Charmonium:
Above the Open Charm Threshold

Estia Eichten
Fermilab

- QCD Dynamics Near Threshold
- The $\psi(3770)$
- Other Charmonium States
- X(3872)
- Y(4260) and Beyond
- To Do List

QCD Dynamics Near Threshold

- QCD dynamics is much richer than present phenomenological models – Lattice QCD
- Gluon/String dynamics
- Light quark loops and strong decays

Below Threshold

Narrow states allow precise experimental probes of the subtle nature of QCD

NRQCD: $< v^2/c^2 > \approx 0.3$

Potential models:

- masses
- spin splittings
- EM transitions
- hadronic transitions
- direct decays

Lattice QCD:

- masses
- spin splittings
- EM transitions

variety of approaches

Supports and will supplant potential models

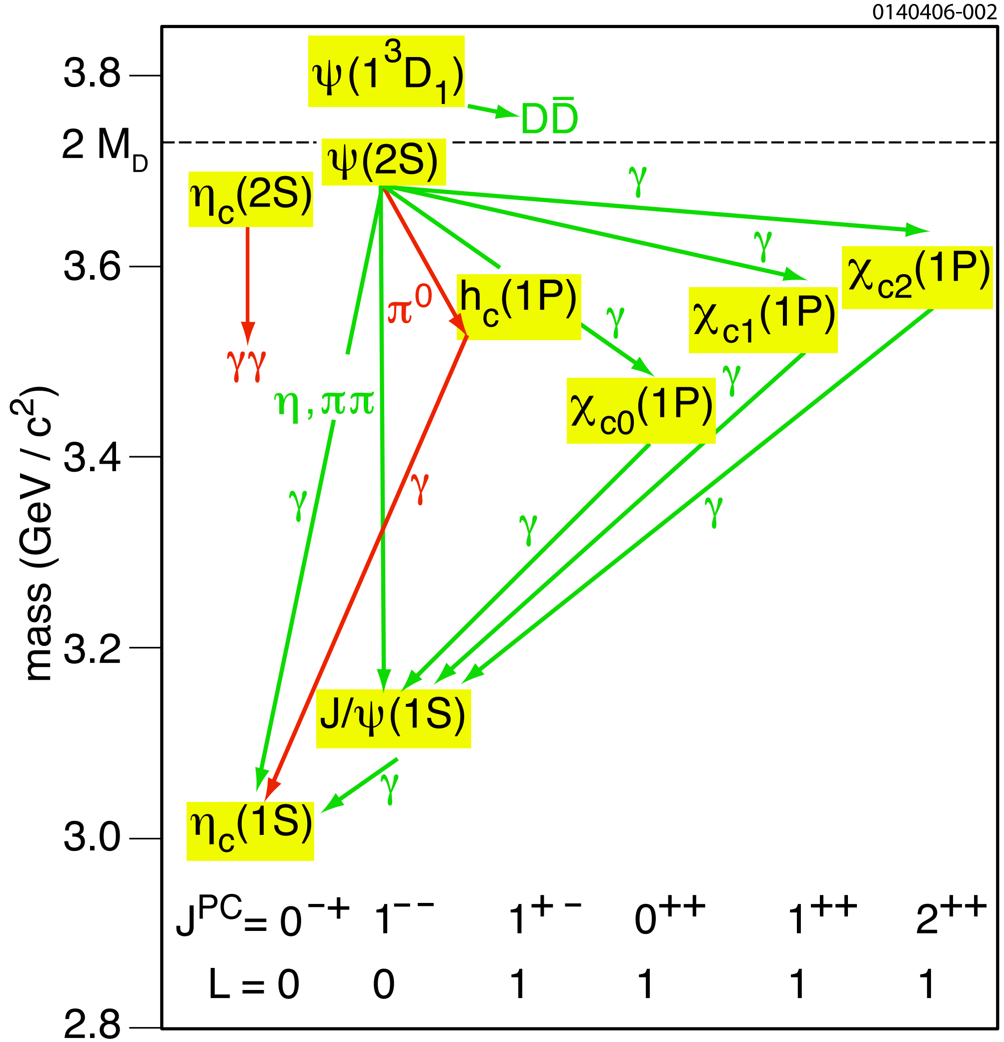


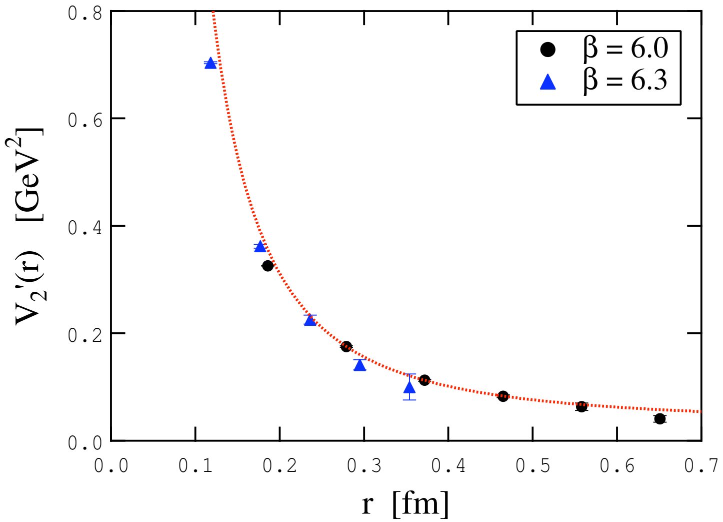
FIGURE 8. Transitions among low-lying charmonium states. From Ref. [65].

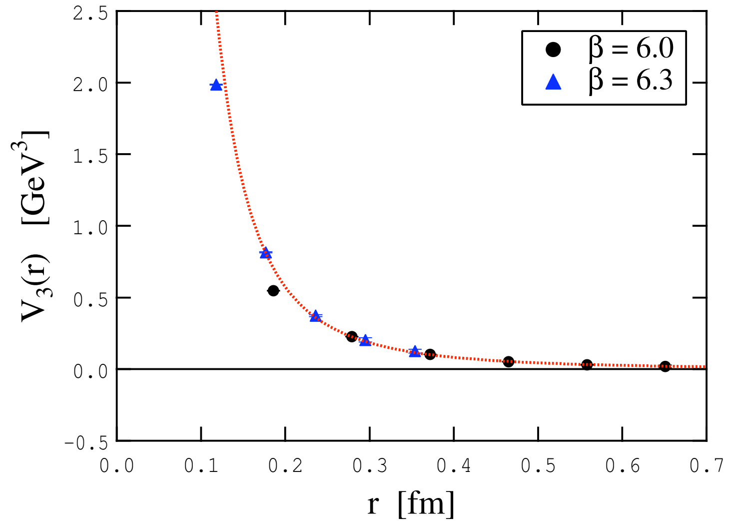
Multi-level algorithm allows lattice determination of potentials with unprecedented precision

Y. Koma, M. Koma and H. Wittig

[PRL 97 (2006) 122003]

Quenched





Heavy quark potential

To $O(1/m^2)$

$$V(r) = V^{(0)}(r) + \left(\frac{1}{m_1} + \frac{1}{m_1}\right) V^{(1)}(r) + O\left(\frac{1}{m^2}\right)$$

$$+ \left(\frac{\vec{s}_1\,\vec{l}_1}{2m_1^2} - \frac{\vec{s}_2\,\vec{l}_2}{2m_2^2}\right)\left(\frac{V^{(0)}(r)'}{r} + 2\frac{V^{(1)}(r)'}{r}\right) + \left(\frac{\vec{s}_2\,\vec{l}_1}{2m_1m_2} - \frac{\vec{s}_1\,\vec{l}_2}{2m_1m_2}\right)\frac{V^{(2)}(r)'}{r}$$

$$+ \frac{1}{m_1m_2}\left(\frac{(\vec{s}_1\,\vec{r})\,(\vec{s}_2\,\vec{r})}{r^2} - \frac{\vec{s}_1\,\vec{s}_2}{3}\right) V^{(3)}(r) + \frac{\vec{s}_1\,\vec{s}_2}{3m_1m_2} V^{(4)}(r)$$

Fine and hyper-fine splitting

Recent LQCD results

Dudek, Edwards, Richards

[PR D73:07450 (2006)]

E1	$\chi_{c0} \to J/\psi\gamma$	$\chi_{c1} \to J/\psi\gamma$	$h_c \to \eta_c\gamma$
β/MeV	542(35)	555(113)	689(133)
ρ/MeV	1080(130)	1650(590)	∞
$\Gamma^{\text{lat.mass}}_{\text{phys.mass}}$/keV	288(60) 232(41)	600(178) 487(122)	663(132) 601(55)
$\Gamma^{\text{PDG}}_{\text{CLEO}}$/keV	115(14) 204(31)	303(44) 364(31)	-

M1	$J/\psi \to \eta_c\gamma$	**M2**	$\chi_{c1} \to J/\psi\gamma$
β/MeV	540(10)	β/MeV	617(142)
$\Gamma^{\text{lat.mass}}_{\text{phys.mass}}$/keV	1.61(7) 2.57(11)	$\frac{M2}{E1}$	$-0.199(121)$
$\Gamma^{\text{PDG}}_{\phi\phi}$/keV	1.14(33) 2.9(1.5)	expt.	$-0.002(^{+8}_{-17})$

Promising but still work to do:

quenched

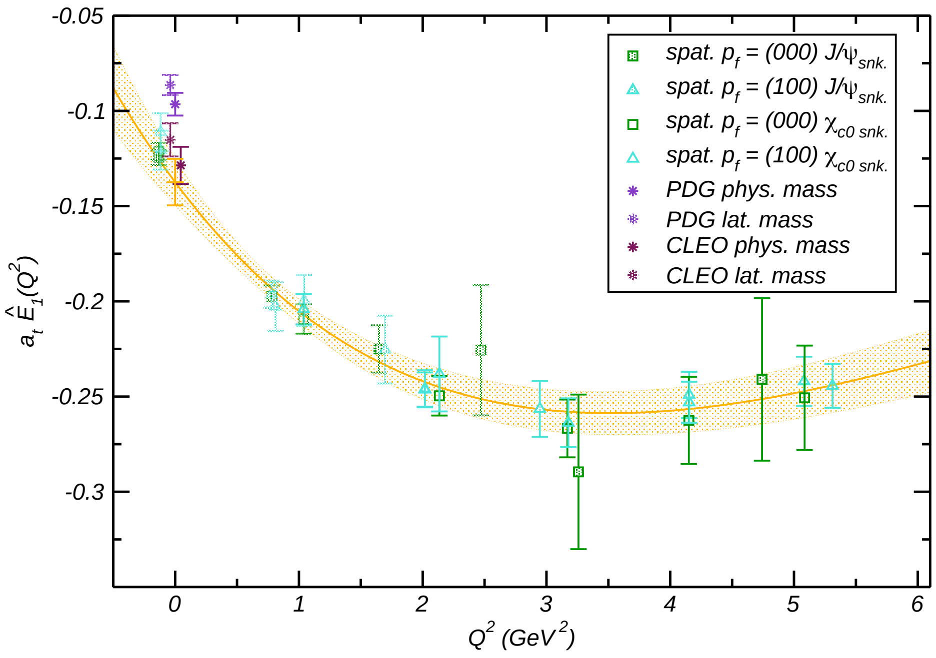
ground states

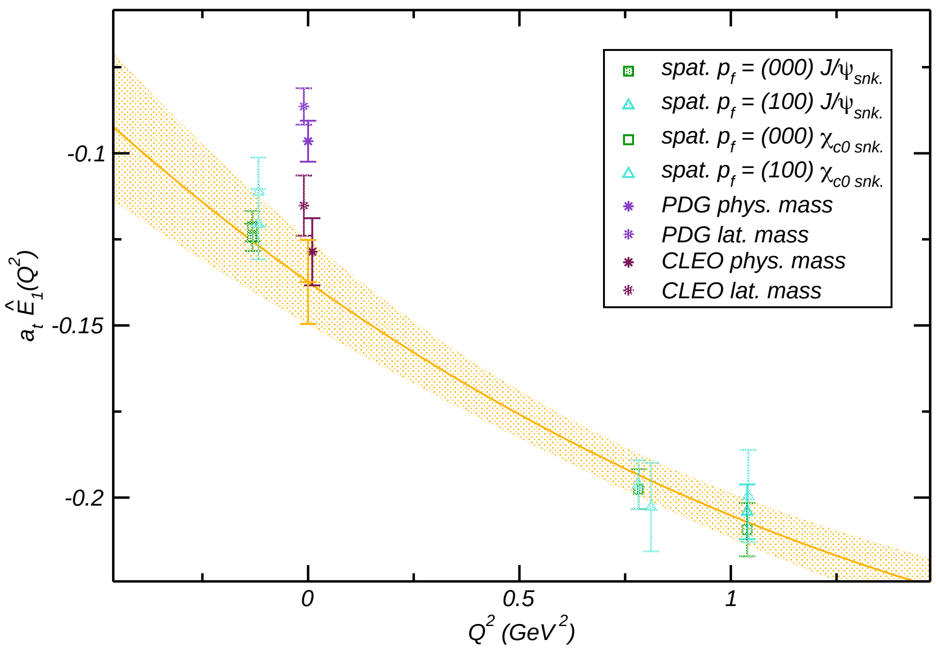
extrapolations

Q^2 -> 0

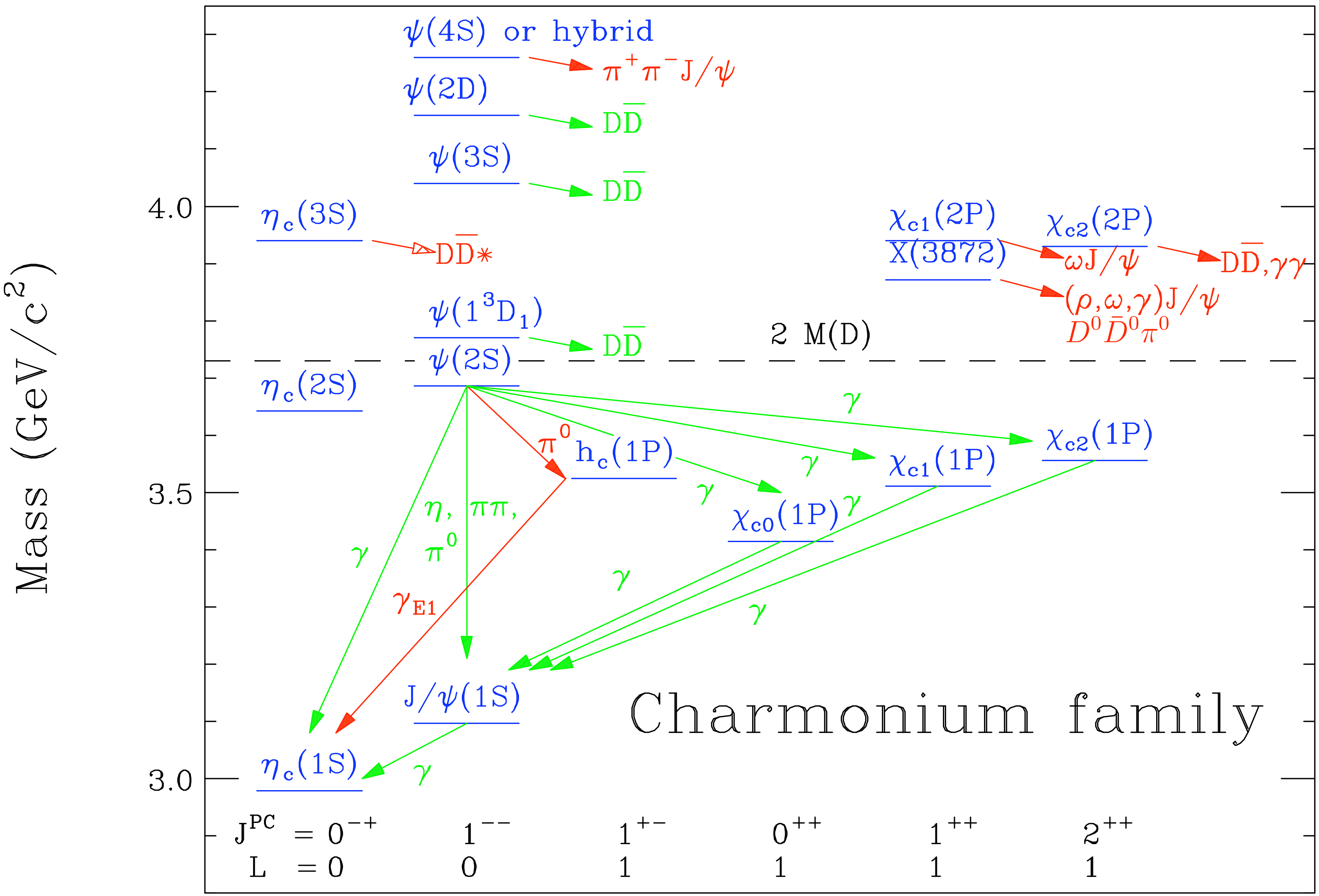
a-> 0

$\chi_{c0} \to J/\psi\gamma$





Above Threshold



Hard to extract states in the threshold region in LQCD

Excited charmonium states

Strong decay channels -- resonances:

Nearby Thresholds

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

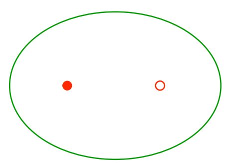
Gluon/String Dynamics

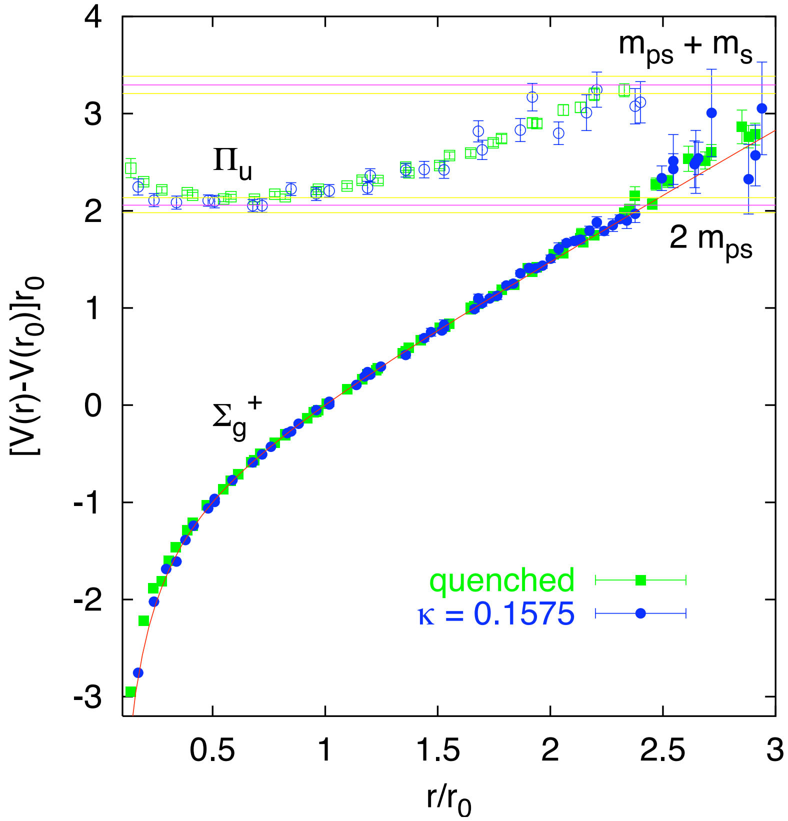
Heavy Quark Limit - Static Energy

Short distance: Perturbative QCD

singlet: $-4/3\ \alpha_s /r$

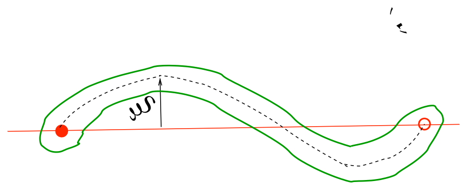
octet : $2/3\ \alpha_s /r$ gluelumps





Large distance: String

σ r NG string behavour



Operators for excited gluon states

TABLE I: Operators to create excited gluon states for small $q\bar{q}$ separation R are listed. $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic operators, respectively. The covariant derivative $\mathbf{D}$ is defined in the adjoint representation [10].

gluon state	J	operator
$\Sigma_g^{+\prime}$	1	$\mathbf{R}\cdot\mathbf{E}$, $\mathbf{R}\cdot(\mathbf{D}\times\mathbf{B})$
Π_g	1	$\mathbf{R}\times\mathbf{E}$, $\mathbf{R}\times(\mathbf{D}\times\mathbf{B})$
Σ_u^-	1	$\mathbf{R}\cdot\mathbf{B}$, $\mathbf{R}\cdot(\mathbf{D}\times\mathbf{E})$
Π_u	1	$\mathbf{R}\times\mathbf{B}$, $\mathbf{R}\times(\mathbf{D}\times\mathbf{E})$
Σ_g^-	2	$(\mathbf{R}\cdot\mathbf{D})(\mathbf{R}\cdot\mathbf{B})$
Π_g'	2	$\mathbf{R}\times((\mathbf{R}\cdot\mathbf{D})\mathbf{B}+\mathbf{D}(\mathbf{R}\cdot\mathbf{B}))$
Δ_g	2	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{B})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{B})^i$
Σ_u^+	2	$(\mathbf{R}\cdot\mathbf{D})(\mathbf{R}\cdot\mathbf{E})$
Π_u'	2	$\mathbf{R}\times((\mathbf{R}\cdot\mathbf{D})\mathbf{E}+\mathbf{D}(\mathbf{R}\cdot\mathbf{E}))$
Δ_u	2	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{E})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{E})^i$

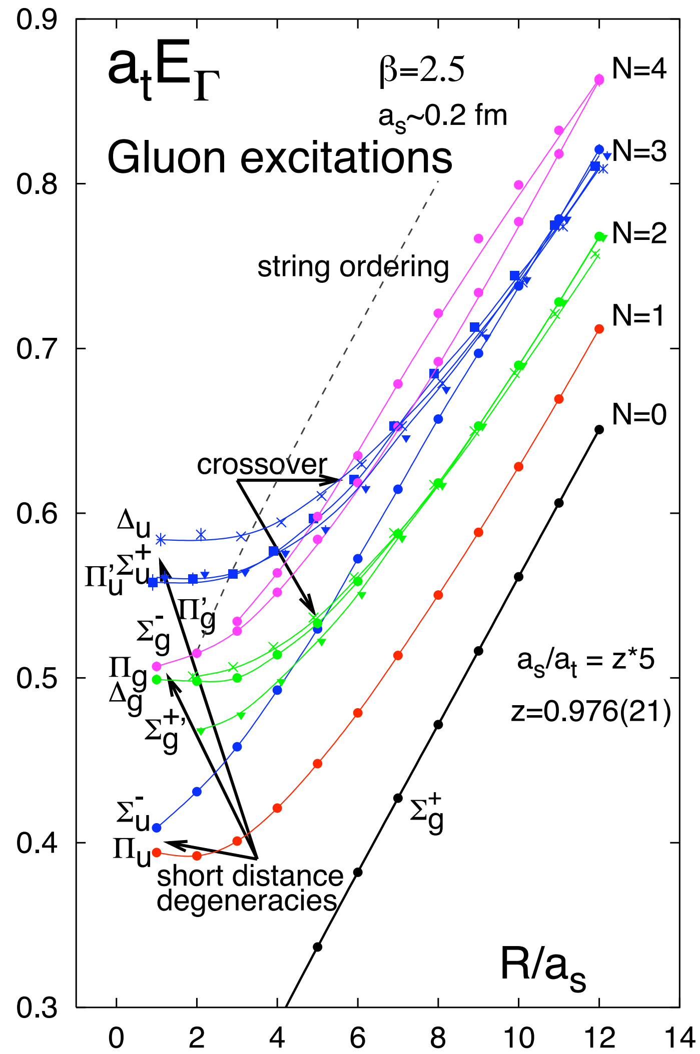


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Hybrid Potentials

Juge, Kuti, Morningstar

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

Solve the Schoedinger Equation for each potential

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r),$$

where

$$\boldsymbol{J}=\boldsymbol{L}+\boldsymbol{S},\quad \boldsymbol{S}=\boldsymbol{s}_Q+\boldsymbol{s}_{\bar{Q}},\quad \boldsymbol{L}=\boldsymbol{L}_{Q\bar{Q}}+\boldsymbol{J}_g$$

$$\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle = L(L+1)-2\Lambda^2+\langle \boldsymbol{J}^2_g\rangle$$

eigenstates

$$|LSJM;\lambda\eta\rangle+\varepsilon|LSJM;-\lambda\eta\rangle$$

where $\varepsilon = \pm 1$, $\Lambda = |\lambda|$

$$P=\varepsilon(-1)^{L+\Lambda+1},\qquad C=\eta\varepsilon(-1)^{L+S+\Lambda}$$

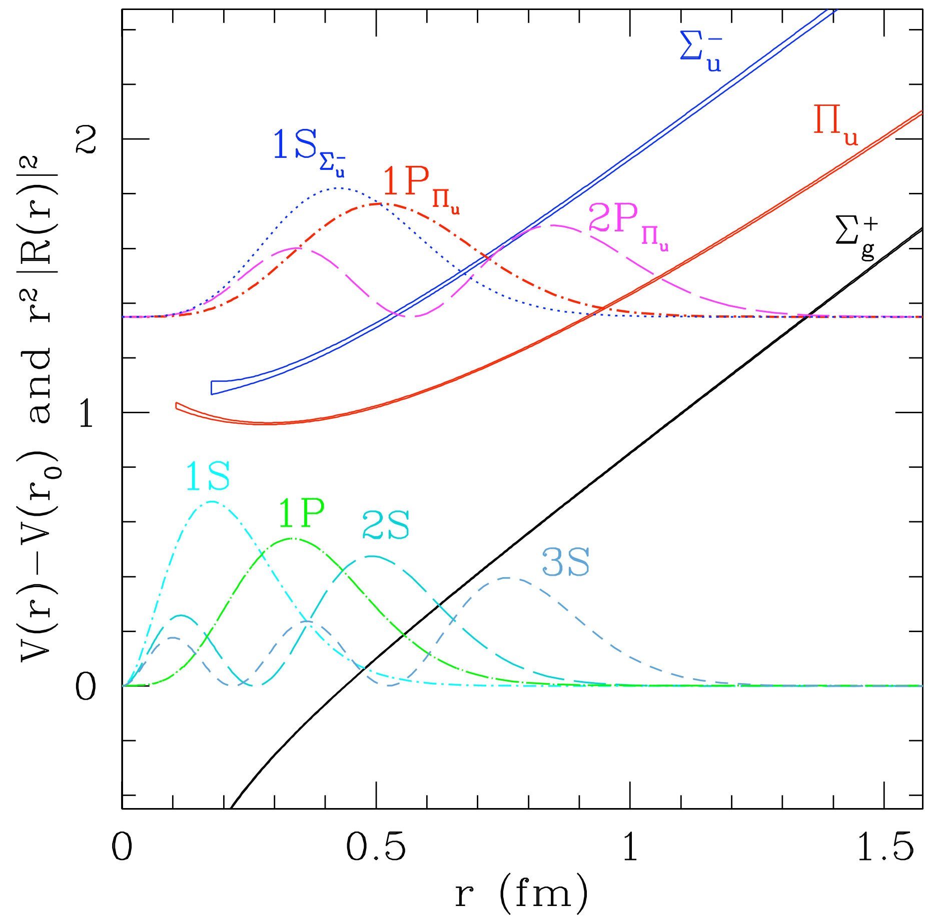
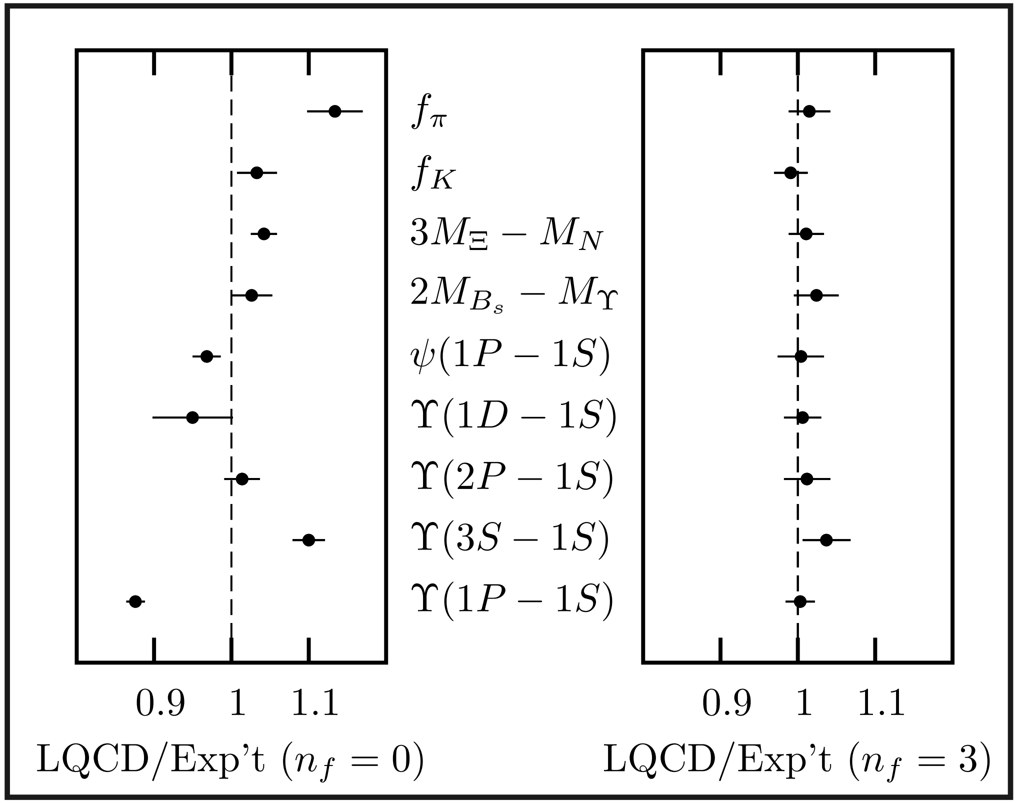
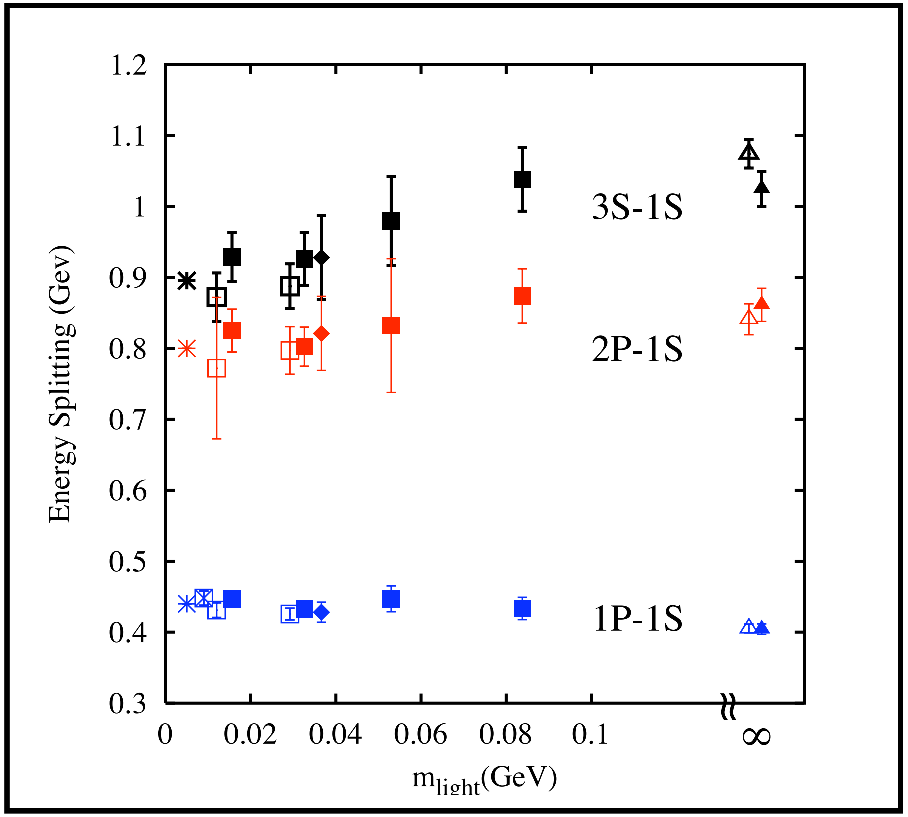


Figure 2. Wavefunctions and potentials for the various hybrid/meson states.

Light quark loops

Effects on spectrum clearly seen in LQCD





C. T. H. Davies et al. [HPQCD, Fermilab Lattice, MILC, and UKQCD Collaborations], PRL 92, 022001 (2004)

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

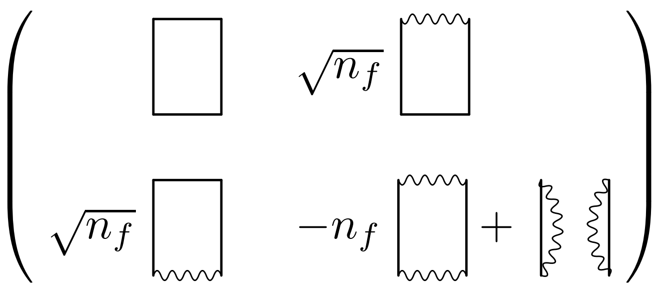
Cornell model (CCCM) $\mathcal{H}_I = \frac{3}{8}\sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}') : d^3r\, d^3r'$

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 effort to extract couplings

$$C(t) \quad = \quad \begin{pmatrix} C_{QQ}(t) & C_{QB}(t) \\ C_{BQ}(t) & C_{BB}(t) \end{pmatrix}$$

$= e^{-2m_Q t}$ 

, (1)

transition amplitude

$$g = \left.\frac{dC_{QB}(t)}{dt}\right|_{t=0} \frac{1}{\sqrt{C_{BB}(0)C_{QQ}(0)}}.$$

difficult to extract accurately

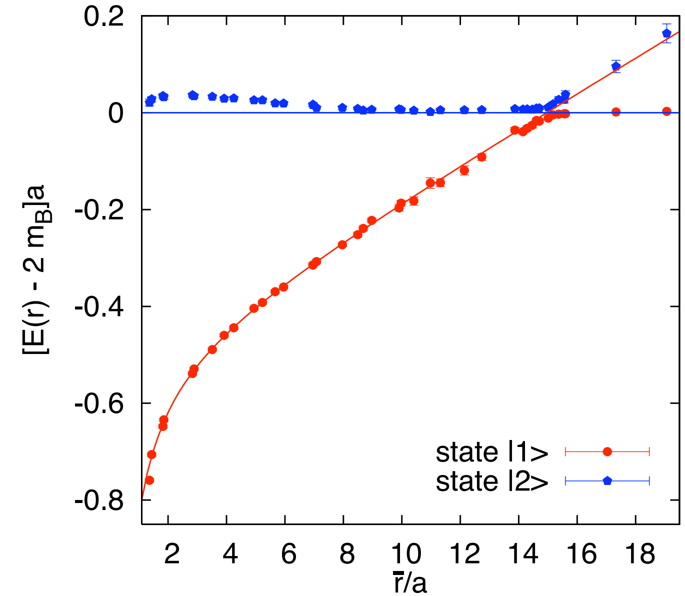


FIG. 13: The two energy levels, as a function of $\overline{r}$, normalized with respect to $2m_B$ (horizontal line). The curve corresponds to the three parameter fit to $E_1(\overline{r})$, Eqs. (80)–(82), for $0.2\,\mathrm{fm} \leq \overline{r} \leq 0.9\,\mathrm{fm} < r_c$.

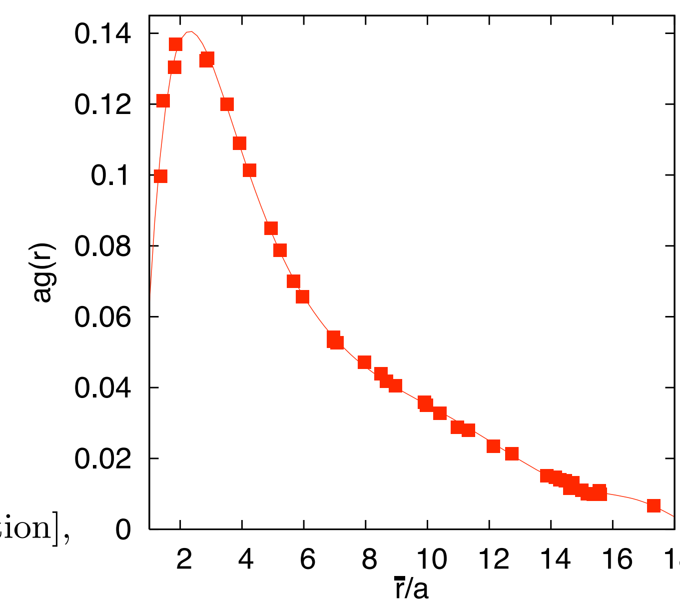


FIG. 18: The transition rate g between $|B\rangle$ and $|Q\rangle$ states, as a function of $\overline{r}$.

G.S. Bali, H. Neff, T. Düssel, T. Lippert and K. Schilling [SESAM Collaboration], *Phys. Rev. D* **71**, 114513 (2005) [arXiv:hep-lat/0505012].

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

ELQ 2004

Solve coupled-state system

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

ψ_0: $\bar{c}c$ $\quad$ ψ_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 ω and ψ_0

Statistical Factors in Strong Decays

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

Effects on the spectrum

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

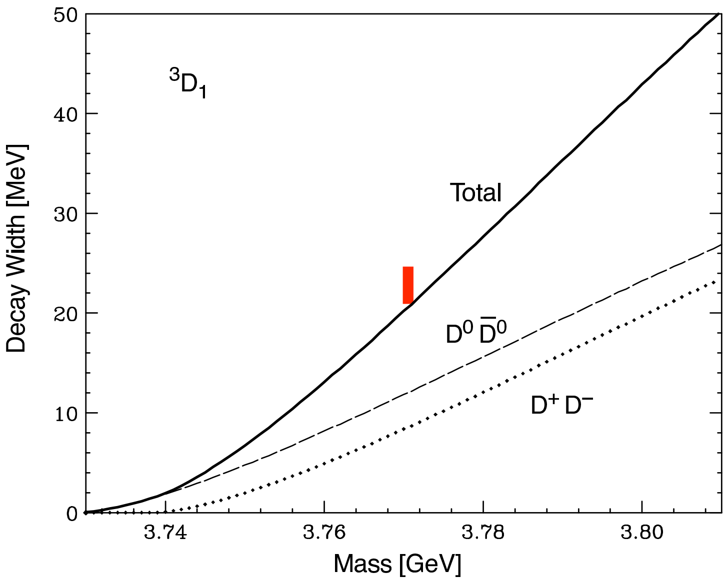
State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5^e	$+2.8$
1^3S_1	$3\,096.9^a$		$+30.2^e$	-0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
1^1P_1	$3\,524.4^f$		$+0.6^e$	$+0.5$
1^3P_2	$3\,556.2^a$		$+31.9^e$	-0.3
⇒ 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	$4\,040^a$		$+22^e$	$+1.0$

The $\psi(3770)$

pdg 2007

Mass *m* = 3772.4 ± 1.1 MeV , (S = 1.8)
Full width Γ = 25.2 ± 1.8 MeV

Decay width in good agreement with theory



CCC Model

Parameterizing the ψ(3770) as a simple mixture of |1D> and |2S> state is inadequate

Production in e^+e^- due to relativistic terms:

(a) Expansion of EM current

$$j_c^i \;=\; s_1\psi^\dagger\sigma^i\chi + \frac{s_2}{m_c^2}\psi^\dagger\sigma^i\mathcal{D}^2\chi$$

S-wave

$$+\frac{d_2}{m_c^2}\psi^\dagger\sigma^j[\frac{1}{2}(\mathcal{D}^i\mathcal{D}^j + \mathcal{D}^j\mathcal{D}^i) - \frac{1}{3}\delta^{ij}\mathcal{D}^2]\chi + \ldots$$

D-wave

(b) S-D mixing terms - short range

(c) Induced mixing from D*-D mass difference - long range

$$\psi(3772) \;=\; 0.10\,|2\mathrm{S}\rangle \;+\; 0.01e^{+0.22i\pi}\;|3\mathrm{S}\rangle \;+\; \ldots$$
$$+\;0.69e^{-0.59i\pi}\;|1\mathrm{D}\rangle \;+\; 0.10e^{+0.27i\pi}\;|2\mathrm{D}\rangle \;+\; \ldots$$

Decays into open charm

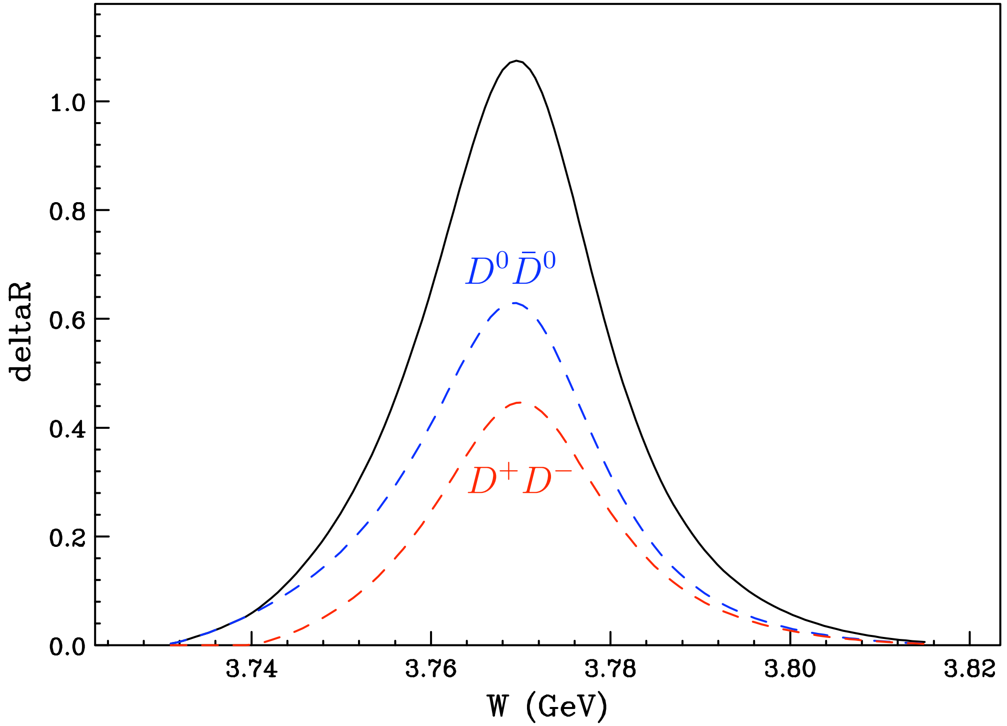
The ratio, $R^{0/+}$, of D^0D^0 to D^+D^- production deviates from one due to isospin violating terms:

(a) up-down mass difference

(b) EM interactions

-> $m(D^+)-m(D^0) = 4.78 \pm 0.10$ MeV

-> different final state interactions



$R^{0/+}$

PDG07	p^3	CCCM
1.28 ± 0.14	1.47	1.36

The shape of the resonance differs from the usual Breit-Wigner:

(1) width Γ(p) not pure p wave

(2) interference with 2S state.

$$\Gamma(p) \sim A\, \frac{p^3}{\Lambda^2} \exp\left(-\frac{p^2}{\Lambda^2}\right)$$

$A = .18 \quad \Lambda = .57$ GeV

$p_0 = 283$ MeV $\quad p_+ = 250$ MeV

Two very important measurement:

(1) Resonance shape

(2) Ratio of charge to neutral DD final states

$$R^{c/n} = \frac{\sigma(e^+e^- \to P^+P^-)}{\sigma(e^+e^- \to P^0\bar{P}^0)}$$

over the whole resonance region

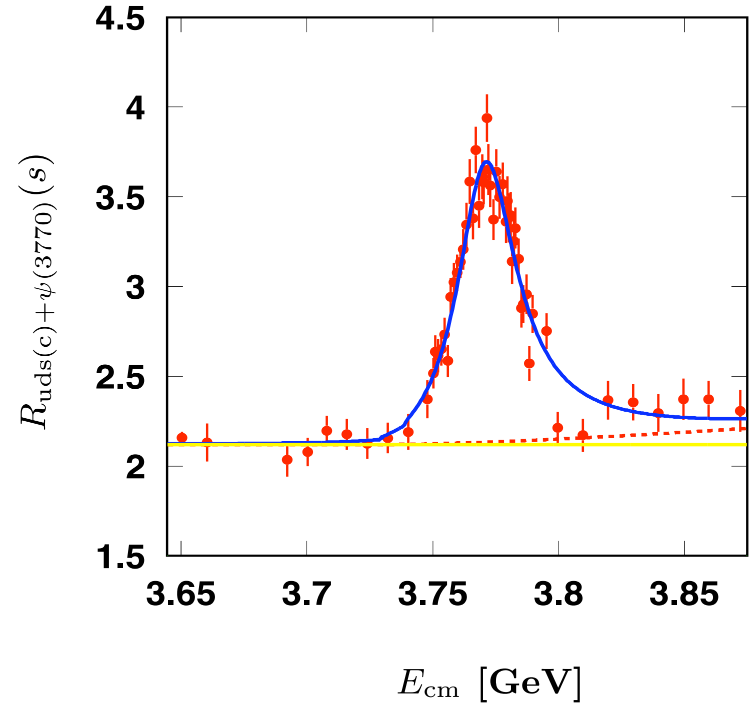


FIG. 1: The $R_{\mathrm{uds(c)}+\psi(3770)}(s)$ versus the c.m. energy
text).

G.P. Lepage, Phys.Rev. D **42**, 3251 (1990).

N. Byers and E. Eichten, Phys.Rev. D **42**, 3885 (1990).

R. Kaiser, A.V. Manohar, and T. Mehen, Report hep-ph/0208194, Aug. 2002 (unpublished)

M.B. Voloshin, Mod.Phys.Lett. A **18**, 1783 (2003).

M.B. Voloshin, Phys.Atom.Nucl. **68**, 771 (2005) [Yad.Fiz. **68**, 804 (2005)].

S. Dubynskiy, A. Le Yaouanc, L. Oliver, J.-C. Raynal, and M. B. Voloshin [arXiv:0704.0293]

QED

quark mass differences

phase shifts

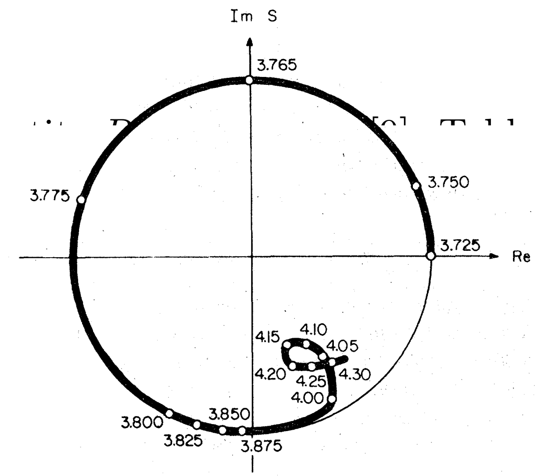


FIG. 9. Argand plot of the $D\bar{D}$ S matrix in the 1^{--} state. The rather narrow elastic $^3D_1$ resonance ψ (3772) is clearly in evidence, as is an inelastic resonance at ~4.15 GeV due to the 3 ^3S $c\bar{c}$ state. The parameters are the same as in Figs. 7 and 8.

E. Eichten, K. Gottfried, T. Kinoshita, K. Lane and T.M. Yan PR D17, 3090 (1978)

Non DD decays of the $\psi(3770)$

- X J/ψ

Theory expectation for $\pi^+\pi^- J/\psi$: 0.1-0.7%

$\psi'' \to \pi^+\pi^- J/\psi$	$0.34 \pm 0.14 \pm 0.09$	BES
	$0.189 \pm 0.020 \pm 0.020$	CLEO
$\psi'' \to \pi^0\pi^0 J/\psi$	$0.080 \pm 0.025 \pm 0.016$	CLEO
$\psi'' \to \eta^0 J/\psi$	$0.087 \pm 0.033 \pm 0.022$	CLEO

- $\gamma\chi_{cJ}$

Good agreement with theory expectations including relativistic effects

Mode	E_γ (MeV) [55]	Predicted (keV)					CLEO (keV) [136]
		(a)	(b)	(c)	(d)	(e)	
$\gamma\chi_{c2}$	208.8	3.2	3.9	4.9	3.3	24±4	< 21
$\gamma\chi_{c1}$	251.4	183	59	125	77	73 ± 9	70 ± 17
$\gamma\chi_{c0}$	339.5	254	225	403	213	523 ± 12	172 ± 30

- light hadrons

No evidence for direct decays to light hadrons seen yet.

Decay Mode	$\sigma_{\psi(3770)\to f}$ [pb]	$\sigma^{\rm up}_{\psi(3770)\to f}$ [pb]	$\mathcal{B}^{\rm up}_{\psi(3770)\to f}$ $[\times 10^{-3}]$
$\phi\pi^0$	$< 3.5^{tn}$	< 3.5	< 0.5
$\phi\eta$	$< 12.6^{tn}$	< 12.6	< 1.9
$2(\pi^+\pi^-)$	$7.4 \pm 15.0 \pm 2.8 \pm 0.8$	< 32.5	< 4.8
$K^+K^-\pi^+\pi^-$	$-19.6 \pm 19.6 \pm 3.3 \pm 2.1^z$	< 32.7	< 4.8
$\phi\pi^+\pi^-$	$< 11.1^{tn}$	< 11.1	< 1.6
$2(K^+K^-)$	$-2.7 \pm 7.1 \pm 0.5 \pm 0.3^z$	< 11.6	< 1.7
ϕK^+K^-	$-0.5 \pm 10.0 \pm 0.9 \pm 0.1^z$	< 16.5	< 2.4
$p\bar{p}\pi^+\pi^-$	$-6.2 \pm 6.6 \pm 0.6 \pm 0.7^z$	< 11.0	< 1.6
$p\bar{p}K^+K^-$	$1.4 \pm 3.5 \pm 0.1 \pm 0.2$	< 7.2	< 1.1
$\phi p\bar{p}$	$< 5.8^{tn}$	< 5.8	< 0.9
$3(\pi^+\pi^-)$	$16.9 \pm 26.7 \pm 5.5 \pm 2.4$	< 61.7	< 9.1
$2(\pi^+\pi^-)\eta$	$72.7 \pm 55.0 \pm 7.3 \pm 8.2$	< 164.7	< 24.3
$2(\pi^+\pi^-)\pi^0$	$-35.4 \pm 24.6 \pm 6.6 \pm 4.0^z$	< 42.3	< 6.2
$K^+K^-\pi^+\pi^-\pi^0$	$-36.9 \pm 43.8 \pm 12.8 \pm 4.2^z$	< 75.2	< 11.1
$2(K^+K^-)\pi^0$	$18.1 \pm 7.7 \pm 0.7 \pm 2.0^n$	< 31.2	< 4.6
$p\bar{p}\pi^0$	$1.5 \pm 3.9 \pm 0.5 \pm 0.1$	< 7.9	< 1.2
$p\bar{p}\pi^+\pi^-\pi^0$	$26.0 \pm 13.9 \pm 2.6 \pm 3.2$	< 49.7	< 7.3
$3(\pi^+\pi^-)\pi^0$	$-12.7 \pm 55.9 \pm 8.7 \pm 1.8^z$	< 92.8	< 13.7

BES [hep-ex/0705.2276]

Puzzle of missing decays

$$\sigma_{\psi(3770)} = 6.38 \pm 0.08 \; ^{+0.41}_{-0.30} \text{ nb}$$

$$\sigma_{\psi(3770)} - \sigma_{\psi(3770)\to D\bar{D}} = -0.01 \pm 0.08 \; ^{+0.41}_{-0.30} \text{nb}$$

CLEO

$$\sigma_{\psi(3770)} = 7.25 \pm 0.27 \pm 0.34 \text{ nb}$$

BES

No evidence of unexpected rates for non DD decays

The remaining D states

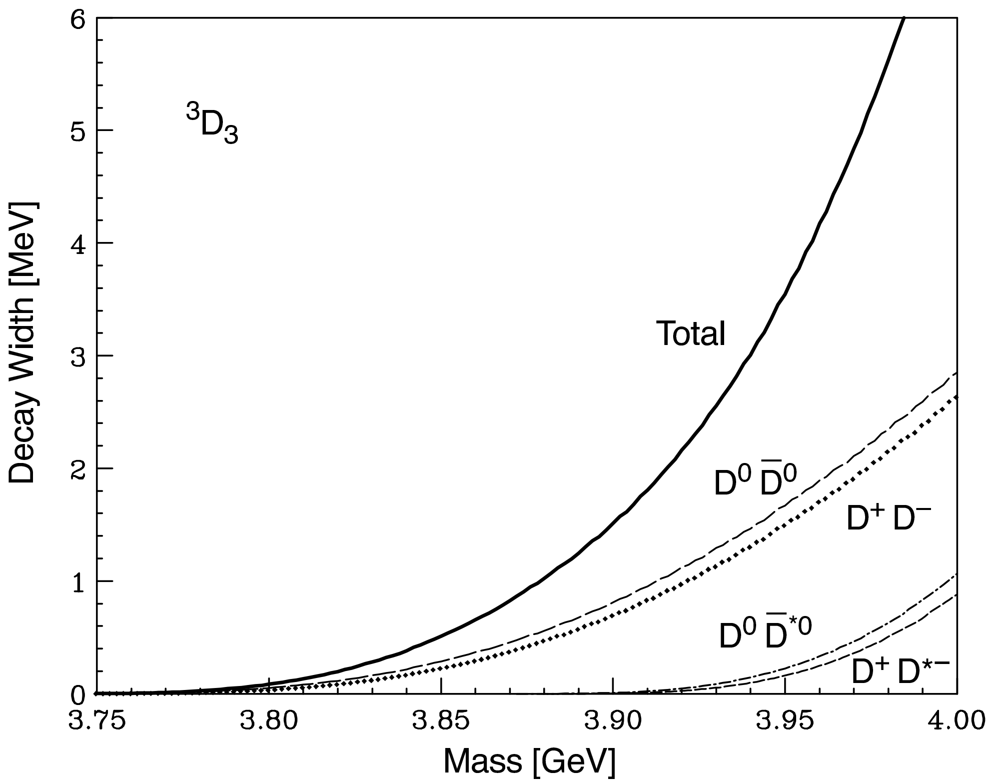
$^3D_2 \qquad ^1D_2$

No strong decays below

$D\bar{D}^* + \bar{D}D^*$ threshold

$^3D_3$ decay width small

search in $D\bar{D}$ channel



All remaining 1D states are narrow

How to produce these states?

Other Charmonium States ?
X(3943), Y(3940), Z(3930), ...

Basic Questions in Charm Threshold Region:

Is it a new state? What are its properties?

Charmonium or not?

If not what? New spectroscopy?

Comments on ΔR

This rich structure arises simply from the 3S and 2D states

Interference between the 3S and 2D plays an important role.

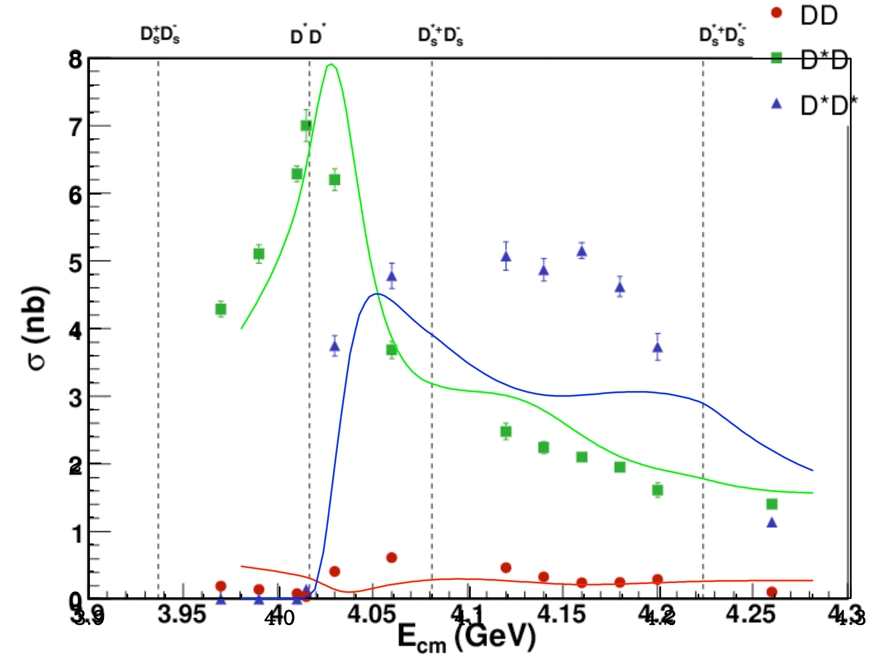
Decay amplitudes for radially excited states have oscillatory structure

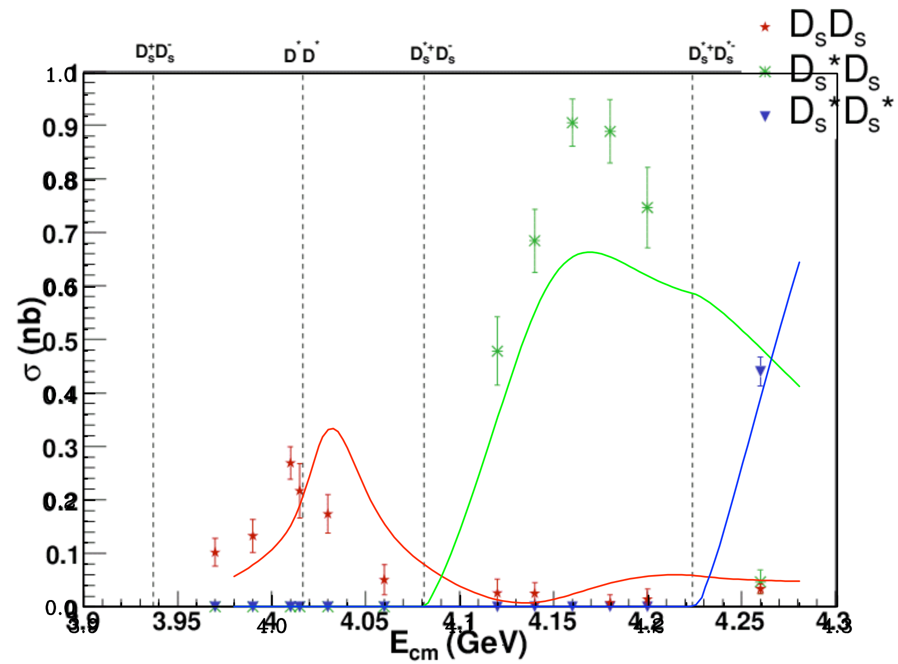
The peaks for individual final states do not coincide

Determining the number and properties of the resonances is impossible without a detail decay model.

A Caution for All

CLEO-c hep-ex/0606016





Updated Cornell Coupled Channel Model

Likely charmonium states:

★ Z(3930) - Observed by Belle in ϒϒ production

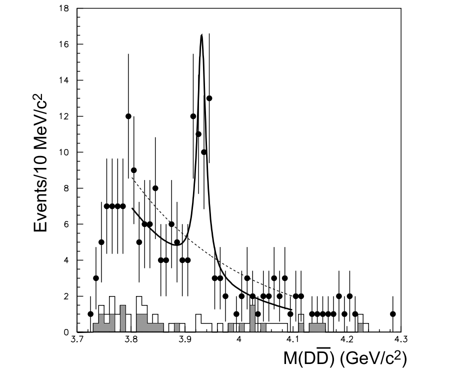


FIG. 3: The sum of the $M(D\bar{D})$ invariant mass distributions for all four processes. The curves show the fits with (solid) and without (dashed) a resonance component. The histograms show the distribution of the events from the D-mass sidebands (see the text).

[PRL 96, 082003 (2006)]

Decay mode DD

Mass = 3929 ± 5(stat) ± 2(sys) MeV

Width = 29 ± 10(stat) ± 2(sys) MeV

J^{PC} = 0^{++} or 2^{++}

DD angular distribution favors J=2

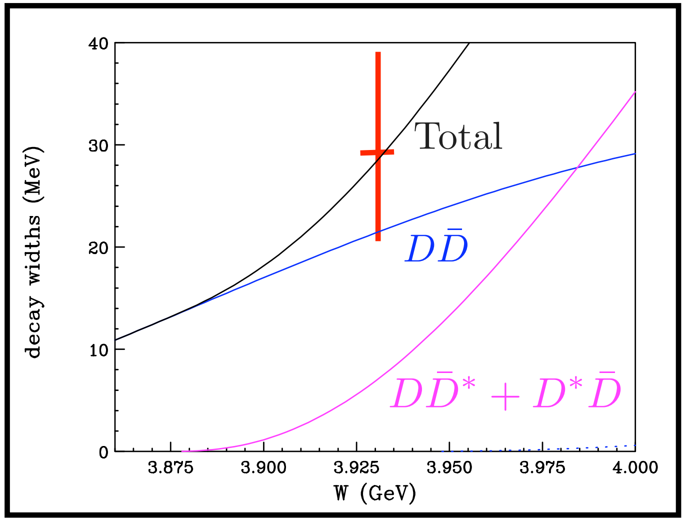
✓ $2\,^3P_2$ $\quad \chi'_{c2}$

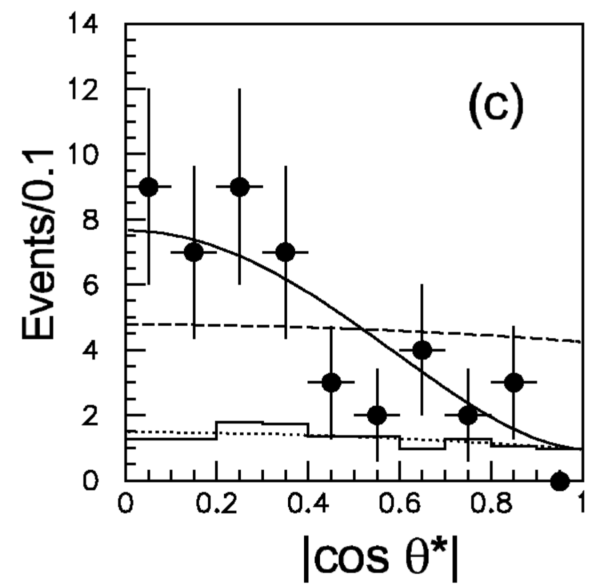
$\Gamma = 29$ MeV Model

$$\frac{D\bar{D}^* + D^*\bar{D}}{D\bar{D}} = 0.32$$

$$\frac{D^+\bar{D}^-}{D^0\bar{D}^0} = 0.95$$

$0.74 \pm 0.43 \pm 0.16$ exp





Other 2P States

	Mass		Spin Splittings		Widths	
2^3P_0	3 881.4		−90	+27.9	$D\bar{D}$	61.5
2^3P_1	3 920.5	$(3\,922)^d$	−8	+6.7	$D\bar{D}^*$	81.0
2^1P_1	3 919.0		0	−5.4	$D\bar{D}^*$	59.5
✓ 2^3P_2	$3\,931^g$		+25	−9.6	$D\bar{D}$	21.5
					$D\bar{D}^*$	7.1
					total	28.8

★ Y(3940) - Observed by Belle in B decays

Seen in decay mode ω J/ψ

Significant branching fraction:

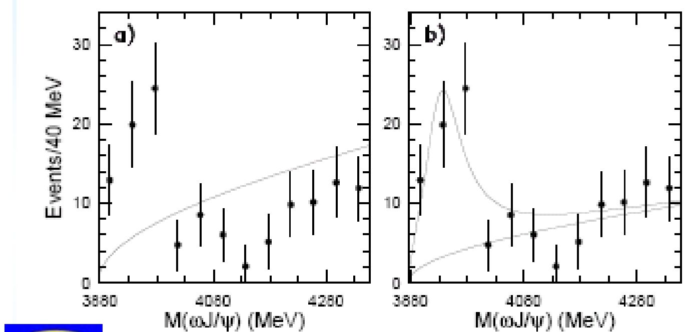
$$\mathcal{B}(B^+ \to K^+ Y(3490)) x \mathcal{B}(Y(3940) \to \omega J/\psi) = 7.1 \pm 1.3 \pm 3.1 \times 10^{-}5$$

$$\mathcal{B}(B^+ \to K^+(c\bar{c})) \sim 6 - 10 \times 10^{-}4 \text{ per mode}$$

so

$$\mathcal{B}(Y(3940) \to \omega J/\psi) \sim 0.1$$

Belle PRL 94, 182002 (2005), 253/fb, >8σ



M=3943±11±13 MeV

Γ=87±22±26 MeV

2^3P_1 interpretation:

Problems with mass and decay mode.

Main decay mode should be DD*

Present bound?

Y(3940) confirmed by Babar

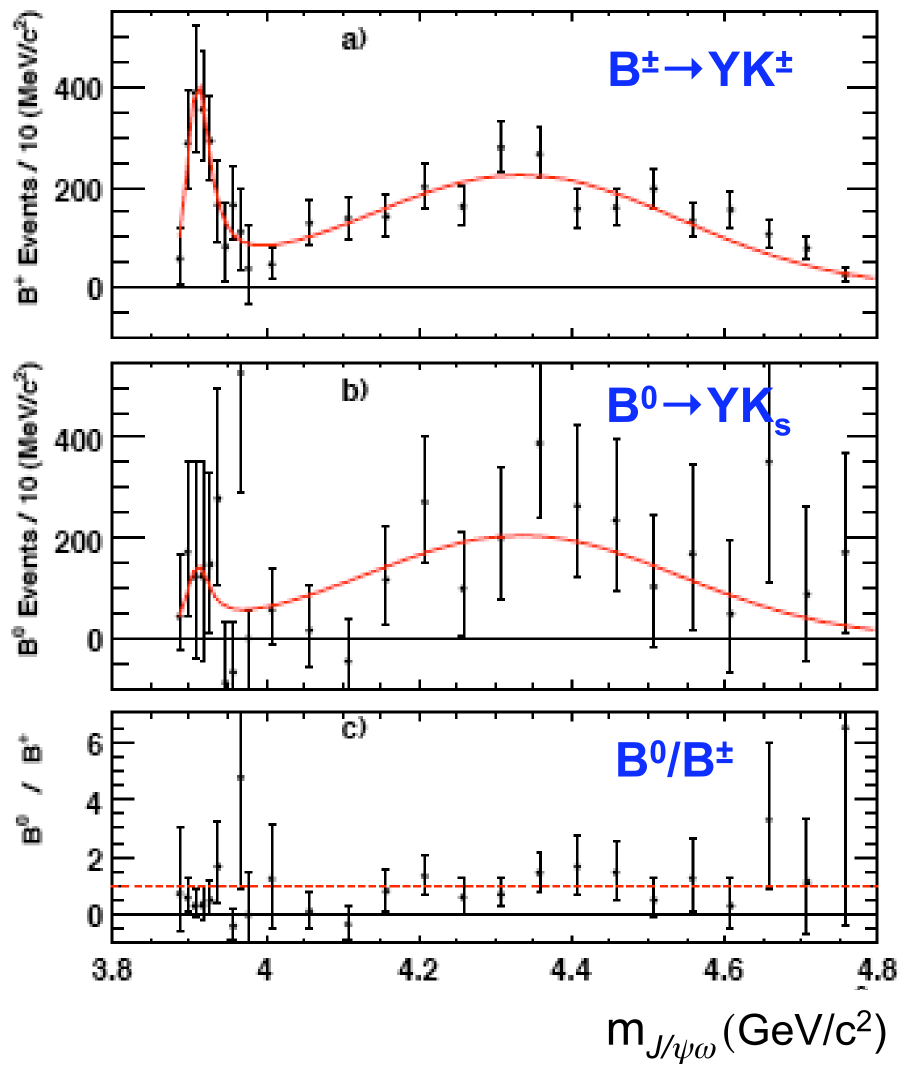
Babar [Cibinetto EPS 2007]

$$M(Y) = (3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst))\ \mathrm{MeV/c^2}$$
$$\Gamma(Y) = (33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst))\ \mathrm{MeV}\,.$$

- ~30MeV lower mass than Belle's
- Narrower width
- Preliminary BF estimate similar to the Belle's (~10^{-5})

✓ 2^3P_1 interpretation:

Mass near expected value



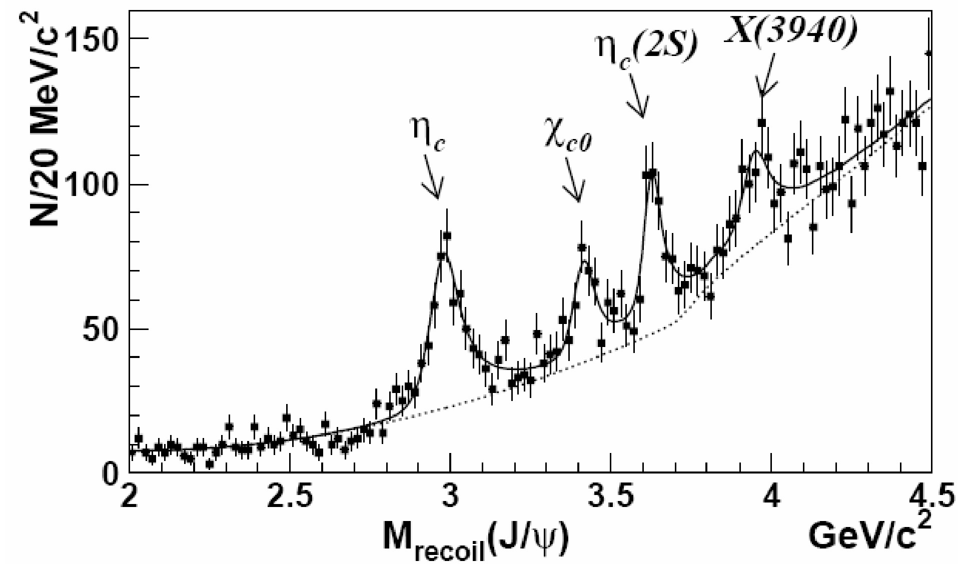
★ X(3943) - Observed by Belle in recoil against J/ψ

Mass = 3942 $^{+7}_{-6}$ ± 6 MeV

Width = 37 $^{+26}_{-15}$ ± 12 MeV

(update EPS 2007)

Phys. Rev. Lett. 98, 082001 (2007)



Not a $^3P_0$ state

$$\mathrm{BR}(D\bar{D}) < 41\% \ @\ 90\%cl$$

$$\mathrm{BR}(D\bar{D}^* + D^*\bar{D}) > 45\% \ @\ 90\%cl$$

✓ Likely the η_c'' state

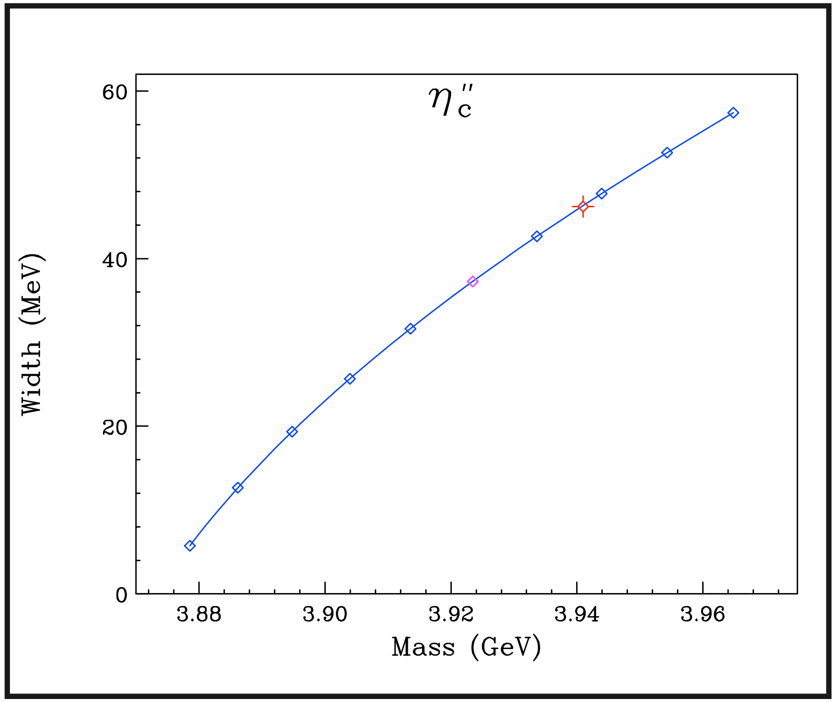
Width ≈ 50 MeV (CCC Model)

but

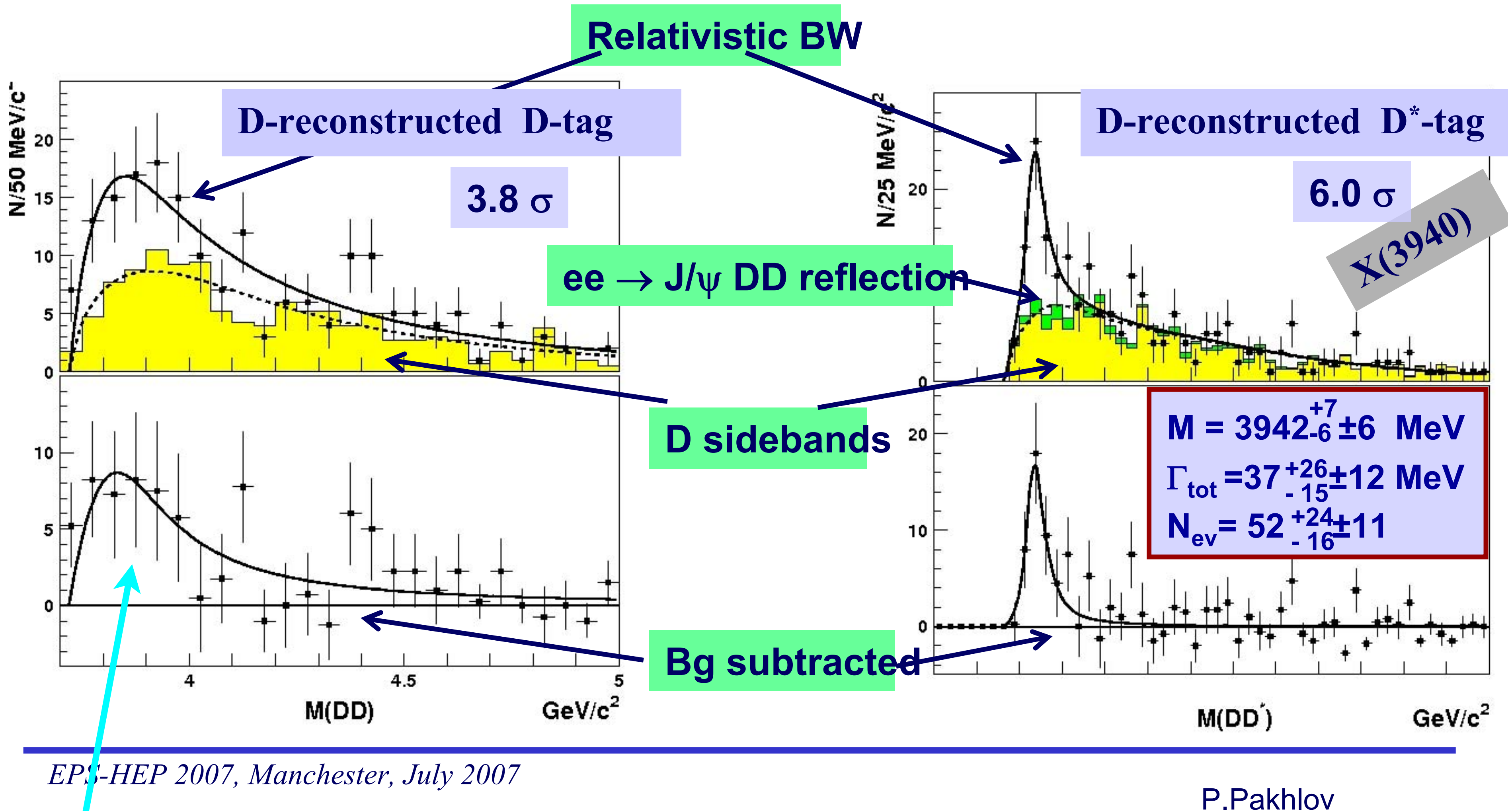
M(ψ(4040) - X(3943)) ≈ 100 MeV (Large)

Requires bare splitting: 88 MeV

Including DDp channels: Expected to add significant spin splitting



Belle - recoil against J/ψ

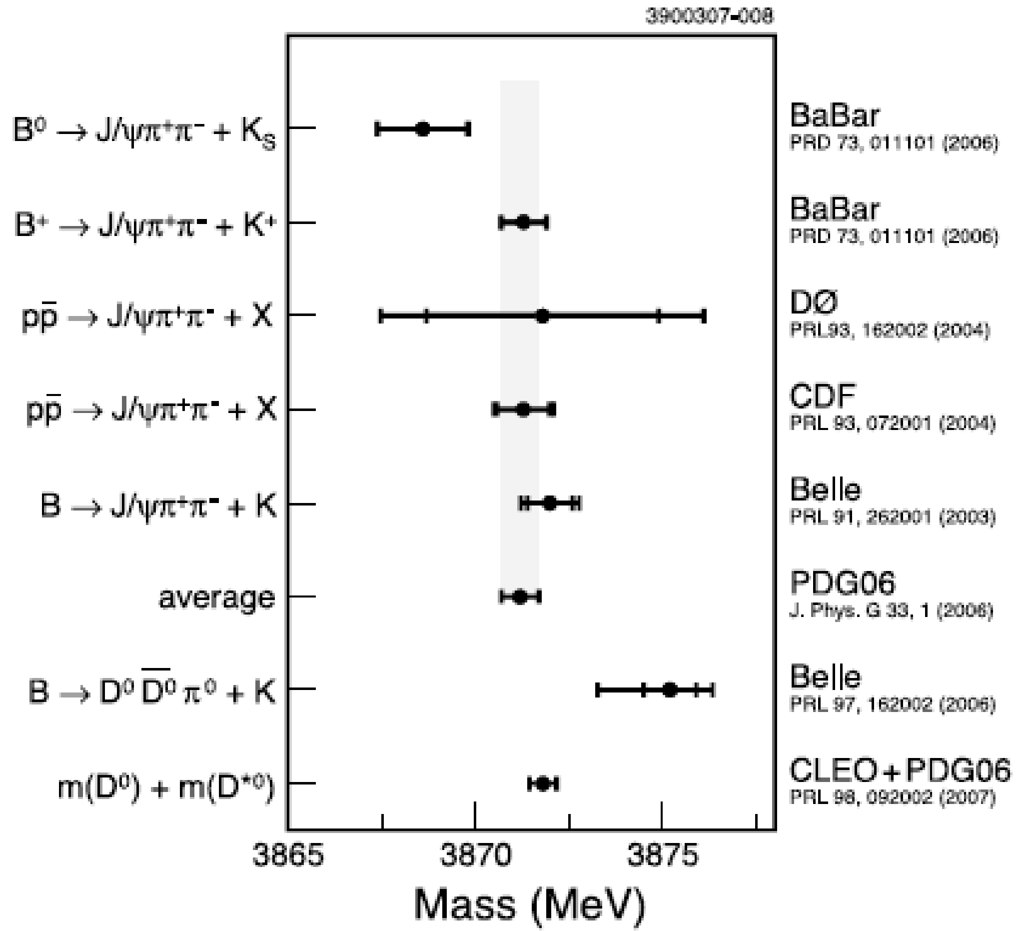


2^3P_0? expected mass 3881,

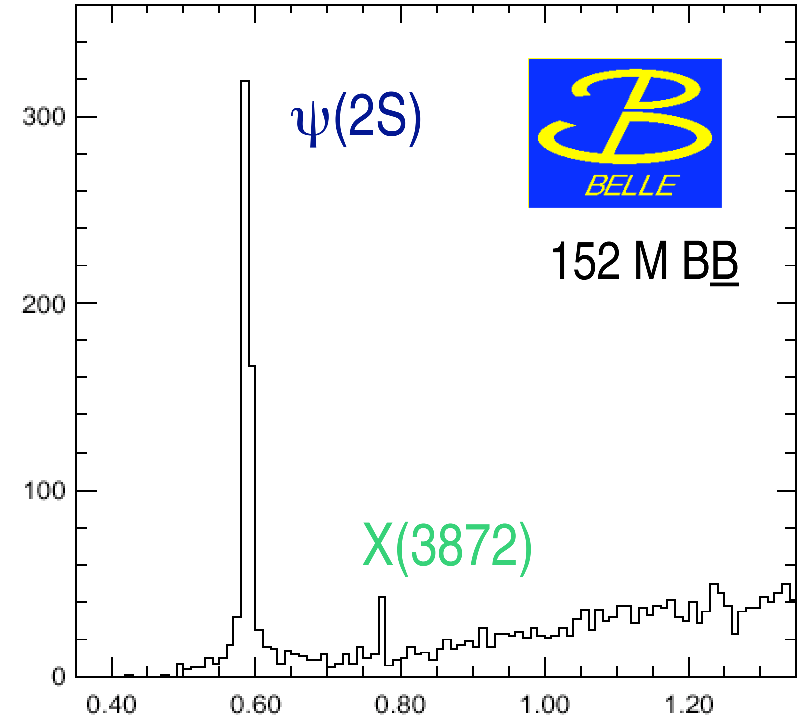
width = 62:

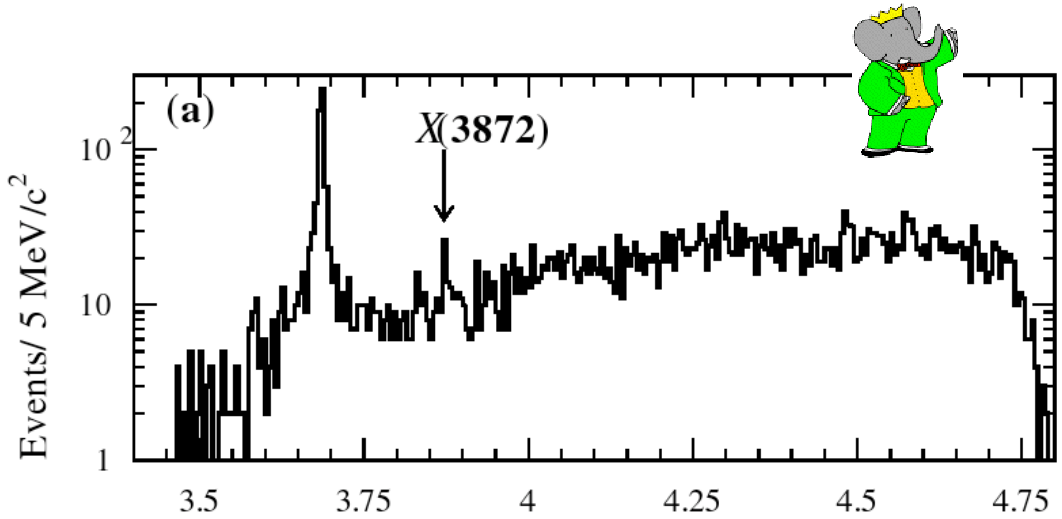
X(3872)

Mass = 3871.2 ± 0.6
Width < 2.3   90% cl

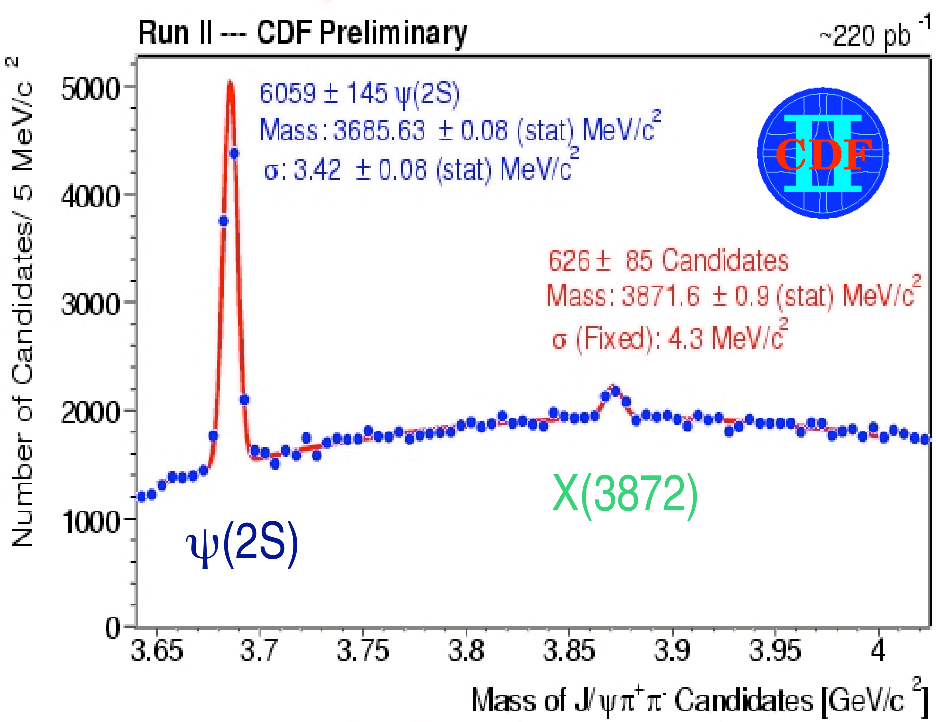


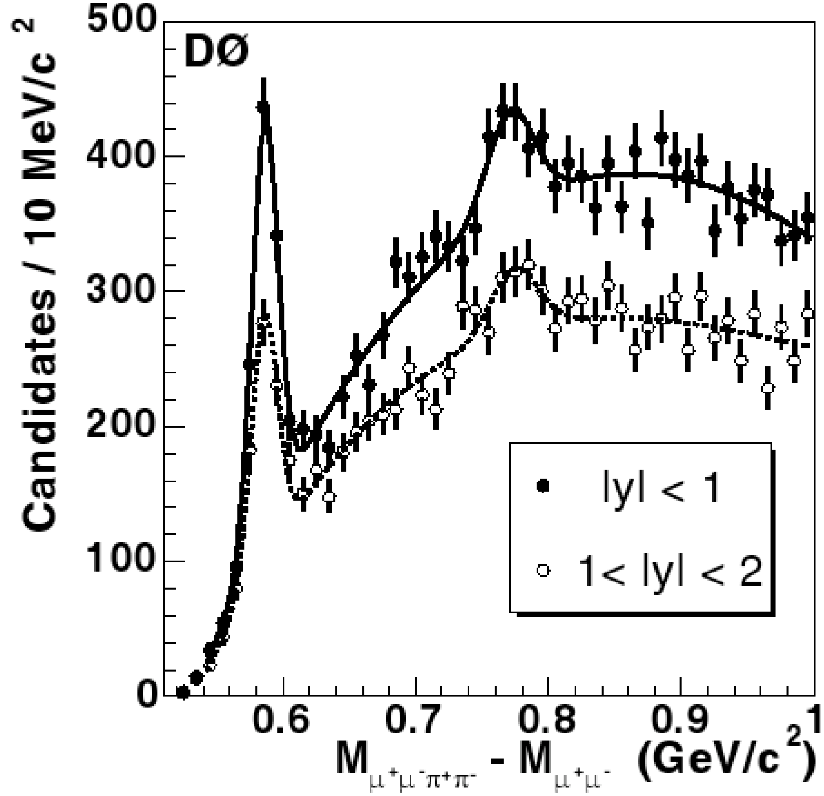
Discovery





- Use $\sim$ 220 pb^{-1} Run II Data





$\pi^+\pi^-$ mass distribution fits ρ J/ψ (L=0)

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

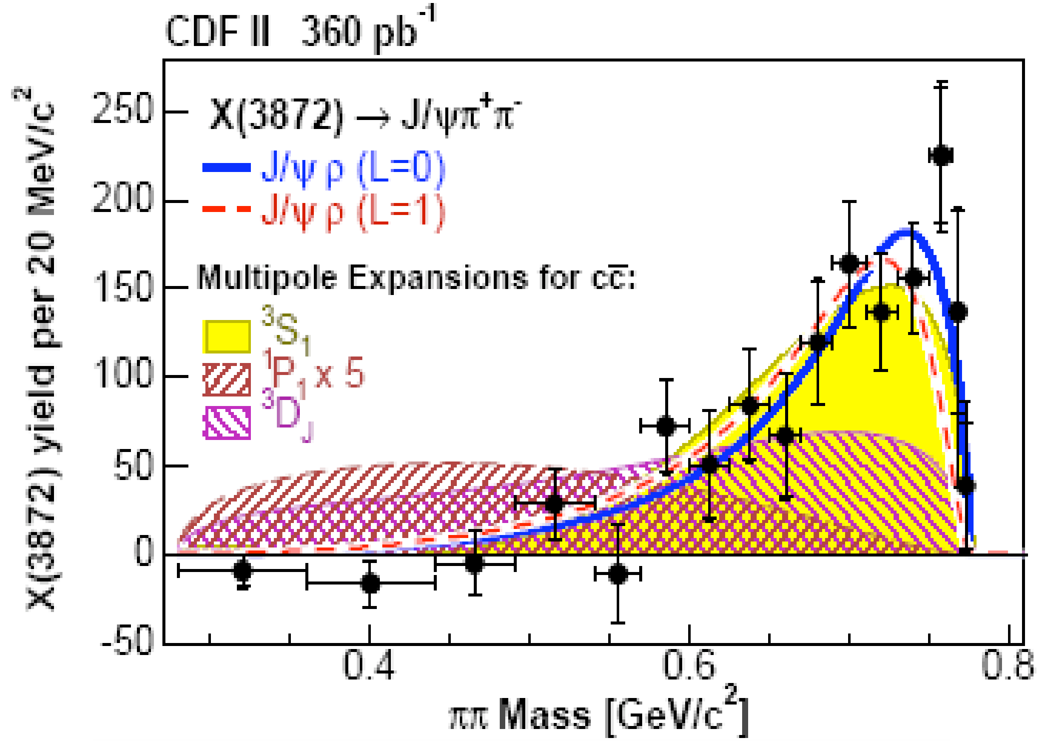
Strongly favored

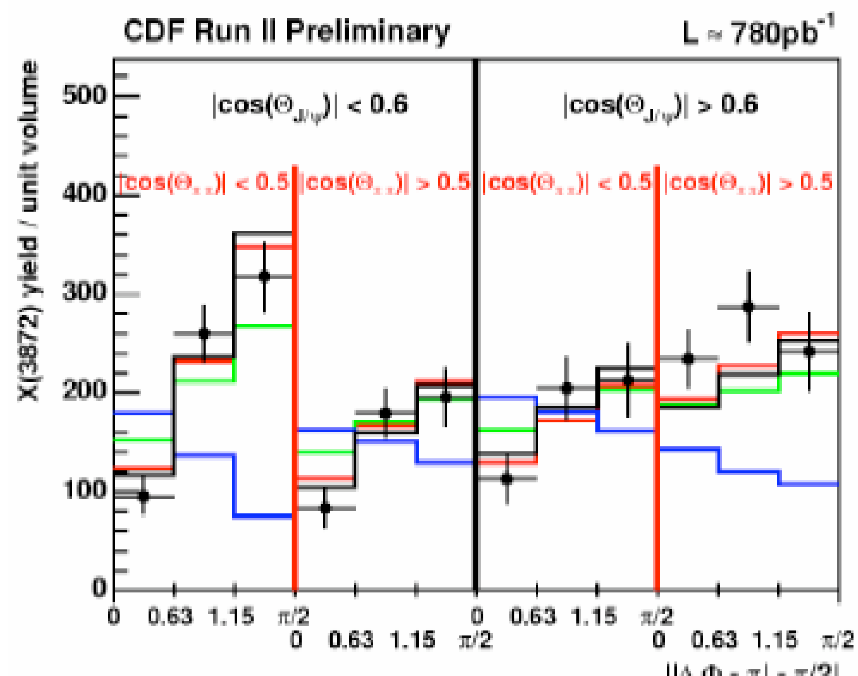
X(3872)
• data points

acc. corrected
prediction for

- 0^{++}_P
- 1^{--}_S
- 1^{++}_P
- 2^{-+}_P

J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$< 1 \cdot 10^{-20}$
0^{++}	$< 1 \cdot 10^{-20}$





Other decay modes:

$$\frac{X(3872) \to "\omega" J/\psi}{X(3872) \to \rho J/\psi} = 1.0 \pm 0.4 \pm 0.3$$

Belle

Measure of isospin breaking

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

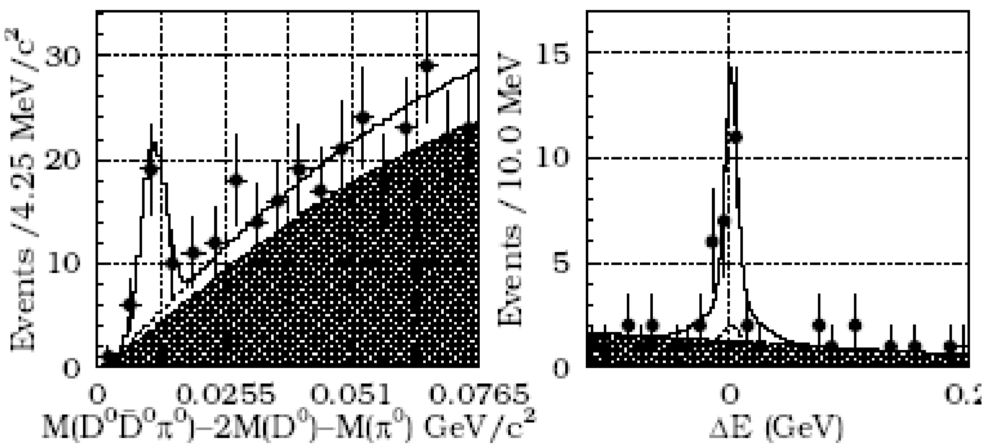
Belle + BaBar

C = +1

Belle

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

$$M = 3875.4 \pm 0.7 \,^{+0.7}_{-1.7} \pm 0.8\text{MeV}$$



DD* "Binding Energy?":

$$M-(m_{D0}+ m_{D^*0}) = +4.3 \pm 0.7 \,^{+0.7}_{-1.7} \text{ MeV}$$

Recent developments

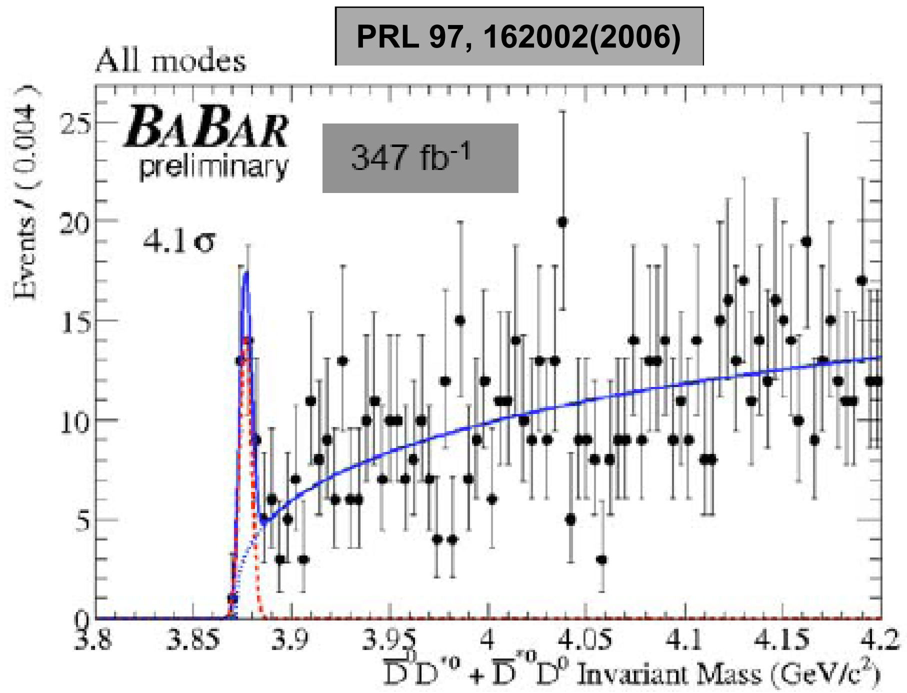
CLEO precise D^0 mass measurement [PRL 98, 092002 (2007)]

1864.847 ± 0.150 ± 0.095 MeV

$M(X) - M(D^0) - M(D^{0*}) = -0.6 \pm 0.6$ MeV

BaBar confirms Belle decay $D^0 D^{*0} \pi^0$ with X mass:

$M = 3875.4_{-2.0}^{+1.2} \pm 0.7 \text{MeV}/c^2$



Two key features of X(3872):

X is extremely close to threshold

$D^0 D^{*0} \pi^0$ mode above threshold

Options for X(3872) (225 papers)

$D^0\bar{D}^{0*}$ molecule:

Tornqvist (8-03, 2-04); Close and Page (9-03); Pakvasa and Suzuki (9-03); Voloshin (9-03, 8-04, 9-05, 5-06); Wong (11-03); Braaten and Kusunoki (11-03; 2-04; 12-04, 6-05, 7-05, 9-06); Swanson (11-03, 6-04, 10-04); Braaten, Kusunoki, and Nussinov (4-04); Kalashnikova (6-05); AlFiky, Gabbiani, and Petrov (6-05); El-Hady (3-06), Chiu and Hsieh (3-06); Zhang, Chiang, Shen and Zou (4-06); Melikhov and Stech (6-06)

threshold cusp:

Bugg (10-04)

tetraquark: $(\bar{c}\bar{q})_3(qc)_{\bar{3}}$

Vijande, Fernandez, and Valcarce (7-04); Maiani, Piccinini, Polosa, and Riquer (12-04); Ishida, Ishida and Maeda (9-05); Ebert, Faustov and Galkin (12-05); Karliner and Lipkin (1-06); Chiu and Hsieh (3-06)

tetraquark: $(\bar{c}c)_8(\bar{q}q)_8$

Hogassen, Richard and Sorba (11-05); Buccella, Hogassen, Richard and Sorba (8-06)

hybrid: $(\bar{c}gc)$

Close and Page (9-03); Li (10-04)

Viable options

Tetraquarks No

No partner states found

Why so close to threshold?

Measurements:

- $\Delta m = (2.7 \pm 1.3 \pm 0.2)$ MeV/c^2 in $B \to J/\psi\pi^+\pi^-$ BaBar: Phys. Rev. D73 (2006) 011101
- $\Delta m = (0.7 \pm 1.9 \pm 0.3)$ MeV/c^2 in $B \to \bar{D}^0 D^{*0} K$ BaBar: Preliminary

Hybrids No

Decays to DD* unexpected

Why so close to threshold?

Charmonium 2^3P_1 No (but may play a role)

Why so close to threshold?

Mass about 50 MeV to high

Isospin issues

Y(3940) may be this 2P state

Threshold cusp May play a role

Molecule Some problems

Expect $$\frac{\mathcal{B}(B^0 \to X + K^0)}{\mathcal{B}(B^+ \to X + K^+)} \sim 0.1$$

Measurements:

- $R(B^0/B^+) = 0.50 \pm 0.30 \pm 0.05$ in $B \to J/\psi\pi^+\pi^-$ BaBar: Phys. Rev. D73 (2006) 011101
- $R(B^0/B^+) = 2.23 \pm 0.93 \pm 0.55$ in $B \to \bar{D}^0 D^{*0} K$ BaBar: Preliminary

What is the binding force? Pion exchange much too febble M.Suzuki

In a two body system with short range interactions and an S-wave bound state sufficiently close to threshold

Universal properties depending only on the large scattering length (a)

Braaten and Hammer [cond-mat/0410417]

This applies to the X(3872)

Braaten and Kusunoki

If $a > 0$ one bound state

$$\frac{1}{a} = \gamma_r + i\gamma_i$$

$$\mathrm{E_X} = \gamma_r^2/(2\mu)$$

$$\Gamma_\mathrm{X} = 2\gamma_r\gamma_i/\mu$$

$$\mu = \frac{M(D^0)M(D^{0*})}{M(D^0) + M(D^{0*})}$$

$$\psi(r) = \frac{\exp(-\gamma_r r)}{r}$$

$$\sigma(E) = \frac{\pi}{\gamma_r^2 + (\gamma_i + \sqrt{2\mu E})^2}$$

Very large average separation between the charm quark and antiquark

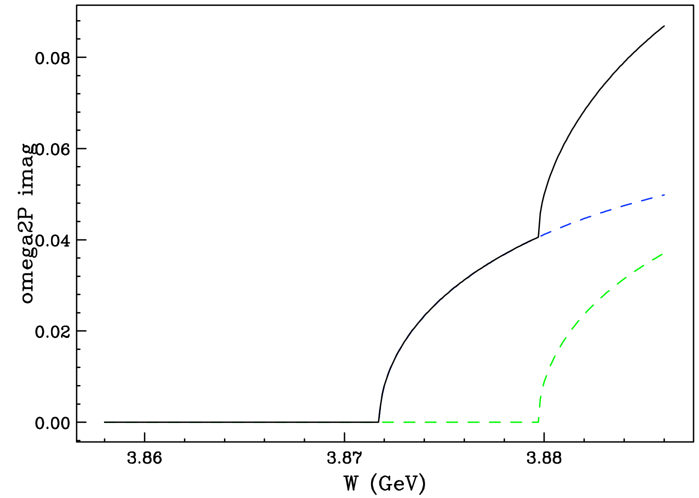
Since this behavior is universal it gives no insight into how the bound state forms

For molecular interpretation cross section for $D^0D^{*0}\pi^0$

$$\sigma(E) = \frac{\pi}{\gamma_r^2 + (\gamma_i + \sqrt{2\mu E})^2}$$

Fit to BaBar data ?

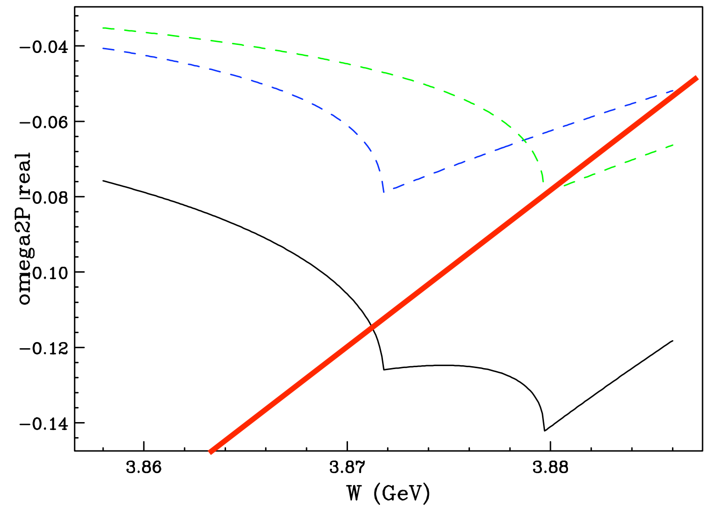
$Im(\Omega)$



One possibility is that the nearby 2^3P_1 state with its strong coupling to DD* provides the needed binding.

$$G(W) \sim \frac{1}{[W - M + \Omega(W) + i\epsilon]}$$

$Re(\Omega)$

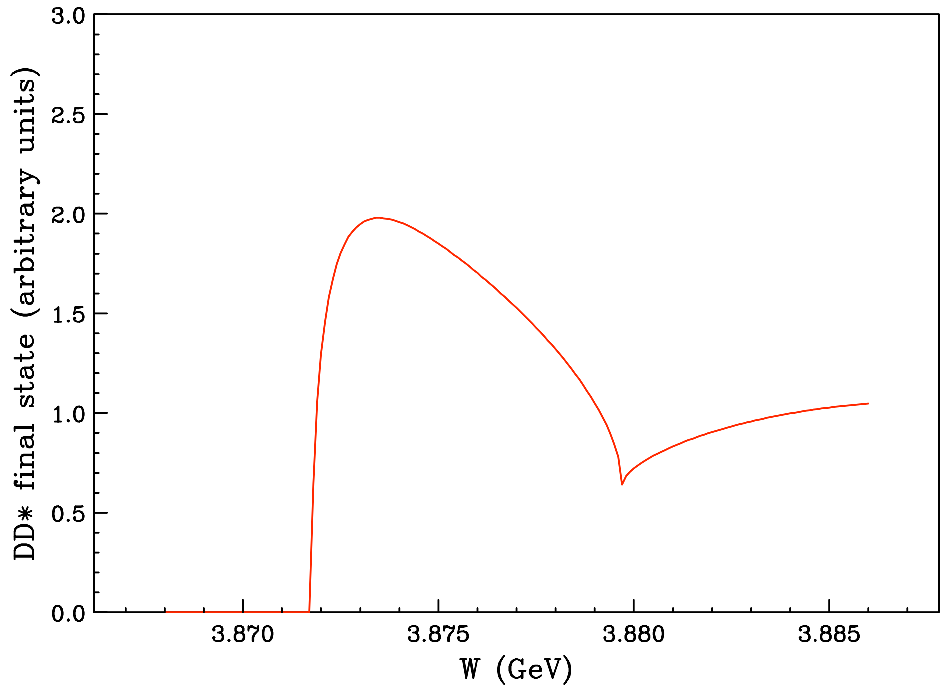


Assume:

Pole at 0.6 MeV below threshold

Small non DD* width - 400 KeV

Obtain for $D^0 D^0 \pi^0$ final state



Even though the X state is slightly below threshold.

More complicated than Braaten and Kusunoki

Real part of Ω varies rapidly

Required conditions for this behaviour:

S wave threshold

Decay into two very narrow hadrons

Nearby state $|M_S - M(\text{threshold})| \leq \Gamma_S$

with sufficiently strong coupling to decay channel.

Y(4260) and Beyond

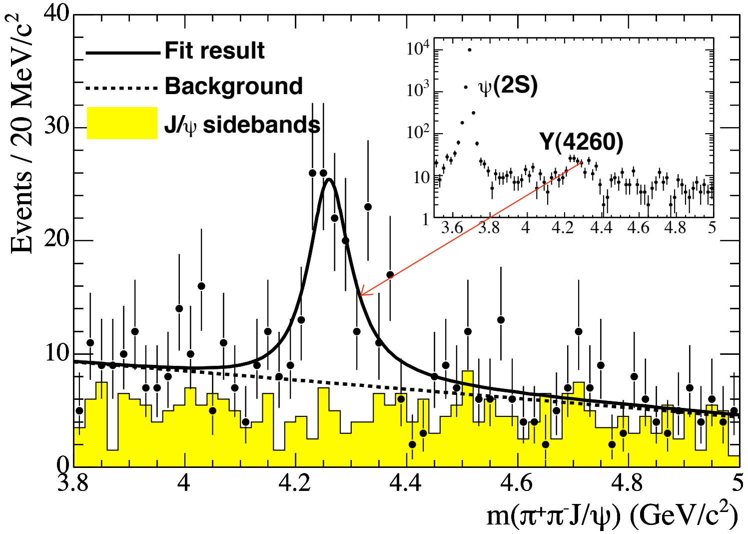
Y(4260)

Production:

Seen by BaBar in ISR production

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

BaBar



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

Width: $88 \pm 23 \,^{+6}_{-4}$ MeV

small ΔR

Confirmed by CLEO and Belle

Decays: $\pi^+\pi^- J/\psi$ discovery mode

$\pi^0\pi^0 J/\psi$

$K^+K^- J/\psi$

CLEO

consistent with isospin zero

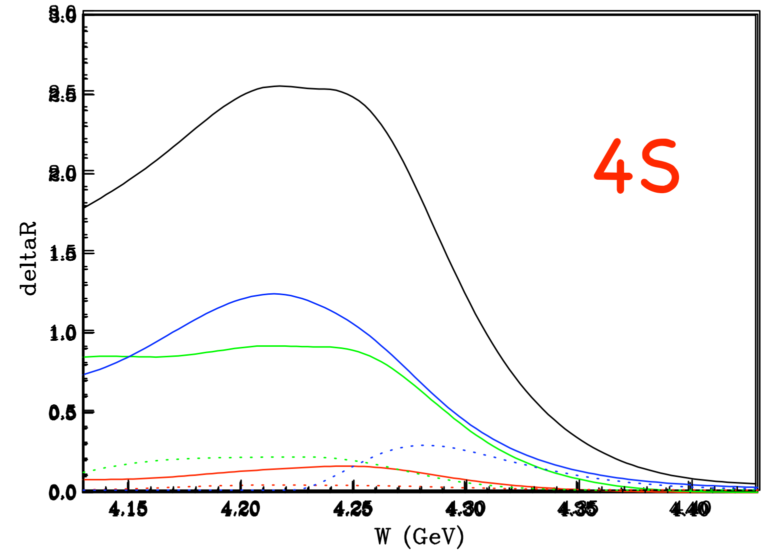
NOT a charmonium state

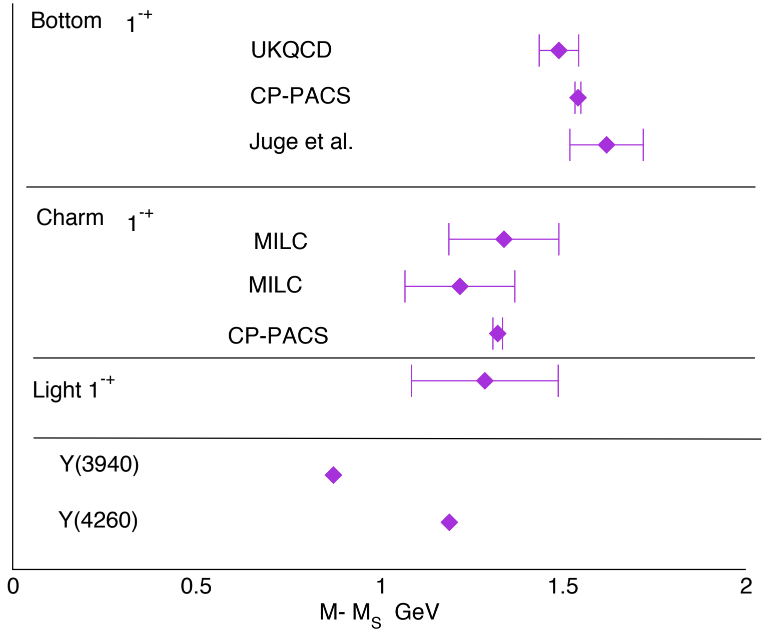
4S state: ΔR ~ 2.5 for 4S at the Y(4260) mass

Ruled out

2D (4160):

Ruled out





Lattice calculations:

$$M(1^{-+}) = M(1^{--}) \text{ (leading order in } 1/m_c)$$

McNeile review

ICHEP 2006

Early attempts of various groups give conflicting results for direct mass calculations

Chiu and Hsieh [hep-lat/0512029]

Luo and Liu [hep-lat/0512044]

Y(4350)

Seen by BaBar in the decay mode

$$\pi^+\pi^-\psi(2S)$$

Mass:

$$4354 \pm 16 \text{ MeV}$$

Width:

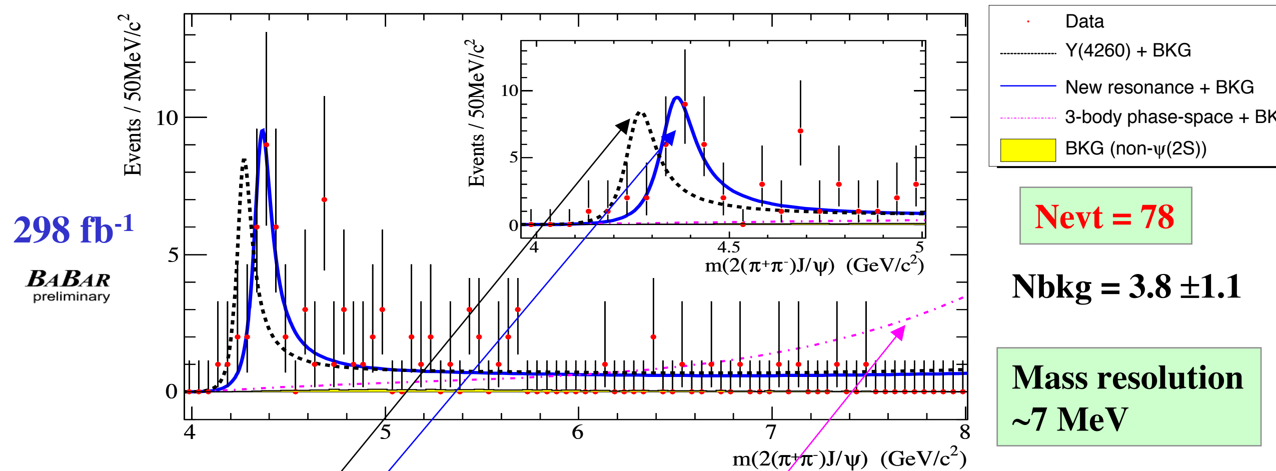
$$106 \pm 9 \text{ MeV}$$

Recently Confirmed by Belle

$M(Y(4360))$	$4361 \pm 9 \pm 9$
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$

...but it's not the Y(4260)...

Fit to $m(2(\pi^+\pi^-)J/\psi)$ to avoid combinatorics.
Try S-wave 3-body phase space, old and new resonance, **cannot find a good fit**



Nevt = 78

Nbkg = 3.8 ±1.1

Mass resolution ~7 MeV

Incompatible with **Y(4260), ψ(4415),** or ***S*-wave 3-body phase-space** production

Assuming a **single resonance** ⟹ **mass=(4354±16) MeV/c², Γ=(106±19) MeV** (statistical errors only)

still **insufficient** to fully describe the spectrum (χ^2-prob = **1.4×10^{-4}**)

compared with χ^2-prob = **1.6×10^{-8} for Y(4260), 4.2×10^{-9} for ψ(4415)**

QWG06, June 27 2006 Shuwei YE 21

Options for Y(4260) (62 papers)

hybrid: $(\bar{c}gc)$

Close and Page (7-05); Kou and Pene (7-05); Zhu (7-05); Juge, O'Cais, Oktay, Peardon and Ryan (10-05); Luo and Liu (12-05); Chiu and Hsieh (12-05); Swanson (9-05, 1-06); Barnes (10-05); Eichten, Lane and Quigg (11-05); S. Godfrey (5-06); Buisseret and Mathieu (7-06);

threshold effect:

Beveren and Rupp (5-06); Rosner (8-06)

tetraquark: $(\bar{c}q)_1(\bar{q}c)_1$, $(\bar{c}\bar{q})_3(qc)_{\bar{3}}$, or $(\bar{c}c)_8(\bar{q}q)_8$

Liu, Zeng and Li, (7-05); Bigi, Maiani, Piccinini, Polosa and Riquer (10-5); Yuan, Wang and Mo (11-05); Ebert, Faustov and Galkin (12-05); Maiani, Riquer, Piccinini and Polosa (3-06); Stancu (7-06); Cui, Chen, Deng and Zhu (7-06); Buccella, Hogassen, Richard and Sorba (8-06)

Y(4260)

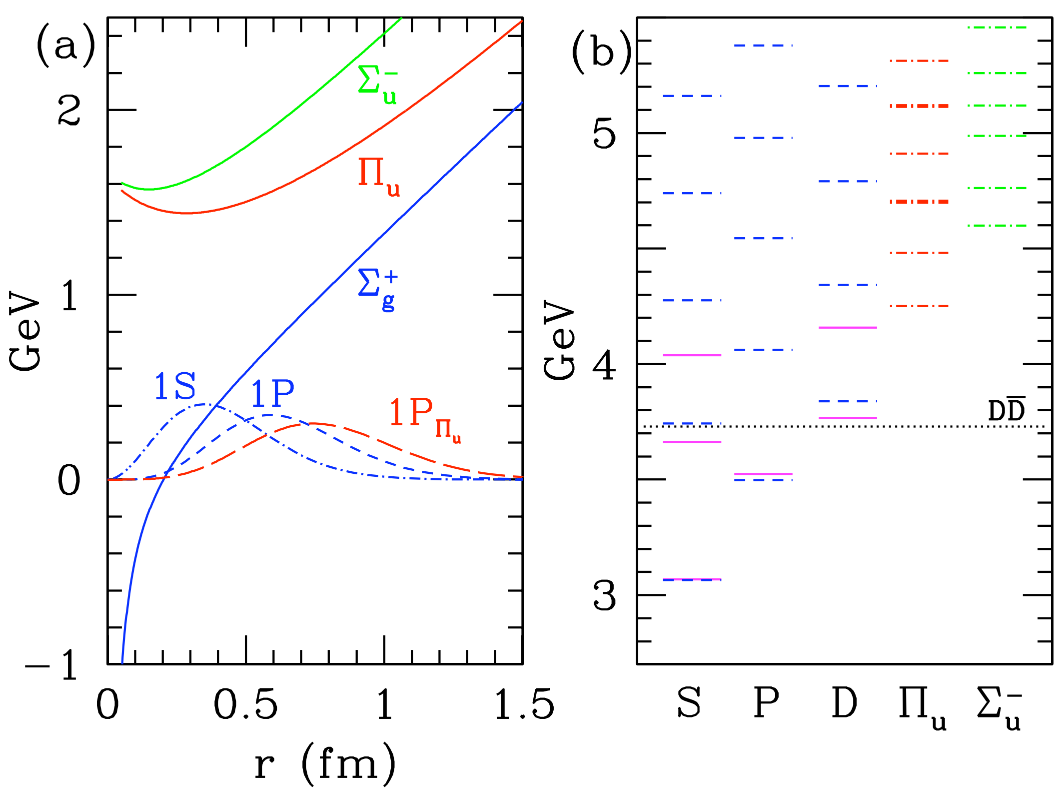
Molecular state - Unlikely

Channel	Threshold Energy	Width	
$D_s^{*+} D_s^{*-}$	4223.8	-	P wave
$D\bar{D}_1(3/2^+)$	4286.5	20.3(1.7)	D wave
$D\bar{D}_1(1/2^+)$	4306(32)	329(76)	S wave
$D\bar{D}_2(3/2^+)$	4327.5	43.8(2.0)	D wave
$D^*\bar{D}_0(1/2^+)$	4315(36)	276(66)	D wave

Threshold effects -

$D^*D\,\pi$ and $D^*D^*\pi$ measurements BES and Belle: Do not support these ideas

Hybrid - Attractive



Close and Page [PL B628 (2005)]

Zhu [PL B625 (2005)]

Charmonium

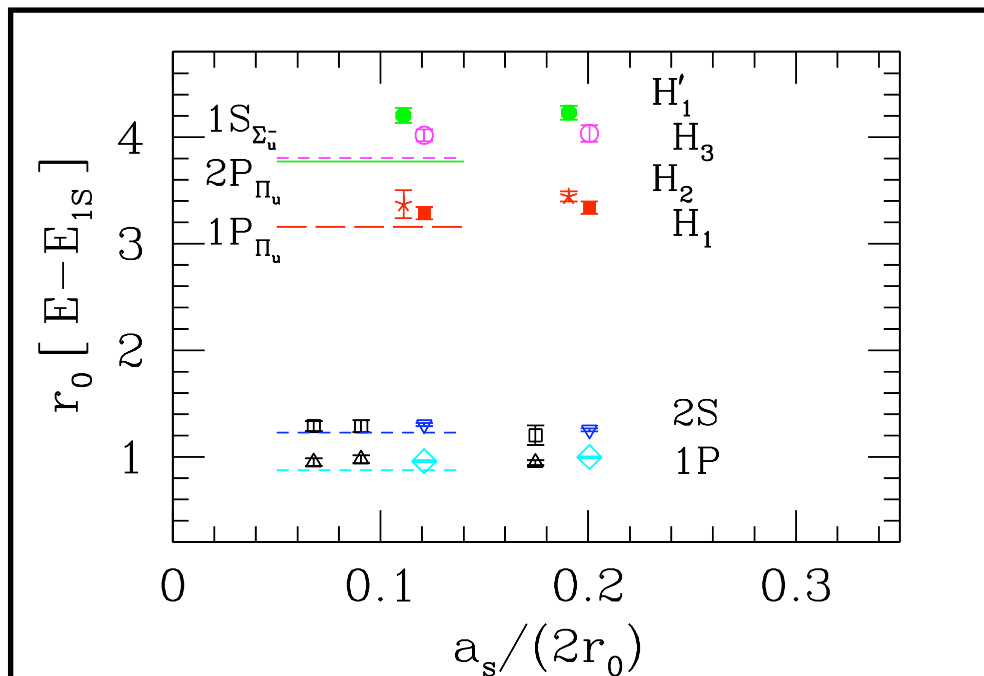
Juge, Kuti,Morningstar [nucl-th/0307116]

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^{+-}	$\chi^\dagger\,\boldsymbol{B}\cdot\boldsymbol{D}\,\psi$

Quenched Spectrum

How many narrow?



Belle

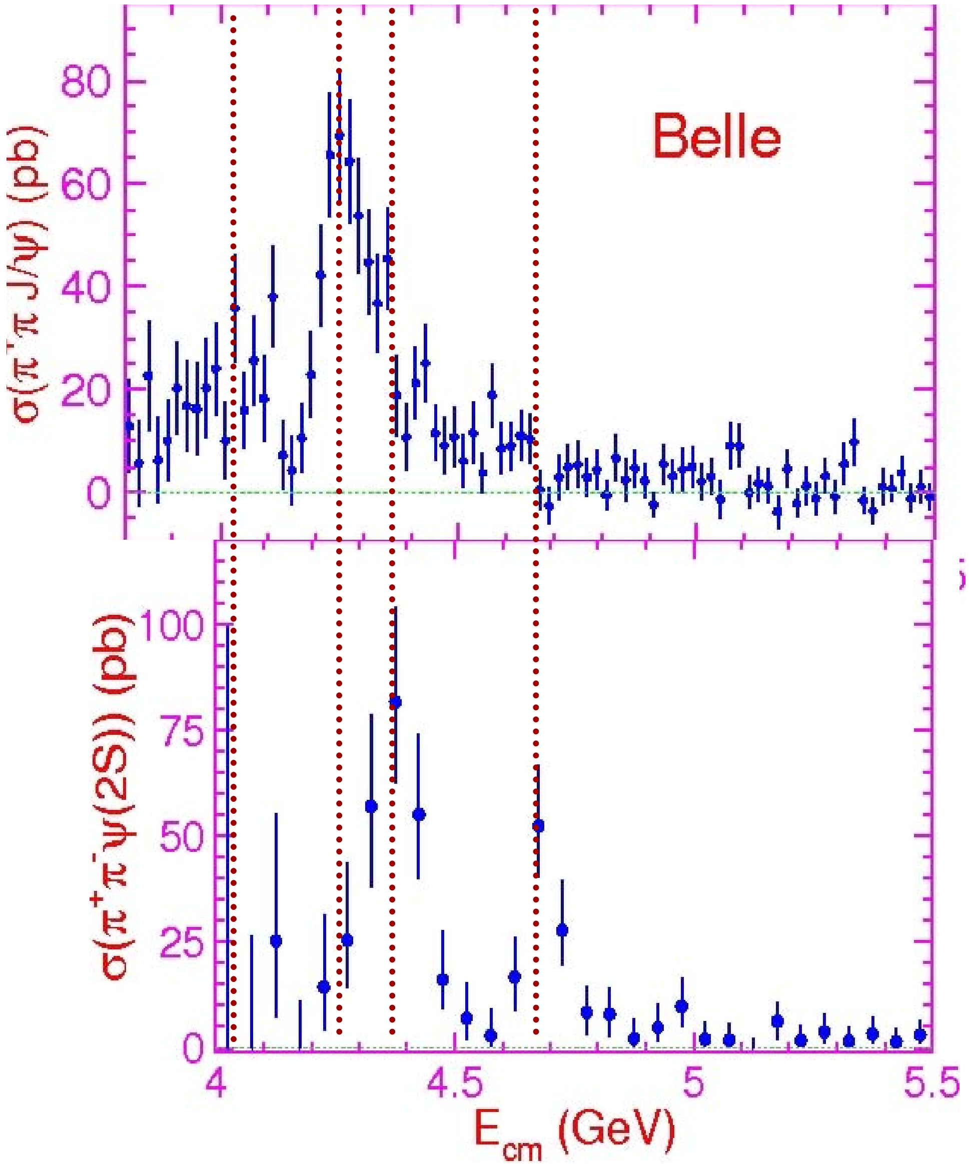
New state Y(4660)observed by Belle in $\pi^+ \pi^- \psi'$

$M(Y(4660))$	$4664 \pm 11 \pm 5$
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$

Very exciting

Y(4260) and Y(4350) might be one wide state with energy dependent branching ratios. (compare 3S region)

Y(4660) is a radial excitation of the charm quarks state (analog of ψ' to J/ψ)



To Do List

Summary and To Do List

We are closer to a theoretical understanding the charm threshold region than it may appear.

The X(3872) is likely D^0 D^{0*} bound state with binding provided by nearby 2^3P_1 state.

The [Y(4260), Y(4350)] and Y(4660) highly suggestive of the hybrid nature of these states.

Lattice calculations will provide insight into theoretical issues.

NRQCD and HQET allows scaling from c to b systems. This will eventually provide critical tests of our understanding of new charmonium states.

Answers in many cases will require the next generation of heavy flavor experiments - BES III, LHCb and Super-B factories.

A list of experimental and theoretical questions:

1 For experiment:

- Measure $R^{+/-}(E)$ in the ψ(3770 resonance region.
- Observe $\psi(3770) \to \gamma\chi_{c2}$
- Angular distribution of $X(3940) \to D + D^*$ to distinguish 0^{-+} and 0^{++}.
- The measurement of the $D^0\bar{D}^0\pi^0$ decay mode of the X(3872) by Belle and Babar is very important to understanding the nature of X(3872). Can more information about the shape of the enhancement be obtained?
- The Y(4260) and/or Y(4350) are above threshold for decays to D^*D_P states. These various decays play an important role in understanding the nature of these states. What limit can you put on the ratio of such decays to the $\pi\pi J/\psi(')$ discovery modes?
- Confirm the Y(4660) in $\pi\pi J/\psi'$. Look for other modes 'light hadrons' $+J/\psi(')$ and $\omega + \chi_{cJ}$.
- Look for Y(4260), Y4350), and Y4660) in $\pi^+\pi^-\psi^{(')}$ at hadron colliders.

2 For theory:

- Compute ΔR_c in the region near the $\psi(3770)$ resonance. This will provide a detailed model for fitting the total cross section.
- Include $D^{(*)} + \bar{D}_P$ final states in coupled channel calculations.
- Investigate the excitation spectrum for hybrid states using the JKM static potential.

3 For lattice:

- The combination of the static energy for hybrids and the SE for obtaining the masses is very practical. If the Y(4260) is a hybrid state, then there is a triplet of nearby states expected (0-+, 1-+, 2-+). The splitting comes from including the heavy quark spin fine structure. How could this be calculated? Even the sign would be useful.
- Much better calculations of the masses of low-lying four quark ($Q\bar{q}q\bar{Q}$) states are needed. What is the prospect obtaining them in the near future. Could a more indirect approach be used to decide if any of the diquark combinations are sufficiently attractive to bind?
- The combination of the static energy for hybrids and the SE for obtaining the masses is very practical. If the Y(4260) is a hybrid state, then there is a triplet of nearby states expected (0-+, 1-+, 2-+). The splitting comes from including the heavy quark spin fine structure. How could this be calculated? Even the sign would be useful.