# New States above Charm Threshold

Estia Eichten
Fermilab

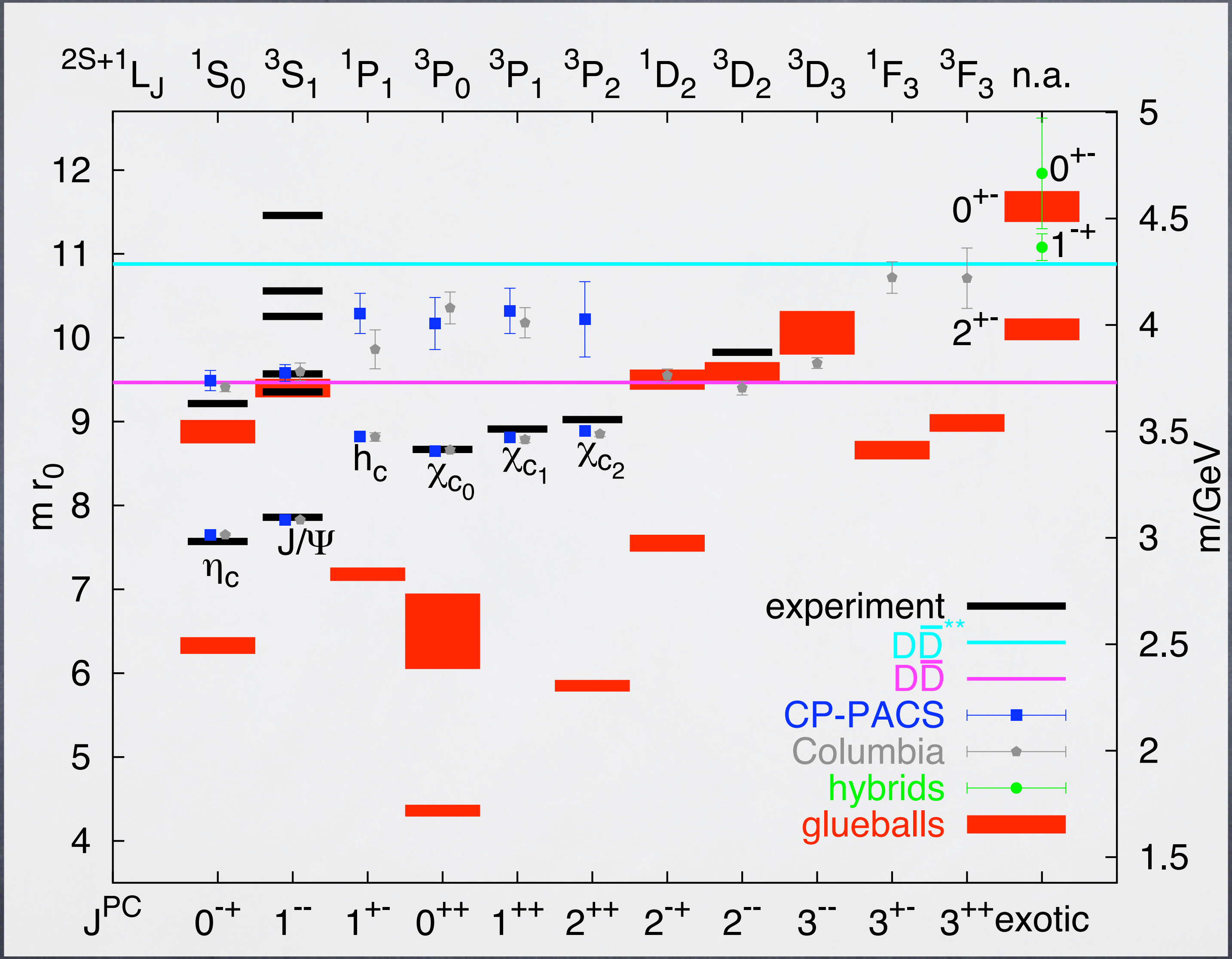
with K. Lane, C. Quigg
hep-ph/0511179

- Narrow States and QCD dynamics
- Missing Charmonium States
- X(3872), Z(3931), Y(3940), Y(4260)...
- Summary and Outlook

# Narrow States and QCD Dynamics

- QCD dynamics is much richer than present phenomological models - Lattice QCD
- Narrow states allow precise experimental probes of the subtle nature of QCD dynamics
- Surprising new narrow states have been observed and more may be expected

# Adding Gluons - Lattice QCD




QWG Yellow Report [hep-ph/0412158]

# Adding Gluons - Lattice QCD

Juge, Kuti, Morningstar

PRL 82:4400 (1999)
PRL 90:161601 (2003)

Hybrid Potentials

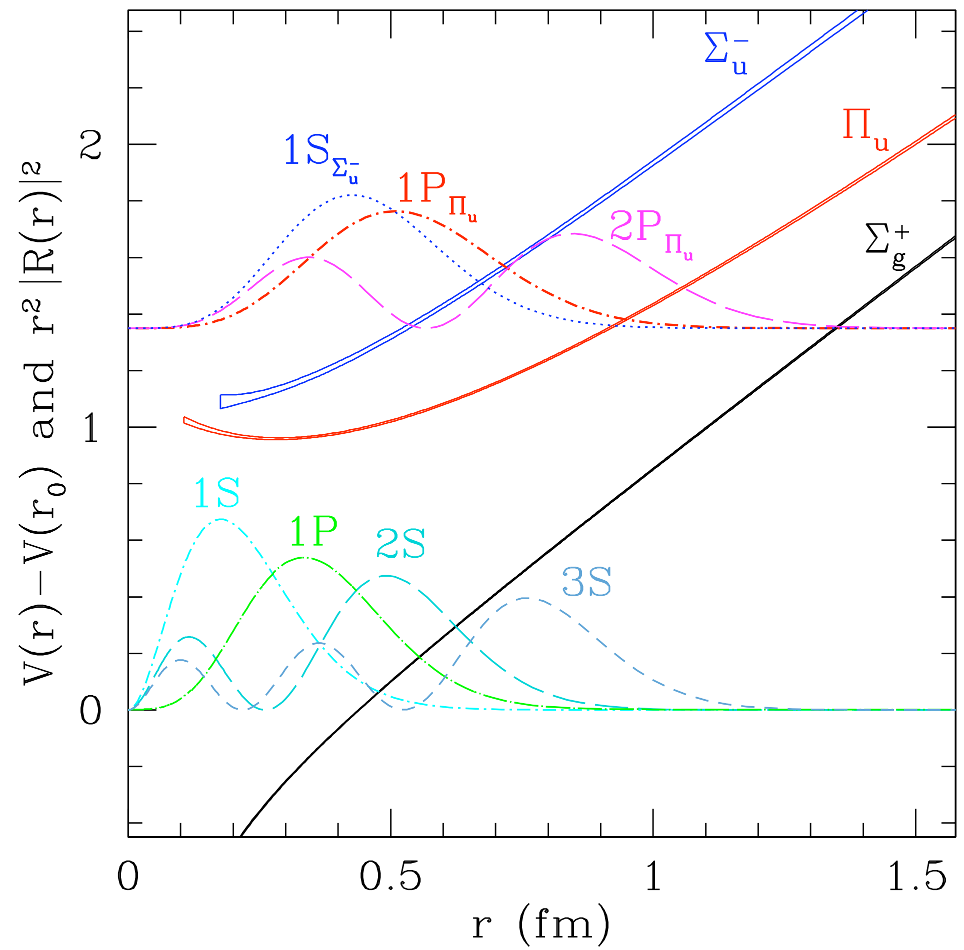
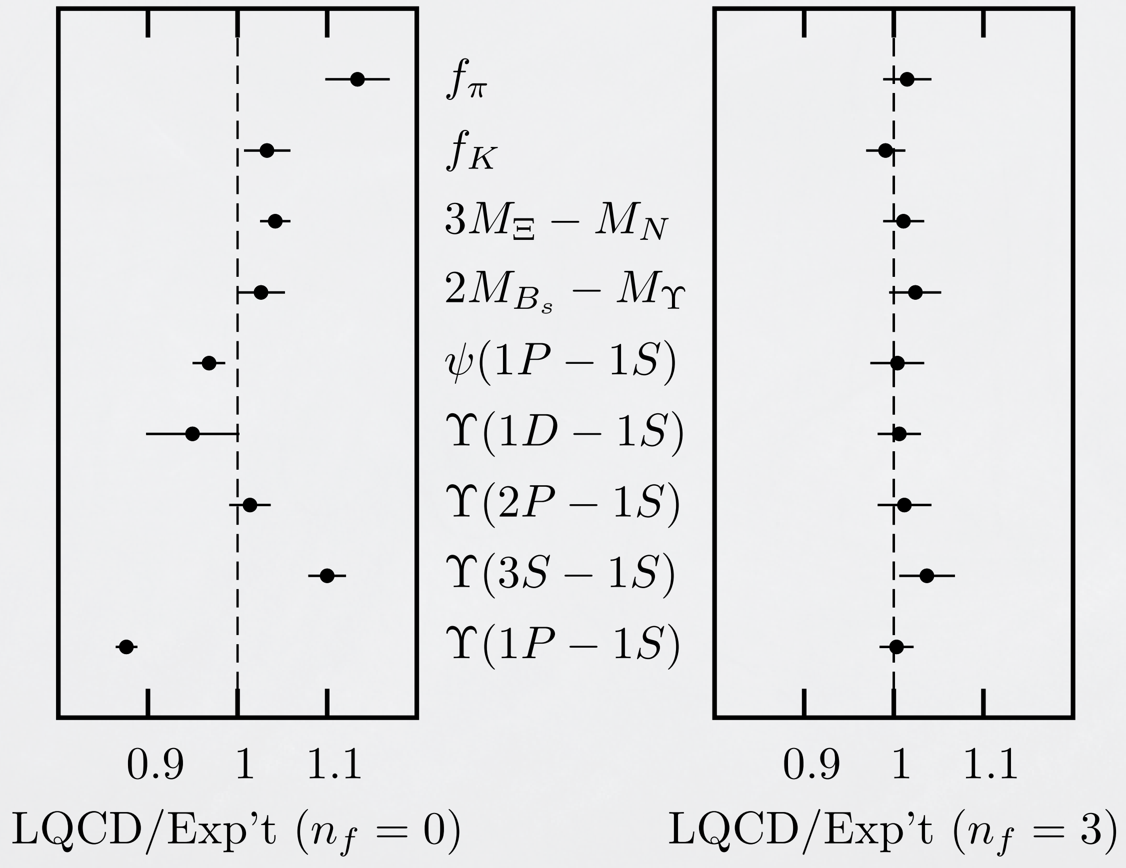



Figure 2. Wavefunctions and potentials for the various hybrid/meson states.

# Including light quark loops




C. T. H. Davies et al. [HPQCD, Fermilab Lattice, MILC, and UKQCD Collaborations], Phys. Rev. Lett. 92, 022001 (2004) [arXiv:hep-lat/0304004].

# New Narrow Mesons

- Chiral Symmetry and Heavy-Light systems: $D_s(0^+)$ and $D_s(1^+)$
- Quarkonium systems:
  - equal masses: $h_c$, $\eta'_c$ and ...
  - unequal masses: $B_c$
- Thresholds and the X(3872), Y(3940), Y(4260), ...

# Quarkonium Systems

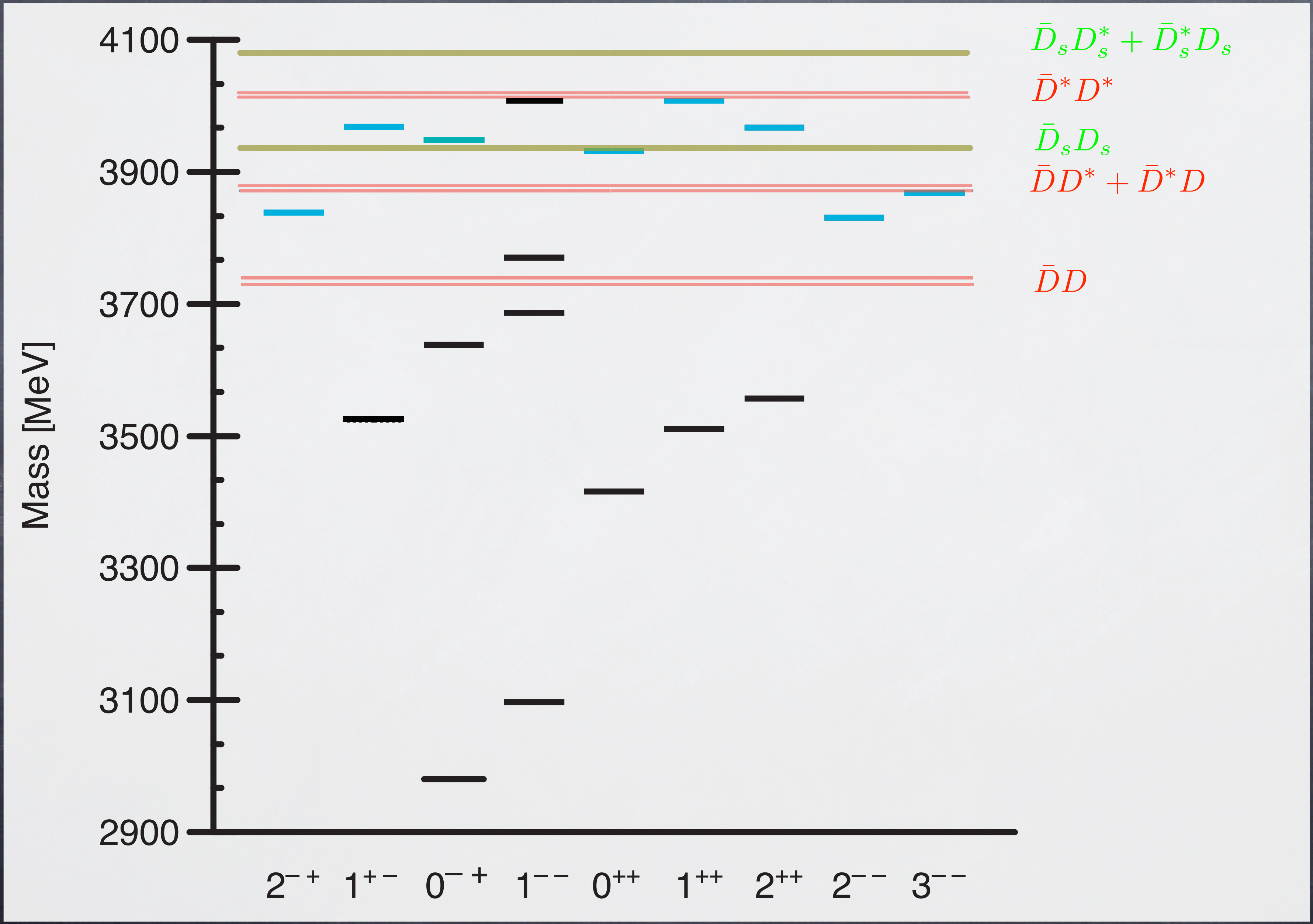
# Charmonium

- By 2002 -twenty five years since any new charmonium state observed.

- In the last three years:
  $\eta'_c$ and $h_c$ below $D\bar{D}$ threshold
  $\eta''_c$ and $\chi'_{c2}$
  X(3872), Y(3940), Y(4260), ...

- Why?
  New experiments and more lumunosity
  New production channels - B decays, $\gamma\gamma$,
  double charmonium production,
  gg in high energy hadron colliders.

# Charmonium States



# Expectations circa 2002

TABLE II: Hadronic decay widths of charmonium states.

| $c\bar{c}$ state | Decay | Partial Width |
|---|---|---|
| $1^1S_0$ | $\eta_c \to gg$ | $17.4 \pm 2.8$ MeV [21] |
| $1^3S_1$ | $J/\psi \to ggg$ | $52.8 \pm 5$ keV [22] |
| $1^1P_1$ | $h_c \to ggg$ | $720 \pm 320$ keV[a] |
| $1^3P_0$ | $\chi_{c0} \to gg$ | $14.3 \pm 3.6$ MeV[b] |
| $1^3P_1$ | $\chi_{c1} \to ggg$ | $0.64 \pm 0.10$ MeV[b] |
| $1^3P_2$ | $\chi_{c2} \to gg$ | $1.71 \pm 0.21$ MeV[b] |
| $2^1S_0$ | $\eta_c' \to gg$ | $8.3 \pm 1.3$ MeV[c] |
| | $\eta_c' \to \pi\pi\eta_c$ | 160 keV[d] |
| $2^3S_1$ | $\psi' \to ggg$ | $23 \pm 2.6$ keV [22] |
| | $\psi' \to \pi\pi J/\psi$ | $152 \pm 17$ keV [22] |
| | $\psi' \to \eta J/\psi$ | $6.1 \pm 1.1$ keV [22] |
| $1^1D_2$ | $\eta_{c2} \to gg$ | 110 keV[e] |
| | $\eta_{c2} \to \pi\pi\eta_c$ | $\approx 45$ keV[d] |
| $1^3D_1$ | $\psi \to ggg$ | 216 keV[f] |
| | $\psi \to \pi\pi J/\psi$ | $43 \pm 15$ keV[g] |
| $1^3D_2$ | $\psi_2 \to ggg$ | 36 keV[f] |
| | $\psi_2 \to \pi\pi J/\psi$ | $\approx 45$ keV[d] |
| $1^3D_3$ | $\psi_3 \to ggg$ | 102 keV[f] |
| | $\psi_3 \to \pi\pi J/\psi$ | $\approx 45$ keV[d] |

[a]Computed from $^3P_J$ rates using formalism of [23]; also see [24].
[b]Compilation of data analyzed by Maltoni, Ref. [23].
[c]Scaled from $\Gamma(\eta_c \to gg)$.
[d]Computed using Eqn. (3.5) of Ref. [20].
[e]Computed using Eqn. (3).
[f]Computed using Eqn. (2).
[g]From rates compiled in Table X of Ref. [20].

TABLE III: Calculated and observed rates for radiative transitions among charmonium levels in the potential (1).

| Transition | $\gamma$ energy $k$ (MeV) | Partial width (keV) Computed | Measured[a] |
|---|---|---|---|
| $\psi \xrightarrow{M1} \eta_c\gamma$ | 115 | 1.92 | 1.13±0.41 |
| $\chi_{c0} \xrightarrow{E1} J/\psi\gamma$ | 303 | 120 (105)[b] | 98±43 |
| $\chi_{c1} \xrightarrow{E1} J/\psi\gamma$ | 390 | 242 (215)[b] | 240±51 |
| $\chi_{c2} \xrightarrow{E1} J/\psi\gamma$ | 429 | 315 (289)[b] | 270±46 |
| $h_c \xrightarrow{E1} \eta_c\gamma$ | 504 | 482 | |
| $\eta_c' \xrightarrow{E1} h_c\gamma$ | 126 | 51 | |
| $\psi' \xrightarrow{E1} \chi_{c2}\gamma$ | 128 | 29 (25)[b] | 22±5 |
| $\psi' \xrightarrow{E1} \chi_{c1}\gamma$ | 171 | 41 (31)[b] | 24±5 |
| $\psi' \xrightarrow{E1} \chi_{c0}\gamma$ | 261 | 46 (38)[b] | 26±5 |
| $\psi' \xrightarrow{M1} \eta_c'\gamma$ | 32 | 0.04 | |
| $\psi' \xrightarrow{M1} \eta_c\gamma$ | 638 | 0.91 | 0.75±0.25 |
| $\psi(3770) \xrightarrow{E1} \chi_{c2}\gamma$ | 208 | 3.7 | |
| $\psi(3770) \xrightarrow{E1} \chi_{c1}\gamma$ | 250 | 94 | |
| $\psi(3770) \xrightarrow{E1} \chi_{c0}\gamma$ | 338 | 287 | |
| $\eta_{c2} \xrightarrow{E1} \psi(3770)\gamma$ | 45 | 0.34 | |
| $\eta_{c2} \xrightarrow{E1} h_c\gamma$ | 278 | 303 | |
| $\psi_2 \xrightarrow{E1} \chi_{c2}\gamma$ | 250 | 56 | |
| $\psi_2 \xrightarrow{E1} \chi_{c1}\gamma$ | 292 | 260 | |

[a]Derived from Ref. [22].
[b]Corrected for coupling to decay channels as in Ref. [16].

ELQ 2002

TABLE I: Thresholds for decay into open charm and nearby hidden-charm thresholds.

| Channel | Threshold Energy (MeV) |
|---|---|
| $D^0 \bar{D}^0$ | 3729.4 |
| $D^+ D^-$ | 3738.8 |
| $D^0 \bar{D}^{*0}$ or $D^{*0} \bar{D}^0$ | 3871.5 |
| $\rho^0 J/\psi$ | 3872.7 |
| $D^\pm D^{*\mp}$ | 3879.5 |
| $\omega^0 J/\psi$ | 3879.6 |
| $D_s^+ D_s^-$ | 3936.2 |
| $D^{*0} \bar{D}^{*0}$ | 4013.6 |
| $D^{*+} D^{*-}$ | 4020.2 |
| $\eta' J/\psi$ | 4054.7 |
| $f^0 J/\psi$ | $\approx$ 4077 |
| $D_s^+ \bar{D}_s^{*-}$ or $D_s^{*+} \bar{D}_s^-$ | 4080.0 |
| $a^0 J/\psi$ | 4081.6 |
| $\varphi^0 J/\psi$ | 4116.4 |
| $D_s^{*+} D_s^{*-}$ | 4223.8 |

# Including Light Quark Effects

$$[\mathcal{H}_0 + \mathcal{H}_2 + \mathcal{H}_I]\psi = \omega\psi$$

$\mathcal{H}_0$ $Q\bar{Q}$ NRQCD (without couplings light quarks)

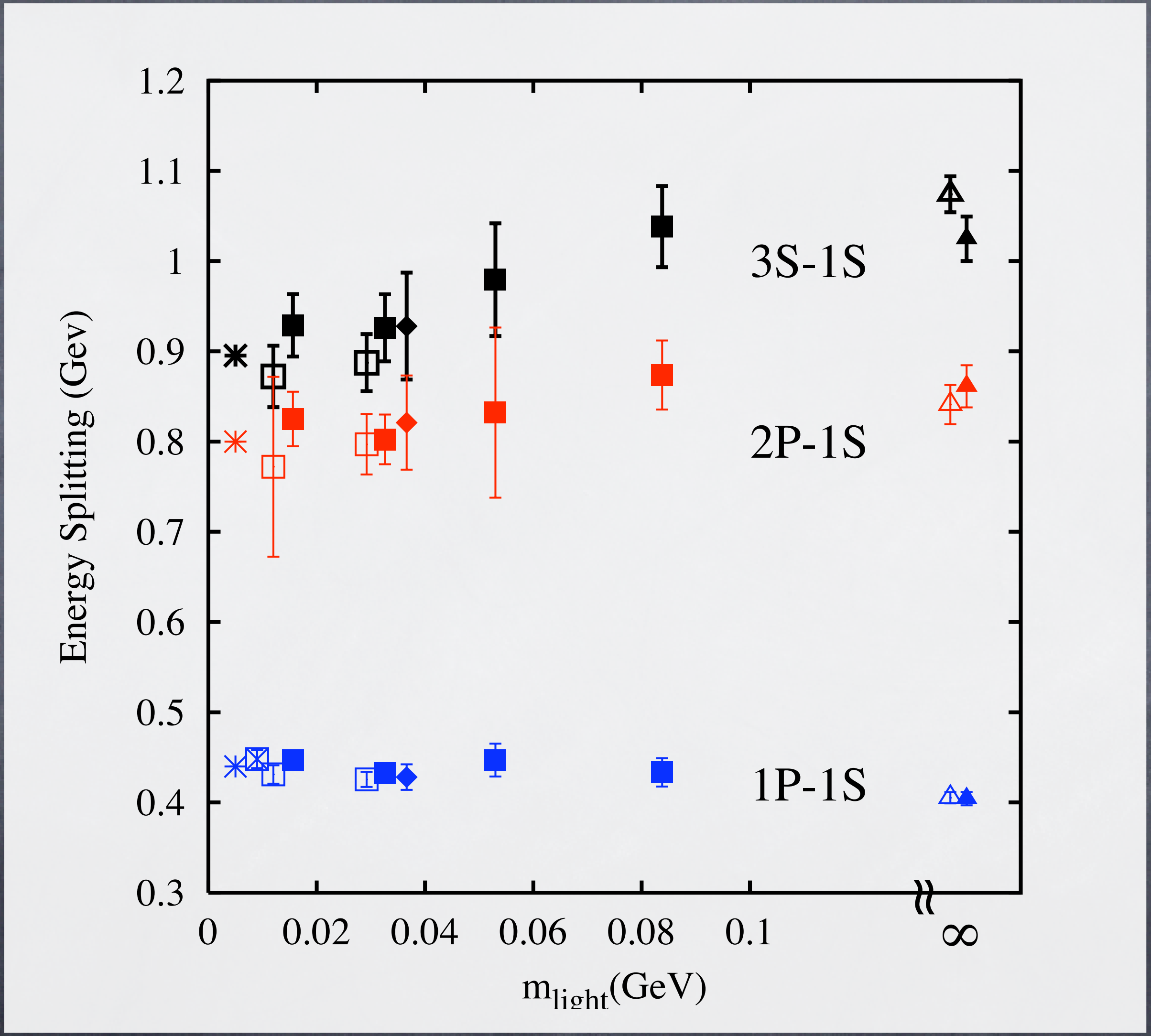
$\mathcal{H}_I$ $Q\bar{Q} \rightarrow Q\bar{q}+q\bar{Q}$ light quark pair creation

Cornell model (CCCM) $\mathcal{H}_I = \frac{3}{8}\sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}') : d^3r\, d^3r'$

Vacuum Pair Creation model (QPC) $\mathcal{H}_I = \gamma \int \bar{\psi}\psi(\mathbf{r}) d^3r$

$\mathcal{H}_2$ $Q\bar{q}+q\bar{Q}$ meson pair interactions

# Lattice QCD



Energy Splitting (Gev)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.02
0.04
0.06
0.08
0.1
∞
m_light(GeV)
3S-1S
2P-1S
1P-1S

# Coupling to open-charm channels

Phenomenological approach:

$$\mathcal{H}_I = \frac{3}{8} \sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r} - \mathbf{r}') \rho_a(\mathbf{r}') : d^3r \, d^3r'$$

$$\rho^a = \bar{c}\gamma^0 t^a c + \bar{q}\gamma^0 t^a q$$

CCCM

Calculate pair-creation amplitudes,

Evaluate $<^3 D_2 | \mathcal{H}_I | D\bar{D}^\star >$, etc.

ELQ 2004

Solve coupled-state system

$$\psi = \psi_0 + \psi_2$$

$\psi_0$: $\bar{c}c$ $\quad$ $\psi_2$: $\bar{D}D$

solve

$$\left[ \mathcal{H}_0 + \mathcal{H}_I^\dagger \frac{1}{\omega - \mathcal{H}_2 + i\epsilon} \mathcal{H}_I \right] \psi_0 = \omega \psi_0$$

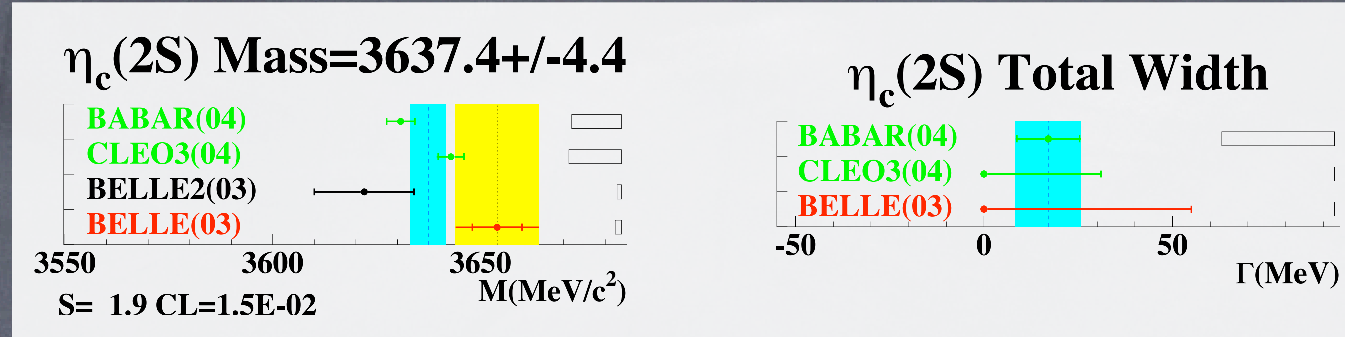
for $\omega$ and $\psi_0$

# Effects on the spectrum

Coupling to virtual channels induces spin-dependent forces in charmonium near threshold, because M(D*) > M(D)

| | State | Mass | Centroid | Splitting (Potential) | Splitting (Induced) |
|---|---|---|---|---|---|
| | $1^1S_0$ | $2\,979.9^a$ | $3\,067.6^b$ | $-90.5^e$ | $+2.8$ |
| | $1^3S_1$ | $3\,096.9^a$ | | $+30.2^e$ | $-0.9$ |
| | $1^3P_0$ | $3\,415.3^a$ | $3\,525.3^c$ | $-114.9^e$ | $+5.9$ |
| | $1^3P_1$ | $3\,510.5^a$ | | $-11.6^e$ | $-2.0$ |
| ⇒ | $1^1P_1$ | $3\,524.4^f$ | | $+0.6^e$ | $+0.5$ |
| | $1^3P_2$ | $3\,556.2^a$ | | $+31.9^e$ | $-0.3$ |
| ⇒ | $2^1S_0$ | $3\,638^a$ | $3\,674^b$ | $-50.1^e$ | $+15.7$ |
| | $2^3S_1$ | $3\,686.0^a$ | | $+16.7^e$ | $-5.2$ |
| ⇒ | $1^3D_1$ | $3\,769.9^a$ | $(3\,815)^d$ | $-40$ | $-39.9$ |
| | $1^3D_2$ | $3\,830.6$ | | $0$ | $-2.7$ |
| | $1^1D_2$ | $3\,838.0$ | | $0$ | $+4.2$ |
| ⇒ | $1^3D_3$ | $3\,868.3$ | | $+20$ | $+19.0$ |
| | $2^3P_0$ | $3\,881.4$ | $(3\,922)^d$ | $-90$ | $+27.9$ |
| | $2^3P_1$ | $3\,920.5$ | | $-8$ | $+6.7$ |
| | $2^1P_1$ | $3\,919.0$ | | $0$ | $-5.4$ |
| | $2^3P_2$ | $3\,931^g$ | | $+25$ | $-9.6$ |
| | $3^1S_0$ | $3\,943^h$ | $(4\,015)^i$ | $-66^e$ | $-3.1$ |
| | $3^3S_1$ | $4\,040^a$ | | $+22^e$ | $+1.0$ |

# Mass shifts:




$M(\eta_c') = 3637.7 \pm 4.4$

## Hyperfine splitting:

$$M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$$

Normalize to

$$M(J/\psi) - M(\eta_c) = 117 \text{ MeV}$$

→

$$M(\psi') - M(\eta_c') = 67 \text{ MeV}$$

Observed

$$(48.3 \pm 4.4) \text{ MeV}$$

Shift

20.9MeV → Agrees

# Modified State Properties

- Mixing

$$\Psi(1^3S_1) = 0.983\,|1^3S_1\rangle - 0.050\,|2^3S_1\rangle - 0.009\,|3^3S_1\rangle + \ldots;\ 96.8\%(c\bar{c})$$

$$\Psi(1^3P_1) = 0.914\,|1^3P_1\rangle - 0.075\,|2^3P_1\rangle - 0.015\,|3^3P_1\rangle + \ldots;\ 84.1\%(c\bar{c})$$

$$\Psi(1^3D_2) = 0.754\,|1^3D_2\rangle - 0.084\,|2^3D_2\rangle - 0.011\,|3^3D_2\rangle + \ldots;\ 57.6\%(c\bar{c})$$

- Isospin breaking

P wave decay - 6%

- Radiative Transitions

| | | | |
|---|---|---|---|
| $1^3D_1(3770) \to$ | $\chi_{c2}\,\gamma(208)$ | $\chi_{c1}\,\gamma(251)$ | $\chi_{c0}\,\gamma(338)$ |
| model | 3.9 | 59 | 225 |
| experiment[a] | $< 20$ | $78 \pm 20$ | |
| $1^3D_2(3831) \to$ | $\chi_{c2}\,\gamma(266)$ | $\chi_{c1}\,\gamma(308)$ | |
| model | 45 | 212 | |
| $1^3D_3(3868) \to$ | $\chi_{c2}\,\gamma(303)$ | | |
| model | 286 | | |

# Decays into open charm

## Decay widths:

ψ″(3770) width
agrees with experiment

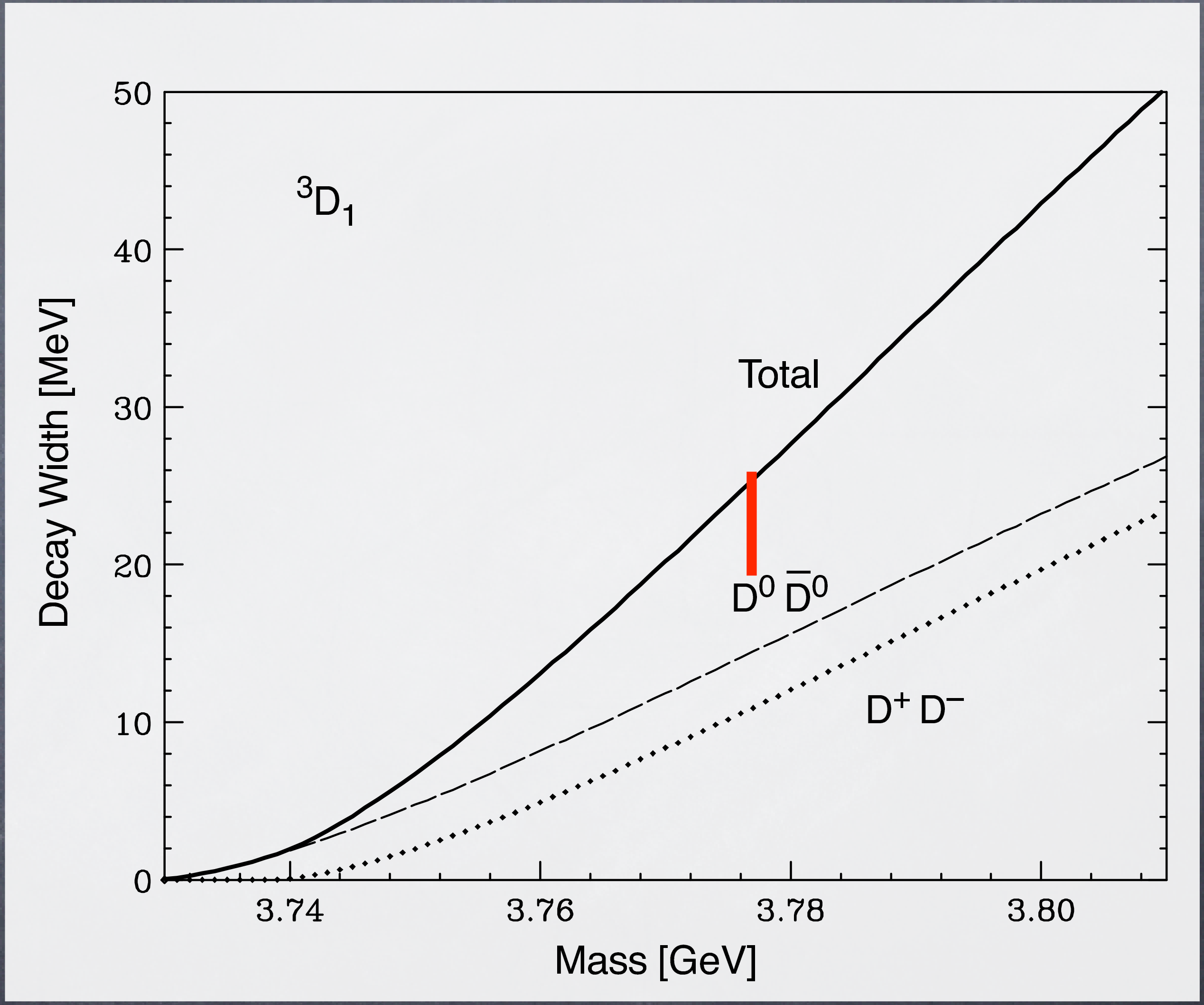
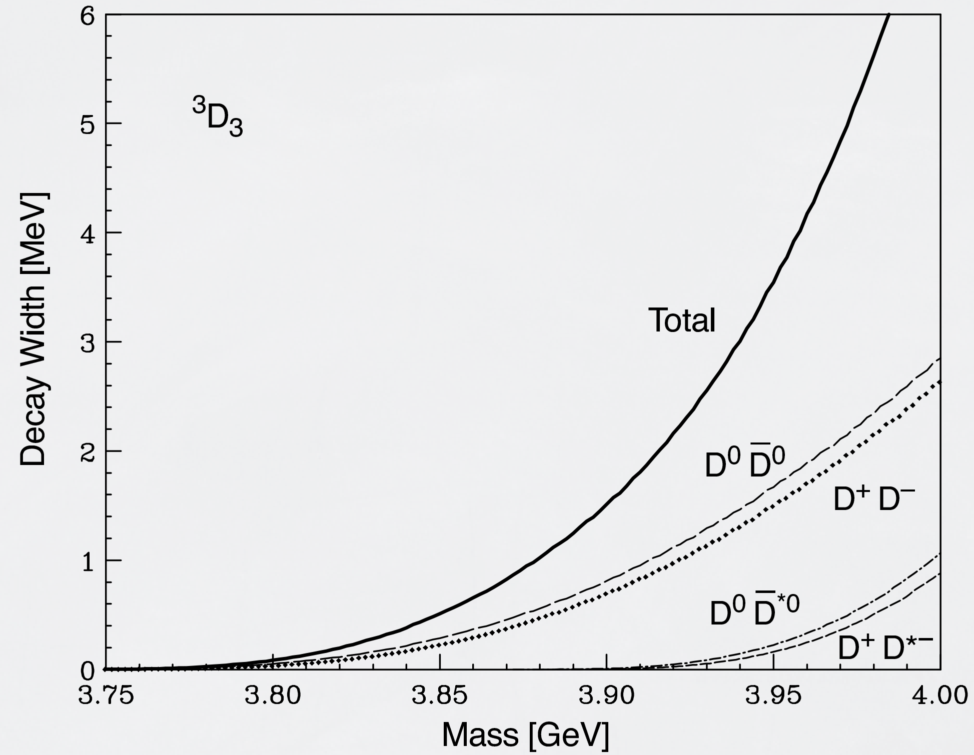


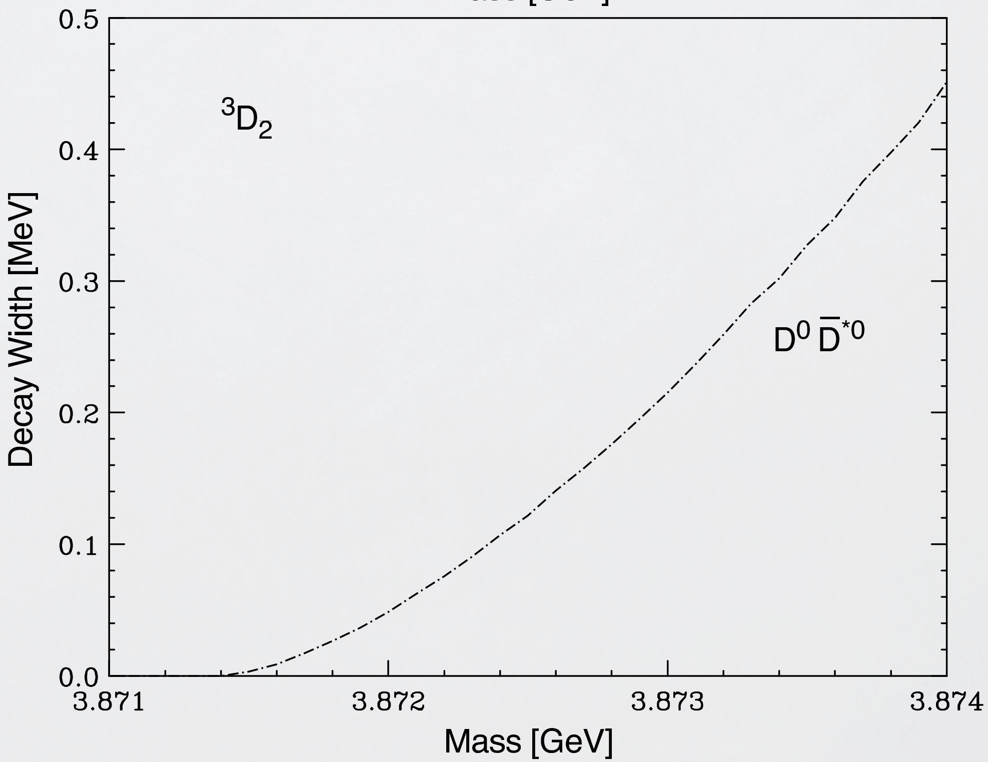
TABLE II: Statistical recoupling coefficients $C$, defined by Eq. D19 of Ref. [10], that enter the calculation of charmonium decays to pairs of charmed mesons. Paired entries correspond to $\ell = L - 1$ and $\ell = L + 1$.

| State | $D\bar{D}$ | $D\bar{D}^*$ | $D^*\bar{D}^*$ |
|---|---|---|---|
| $^1S_0$ | $- : 0$ | $- : 2$ | $- : 2$ |
| $^3S_1$ | $- : \frac{1}{3}$ | $- : \frac{4}{3}$ | $- : \frac{7}{3}$ |
| $^3P_0$ | $1 : 0$ | $0 : 0$ | $\frac{1}{3} : \frac{8}{3}$ |
| $^3P_1$ | $0 : 0$ | $\frac{4}{3} : \frac{2}{3}$ | $0 : 2$ |
| $^1P_1$ | $0 : 0$ | $\frac{2}{3} : \frac{4}{3}$ | $\frac{2}{3} : \frac{4}{3}$ |
| $^3P_2$ | $0 : \frac{2}{5}$ | $0 : \frac{6}{5}$ | $\frac{4}{3} : \frac{16}{15}$ |
| $^3D_1$ | $\frac{2}{3} : 0$ | $\frac{2}{3} : 0$ | $\frac{4}{15} : \frac{12}{5}$ |
| $^3D_2$ | $0 : 0$ | $\frac{6}{5} : \frac{4}{5}$ | $\frac{2}{5} : \frac{8}{5}$ |
| $^1D_2$ | $0 : 0$ | $\frac{4}{5} : \frac{6}{5}$ | $\frac{4}{5} : \frac{6}{5}$ |
| $^3D_3$ | $0 : \frac{3}{7}$ | $0 : \frac{8}{7}$ | $\frac{8}{5} : \frac{29}{35}$ |
| $^3F_2$ | $\frac{3}{5} : 0$ | $\frac{4}{5} : 0$ | $\frac{11}{35} : \frac{16}{7}$ |
| $^3F_3$ | $0 : 0$ | $\frac{8}{7} : \frac{6}{7}$ | $\frac{4}{7} : \frac{10}{7}$ |
| $^1F_3$ | $0 : 0$ | $\frac{6}{7} : \frac{8}{7}$ | $\frac{6}{7} : \frac{8}{7}$ |
| $^3F_4$ | $0 : \frac{4}{9}$ | $0 : \frac{10}{9}$ | $\frac{12}{7} : \frac{46}{63}$ |
| $^3G_3$ | $\frac{4}{7} : 0$ | $\frac{6}{7} : 0$ | $\frac{22}{63} : \frac{20}{9}$ |
| $^3G_4$ | $0 : 0$ | $\frac{10}{9} : \frac{8}{9}$ | $\frac{2}{3} : \frac{4}{3}$ |
| $^1G_4$ | $0 : 0$ | $\frac{8}{9} : \frac{10}{9}$ | $\frac{8}{9} : \frac{10}{9}$ |
| $^3G_5$ | $0 : \frac{5}{11}$ | $0 : \frac{12}{11}$ | $\frac{16}{9} : \frac{67}{99}$ |

# $^3D_3$ decay width small

Search for $D\bar{D}$ final states



# $\eta_c''$

Belle [hep-ex/0507019]

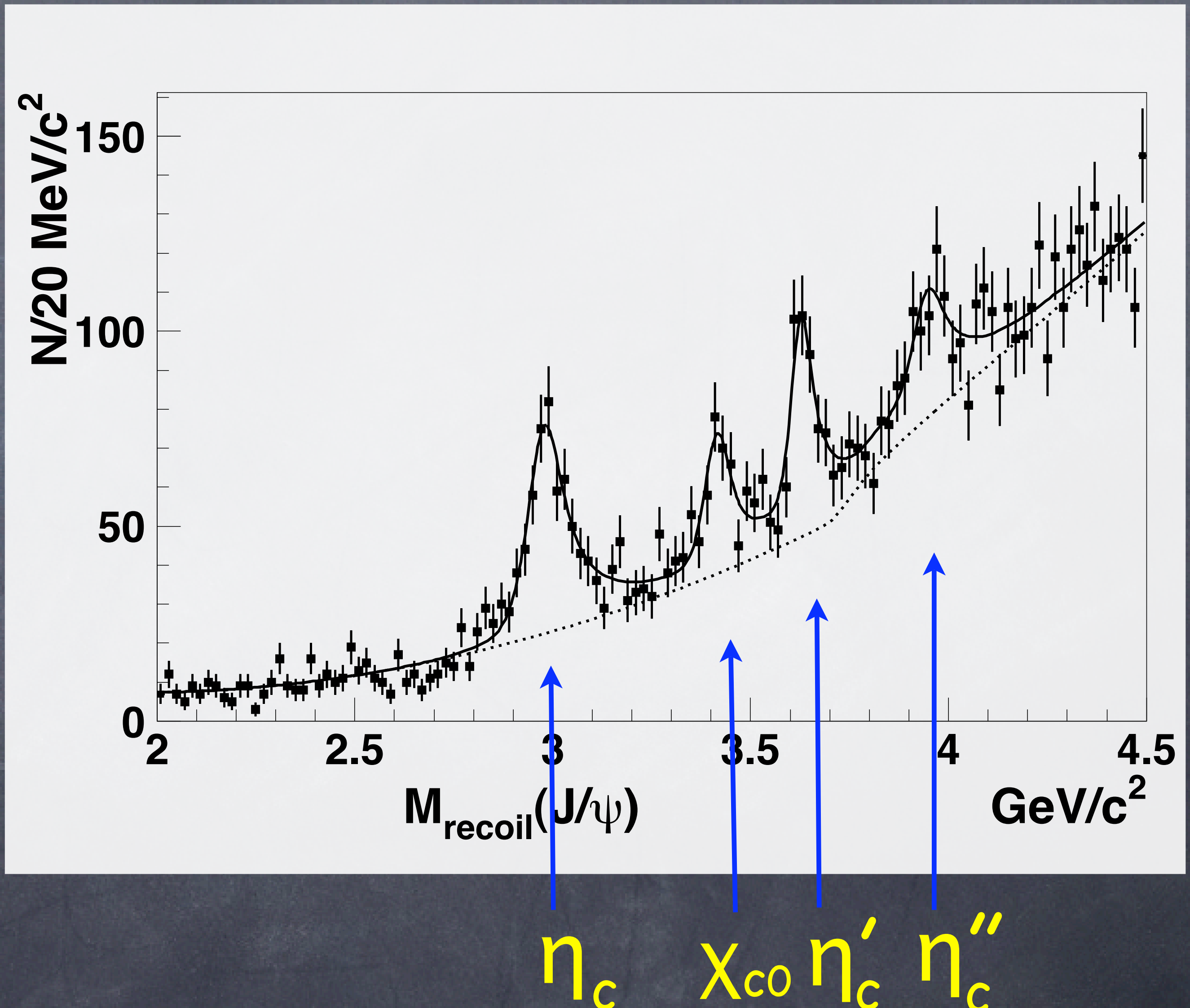
X(3943) decays into DD*
$\Rightarrow$ not $2^3P_0$

$\Gamma$(X(3943) < 56 MeV (90%cl)

M($\psi$(4040) - X(3943)) $\approx$ 100 MeV

Too large ?

BaBar ?

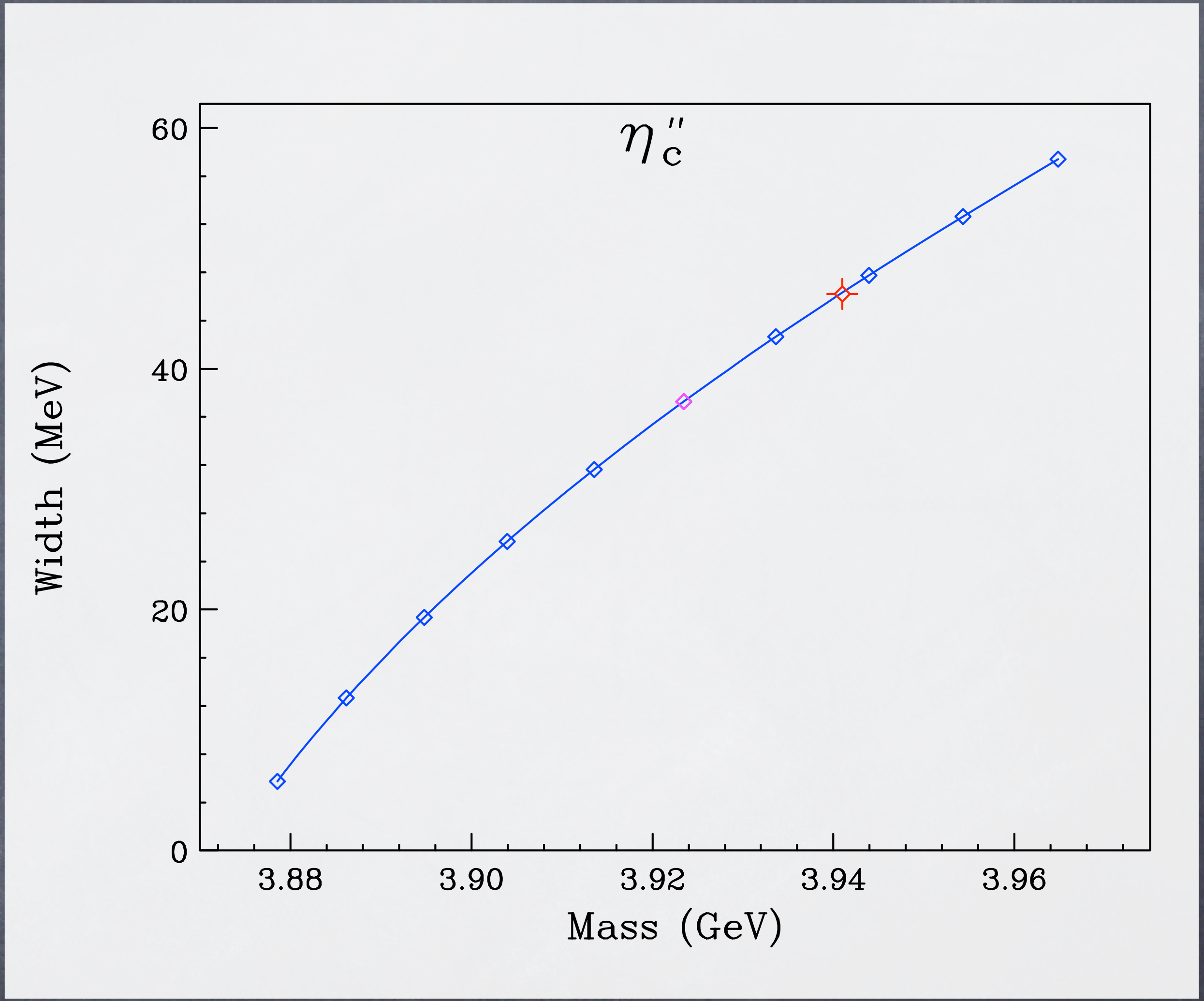


# Coupled Channels Results

$\Gamma \approx 50$ MeV

3S Spin Splitting **increased**

Requires bare splitting: 88 Mev




**To do:**

Extract $3^3S_1$ pole from CCC model of $\Delta R$.

Including $DD_P$ channels:

Expected to add significant spin splitting

# 2P States

Belle observes the Z(3931) in $\Upsilon\Upsilon$ production

Mass = 3931 ± 4(stat) ± 2(sys) MeV

Width = 20 ± 8(stat) ± 3(sys) MeV

Decay mode $D\bar{D}$

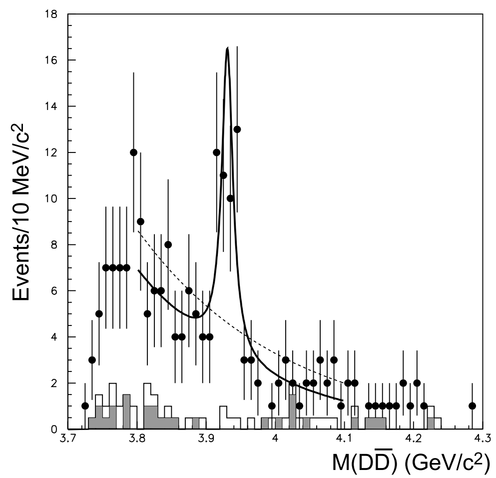



FIG. 3: The sum of the $M(D\bar{D})$ invariant mass distributions for all four processes. The curves show the fits with (solid) and without (dashed) a resonance component. The histograms show the distribution of the events from the $D$-mass sidebands (see the text).

Good agreement with expectations

Likely $X'_{c2}$

# Decay Widths

2P

J=0,1 states wide

J=2 state narrow

TABLE V: Open-charm strong decay modes of the charmonium states near threshold. The theoretical widths using the $C^3$ model [8] are shown.

| State | $n^{2s+1}L_J$ | Mode | Decay Width (MeV) Experiment | Computed |
|---|---|---|---|---|
| $\psi(3770)$ | $1^3D_1$ | $D^0\bar{D}^0$ | | 11.8 |
| | | $D^+D^-$ | | 8.3 |
| | | total | $23.6 \pm 2.7^b$ | 20.1 |
| $\psi(3868)$ | $1^3D_3$ | $D\bar{D}$ | | 0.82 |
| | | total | | 0.82 |
| $\chi'_{c0}(3881)$ | $2^3P_0$ | $D\bar{D}$ | | 61.5 |
| | | total | | 61.5 |
| $h'_{c1}(3919)$ | $2^1P_1$ | $D\bar{D}^*$ | | 59.8 |
| | | total | | 59.8 |
| $\chi'_{c1}(3920)$ | $2^3P_1$ | $D\bar{D}^*$ | | 81.0 |
| | | total | | 81.0 |
| $\chi'_{c2}(3931)$ | $2^3P_2$ | $D\bar{D}$ | | 21.5 |
| | | $D\bar{D}^*$ | | 7.1 |
| | | total | $20 \pm 8(\text{stat}) \pm 3(\text{sys})^d$ | 28.6 |
| $\eta''_c(3943)$ | $3^1S_0$ | $D\bar{D}^*$ | | 49.8 |
| | | total | $< 52^e$ | 49.8 |
| $\psi(4040)$ | $3^3S_1$ | $D\bar{D}$ | | 0.1 |
| | | $D\bar{D}^*$ | | 33. |
| | | $D_s\bar{D}_s$ | | 8. |
| | | $D^*\bar{D}^*$ | | 33. |
| | | total | $\left\{ 52 \pm 10^b ;\ 88 \pm 5^c \right\}$ | 74. |
| $\psi(4159)$ | $2^3D_1$ | $D\bar{D}$ | | 3.2 |
| | | $D\bar{D}^*$ | | 6.9 |
| | | $D^*\bar{D}^*$ | | 41.9 |

X(3872), Y(3940), Y(4260)

# Charmonium or Not?

Including light quark effects seems to blur the distinction between charmonium and (molecules or hybrids).

Not true for narrow states near thresholds.

A molecular or hybrid state exists only if an addition narrow state is seen in a given channel.

Purely counting states.

Levinson's theorem
Schwinger

# X(3872)

## Belle

(Phys.Rev.Lett.91:262001,2003)

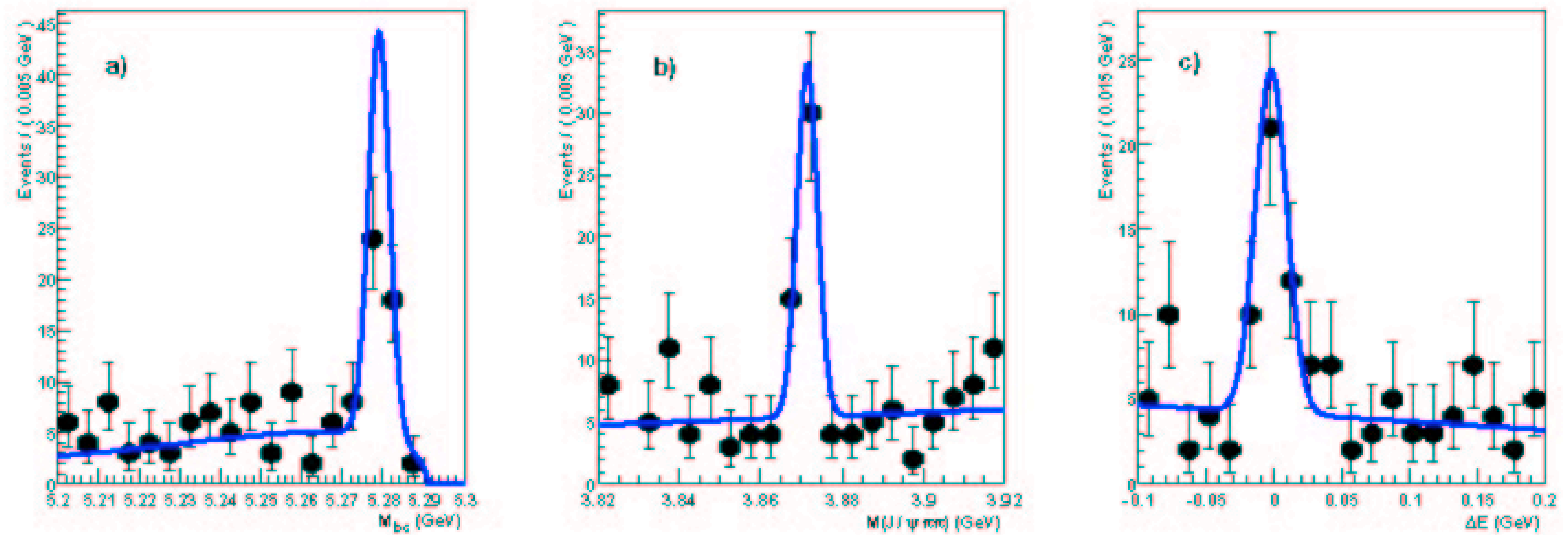
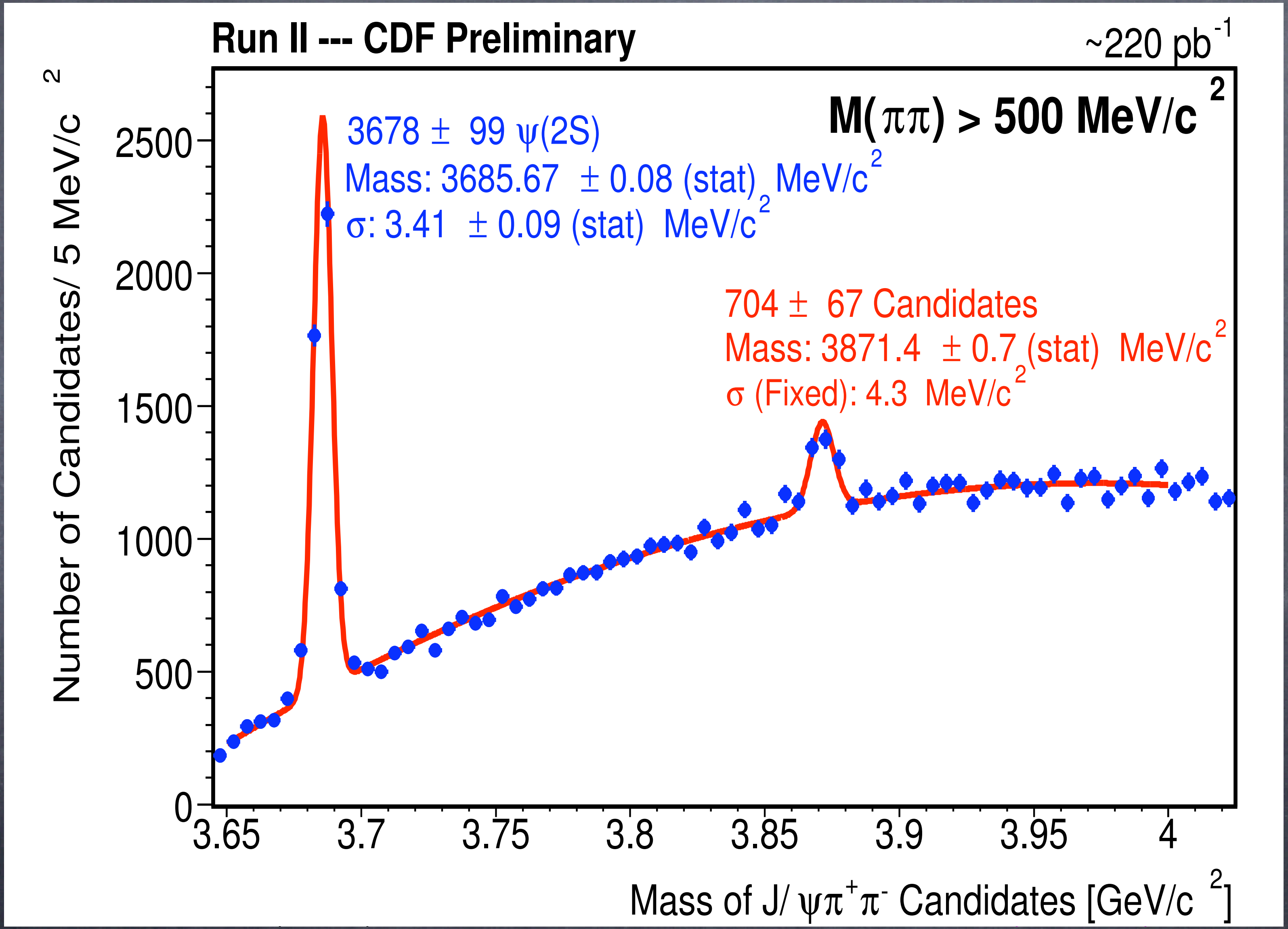



FIG. 2: Signal-band projections of (a) $M_{\mathrm{bc}}$, (b) $M_{\pi^+\pi^- J/\psi}$ and (c) $\Delta E$ for the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.

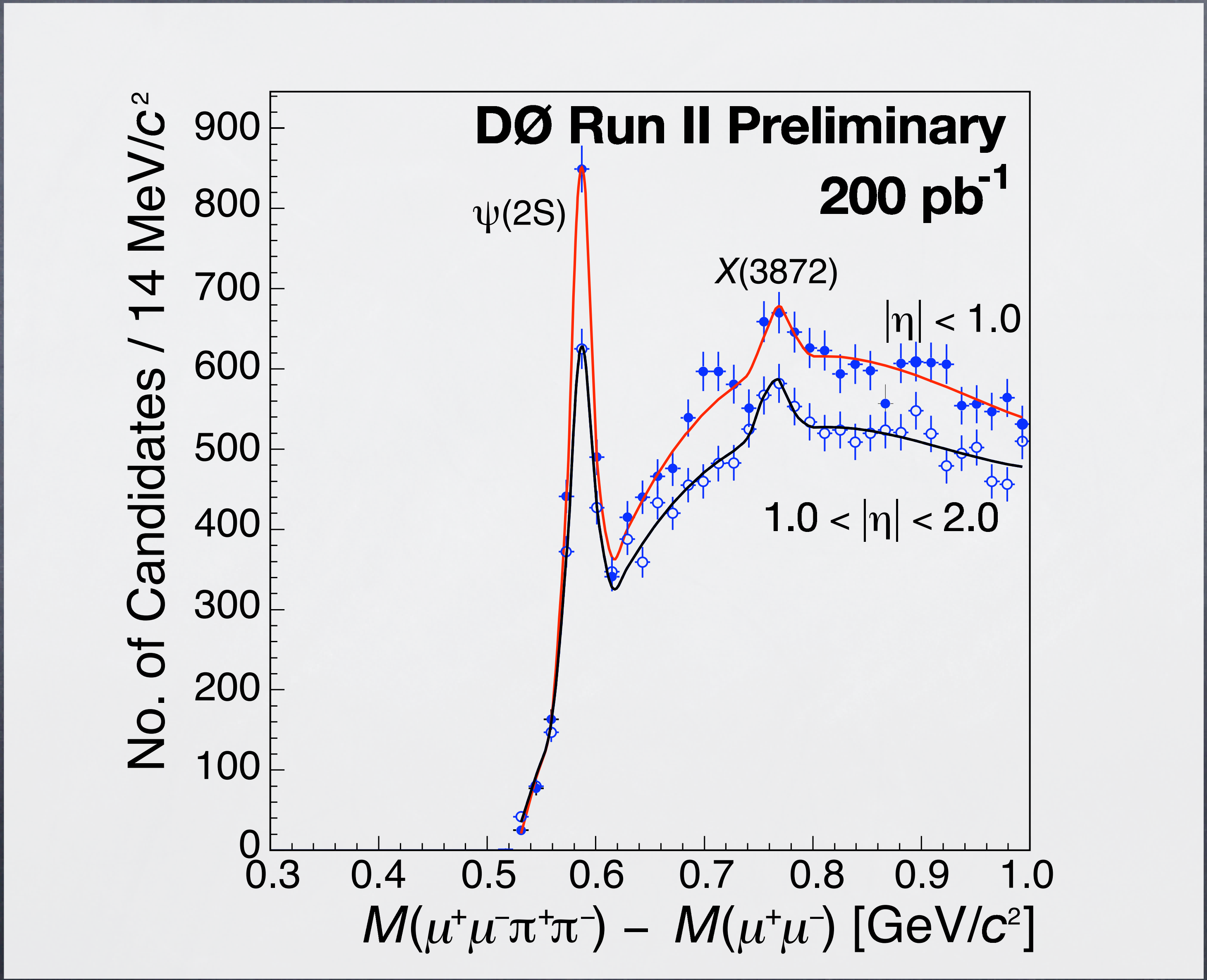
# CDF

Phys. Rev. Lett. 93, 072001 (2004)

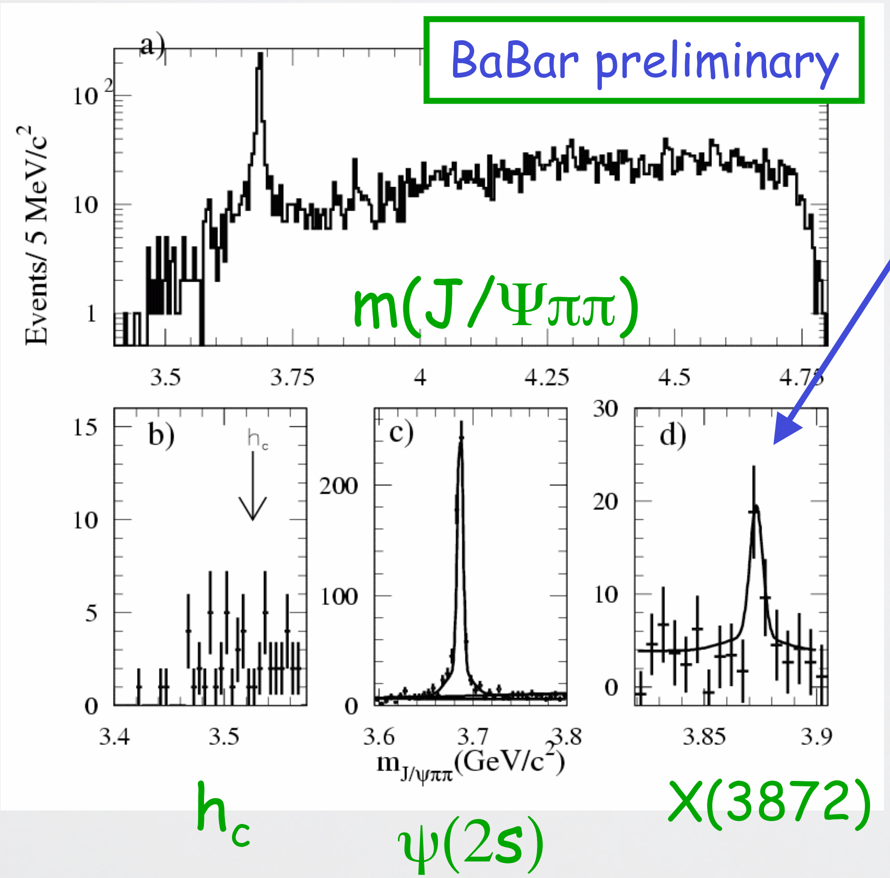


DO

Phys. Rev. Lett. 93, 162002 (2004)



# BaBar




$m_X = 3873.4 \pm 1.4$ MeV/$c^2$

$BR(B^- \to X(3872)K^-) \times BR(X \to J/\Psi\pi\pi) =$
$= (1.28 \pm 0.41) \times 10^{-5}$

Cross-check separating $J/\Psi \to ee, \mu\mu$

ee : $BR = (1.94 \pm 0.62) \times 10^{-5}$
$\mu\mu$: $BR = (0.52 \pm 0.46) \times 10^{-5}$

# What we know about X(3872)

Mass:

| Experiment | Sample | Events | Mass (MeV) |
|---|---|---|---|
| Belle | 152M $\Upsilon(4S) \to B\bar{B}$ | $35.7 \pm 6.8$ | $3872.0 \pm 0.8$ |
| CDF | 220 $pb^{-1}$ | $730 \pm 90$ | $3871.4 \pm 0.8$ |
| DØ | 230 $pb^{-1}$ | $522 \pm 100$ | $3871.8 \pm 4.3$ |
| BaBar | 117M $\Upsilon(4S) \to B\bar{B}$ | $25.4 \pm 8.7$ | $3873.4 \pm 1.4$ |
| | Average | | $3871.9 \pm 0.6$ |

3871.9 ± 0.6 MeV

DD* thresholds: (3871.3 ± 1.0 MeV) (3878.6 ± 1.0 MeV)

higher than expected in models (3815 MeV)

Width: < 2.3 MeV Belle

## Decay:

$X(3872) \Rightarrow \pi\,\pi + J/\psi$

Only seen in discovery mode
All other channels limits only

Perhaps a sighting ?

$X(3872) \Rightarrow \text{“}\omega\text{”} + J/\psi$

Offshell - needs confirmation

## Production:

Belle and BaBar - Produced in B decays.

CDF and D0 - Significant prompt production.

Expect Charmonium D wave state, BUT:

## Charmonium issues for 1D state: ➡ CCCM

Mass Splitting from ψ″(3770) too large. — ok

Radiative transition rates too small. — problem reduced

# Belle

## X(3872) ⇒ ‘ω’ + J/ψ

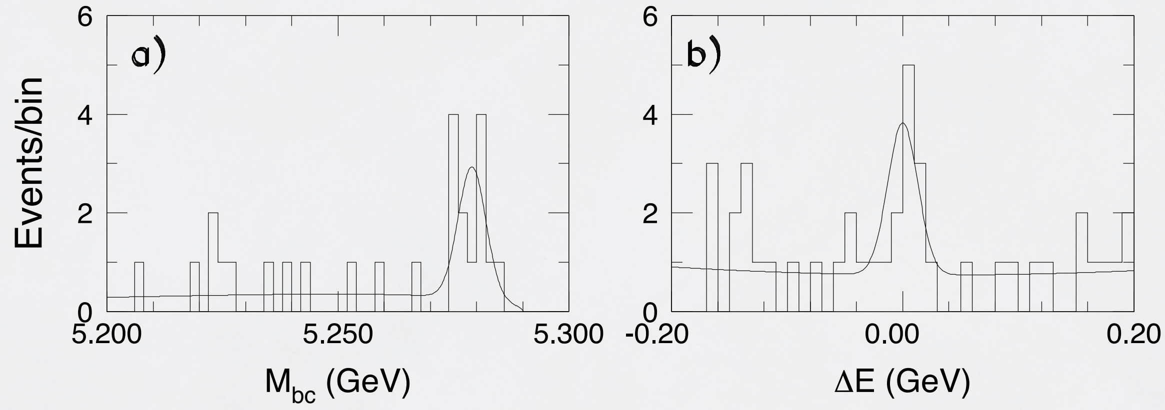
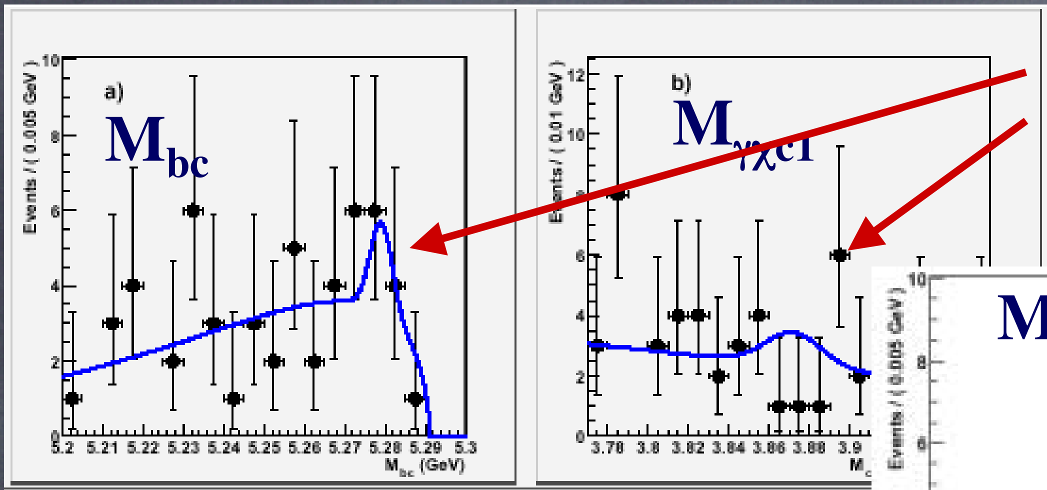



FIG. 8: **(a)** The $M_{bc}$ and **(b)** $\Delta E$ distributions for candidate $B \rightarrow K\pi^+\pi^-\pi^0 J/\psi$ decays with $M(\pi^+\pi^-\pi^0) > 0.75$ GeV. The curves are the result of the fit described in the text.

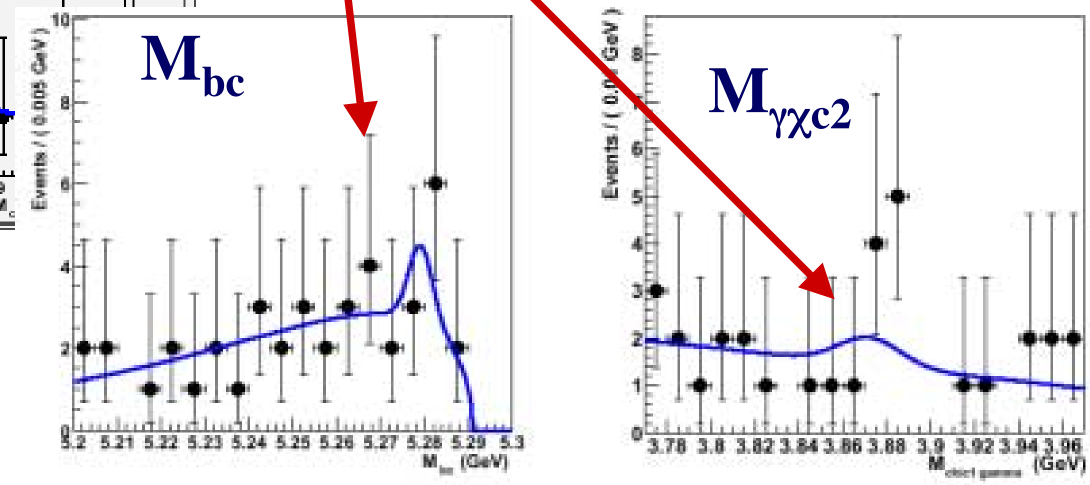
$$10.0 \pm 3.6 \text{ events and } S/B = 5$$

$$\frac{\Gamma(X \rightarrow \omega J/\psi)}{\Gamma(X \rightarrow \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3(\text{stat}) \pm 0.1(\text{syst})$$

# Belle




No signals !!



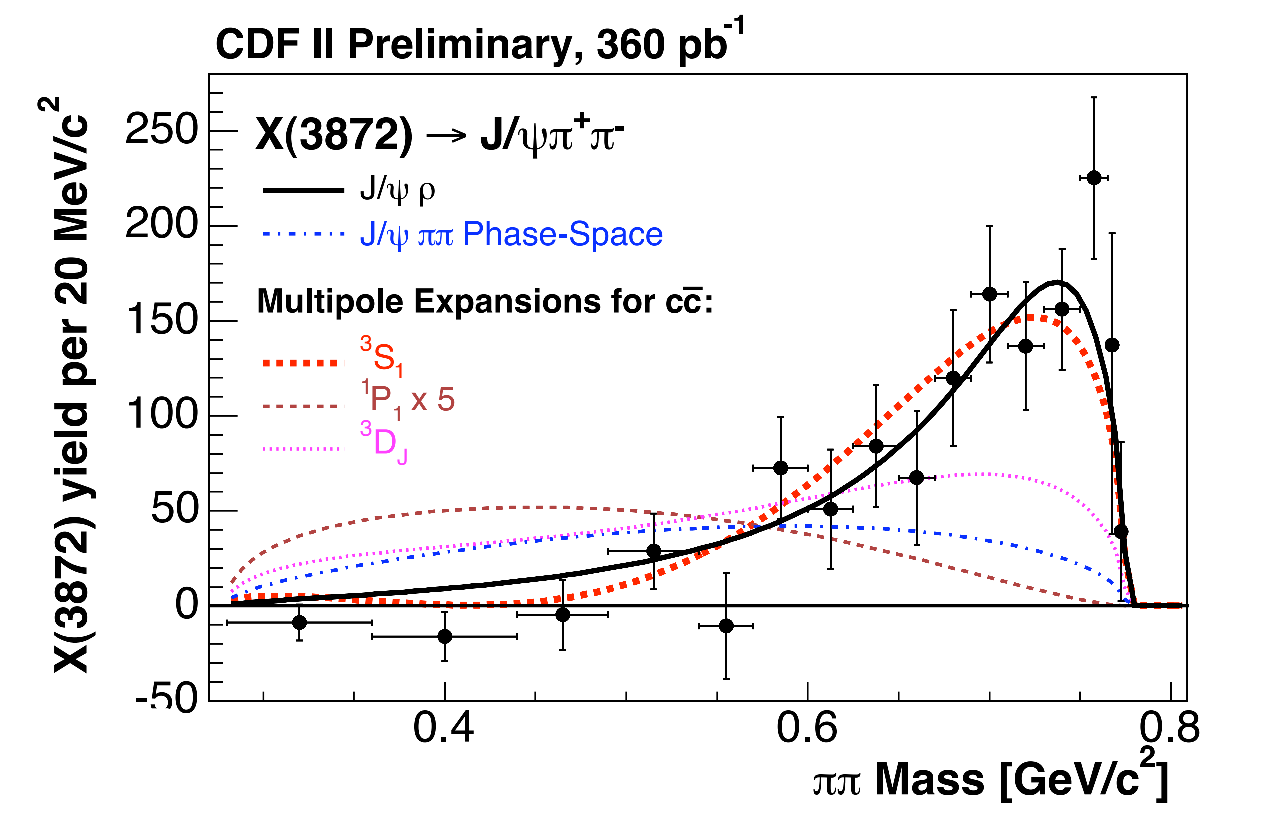

$$\frac{\Gamma(X \rightarrow \gamma\chi_{c1})}{\Gamma(X \rightarrow \pi^+\pi^- J/\psi)} < 0.9$$

$$\frac{\Gamma(X \rightarrow \gamma\chi_{c2})}{\Gamma(X \rightarrow \pi^+\pi^- J/\psi)} < 1.1$$

Large two pion transition rate ?

More peaked than $^3D_J$ Multipole Expansion

Better fit to $^3S_1$ ME or $\rho$




CDF Public Note
Update in hep-ex/0512074

Large Isospin breaking ? Maybe not Suzuki

Measure $\frac{X(3872) \to \pi^0\pi^0 \, J/\psi}{X(3872) \to \pi^+\pi^- J/\psi}$

# In the last few months

Belle
hep-ex/0505037

$X(3872) \Rightarrow \gamma + J/\psi \quad \Rightarrow \quad C = +1$

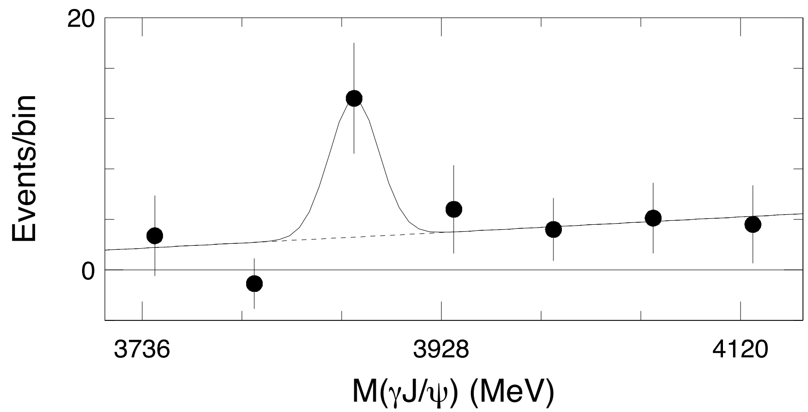



FIG. 2: The signal yields from fits to the $M_{bc}$ and $\Delta E$ distributions in bins of $M(3872)$. The curves are results of fits described in the text.

$$\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05.$$

$J^{PC} = 1^{++}$ Strongly favored

Belle
hep-ex/0505038

# Is the X(3872) the $2^3P_1$ charmonium state ?

Mass too low:

Setting the $\chi'_{c2}$ to the observed mass and including the coupled channel effects:

$M(\chi'_{c1}) = 3920$ MeV

Radiative transitions:

50% admixture of $D^0\overline{D}^0$

Belle

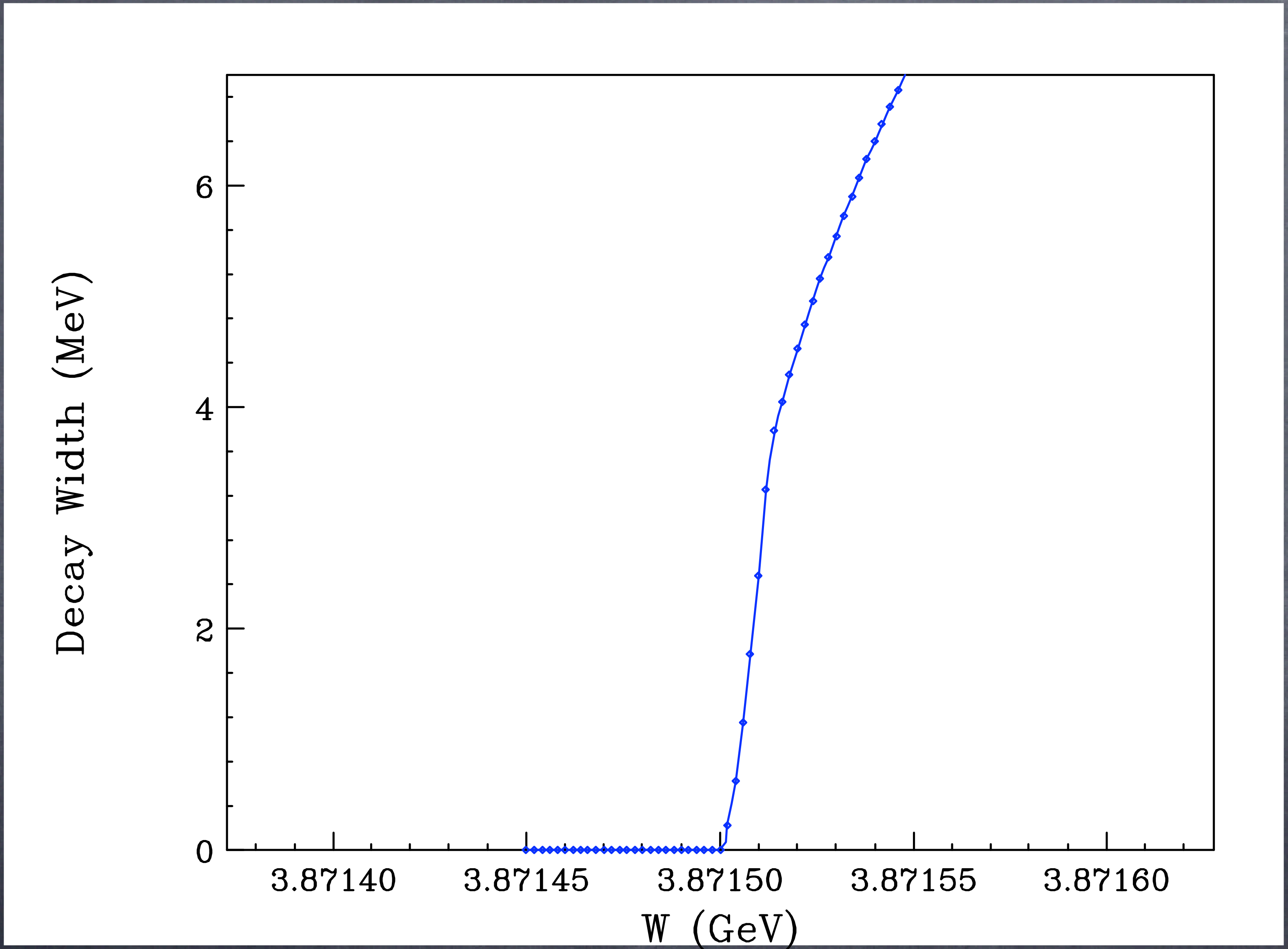
$\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05.$

TABLE VI: E1 radiative transition rates.

| | Partial Width (keV) | |
|---|---|---|
| $2^3P_1(3872) \to$ | $1^3D_1\,\gamma(101)$ | $1^3D_2\,\gamma(41)$ |
| model | 1.05 | 0.2 |
| $2^3P_1(3872) \to$ | $J/\psi\,\gamma(698)$ | $\psi'\,\gamma(182)$ |
| model | 34.7 | 21.1 |

Width Problems:

# Decay Width to $D^0\overline{D}^{0*}+D^{0*}\overline{D}^0$



# Including Light Quark Effects

$$[\mathcal{H}_0 + \mathcal{H}_2 + \mathcal{H}_I]\psi = \omega\psi$$

$\mathcal{H}_0$. $Q\bar{Q}$ NRQCD (without couplings light quarks)

$\mathcal{H}_I$ $Q\bar{Q} \rightarrow Q\bar{q} + q\bar{Q}$ light quark pair creation

Cornell model (CCCM) $\mathcal{H}_I = \frac{3}{8}\sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}') : d^3r\, d^3r'$

Vacuum Pair Creation model (QPC) $\mathcal{H}_I = \gamma \int \bar{\psi}\psi(\mathbf{r}) d^3r$

$\mathcal{H}_2$ $Q\bar{q} + q\bar{Q}$ meson pair interactions

# The Nature of $\mathcal{H}_2$

$\bar{Q}q + \bar{q}Q \rightarrow \bar{Q}q + \bar{q}Q$ dominant at large $\bar{Q}Q$ separation

one pion exchange Tornqvist

strong for S wave Suzuki

General formulation at large scattering length Braaten and Kusunoki

$\bar{Q}q + \bar{q}Q \rightarrow \bar{Q}Q + \bar{q}q$ mainly at smaller $\bar{Q}Q$ separation

constituent exchange terms

Swanson emphasizes that there are other nearby states

$J/\psi + \rho$ $J/\psi + \omega$

# Assignment for X if NOT Charmonium State

## Molecular State

S wave: $1^{++}, 1^{+-}$

Braaten and Kusunoki

Large couplings near threshold

Model independent analysis

$1^{+-}$ Ruled out

Belle

pion exchange

Tornqvist

Deuson

$1^{++}$ or $0^{-+}$

Decay by dissociation

Large Isospin Breaking

Maybe analogy states near $D^{*}\bar{D}^{*}$ thresholds

Analogy states in $B\bar{B}$ more deeply bound

## Other

hybrid M > 4200 MeV LQCD

Liao, Manke

Juge, Kuti, Morningstar

# Issues for Molecular Interpertation

What is the average $Q\bar{Q}$ separation?

Large - Pro: Small binding, two meson states.

Con: Long range forces not strong enough

M. Suzuki hep-ph/0508258

< ≈1 fm - Pro: Strong forces

Con: Complicated state

Near degeneracy with threshold is accidental

Braaten and Kusunogi require nearby $\chi'_{c1}$

Four quark states require just so dynamics.

# Key Measurements For X(3872):

$$\frac{X(3872) \to \gamma\, J/\psi}{X(3872) \to \pi^+\pi^- J/\psi}$$ ≈ 0.14± 0.05 Belle

$$\frac{X(3872) \to \pi^0\, D^0\bar{D}^0}{X(3872) \to \pi^+\pi^- J/\psi}$$ ≈ 10 Belle

$$\frac{X(3872) \to \gamma\, D^0\bar{D}^0}{X(3872) \to \pi^+\pi^- J/\psi}$$

$$\frac{X(3872) \to \pi^0\pi^0\, J/\psi}{X(3872) \to \pi^+\pi^- J/\psi}$$ -> Isospin violation

$$\frac{X(3872) \to \gamma\, \psi'}{X(3872) \to \gamma\, J/\psi}$$ ≈ 0.6 if $2^3P_1$

# More states

- Z(3931) seen in two photons --> $\chi_{c2}'$
  $D\overline{D}$ angular distribution favors J=2
  $\Gamma$ = 29 MeV Exp 20 ± 8 ± 3 MeV Belle
- X(3943) recoiling against J/ψ --> $\eta_c''$
  decays into DD*
  $\Gamma$ = 50 MeV Exp < 52 MeV Belle
- Y(3940) seen in B decays
  decay into ω J/ψ
  Exp $\Gamma$ = 87 ± 22 ± 26 MeV Belle
- Y(4260) seen in $e^+e^-$ ISR
  decay into ππ+J/ψ
  Exp $\Gamma$ = 50 to 90 MeV BaBar

# Y(3940)

Mass = 3943 ± 11 ± 13 Mev

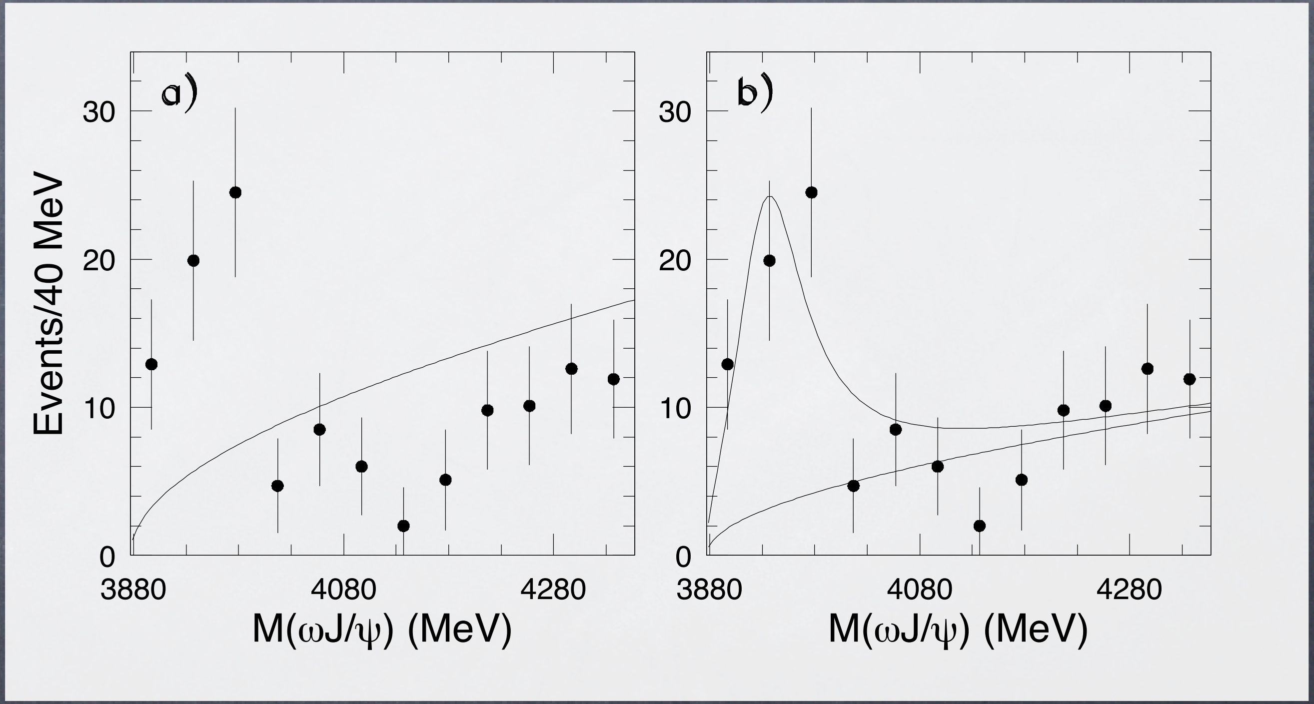
B decay Belle

B -> K Y

Γ = 87 ± 22 ± 26 MeV

Decay mode:
ωψ

Needs confirmation



# Nothing but questions:

Is this related to the other nearby states ?

How good is Zweig's rule ?

Isgur and Thacker PR D64:094507 (2001)
Geiger and Isgur PR D44, 799 (1991)

Cancellation fails in the threshold region

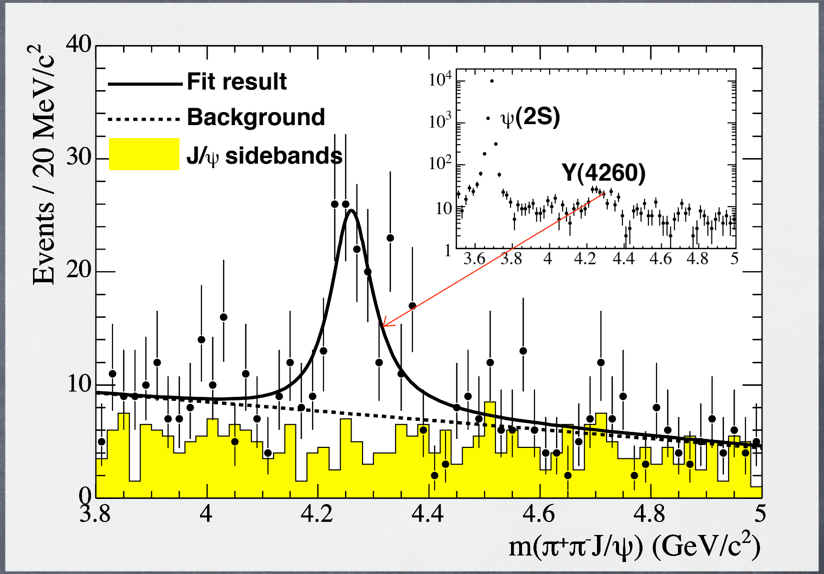
Near $D_s \bar{D}_s$ threshold. So what?

# Y(4260)

$J^{PC} = 1^{--}$

ISR production

BaBar




Mass = $4259 \pm 8\ ^{+2}_{-6}$ MeV

$\Gamma = 88 \pm 23\ ^{+6}_{-4}$ MeV

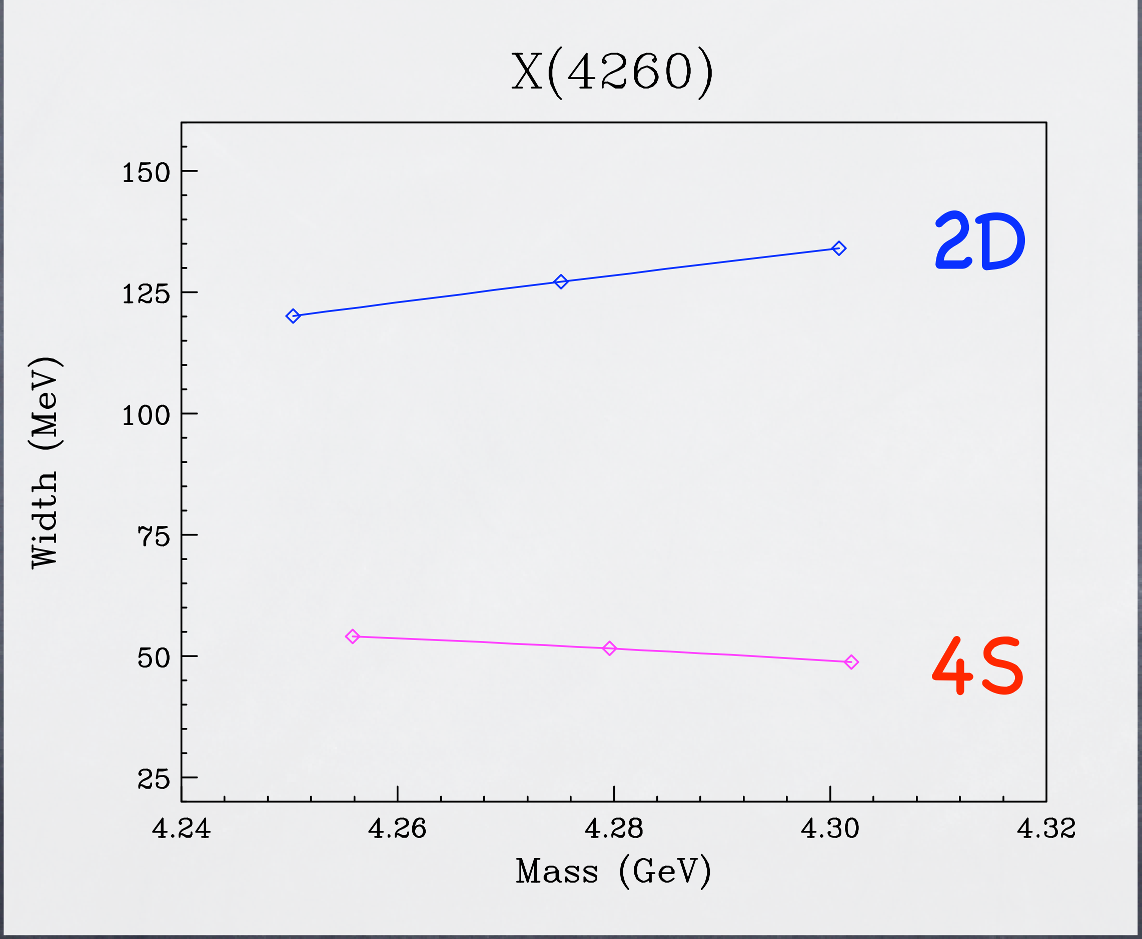
Small $\Delta R$

$$\Gamma(Y(4260) \to e^+e^-) \cdot \mathcal{B}(Y \to J/\psi\pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7}\ \text{eV}.$$

Not the 4S - $\Delta R$

Not the 2D - Decay modes

# Decay Widths



# The Y(4260) is something New

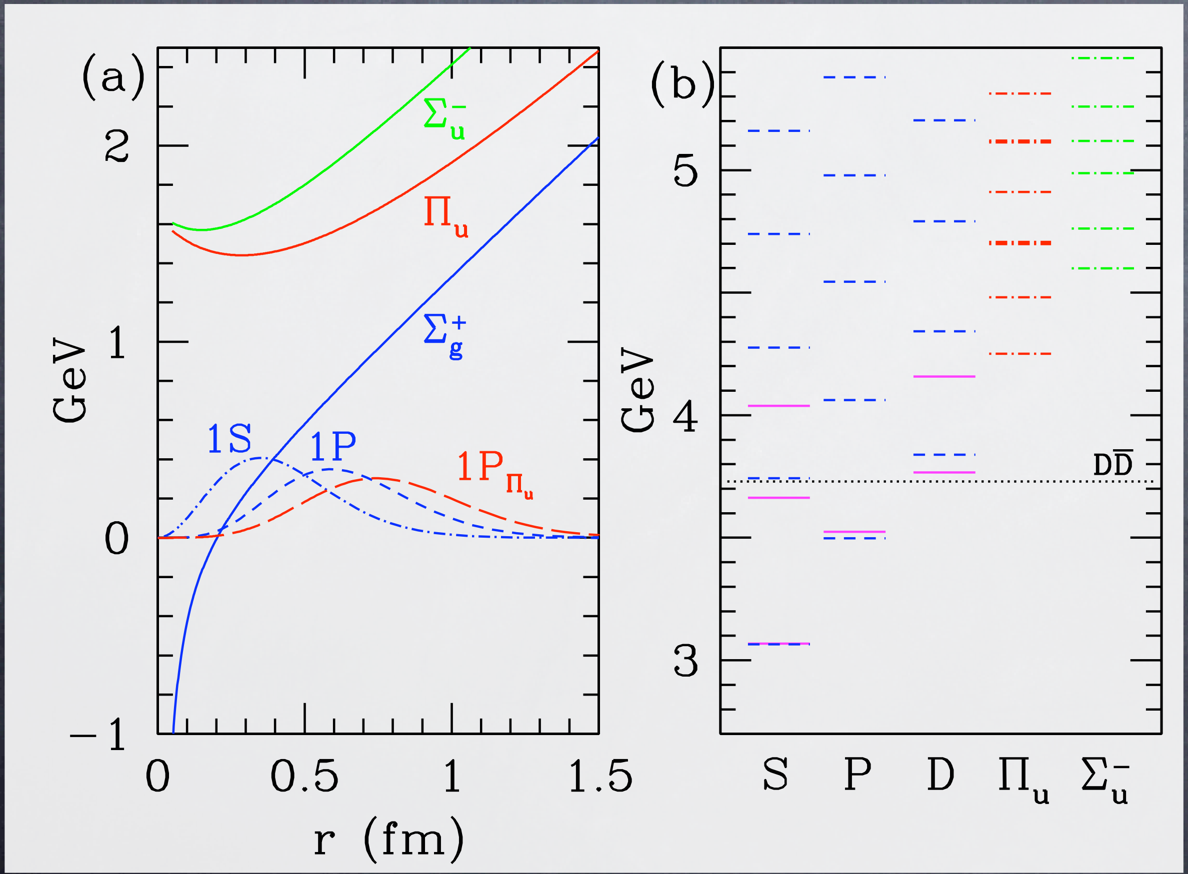
Molecular state - S wave thresholds

$DD_p$ -- but $D_p$ not narrow

Hybrid -

Close and Page [hep-ph/0507199]

Zhu [hep-ph/0507025]




Charmonium

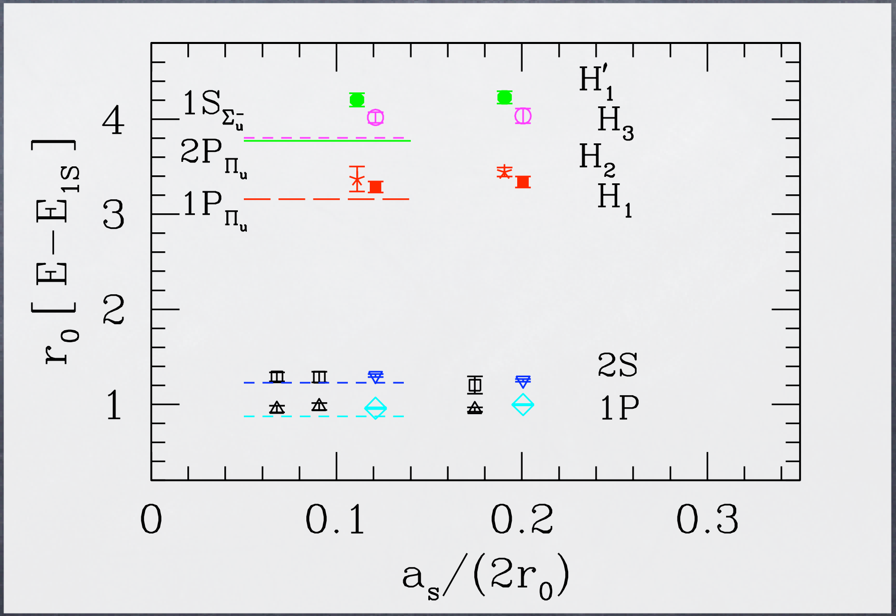
Juge, Kuti,Morningstar [nucl-th/0307116]

Expect triplet partners

| $J^{PC}$ | | Degeneracies | Operator |
|---|---|---|---|
| $0^{-+}$ | $S$ wave | $1^{--}$ | $\chi^\dagger\,(\boldsymbol{D}^2)^p\,\psi$ |
| $1^{+-}$ | $P$ wave | $0^{++}, 1^{++}, 2^{++}$ | $\chi^\dagger\,\boldsymbol{D}\,\psi$ |
| $1^{--}$ | $H_1$ hybrid | $0^{-+}, 1^{-+}, 2^{-+}$ | $\chi^\dagger\,\boldsymbol{B}(\boldsymbol{D}^2)^p\,\psi$ |
| $1^{++}$ | $H_2$ hybrid | $0^{+-}, 1^{+-}, 2^{+-}$ | $\chi^\dagger\,\boldsymbol{B}\times\boldsymbol{D}\,\psi$ |
| $0^{++}$ | $H_3$ hybrid | $1^{+-}$ | $\chi^\dagger\,\boldsymbol{B}\cdot\boldsymbol{D}\,\psi$ |

How many narrow?

## Quenched Spectrum



# X, Y, Z 's Status Table

| Observed | State | JPC | $(\bar{c}c)$ | Alternative |
|---|---|---|---|---|
| Many | X(3872) | 1++ | $\chi'_{c1}$ ✓ | D D* Molecule |
| Belle | Z (3934) | 2++ | $\chi'_{c2}$ ✓✓✓ | |
| Belle | Y (3940) | JP+ | ? | ? |
| Belle | X (3943) | 0-+ | $\eta''_c$ ✓✓ | |
| Babar | Y (4260) | 1-- | $2^3D_1$ ✗ | Hybrid |

# Summary and Outlook

- Narrow heavy-heavy states:
  - The $2^3P_2$ and $3^1S_0$ charmonium states likely found.
  - All three remaining low-lying L=2 charmonium states are narrow: $1^3D_2, 1^1D_2, 1^3D_3$
  - A proper calculation for the masses and decay rates of these states must include the large effects from nearby (real/virtual) open charm decay channels.
  - Detailed predictions for masses, mixings and decays using the CCCM give sensible results and can be used to guide the identification of other missing charmonium states.

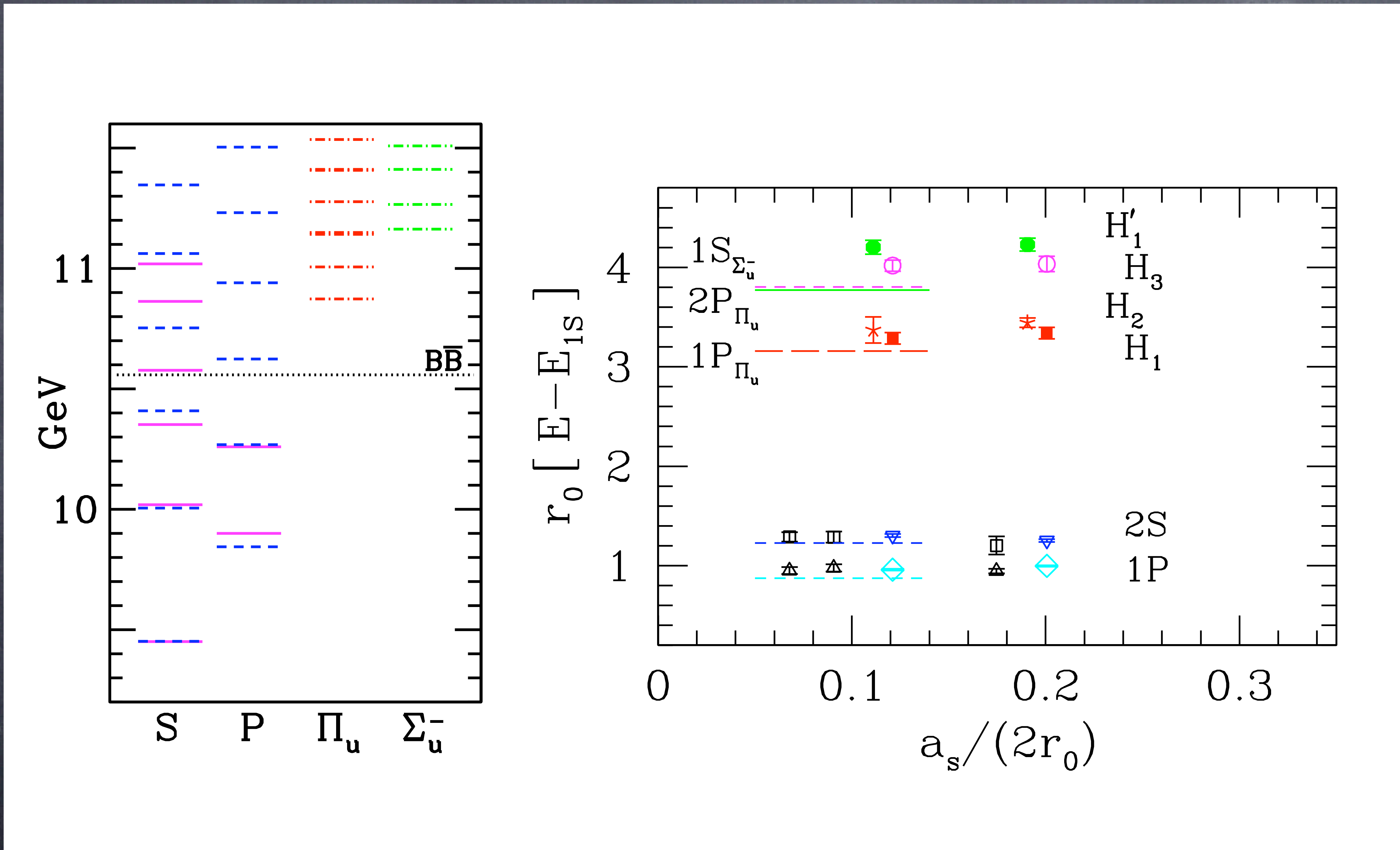
- QCD in all its richness:
  - The three states: X(3872), Y(3940) and Y(4260) do not fit gracefully in any simple charmonium interpretation.
- If X(3872) is a molecular state:
  - Possible analogy states in $\bar{b}b$ system
  - Possible analogy states near other S-wave thresholds.
- If Y(4260) is a hybrid state:
  - $0^{-+}$, $1^{-+}$ and $2^{-+}$ nearby states.
- Need lattice calculations of spectrum and properties.

# Extra Slides

# Wish List

- For charmonium states:
  - Branching ratios to charm meson pairs: DD, DD*, D*D*, $D_sD_s$, $D_sD_s$*, $D_s$*$D_s$*
  - Keep looking for missing 1D states
- For X(3872):
  - D D pi and D D gamma
  - look for radiative transition to ψ′
- For Y(4260):
  - look at D D pi pi for S-wave + P-wave charmed meson final state.
  - look for $D_s$*$D_s$*
- Look for more new states

# Hybrid Spectrum Lattice QCD




QWG Yellow Report [hep-ph/0412158]