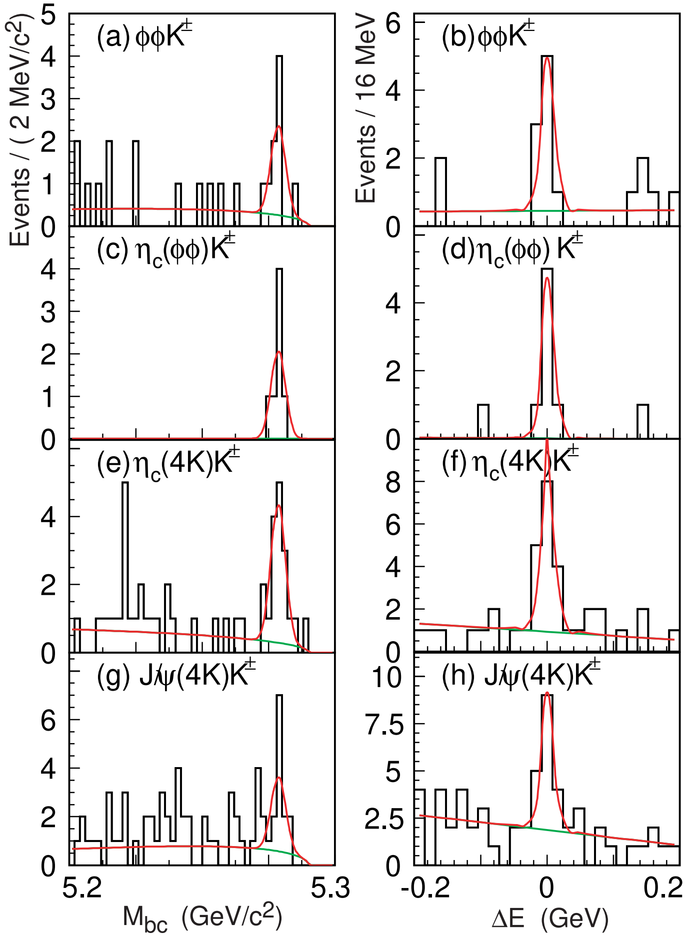
$\gamma\gamma \to \eta_c \to K_s K\pi$, $\gamma\gamma \to \eta_c(2S) \to K_s K\pi$

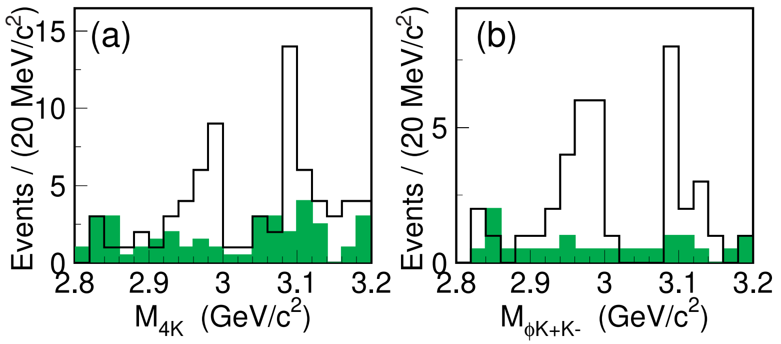
- $N = 29 \pm 8$ **events at** $M(\eta_c(2S)) = 3642.5 \pm 3.4$ **MeV**

New Results on Charmonia Decays (I)

New η_c and J/ψ Decay Modes (Belle)

By investigating $B \to \phi\phi K$, Belle obtained new results on η_c and J/ψ decays (78 fb^{-1}):





Decay Mode	$\mathcal{B}$ (Belle)	$\mathcal{B}$ (PDG)
$\eta_c \to \phi\phi$	$(1.8^{+0.8}_{-0.6} \pm 0.7) \times 10^{-3}$	$(7.1 \pm 2.8) \times 10^{-3}$
$\eta_c \to \phi K^+ K^-$	$(2.9^{+0.9}_{-0.8} \pm 1.1) \times 10^{-3}$	—
$\eta_c \to 2(K^+ K^-)$	$(1.4^{+0.5}_{-0.4} \pm 0.6) \times 10^{-3}$	$(2.1 \pm 1.2)\%$
$J/\psi \to \phi K^+ K^-$	$(2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-3}$	$(7.4 \pm 1.1) \times 10^{-4}$
$J/\psi \to 2(K^+ K^-)$	$(1.4^{+0.5}_{-0.4} \pm 0.2) \times 10^{-3}$	$(7.0 \pm 3.0) \times 10^{-4}$

(hep-ex/0305068)

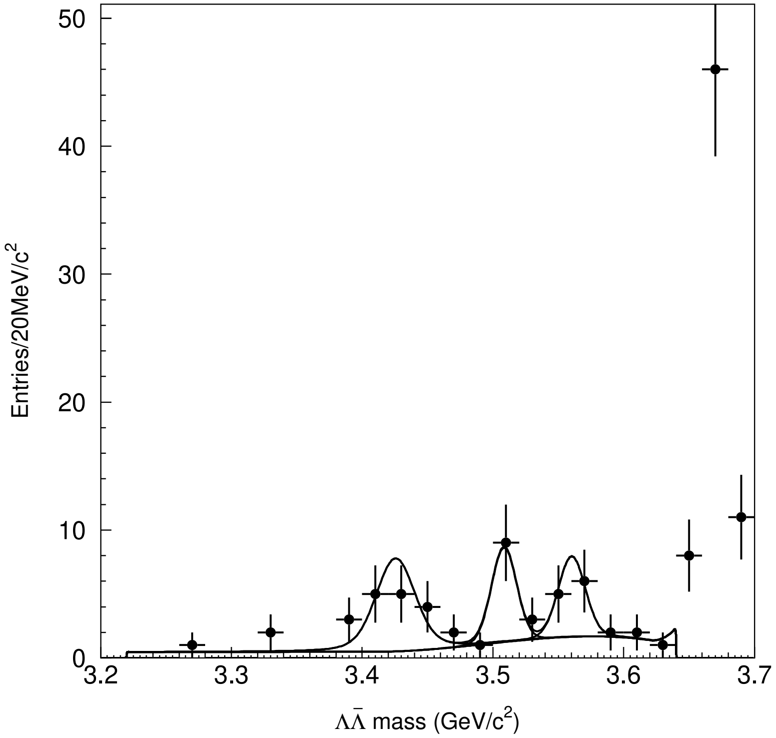
New Results on Charmonia Decays (II)

Selected New Results from the BES Collaboration

(1) Searching for lepton flavor violation in $J/\psi \to e\mu$:
$\mathcal{B}(J/\psi \to e\mu) < 1.1 \times 10^{-6}$ **@ 90% CL (hep-ex/0303005)**

(2) Several predictions for $\chi_{cJ} \to p\bar{p}$ using color-octet mechanism are in agreement with exp. measurements.

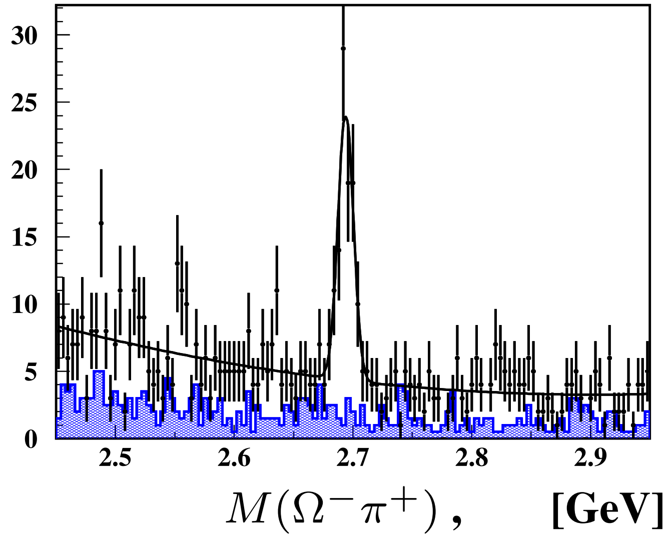
BES obtained first evidence for $\chi_{cJ} \to \Lambda\bar{\Lambda}$ on the data sample of 15M $\psi(2S)$ decays.



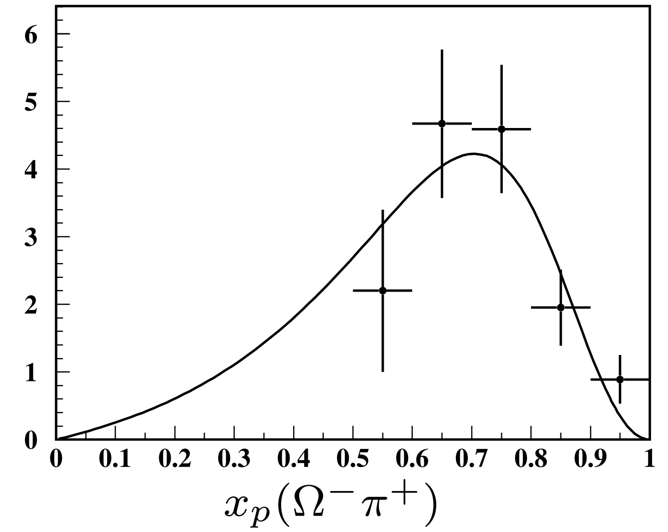
- **Reconstruction of $\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \Lambda\bar{\Lambda}$**
  - $\mathcal{B}(\chi_{c0} \to \Lambda\bar{\Lambda}) = (4.7^{+1.3}_{-1.2} \pm 1.0) \times 10^{-4}$
  - $\mathcal{B}(\chi_{c1} \to \Lambda\bar{\Lambda}) = (2.6^{+1.0}_{-0.9} \pm 0.6) \times 10^{-4}$
  - $\mathcal{B}(\chi_{c2} \to \Lambda\bar{\Lambda}) = (3.3^{+1.5}_{-1.3} \pm 0.7) \times 10^{-4}$
    - **(hep-ex/0304012)**
- **Obtained BF's are in agreement within errors with measured BF's for $\chi_{cJ} \to p\bar{p}$**

Ω_c^0 Mass Measurement using $\Omega_c^0 \to \Omega^- \pi^+$ / Belle, 87 fb^{-1}

The Ω_c^0 is the least well understand ground state charmed baryon



- $N(\Omega_c^0 \to \Omega^- \pi^+) = 80.5 \pm 10.8$ **events at**
- **Belle preliminary:**
  $M(\Omega_c^0) = 2693.9 \pm 1.1 \pm 1.4$ **MeV**
  - **- in a good agreement with CLEO measurement** $2694.6 \pm 2.6 \pm 1.9$ **MeV.**

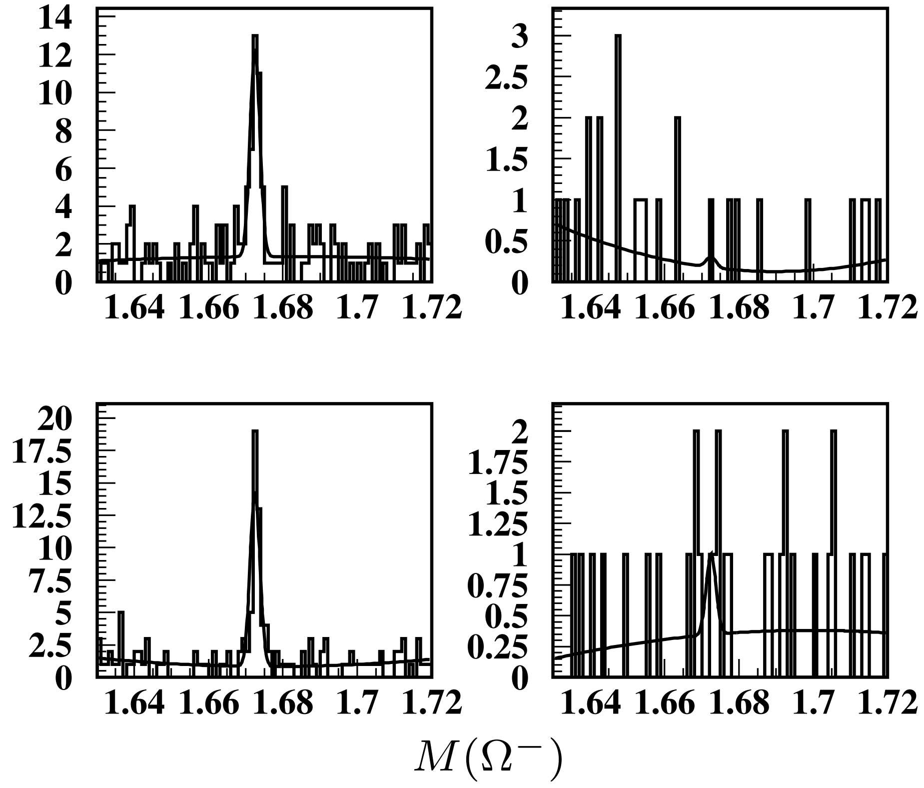


- Ω_c^0 **production study, Belle preliminary:**
  - $\epsilon_p = 0.12^{+0.04}_{-0.03} \pm 0.04$
  - $\sigma(\Omega_c^0 | x_p > 0.5) \times \mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) =$ $14.3 \pm 1.9 \pm 1.3$ **fb**
    (in agreement with CLEO result $11.3 \pm 3.9 \pm 2.0$ **fb)**
  - $\sigma(\Omega_c^0) \times \mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = 19.1^{+8.8}_{-6.2} \pm 1.9$ **fb**

$\Omega_c^0 \to \Omega^- l^+ \nu$ / Belle, 87 fb^{-1}

Belle observes both $\Omega_c^0 \to \Omega^- e^+ \nu$ and $\Omega_c^0 \to \Omega^- \mu^+ \nu$:

Ω^- with right-sign lepton Ω^- with wrong-sign lepton

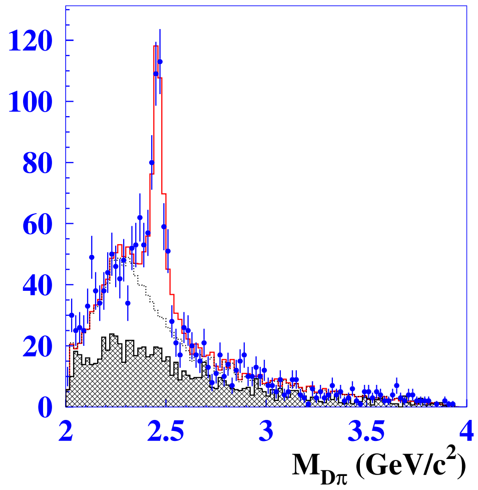


- 35.5 ± 6.1 **signal** $\Omega^- e^+$ **events**
- 43.7 ± 7.1 **signal** $\Omega^- \mu^+$ **events**

- **After bkg. subtr'n Belle preliminary results are:**
  - $\sigma(\Omega_c^0 | x_p > 0.5) \times \mathcal{B}(\Omega_c^0 \to \Omega^- l^+ \nu) = 17.5 \pm 3.0$ **fb (PRELIMINARY)**
  - $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- l^+ \nu)} = 0.8 \pm 0.3$, **(CLEO:** $0.40 \pm 0.19 \pm 0.04$**)**

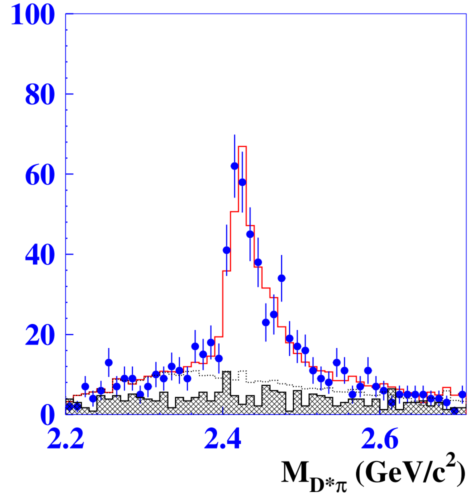
Observation of new $c\bar{u}$ states / Belle, 60 fb^{-1} (updated from ICHEP'02)

Using full reconstruction of D^+ and D^{*+} mesons, Belle studied B decays to $D^{(*)+}\pi^-\pi^-$ and observed two broad P-wave D^{**0} mesons. Dalitz analysis was performed.



The minimal $D^+\pi^-$ mass for $B^- \to D^+\pi^-\pi^-$ candidates

- $M(D_0^{*0}) = (2308 \pm 17 \pm 15 \pm 20)$ **MeV**
- $\Gamma(D_0^{*0}) = (276 \pm 21 \pm 18 \pm 60)$ **MeV**
  - **for known narrow resonance** $M(D_2^{*0}) = (2461.6 \pm 2.1 \pm 0.5 \pm 3.3)$ **MeV and** $\Gamma(D_2^{*0}) = (45.6 \pm 4.4 \pm 6.5 \pm 1.6)$ **MeV** **(higher than world average of** $\Gamma = 23 \pm 5$ **MeV)**

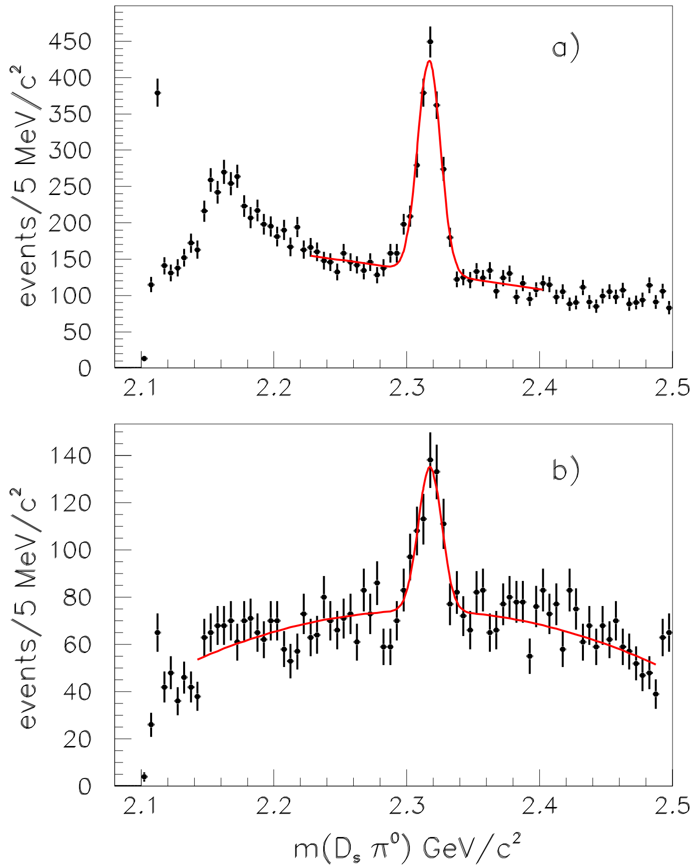


The minimal $D^{*+}\pi^-$ mass for $B^- \to D^{*+}\pi^-\pi^-$ candidates

- $M(D_1^{*0}) = (2427 \pm 26 \pm 20 \pm 15)$ **MeV**
- $\Gamma(D_1^{*0}) = (384^{+107}_{-75} \pm 24 \pm 70)$ **MeV**
- **consistent with the prelim. results previously reported by CLEO**
  - **for known narrow resonance** $M(D_1^0) = (2421.4 \pm 2.0 \pm 0.4 \pm 0.8)$ **MeV and** $\Gamma(D_1^0) = (23.7 \pm 2.7 \pm 0.2 \pm 4.0)$ **MeV**

Observation of new $c\bar{s}$ states / BaBar

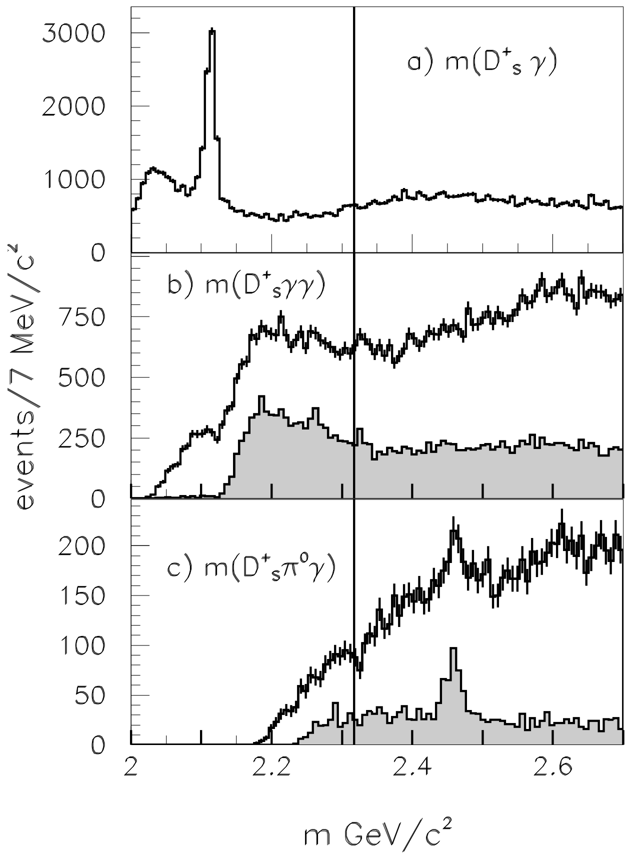
$D_{sJ}(2317) \to D_s\pi^0$



$$M(D_{sJ}(2317)) = 2316.8 \pm 0.4 \textbf{ MeV}$$

hep-ex/0304021

Evidence for the new state

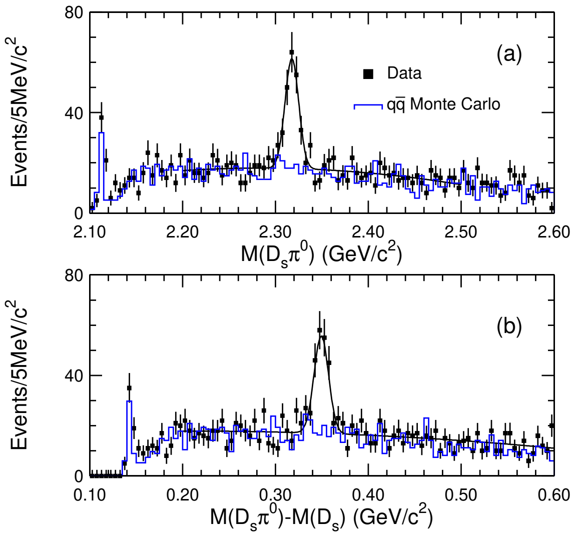


$$M(D_{sJ}(2460)) \approx 2460 \textbf{ MeV}$$

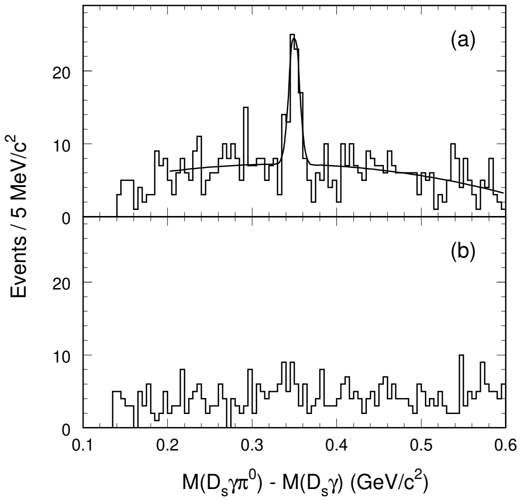
Observation of new $c\bar{s}$ states / CLEO

- Treated by Sheldon Stone

Confirmation of $D_{sJ}(2317)$



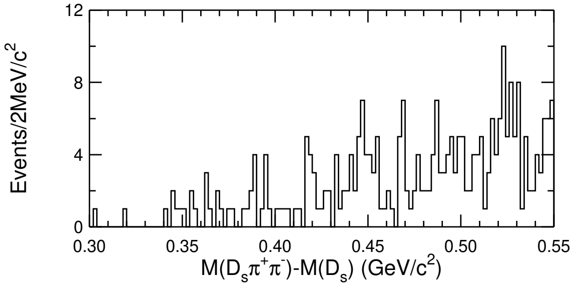
Observation of $D_{sJ}(2460)$



Search for

$D^{**}_{sJ} \to D_s\pi^+\pi^-$

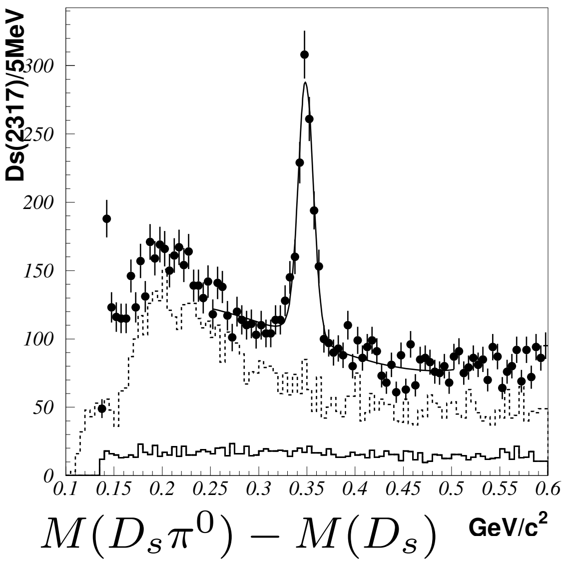
(*forbidden for* 0^+ *state*)



- $\Delta M = M(D_{sJ}(2317)) - M(D_s) = 350.0 \pm 1.2 \pm 1.0$ **MeV,**
  $\Delta M = M(D_{sJ}(2460)) - M(D^*_s) = 351.2 \pm 1.7 \pm 1.0$ **MeV**
- **naturally interpreted as $c\bar{s}$ mesons with $J^P = 0^+$ and $J^P = 1^+$**
- **consistent with model of Bardeen, Eichten and Hill who predicted**
  $\Delta M(1^+ - 1^-) = \Delta M(0^+ - 0^-)$

(hep-ex/0305100)

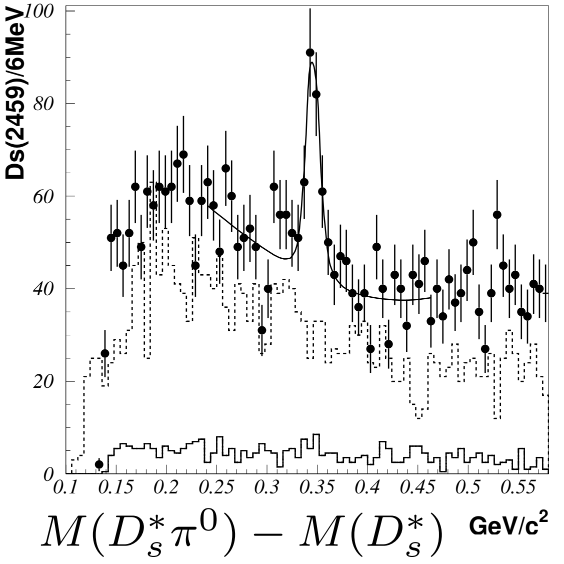
$D_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ at Belle, 78 fb^{-1}



$D_{sJ}(2317) \to D_s^+\pi^0$

Results after feed-across account (preliminary):

- $N = 643.2 \pm 50.4$ **events at**
- $\delta M = M(D_{sJ}(2317)) - M(D_s) = 348.9 \pm 0.5$ **MeV**
- $M(D_{sJ}(2317)) = 2317.4 \pm 0.5$ **MeV**
- **In agreement with BaBar and CLEO measurements**



$D_{sJ}(2460) \to D_s^{*+}\pi^0$

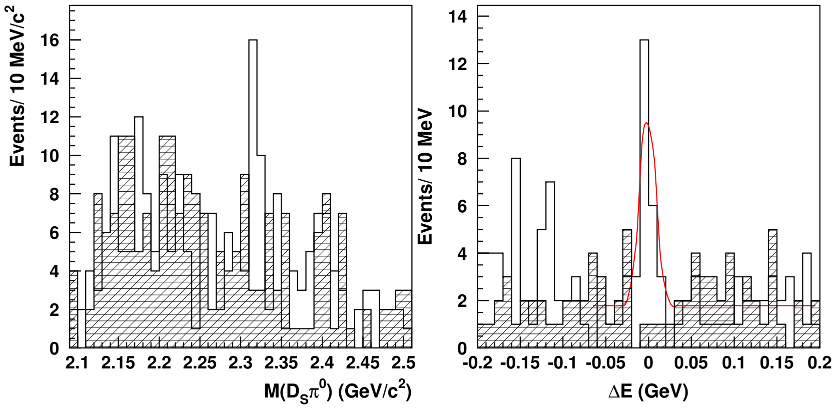
Results after feed-across account (preliminary):

- $N = 79.1 \pm 18.0$ **events at**
- $\delta M = M(D_{sJ}(2460)) - M(D_s^*) = 345.4 \pm 1.3$ **MeV**
- $M(D_{sJ}(2460)) = 2457.8 \pm 1.4$ **MeV**
- **In agreement with BaBar and CLEO measurements**
  - **Also in agreement with theoretical prediction**

Observation of the $D_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ in B decays / Belle, 90 fb^{-1}

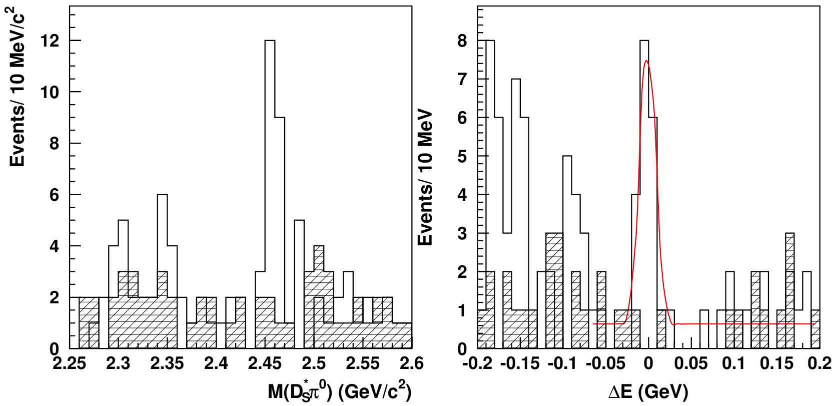
- **Treated by Karim Trabelsi**

Study of $D_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ production in B decays aims to shed light on the nature of the these states.



$B \to DD_{sJ}(2317)$, $D_{sJ}(2317) \to D_s^+\pi^0$

- $N = 18.8^{+5.4}_{-4.8}$ **events,** $\Sigma = 5.3\sigma$
- $M = 2318 \pm 4$ **MeV**
- $\mathcal{B}(B \to DD_{sJ}(2317)) \times \mathcal{B}(D_{sJ}(2317) \to D_s^+\pi^0)$ $= (9.9^{+2.8}_{-2.5} \pm 3.0) \times 10^{-4}$



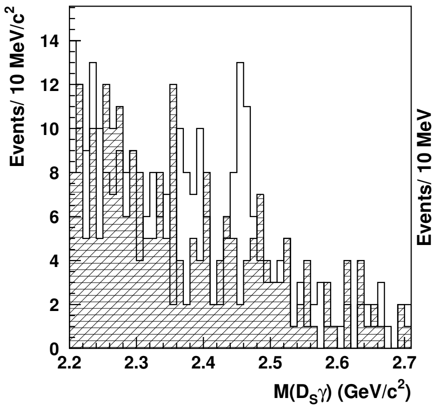
$B \to DD_{sJ}(2460)$, $D_{sJ}(2460) \to D_s^{*+}\pi^0$

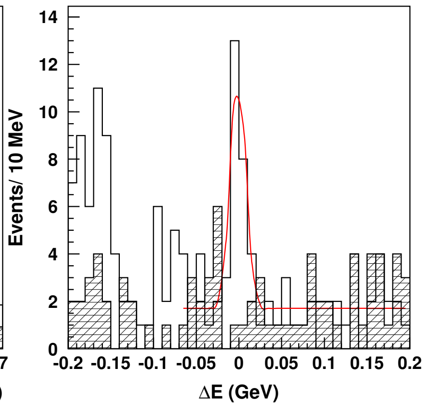
- $N = 16.7^{+4.8}_{-4.1}$ **events,** $\Sigma = 6.0\sigma$
- $M = 2460 \pm 3$ **MeV**
- $\mathcal{B}(B \to DD_{sJ}(2460)) \times \mathcal{B}(D_{sJ}(2460) \to D_s^{*+}\pi^0)$ $= (25.8^{+7.0}_{-6.0} \pm 7.7) \times 10^{-4}$

PRELIMINARY

- Treated by Karim Trabelsi

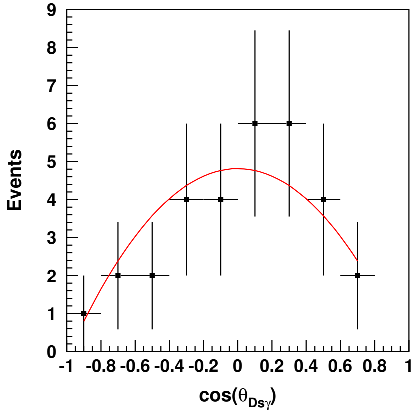
The $D_{sJ}(2460)^+ \to D_s^+\gamma$ is forbidden if this state has $J^P = 0^+$.





$B \to DD_{sJ}(2460)$, $D_{sJ}(2460) \to D_s^+\gamma$

- $N = 21.8^{+5.8}_{-5.1}$ events, $\Sigma = 5.9\sigma$
- $M = 2460 \pm 2$ MeV
- $\mathcal{B}(B \to DD_{sJ}(2460)) \times \mathcal{B}(D_{sJ}(2460) \to D_s^+\gamma)$ $= (5.3^{+1.4}_{-1.3} \pm 1.6) \times 10^{-4}$



Angular analysis helps to identify total J of $D_{sJ}(2460)$

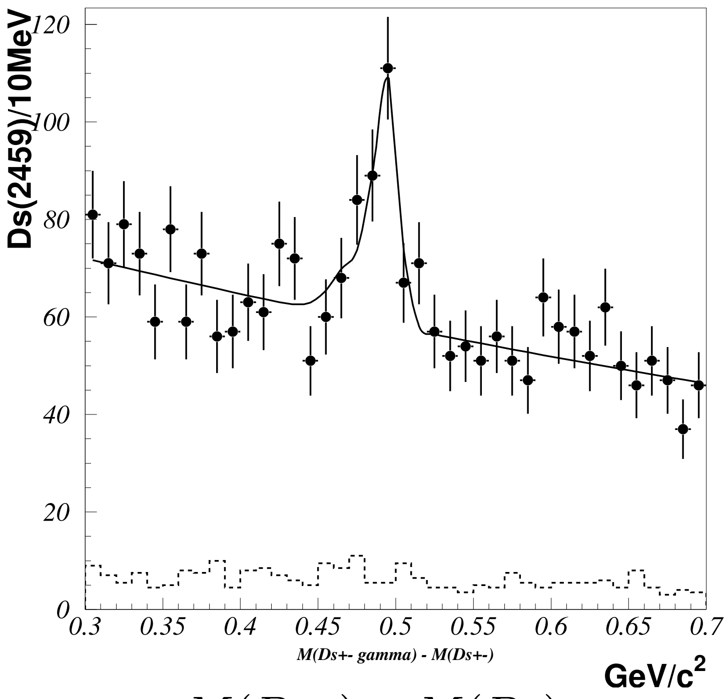
- consistent with $sin^2\theta$ (expected for 1^+ state: $sin^2\theta$)
- exp.ratio $\frac{\mathcal{B}(D_{sJ}(2460)\to D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2460)\to D_s^{*+}\pi^0)} = 0.21 \pm 0.07 \pm 0.03$ consistent with theoretical predictions
- Belle results are in agreement with hypothesis that $D_{sJ}(2317)$ and $D_{sJ}(2460)$ are P-wave states with $j_q = 1/2$.

priliminary

Observation of $D_{sJ}(2460)^+ \to D_s^+\gamma$ / Belle, 78 fb^{-1} (cont'd)

Belle observed this decay mode also in continuum:

Similar analysis as for $D_{sJ}^{**} \to D_s^{(*)}\pi^0$ was performed. (+ more tight cuts for γ selection)



$M(D_s\gamma) - M(D_s)$

- **No peak for $D_{sJ}(2317)$ (consistent with assignment $J^P = 0^+$ for $D_{sJ}(2317)$ since $0^+ \to 0^- 1^-$ is forbidden by spin-parity)**
- **Significant signal for $D_{sJ}(2460)^+ \to D_s^+\gamma$**
  - $N = 128 \pm 20$ **events**
- **This excludes a possibility of $D_{sJ}(2460)^+$ being 0^- state!**

very preliminary

Summary on Charmonia and other charmed hadrons

- $\underline{\eta_c(2S)}$ is seen now with Belle, BaBar and CLEO in different processes - in exclusive B decays, $e^+e^- \to J/\psi\eta_c(2S)$ and $\gamma\gamma$
  - Belle, BaBar, CLEO masses of $\eta_c(2S)$ are consistent and somewhat higher than previous Crystall Ball measurement and theoretical expectations
- Belle and BES obtained several new results on η_c, J/ψ and χ_{cJ} decays - interesting for QCD
- Belle measurement of Ω_c^0 mass in good agreement with previous CLEO measurement - check model predictions

Summary on new $c\bar{q}$ states

- **Belle performed Dalitz analysis for $B \to D^{(*)+}\pi^-\pi^-$ and observed missing P-wave states $D_0^{*0}(0^+)$ and $D_1^{*0}(1^+)$**
- **BaBar observed new $c\bar{s}$ state $D_{sJ}(2317) \to D_s\pi^0$**
  - **CLEO and Belle confirm this state**
  - **no evidences for $D_{sJ}(2317) \to D_s\gamma, D_s^*\gamma$ or $D_s\pi^+\pi^-$**

    (forbidden for 0^+ and allowed for 1^+)
- **BaBar presented evidence for another state $D_{sJ}(2460) \to D_s^*\pi^0$**
  - **CLEO and Belle observed this narrow state**
    - **since its mass is above DK threshold, the $D_{sJ}(2460)$ would decay to DK if $J^P = 0^+$ (then should be broad)**
- **all mass measurements are in good agreement**

Summary on new $c\bar{q}$ states (continued)

- **Belle observed exclusive $B \to DD_{sJ}(2317)$ and $B \to DD_{sJ}(2460)$ decays:** $\Rightarrow$
  consistent with 0^+ and 1^+ (both having $j_q = 1/2$), since
  - **production of D_{sJ}^{**} with $j_q = 3/2$ in B decays is suppressed compared to that with $j_q = 1/2$ according to theoretical expectations (works of A.Le Yaouanc *et al.*)**
- **Belle observed new decay mode $D_{sJ}(2460) \to D_s\gamma$ both in continuum and in B decays**
  - **preliminary angular analysis for $D_{sJ}(2460) \to D_s\gamma$ using exclusive decays $B \to DD_{sJ}(2460)$ favours the hypothesis that $D_{sJ}(2460)$ state has $J^P = 1^+$**

Summary on new $c\bar{q}$ states (cont'd 2)

- *Currently we have candidates for all P-wave $c\bar{u}$ and $c\bar{s}$ states*

But the measured by Belle masses of broad P-wave $c\bar{u}$ states (0^+ and 1^+ with $j_q = 1/2$) are even the same as $D_{sJ}(2317)$ and $D_{sJ}(2460)$ have - the natural candidates for 0^+ and 1^+ $c\bar{s}$ P-wave states with $j_q = 1/2$.

To solve this fresh puzzle:

"why these two new $c\bar{s}$ states have so small masses?"

one should carefully measure their properties further!