Quarkonium and the New States

Estia Eichten

Plan of Talk

- ☐ Narrow States Below Threshold
  - ○ Spin singlets
  - ○ Why it works so well
- ☐ Above Threshold and New States
  - ○ $Z^+(4430)$
  - ○ X(3872)
  - ○ States in the 3940 and 4160 mass regions
  - ○ Y(4260) et. al.
- ☐ Summary and Outlook

Narrow States Below Threshold

HQET $\frac{\Lambda}{m_Q}$

NRQCD v

- ☐ The NRQCD approach:

Kinetic Potential

Static Energy

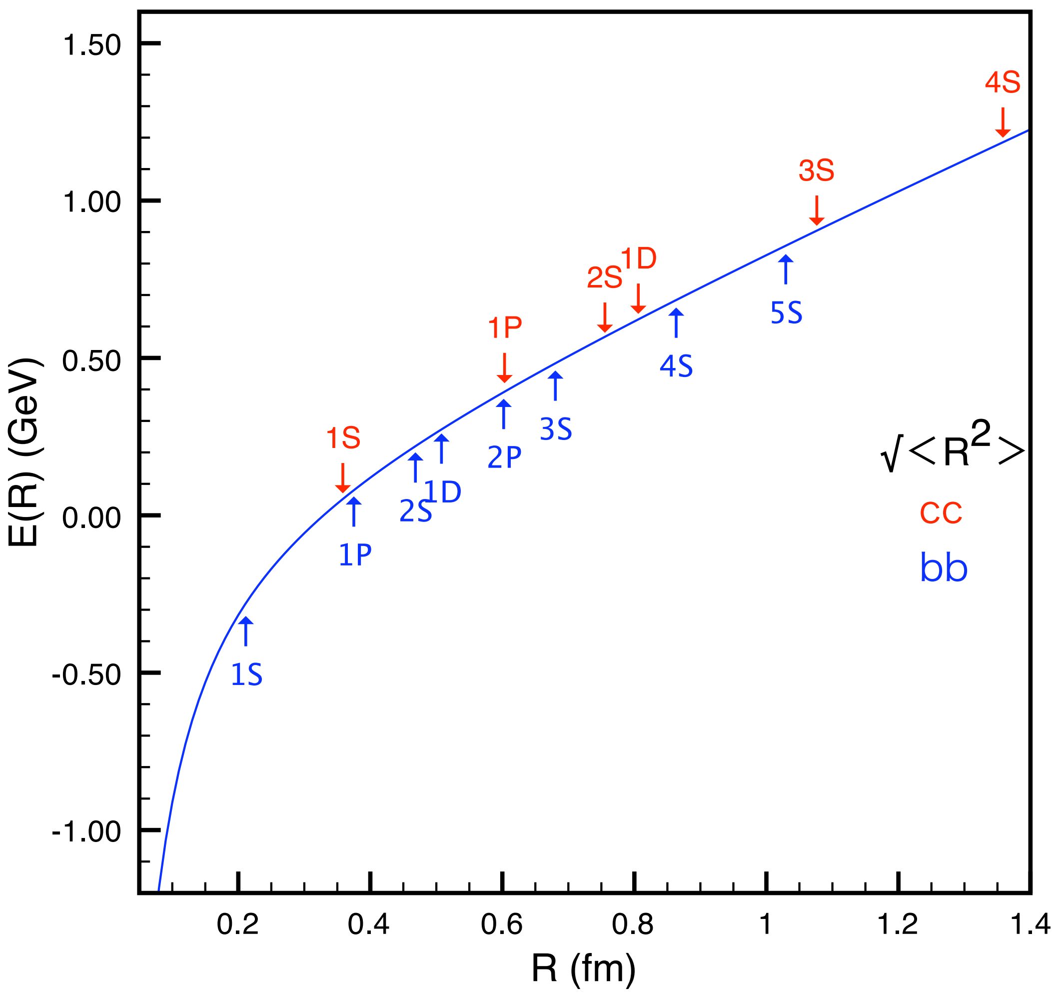
relativistic corrections

$$\begin{aligned}\mathcal{H} \;=\; & Q^\dagger\left[\delta m_Q - \frac{\mathbf{D}^2}{2m_Q}\right]Q + \int d^3x\, j_a^0(x)\,\mathcal{G}^{ab}\, j_b^0(0)\\ & -Q^\dagger\left[\frac{c_4}{8m_Q^3}(\mathbf{D}^2)^2 + \frac{c_D}{8m_q^2}(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\right]Q\\ & -Q^\dagger\left[\frac{c_s}{8m_q^2}\, i\sigma(\mathbf{D}\times g\mathbf{E} + g\mathbf{E}\times\mathbf{D}) + \frac{c_f}{2m_q}\sigma\cdot g\mathbf{B}\right]Q + \ldots\end{aligned}$$

where $j_a^0 = Q^\dagger g t_a Q + g^2 f^{abc}\mathbf{E}_b\cdot\mathbf{A}_c + \ldots$

and $\mathcal{G}^{ab} = \frac{1}{\nabla \mathbf{D}}\nabla^2\frac{1}{\nabla \mathbf{D}}$

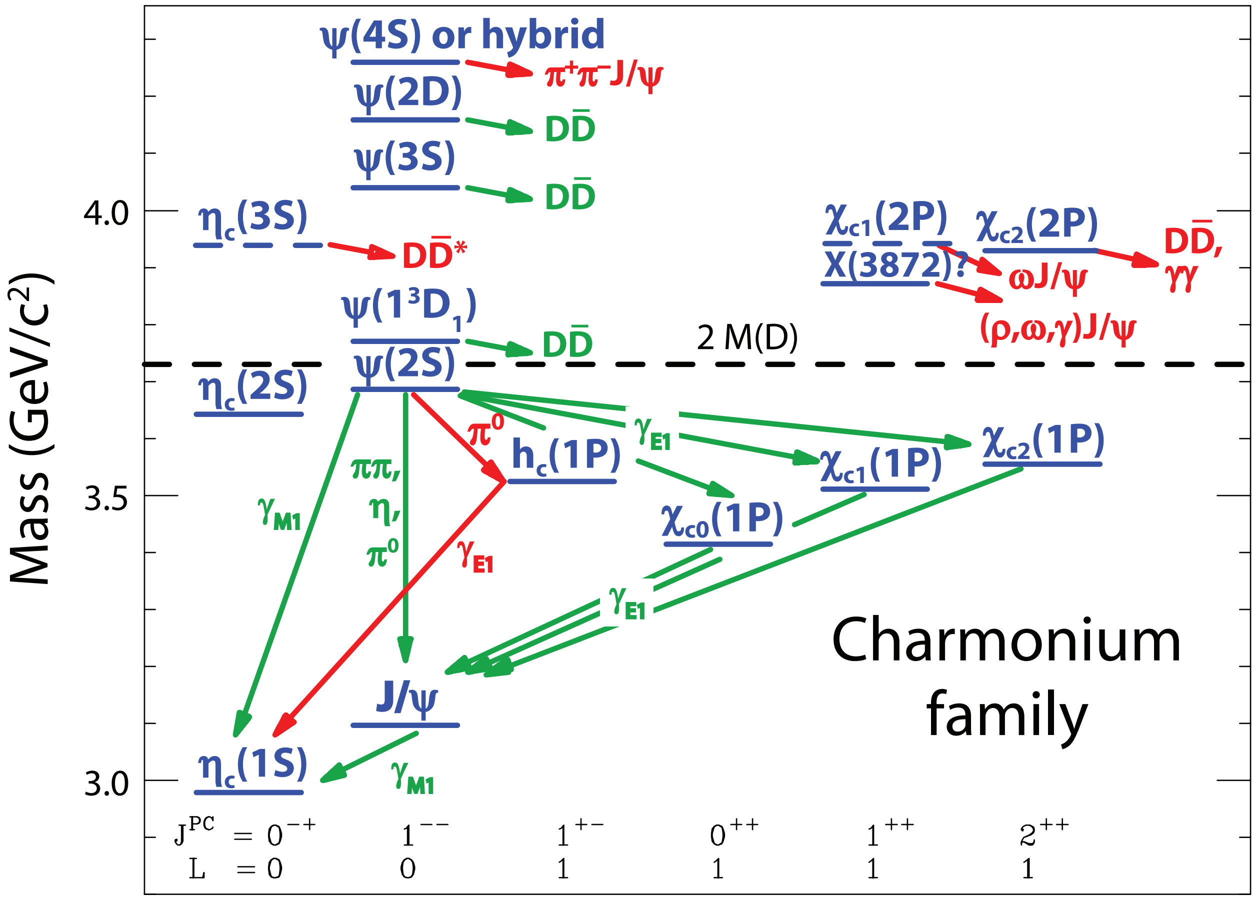
Potential model

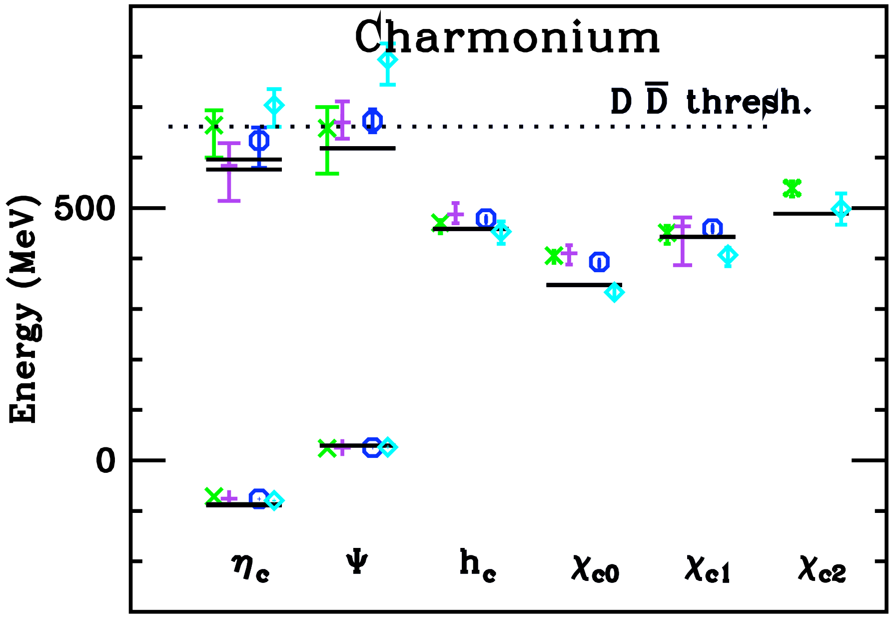


- ☐ Consistency between $(b\bar{b})$ and $(c\bar{c})$ systems validates NRQCD approach.

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

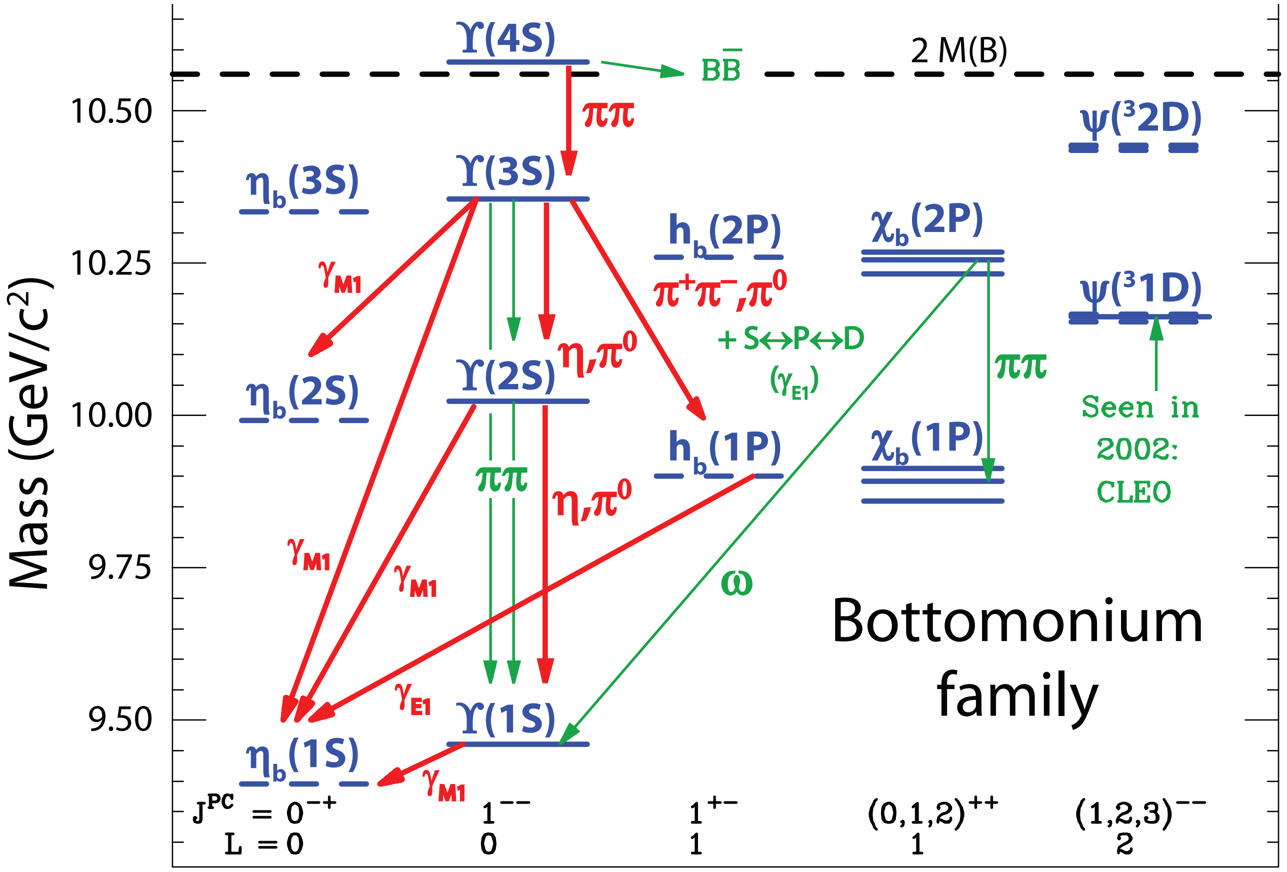
- Below threshold for heavy flavor meson pair production
  - Narrow states allow precise experimental probes of the subtle nature of QCD.
  - Lattice QCD supports and will supplant potential models
  - A variety of lattice approaches





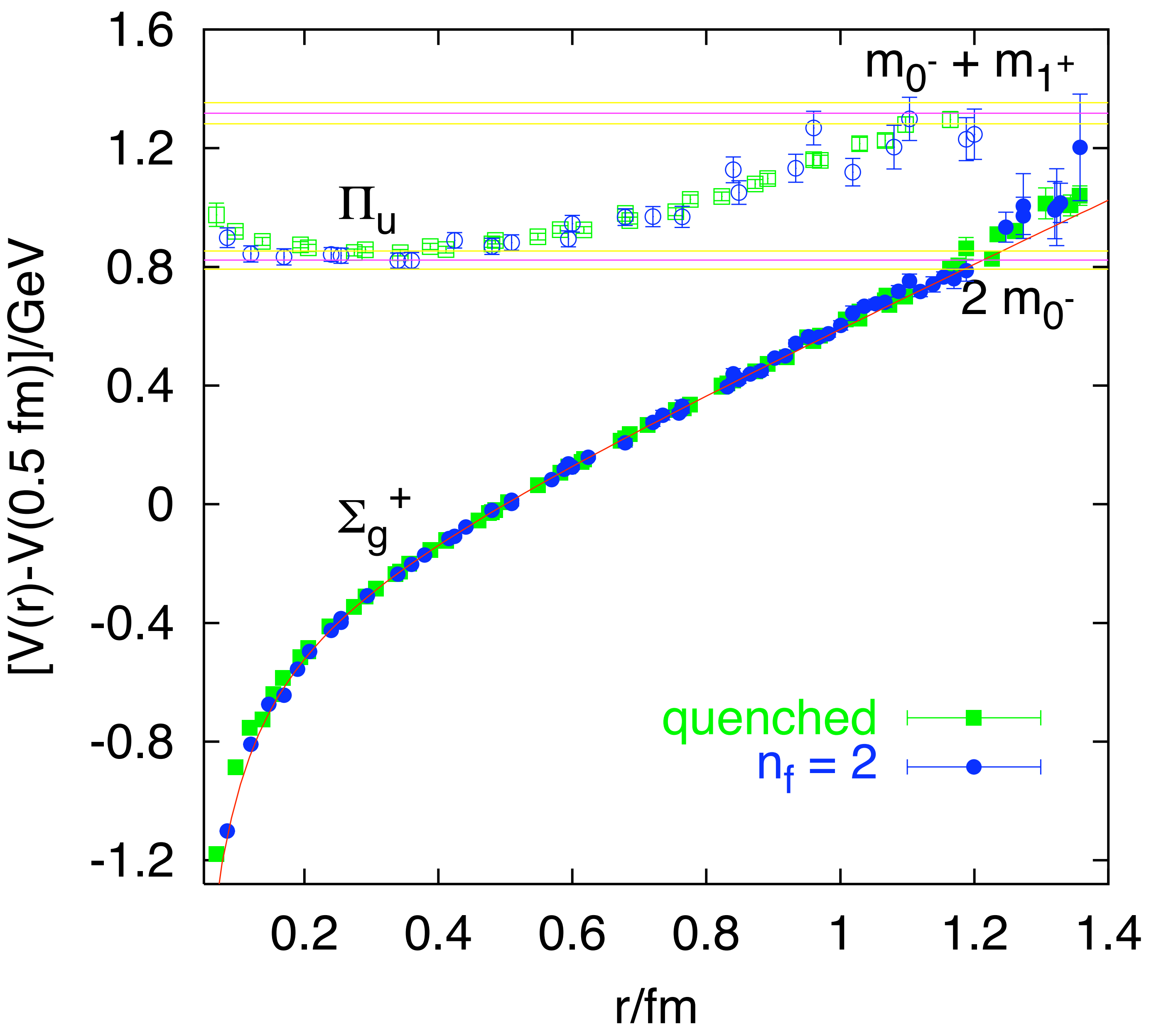
S. Gottlieb et al., PoS LAT2006

Figure 5: Summary of charmonium spectrum.



QCD Static Energy

- ☐ Lattice calculation of the QCD static energy between QQ versus R.
- ☐ Agrees with potential models.
- ☐ Masses of low-lying states directly calculable by LQCD.
- ☐ Excitation of gluonic degrees of freedom (string) also calculable.



Lattice QCD calculation of the spin-dependent relativistic corrections.

Heavy quark potential

To $O(1/m^2)$

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

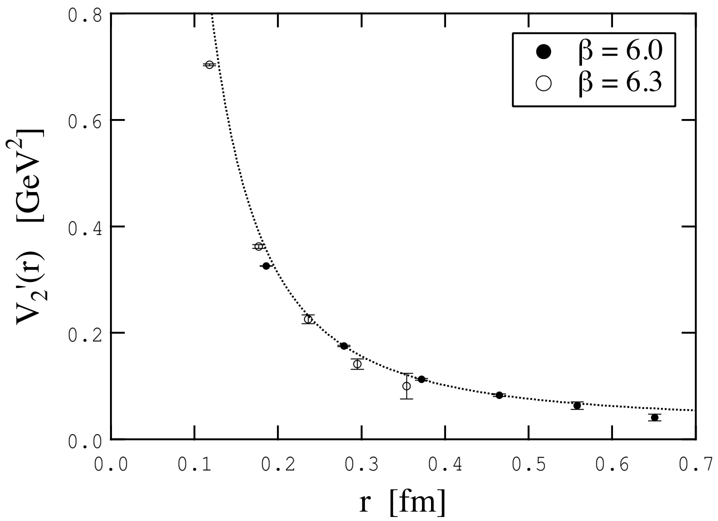
$$+ \left(\frac{\vec{s}_1\,\vec{l}_1}{2m_1^2} - \frac{\vec{s}_2\,\vec{l}_2}{2m_2^2}\right)\left(\frac{V^{(0)}(r)'}{r} + 2\frac{V^{(1)}(r)'}{r}\right) + \left(\frac{\vec{s}_2\,\vec{l}_1}{2m_1 m_2} - \frac{\vec{s}_1\,\vec{l}_2}{2m_1 m_2}\right)\frac{V^{(2)}(r)'}{r}$$

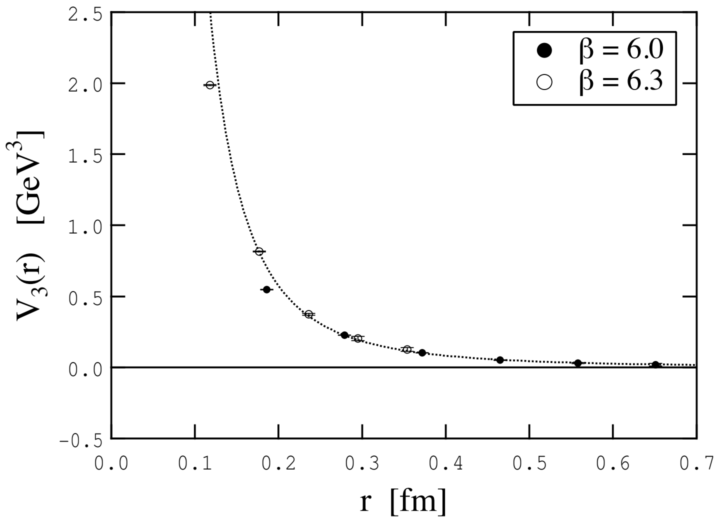
Long range component

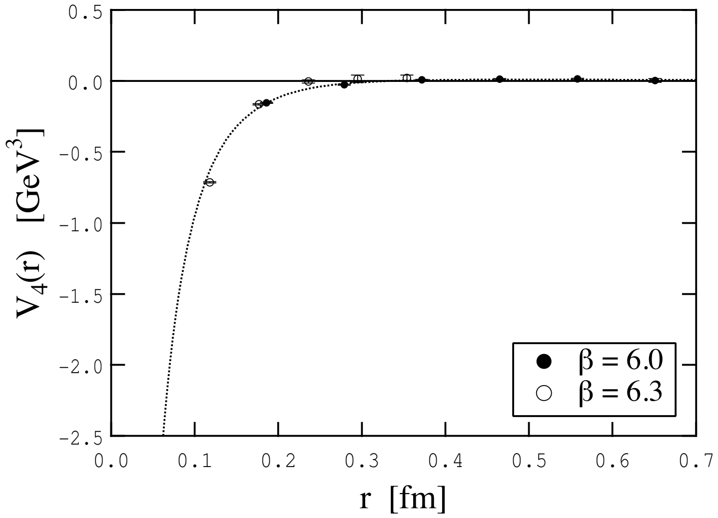
$$+\frac{1}{m_1 m_2}\left(\frac{(\vec{s}_1\,\vec{r})\,(\vec{s}_2\,\vec{r})}{r^2} - \frac{\vec{s}_1\,\vec{s}_2}{3}\right) V^{(3)}(r) + \frac{\vec{s}_1\,\vec{s}_2}{3m_1 m_2} V^{(4)}(r)$$

Short range

Fine and hyper-fine splitting







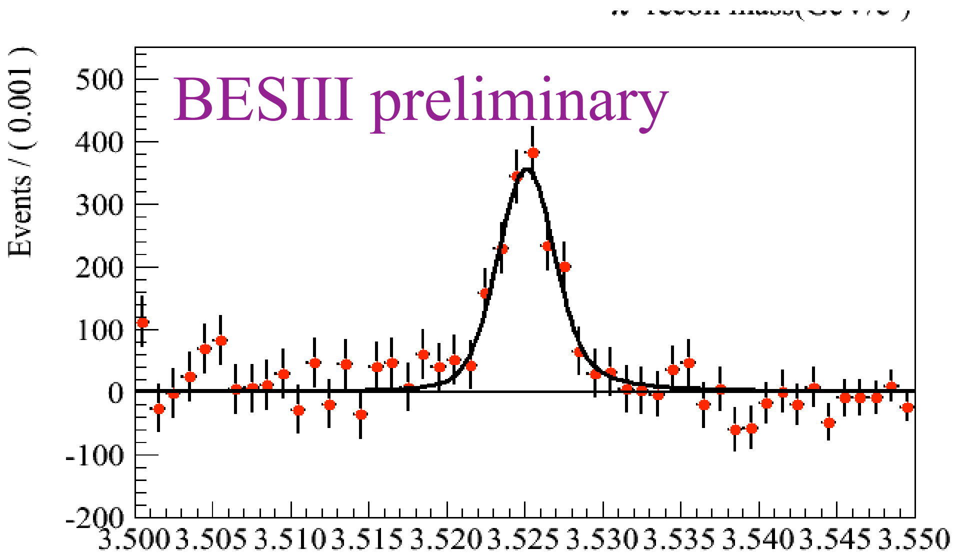
Y. Koma, M. Koma and H. Wittig [Nucl. Phys. B769:79 (2007)]

Spin Singlet States

- h_c
  - Observation CLEOc,
    NEW - BESIII

$$e^+e^- \to \psi(2S) \to \pi^0 h_c, \qquad h_c \to \gamma\eta_c, \qquad \pi^0 \to \gamma\gamma.$$

Briere



$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4$$

$$\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$$

  - Partial widths and decay modes:

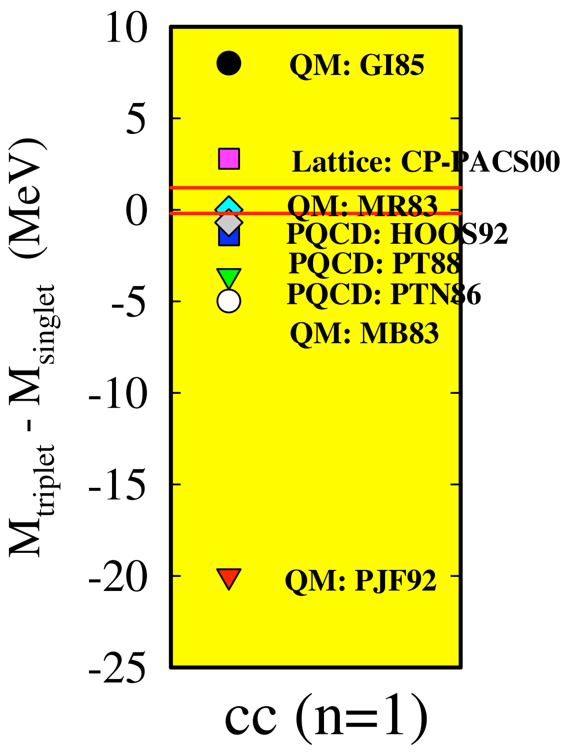
$$\Gamma(h_c \to \gamma\eta_c) = (\frac{k^\gamma_{h_c}}{k^\gamma_{\chi_{c1}}})^3 \Gamma(\chi_{c1} \to \gamma J/\psi) \approx 340 keV$$

$\Gamma(h_c \to$ light hadrons$)$

J. L. Rosner et al., PRL 95, 102003 (2005)

  - Spin -dependent forces:

$$\Delta M_{\rm hf}(\langle M(^3P_J)\rangle - M(^1P_1)) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}.$$



Confirms the short range nature of spin-spin and tensor potentials. Phenomenological models which closely follow pert QCD are best.

S. Godfrey [hep-ph/0501083]

η_c

- M1 transition was a theoretical disaster
  - Basics

$$\Gamma(i \xrightarrow{\text{M1}} f + \gamma) = \frac{4\alpha e_Q^2}{3m_Q^2}(2J_f+1)k^3[\mathcal{M}_{if}|]^2$$

$$\mathcal{M}_{if} = \int r^2 dr\, R_{n_i \mathrm{L}_i}(r) j_0(\frac{rk}{2}) R_{n_f \mathrm{L}_f}(r)$$

$j_0 = 1 - (kr)^2/24 + \ldots$, so in NR limit

$$\begin{aligned} k = 0: \quad \mathcal{M}_{if} &= 1 \quad n_i = n_f; L_i = L_f \\ &= 0 \quad \text{otherwise} \end{aligned}$$

  - pNRQCD

Model independent - completely accessible by perturbation theory to o(v^2)

$$\Gamma(J/\psi \to \eta_c \gamma) = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}\left[1 + C_F \frac{\alpha_s(M_{j/\psi}/2)}{\pi} + \frac{2}{3}(C_F \alpha_s(p_{J/\psi}))^2\right]$$

Brambilla, Jia & Vairo
[PR D73:054005 (2006)]

No large anomalous magnetic moment

No scalar long range interaction

$$\Gamma(J/\psi \to \eta_c \gamma) = (1.5 \pm 1.0) \text{ keV}.$$

  - LQCD

$$\Gamma(J/\psi \to \eta_c \gamma) = (2.0 \pm 0.1 \pm 0.4) \text{ keV}$$

Dudek, Edwards, Richards
[PR D73:074507 (2007)]

  - J/ψ -> γ + η_c M1 transition

$$1.19 \pm 0.33 \text{ keV}$$

Exp
[Crystal Ball]

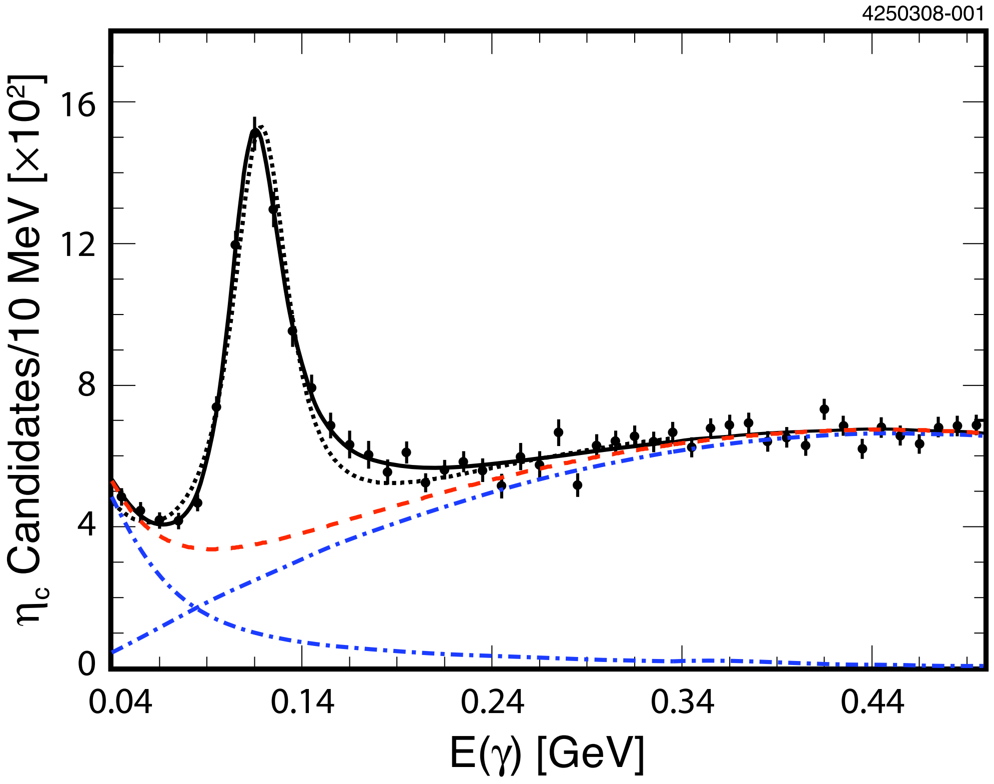
half the expected theoretical result

- CLEO measurement solves the issue

R. E. Mitchell et al., [arXiv:0805.0252] [hep-ex]

$$\mathcal{B}(\psi(2S) \to \gamma\eta_c) = (4.32 \pm 0.16 \pm 0.60) \times 10^{-3}$$

$$\mathcal{B}(J/\psi \to \gamma\eta_c) = (1.98 \pm 0.09 \pm 0.30) \times 10^{-3}$$



- Mass splittings

$$\begin{aligned} M(\eta_c) &= 2976.7 \pm 0.6\ \text{MeV}/c^2 \quad \text{Breit-Wigner} \\ &= 2982.2 \pm 0.6\ \text{MeV}/c^2 \quad \text{Modified Breit-Wigner} \end{aligned}$$

long tail

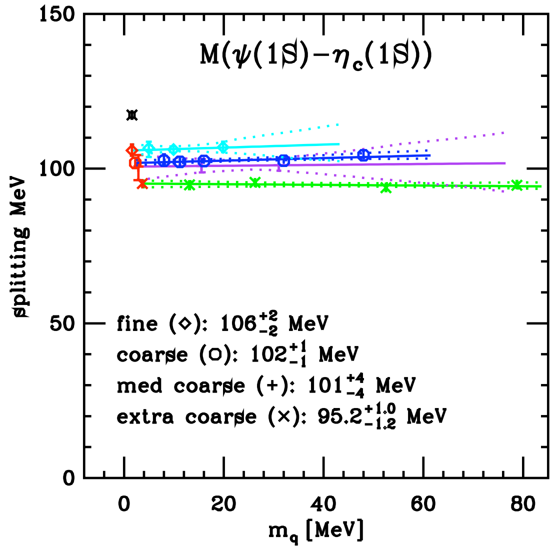
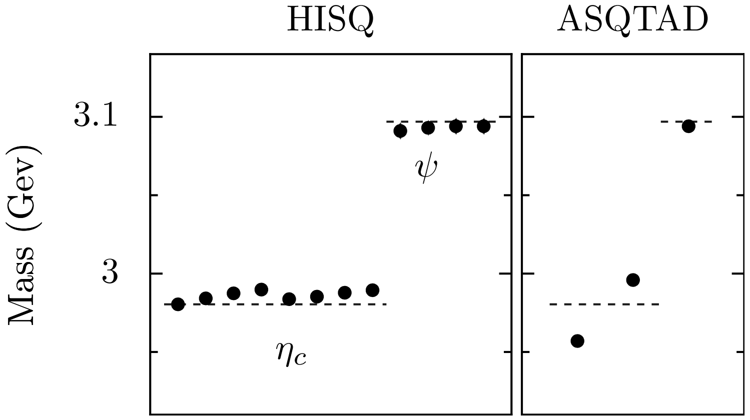
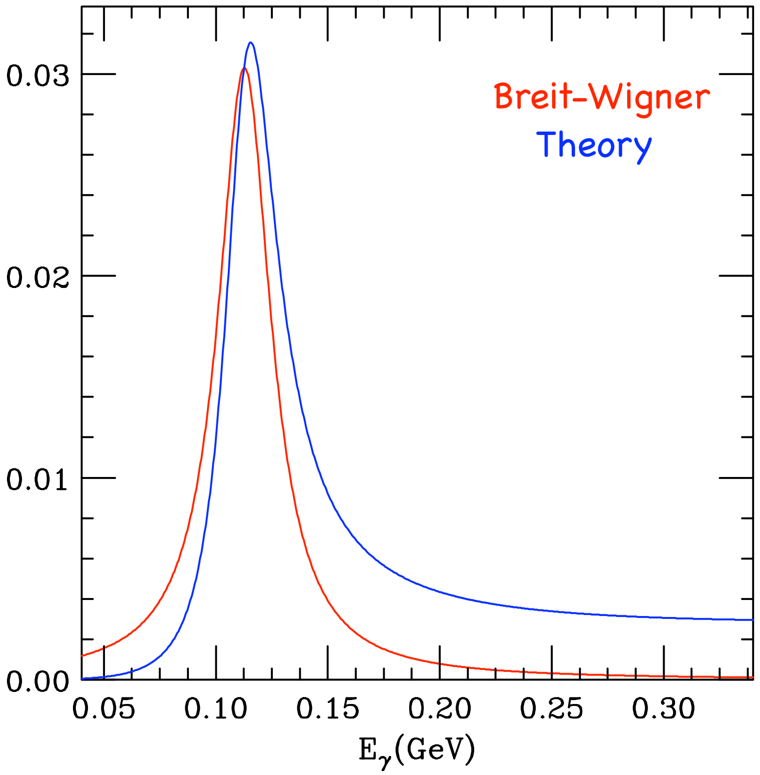


Figure 4: Hyperfine splitting of the 1*S* states.



E. Follana et al.,[HPQCD] PR D 75, 054502 (2006)

S. Gottlieb et al., PoS LAT2006



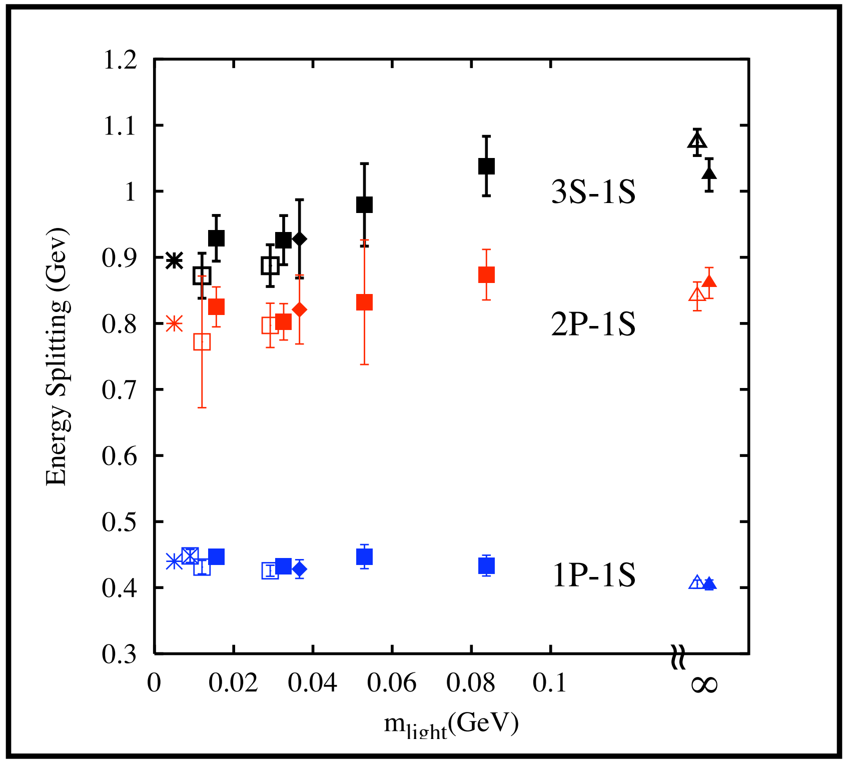
η_c':

- Spin splitting $\Delta M = M(\Upsilon(2S)) - M(\eta_c') = 49 \pm 4$ MeV$/c^2$ PDG 2008

  Too small - scaling from 1S; most models.

  Are we seeing threshold effects?

- Effects of light quark loops significant



Effects on spectrum seen in LQCD

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

- Strong coupling to virtual decay channels induces spin-dependent forces in charmonium near threshold, because M(D*) > M(D)
- Spin dependent shifts small far below threshold

Less that 1 MeV shift ⇒

Reduces ΔM(2S) by 21 MeV ⇒

ELQ PRD 73:014014 (2006)

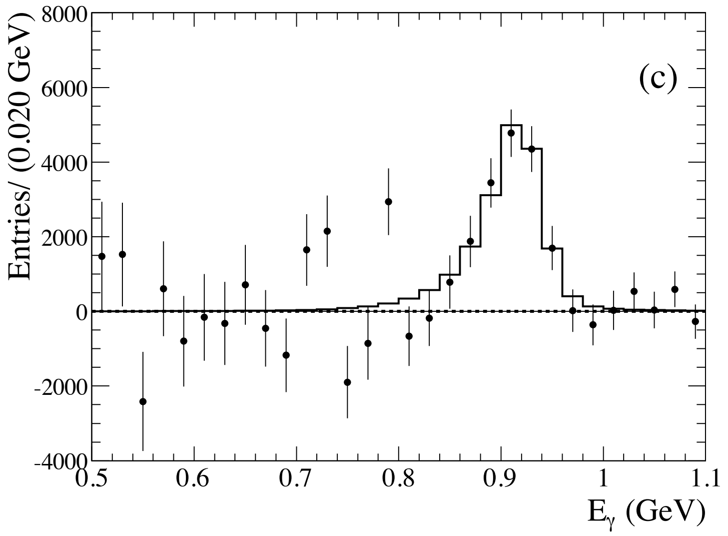
State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5^e	$+2.8$
1^3S_1	$3\,096.9^a$		$+30.2^e$	-0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
1^1P_1	$3\,524.4^f$		$+0.6^e$	$+0.5$
1^3P_2	$3\,556.2^a$		$+31.9^e$	-0.3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

η_b:

BaBar [PRL 101, 071801 (2008)]

- Observed by BaBar in ϒ(3S) radiative decays

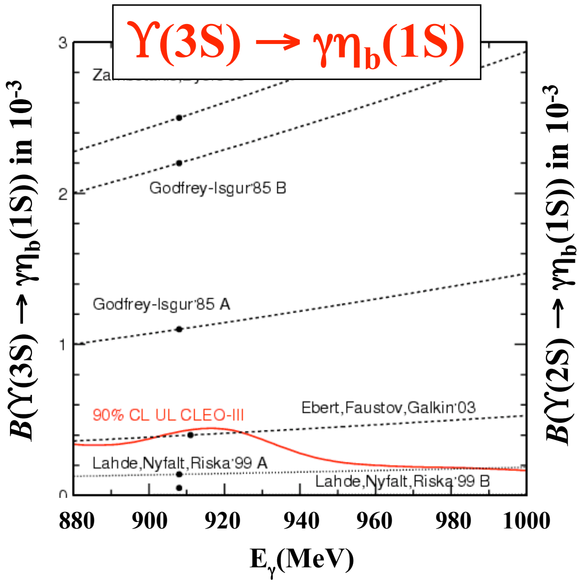
$$E_\gamma = 921.2 \ {}^{+2.1}_{-2.8} \pm 2.4$$
$$M(\eta_b) = 9388.9 \ {}^{+3.1}_{-2.3} \pm 2.7 \text{ MeV}$$

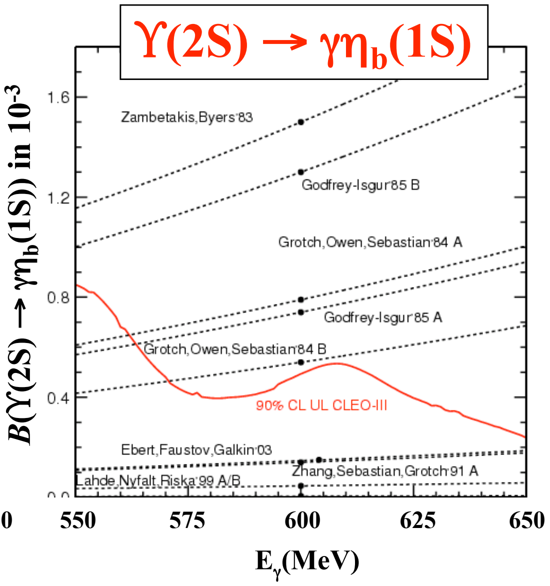


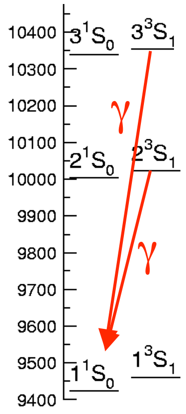
- Hyperfine splitting: $M(\Upsilon(1S)) - M(\eta_b) = 71.4 \ {}^{+2.3}_{-3.1} \pm 2.7$ MeV

$$\text{Naive} \ : \ \frac{\alpha_s(m_b^2)}{\alpha_s(m_c^2)} \frac{4\Gamma_{e^+e^-}(\Upsilon)}{\Gamma_{e^+e^-}(J/\Psi)} [M(J/\Psi) - M(\eta_c)] \approx 68 \ (\text{MeV})$$
$$\text{QCD NNL} \ : \ 39 \pm 11 \ {}^{+\ 9}_{-\ 8} \ (\text{MeV}) \quad [\text{PRL 92 242001 (2004)}]$$
$$\text{LQCD} \ : \ 61 \pm 14 \ (\text{MeV}) \quad [\text{PR D72 : 094507 (2005)}]$$

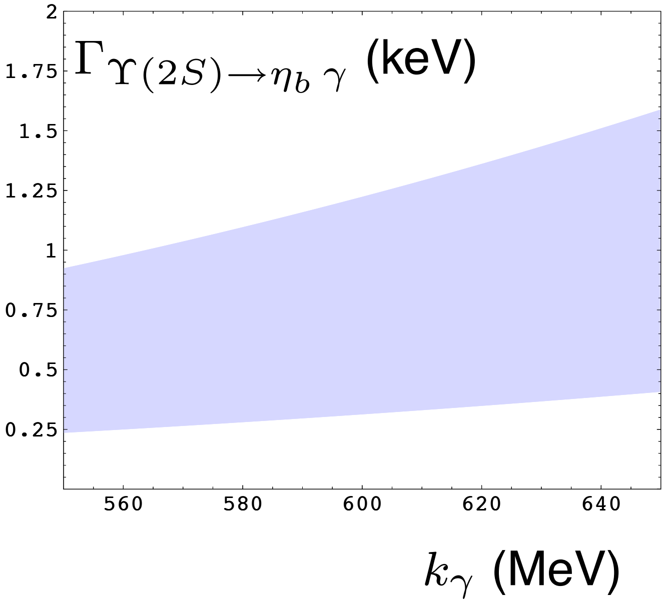
- Hindered M1 Transitions:
  - Relativistic corrections poorly understood. Phenomenological models for ϒ(3S) -> $\gamma\eta_b$ and ϒ(2S) -> $\gamma\eta_b$ vary greatly.







pNRQCD



  - ϒ(3S) -> $\gamma\eta_b$: $Br(\Upsilon(3S) \to \gamma\eta_b) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$
  - Expectations for ϒ(2S) -> $\gamma\eta_b$: CLEO < 0.09 keV (90%c.l.) at E_γ = 615 MeV

- Narrow states still missing
  - Charmonium - 3 - $^1D_2$, $^3D_2$, and $^3D_3$
  - Bottomonium - 23 - 1^3D_1, 1^3D_3, 1^3F_J, 2^3D_J, 1^3G_J, 3^3P_J, 1^1P_1, 2^1S_0, 1^1D_2, 2^1P_1, 3^1S_0, 1^1F_3, 2^1D_2, 1^1G_4, 3^1P_1
- Multipole expansion approach for EM and hadronic transitions works well.
  - Puzzling exceptions to expectations resolved by well understood dynamical suppression of the leading order expansion coefficient: $\Upsilon(3S) \to \gamma + \chi_b(1P)$ E1 rate; $\psi(2S) \to \gamma+\eta_c$, $\Upsilon(2S) \to \gamma+\eta_b(1S)$ and $\Upsilon(3S) \to \gamma+\eta_b(1S)$ M1 rates; $\Upsilon(3S) \to \Upsilon(1S) + 2\pi$ E1-E1 term; $\Upsilon(nS) \to \Upsilon(mS) + 2\pi$, M1-M1 terms.
  - Higher order relativistic corrections needs better theory -> Lattice QCD.
- Direct decays provide a wealth of information

Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E.
[Rev. Mod. Phys. 80, 1161 (2008)]

Why it works so well

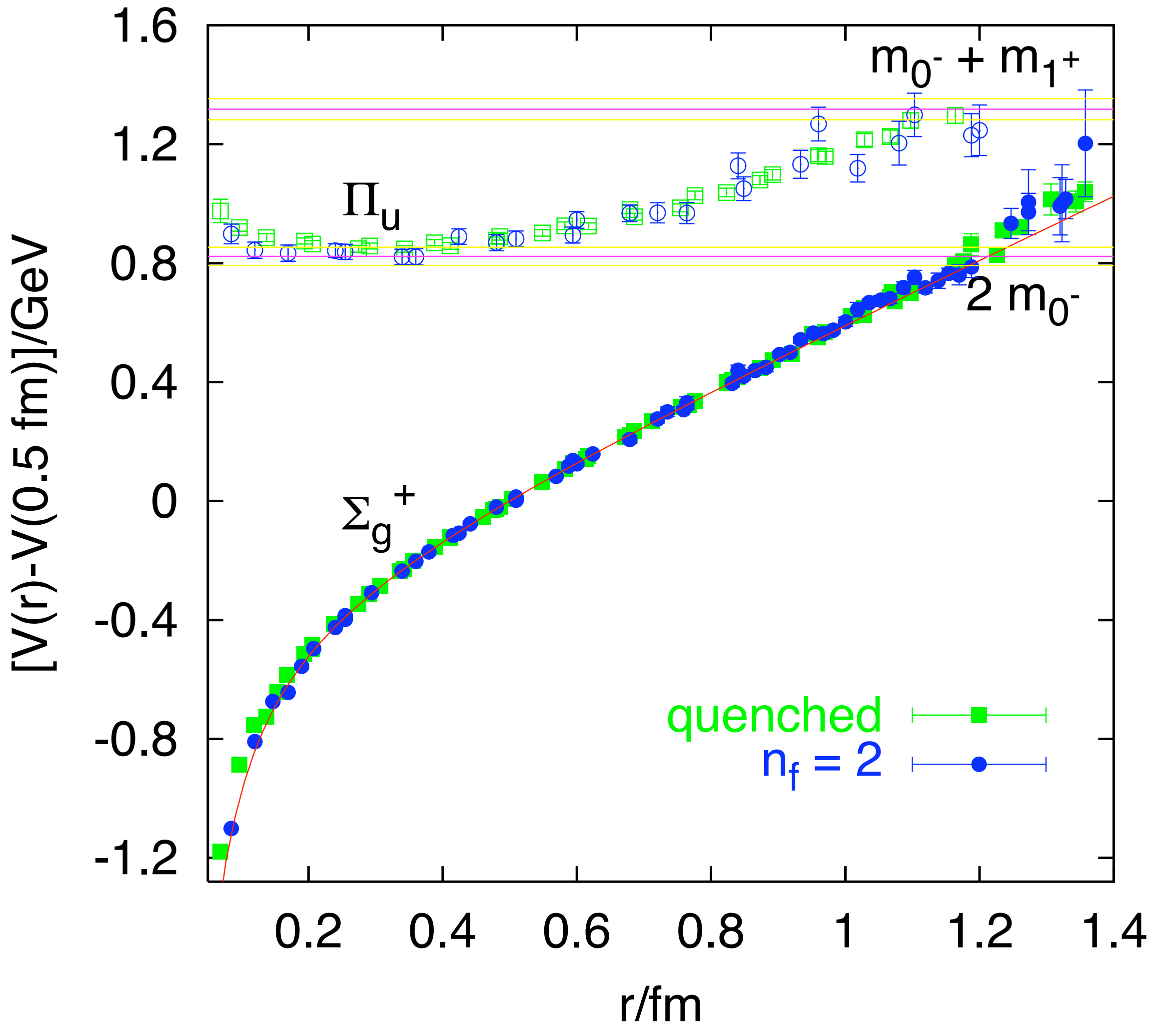
- ☐ What about the gluon and light quark degrees of freedom of QCD?

- ☐ Two thresholds:
  - ○ Usual $(Q\bar{q}) + (q\bar{Q})$ decay threshold
  - ○ Excite the string - hybrids

- ☐ Hybrid states will appear in the spectrum associated with the potential Π_u, ...

- ☐ In the static limit this occurs at separation: $r \approx 1.2$ fm.
  Between 3S-4S in $(c\bar{c})$;
  just above the 5S in $(b\bar{b})$.

Heavy Quark Limit
Static Energy



Above Threshold and New States

- Need to account for strong decays
  - Threshold Formalism For Strong Decays

ψ_1 : one particle states
ψ_2 : multi particle states

$$\begin{pmatrix} \mathcal{H}_0 & \mathcal{H}_I^\dagger \\ \mathcal{H}_I & \mathcal{H}_2 \end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = z\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

Eliminating ψ_2:

$$\left(\mathcal{H}_0 + \underbrace{\mathcal{H}_I^\dagger \frac{1}{z-\mathcal{H}_2}\mathcal{H}_I}_{\Omega(z)}\right)\psi_1 = z\psi_1$$

All the complexity of the strong decay
in the matrix $\Omega(z)$:

  - Simplifying assumptions of phenomenological models (CCCM)

- $\mathcal{H}_2$ - free heavy meson pairs – No final state or exchange interactions. No bound states like a X(3872) molecule.

- $\mathcal{H}_0\,\psi_l = z\psi_l$ – A complete basis set quarkonium states |n> – No hybrid states.

$$< n|\mathcal{G}(z)|m >=< n|\frac{1}{z-\mathcal{H}_0-\Omega(z)}|m >$$

- Generalized VMD

$$R_Q \sim \frac{1}{s}\sum_{nm}\lim_{r\to 0}\psi_n^*(r)\mathrm{Im}\mathcal{G}_{nm}(W+i\epsilon)\psi_m(r)$$

Decay amplitudes

$$\Omega_{nL,mL'}(W) = \sum_i \int_0^\infty P^2\,dP \frac{H^i_{nL,mL'}(P)}{W - E_1(P) - E_2(P) + i0}$$

where

Statistical factor

$$H^i_{nL,mL'}(P) = f^2 \sum_l C(JLL';l) I^l_{nL}(P) I^l_{mL'}(P)$$

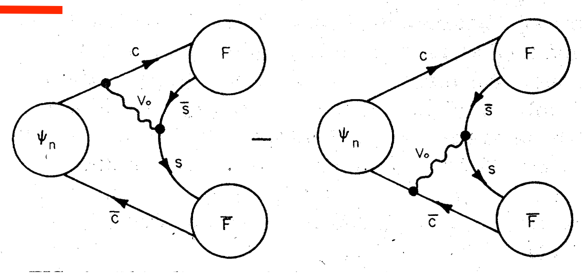
and reduced decay amplitude is given by

$$I^l_{nL}(P) = \int_0^\infty dt\,\Phi(t) R_{nL}(t\beta^{-1/2}) j_l(\mu_c \beta^{-1/2} P t)$$

ONLY the function $\Phi(t)$ depends on the pair production dynamics.

(separation between heavy quarks: $r = t\sqrt{\beta}$)

Details for CCCM:



radial wavefunctions:

$n^{2s+1}L_J$ QQbar state: $R_{nL}(r)$

Qqbar ground state:

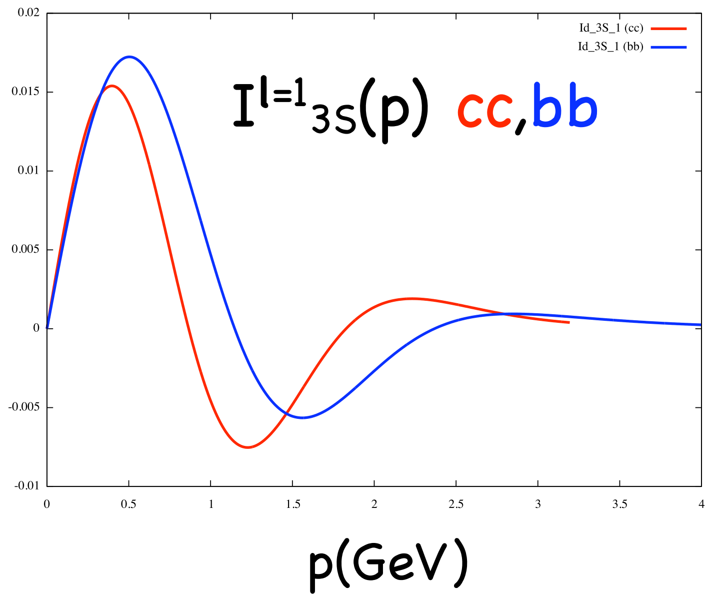
$$\phi(x) \sim \exp(-x^2\beta_S) \quad [\beta_S = \frac{1}{2a^2}(\frac{4\mu a}{3\sqrt{(\pi)}})^{2/3}]$$

$$\langle C_1(\vec{P}\lambda_1)\bar{C}_2(\vec{P}'\lambda_2)|H_I|\psi_n\rangle = -i(2\pi)^{-3/2}\delta^3(\vec{p}+\vec{p}')3^{-1/2}A_{12}(\vec{P}\lambda_1\lambda_2;n)$$

$$A_{12}(\vec{P}\lambda_1\lambda_2;n) = \frac{1}{m_q}\sum_{\{s\}} \int d^3x\,d^3y [\chi^\dagger(s_2')\vec{\sigma}\cdot\hat{x}\chi(-s_1')] \frac{dV(|\vec{x}|)}{d|\vec{x}|} \phi_1^*(\vec{x}s_1s_1')\phi_2^*(\vec{x}-\vec{y}, s_2s_2')\psi_n(\vec{y}s_1s_2)e^{-i\mu_c\vec{P}\cdot\vec{y}}$$

$\Phi(t)$

Sample decay amplitudes (CCCM)

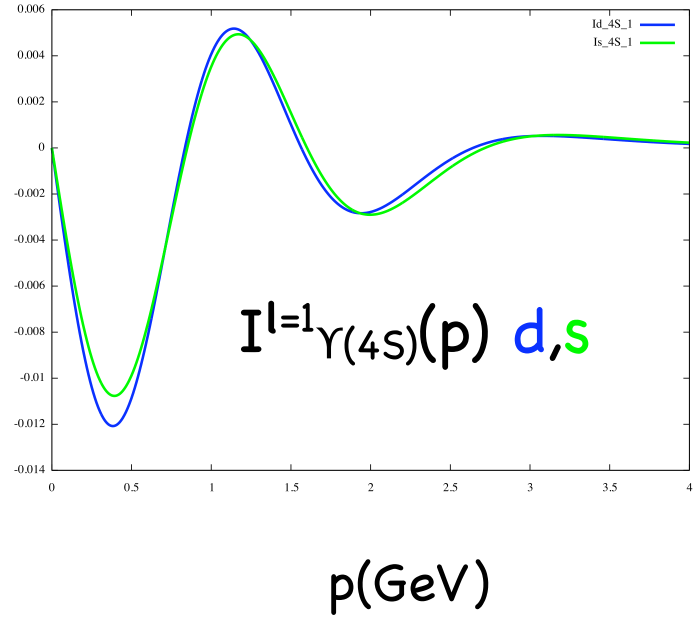


- Contains all dependence on light quark pair production dynamics.

  e.g. for CCCM: $\Phi(t) = te^{-t^2} + (\pi/2)^{1/2}(t^2-1)e^{-t^2/2}\,\mathrm{erf}(t/\sqrt{2})$

- Using HQET, $\Phi(t)$ is the same for all final states in a j_l^P multiplet.

- Apart from overall light quark mass factors $\Phi(t)$ is approximately SU(3) invariant.

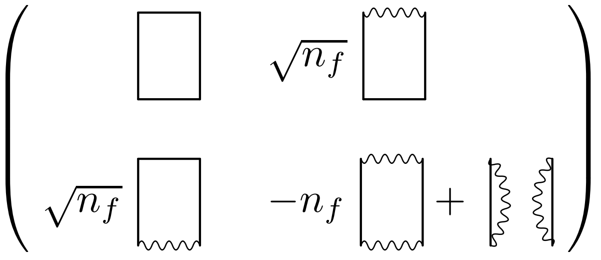


- One universal function, $\Phi(t)$, determines $\Omega(W)$ in the threshold region.

- Lattice QCD can be used to calculate $\Phi(t)$:

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

$$= e^{-2m_Q t}$$



, (1)

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

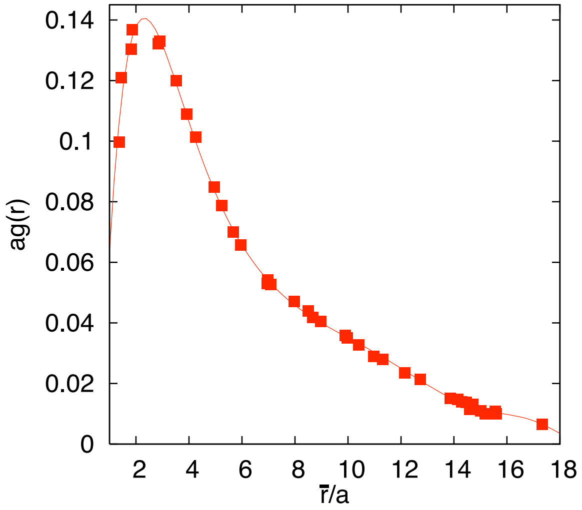


FIG. 18: The transition rate g between $|B\rangle$ and $|Q\rangle$ states, as a function of $\bar{r}$.

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

Why all this?

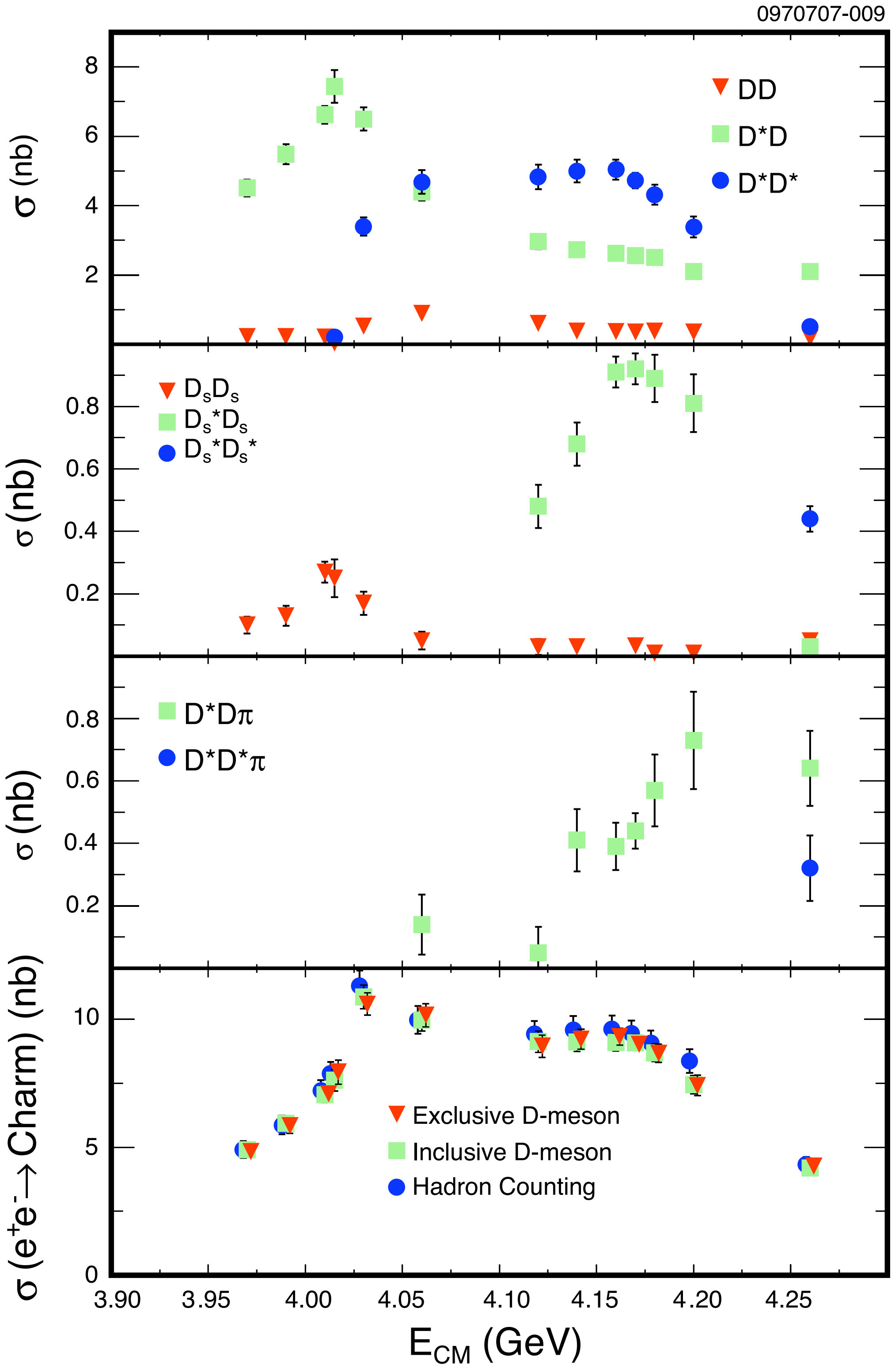
- Suppose we had no NRQCD expectations and had first measured the exclusive charm pair production contributions to Rc in the threshold region.

- How many resonances would you find?

- But in fact we know that the coupled channel calculations with only the usual charmonium resonances describes the data fairly well.

- We don't have this analysis for other production modes: B decays, γγ, recoil against J/Ψ in e^+e^-, ppbar. Proceed with caution.

CLEOc [arXiv:0807.1220]



New States Above Charm Threshold

New

State	EXP	$M + i\,\Gamma$ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle, CDF, D0, BaBar	$3871.2 \pm 0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3872.6^{+0.5}_{-0.4} \pm 0.4 + i(3.9^{+2.5}_{-1.3}{}^{+0.8}_{-0.3})$ $3875.1^{+0.7.}_{-0.5} \pm 0.5 + i(3.0^{+1.9}_{-1.4} \pm 0.9)$		$D^0 D^{*0}$	B decays
Z(3930)	Belle	$3929 \pm 5 \pm 2 + i(29 \pm 10 \pm 2)$	2^{++}	$D^0 \bar{D}^0$, $D^+ D^-$	$\gamma\gamma$
Y(3940)	Belle BaBar	$3943 \pm 11 \pm 13 + i(87 \pm 22 \pm 26)$ $3914.3^{+3.8}_{-3.4} \pm 1.6 + i(33^{+12}_{-8} \pm 0.60)$	J^{P+}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6} \pm 6 + i(37^{+26}_{-15} \pm 8)$	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle BaBar	$4008 \pm 40^{+72}_{-28} + i(226 \pm 44^{+87}_{-79})$ (not seen)	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
Y(4140)	CDF	$4143.0 \pm 2.9 \pm 1.2 + i(11.7^{+8.3}_{-5.0} \pm 3.7)$	J^{P+}	$\phi\, J/\psi$	ppbar
X(4160)	Belle	$4156^{+25}_{-20} \pm 15 + i(139^{+111}_{-61} \pm 21)$	J^{P+}	$D^* \bar{D}^*$	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259 \pm 6^{+2}_{-3} + i(105 \pm 18^{+4}_{-6})$ $4284^{+17}_{-16} \pm 4 + i(73^{+39}_{-25} \pm 5)$ $4247 \pm 12^{+17}_{-32} + i(108 \pm 19 \pm 10)$	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324 \pm 24 + i(172 \pm 33)$ $4361 \pm 9 \pm 9 + i(74 \pm 15 \pm 10)$	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle BaBar	$4433 \pm 4 \pm 1 + i(44^{+17}_{-13}{}^{+30}_{-11})$ (not seen)	J^P	$\pi^+ \psi(2S)$	B decays
Y(4660)	Belle	$4664 \pm 11 \pm 5 + i(48 \pm 15 \pm 3)$	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)

General Comments

- Basic Questions:
  - Is it a new state?
  - What are its properties?: Mass, width, J^{PC}, decay modes
  - Charmonium state or not?
  - If not what? New spectroscopy.

- Options for new states:
  - Four quark states -

$(Q\bar{q})(q\bar{Q})$ Molecules

N.A. Tornqvist PLB 590, 209 (2004)
E Braaten and T Kusunoki PRD 69 074005 (2004)
C.Y. Wong PRC 69, 055202 (2004)
E.S. Swanson PLB 598,197 (2004)
M.B. Voloshin PLB 579, 316 (2004)
F. Close and P. Page PLB 578,119 (2004)
X. Liu [arXiv:0708..4167]
...

$(Qq)(\bar{q}\bar{Q})$ Diquark-Antidiquark

L. Maiani et.al. PRD 71,014028 (2005)
T-W Chiu and T.H. Hsieh PRD 73, 111503 (2006)
D. Ebert et.al. PLB 634, 214 (2006)

$(Q\bar{Q})(\bar{q}q)$ Hadro-charmonium

S. Dubynski et al PLB 666,344 (2008)

  - Hybrids - Exciting the gluonic degrees of freedom:

valance gluons, string

F. E. Close and P.R. Page PLB 628, 215 (2005)
E. Kou and O. Pene PLB 631, 164 (2005)
S.L. Zhu PLB 625, 212 (2005)

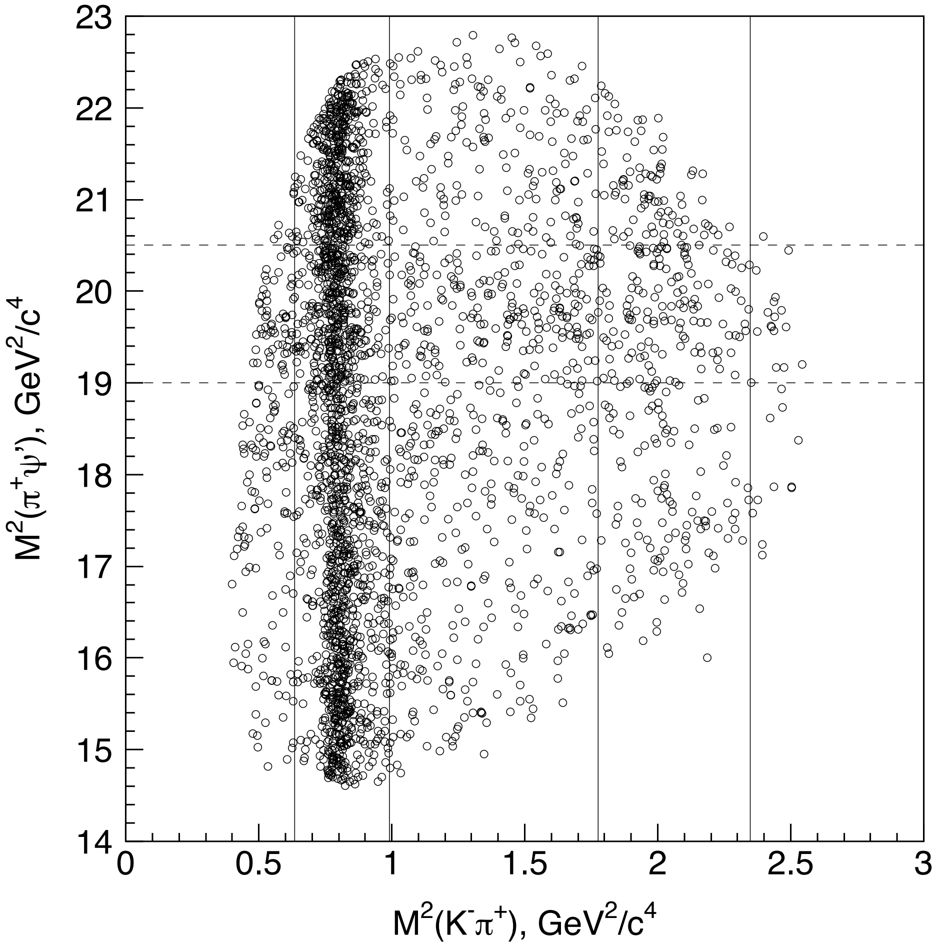
  - Strong threshold effects:

strong interactions,
interplay of decay channels

Y. S. Kalashnikova PR D72, 034010 (2005)
E.van Beveren G. Rupp [arXiv:0811.1755v1]

$Z^+(4430)$

- **Belle**
  - Mass and Width
    $M(Z^+) = 4433 \pm 4 \pm 1$ MeV
    $\Gamma(Z^+) = 44^{+17\ +30}_{-13\ -11}$ MeV
  - Decay Modes
    $Z^+(4433) \rightarrow \pi^+ + \psi(2S)$
  - Updated analysis [arXiv:0905.4313] confirmed 6.4 sigma

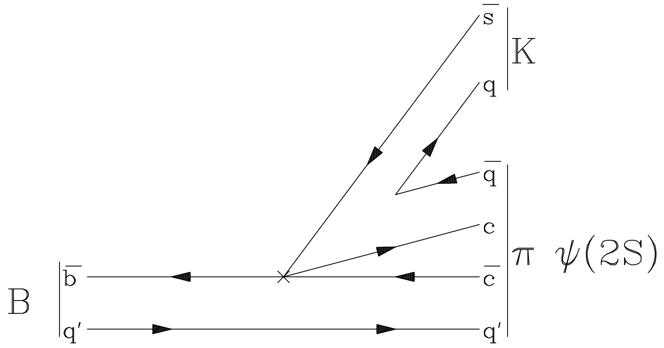


- **BaBar** [arXiv:0811.0564v1]
  - Not seen

- Tetraquark state (if confirmed)

Isospin multiplet

Possible production mechanism



J. Rosner PRD, 76, 114002 (2007)

☐ X(3872)

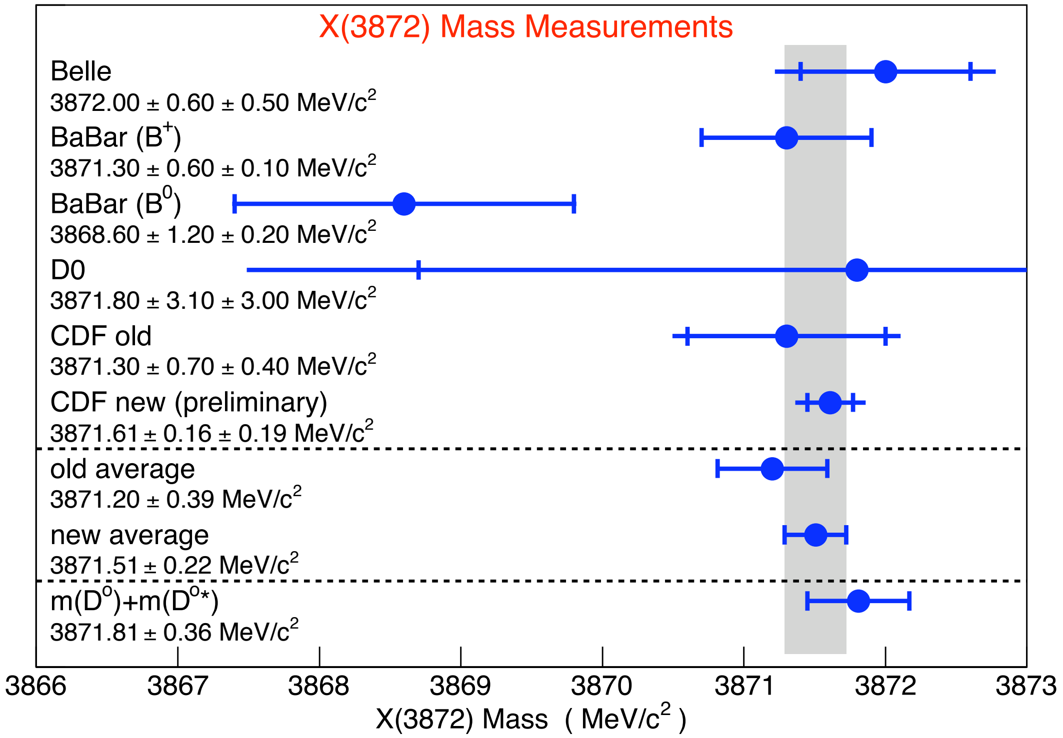
○ Mass

- At threshold within errors:
  M(X) = 3871.51±0.22 MeV (+CDF)
  $M(D^0) + M(D^{*0})$ = 3871.81±0.36 MeV (CLEO)

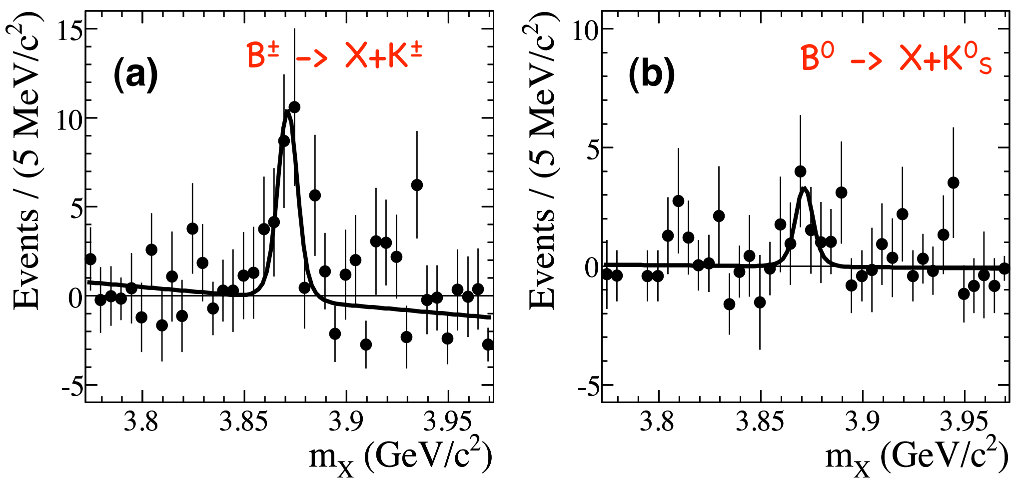
○ Decay Modes

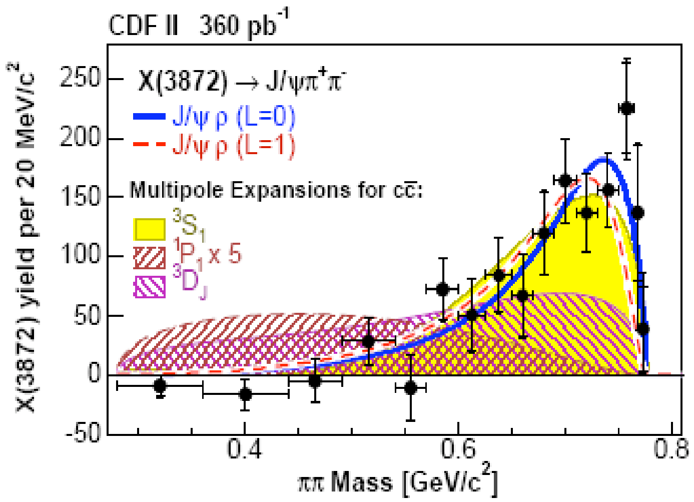
- X(3872) -> $\pi^+\pi^- + J/\psi$ (Γ_0) (ρ like)
  (Belle, CDF, D0, BaBar)
- Γ(X(3872)->` ω`+J/ψ)/Γ_0 = $1.0\pm0.4\pm0.3\,^{+2.3}_{-3.0}$
  ⇒ Isospin violating large (Belle)
- $\Gamma(X(3872)\to\Upsilon+J/\psi)/\Gamma_0 = 0.14\pm0.05$
  ⇒ C=+1 (Belle, BaBar)
- $\Gamma(X(3872)\to\Upsilon+\psi')/\Gamma(X(3872)\to\Upsilon+J/\psi)$
  $= 3.4\pm1.4\,^{+1.2}_{-2.0}$ (BaBar)
  Compare 2^3P_1 (bb) ratio = 2.5±0.5
- $J^{PC} = 1^{++}$ Strongly favored (Belle, CDF)

CDF [note 9454]



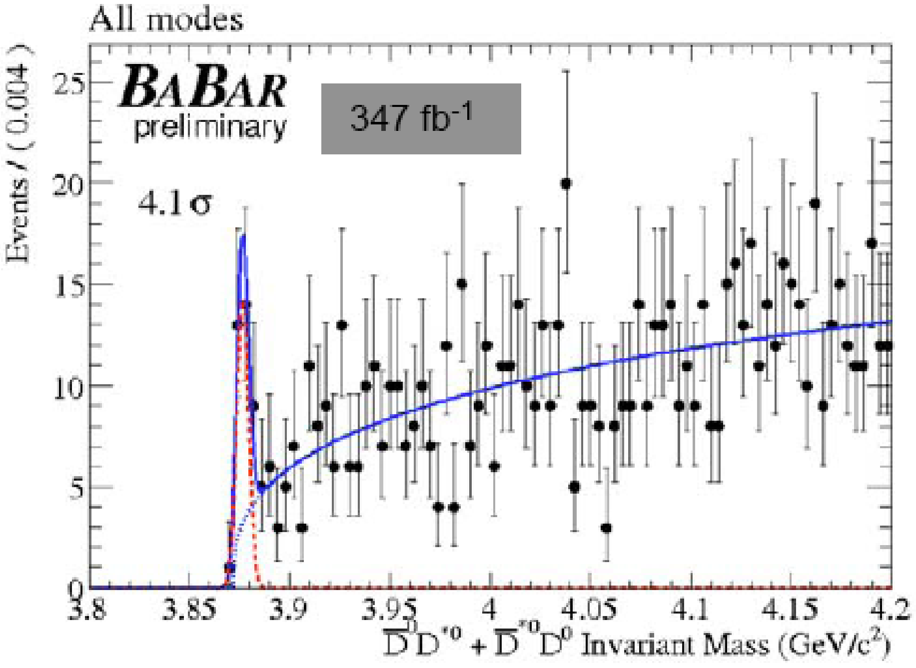
BaBar [arXiv:0809.0042v2] X->Υ+ψ'





Decay Modes (above threshold)

- $\Gamma(X(3875) \to D^0D^{*0}+D^{*0}D^0)/\Gamma_0 = 12.2 \pm 3.1 \, ^{+2.3}_{-3.0}$



BaBar:

$M = 3875.1 \, ^{+0.7}_{-0.5} \pm 0.7$ Mev/c^2

$\Gamma = 3.0 \, ^{+1.9}_{-1.4} \pm 0.9$ MeV

Belle:

$M = 3872.6 \, ^{+0.5}_{-0.4} \pm 0.4$ Mev/c^2

$\Gamma = 3.9 \, ^{+2.5}_{-1.3} \, ^{-0.8}_{-0.3}$ MeV

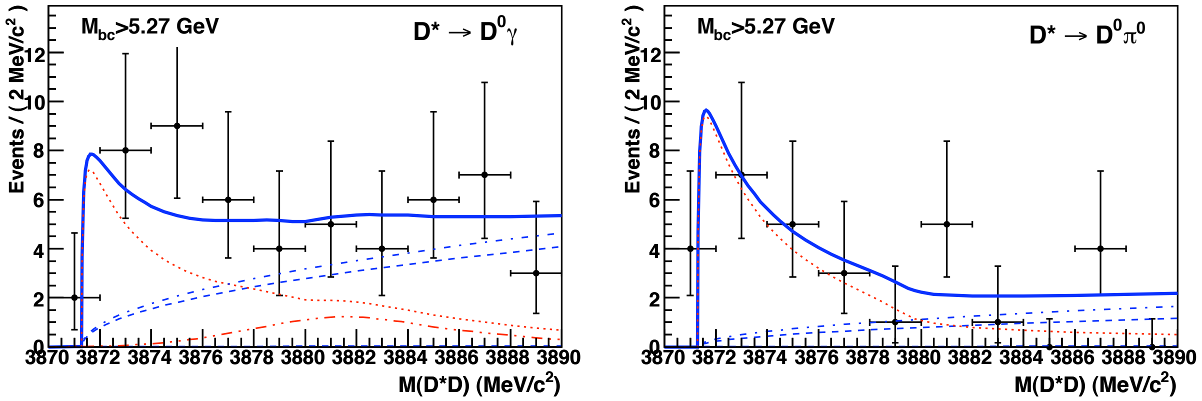


FIG. 4: Distribution of M_{D^*D} for $M_{\rm bc} > 5.27\,$GeV, for $D^{*0} \to D^0\gamma$ (left) and $D^{*0} \to D^0\pi^0$ (right). The points with error bars are data, the dotted curve is the Flatté distribution, the dashed curve is the background, the dash-dotted curve is the sum of the background and the $B \to D^*DK$ component, the dot-dot-dashed curve is the contribution from D^0–$\bar{D}^0$ reflections, and the solid curve is the total fitting function.

If its same state as the X(3872) ?

$\Gamma(X(3872) \to \Upsilon+\psi') \approx (5.7 \pm 1.6) \times 10^{-2} \Gamma(X(3875) \to D^0D^{*0}+D^{*0}D^0)$
$\approx 170 \pm 50$ keV

Same as the expected rate for the charmonium $2^3P_1 \to \Upsilon+\psi'$ transition !!

What is the X?

- Key feature X(3872) extremely close to threshold.

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

1864.847 ± 0.150 ± 0.095 MeV

CDF precise X mass measurement [CDF note 9454]

3871.61. ± 0.16 ± 0.19 MeV

$\Rightarrow M(X) - M(D^0) - M(D^{0*}) = -0.3 \pm 0.4$ MeV

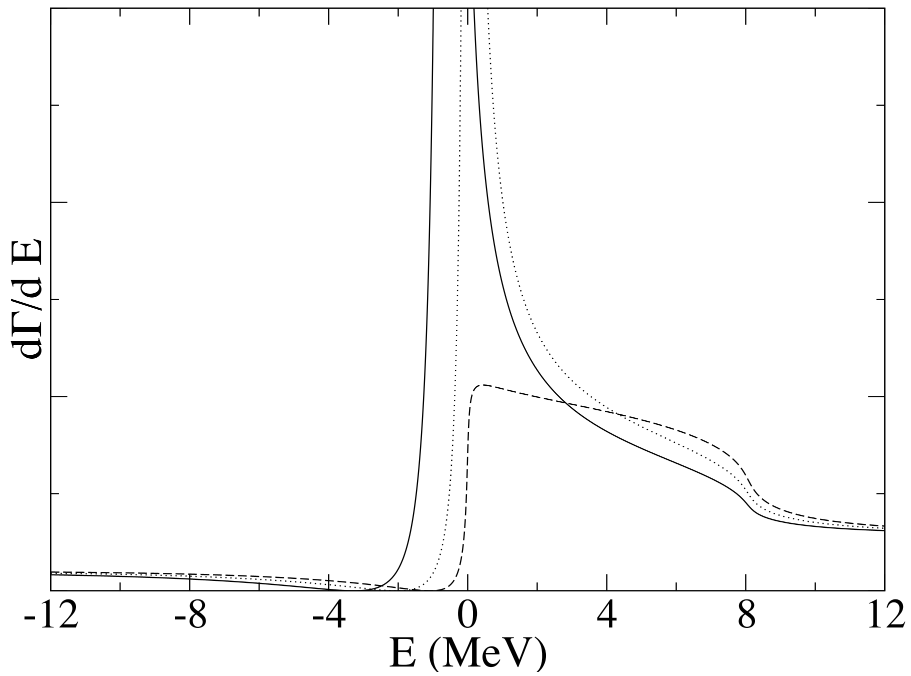
DD* "Binding Energy?":

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

- Options -Tetraquark state or Hybrid state highly improbable to be this near threshold.
- D^0D^{*0} molecule seemed the most likely possibility.
- Need to measure the line shape of the X in various production modes and decay channels to establish it's true mass.

Braaten and Lu [PR D 76:094028 (2007)]

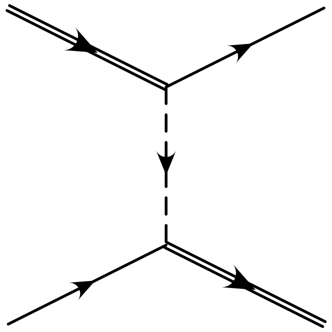
$B^0 \to K^0 + X$



Dependence of dΓ/dE on inverse scattering length γ

Revisiting the 2^3P_1 charmonium (χ'_{c1}) interpretation

- The binding of the "molecule" must come from short distance. The long range pion exchange force is weak.



$$\mu^2 = (m(D^{0*}) - m(D^0))^2 - m(\pi^0)^2$$

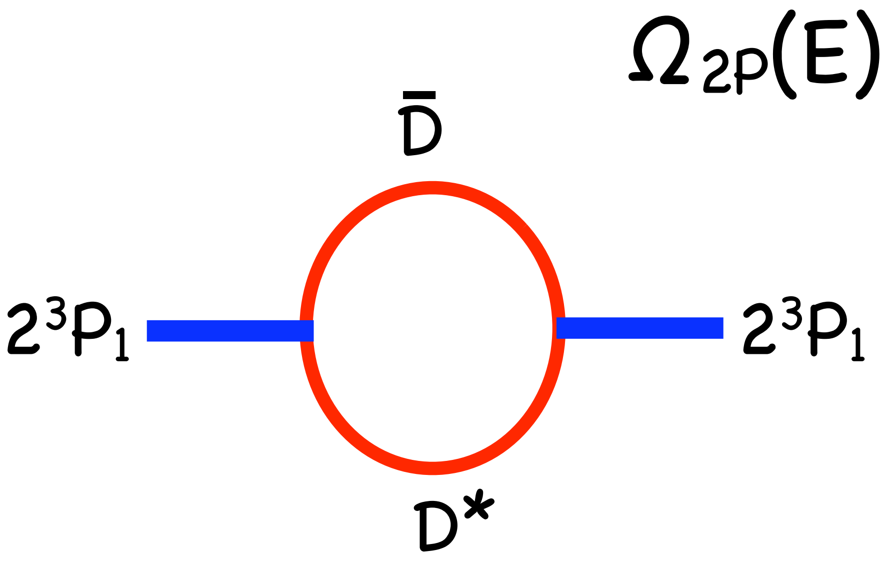
$$\frac{g^2}{2f_\pi^2}\,\frac{\vec{\epsilon}^{\,*}\cdot\vec{q}\,\vec{\epsilon}\cdot\vec{q}}{\vec{q}^{\,2}-\mu^2},$$

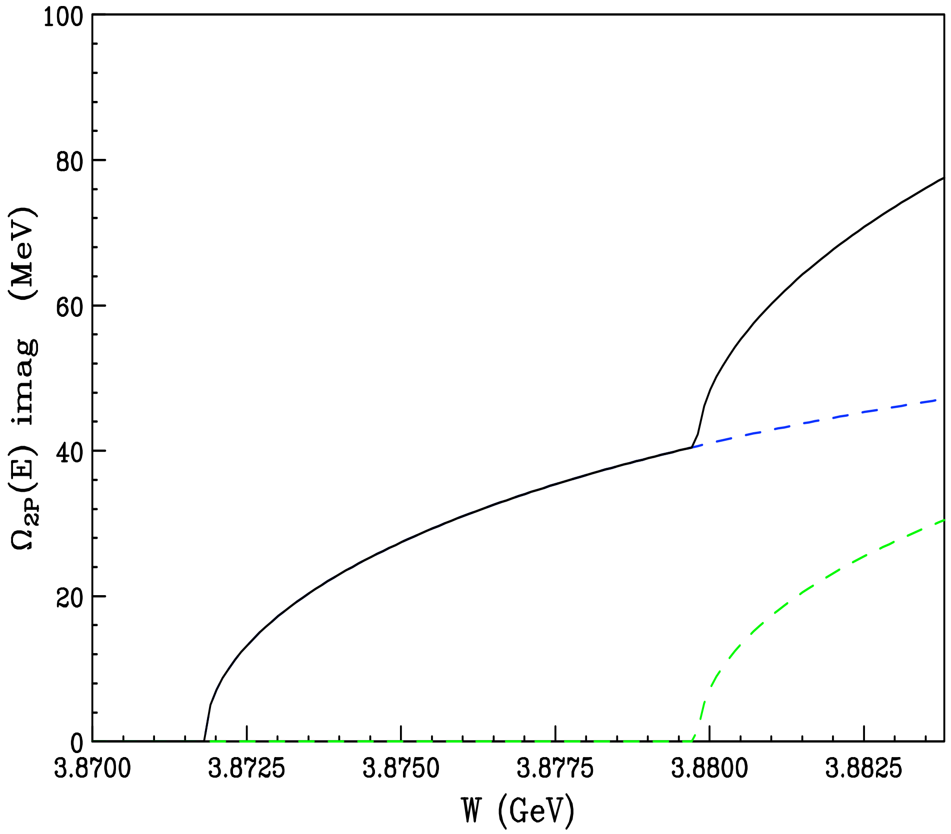
NN system $\frac{g_A^2 M_N m_\pi}{8\pi f_\pi^2} \approx \frac{1}{2}$

DD* system $\frac{g^2 M_{DD^*}\mu}{4\pi f_\pi^2} \approx \frac{1}{20} - \frac{1}{10}$

M. Suzukl PR D72, 114013 (2005)
S. Fleming, M. Kusunoki, T. Mehen and U. van Kolck PR D76, 034006 (2007)

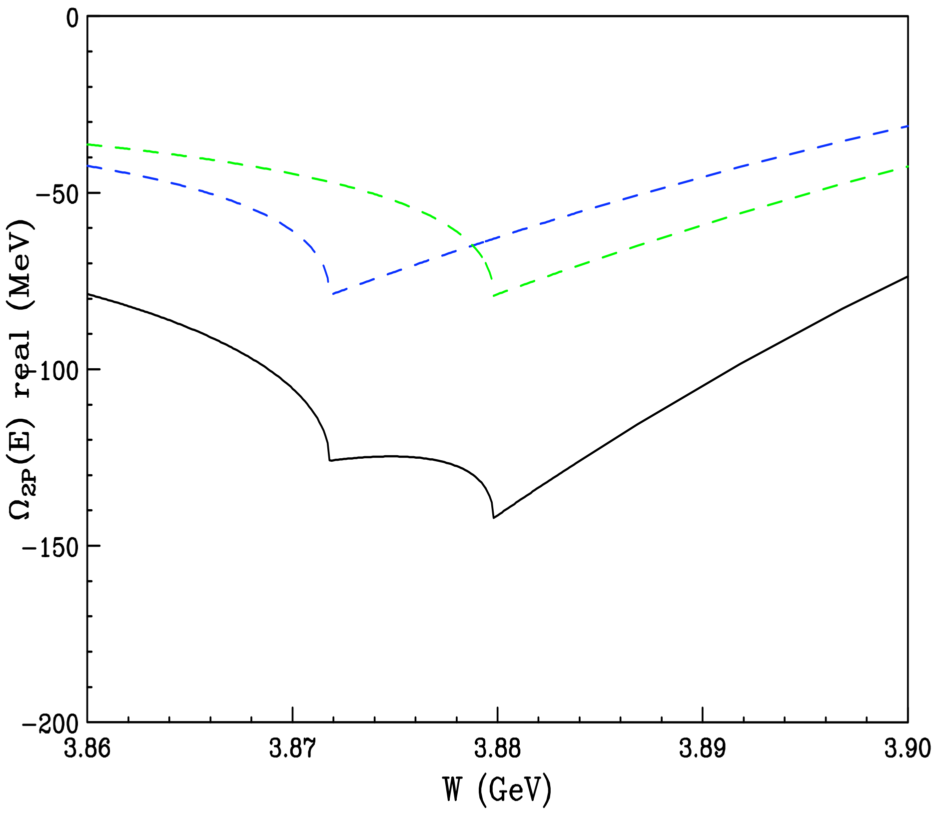
- The coupling between the 2^3P_1 state and the DD* final states is S-wave and strong. The $^3P_1$ states have no coupling to DD final state.

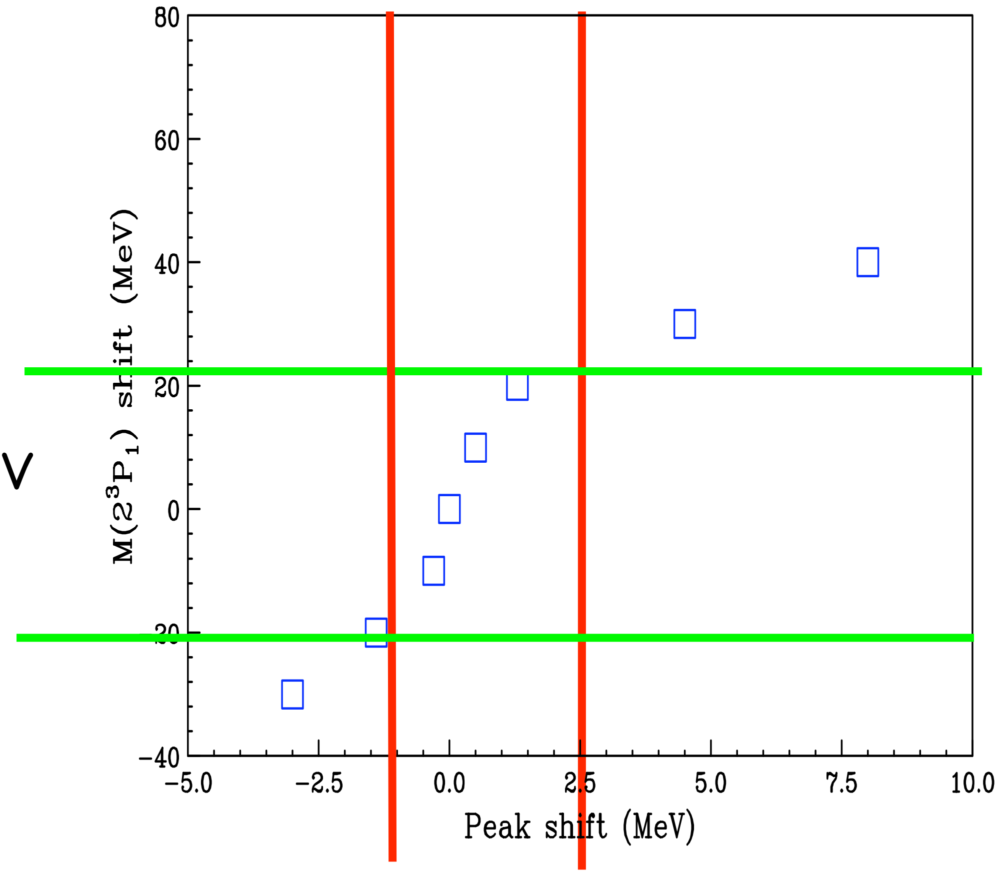




- The photon transitions ratio to ψ' over J/ψ is naturally satisfied.
- What about the miracle of nearness to threshold? Dynamical Focusing !

Physical pole at E = [$M_0(2^3P_1)$ + real $\Omega(E)$].
Hence real $\Omega(E)$ shifts the 2^3P_1 pole position.





42 MeV

4 MeV

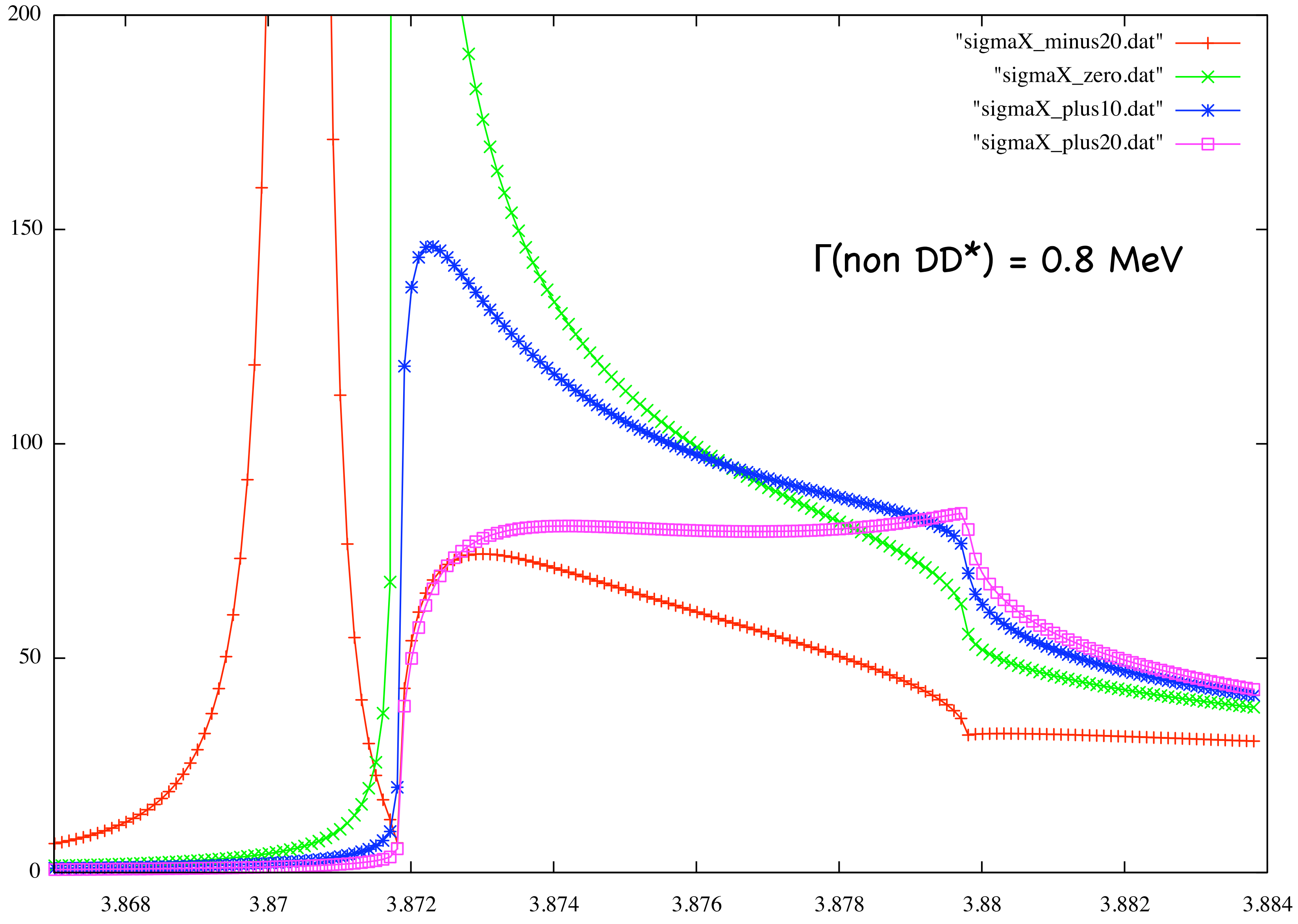
The large and rapid energy dependence
near DD* threshold

⇒

More than 10:1 dynamically focusing

Assuming no D^0D^{*0} binding other than its coupling to charmonium $^3P_1$ states

$\sigma(B \to X\ K)/f_a^2$



lineshape

Produces the same behaviour as expected for “molecule” interpretation.

- General conditions require a nearby QQ state with appropriate J^{PC} for which:
  (a) Strong decay into two very narrow hadrons;
  (b) S-wave threshold;
  (c) $|M_S$ - M(threshold)$| < \Gamma_S$.

- Remaining issue is the induced isospin breaking (from D^+ - D^0 mass difference) is about 6%. This implies a large implied decay partial rate to omega ω J/ψ (if not phase space suppressed). We also see this in the Υ(5S) -> ππ J/ψ decays. Are the mechanisms related?

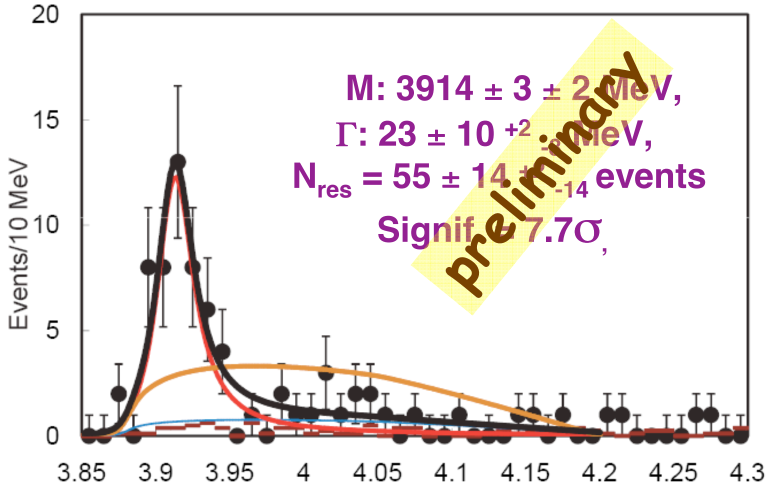
- Comments:
  (a) compare $D^{0*}D^0/D^+D^{*-}$ channels just above D^+D^{-*} threshold.
  (b) look for ππ 1^3P_1 decay. S. Dubynskiy, M. B. Voloshin PR D77, 014013 (2008)
  (c) unlikely to see an BB* molecule. (the P states are too far away).

☐ C=+1 states in the Y(3940) and Y(4160) mass regions.

Two new states seen:

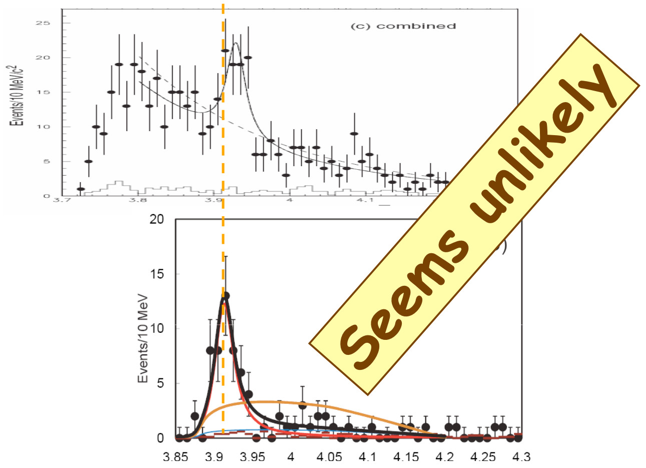
- new structure observed by Belle:
  - Produced in γγ ($J^{PC}=0^{++},2^{++}$)
  - Observed in the decay mode ω+J/ψ
  - Near the Z(3930) previously observed by Belle in the γγ channel via the DD decay mode. [2^3P_2 (cc) state]
- Y(4140) discovery at CDF
  - Mass = 4143 ± 2.9 ± 1.2 MeV
  - Width = 11.7 $^{+8.3}_{-5.0}$ ± 3.7 MeV
  - Produced in B decays
  - Observed in the decay mode ϕ+J/ψ
  - Near the Y(4160) previously observed by Belle in e^+e^- (recoil against J/ψ).

Olsen talk at Charm 2009

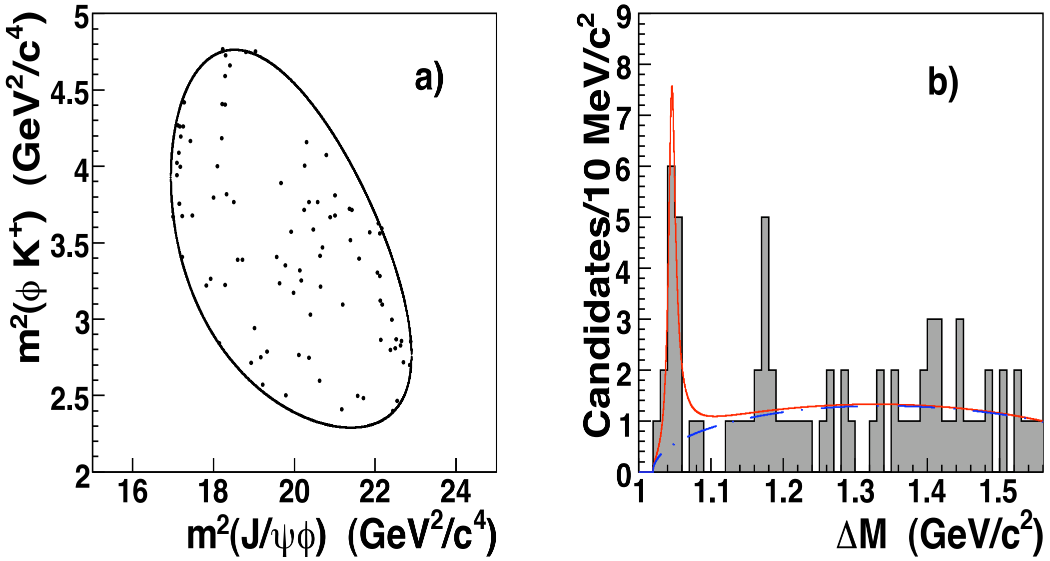


preliminary

Could it be the Z(3930)?



Seems unlikely

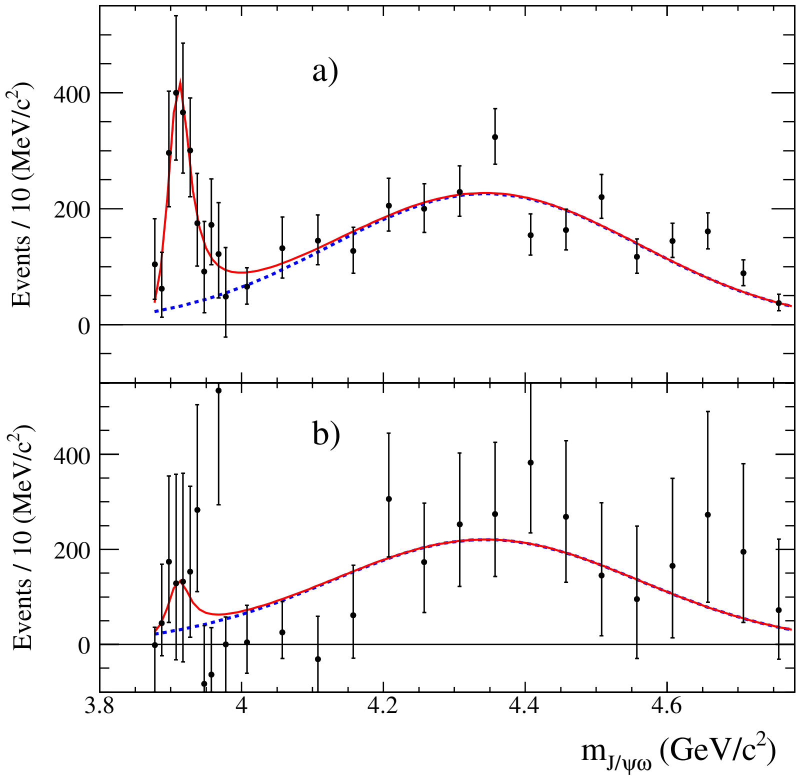


Plus the previously observed states:

- Y(3940)
  - Belle discovery in B decays confirmed by BaBar.

	Belle	BaBar	
Mass =	3943 ± 11;	$3914.6 \, ^{+12}_{-8} \pm 5.0$	MeV
Width =	83 ± 22;	$39 \, ^{+3.8}_{-3.4} \pm 2.0$	MeV

  - Decay mode ω+J/ψ



- X(3940)
  - Mass = $3942 \, ^{+7}_{-6} \pm 6$ MeV
  - Width = $37 \, ^{+26}_{-15} \pm 8$ MeV
  - Produced in e^+e^- (recoil against J/ψ)
  - Observed in the decay mode DD*

Disentangling these states

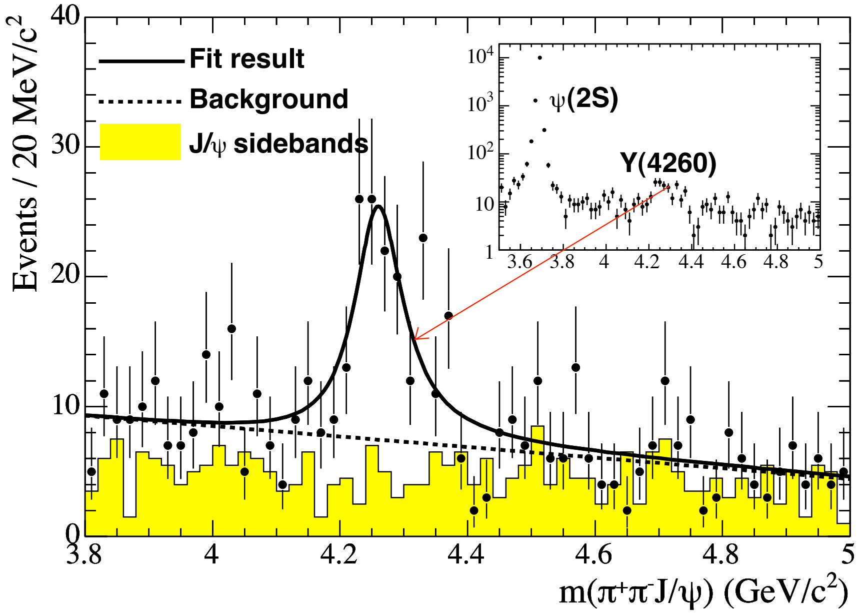
- In the 3940 region the Z(3930) is the 2^3P_2 charmonium state. The remaining 2^3P_0 and 2^3P^1 are not clearly identified yet. In the 4160 region, may have the 3^3P_0 or 3^1S_0 states. Identifying the J^P of the observed states will be very useful.
- The η_c is produced copiously in B decays. Should observe the 3^1S_0 state.
- Using the observed production of narrow charmonium states, we expect large production of $J^{PC} = 0^{++}, 0^{--}$ states recoiling against J/ψ in e+e- and $J^{PC} = 0^{-+}, 1^{--}, 1^{++}$ in B decays X+K.
- There is an observed pairing of nearby states. One is seen in the decay mode light hadrons + J/ψ and the other in charm meson pair decays. Is this like the X(3872) case? If true both states must have the same J^{PC}.

S : D wave thresholds for P states.

J^{PC}	QQ	H H	H H*	H* H*
0^{++}	$^3P_0$	1 : 0	0 : 0	1/3 : 8/3
1^{++}	$^3P_1$	0 : 0	4/3 : 2/3	0 : 2
2^{++}	$^3P_2$	0 : 2/5	0 : 6/5	4/3 : 16/15

State	D D	D D*	D* D*
X(3930)	Γ(DD) ≈ 37 MeV	Γ(DD*) not seen	not allowed
X(3940)	Γ(DD) not seen	Γ(DD*) ≈ 29 MeV	not allowed
Y(4160)	Γ(DD)/Γ(D*D*) < 0.09	Γ(DD*)/Γ(D*D*) < 0.22	Γ(D*D*) ≈ 140 MeV

Y(4260) and the 1^{--} states beyond



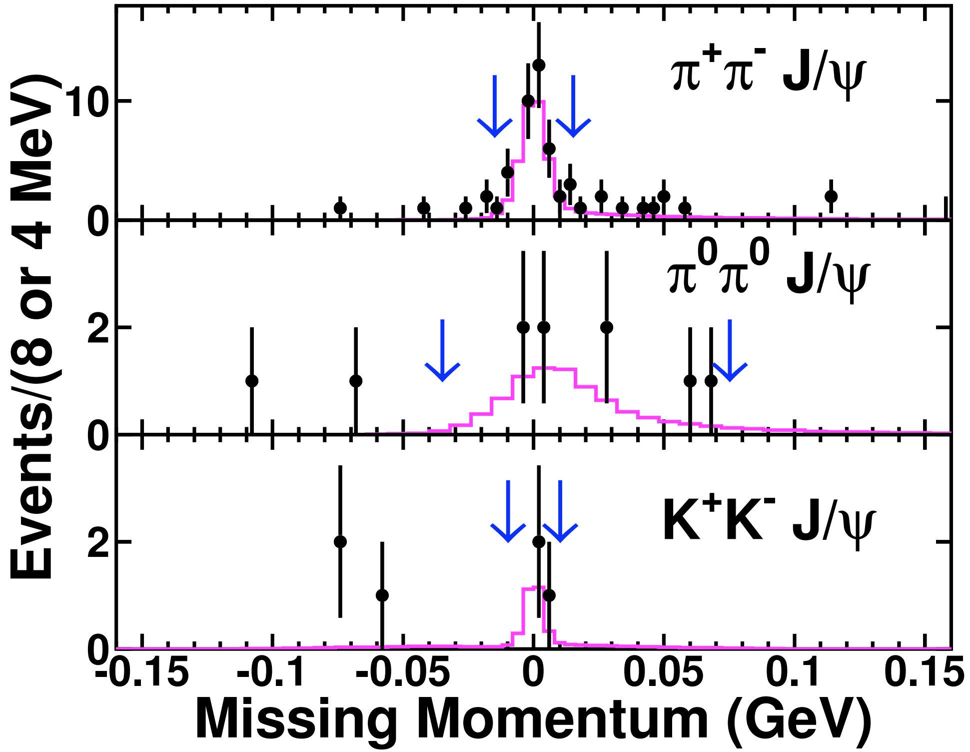
- Y(4260)

  Seen by BaBar in ISR production
  confirmed by CLEO and Belle ⇒ $J^{PC} = 1^{--}$

  Mass = $4264 \pm^{10}_{12}$ MeV; Width = $83 \pm^{20}_{17}$ MeV

  - Decays
    - Y(4260) -> $\pi^+\pi^- + J/\psi$ (BaBar, CLEO, Belle)
    - Y(4260) -> $\pi^0\pi^0 + J/\psi$ (CLEO)
    - Y(4260) -> $K^+K^- + J/\psi$ (CLEO)

    consistent with I = 0
  - Not a charmonium state
    - Small ΔR - 4^3S_1 state at 4.26 would have ΔR≈2.5
    - 1^3D_1 state ψ(4160)



T. E. Coan, et al. PRL **96**:162003 (2006)

X(4008)

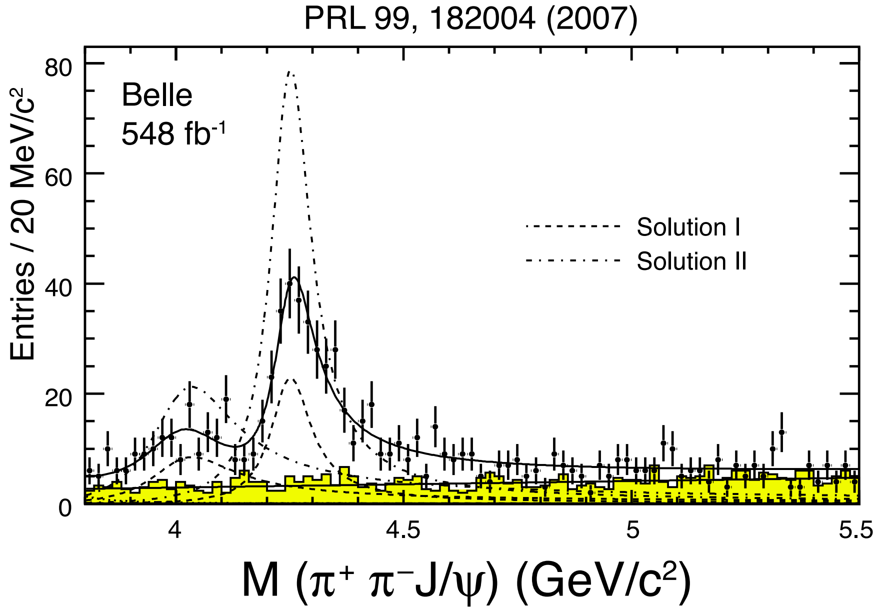
Mass = $4008 \pm 40 ^{+72}_{-28}$ MeV/c^2

Width = $226 \pm 44 ^{+87}_{-79}$ MeV

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

Seen by **Belle** in $\pi^+\pi^- + J/\psi$ final state

Not confirmed by **BaBar [arXiv:0808.1543v2]**


PRL 99, 182004 (2007)

Y(4350)

Mass = $4361 \pm 9 \pm 9$ MeV/c^2

Width = $74 \pm 15 \pm 10$ MeV

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

Seen by**BaBar, Belle** in $\pi^+\pi^- + \psi(2S)$ final state

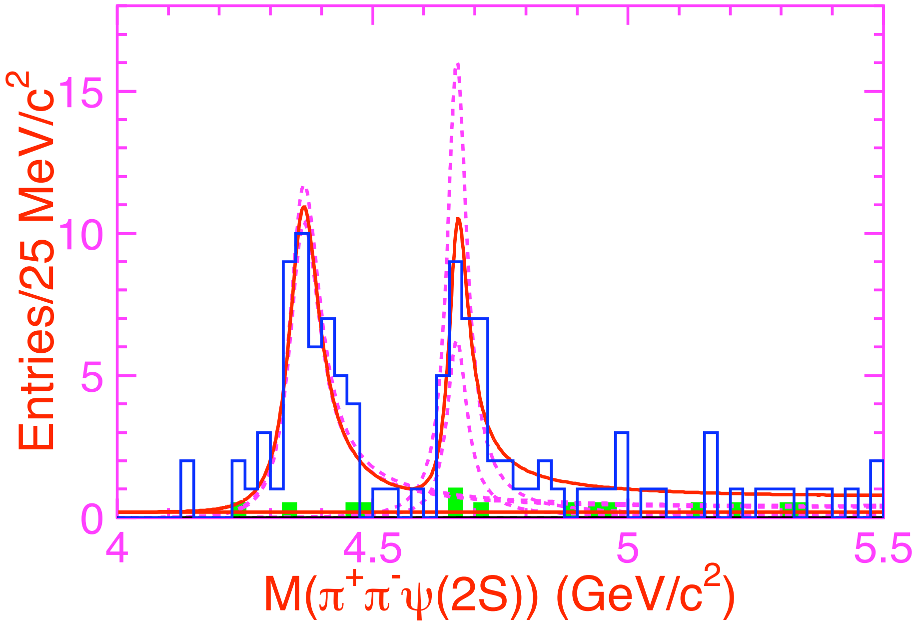
Y(4660)

Mass = $4664 \pm 11 \pm 5$ MeV/c^2

Width = $48 \pm 15 \pm 3$ MeV

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

Seen by **Belle** in $\pi^+\pi^- + \psi(2S)$ final state

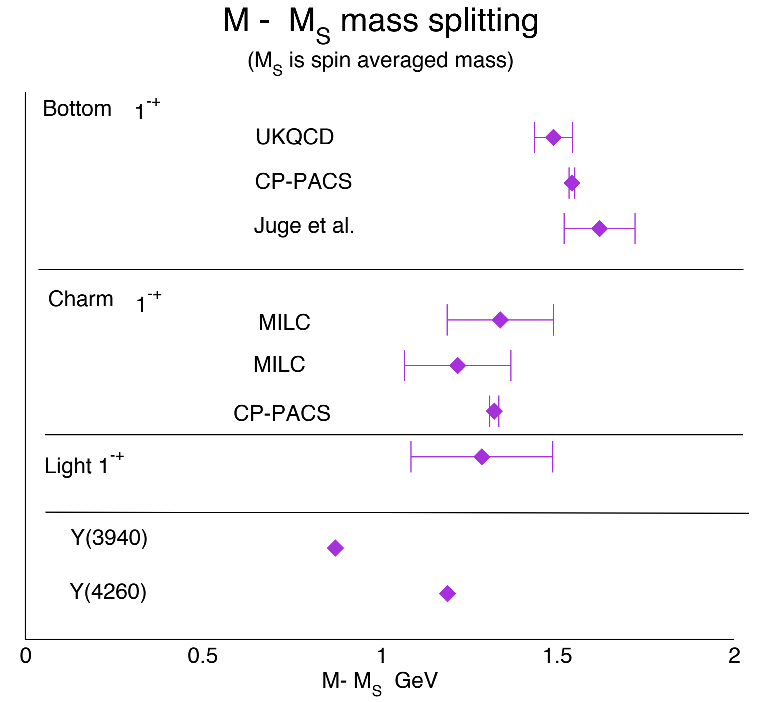


X. L. Wang, et al. PRL **99**:142002 (2007)

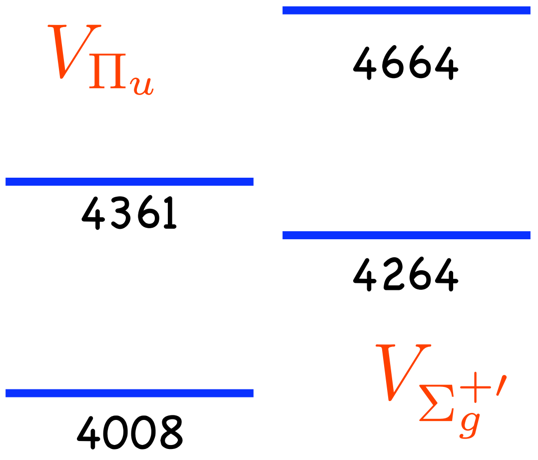
What are the Y(4260), Y(4350) and Y(4660)?

- Various options - see Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E. [Rev. Mod. Phys. 80, 1161 (2008)]

McNeile ICHEP 2006



- One attractive possibility - hybrid states
  - Lattice calculations put states in this region
  - The Y(4660) state could be the first radial excitation of the charm quarks from the ground state Y(4260) (analog of ψ′ to J/ψ). This would naturally explain its preference for decays to ππ+ψ′.
  - Similarly, the Y(4360) would the radial excitation of the charm quarks from a ground state X(4008).
  - Heavy quark spin symmetry: 1^{--} -> 0^{-+}, 1^{-+}, 2^{-+} states nearby (for Π_u potential)
  - How many states would be narrow?



Summary and Outlook

- The wealth of precision data has solidified our confidence in the NRQCD approach
  - The velocity expansion for the spectrum and the multipole expansions for both electromagnetic and hadronic transitions hold up well.
  - Relativistic corrections: Significant relativistic for the cc system. Reduced for the bb system. Generally consistent with velocity scaling expectations. Here phenomenological models inadequate. Need lattice QCD and pNRQCD.
  - Quarkonium resonances have been used as factories:
    - $\Upsilon(4S)$, $\Upsilon(5S)$ - $B^{\pm}$, B^{0}, $B_s^{\pm}$ studies
    - $\psi(3772)$ - $D^{\pm}$, D^{0} studies
    - $\psi(4160)$ - $D_s^{\pm}$ studies
    - J/ψ, ψ', Υ, Υ'',... - direct decays

- The situation above threshold is not yet clear:
  - Need J^P determination for many of the new states.
  - New states and possibly a new spectroscopy: X(3872), X(4008), Y(4140), Y(4260), Y(4350), Y(4660), Z^+(4430), ...
    - X(3872) large 2^3P_1 component. Molecular interpretation less attractive. Strong decay dynamics plays an important role. Look for decay mode $\pi\pi\chi_{c1}$
    - The states in the 3940 and 4160 regions also seem paired. A signal of decay dynamics in the $J^{PC} = 2^{++}, 0^{++}$ (2^3P_J), and/or the 0^{-+} (3^1S_0) channels? Any relation to unexpectedly large hadronic transition rates:
      $\Upsilon(5S) \to \Upsilon(nS) + 2\pi$ (n=1,2,3) ?
    - The Y(4260) and related 1^{--} new states. Hybrid states?
    - [If confirmed] Z^+(4430) smoking gun for four quark states. Not I=0. Look for isospin partners.
- Future prospects
  - NRQCD and HQET allows scaling from c to b systems. This will eventually provide critical tests of our understanding of new charmonium states.
  - Lattice calculations will provide insight into theoretical issues.
  - Answers in many cases will require the next generation of heavy flavor experiments - BES III, LHCb and Super-B factories.

Extra Slides

- # Charm Meson Pair Thresholds

L=0 $c\bar{q}\ [j_l^P = \frac{1}{2}^-]$

Meson	Mass (MeV/c^2)	Width (eV)
D^0	1864.84 ± 0.17	$(1.60 \pm 0.01) \times 10^{-3}$
D^+	1869.62 ± 0.20	$(6.33 \pm 0.04) \times 10^{-4}$
D_s^+	1968.49 ± 0.34	$(1.32 \pm 0.02) \times 10^{-3}$
D^{*0}	2006.97 ± 0.19	77×10^3 [21]
D^{*+}	2010.27 ± 0.17	$(96 \pm 4 \pm 22) \times 10^3$
D_s^{*+}	2112.3 ± 0.5	440 [21]

L=1 $c\bar{q}\ [j_l^P = \frac{1}{2}^+]$

Meson (J^P)	Mass (MeV/c^2)	Width (MeV)
$D^{*0}(0^+)$	2352 ± 50	261 ± 50
$D^{*+}(0^+)$	2403 ± 38	283 ± 42
$D_s^{*+}(0^+)$	2317.8 ± 0.6	0.023 [21]
$D^0(1^+)$	2427 ± 35	$384\ ^{+130}_{-105}$
$D^+(1^+)$	2427 (a)	384 (a)
$D_s^+(1^+)$	2459.6 ± 0.6	0.038 [21]

$c\bar{q}\ [j_l^P = \frac{3}{2}^+]$

Meson (J^P)	Mass (MeV/c^2)	Width (MeV)
$D^0(1^+)$	2422.3 ± 1.3	20.4 ± 1.7
$D^+(1^+)$	2423.4 ± 3.1	25 ± 6
$D_s^+(1^+)$	2535.35 ± 0.6	0.29 (a)
$D^{*0}(2^+)$	2461.1 ± 1.6	42 ± 4
$D^{*+}(2^+)$	$2460.1\ ^{+2.6}_{-3.5}$	37 ± 6
$D_s^{*+}(2^+)$	2572.6 ± 0.9	20 ± 5

Narrow Thresholds

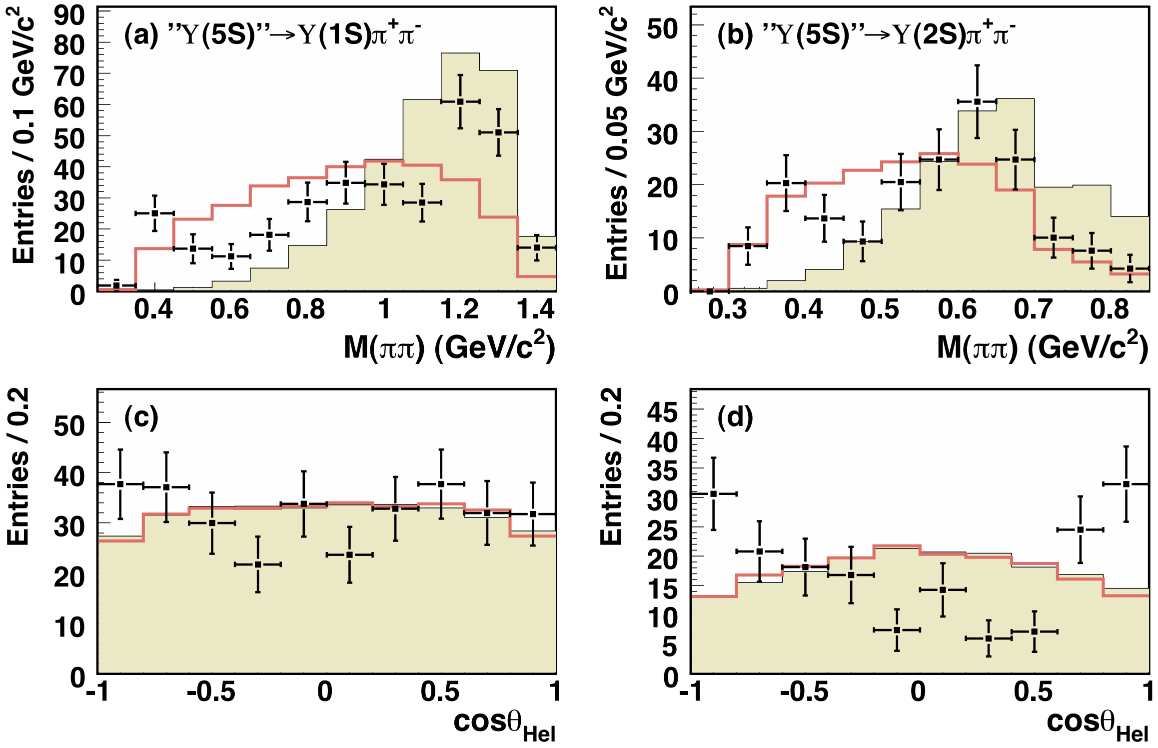
$D\bar{D}$	3729.7(+9.56)	P-wave
$D\bar{D}^* + D^*\bar{D}$	3,871.8(+8.08)	
$D_s\bar{D}_s$	3,937.0	
$D^*\bar{D}^*$	4,013.9(+6.6)	
$D_s\bar{D}_s^* + \bar{D}_sD_s^*$	4,080.8	
$D_s^*\bar{D}_s^*$	4,224.6	
$D\bar{D}(1^+) + D(1^+)\bar{D}$	4,287.1(+5.9)	D-wave
$D\bar{D}(2^+) + D(2^+)\bar{D}$	4,325.9(+3.8)	
$D^*\bar{D}(1^+) + D(1^+)\bar{D}^*$	4,429.3(+4.4)	
$D^*\bar{D}(2^+) + D(2^+)\bar{D}^*$	4,468.1(+2.3)	
$D_s\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s$	4,428.1	S-wave
$D_s^*\bar{D}_s(0^+) + D_s(0^+)\bar{D}_s^*$	4,430.1	
$D_s^*\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s^*$	4,571.9	
$D_s\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s$	4,540.9	D-wave
$D_s\bar{D}_s(2^+) + D_s(2^+)\bar{D}_s$	4,541.1	
$D_s^*\bar{D}_s(1^+) + D_s(1^+)\bar{D}_s^*$	4,647.7	
$D_s^*\bar{D}_s(2^+) + D_s(2^+)\bar{D}_s^*$	4,684.9	
$\cdots$		

wide $D^*D(0^+), D^{(*)}D'(1^+), \ldots$ S-wave

New Belle Measurements - [hep-ex/0710.2577]
$\Upsilon(5S) \to \pi^+\pi^- + \Upsilon(nS)$ (n=1,2,3)

Process	N_s	Σ	Eff.(%)	σ(pb)	$\mathcal{B}$(%)	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	325^{+20}_{-19}	20σ	37.4	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	186 ± 15	14σ	18.9	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$10.5^{+4.0}_{-3.3}$	3.2σ	1.5	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$20.2^{+5.2}_{-4.5}$	4.9σ	20.3	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.061^{+0.016}_{-0.014} \pm 0.010$	$0.067^{+0.017}_{-0.015} \pm 0.013$

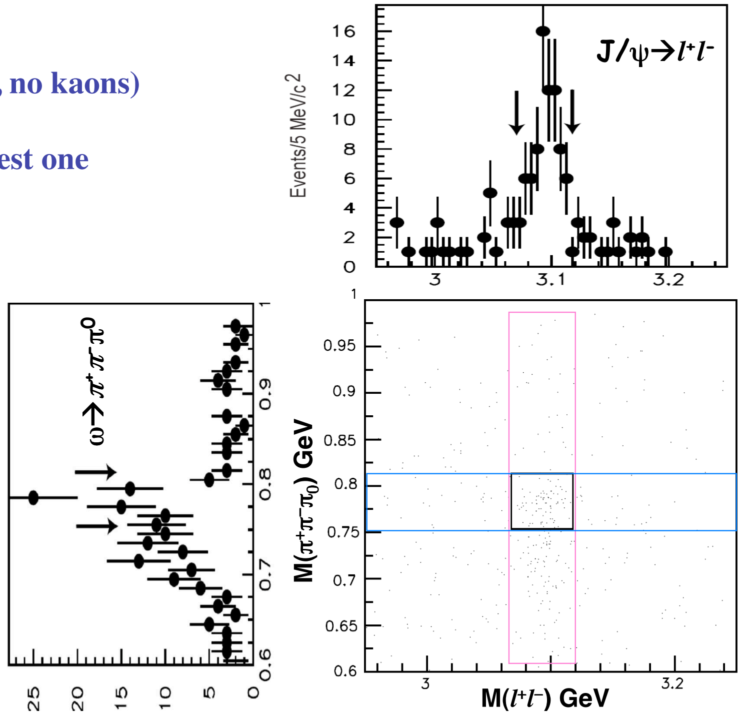
- Large partial rates.
  Continuum $e^+e^- \to \pi\pi\Upsilon(nS)$ background not subtracted.



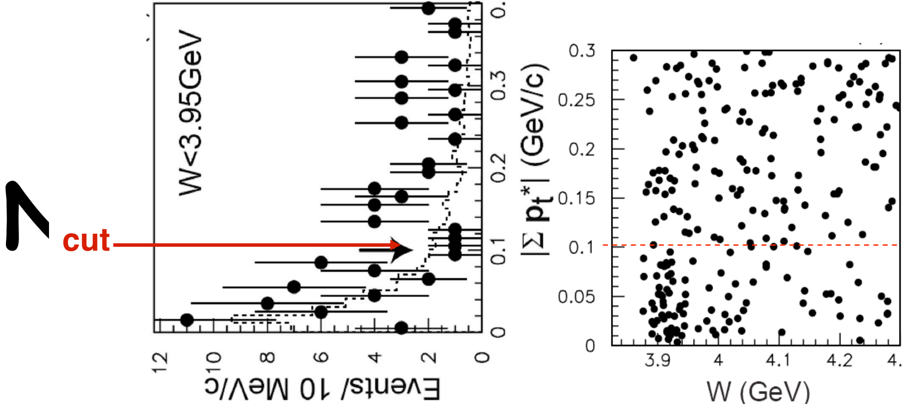
- M(ππ) and angular distribution.
  Compare to $\Upsilon(4S)$.

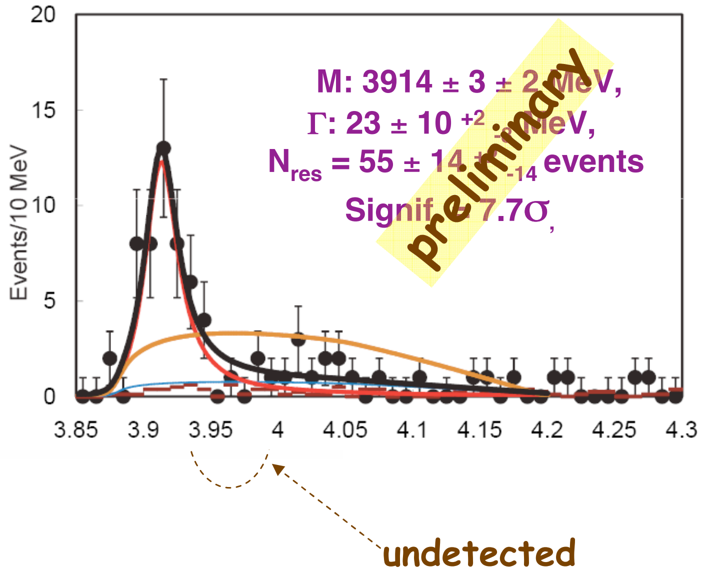
$M(\pi^+\pi^-\pi^0)$ *vs* $M(l^+l^-)$

- 4 trks (≥1 lepton, no kaons)
- $\Sigma q_i = 0$
- ≥1 π^0 ← select best one
- veto $\psi' \to \pi^+\pi^- J/\psi$
- W<4.3 GeV
- $\Sigma \vec{p}_T < 0.1$GeV
- …



$\Sigma \vec{p}_T$ *vs* W





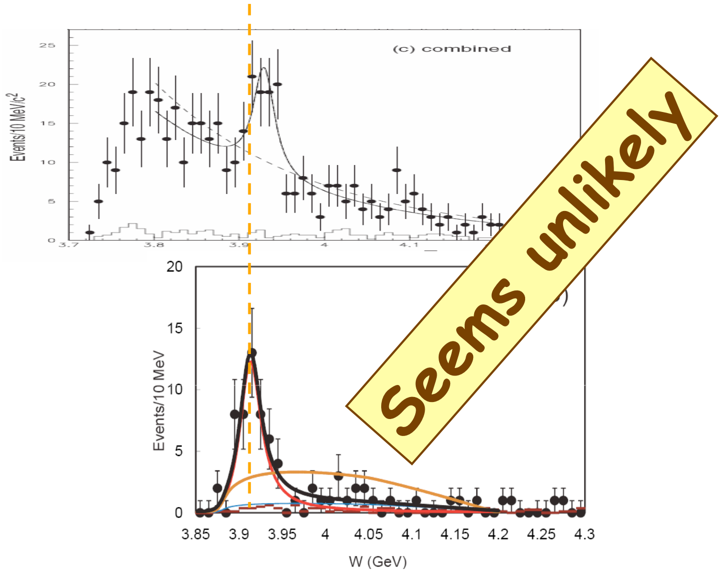
M: 3914 ± 3 ± 2 MeV,

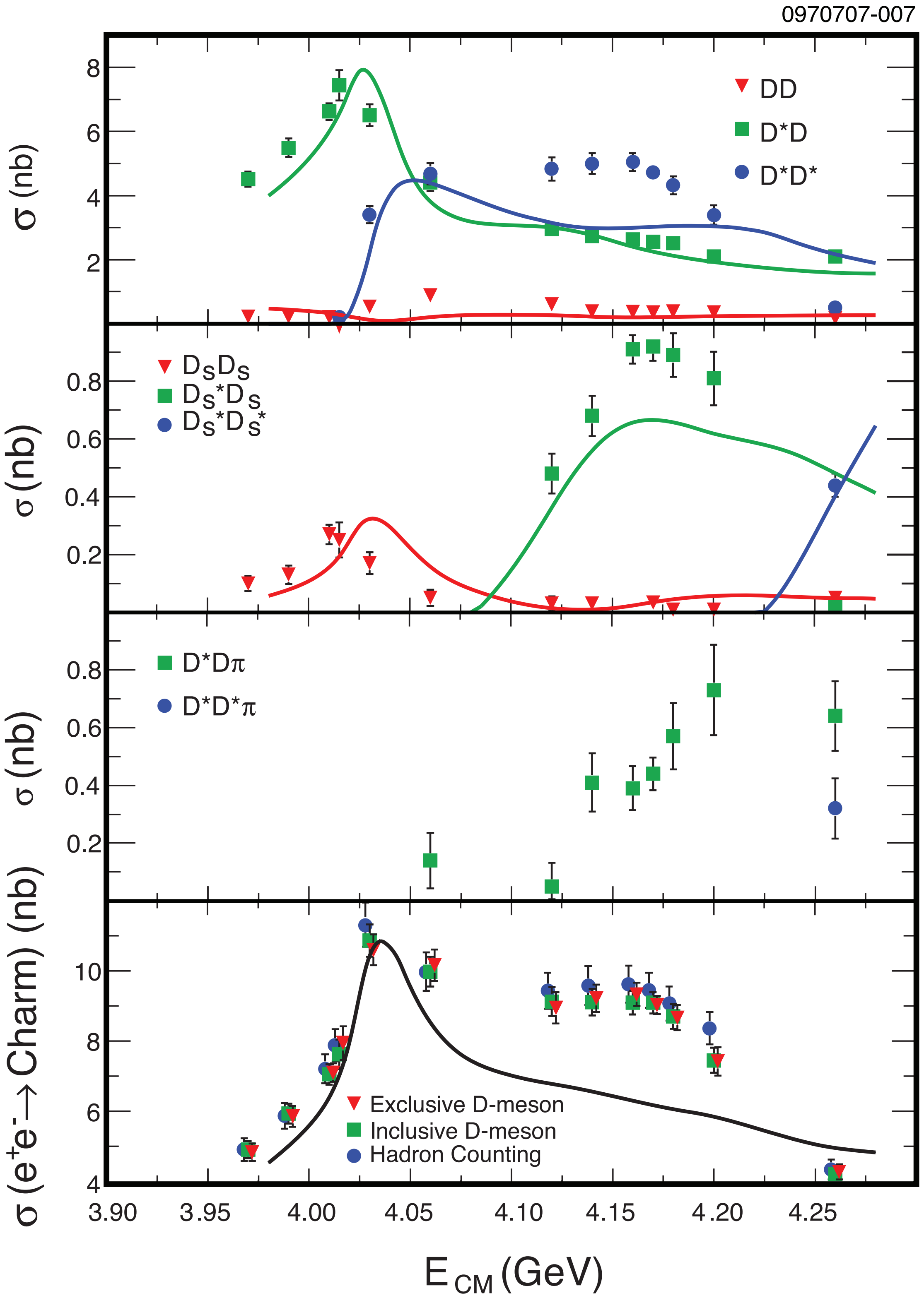
Γ: 23 ± 10 $^{+2}_{-8}$ MeV,

N_{res} = 55 ± 14 $^{+2}_{-14}$ events

Signif = 7.7σ,

Could it be the Z(3930)?



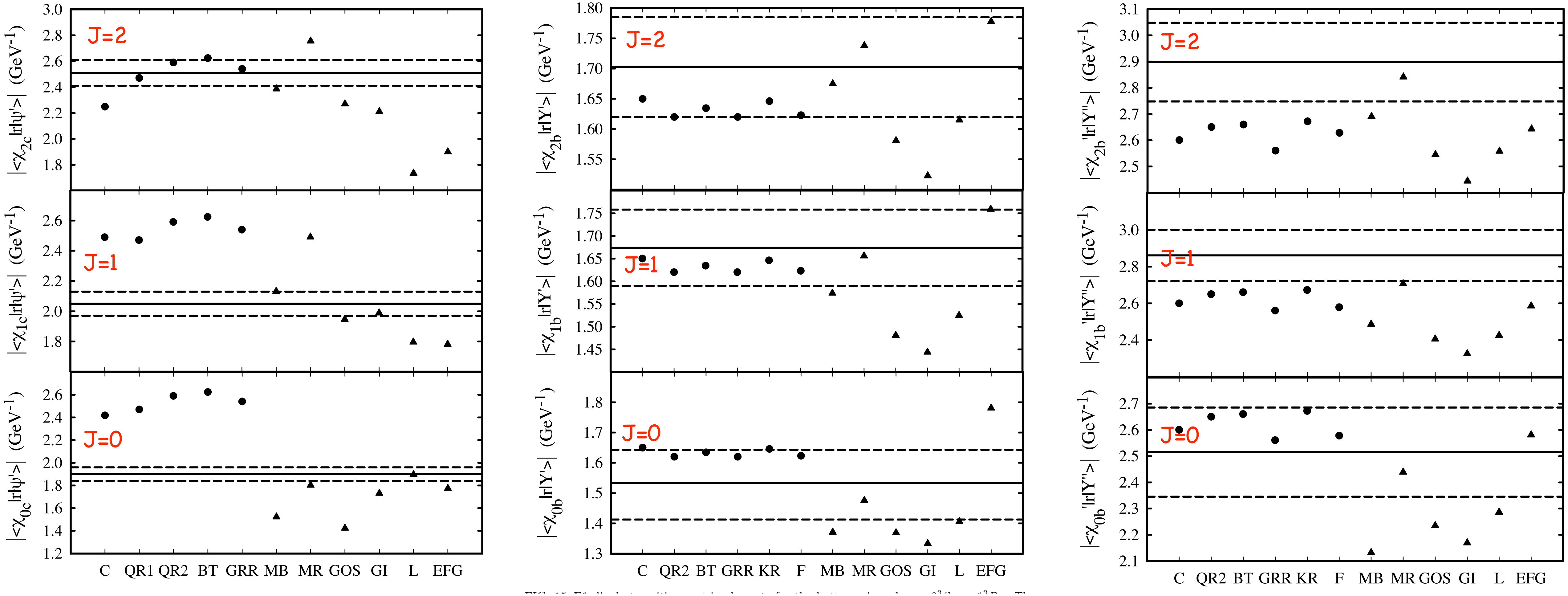

0970707-007
σ (nb)
8
6
4
2
DD
D*D
D*D*
σ (nb)
0.8
0.6
0.4
0.2
D_sD_s
$D_s{}^*D_s$
$D_s{}^*D_s{}^*$
σ (nb)
0.8
0.6
0.4
0.2
D*Dπ
D*D*π
$\sigma\,(e^+e^- \to \mathrm{Charm})$ (nb)
10
8
6
4
Exclusive D-meson
Inclusive D-meson
Hadron Counting
3.90
3.95
4.00
4.05
4.10
4.15
4.20
4.25
E_{CM} (GeV)

S states -> P states

$\mathcal{E}_{if}$

- Generally good agreement with NR MPE
- Relativistic corrections 10%-20% effects in cc system.
- Need better theoretical guidance.

State	$<\|r\|>$ (fm)	$<v^2>$
$c\bar{c}$		
J/ψ	0.32	0.26
$\chi_c(1P)$	0.57	0.24
$\psi(2S)$	0.70	0.29
$\psi(3770)$	0.78	0.28
$b\bar{b}$		
State	$<\|r\|>$ (fm)	$<v^2>$
$\Upsilon(1S)$	0.19	0.091
$\chi_b(1P)$	0.35	0.072
$\Upsilon(2S)$	0.44	0.086
$\Upsilon(1D)$	0.50	0.080
$\chi_b(2P)$	0.56	0.089
$\Upsilon(3S)$	0.63	0.100
$\Upsilon(4S)$	0.80	0.116



$2^3S_1 \to 1^3P_J$ ($c\bar{c}$)

$2^3S_1 \to 1^3P_J$ ($b\bar{b}$)

$3^3S_1 \to 2^3P_J$ ($b\bar{b}$)

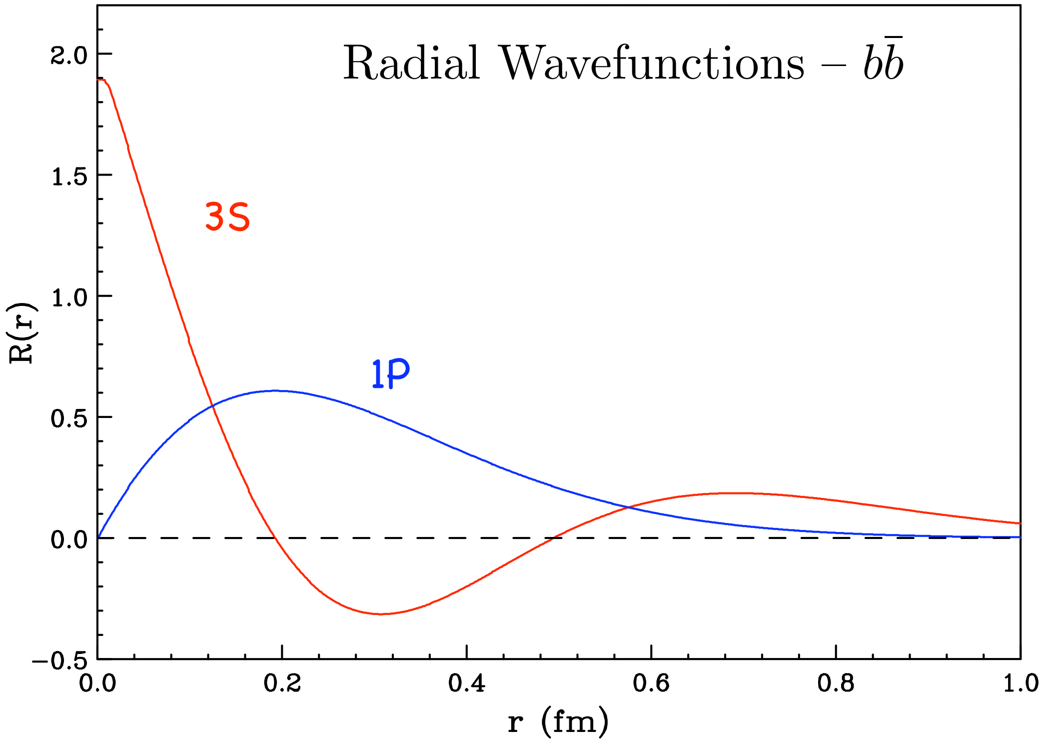
Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E. [Rev. Mod. Phys. 80, 1161 (2008)]

- 3^3S_1 -> 1^3P_J transition dynamically suppressed. Rate very sensitive to relativistic corrections.

$$\begin{aligned} \mathcal{E}(3^3S_1, 1^3P_0) &= 0.067 \pm 0.012 \text{ GeV}^{-1} \\ <\mathcal{E}(3^3S_1, 1^3P_J)>_J &= 0.050 \pm 0.006 \text{ GeV}^{-1} \\ J = (2,1,0) & \quad (0.097, 0.045, -0.015) \end{aligned}$$

Exp

GI Model

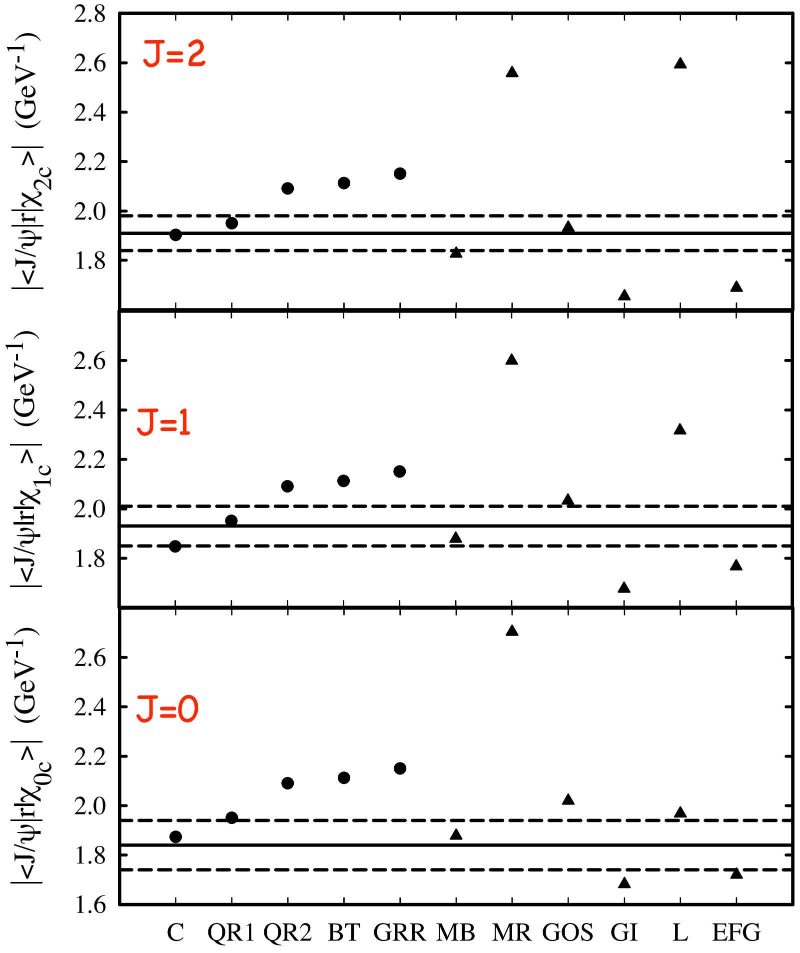


- nP -> mS transitions. Generally good agreement with NR predictions. Again better theoretical control for relativistic corrections needed

Table 1: Cancellations in $\mathcal{E}_{if}$ by node regions.

$b\bar{b}$	initial state node			
Transition	< 1	1 to 2	2 to 3	total
$2S \to 1P$	0.07	−1.68		−1.61
$3S \to 2P$	0.04	−0.12	−2.43	−2.51
$3S \to 1P$	0.04	−0.63	0.65	0.06

1^3P_J ->1^3S_1 ($c\bar{c}$)



Level	Final state	Predicted $\mathcal{B}$ (%) (2)	Measured $\mathcal{B}$ (%) (12)
2^3P_0	$\gamma + 1S$	0.96	0.9 ± 0.6
	$\gamma + 2S$	1.27	4.6 ± 2.1
2^3P_1	$\gamma + 1S$	11.8	8.5 ± 1.3
	$\gamma + 2S$	20.2	21 ± 4
2^3P_2	$\gamma + 1S$	5.3	7.1 ± 1.0
	$\gamma + 2S$	18.9	16.2 ± 2.4

	$\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ in keV		
	$J=2$	$J=1$	$J=0$
Our results CLEO [PR D74 (2006) 031106]	< 21	70 ± 17	172 ± 30
Rosner (non-relativistic) [7]	24 ± 4	73 ± 9	523 ± 12
Ding-Qin-Chao [6]			
non-relativistic	3.6	95	312
relativistic	3.0	72	199
Eichten-Lane-Quigg [8]			
non-relativistic	3.2	183	254
with coupled-channels corrections	3.9	59	225
Barnes-Godfrey-Swanson [9]			
non-relativistic	4.9	125	403
relativistic	3.3	77	213

- $\psi(3770) \to 1^3P_J$ transitions:
  Can study relativistic effects including coupling to decay channels.

	$\chi_{cJ} \to J/\psi + \gamma$		
J	theory	E835	PDG
2	$a_2 \approx -\frac{\sqrt{5}}{3}\frac{k}{4m_c}(1+\kappa_c)$	$-0.093^{+0.039}_{-0.041} \pm 0.006$	-0.140 ± 0.006
2	$a_3 \approx 0$	$0.020^{+0.055}_{-0.044} \pm 0.009$	$0.011^{+0.041}_{-0.033}$
1	$a_2 \approx -\frac{k}{4m_c}(1+\kappa_c)$	$0.002 \pm 0.032 \pm 0.004$	$-0.002^{+0.008}_{-0.017}$

J	$\psi\,' \to \chi_{cJ} + \gamma$ theory
2	$a_2 \approx -\frac{\sqrt{3}}{2\sqrt{10}}\frac{k}{m_c}[(1+\kappa_c)(1+\frac{\sqrt{2}}{5}X) - i\frac{1}{5}X]/[1-\frac{1}{5\sqrt{2}}X]$
2	$a_3 \approx -\frac{12\sqrt{2}}{175}\frac{k}{m_c}X[1+\frac{3}{8}Y]/[1-\frac{1}{5\sqrt{2}}X]$
1	$a_2 \approx -\frac{k}{4m_c}[(1+\kappa_c)(1+\frac{2\sqrt{2}}{5}X) + i\frac{3}{10}X]/[1+\frac{1}{\sqrt{2}}X]$

- $\psi'(2S) \to 1^3P_J \to J/\psi$ transitions:
  Can study size of higher multipole terms M2 and E3.

Model generally in good agreement with experiment

Table 4: Two pion transitions observed in the $c\bar{c}$ system.

Transition $i \to f$	$+ \ X$	$m_{\pi\pi}^{(\max)}$ (MeV)	Branching Fraction (%)	Partial Width ^{1} (keV)
$\psi(2S) \to J/\psi$	$\pi^+\pi^-$	589	$33.54 \pm 0.14 \pm 1.10$	113.0 ± 8.4
	$\pi^0\pi^0$		$16.52 \pm 0.14 \pm 0.58$	55.7 ± 4.1
$\psi(3770) \to J/\psi$	$\pi^+\pi^-$	676	$(1.89 \pm 0.20 \pm 0.20) \times 10^{-1}$	43.5 ± 11.5
	$\pi^0\pi^0$		$(0.80 \pm 0.25 \pm 0.16) \times 10^{-1}$	18.4 ± 9.8

=> $|C_1| = 8.87 \times 10^{-3}$

=> $|C_2|/|C_1| = 1.52\ ^{+0.35}_{-0.45}$

Table 5: Two pion transitions observed in the $b\bar{b}$ system.

Transition $i \to f$	$+ \ X$	$m_{\pi\pi}^{(\max)}$ (MeV)	Branching Fraction (%)	Partial Width ^{2} (keV)
$\Upsilon(2S) \to \Upsilon(1S)$	$\pi^+\pi^-$	563	18.8 ± 0.6	6.0 ± 0.5
	$\pi^0\pi^0$		9.0 ± 0.8	2.6 ± 0.2
$\Upsilon(3S) \to \Upsilon(1S)$	$\pi^+\pi^-$	895	4.48 ± 0.21	0.77 ± 0.06
	$\pi^0\pi^0$		2.06 ± 0.28	0.36 ± 0.06
$\Upsilon(3S) \to \Upsilon(2S)$	$\pi^+\pi^-$	332	2.8 ± 0.6	0.48 ± 0.12
	$\pi^0\pi^0$		2.00 ± 0.32	0.35 ± 0.07
$\Upsilon(4S) \to \Upsilon(1S)$	$\pi^+\pi^-$	1120	$(0.90 \pm 0.15) \times 10^{-2}$	1.8 ± 0.4
$\Upsilon(4S) \to \Upsilon(2S)$	$\pi^+\pi^-$	557	$(0.83 \pm 0.16) \times 10^{-2}$	1.7 ± 0.5
$\chi_{b2}(2P) \to \chi_{b2}(1P)$	$\pi^+\pi^-$	356	$(6.0 \pm 2.1) \times 10^{-1}$	0.83 ± 0.32
$\chi_{b1}(2P) \to \chi_{b1}(1P)$	$\pi^+\pi^-$	363	$(8.6 \pm 3.1) \times 10^{-1}$	0.83 ± 0.32

Rescaled Kuang &Yan model

} 9.4

} 1.4

} 0.6

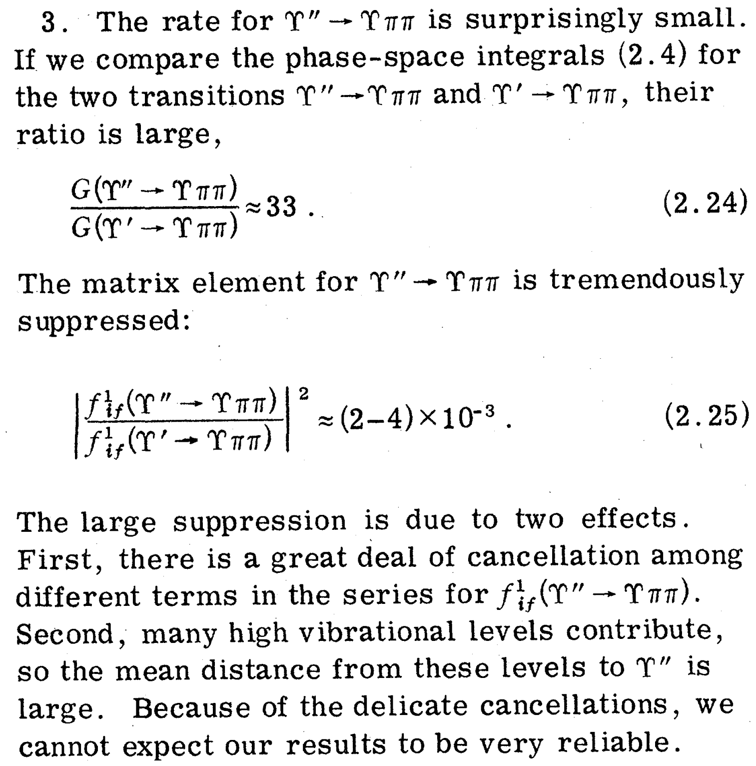
0.6

0.6

Like the E1 case ?

$\Delta n = 2$ overlap suppressed.

Predicted for Υ(3S)->Υ(1S)



3. The rate for $\Upsilon'' \to \Upsilon\pi\pi$ is surprisingly small. If we compare the phase-space integrals (2.4) for the two transitions $\Upsilon'' \to \Upsilon\pi\pi$ and $\Upsilon' \to \Upsilon\pi\pi$, their ratio is large,

$$\frac{G(\Upsilon'' \to \Upsilon\pi\pi)}{G(\Upsilon' \to \Upsilon\pi\pi)} \approx 33\,. \qquad (2.24)$$

The matrix element for $\Upsilon'' \to \Upsilon\pi\pi$ is tremendously suppressed:

$$\left|\frac{f^1_{if}(\Upsilon'' \to \Upsilon\pi\pi)}{f^1_{if}(\Upsilon' \to \Upsilon\pi\pi)}\right|^2 \approx (2\text{–}4)\times 10^{-3}\,. \qquad (2.25)$$

The large suppression is due to two effects. First, there is a great deal of cancellation among different terms in the series for $f^1_{if}(\Upsilon'' \to \Upsilon\pi\pi)$. Second, many high vibrational levels contribute, so the mean distance from these levels to Υ'' is large. Because of the delicate cancellations, we cannot expect our results to be very reliable.

Kuang &Yan (1981)

Below lowest intermediate state threshold

$$\sum_{nl} \frac{|\Psi_{nl} >< \Psi_{nl}|}{E_i - E_{nl}} \sim \frac{1}{E_i - E^{\mathrm{TH}}_{\mathrm{string}}} + \cdots$$

Hence transition rates fairly insensitive to intermediate states details

Transition	G (GeV^7)	$\vert < i\vert r^2\vert f > \vert$ (GeV^{-2})	$G < i\vert r^2\vert f >^2$ $\times 10^2$
$\psi(2S) \to J/\psi$	3.56×10^{-2}	3.36	40.2
$\Upsilon(2S) \to \Upsilon(1S)$	2.87×10^{-2}	1.19	4.06
$\Upsilon(3S) \to \Upsilon(1S)$	1.09	2.37×10^{-1}	0.61
$\Upsilon(3S) \to \Upsilon(2S)$	9.09×10^{-5}	3.70	0.12
$\Upsilon(4S) \to \Upsilon(1S)$	5.58	9.74×10^{-2}	0.48
$\Upsilon(4S) \to \Upsilon(2S)$	2.61×10^{-2}	4.64×10^{-1}	0.56

Note the large variations in phase space and overlaps for the various Υ states.

If leading <E1-E1> suppressed, can the <M1-M1> significant?

Single hadron transitions

higher order <E1 M1>; <M1 M1>, <E1 M2>

$C_iC_f = -1 \qquad +1$

$$O(v) \qquad O(v^2)$$

symmetry breaking:
π; η, ω

$$\tilde{\pi}^0 = \pi^0 + \epsilon\eta + \epsilon'\eta'$$

$$\tilde{\eta} = \eta - \epsilon\pi^0 + \theta\eta'$$

$$\tilde{\eta}' = \eta' - \theta\eta - \epsilon'\pi^0,$$

Transition $i \rightarrow f$	$+ X$	Branching Fraction [3] (%)	Partial Width (keV)
$\psi(2S) \rightarrow J/\psi$	η	$3.25 \pm 0.06 \pm 0.11$	11.0 ± 0.84
	π^0	$0.13 \pm 0.01 \pm 0.01$	0.44 ± 0.06
$\psi(2S) \rightarrow h_c(1P)$	π^0	$(1.0 \pm 0.2 \pm 0.18) \times 10^{-1}$	0.34 ± 0.10
$\psi(3770) \rightarrow J/\psi$	η	$(0.87 \pm 0.33 \pm 0.22) \times 10^{-1}$	20 ± 11

Transition $i \rightarrow f$	$+ X$	Branching Fraction (%)	Partial Width [4] (keV)
$\Upsilon(2S) \rightarrow \Upsilon(1S)$	η	$(2.5 \pm 0.7 \pm 0.5) \times 10^{-2}$	$(7.2 \pm 2.3) \times 10^{-3}$
$\chi_{b1}(2P) \rightarrow \Upsilon(1S)$	ω	$1.63 \pm 0.33 \pm 0.16$	1.56 ± 0.59
$\chi_{b2}(2P) \rightarrow \Upsilon(1S)$	ω	$1.10 \pm 0.30 \pm 0.11$	1.52 ± 0.64

chiral effective theory:

$$\epsilon = \frac{(m_d - m_u)\sqrt{3}}{4(m_s - \frac{m_u + m_d}{2})}, \qquad \epsilon' = \frac{\tilde{\lambda}(m_d - m_u)}{\sqrt{2}(m_{\eta'}^2 - m_{\pi^0}^2)}, \qquad \theta = \sqrt{\frac{2}{3}}\,\frac{\tilde{\lambda}\left(m_s - \dfrac{m_u + m_d}{2}\right)}{m_{\eta'}^2 - m_\eta^2}.$$

Hybrid states and Lattice QCD

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

$$\Psi_{Q\bar{Q}}(\vec{r}) = \frac{u_{nl}(r)}{r}\mathrm{Y}_{\mathrm{lm}}(\theta,\phi)$$

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

$$\langle L_r J_{gr}\rangle = \langle J^2_{gr}\rangle = \Lambda^2$$

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

$$< J^2_g >= 0, 2, 6, \ldots$$

naively 0, 1, 2, ... valence gluons

Spectroscopic notation of diatomic molecules

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

Λ = 0, 1, 2, ... denoted Σ, Π, Δ, ...

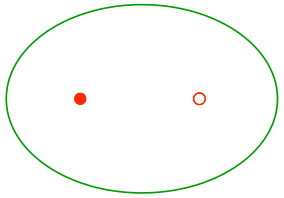
η= ±1 (symmetry under combined charge conjugation and spatial inversion) denoted g(+1) or u(-1).

$|LSJM;\lambda\eta\rangle+\varepsilon|LSJM;-\lambda\eta\rangle$ with ε=+1 for Σ^+ and ε=-1 for Σ^- both signs for Λ>0.

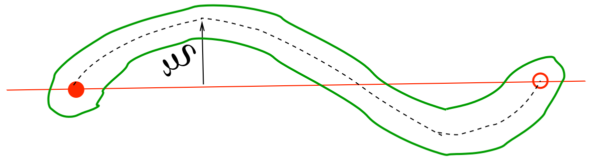
Potentials computed by lattice QCD

K.J. Juge, J. Kuti and C. Morningstar [PRL 90, 161601 (2003)]

Short distance: gluelumps
Perturbative QCD, pNRQCD
singlet: -4/3 α_s /r
octet : 2/3 α_s /r



Large distance: String
σ r + πN/r
Nambu-Gato string behaviour



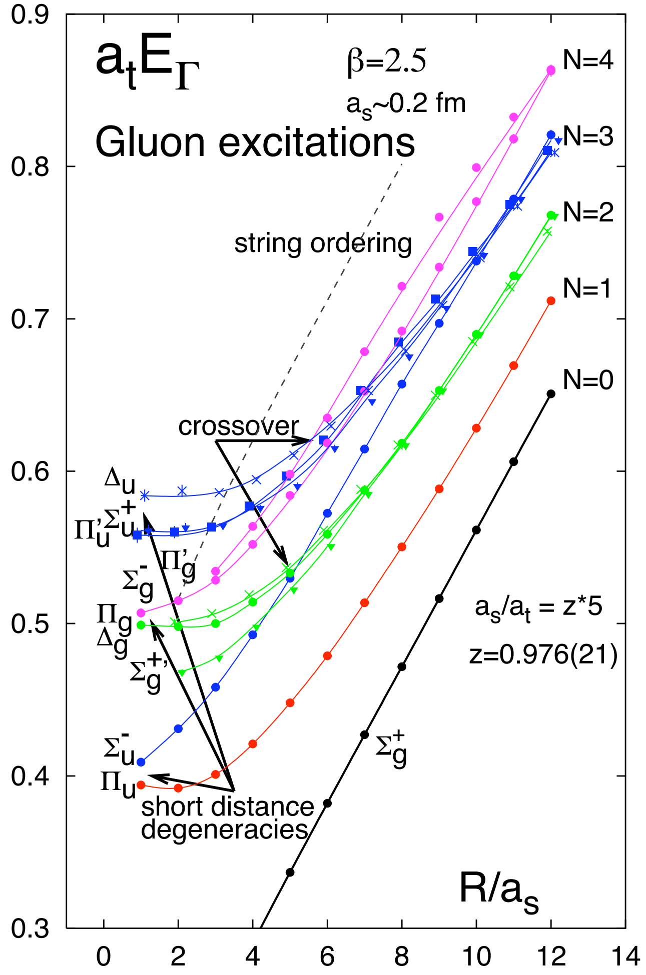


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

○ Non DD decays of the $\psi(3770)$

- X J/ψ

$\psi'' \to \pi^+\pi^- J/\psi$	$0.34 \pm 0.14 \pm 0.09$	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

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

- $\gamma\chi_{cJ}$

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

Good agreement with theory expectations including relativistic effects

- light hadrons

No evidence for direct decays to light hadrons seen yet.

Puzzle of missing decays

Decay Mode	$\sigma_{\psi(3770)\to f}$ [pb]	$\sigma^{\mathrm{up}}_{\psi(3770)\to f}$ [pb]	$\mathcal{B}^{\mathrm{up}}_{\psi(3770)\to f}$ [$\times 10^{-3}$]
$\phi\pi^0$	$< 3.5^{tn}$	< 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]

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

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

CLEO

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

BES

No evidence of unexpected rates for non DD decays