Charmed Meson Spectroscopy at BELLE

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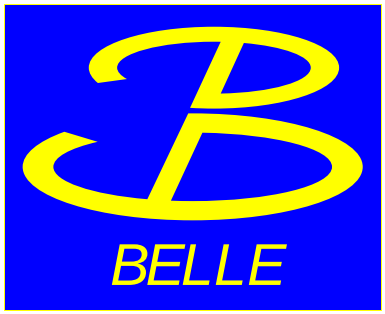
Contents



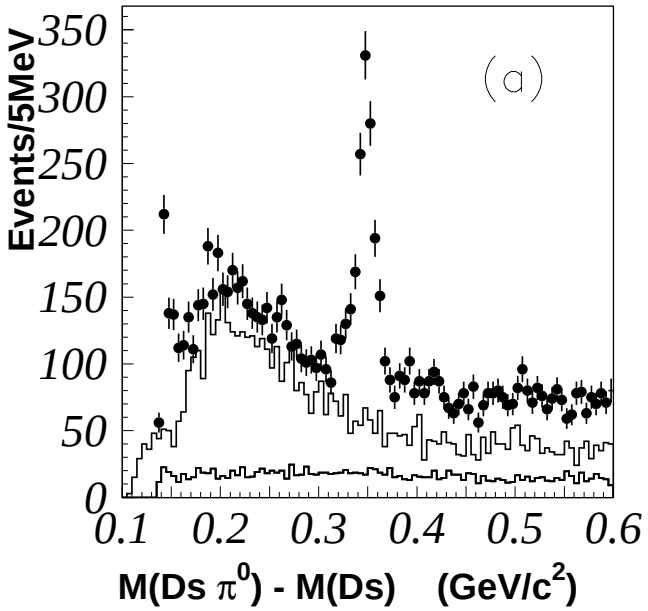
Introduction of $D_{sJ}^{\pm}$

- **BaBar discovered new narrow resonance $D_{sJ}(2317)$ from isospin violating $D_{sJ}(2317) \to D_s^{\pm}\pi^0$ decay. They provided a hint of 2.46 GeV/c^2 resonance.**

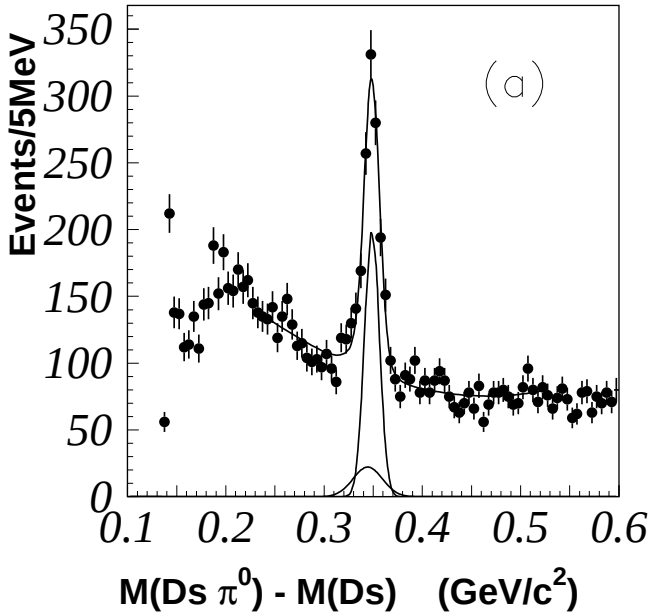
- **CLEO established the new resonance around 2.46 GeV/c^2 from $D_s^*\pi^0$ decay.**

- **BELLE observed both D_{sJ} states in B decay and continuum process ($e^+e^- \to c\overline{c}$).**
- **BELLE observed both radiative decay and dipion decay of $D_{sJ}(2457)$.**

- **BELLE 87 fb^{-1} data of $e^+e^- \to c\bar{c}$ process**
  (Phys. Rev. Lett. 92, 012002 (2004))
- $D_{sJ}(2317)^{\pm} \to D_s^{\pm}\pi^0$ and $D_s^{\pm} \to \phi(\to K^+K^-)\pi^{\pm}$
- $\mathrm{N_{evts}}(D_{sJ}(2317)) = 761 \pm 44(\mathrm{stat}) \pm 30(\mathrm{syst})$ $(P_{D_{sJ}} \geq 3.5$ GeV/c in e^+e^- CM)
- **Below D K mass threshold**



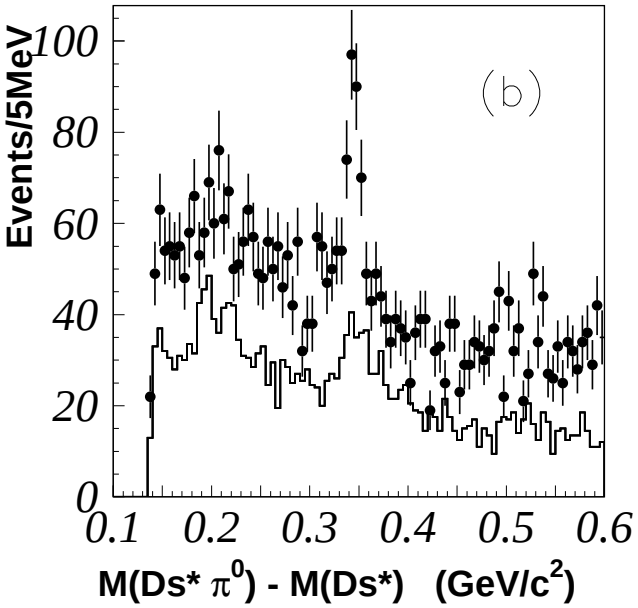
Histograms: π^0/D_s sideband backgrounds



Small peak is feeddown from $D_{sJ}(2457)$

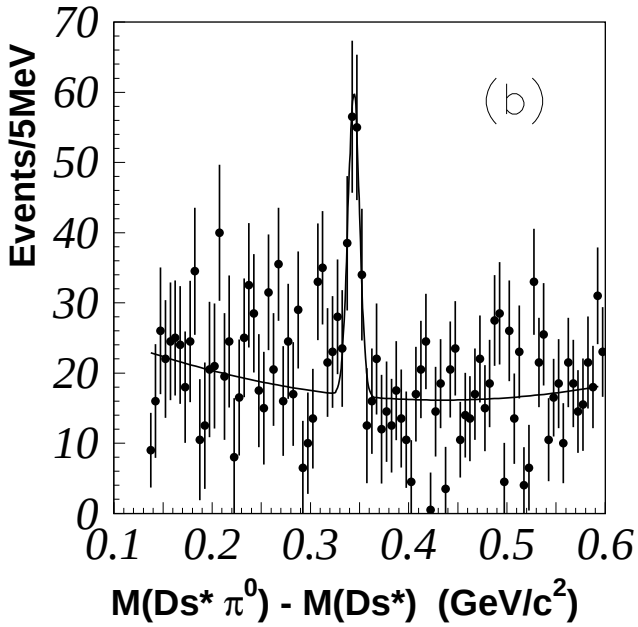
- $M(D_{sJ}^+(2317)) = 2317.2 \pm 0.5(\mathrm{stat}) \pm 0.9(\mathrm{syst})$ **MeV/c^2**
- $\Gamma(D_{sJ}(2317)) \leq 4.6$ MeV/c^2 (90% C.L.)

- $D_{sJ}(2457)^{\pm} \to D_s^{*\pm}\pi^0$, $D_s^{*\pm} \to D_s\gamma$ and $D_s^{\pm} \to \phi\pi^{\pm}$
- $\mathrm{N_{evts}}(D_{sJ}(2457)) = 126 \pm 25(\mathrm{stat}) \pm 12(\mathrm{syst})$ $(P_{D_{sJ}} \geq 3.5$ GeV/c in e^+e^- CM)
- Below D^* K mass threshold
- **Feedacross background contamination is dominant**



Histogram: $D_s^{*\pm}$ sideband backgrounds

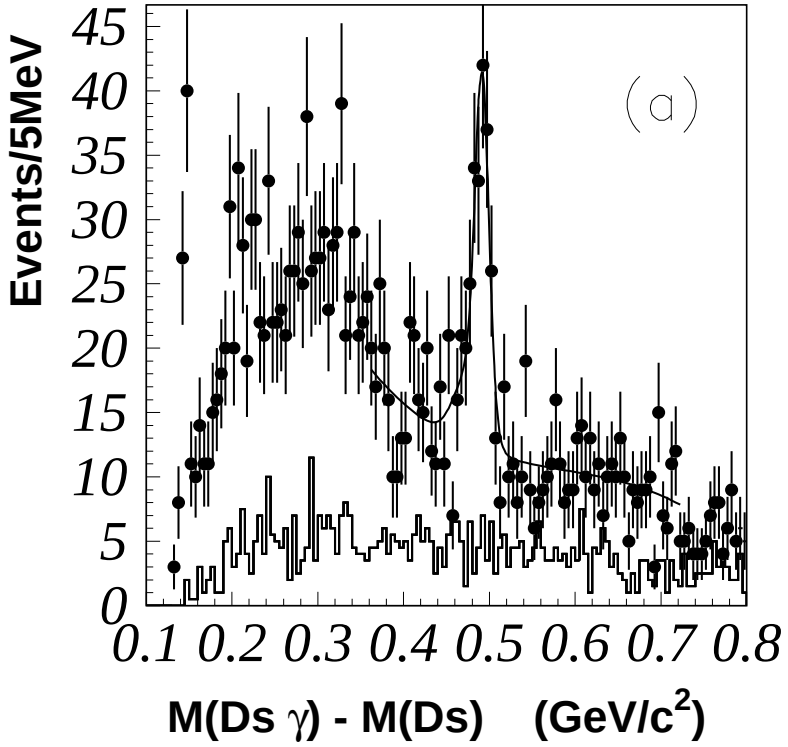
(Feedup background + broken signal)



$D_s^{*\pm}$ sideband subtracted

- $M(D_{sJ}^{+}(2457)) = 2456.5 \pm 1.3(\mathrm{stat}) \pm 1.3(\mathrm{syst})$ **MeV/c^2**
- $\Gamma(D_{sJ}(2457)) \leq 5.5$ MeV/c^2 (90% C.L.)

- $D_{sJ}(2457)^{\pm} \to D_s^{\pm}\gamma$ and $D_s^{\pm} \to \phi\pi^{\pm}$ in $e^+e^- \to c\bar{c}$ process
- $\mathrm{N_{evts}}(D_{sJ}(2457)) = 152 \pm 18(\mathrm{stat})$
  ($P_{D_{sJ}} \geq 3.5$ GeV/c, $E_\gamma \geq 600$ MeV/c in e^+e^- CM)



Histogram: $D_s^{\pm}$ sideband background

$$\frac{Br(D_{sJ}(2457)^+ \to D_s^+\gamma)}{Br(D_{sJ}(2457)^+ \to D_s^{*+}\pi^0)} = 0.55 \pm 0.13\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})$$

(BELLE, $B \to \overline{D} D_{sJ}(2457)$; $0.38 \pm 0.11 \pm 0.04$)

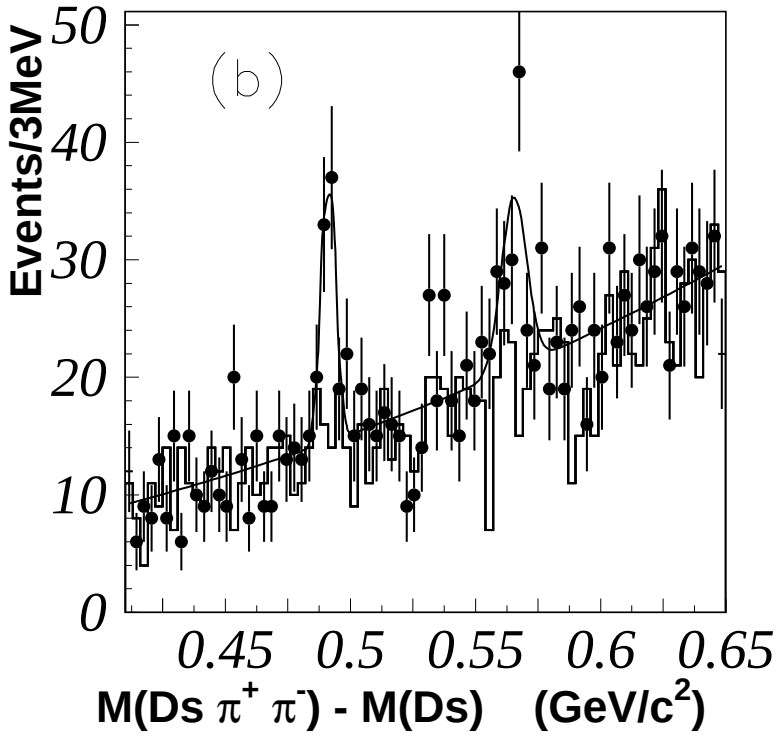
(D_{s1} assumption: 0.62, Godfrey, Phys. Lett. B 568, 254 (2003).)

$J^P = 0^{\pm}$ is ruled out for $D_{sJ}(2457)$.

$$\frac{Br(D_{sJ}(2317)^+ \to D_s^+\gamma)}{Br(D_{sJ}(2317)^+ \to D_s^+\pi^0)} \leq 0.05$$

(J^P constrain; $= 0$)

- $D_{sJ}(2457)^{\pm} \to D_s^{\pm}\pi^+\pi^-$ and $D_s^{\pm} \to \phi\pi^{\pm}$ in $e^+e^- \to c\bar{c}$ process
- $\mathrm{N_{evts}}(D_{sJ}(2457)) = 60 \pm 11(\mathrm{stat})$ (5.7σ); $\Delta M = 491.4 \pm 0.9(\mathrm{stat}) \pm 1.5(\mathrm{syst})$ MeV/c^2
  $\mathrm{N_{evts}}(D_{s1}(2536)) = 57 \pm 13(\mathrm{stat})$ (4.5σ); $\Delta M \sim 570$ MeV/c^2
  ($P_{D_{sJ}} \geq 3.5$ GeV/c, One $P_{\pi^+} \geq 300$ MeV/c in e^+e^- CM)



Histogram: $D_s^{\pm}$ sideband background

$$\frac{Br(D_{sJ}^+(2457)\to D_s^+\pi^+\pi^-)}{Br(D_{sJ}^+(2457)\to D_s^{*+}\pi^0)} = 0.14 \pm 0.04(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

(D_{s1} assumption: 0.16, Godfrey, Phys. Lett. B 568, 254 (2003).)

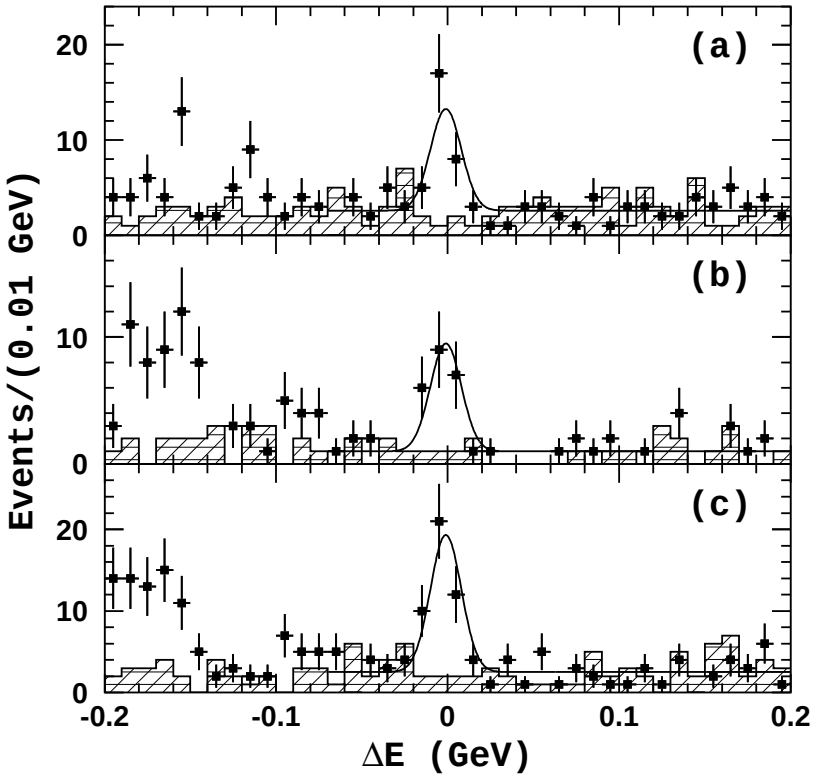
$J^P = 0^+$ is ruled out for $D_{sJ}(2457)$.

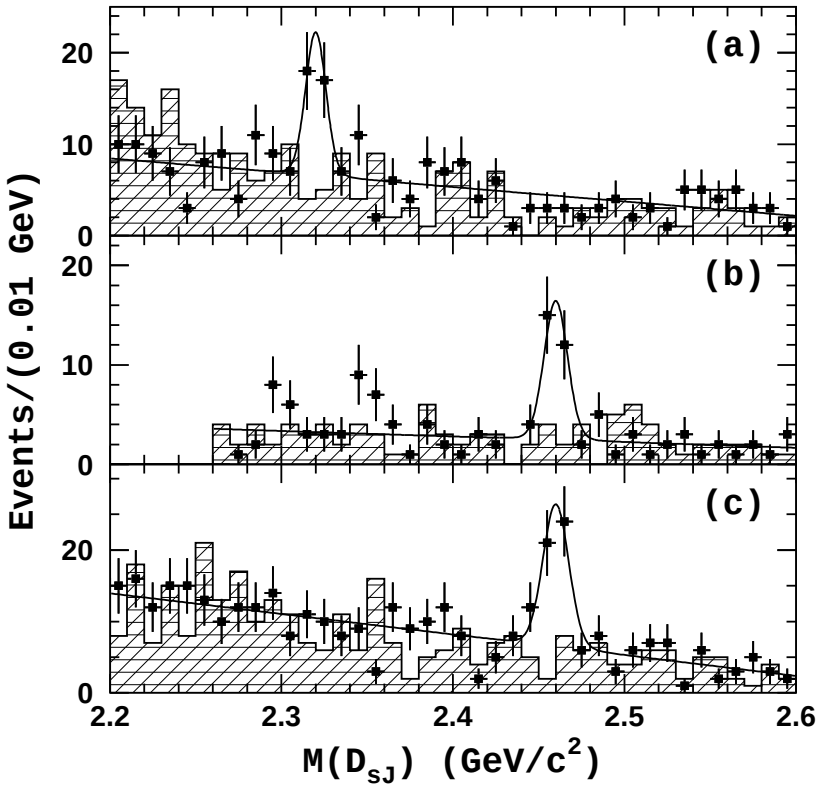
$$\frac{Br(D_{sJ}^+(2317)\to D_s^+\pi^+\pi^-)}{Br(D_{sJ}^+(2317)\to D_s^+\pi^0)} \leq 4 \times 10^{-3}\ (90\%\ C.L.)$$

$$\frac{\sigma(D_{s1}(2536)) \cdot Br(D_{s1}^+(2536) \to D_s^+\pi^+\pi^-)}{\sigma(D_{sJ}(2457)) \cdot Br(D_{sJ}^+(2457) \to D_s^+\pi^+\pi^-)} = 1.05 \pm 0.32(\mathrm{stat}) \pm 0.06(\mathrm{syst}).$$

First evidence of $D_{s1}^+(2536) \to D_s^+\pi^+\pi^-$.

- **BELLE 128M $B\overline{B}$ pairs**
- $B \to \overline{D} D_{sJ}$ (Phys. Rev. Lett. 91, 262002 (2003))





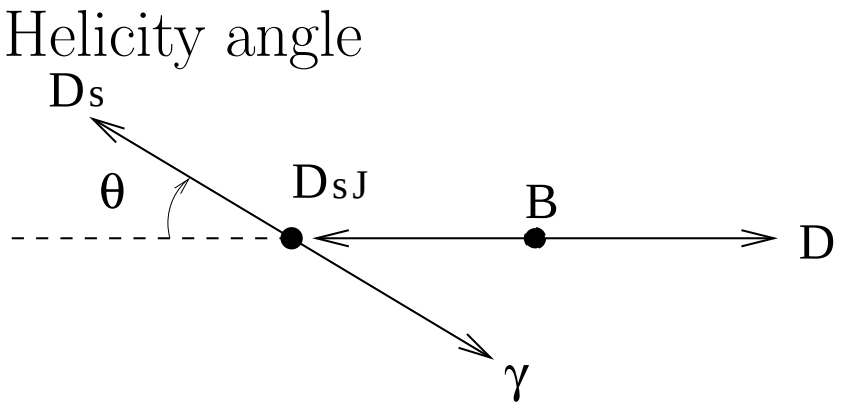
$\Delta \mathrm{E} = \Sigma_i \; E_i \; \text{-} \; E_{beam}$

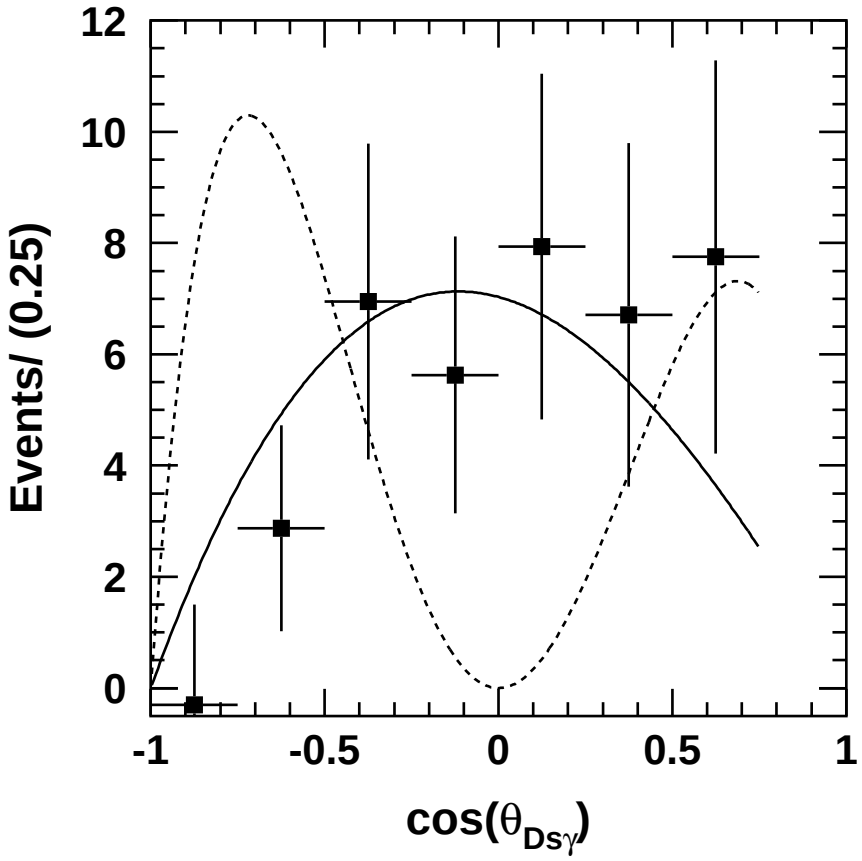
a) $Br(B \to \overline{D} D_{sJ}(2317)[D_s\pi^0]) = (\; 8.5^{+2.1}_{-2.9} \pm 2.6) \times 10^{-4}$ $(6.1\ \sigma)$

b) $Br(B \to \overline{D} D_{sJ}(2457)[D_s^*\pi^0]) = (17.8^{+4.5}_{-3.9} \pm 5.3) \times 10^{-4}$ $(6.4\ \sigma)$

c) $Br(B \to \overline{D} D_{sJ}(2457)[D_s\ \gamma]) = (\; 6.7^{+1.3}_{-1.2} \pm 2.0) \times 10^{-4}$ $(7.4\ \sigma)$

Angular analysis in $B \to \overline{D} D_{sJ}(2457)(\to D_s\gamma)$ decay





Solid line: $\boldsymbol{J = 1}$ (χ^2/n.d.f = 5/6)

Dashed line: $\boldsymbol{J = 2}$ (χ^2/n.d.f = 44/6)

Spin-parity assignment for $D_{sJ}(2317)$

- Decay to pseudoscalar pair final state ($D_s\pi^0$) is ovserved.
  (J = L, then P = $(-1)^J$)
  $\longrightarrow$ If S-wave case (most likely) in $D_s\pi^0$, $J^P = 0^+$.
  $\longrightarrow$ If P-wave case, $J^P = 1^-$.

- $D_s\gamma$ decay is not observed $\longrightarrow$ favors $0^\pm$
  (If D_{sJ} has $J^P = 1^\pm$, it can decay into this final state.)
- $D_s\pi^+\pi^-$ decay is not observed $\longrightarrow$ favors 0^+

- $B \to \overline{D}D_{sJ}(2317)$ likely not to be high J.

These support $J^P = 0^+$ for $D_{sJ}(2317)$.

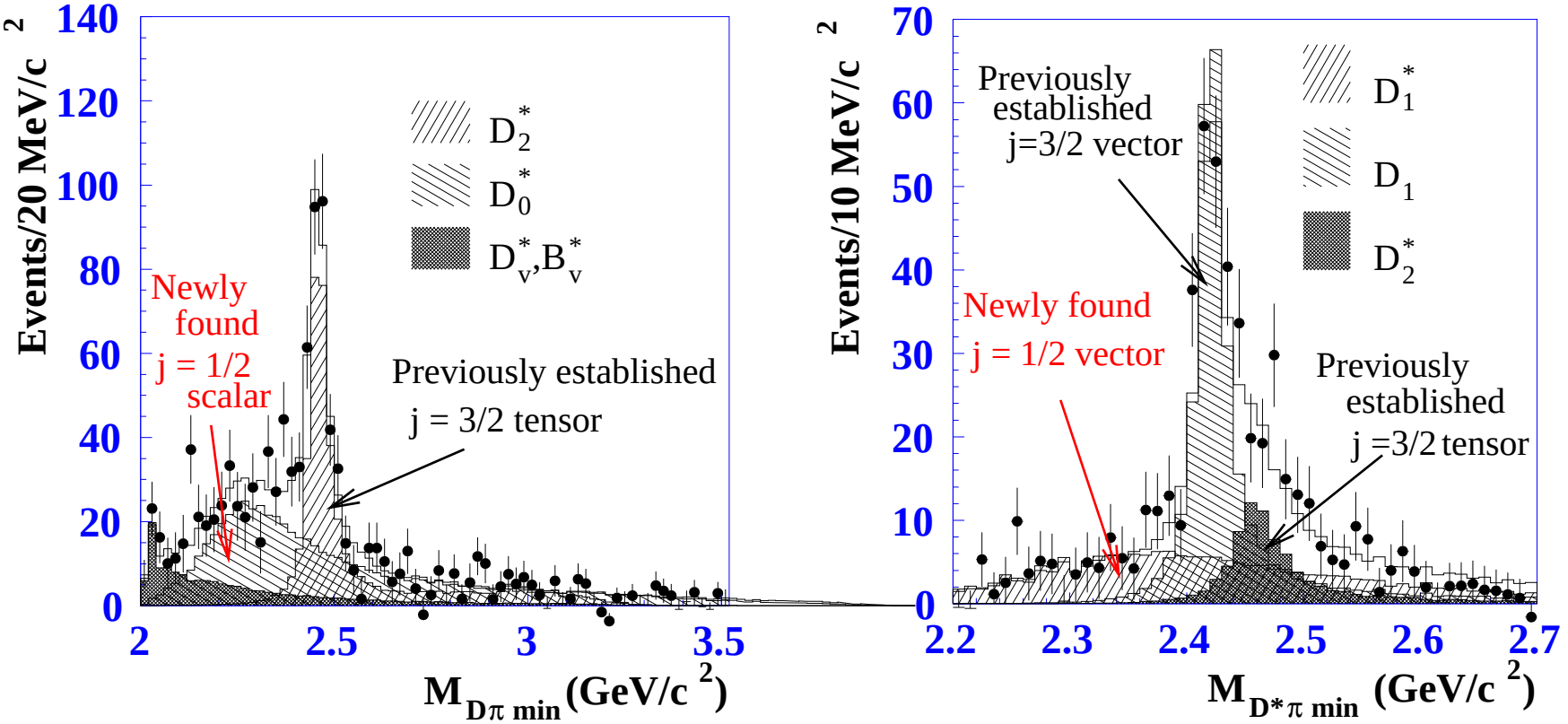
Spin-parity assignment for $D_{sJ}(2457)$

- $D_s^*\pi^0$ final state is dominant.
  $\longrightarrow$ If S-wave case (most likely), $J^P = 1^+$.
  $\longrightarrow$ If P-wave case, $J^P = 0^-$ or 2^-.
- $D_s\pi^0$ decay is not observed $\longrightarrow$ favors 0^-, 1^+, 2^- . . .
- $D_s\gamma$ decay is observed $\longrightarrow$ ruled out $0^\pm$
- $D_s\pi^+\pi^-$ is observed $\longrightarrow$ ruled out 0^+
- $B \to \overline{D}D_{sJ}(2457)(\to D_s\gamma)$ helicity distribution
  $\longrightarrow$ Consistent with J =1 and inconsistent with J = 2.
- $B \to \overline{D}D_{sJ}(2457)$ likely not high J.

These support $J^P = 1^+$ for $D_{sJ}(2457)$.

Newly established broad D^{**0} states

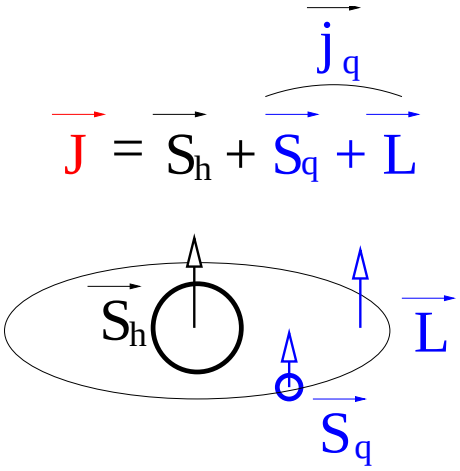
- **BELLE 65M $B\overline{B}$ pairs** (hep-ex/0307021 submitted to PRD)
- $B^{\mp} \to D^{\pm}\pi^{\mp}\pi^{\mp}$ and $B^{\mp} \to D^{*\pm}\pi^{\mp}\pi^{\mp}$



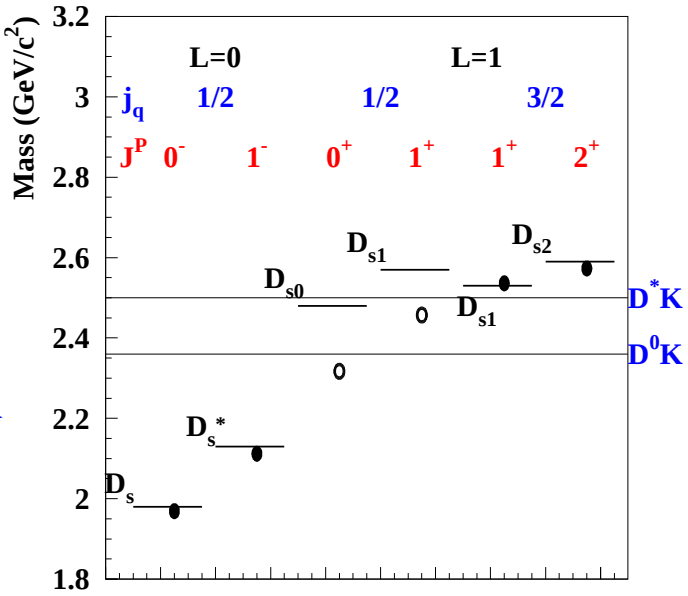
	$J^P(j_q)$	M [MeV/c^2]	Γ [MeV/c^2]
D_0^*	0^+ $(j_q = 1/2)$	$2308 \pm 17 \pm 15 \pm 28$	$276 \pm 21 \pm 18 \pm 60$
$D_1'^0$	1^+ $(j_q = 1/2)$	$2427 \pm 26 \pm 20 \pm 15$	$384\ ^{+107}_{-75} \pm 24 \pm 70$
D_1^0	1^+ $(j_q = 3/2)$	$2421.4 \pm 1.5 \pm 0.4 \pm 0.8$	$23.7 \pm 2.7 \pm 0.2 \pm 4.0$
D_2^{*0}	2^+ $(j_q = 3/2)$	$2461.6 \pm 2.1 \pm 0.5 \pm 3.3$	$45.6 \pm 4.4 \pm 6.5 \pm 1.6$

These two broad states (D_0^*, $D_1'^0$) are first observation.

Mass inconsistent with potential model in $M(c\bar{s})$



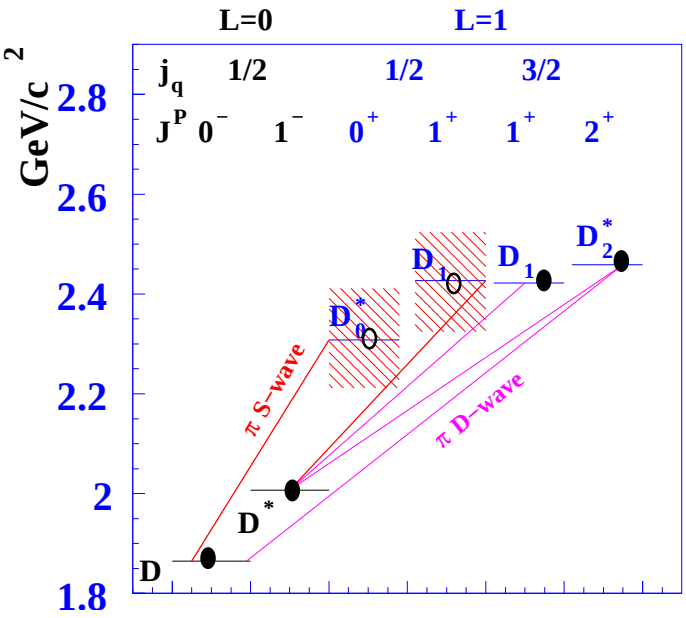
$M(c\bar{s})$



— Potential model prediction
(Isgur and Wise, Phys Rev Lett 66(1991)1130)

- Previously established
- o Newly established D_{sJ} states

$M(c\bar{u})$



— Potential model prediction
(Isgur, Wise, Rosner, Godfrey, Kokoski)

- Previously established
- o Newly established D^{**0} states

Potential model need correction for $M(c\bar{s})$ system.

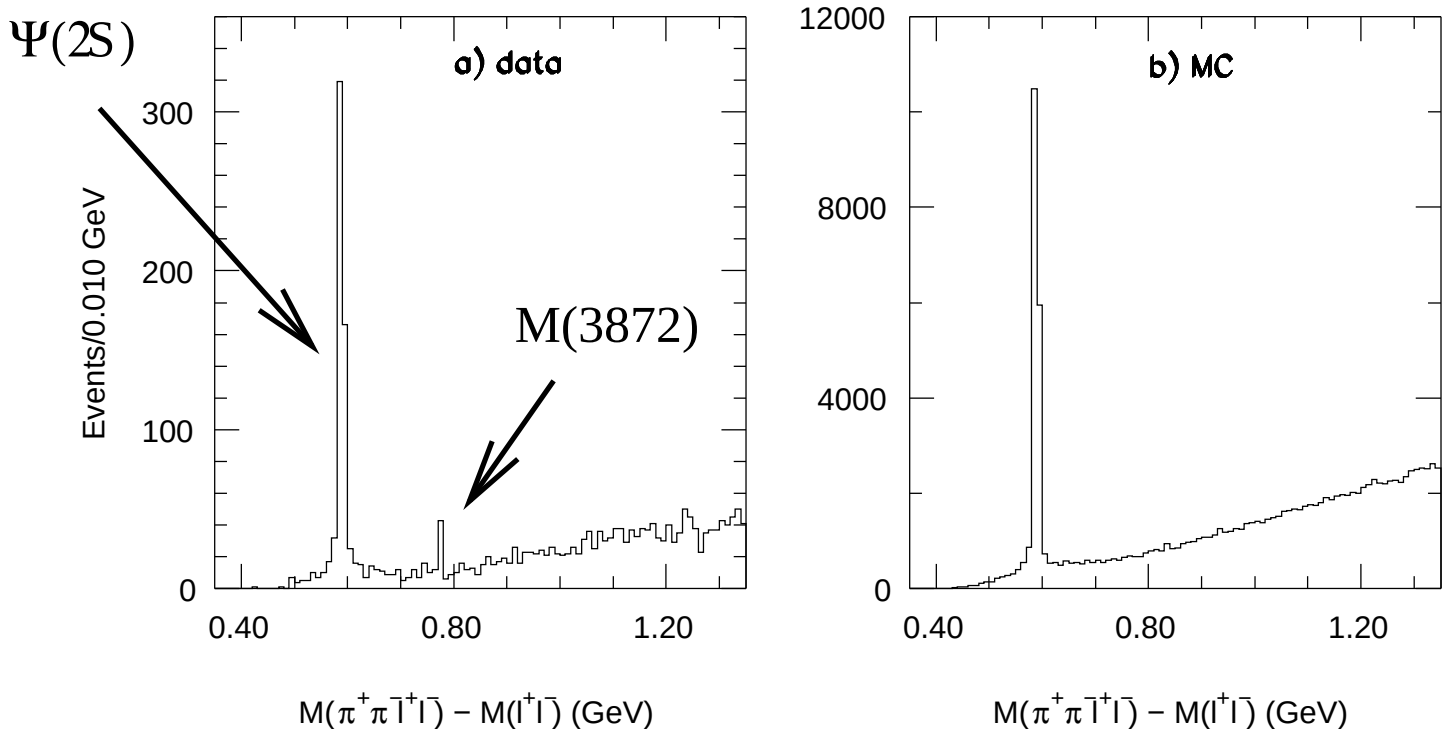
$\longrightarrow$ Interpretation with chiral symmetry in heavy-light meson system.
(Bardeen, Eichten, and Hill, Phys. Rev. D 68, 054024 (2003).)

Newly Found X(3872)

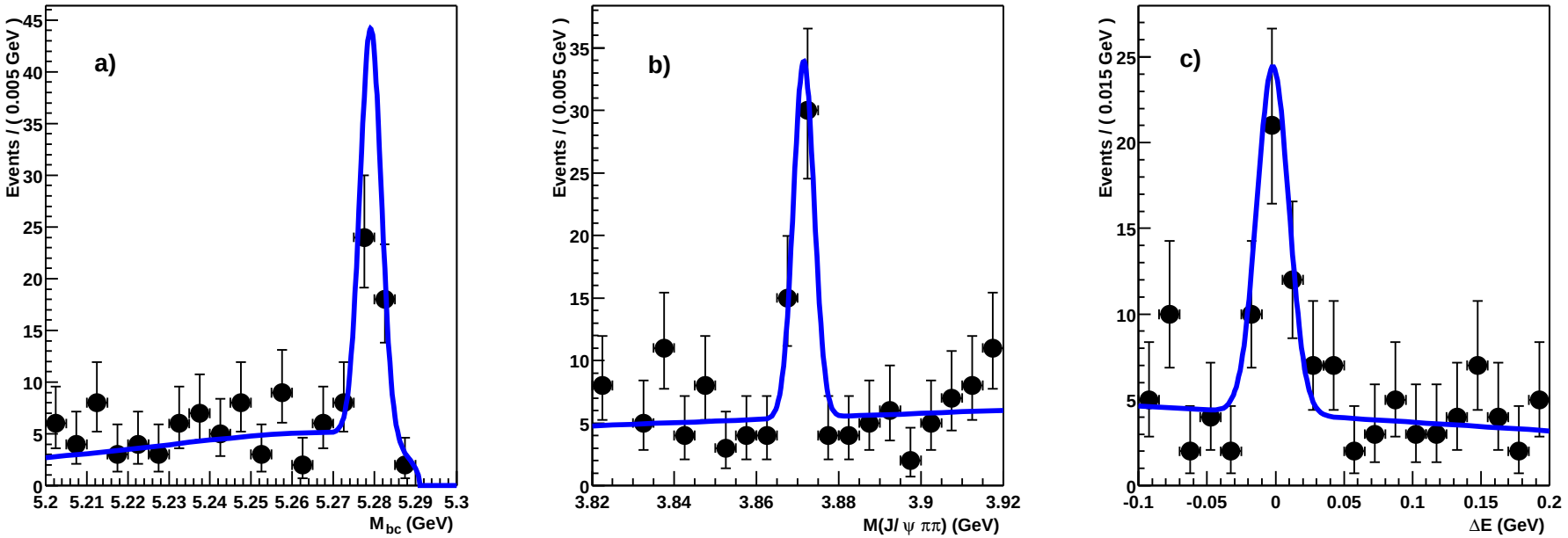
from $J/\Psi\ \pi^+\pi^-$

Charmonium-like $X(3872)$

- **BELLE 152M $B\overline{B}$ pairs** (PRL 91, 262001 (2003))
- $B^{\pm} \to K^{\pm} X(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$
- Δ **M = 0.775 GeV/c^2 corresponds to** $X(3872)$
- $\mathrm{N_{evts}}(X(3872)) = 35.7 \pm 6.8(\mathrm{stat})$ (10σ significance)
- $M_X = 3872.0 \pm 0.6(stat) \pm 0.5(syst)$ **MeV/c^2**
- Narrow as $\Gamma \leq 2.3$ MeV/c^2 (90% C.L.) in spite of $M_{X(3872)} \geq M_D + M_{\overline{D}}$.



Charmonium-like $X(3872)$ [cont'd]



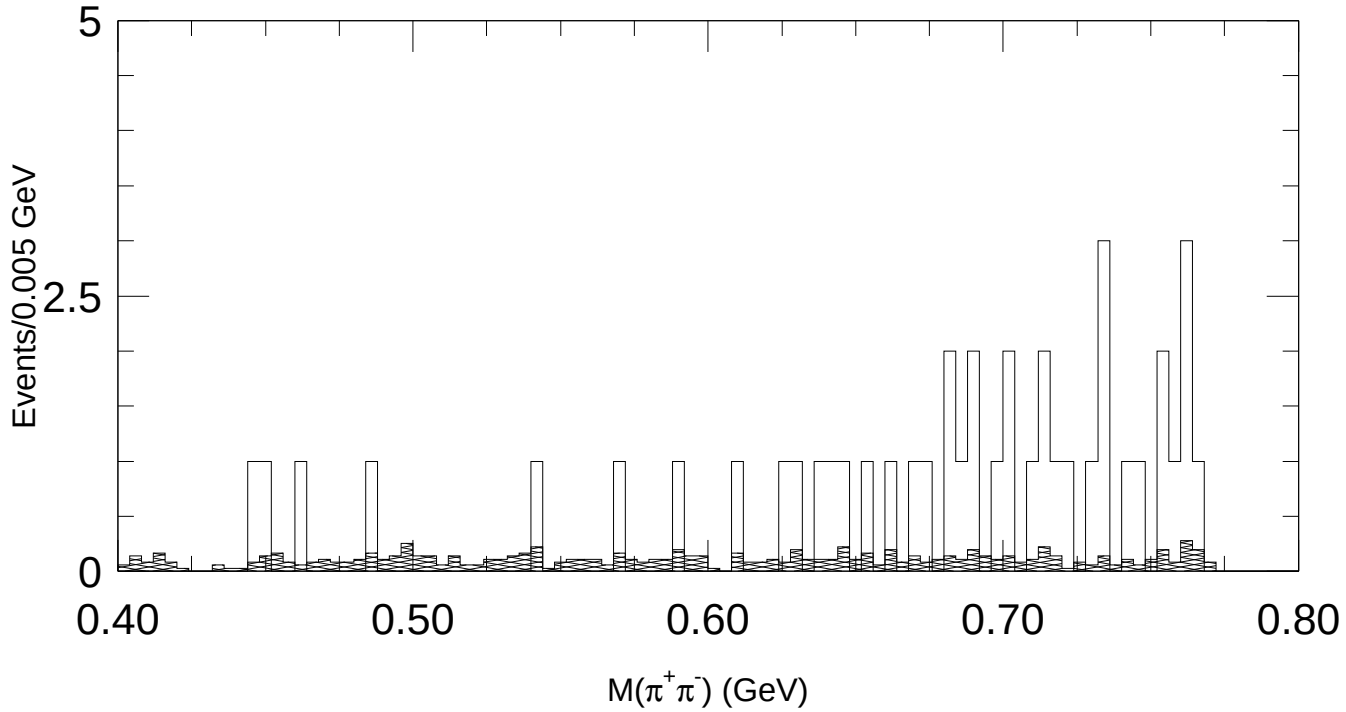
Simultaneous fit to

(a) $M_{bc} \equiv \sqrt{(E^{CM}_{beam})^2 - (P^{CM}_B)^2}$, **(b)** $M_{J/\psi\pi^+\pi^-}$, **and (c)** $\Delta E \equiv E^{CM}_B - E^{CM}_{beam}$

$$\frac{\mathcal{B}(B^+ \to K^+ X(3872)) \times Br(X(3872) \to \pi^+\pi^- J/\psi)}{Br(B^+ \to K^+\psi') \times Br(\psi' \to \pi^+\pi^- J/\psi)} = 0.063 \pm 0.012(\text{stat}) \pm 0.007(\text{syst})$$

$\pi^+\pi^-$ Invariant mass distribution

- **Tend to cluster near the kinematic boundary. (near ρ mass)**



X(3872) signal region (shaded histogram is sideband data).

- $X(c\bar{c}) \to J/\psi\ \rho$ **is isospin violating.**

Properties of X(3872)

- Decay into $J/\psi\ \pi^+\pi^-$ and no isospin partners.
  $\rightarrow$ **charmonium-like**

- Above $D\overline{D}$ threshold and narrow
  $\rightarrow$ **Disfavor $D\overline{D}$-allowed states (0^{++}, 1^{--}, 2^{++})**

- Produced in exclusive $B^+ \rightarrow K^+ X(3872)$ decays
  $\rightarrow$ **Not likely to be high J**

- Data prefers ρ-like $M_{\pi^+\pi^-}$ (not definitive)
  $\rightarrow$ $J/\psi\ \pi^0\pi^0$ **analysis is on-going**

Possible candidate: 2^1P_{c1}, 1^1D_{c2}, 1^3D_{c2} ...

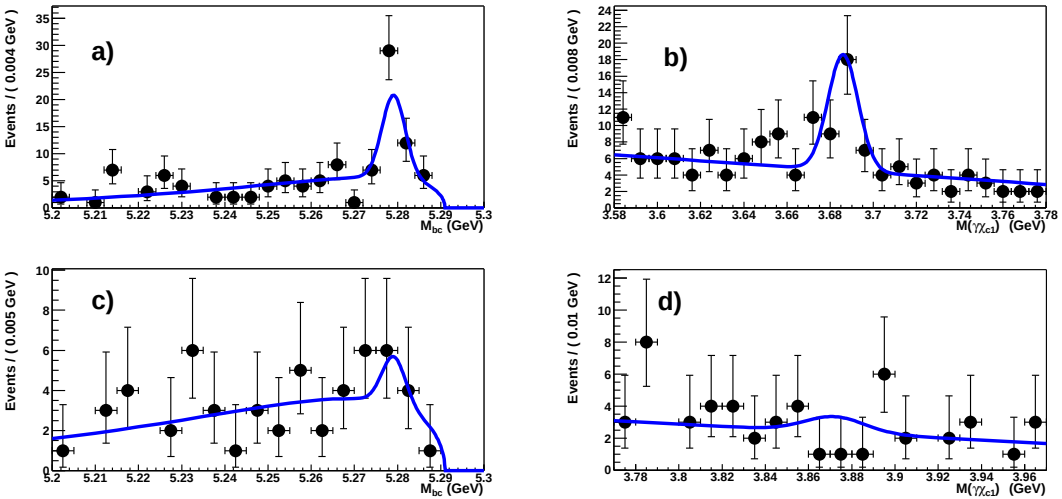
- If this is ${}^3D_{c2}$ state; $\Gamma({}^3D_{c2} \to \gamma\chi_{c1}) \geq 2 \times \Gamma({}^3D_{c2} \to \pi^+\pi^- J/\psi)$

  (Eichten, Lane, Quigg, hep-ph/0401210)

- $B^\pm \to K^\pm \gamma\chi_{c1}$ **and** $\chi_{c1} \to \gamma J/\psi$

$B^\pm \to K^\pm \Psi'(2S)$

$B^\pm \to K^\pm X(3872)$



$M_{bc} \equiv \sqrt{(E^{CM}_{beam})^2 - (P^{CM}_B)^2}$, $M_{\gamma\chi_{c1}}$

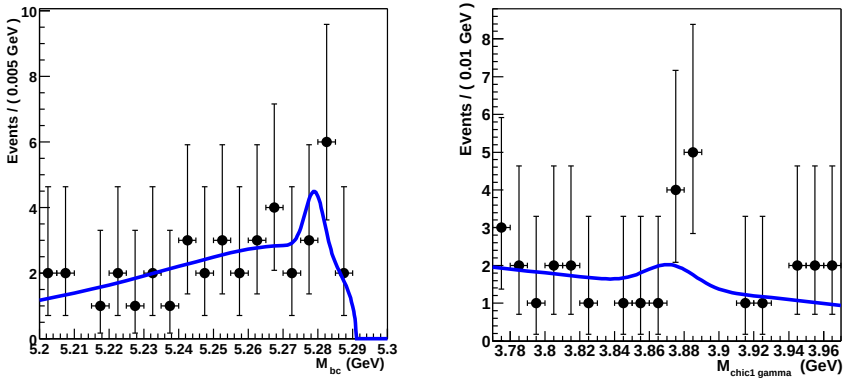
No signal in $X(3872)$ region

$$\frac{\Gamma(X(3872) \to \gamma\chi_{c1})}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} \leq 0.89 \ (90\% \text{ C.L.})$$

$\to$ inconsistent with ${}^3D_{c2}$.

- $B^\pm \to K^\pm \gamma\chi_{c2}$ **and** $\chi_{c2} \to \gamma J/\psi$

$B^\pm \to K^\pm X(3872)$



$M_{bc} \equiv \sqrt{(E^{CM}_{beam})^2 - (P^{CM}_B)^2}$, $M_{\gamma\chi_{c2}}$

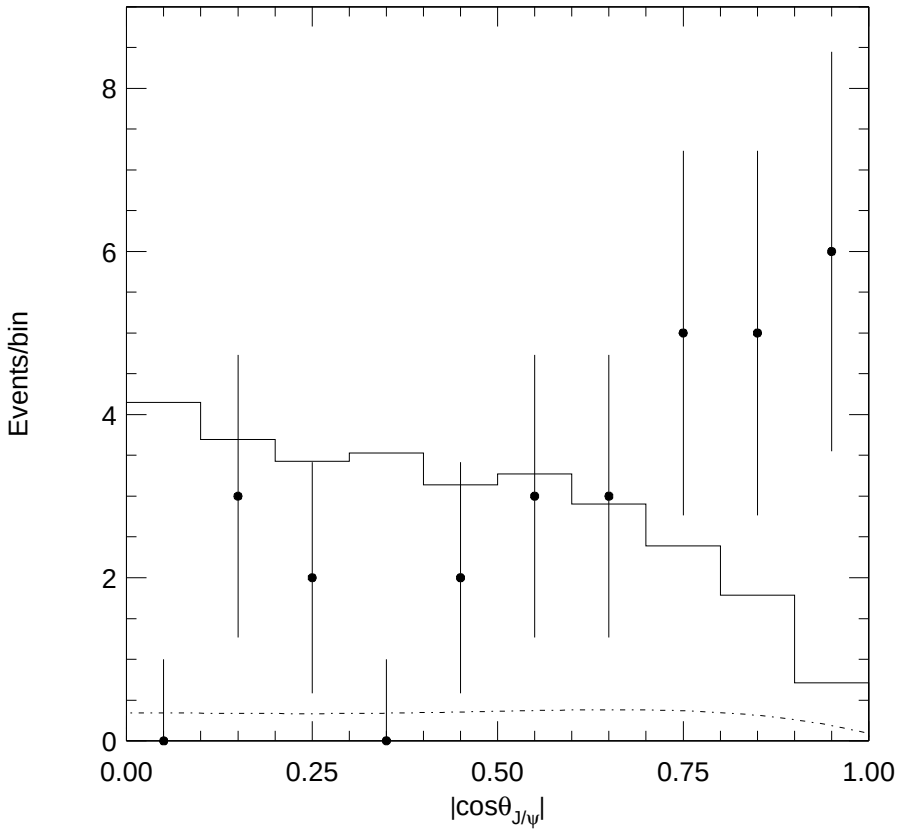
No signal in $X(3872)$ region

$$\frac{\mathcal{B}(X \to \gamma\chi_{c2})}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} < 1.1 \ (90\%(C.L.))$$

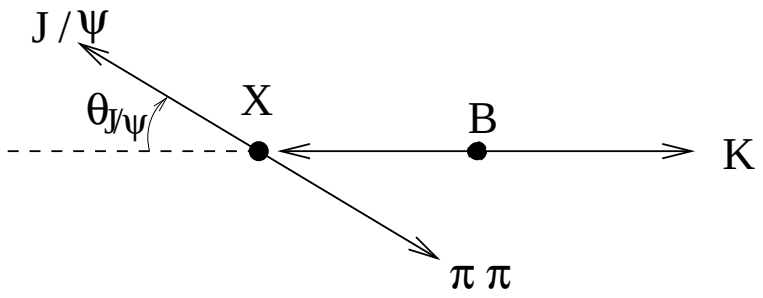
(Preliminary)

$\theta_{J/\psi}$ distribution rules out 1^{+-} (h_c' (2^1P_1))

(Preliminary)



Histogram: $sin^2\theta$ **assumption**



$$\frac{dN}{d\cos\theta_{J/\psi}} \propto 1 - \cos^2\theta_{J/\psi}$$

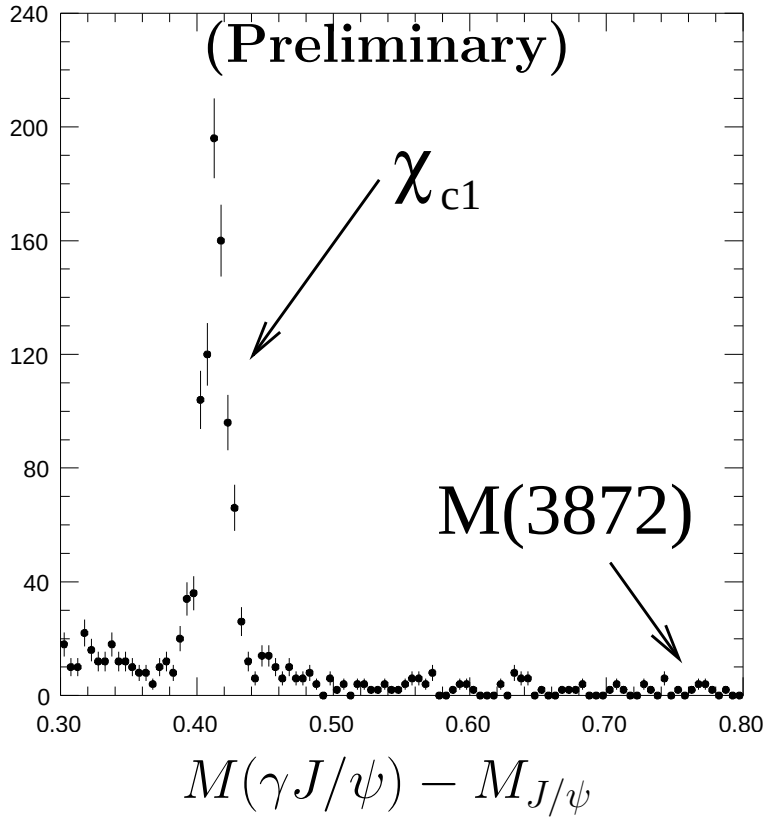
Inconsistent with data

$(\chi^2/\mathbf{n.d.f} = \mathbf{75/9})$

Absence of $X(3872) \to \gamma J/\psi$ rules out χ'_{c1} (2^3P_1)

- $\Gamma(2^3P_1 \to \gamma J/\psi) \sim 11\,\mathrm{keV}$ Barnes, Godfrey, hep-ph/0311162
- $\Gamma(2^3P_1(1^{++}) \to \pi^+\pi^- J/\psi) \sim \Gamma(\psi' \to \pi^0 J/\psi) \sim 0.3\,\mathrm{keV}$
- **Expect ratio**

$$\frac{\Gamma(2^3P_1 \to \gamma J/\psi)}{\Gamma(2^3P_1 \to \pi^+\pi^- J/\psi)} \sim 30$$



- **Clear peak corresponding to** $B \to K\chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$ **(0.413 GeV)**
- **No peak for** $X(3872)$ **(0.775 GeV)**

$$\frac{\mathcal{B}(X(3872) \to \gamma J/\psi)}{\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)} < 0.4$$

(Preliminary)

Charmonium states

0^{++}	$D\overline{D}$ **is not observed**
1^{--}	$D\overline{D}$ **is not observed**
2^{++}	$D\overline{D}$ **is not observed**
$0^{-+}(\eta_c'')$	**should be much wider**
$1^{+-}(h_c')$	$\theta_{J/\psi}$ **distribution is inconsistent with** 1^{+-}
$1^{++}(\chi_{c1}')$	$\Gamma(\gamma J/\psi)$ **is too small**
$2^{--}(\psi_2)$	$\Gamma(\gamma\chi_{c1})$ **is too small**
$3^{--}(\psi_3)$	$\Gamma(\gamma\chi_{c2})$ **is too small**

Further analysis is ongoing

- Search for $J/\psi\pi^0\pi^0$

One interesting note:

$$M_X = \mathbf{3872.0 \pm 0.6(stat) \pm 0.5(syst)\ MeV/c^2}$$

$$M_{D^0} + M_{D^{0*}} = \mathbf{3871.2 \pm 1.0\ MeV/c^2}$$

$$M_X \sim M_{D^0} + M_{D^{0*}}$$

Summary

B factory is also a Charm factory

- **$M(D_{sJ})$ and $M(D^{**0})$ measurement**

- $M(c\bar{s})$ **(L =1, j_q = 1/2) is lower than potential model prediction.**
- $D^+_{s0}(2317)$ **is consistent with $J^P = 0^+$ and $D^+_{s1}(2457)$ is $J^P = 1^+$.**
- D^{**0} **states seen in first time.**
- **Similar doublets (L=1, j_q=1/2) are observed both in $c\bar{s}$ and $c\bar{u}$.**

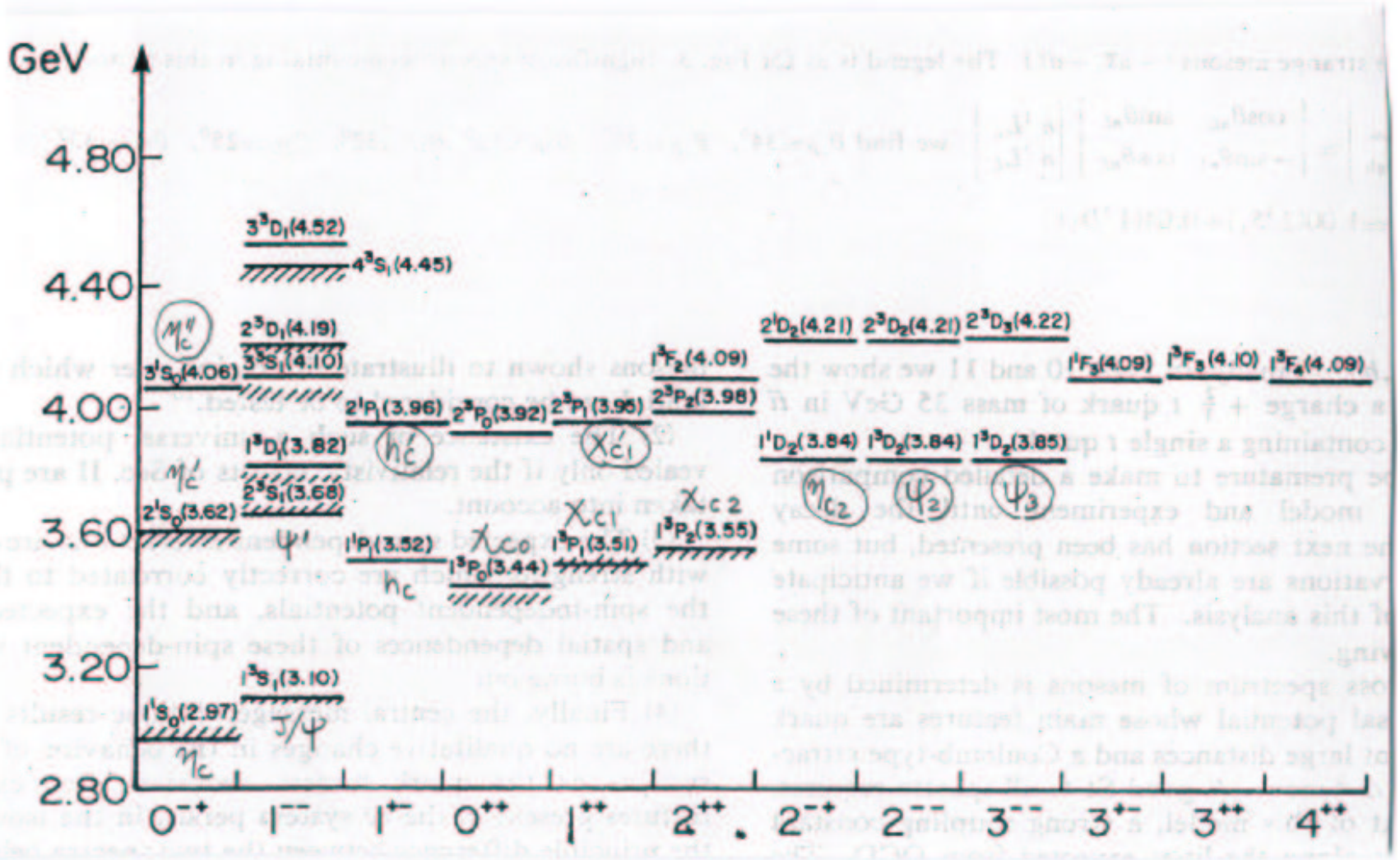
- **Branching fraction measurement for newly D_{sJ} state**

- **First observation of new D_{sJ} from B decay**
- **First observation of $D_{s1}(2457)$ radiative decay and dipion decay.**
- **First evidence of $D_{s1}(2536)$ dipion decay.**

- **New resonance $X(3872)$**

- **First observation of X(3872) from $J/\psi\ \ \pi^+\pi^-$.**
- **No obvious charmonium.**
- $M_X(3872) \sim M_{D^0} + M_{D^{0*}}$

Backups



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Comparison of mass splitting

L=1, j_q = 1/2 , (0^+, 1^+) doublet (newly established) splitting:

$c\bar{u}$: $M(D_{1^+}^{\prime 0})$ - $M(D_{0^+}^{*})$ = 2427 - 2308 = 119 ± 51 MeV/c^2

$c\bar{s}$: $M(D_{s1^+})$ - $M(D_{s0^+})$ = 2457 - 2317 = 140 ± 2 MeV/c^2

L=0, j_q = 1/2, (0^-, 1^-) doublet splitting:

$c\bar{u}$: $M(D^{*+})$ - $M(D^{+})$ = 2010.0 - 1869.3 = 140.7 ± 0.7 MeV/c^2

$c\bar{s}$: $M(D_s^{*})$ - $M(D_s)$ = 2112.4 - 1968.5 = 143.9 ± 0.9 MeV/c^2

j_q = 1/2 of $c\bar{s}$ splitting between J = 1 and J = 0:

L=0: $M(D_s^{*})$ - $M(D_s)$ = 2112.4 - 1968.5 = 143.9 ± 0.9 MeV/c^2

L=1: $M(D_{s1^+})$ - $M(D_{s0^+})$ = 2456.5 - 2317.2 = 139.3 ± 2.1 MeV/c^2

j_q = 1/2 of $c\bar{u}$ splitting between J = 1 and J = 0:

L=0: $M(D^{*+})$ - $M(D^{+})$ = 2010.0 - 1869.3 =140.7 ± 0.7 MeV/c^2

L=1: $M(D_{1^+}^{\prime 0})$ - $M(D_{0^+}^{*})$ = 2427 - 2308 = 119 ± 51 MeV/c^2

L=1, j_q = 1/2 splitting between $c\bar{s}$ and $c\bar{u}$:

1^+:$M(D_{s1^+})$ - $M(D_{1^+}^{\prime 0})$= 2457 - 2427 = 30 ± 36 MeV/c^2

0^+:$M(D_{s0^+})$ - $M(D_{0^+}^{*})$ = 2317 - 2308 = 9 ± 23 MeV/c^2

L=0, j_q = 1/2 splitting between $c\bar{s}$ and $c\bar{u}$:

1^-:$M(D_s^{*})$ - $M(D^{*+})$ = 2112.4 - 2010.0 = 102.4 ± 0.9 MeV/c^2

0^-:$M(D_s)$ - $M(D^{+})$ = 1968.5 - 1869.3 = 99.2 ± 0.8 MeV/c^2

J=1, j_q = 1/2 splitting between $c\bar{s}$ and $c\bar{u}$:

L=1:$M(D_{s1^+})$ - $M(D_{1^+}^{\prime 0})$= 2457 - 2427 = 30 ± 36 MeV/c^2

L=0:$M(D_s^{*})$ - $M(D^{*+})$ = 2112.4 - 2010.0 = 102.4 ± 0.9 MeV/c^2

J=0, j_q = 1/2 splitting between $c\bar{s}$ and $c\bar{u}$:

L=1:$M(D_{s0^+})$ - $M(D_{0^+}^{*})$ = 2317 - 2308 = 9 ± 23 MeV/c^2

L=0:$M(D_s)$ - $M(D^{+})$ = 1968.5 - 1869.3 = 99.2 ± 0.8 MeV/c^2