Charmonium III: Above Threshold

- Dynamics near threshold
  - Threshold formalism
  - Strong Decays
  - R_c in the threshold region
- The XYZ states
  - Transitions
  - New degrees of freedom?
- Summary and outlook

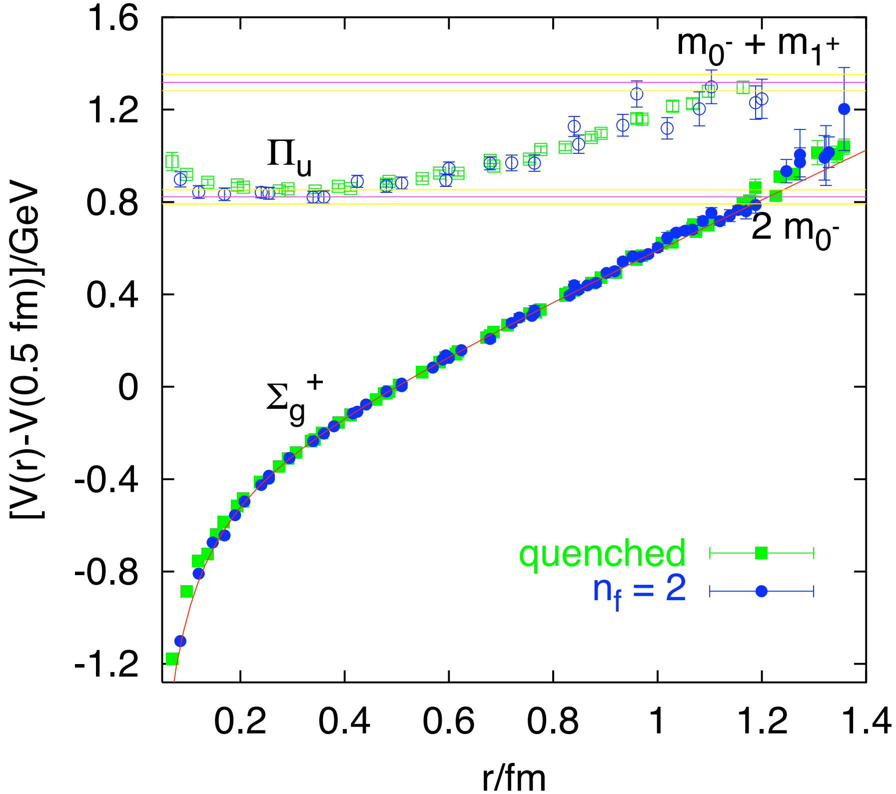
QCD Dynamics at Threshold

- Lattice calculation V(r), then SE

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

- 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 ≈ 1.2 fm. Between 3S-4S in $(c\bar{c})$; just above the 5S in $(b\bar{b})$.

LQCD calculation of static energy



Heavy-Light mesons

- The low-lying spectrum for heavy-light mesons $H_L^j = (Q\bar{q})(L,j)$

$H_d^{5/2} = \{H_d(2^-), H_d(3^-)\}$

$H_d^{3/2} = \{H_d(1^-), H_d(2^-)\}$

$H'^{1/2}_s = \{H'_s(0^-), H'^*_s(1^-)\}$

$H_P^{3/2} = \{H(1^+), H(2^+)\}$

$H_P^{1/2} = \{H(0^+), H(1^+)\}$

$H_s^{1/2} = \{H_s(0^-), H^*_s(1^-)\}$

- The doublet degeneracy is split by $1/m_Q$ terms: $H_L^j \rightarrow$ $H_L([J=j+1/2]^P)$, $H_L([J=j-1/2]^P)$
- Transition branching ratios $H_1 \to H_2 + (\pi, K, \ldots)$ predicted by HQET

M. Di Pierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001).

Heavy-Light mesons

- The low-lying charmed mesons
  - $D_{(u,d)}$ $m(D^+)-m(D^0) = 4.77 \pm 0.10$ MeV

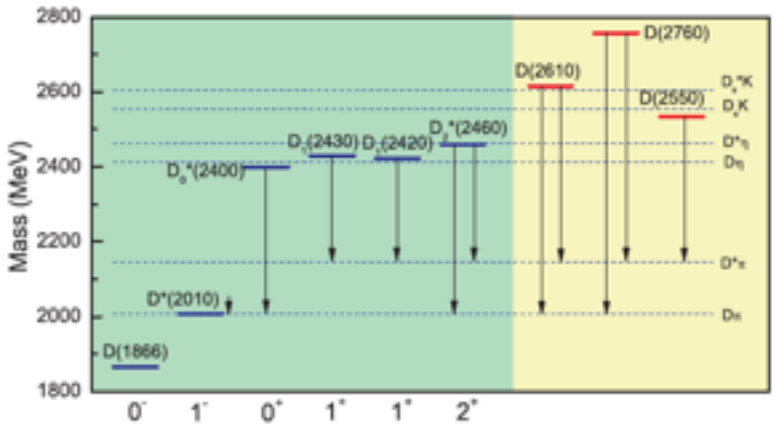
T.P. Sun, J.S. Yu, X. Liu, T. Matsuki [arXiv:1008.3120]

jP (D^0, D^+)	$J^P(n\,^{2s+1}L_J)$	Expt.[1, 2]	GI[3]	MMS[4]	PE[5]	EFG[6]	Width
1/2 -	$0^-(1^1S_0)$	1867	1880	1869	1868	1875	--
1/2 -	$1^-(1^3S_1)$	2008	2004	2011	2005	2009	(77, 96) keV
1/2 +	$0^+(1^3P_0)$	2400	2400	2283	2377	2438	276 MeV
1/2+	$1^+(1\,``^3P_1")$	2427	2490	2421	2417	2501	380 MeV
3/2+	$1^+(1\,``^1P_1")$	2420	2440	2425	2460	2414	31.0 MeV *
3/2+	$2^+(1^3P_2)$	2460	2500	2468	2490	2459	50.5 MeV *
1/2 -	* $0^-(2^1S_0)$	2533	2580	2483	2589	2579	128 MeV *
1/2 -	$1^-(2^3S_1)$	2619	2640	2671	2692	2629	92.9 MeV *
3/2 -	* $1^-(1^3D_1)$	2763	2820	2762	2795	-	83.9 MeV *

* J. Benitez et al. (BaBar Collaboration) (ICHEP2010)

Heavy-Light mesons (Charm)

- Decay patterns as expected for heavy light mesons



T.P. Sun, J.S. Yu, X. Liu, T. Matsuki [arXiv:1008.3120]

- D_s^+

jP (D_s^+)	Mass (MeV)	Width
1/2 -	1968	--
1/2 -	2112	0.44 keV
1/2 +	2317	23 keV *
1/2+	2459	38 keV *
3/2+	2535	290 keV
3/2+	2573	20 MeV

* Theoretical expectations - Below threshold for Zweig allowed decays

Threshold behavior of R_c

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Consider the contribution to R from heavy quark (Q = c, b or t) near pair production threshold:

$$i\int d^4x\, e^{iqx} \langle 0| T j_Q^\mu(x) j_Q^\nu(0) |0\rangle = (g^{\mu\nu}q^2 - q^\mu q^\nu)\Pi_Q(q^2)$$

hence R_Q is given by:

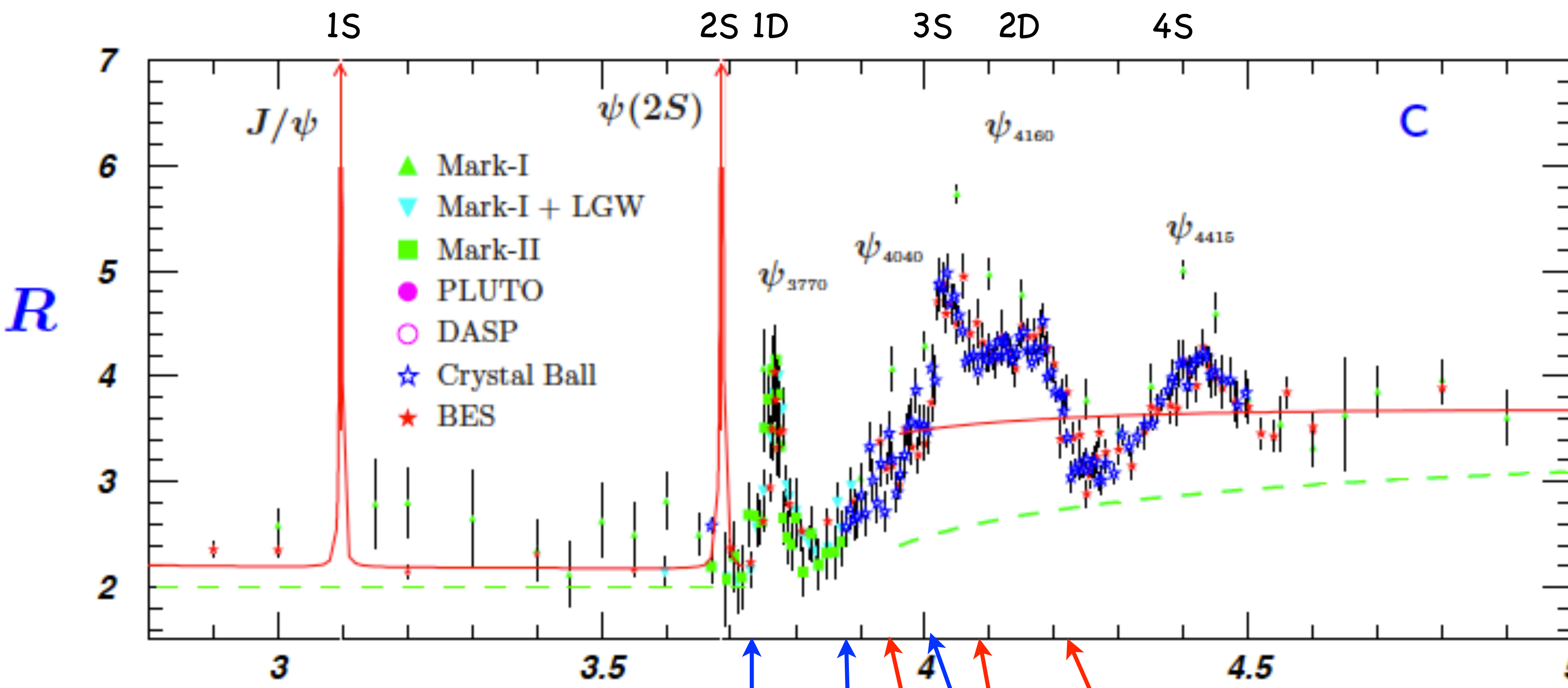
$$R_Q = 12\pi e_Q^2 Im\Pi(s+i\epsilon)$$

and the electromagnetic current can be expressed in nonrelativistic form:

$$j_Q^i = s_1\psi^\dagger\sigma^i\chi + \frac{s_2}{m_Q^2}\psi^\dagger\sigma^i\mathcal{D}^2\chi + \frac{d_2}{m_Q^2}\psi^\dagger\sigma^j[\frac{1}{2}(\mathcal{D}^i\mathcal{D}^j + \mathcal{D}^j\mathcal{D}^i) - \frac{1}{3}\delta^{ij}\mathcal{D}^2]\chi + ..$$

s_1, s_2, d_2 calculable in perturbative QCD

Charmed Threshold Region



P-wave thresholds: DD, DD*, D*D*,
D_sD_s $D_sD_s^*$ $D_s^*D_s^*$

Charmed Meson Pair Thresholds

Narrow Thresholds

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

Broad Thresholds

*D*D(0+)*	4,270	S-wave
D D'(1+)	4,270	S-wave
*D*D'(1+)*	4,430	S-wave
...		

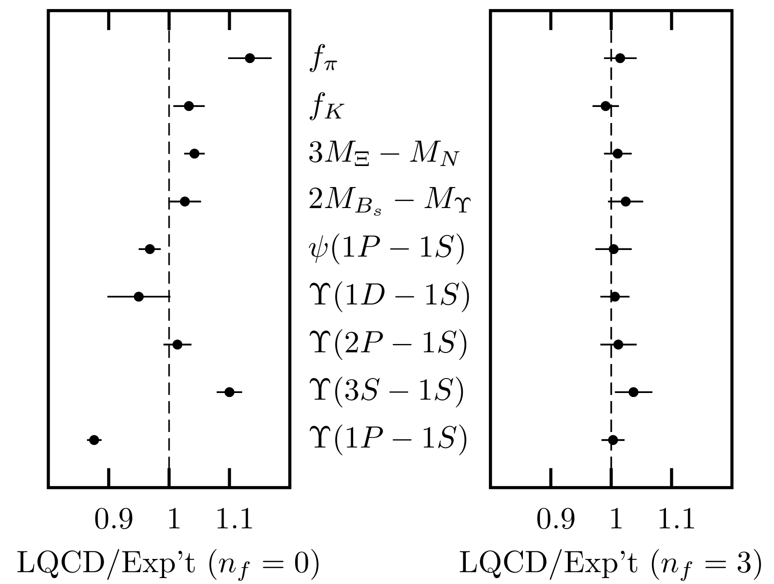
Charm Threshold Region

- Strong decays for charmonium states into charmed meson pairs. Need model to:
  - Extract the masses and widths of charmonium resonances
  - Calculate the behavior of ΔRc both total and individual exclusive channels
- Significantly differs from expectations for light hadrons
  - Kinematics - m_Q large => $\Delta E / \Delta p$ small
  - Many Narrow Two Body Channels Opening
  - Radially Excited Charmonium Resonances
- Result:
  - Complicated Threshold Behavior Expected
  - Difficult region for direct lattice calculations

Light quarks effects

- Light quark loops
  - Corrections even below threshold

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



- Above threshold: Zweig allowed strong decay

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

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

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

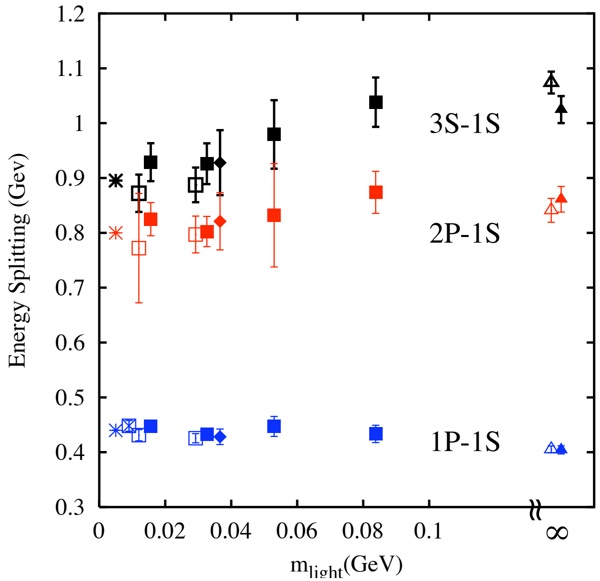
Cornell model (CCCM)

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

Vacuum Pair Creation model (QPC)

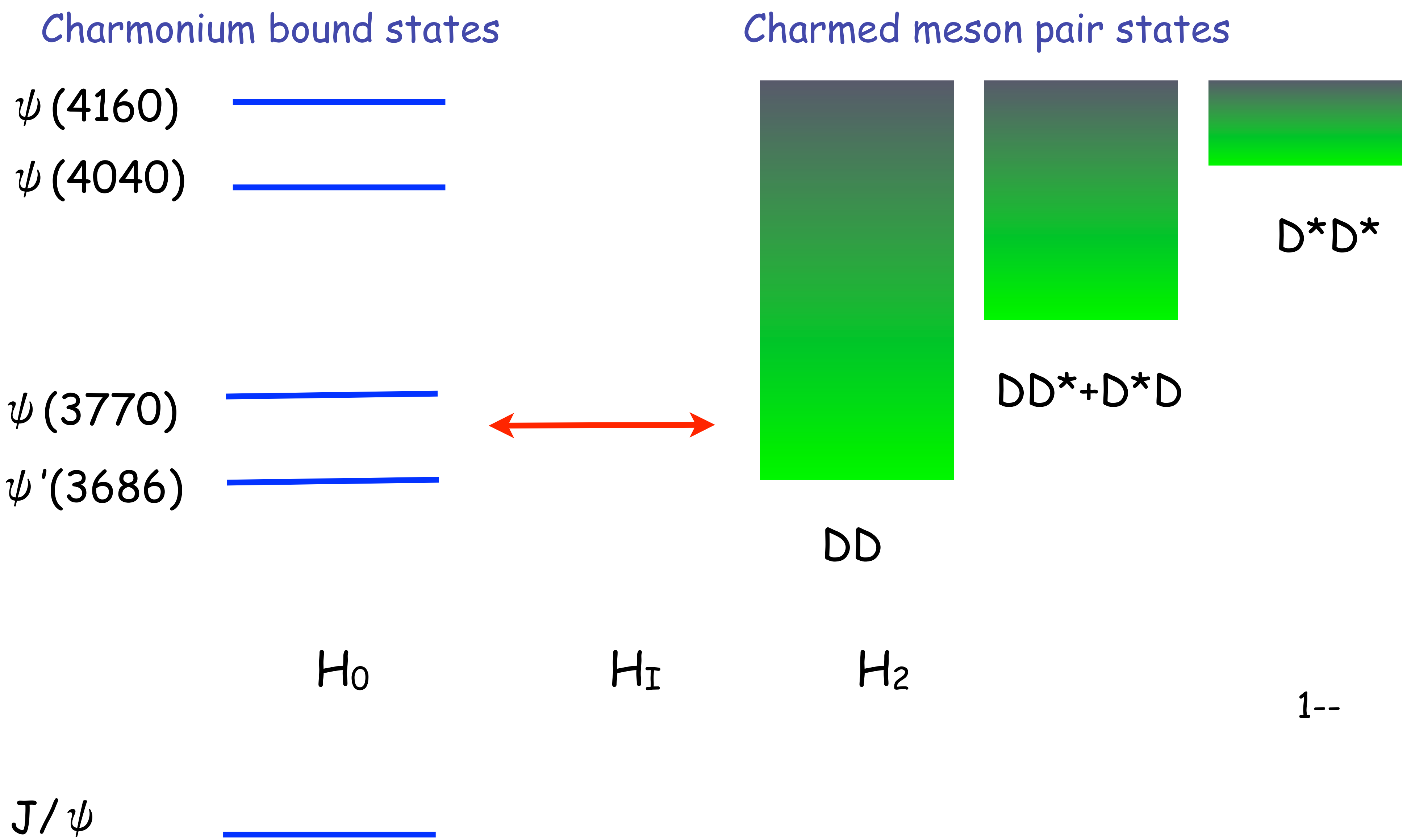
$$\mathcal{H}_I = \gamma \int \bar{\psi}\psi(\mathbf{r})d^3r$$

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



Threshold Formalism

- Two set of states near threshold in each J^{PC} channel



Threshold Formalism

- Coupled channel problem

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

- Formally eliminate ψ_2

defines $\Omega(z)$

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

- Decay amplitude $\langle DD|H_I|\psi\rangle$
- Simplifying assumptions
  - H_2 - free meson pairs no final state interactions
  - H_0 - charmonium states are a complete basis - no hybrids

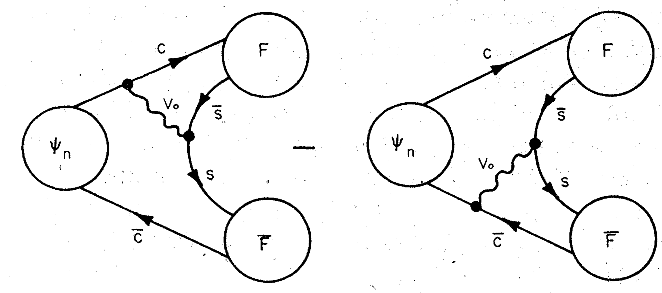
$$< n|\mathcal{G}(z)|m > = < n|\frac{1}{z - \mathcal{H}_0 - \Omega(z)}|m >$$

- Assuming vector meson dominance. Can compute R_c

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

Decay Amplitudes

- Cornell Coupled Channel Model
  - ψ_n potential model wavefunction
  - Final mesons: $\phi(x) \sim \exp(-x^2\beta_S)$ $[\beta_S = \frac{1}{2a^2}(\frac{4\mu a}{3\sqrt{(\pi)}})^{2/3}]$



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

where

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

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

- $dV(x)/dx = 1/a^2 + \kappa/x^2$ => no free parameters
  setting $\kappa = 0$ => same form as the vacuum pair creation model ($^3P_0$)

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

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

Statistical factor

Reduced decay amplitudes I(p)

C

$H = (Q\bar{q})$

$H_s = \{H, H^*, H_s\}$

$H_P^{1/2} = \{H(0^+), H(1^+), H_s(0^+), H_s(1^+)\}$

$H_P^{3/2} = \{H(1^+), H(2^+), H_s(1^+), H_s(2^+)\}$

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

- Reduced decay amplitudes:

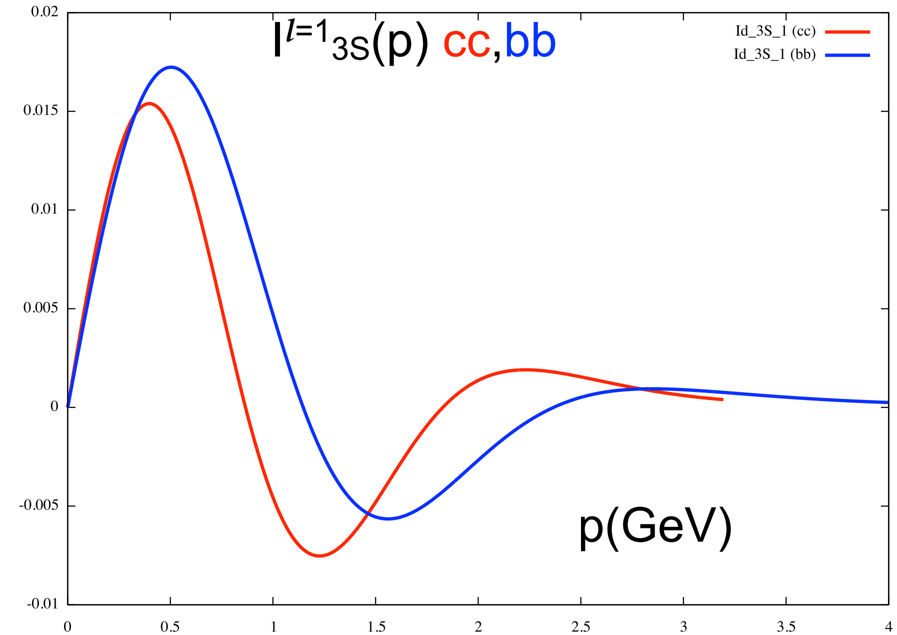
$$I^{l}_{nL}(P) = \int_0^\infty dt\, \Phi(t) R_{nL}(t\beta^{-1/2}) j_l(\mu_c \beta^{-1/2} P t)$$

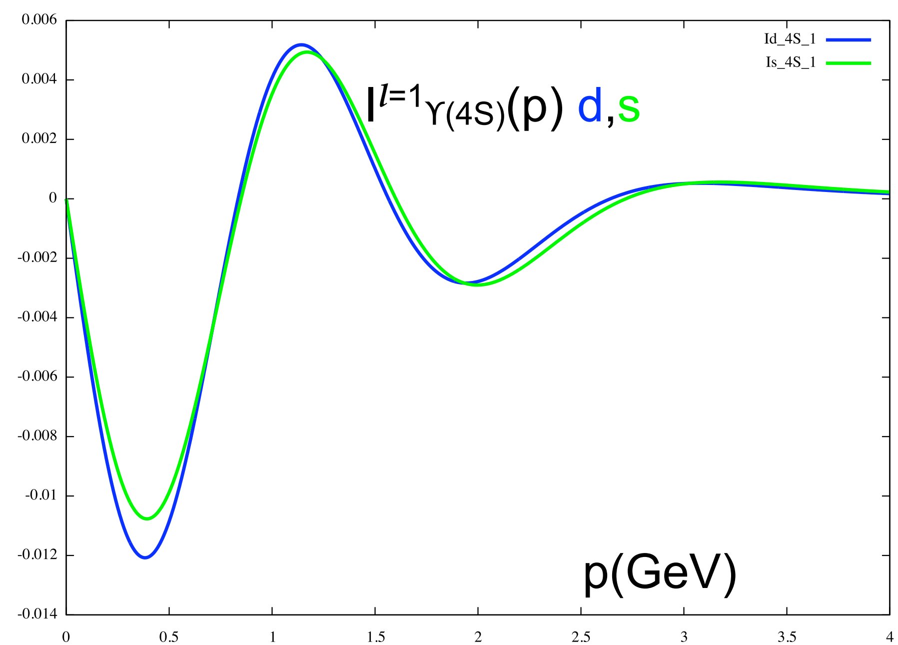
- Key points:
  - The decay amplitudes $I^l_{nL}(p)$ have nodes reflecting the nodes in the radially excited charmonium initial state.
  - The only part of I(p) that depends on the pair production model is the function Φ(t):
    - For the CCCM model:

$$\Phi(t) = t e^{-t^2} + (\pi/2)^{1/2}(t^2 - 1) e^{-t^2/2} \mathrm{erf}(t/\sqrt{2})$$

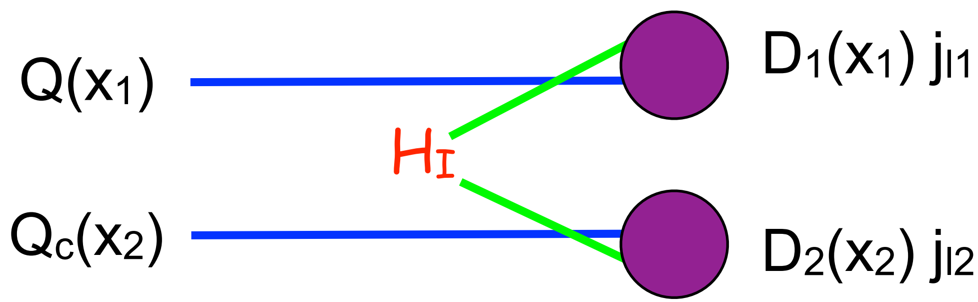
  - Using HQET this function Φ(t) is the same for all members of the same j_l^P multiplet.
  - Apart from overlap light quark mass factors Φ(t) is essentially SU(3) invariant.

Sample decay amplitudes I(p)





- One universal function, $\Phi(t)$, determines R_Q in the threshold region. The same $\Phi(t)$ for DD, DD*+D*D, and D*D* final states. This a general result that does not depend on the details of the CCC Model.
- Consider the static limit: $\langle D_1(x_1)\ D_2(x_2)\ |H_I|0;x_1,x_2\rangle$

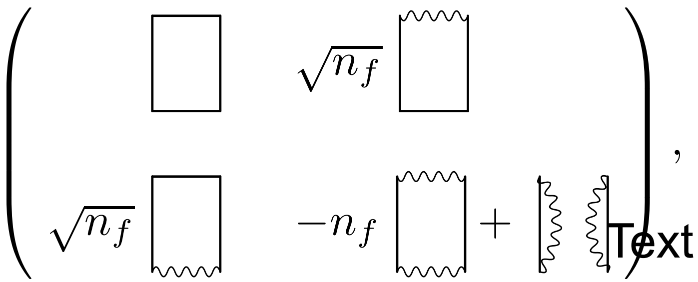


- H_I should only depend on the spins (s_1,s_2) and position (y) of the light quark pair creation and the heavy quark positions x_1, x_2. $[H_I = (s_1+s_2)\cdot H]$. Integrating over y and the final state heavy-light meson wavefunctions defines $\Phi(t)$. So it is independent of heavy quark spins.
- .For $j_{l1} = j_{l2} = 1/2^-$ (D, D*) there is a single invariant function: for all other heavy-light systems two invariant functions $\Phi^{j1,j2}{}_+(t)$ and $\Phi^{j1,j2}{}_-(t)$.
- Can probe these functions using Lattice QCD

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

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

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



, (1)

transition amplitude is difficult to extract accurately

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

This is exactly the function Φ(r) we need!

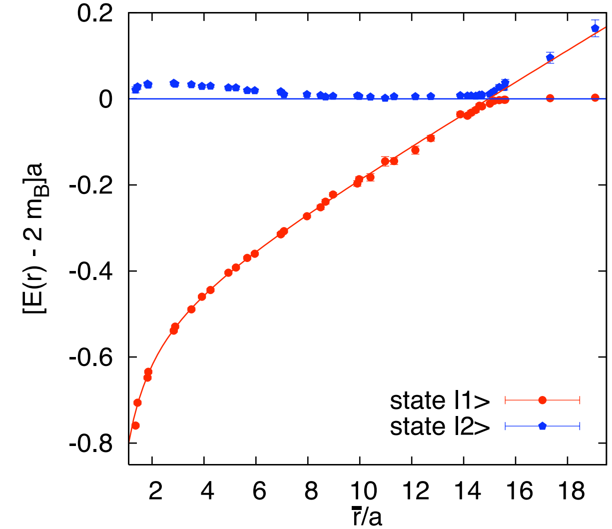


FIG. 13: The two energy levels, as a function of $\overline{r}$, normalized with respect to $2m_B$ (horizontal line). The curve corresponds to the three parameter fit to $E_1(\overline{r})$, Eqs. (80)–(82), for $0.2\,\text{fm} \leq \overline{r} \leq 0.9\,\text{fm} < r_c$.

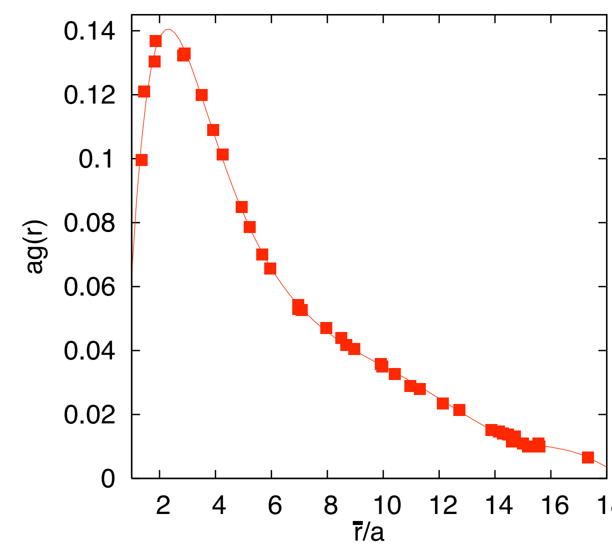


FIG. 18: The transition rate g between $|B\rangle$ and $|Q\rangle$ states, as a function of $\overline{r}$.

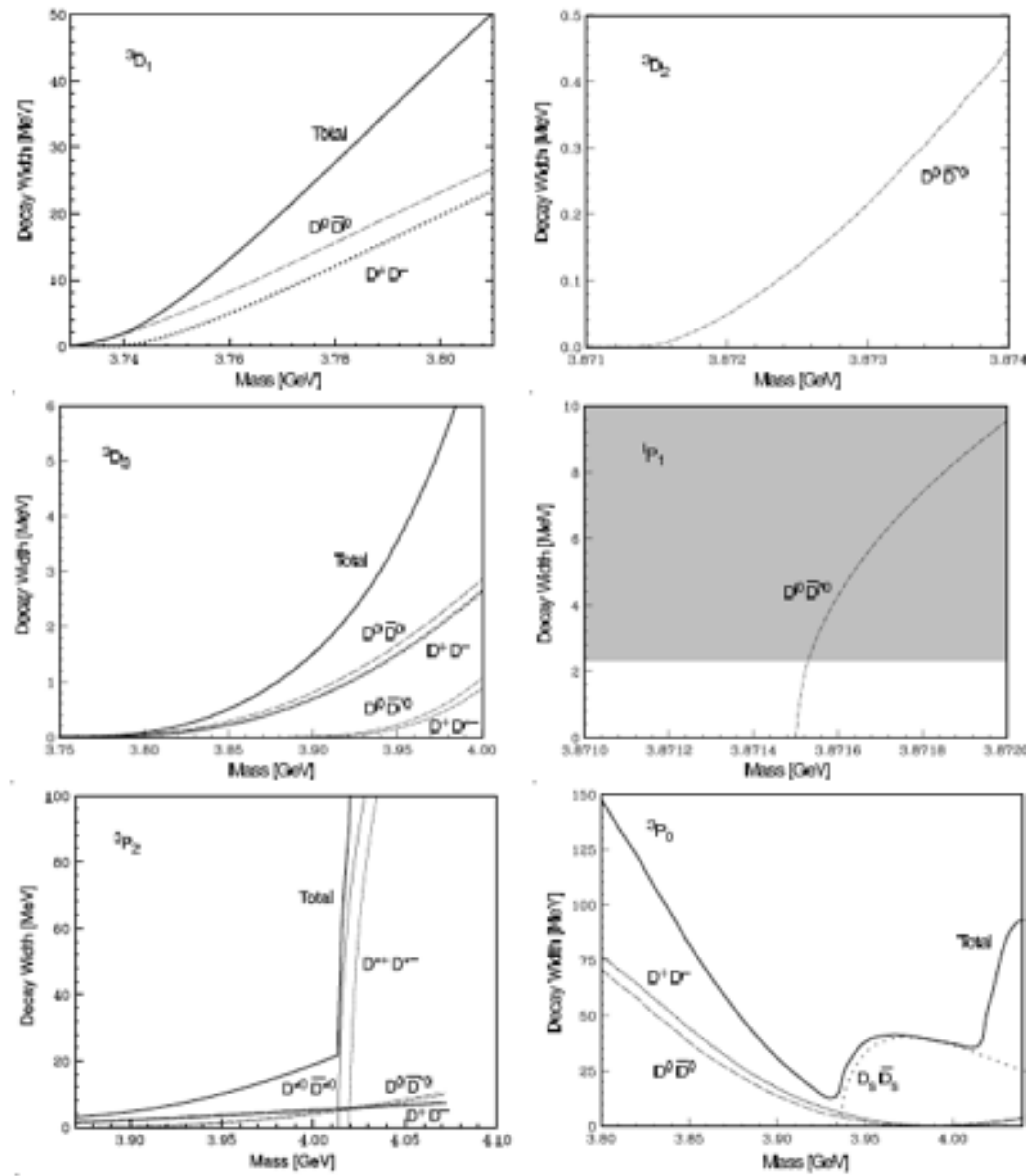
Sample mass shifts and decay widths (CCCM)

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

$$= \quad \Delta M(W) + \Gamma(W)$$

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	2979.9[a]	3067.6[b]	−90.5	+2.8
1^3S_1	3096.9[a]		+30.2	−0.9
1^3P_0	3415.3[a]	3525.3[c]	−114.9[c]	+5.9
1^3P_1	3510.5[a]		−11.6[c]	−2.0
1^1P_1	3525.3		+1.5[c]	+0.5
1^3P_2	3556.2[a]		−31.9[c]	−0.3
2^1S_0	3637.7[a]	3673.9[b]	−50.4	+15.7
2^3S_1	3686.0[a]		+16.8	−5.2
1^3D_1	3769.9[ab]	(3815)[d]	−40	−39.9
1^3D_2	3830.6		0	−2.7
1^1D_2	3838.0		0	+4.2
1^3D_3	3868.3		+20	+19.0
2^3P_0	3931.9	3968[d]	−90	+10
2^3P_1	4007.5		−8	+28.4
2^1P_1	3968.0		0	−11.9
2^3P_2	3966.5		+25	−33.1

ΔM

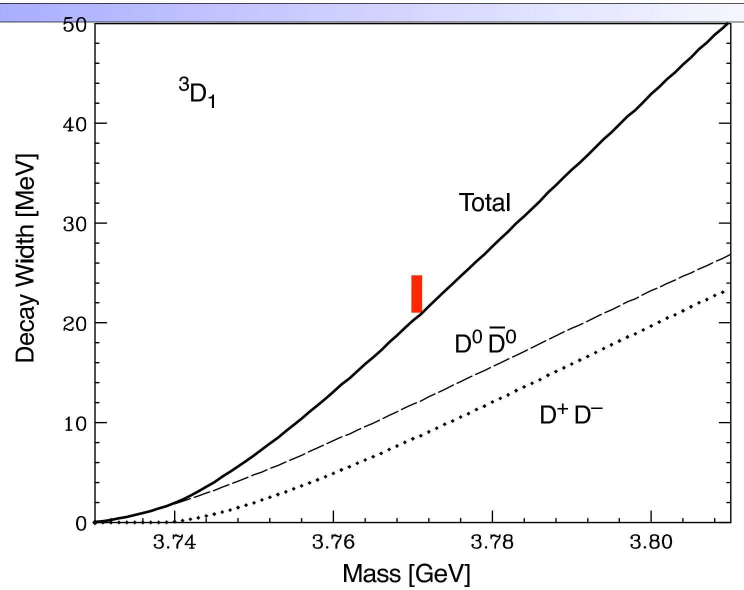


$\Gamma(W)$

The $\psi(3770)$ decays

$$\text{Mass m} = 3772.92 \pm 0.35 \text{ MeV}$$

$$\text{Full width } \Gamma = 27.3 \pm 1.0 \text{ MeV}$$



CCC Model

Decay width in good agreement with theory

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

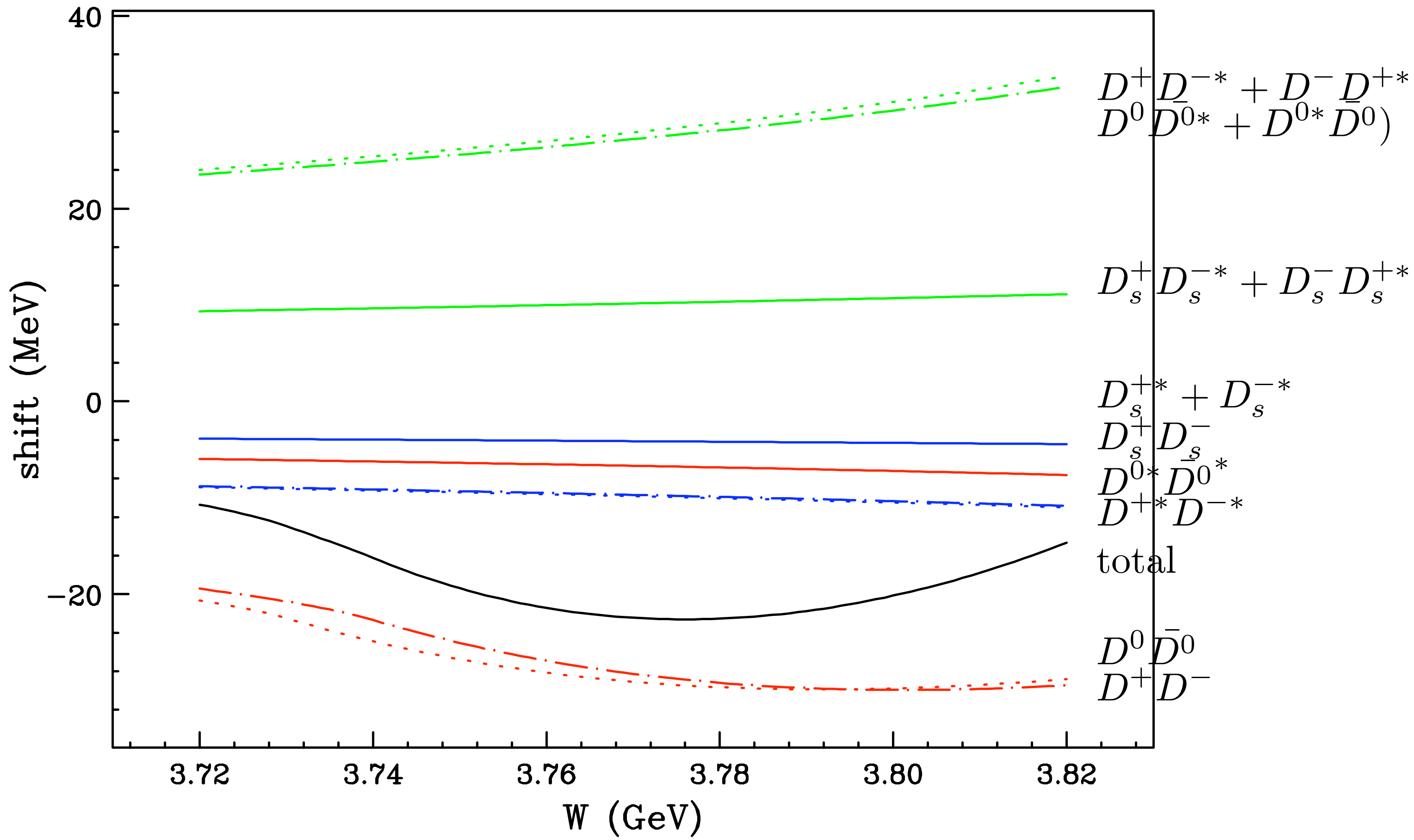
$$+ \frac{d_2}{m_c^2} \psi^\dagger \sigma^j [\frac{1}{2}(\mathcal{D}^i \mathcal{D}^j + \mathcal{D}^j \mathcal{D}^i) - \frac{1}{3} \delta^{ij} \mathcal{D}^2] \chi + \ldots$$ D-wave

(b) S-D mixing terms - short range: ~5 MeV

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

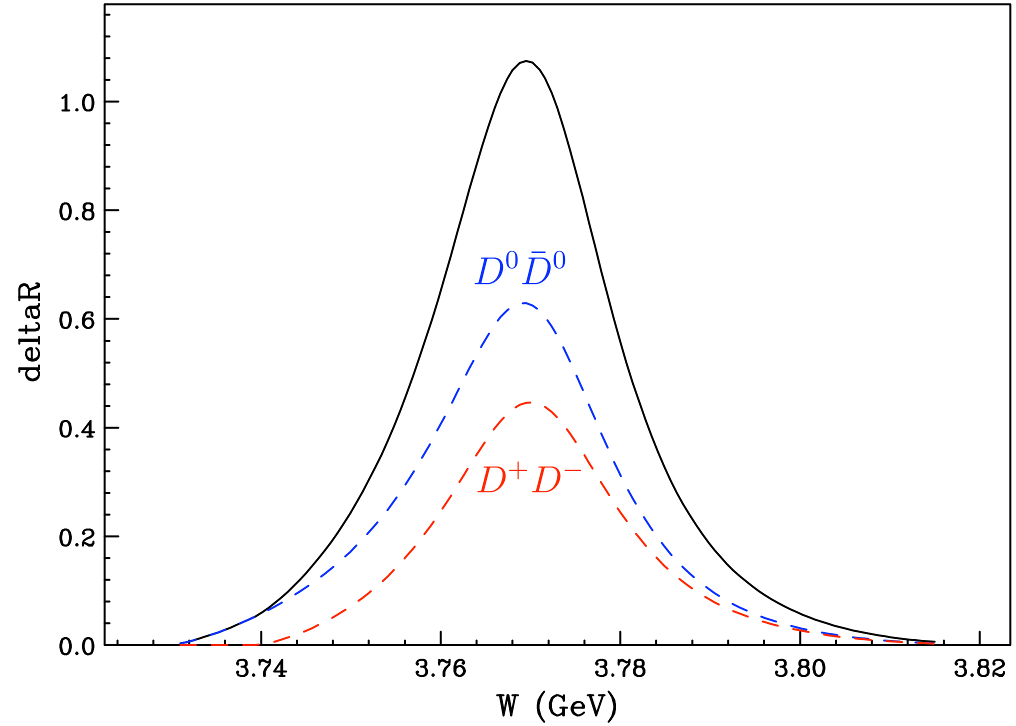
$$\psi(3772) = 0.10\, |2\text{S}\rangle + 0.01 e^{+0.22 i\pi}\, |3\text{S}\rangle + \ldots$$
$$+ 0.69 e^{-0.59 i\pi}\, |1\text{D}\rangle + 0.10 e^{+0.27 i\pi}\, |2\text{D}\rangle + \ldots$$

Induced 2S-1D tensor mixing term



At $\psi(3773)$: -23 MeV (total)

Cancellations between (DD, DD*, and D*D*)contributions



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

$R^{0/+}$

CLEO	pdg07	p^3	CCCM
1.25	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, 3S state.

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

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

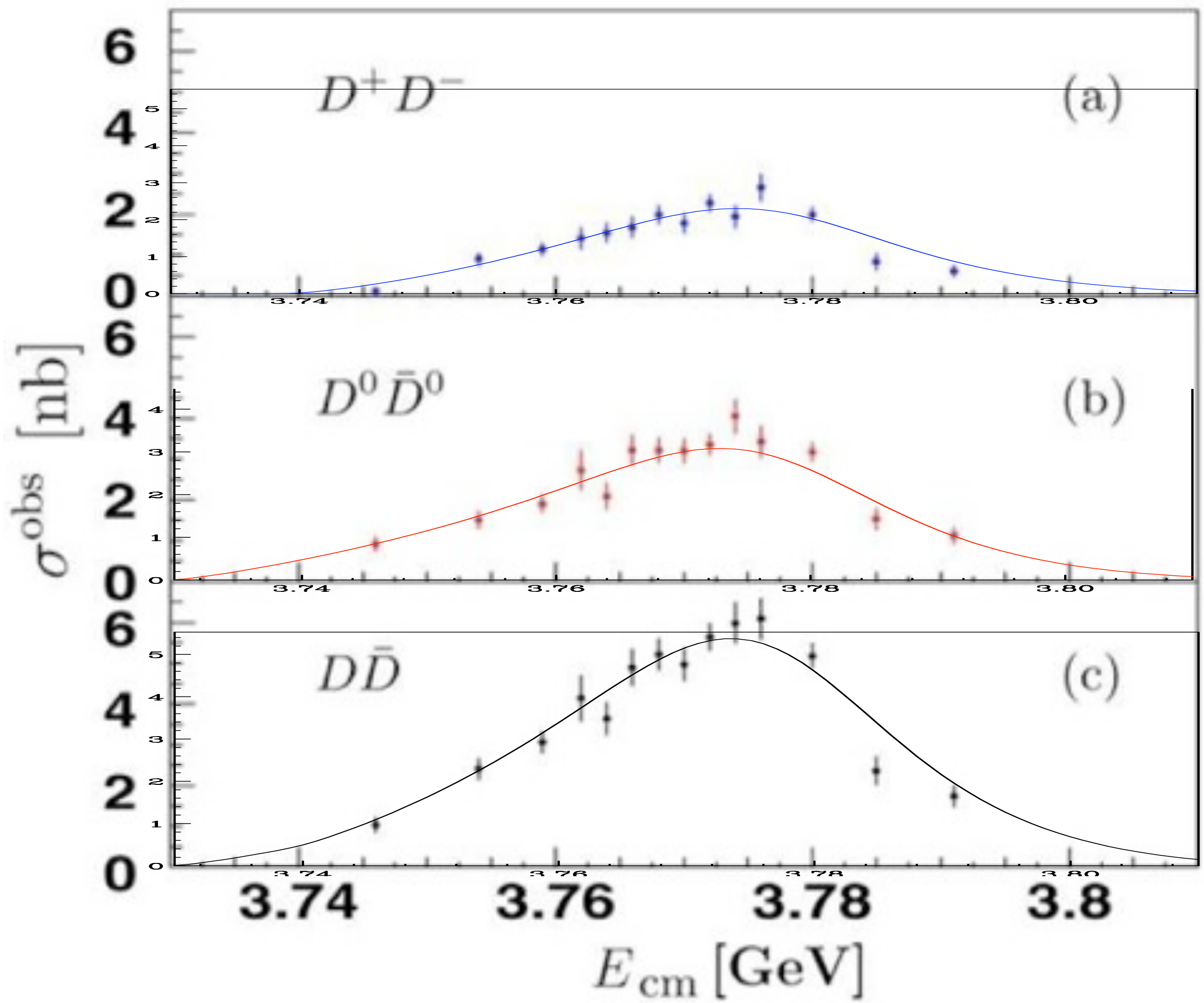
$p_0 = 283$ MeV $\quad p_+ = 250$ MeV

R_c in the $\psi(3770)$ region

- Using the CCCM formalism one obtains:

H. L. Ma [BES Collaboration], arXiv:0810.3541 [hep-ex].

BES data



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) (a)	(b)	(c)	(d)	(e)	CLEO (keV) [136]
$\gamma\chi_{c2}$	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

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

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

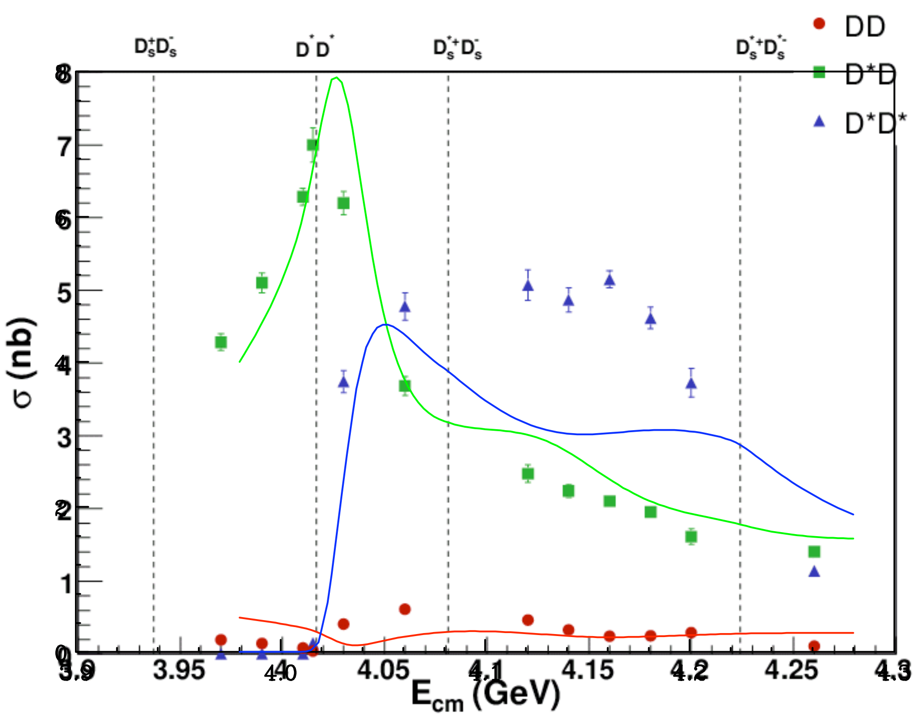
CLEO

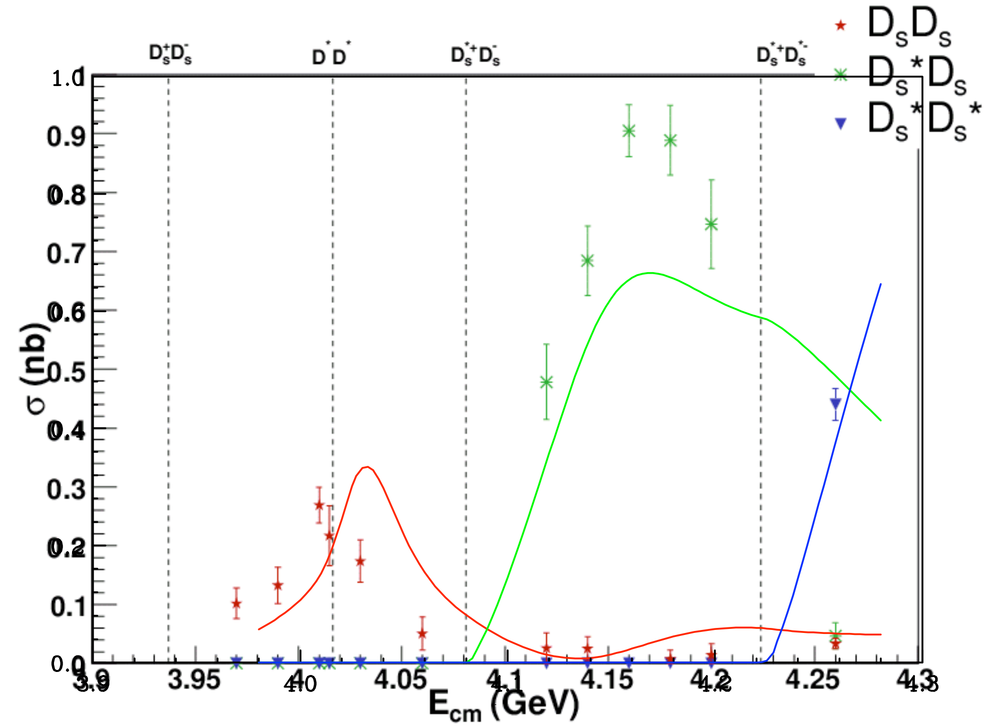
$$\sigma_{\psi(3770)} = 7.25 \pm 0.27 \pm 0.34 \text{ nb}$$

BES

No evidence of unexpected rates for non DD decays

Structure in R_c: $3.8 < \sqrt{s} < 4.3$ GeV

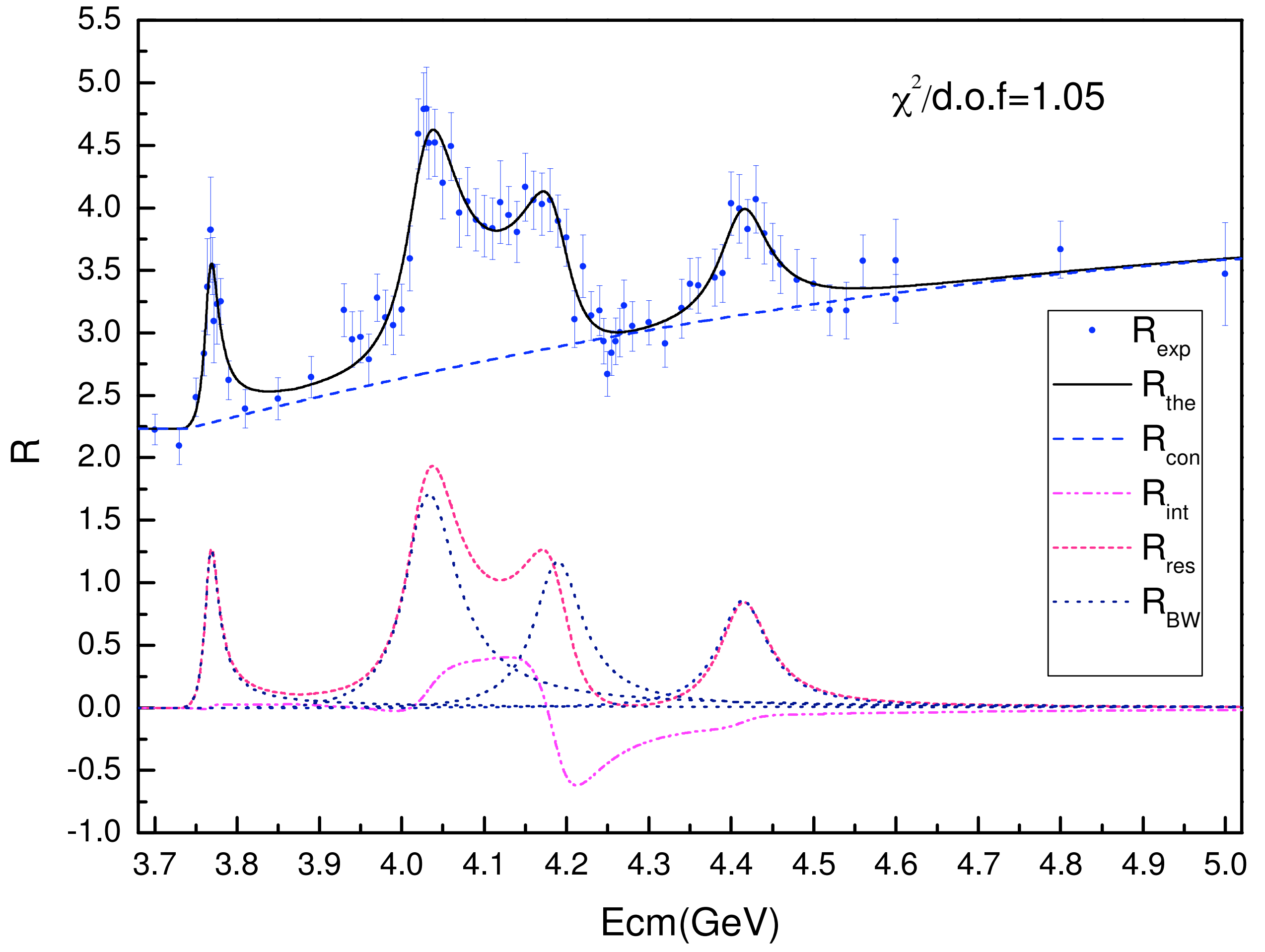




J. Libby [CLEO Collaboration], Nucl. Phys. Proc. Suppl. **181-182**, 127 (2008) [arXiv:0807.1220 [hep-ex]].

- The CCC model results show the complicated behavior seen in the data, but does not fully reproduce the details.
- Search for a better Φ using lattice.
- The 3770 region needs a detailed theoretical study.

M. Ablikim et al. [BES Collaboration] [arXiv:0705.4500]



Comments

- Detailed measrements of Rc in the threshold region provides a wealth of information. Particularly useful are scans of exclusive charm meson pair channels.
- Much of the rich structure in Rc in the threshold region arises simply from the behavior (i.e. nodes) of decay amplitudes for radially excited states.
- The peaks in R for individual final states do not coincide.
- Determining the number and properties of resonances in the threshold region is difficult without a detailed decay model.
- Simple phenomenological models work reasonably well but a sounder theoretical footing is needed.
- Above the opening of the D_S D_P decay channels the structure of individual resonances disappears. Many new channels with excited charm mesons become available. A dual picture from perturbative QCD is more appropriate.

New XYZ States

State	M (MeV)	Γ(MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6 (<2.2)	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [74, 75] (12.8), BABAR [76] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [77–79] (np), DØ [80] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [81] (4.3), BABAR [82] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [83, 84] (6.4), BABAR [85] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [81] (4.0), BABAR [86, 87] (3.6)		
				$B \to K(\gamma\psi(2S))$	BABAR [87] (3.5), Belle [88] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [89] (8.1), BABAR [90] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [91] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(DD^*)$	Belle [92] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [50] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [25] (np), Belle [22] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [93] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [94] (5.0)	2008	NC!
$Y(4140)$	4143.0 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [95] (3.8)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi D\bar{D}^*$	Belle [92] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [94] (5.0)	2008	NC!

and

$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [96, 97] (8.0)	2005	OK
					CLEO [98] (5.4)		
					Belle [93] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [99] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [99] (5.1)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [100] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	BABAR [101] (np), Belle [102] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [103, 104] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [23] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [102] (5.8)	2007	NC!
Y_b	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$	Belle [33, 105] (3.2)	2010	NC!

"Heavy quarkonium: progress, puzzles and opportunities"
N. Brambilla, et.al. (in preparation)

Understanding the New XYZ States

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

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

      - diquark-antidiquark

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

      - hadro-charmonium

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

    - Hybrid
      - valence gluons, string
    - Strong threshold effects
      - strong decay channel effects

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]
...

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)

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

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)

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

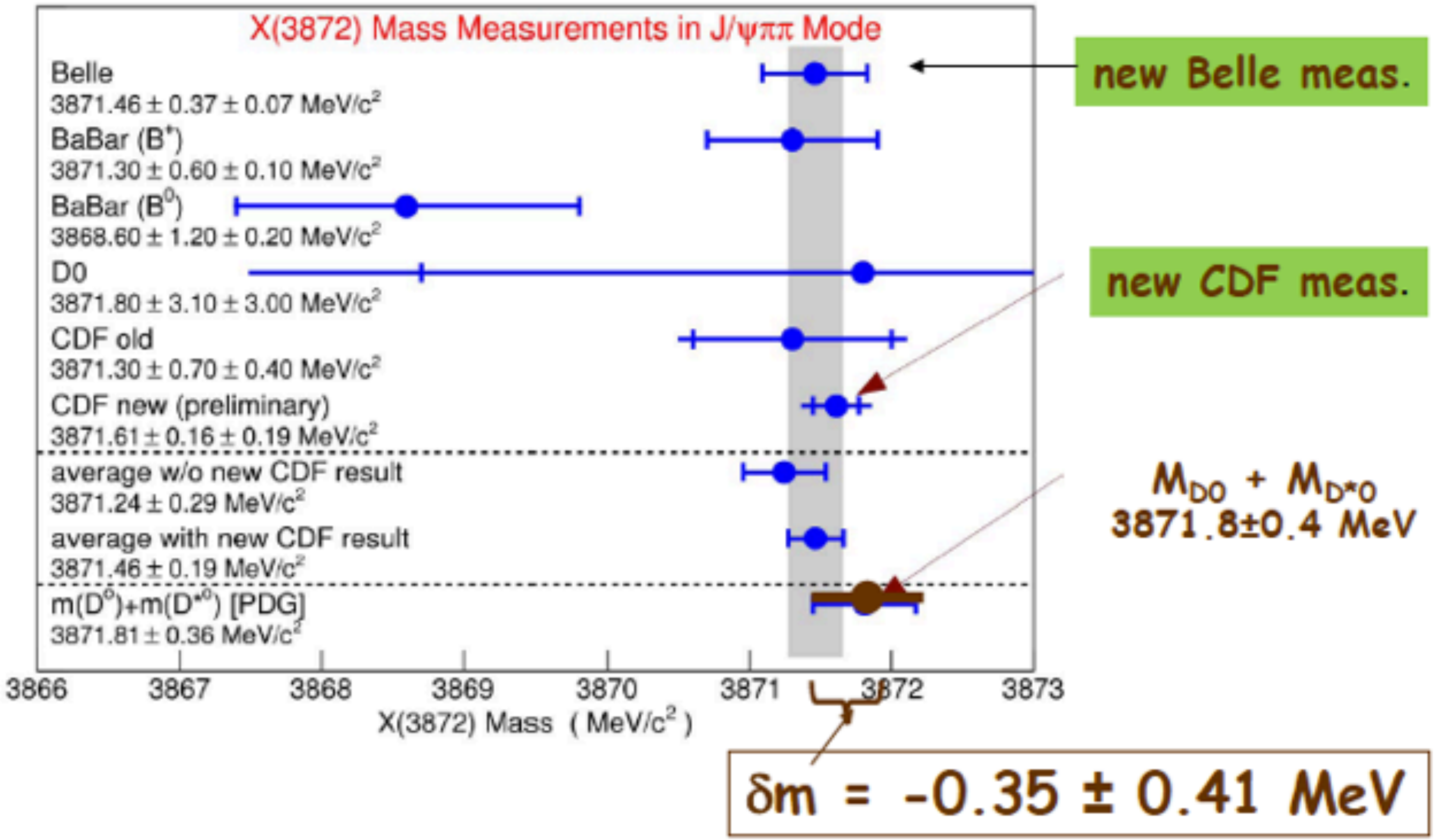
S. Godfrey and S. L. Olsen, Ann. Rev. Nucl. Part. Sci. 58, 51 (2008) [arXiv:0801.3867 [hep-ph]].

- If confirmed $Z^+(4430)$, $Z_1^+(4050)$ and $Z_2^+(4250)$ must be four quark states -> new spectroscopy
- G(3900) is not a new resonance. It is just the coupling channel effects in the 3S region.
- The 3940 and 4160 have C=+1 states in regions with charmonium P states expected.
- X(3872) at D^0 D^{0*} threshold: m(X) - m(D0) - m(D0*) = -0.42 ±0.39 MeV -> D^0 D^{0*} threshold bound state or strong threshold effect.
- Y(4260), Y(4350), Y(4660) are seen in ($\pi\pi$ J/ψ), ($\pi\pi$ ψ'), ($\pi\pi$ ψ') decays respectively -> candidates for hybrid states.

X(3872)

MASS

X(3872) right at threshold -> molecular bound state



DECAYS

$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [74, 75] (12.8), BABAR [76] (8.6)
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [77–79] (np), DØ [80] (5.2)
				$B \to K(\omega J/\psi)$	Belle [81] (4.3), BABAR [82] (4.0)
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				$B \to K(\gamma J/\psi)$	Belle [81] (4.0), BABAR [86, 87] (3.6)
				$B \to K(\gamma\psi(2S))$	BABAR [87] (3.5), Belle [88] (0.4)

$\pi\pi$ J/ψ decay mode -> isospin ≠ 0

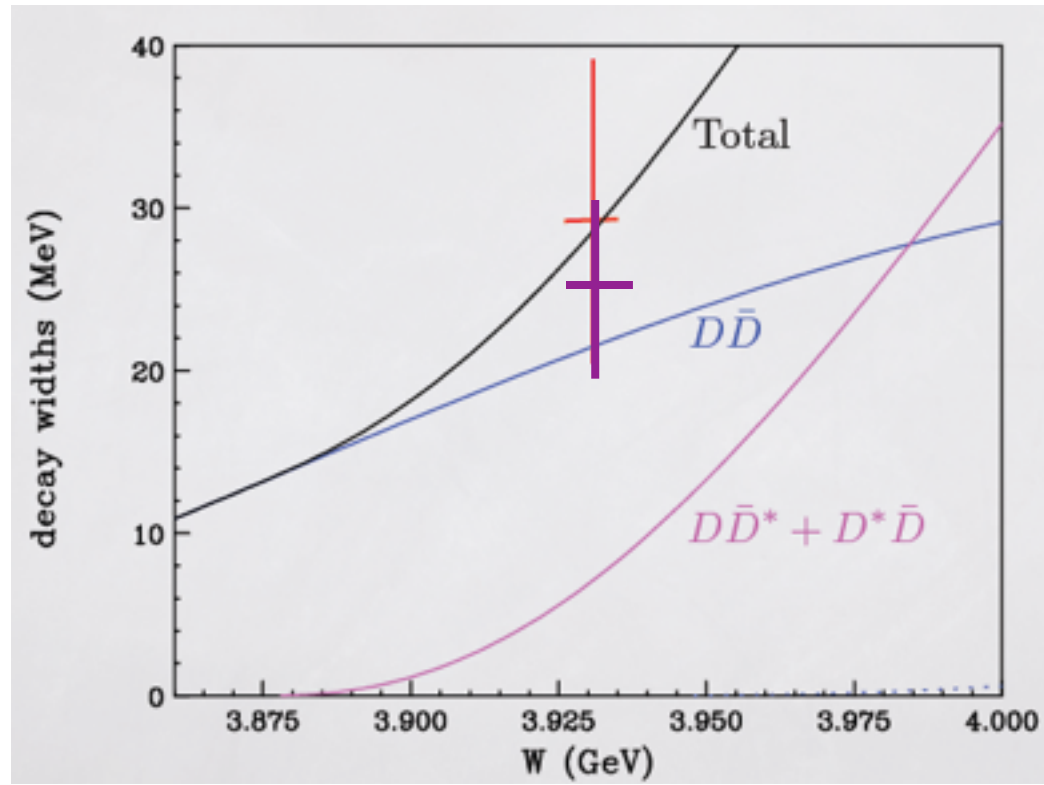
J^{PC} 1++ favored but 2+- still possible

large γ ψ' decay mode -> disfavors molecular interpertation

Where are the charmonium 2^3P_J states?

$\chi_{c2}(2P)$ 3927.2 ± 2.6 24.1±6.1 2^{++} $e^+e^- \to e^+e^-(D\bar{D})$ Belle [51] (5.3), BABAR [52] (5.8)

J=2 2^3P_2 state



Agreement is good

CCCM

J=0 2^3P_0 state

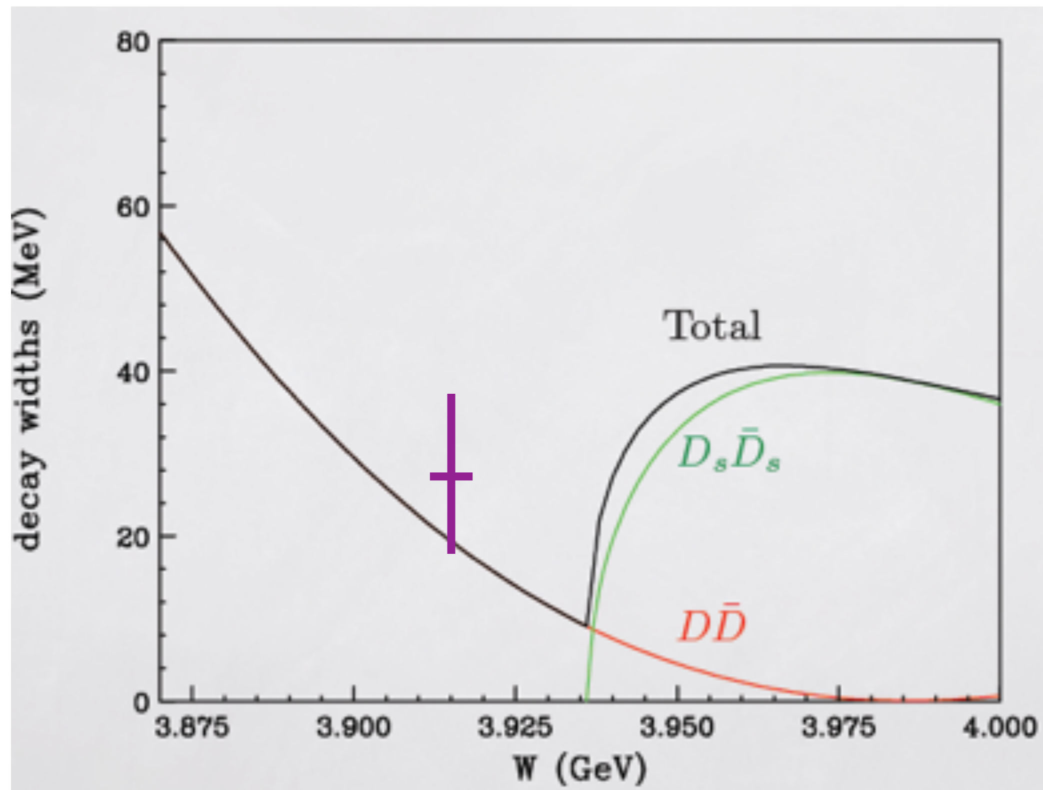
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$ $e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [89] (8.1), BABAR [90] (19) Belle [91] (7.7)

Issue is small decay rate into DD channel - ok

Still issue of large $\omega J/\psi$ decay mode

Plausible candidate

CCCM



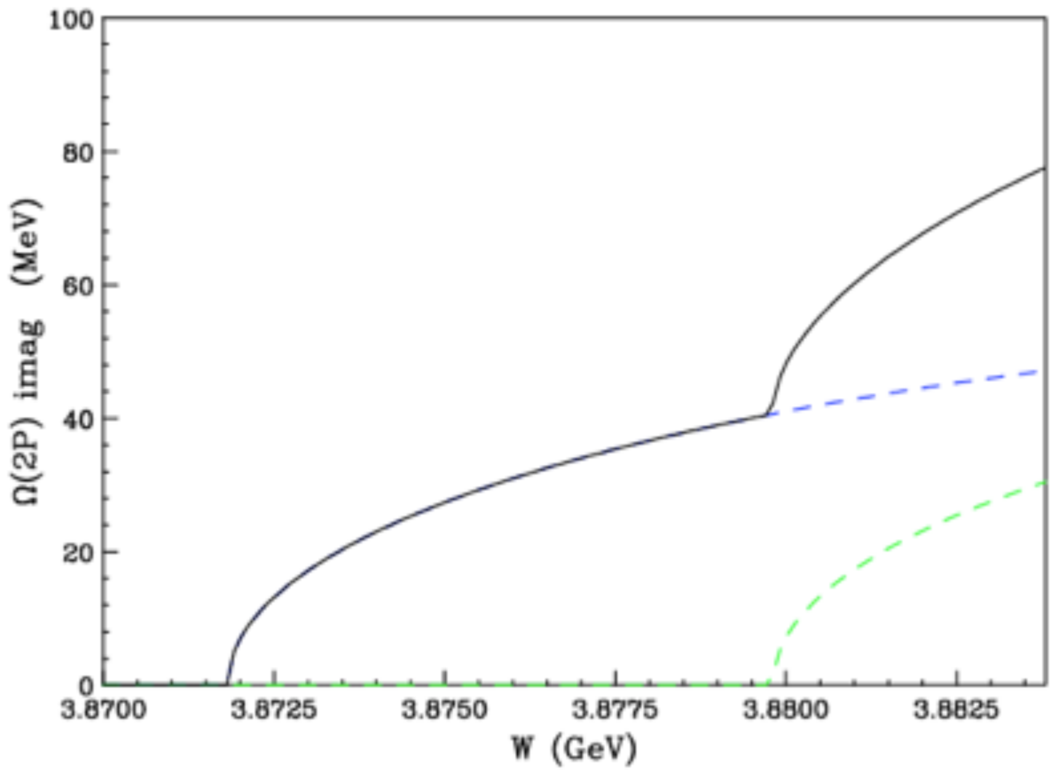
J=1 2^3P_1 state

Missing

But this is not surprising width would be 140 MeV for M = 3.940

Rules out the X(3940) as the 2^3P_1.

The status of the X(3872) is not resolved and the 2^3P_1 state not yet observed.



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

- Y(4260)

Seen by BaBar in ISR production $\Rightarrow J^{PC} = 1^{--}$

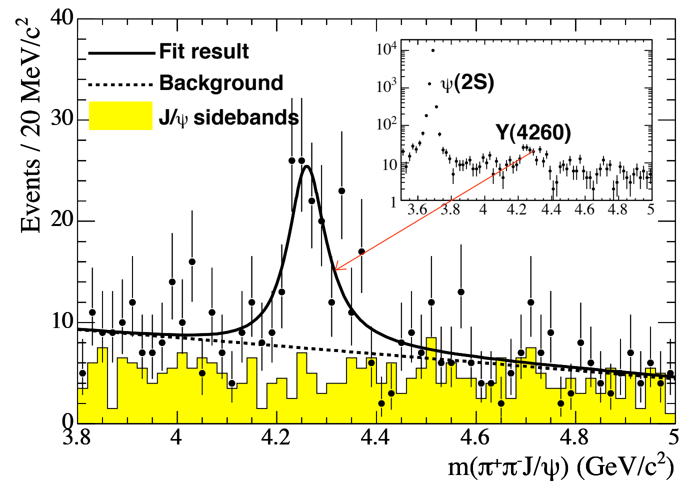
confirmed by CLEO and Belle

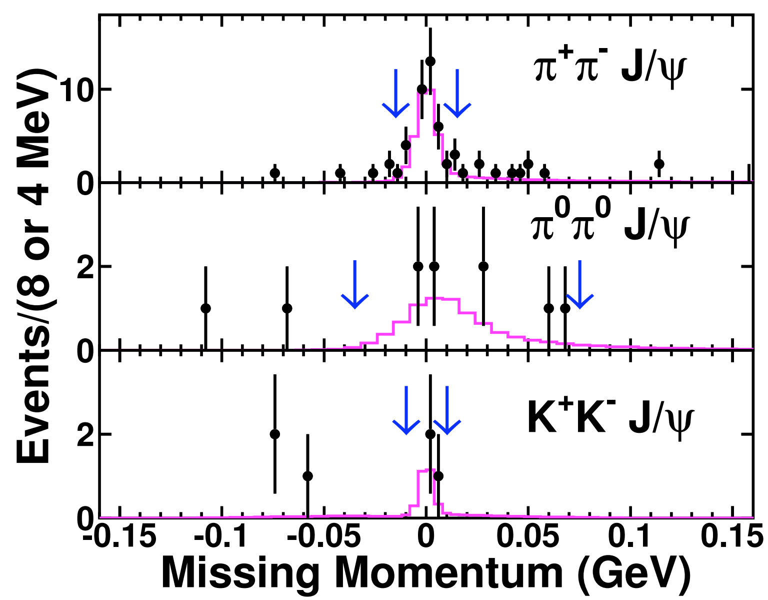
Mass = $4264 \pm ^{10}_{12}$ MeV; Width = $83 \pm ^{20}_{17}$ MeV

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

  consistent with I = 0

- Not a charmonium state
  - Small ΔR - 4^3S_1 state at 4.26 would have $\Delta R \approx 2.5$
  - 1^3D_1 state ψ(4160)





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

Hybrid States and Lattice QCD

- Heavy quark limit: Born-Oppenheimer approximation

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

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

Spectroscopic notation of diatomic molecules

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

$$\langle L_r J_{gr}\rangle = \langle J^2_{gr}\rangle = \Lambda^2 \qquad \langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle = L(L+1)-2\Lambda^2+\langle \boldsymbol{J}^2_g\rangle. \qquad < J_g^2 >= 0, 2, 6, \ldots$$

Λ = 0, 1, 2, … denoted Σ, Π, Δ, …

naively 0, 1, 2, … valence gluons

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

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.

$V_{QQ}(r)$ determined by direct lattice calculations

- 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	$\mathbf{R}\cdot\mathbf{E}, \quad \mathbf{R}\cdot(\mathbf{D}\times\mathbf{B})$
Π_g	1	$\mathbf{R}\times\mathbf{E}, \quad \mathbf{R}\times(\mathbf{D}\times\mathbf{B})$
Σ_u^-	1	$\mathbf{R}\cdot\mathbf{B}, \quad \mathbf{R}\cdot(\mathbf{D}\times\mathbf{E})$
Π_u	1	$\mathbf{R}\times\mathbf{B}, \quad \mathbf{R}\times(\mathbf{D}\times\mathbf{E})$
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	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{E})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{E})^i$

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

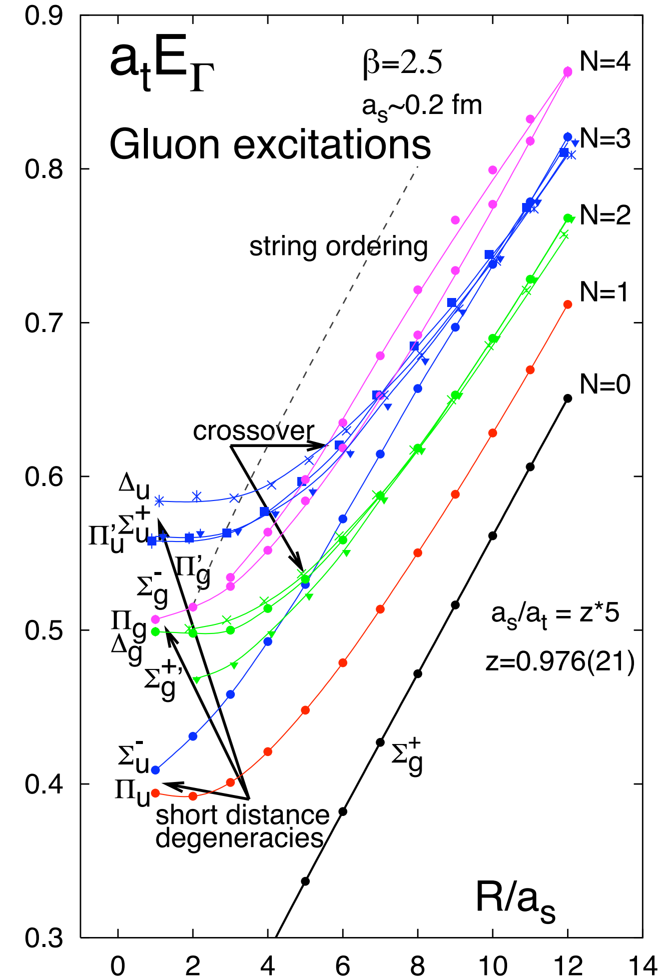


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

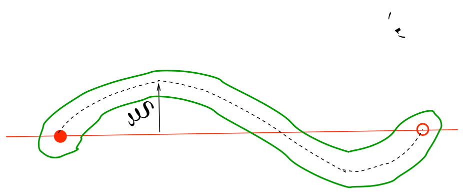
- Mainly interested in non-exotics: $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}, 1^{+-}, \ldots$
- Need Hybrid potentials for: $\Sigma'^{+}_g, \Sigma^-_g, \Pi_g, \Sigma^+_u, \Pi_u, \Delta_g$

Determining the Hybrid Potentials

$V_{Q\bar{Q}}(r)$

Long distance: String

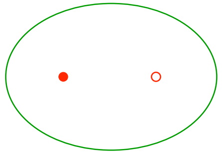
$\sigma\, r + \pi N/r$ Nambu-Goto string behavior



Short distance: Perturbative QCD, pNRQCD

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

octet : $1/6\ \alpha_s/r$ gluelumps



For cc and bb systems neither is adequate.
Need to combine behavior with lattice calculations
in the region [0.25 fm < R < 2 fm]

Determining the Hybrid Potentials

- Short distance (R < 0.25 fm)

The short distance behavior of pNRQCD is confirmed by lattice studies of hybrid potentials and the relation to gluelumps is computed.

G. S. Bali and A. Pineda, Phys. Rev. D 69, 094001 (2004)

A. Pineda [hep-lat/0702019]

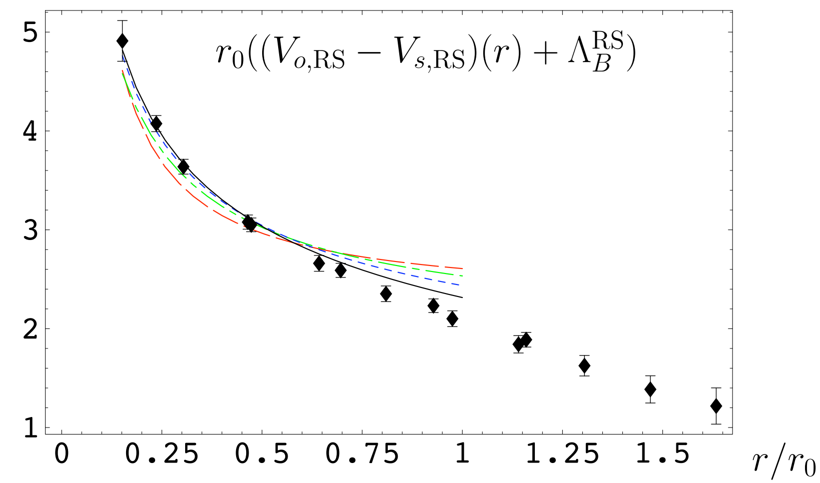
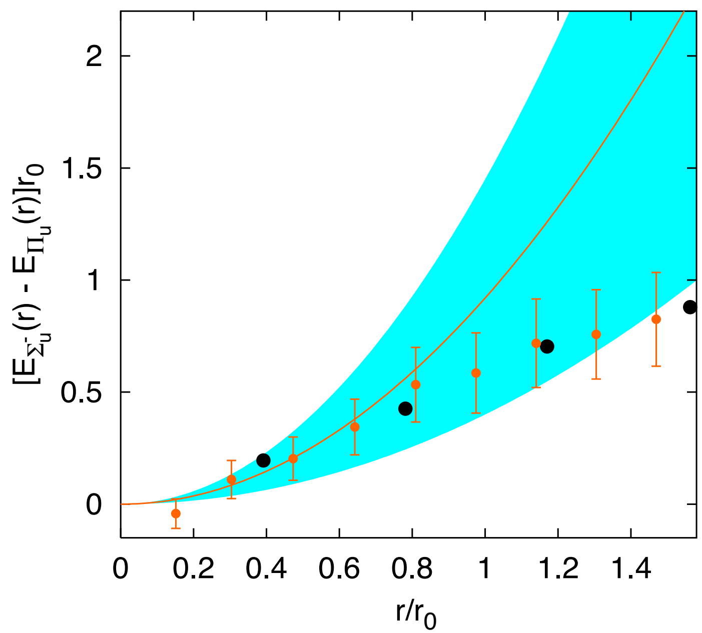


Figure 12: *Splitting between the Π_u and the Σ_g^+ potentials and the comparison with Eq. (65) for $\nu = \nu_i$ [see Eq. (16)] at $\nu_f = 2.5\, r_0^{-1}$. $r_0[(V_{o,\mathrm{RS}} - V_{s,\mathrm{RS}})(r) + \Lambda_B^{\mathrm{RS}}]$ is plotted at tree level (dashed line), one-loop (dashed-dotted line), two loops (dotted line) and three loops (estimate) plus the leading single ultrasoft log (solid line).*



The corrections of order R^2 split the gluelump degeneracies:

Roughly speaking $V(R) = 1/6\ \alpha(R)/R + C_0(\text{gluelump state}) + C_2(R)R^2 + \ldots$

Determining the Hybrid Potentials

- Putting the ends together
- Toy model - minimal parameters

$$V_n(R) = \frac{\alpha_s}{6R} + \sigma R \sqrt{1 + \frac{2\pi}{\sigma R^2}\left(n(R) - \frac{1}{24}(d-2)\right)} + V_0 \quad (n > 0)$$

$$V_{\Sigma_g^+}(R) = -\frac{4\alpha_s}{3R} + \sigma R + V_0 \quad (n = 0)$$

Fixes Mc = 1.84 GeV, $\sqrt{\sigma}$ = .427 GeV, α_s = 0.39

n(R) = [n] (string level) if no level crossing
[n - 2 tanh(R_0/R)] for Σ^-_u potential (n=3)

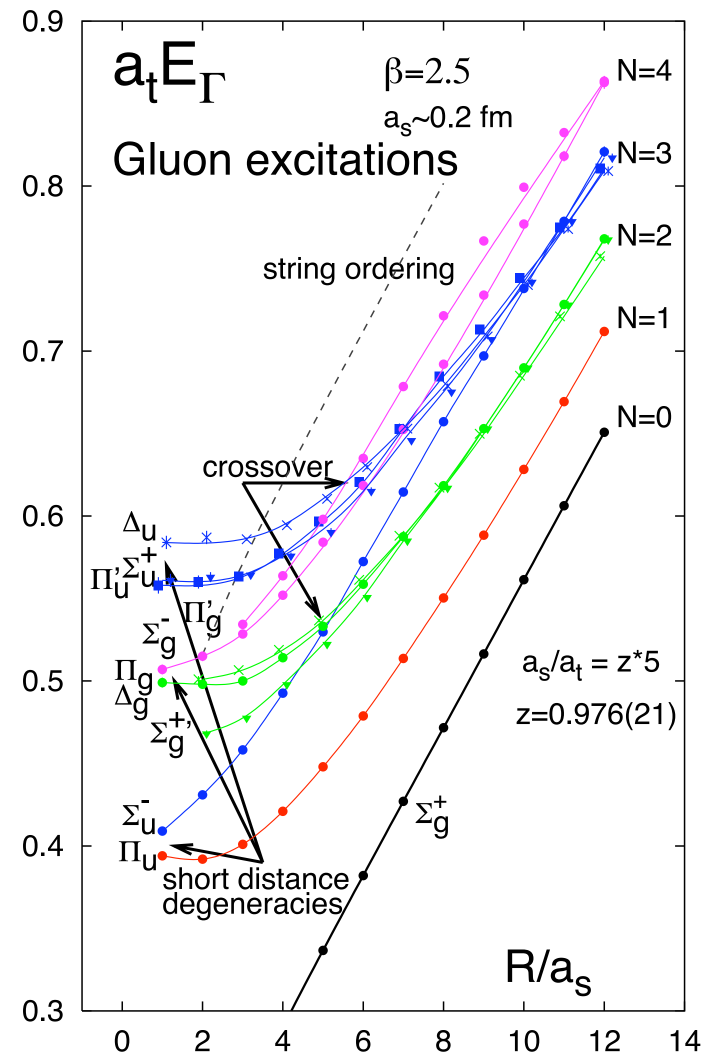
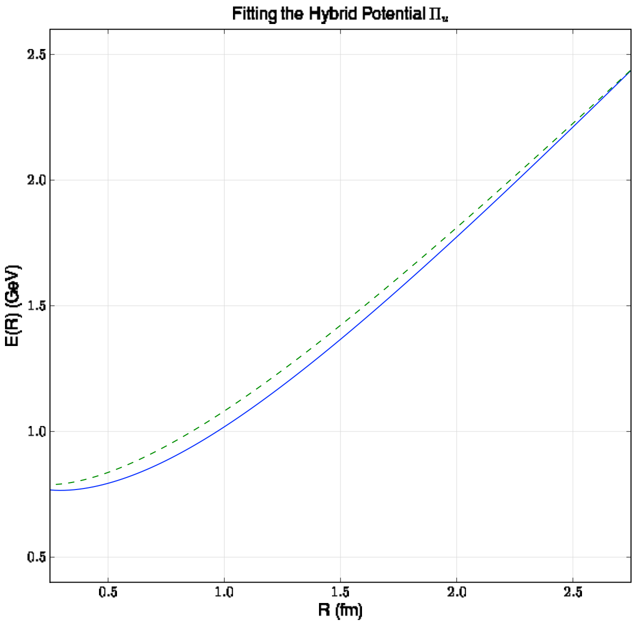
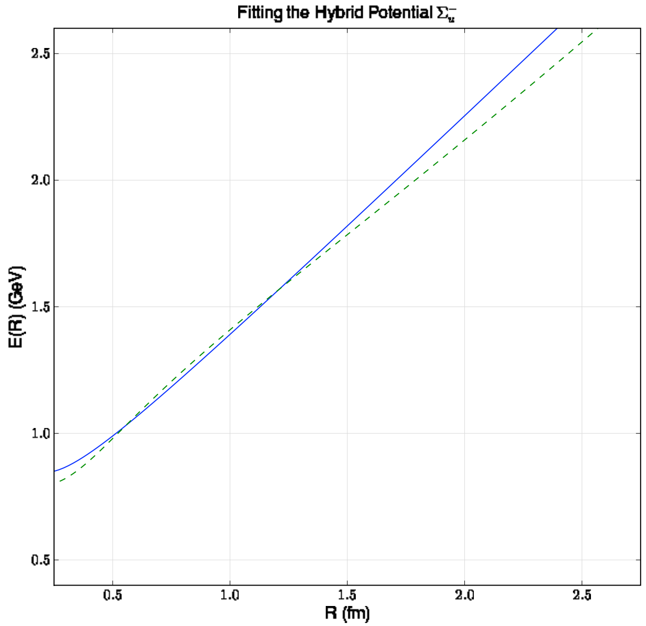
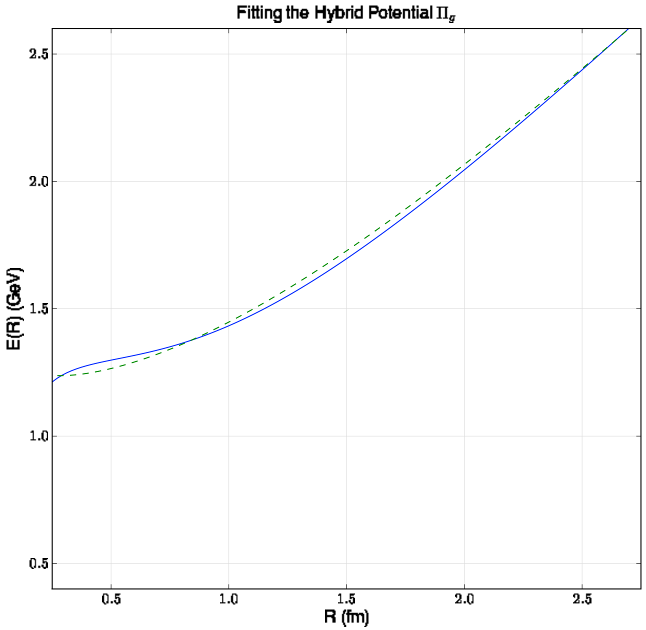


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Comparing Toy Model to Lattice Results



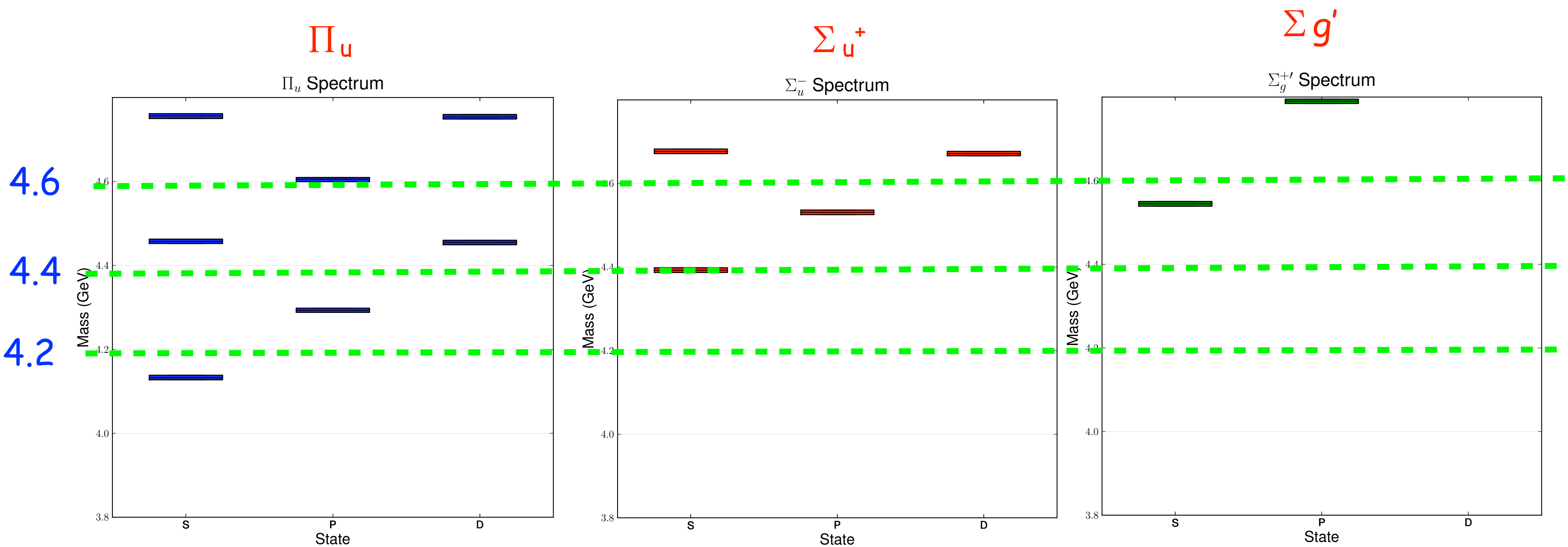




Comparing this model (dashed lines) to the parameterization of The fits to Juge, Kuti and Morningstar lattice results (thanks to Juge) (solid lines) one finds fairly good agreement in the region (0.25 fm < R < 2 fm)

Spectrum of Low-Lying Hybrid States

- Only interested in states below 4.8 GeV for cc system. Unlikely higher states will be narrow (DD, glueball+J/ψ, etc)

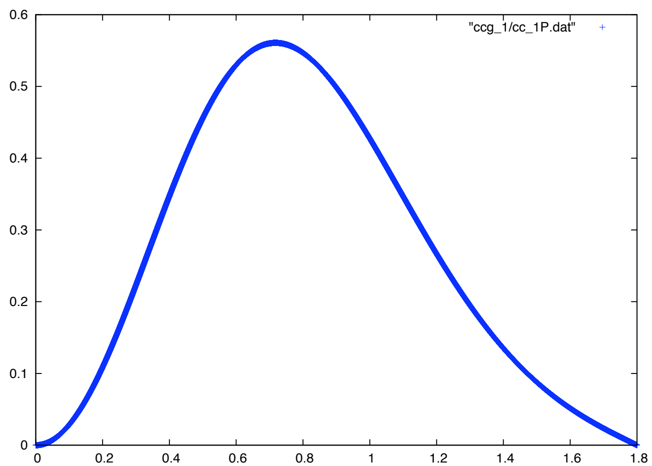


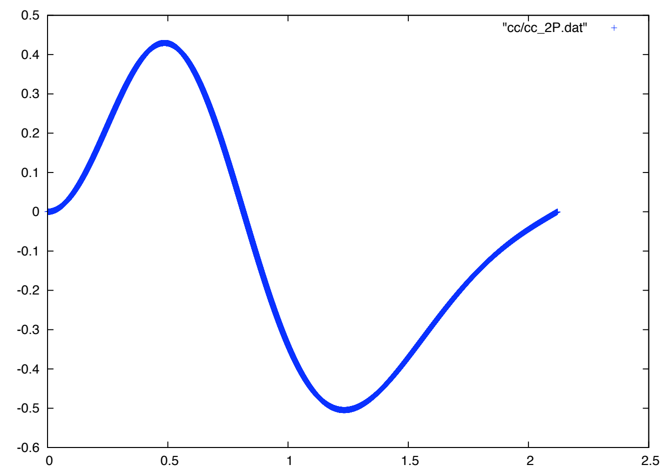
- Only Π_u, Σ_u^-, and $\Sigma_g^{+\prime}$ systems have sufficiently light states.

Spectrum of Low-Lying Hybrid States

- Π_u (1S) m = 4.132 GeV Π_u (2S) m = 4.465 GeV $J^{PC} = 0^{++}, 0^{--}, 1^{+-}, 1^{-+}$

  Π_u (1P) m = 4.445 GeV Π_u (2P) m = 4.773 GeV $J^{PC} = 1^{--}, 1^{++}, 0^{-+}, 0^{+-}, 1^{+-}, 1^{-+}, 2^{+-}, 2^{-+}$





- $\Sigma_g^{+\prime}$(1S) m = 4.547 GeV $J^{PC} = 0^{-+}, 1^{--}$
- The Π_u (1P), Π_u (2P) and $\Sigma_g^{+\prime}$(1S) have 1^{--} states with spacing seen in the Y(4260) system
- Σ_u^-(1S) m = 4.292 GeV Σ_u^-(1P) m = 4.537 GeV Σ_u^-(2S) m = 4.772 GeV
- Numerous states with C=+ in the 4.2 GeV region.
- **Approach looks promising but more work is required.**

Summary

- The wealth of precision data has solidified our confidence in the NRQCD approach below threshold [Spectrum, transitions and decays]
- The situation above threshold is not yet clear:
  - Need measurements of transition rates for established resonances.
  - Detailed measurements of R in each exclusive channel useful for probing strong decay amplitudes.
  - Need J^P determination for many of the new states.
  - New states and possibly a new spectroscopy: X(3872), X(4008), Y(4140), Y(4160), Y(4350), Y(4260), Y(4360), Y(4660), Z^+(4430), ...
- The hybrid potential approach looks promising:
  - X(3872) and Z^+(4430) states not hybrid candidates.
  - The states in the 4160 region with C=+ may contain hybrid states.
  - The Y(4260) and related 1^{--} new states. Hybrid states?

Outlook

- Improvements for hybrid spectrum
  - Can include spin dependent corrections using results from lattice and pNRQCD.
  - Understand the level crossover behavior in QCD.
  - New states with exotic quantum numbers are expected. Masses determined relative to non exotic hybrid spectrum..
  - Directly apply results to the bottomium system. No new parameters.
  - Any relation to unexpectedly large hadronic transition rates: $\Upsilon(5S) \to \Upsilon(nS)+2\pi$ (n=1,2,3) ?
- 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.

Thank You

謝謝