Hadronic Transitions in Quarkonium

Estia Eichten (Fermilab)

Outline:

- Quarkonium Basics
- QCDME approach
- Present Status and Some Puzzles
  - η transitions in J/ψ and Υ systems
  - Υ(5S) ->Υ(nS) + $\pi\pi$ transitions
- Revisiting the QCDME assumptions
  - Threshold effects
  - Hybrid potentials and XYZ states
- Summary and outlook

NRQCD

Kinetic | Potential | Static Energy

$$\mathcal{H} = \mathsf{Q}^\dagger\left[\delta m_Q - \frac{\mathbf{D}^2}{2m_Q}\right]\mathsf{Q} + \int d^3x\, j_a^0(x)\mathcal{G}^{ab} j_b^0(0)$$

$$-\mathsf{Q}^\dagger\left[\frac{c_4}{8m_Q^3}(\mathbf{D}^2)^2 + \frac{c_D}{8m_q^2}(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\right]\mathsf{Q}$$

relativistic corrections

$$-\mathsf{Q}^\dagger\left[\frac{c_s}{8m_q^2} i\sigma(\mathbf{D}\times g\mathbf{E} + g\mathbf{E}\times\mathbf{D}) + \frac{c_f}{2m_q}\sigma\cdot g\mathbf{B}\right]\mathsf{Q} + \dots$$

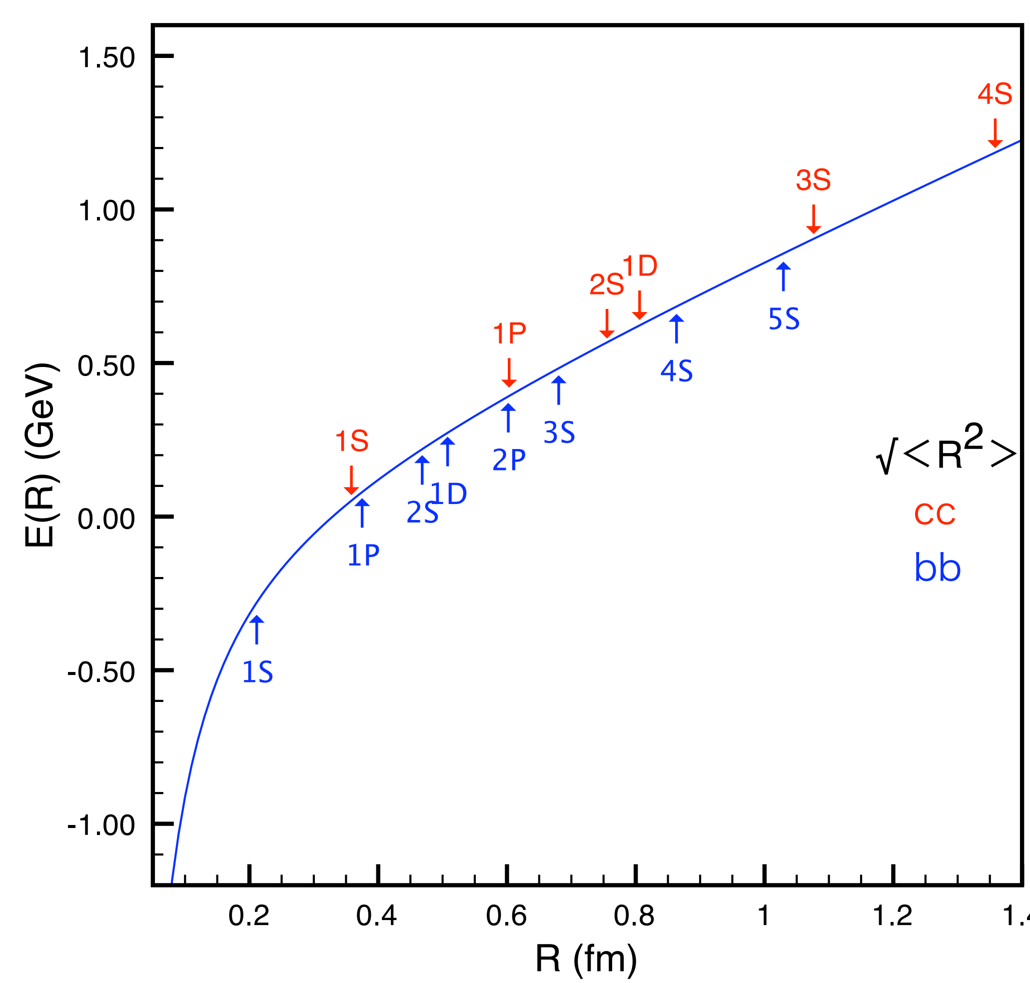
where $j_a^0 = \mathsf{Q}^\dagger g t_a \mathsf{Q} + g^2 f^{abc}\mathbf{E}_b\cdot\mathbf{A}_c + \dots$

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

$$\frac{\Lambda_{QCD}}{m_Q}\ \text{(HQET)};\qquad v\ \text{(NRQCD)}$$

- Consistency between $(b\bar{b})$ and $(c\bar{c})$ systems validates NRQCD approach.
  - masses (pNRQCD, LQCD)
  - spin splittings (pNRQCD, LQCD)
  - EM transitions (ME, LQCD)
  - hadronic transitions (ME)
  - direct decays (pQCD)

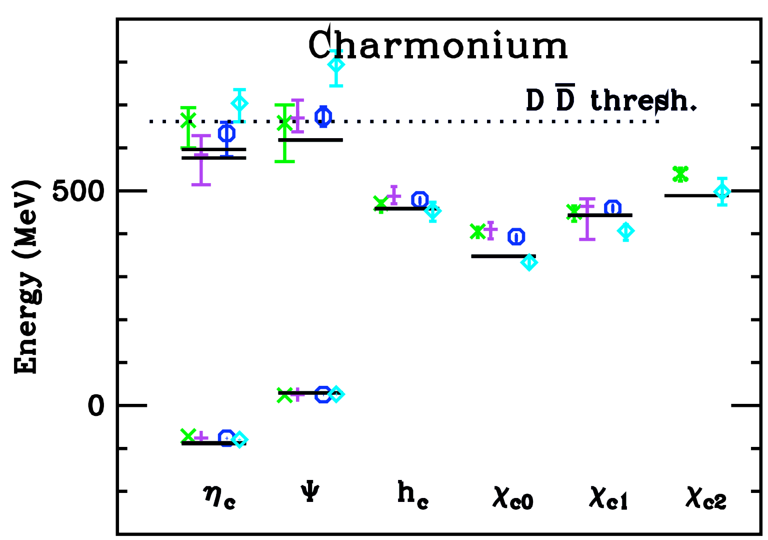
Potential model



Present Status

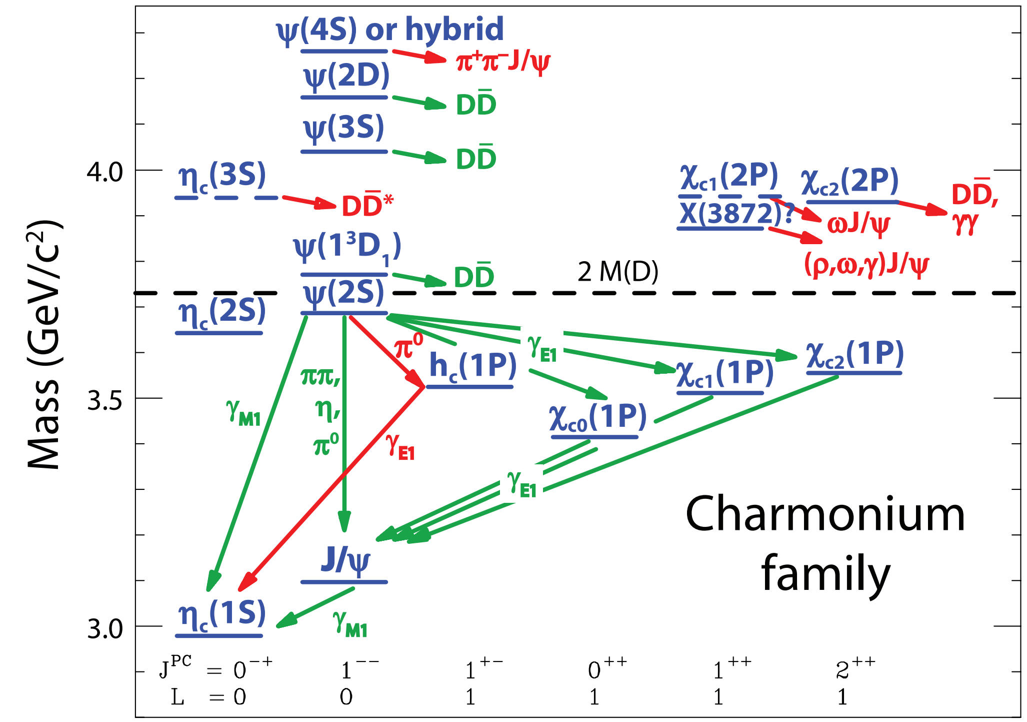
- Below threshold for heavy flavor meson pair production
  - Narrow states allow precise experimental probes of the subtle nature of QCD.
  - Lattice QCD supports and will supplant potential models
  - A variety of lattice approaches

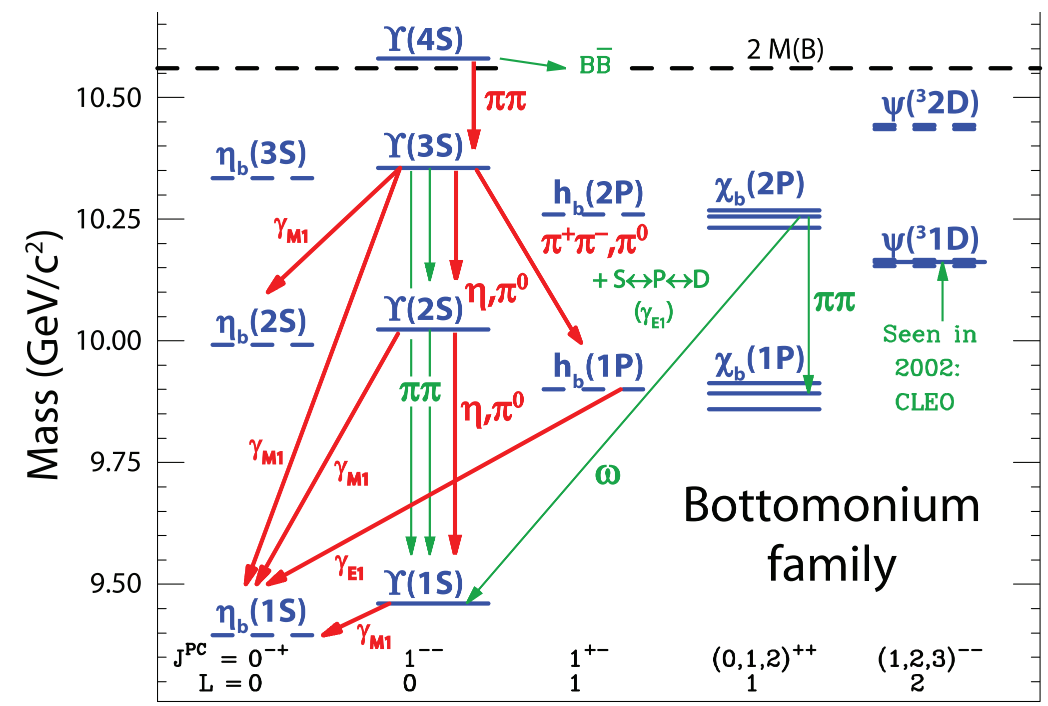
Low-lying states directly calculated in LQCD.



S. Gottlieb et al., PoS LAT2006

Figure 5: Summary of charmonium spectrum.





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

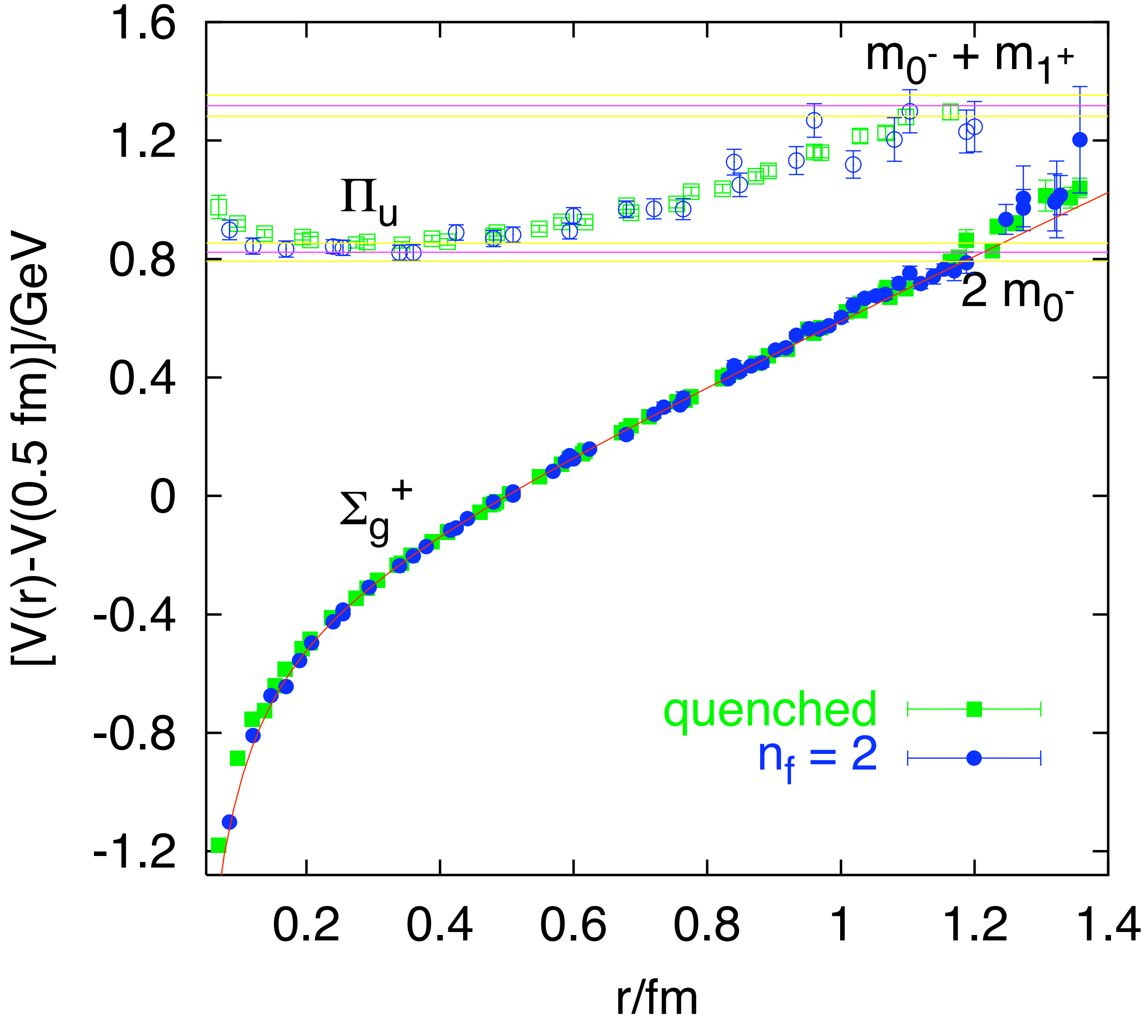
Why it works so well

- 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



QCDME

- QCD multipole expansion (basics)
  - Use dressed fields (Yan)

$$\tilde{\psi}(\mathbf{x},t) \equiv U^{-1}(\mathbf{x},t)\psi(x) \qquad U(\mathbf{x},t) = P\exp\left[ig_s \int_{\mathbf{X}}^{\mathbf{x}} \mathbf{A}(\mathbf{x}',t)\cdot d\mathbf{x}'\right]$$

$$\tilde{A}_\mu(\mathbf{x},t) \equiv U^{-1}(\mathbf{x},t)A_\mu(x)U(\mathbf{x},t) - \frac{i}{g_s}U^{-1}(\mathbf{x},t)\partial_\mu U(\mathbf{x},t).$$

  - Expand about X(CM) of $Q\bar{Q}$ system.
    r = |x-X|.

$$\tilde{A}_0(\mathbf{x},t) = A_0(\mathbf{X},t) - (\mathbf{x}-\mathbf{X})\cdot\mathbf{E}(\mathbf{X},t) + \cdots$$

$$\tilde{\mathbf{A}}(\mathbf{X},t) = -\frac{1}{2}(\mathbf{x}-\mathbf{X})\times\mathbf{B}(\mathbf{X},t) + \cdots,$$

  - Analogous to QED multipole expansion:
    E1, M1, E2, M2, E3,...
    For gluon momentum k,
    QCDME expansion parameter (rk)

$$H^{\mathrm{eff}}_{\mathrm{QCD}} = H^{(0)}_{\mathrm{QCD}} + H^{(1)}_{\mathrm{QCD}} + H^{(2)}_{\mathrm{QCD}}$$

$$H^{(1)}_{\mathrm{QCD}} \equiv Q_a A^a_0(\mathbf{X},t)$$ zero for color singlet

  - $H^{(0)}$ is treated exactly (color singlet $Q\bar{Q}$).
    The $H^{(2)}$ correction appears first in second order [couples color singlet to octet $Q\bar{Q}$].

E1 M1 ...

$$H^{(2)}_{\mathrm{QCD}} \equiv -\mathbf{d}_a\cdot\mathbf{E}^a(\mathbf{X},\mathbf{t}) - \mathbf{m_a}\cdot\mathbf{B^a}(\mathbf{X},\mathbf{t}) + \cdots$$

QCDME

- QCD multipole expansion (basics)
  - Factorize heavy quark dynamics and light hadron production.

$$\mathcal{M}(\Phi_i \to \Phi_f + h) =$$
$$\frac{1}{24}\sum_{KL}\frac{\langle f|d_m^{ia}|KL\rangle\langle|KL|d_{ma}^{j}|i\rangle}{E_i - E_{KL}}\langle h|\mathbf{E}^{ai}\mathbf{E}_a^j|0\rangle$$

+ higher order multipole terms.

  - Assume models for spectrum of $H^{(0)}$ (potential model) and intermediate states |KL> (QCS Buchmueller-Tye)

where |KL> are a complete set of intermediate states.

$$\langle f\ h|H_2\mathcal{G}(E_i)H_2|i\rangle = \sum_{KL}\langle f\ h|H_2|KL\rangle\frac{1}{E_i - E_{KL}}\langle KL|H_2|i\rangle$$

with

$$\mathcal{G}(E) = \frac{1}{E - H_{\rm QCD}^{(0)} + i\partial_0 - H_{\rm QCD}^{(1)} + i\epsilon}$$

  - Chiral effective lagrangian to parameterize light hadron matrix elements.

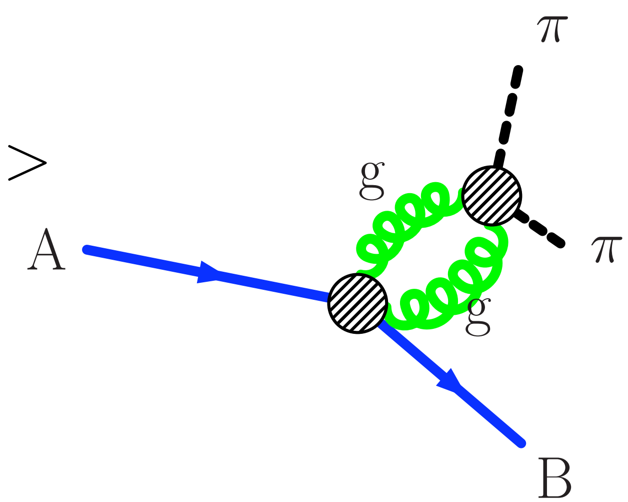
QCDME

- two pion transitions (E1-E1) $(C_A C_B = +1)$
  - Factorization

$$\mathcal{M}_{if}^{gg} = \frac{1}{16} < B|\mathbf{r_i}\xi^a \mathcal{G} \mathbf{r_j}\xi^a|A > \quad \frac{g_{\mathrm{E}}^2}{6} < \pi_\alpha \pi_\beta | Tr(\mathbf{E^i E^j}) | 0 >$$

$$\alpha^{EE}_{AB}$$

Hadronize



  - Chiral symmetry

S-wave D-wave

$$\frac{\delta_{\alpha\beta}}{\sqrt{(2\omega_1)(2\omega_2)}} \left[C_1 \delta_{kl} q_1^\mu q_{2\mu} + C_2 \left(q_{1k} q_{2l} + q_{1l} q_{2k} - \frac{2}{3} \delta_{kl} \, (q_1 \cdot q_2) \right) \right]$$

  - Explicit model - Kuang & Yan (PR D24, 2874 (1981))

$$d\Gamma \sim K \sqrt{1 - \frac{4m_\pi^2}{M_{\pi\pi}^2}} (M_{\pi\pi}^2 - 2m_\pi^2)^2 \; dM_{\pi\pi}^2 \qquad K \equiv \frac{\sqrt{(M_A+M_B)^2 - M_{\pi\pi}^2} \sqrt{(M_A-M_B)^2 - M_{\pi\pi}^2}}{2M_A}$$

S state -> S state

$$\Gamma = \mathrm{G} \; |\alpha^{\mathrm{EE}}_{\mathrm{AB}} \; \mathrm{C}_1|^2$$

Phase Space

Overlap - Buchmuller-Tye string inspired model)

QCDME

- eta transitions (E1-M2, M1-M1) $(C_A C_B = +1)$ $O(v^2)$
  - E1-M2 expected to dominate
  - Factorization

$$\mathcal{M}_{if}^{gg} = \underbrace{\frac{1}{16} < B|\mathbf{r_i}\xi^a \mathcal{G} \mathbf{r_j}\xi^a|A >}_{\alpha_{AB}^{EE}} \quad \frac{g_e g_M}{6} \langle \eta | \mathbf{E}_i \partial_j \mathbf{B}_k | 0 \rangle \; \frac{(\epsilon_B^* \times \epsilon_A)_k}{3m_Q}$$

Hadronize

  - Chiral symmetry

$$i(2\pi)^{3/2} C_3 q_k$$

  - Relation to other single pseudoscalar transitions

Chiral symmetry breaking - Chiral effective lagrangian

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

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

Present Status of Hadronic Transitions

Transition	Partial Width (keV)	
	Exp	Theory
$\psi(2S)$		
$\to J/\psi + \pi^+\pi^-$	102.3 ± 3.4	input($\|C_1\|$)
$\to J/\psi + \eta$	10.0 ± 0.4	input(C_3/C_1)
$\to J/\psi + \pi^0$	0.411 ± 0.030 [122]	0.64 [114]
$\to h_c(1P) + \pi^0$	0.26 ± 0.05 [123]	0.12-0.40 [46]
$\psi(3770)$		
$\to J/\psi + \pi^+\pi^-$	52.7 ± 7.9	input($C_2/C_\|$)
$\to J/\psi + \eta$	24 ± 11	
$\psi(3S)$		
$\to J/\psi + \pi^+\pi^-$	< 320 (90%cl)	
$\Upsilon(2S)$		
$\to \Upsilon(1S)+\pi^+\pi^-$	5.79 ± 0.49	8.7 [115]
$\to \Upsilon(1S) + \eta$	$(6.7 \pm 2.4) \times 10^{-3}$	0.025 [117]
$\Upsilon(1^3D_2)$		
$\to \Upsilon(1S)+\pi^+\pi^-$	0.188 ± 0.046 [107]	0.07 [121]
$\chi_{b1}(2P)$		
$\to \chi_{b1}(1P) + \pi^+\pi^-$	0.83 ± 0.33 [106]	0.54 [124]
$\to \Upsilon(1S) + \omega$	1.56 ± 0.46	
$\chi_{b2}(2P)$		
$\to \chi_{b2}(1P) + \pi^+\pi^-$	0.83 ± 0.31 [106]	0.54 [124]
$\to \Upsilon(1S) + \omega$	1.52 ± 0.49	
$\Upsilon(3S)$		
$\to \Upsilon(1S)+\pi^+\pi^-$	0.894 ± 0.084	1.85 [115]
$\to \Upsilon(1S)+\eta$	$< 3.7 \times 10^{-3}$	0.012 [117]
$\to \Upsilon(2S)+\pi^+\pi^-$	0.498 ± 0.065	0.86 [115]
$\Upsilon(4S)$		
$\to \Upsilon(1S)+\pi^+\pi^-$	1.64 ± 0.25	4.1 [115]
$\to \Upsilon(1S)+\eta$	4.02 ± 0.54	
$\to \Upsilon(2S)+\pi^+\pi^-$	1.76 ± 0.34	1.4 [115]
$\Upsilon(5S)$		
$\to \Upsilon(1S)+\pi^+\pi^-$	228 ± 33	
$\to \Upsilon(1S)+K^+K^-$	26.2 ± 8.1	
$\to \Upsilon(2S)+\pi^+\pi^-$	335 ± 64	
$\to \Upsilon(3S)+\pi^+\pi^-$	206 ± 80	

Experiment vs Theory

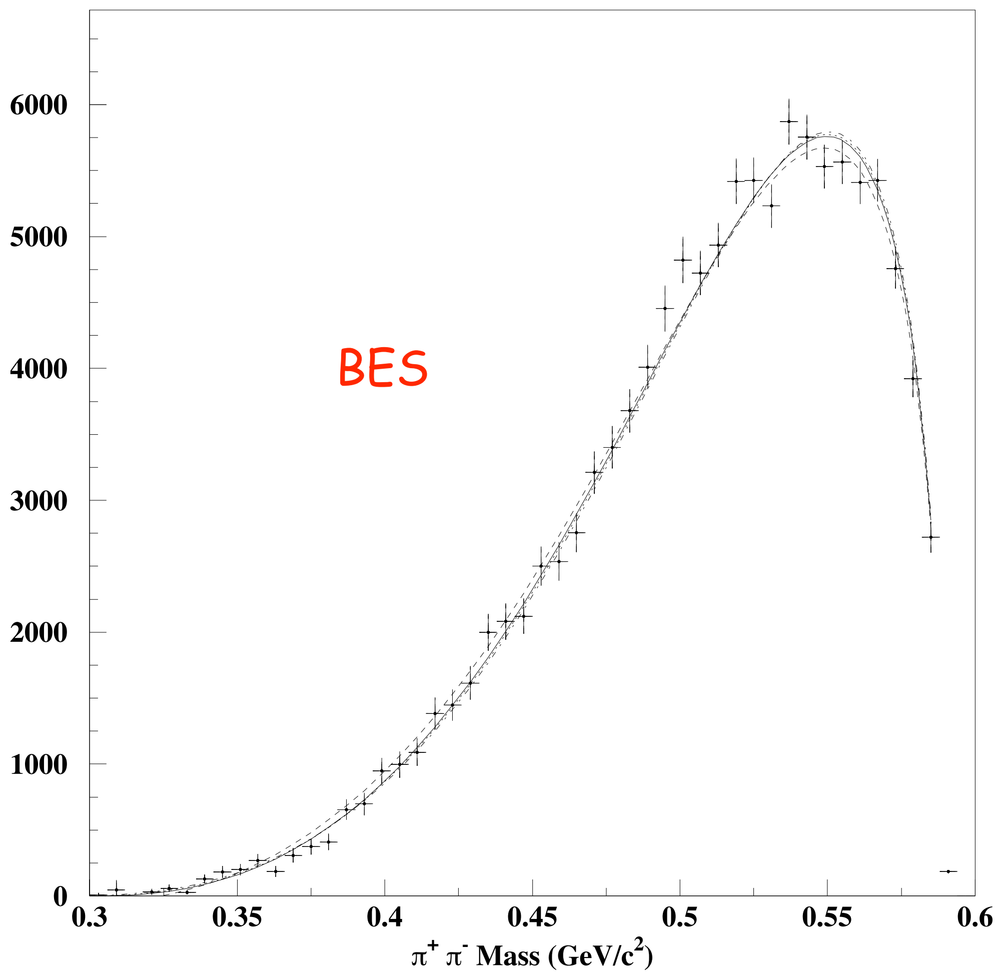
- Many transitions observed.
- Some missing theory entries.
- Generally good agreement for hadronic transitions between low-lying quarkonium states.
- The coefficients in the light hadron matrix elements set by data:
  - $|C_1| = (10.2 \pm 0.2) \times 10^{-3}$
  - $|C_2/C_1| = 1.75 \pm 0.14$ (Cornell)
  - $|C_3/C_1| = 0.78 \pm 0.02$
- Two puzzles:
  - η transitions J/ψ and Υ systems
  - $\Upsilon(5S) \to \Upsilon(nS)\,\pi\,\pi$

Avoid dependence on BT model

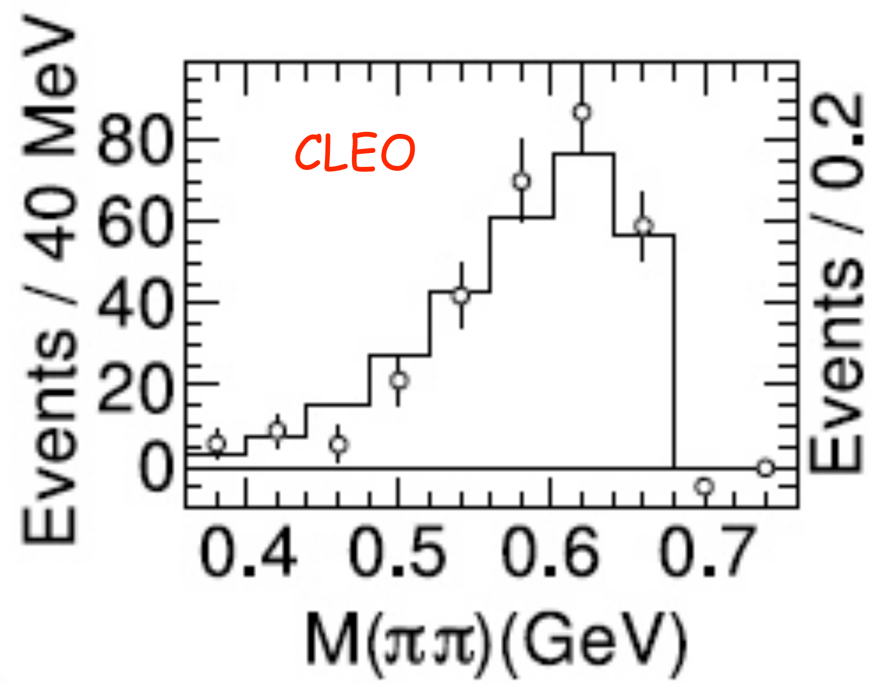
Some Puzzles

- Observed $M_{\pi\pi}$ distributions:

ψ'->J/ψ $\pi^+\pi^-$



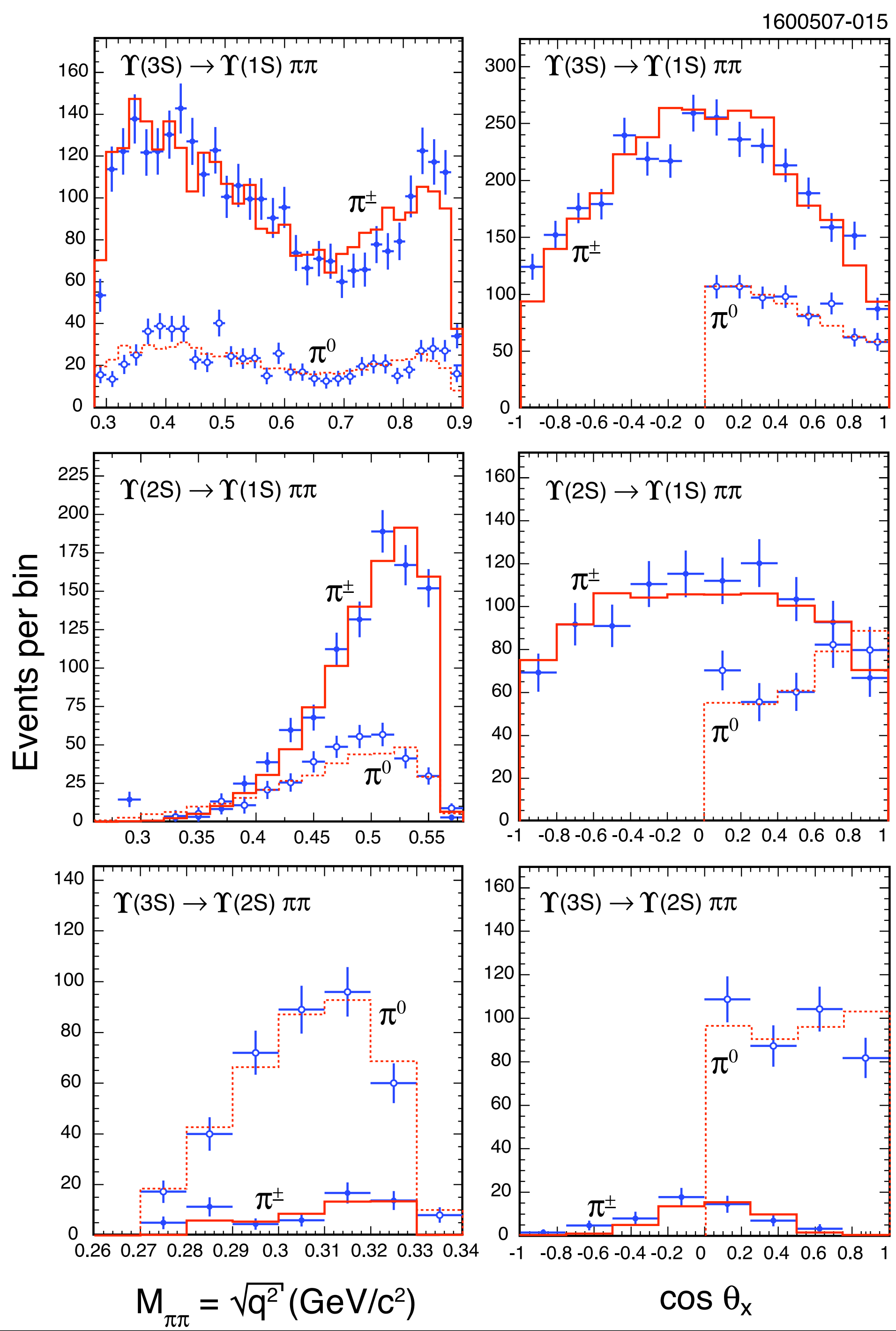
ψ(3770)->J/ψ $\pi^+\pi^-$

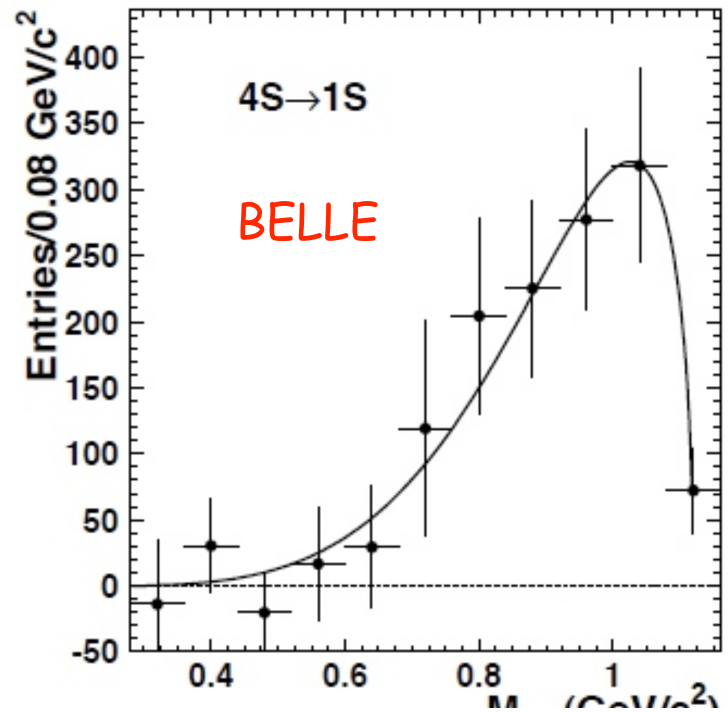


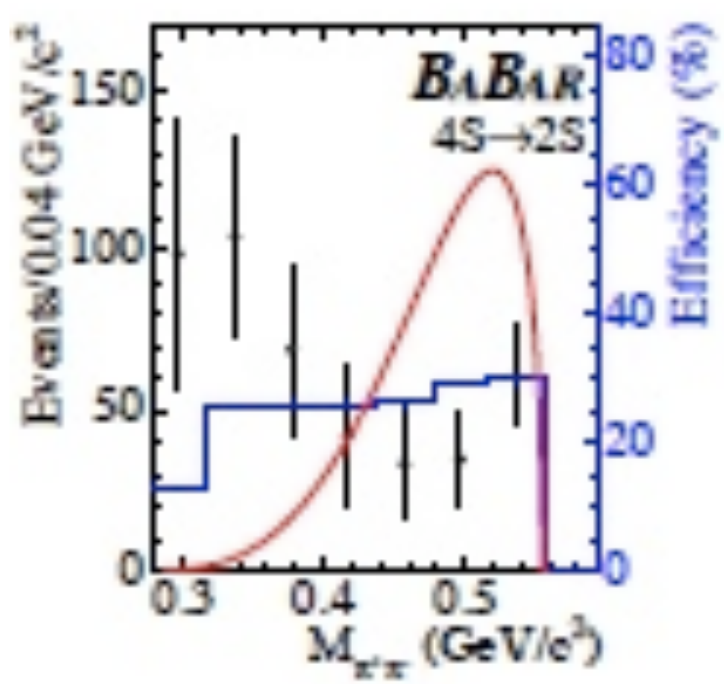
Some Puzzles

- $\Upsilon(3S) \to \Upsilon(1S)\ \pi\pi$ and $\Upsilon(4S) \to \Upsilon(2S)\ \pi\pi$

  $M_{\pi\pi}$ distributions not expected S-wave







Some Puzzles

- Reducing model dependence
  - transitions well below the first string excitation (E_{TH}), so expand

$$\mathcal{G}(E) = \sum_{KL} |KL\rangle \frac{1}{E - E_{KL}} \langle KL|$$
$$= \frac{1}{E - E_{\rm TH}} + \sum_{KL} (\frac{E_{KL} - E_{\rm TH}}{E - E_{\rm TH}}) |KL\rangle \frac{1}{E - E_{KL}} \langle KL|$$

model dependence suppressed

(a) E << E_{TH}

(b) small overlap of low-lying QQ states with high |KL> states.

  - for E1-E1 transitions

$$\langle B|\mathbf{r}^i \chi^a \mathcal{G}(E_i) \mathbf{r}^j \chi_b |A\rangle = \frac{\delta^{ij}\delta^a_b}{E_A - E_{\rm TH}} \langle B|\mathbf{r}^2|A\rangle + \cdots$$

  - compare results with known transitions

$E^{c\bar{c}}_{\rm TH} = 4.5\ GeV$ and $E^{b\bar{b}}_{\rm TH} = 11.25\ GeV$ assumed

Transition	G $(\mathrm{GeV})^7$	$\langle f|r^2|i\rangle > (\mathrm{GeV})^{-2}$	Γ(exp) (keV)	Γ(overlap) (keV)
$\psi(2S) \to J/\psi + \pi^+\pi^-$	3.56×10^{-2}	3.36	102.3 ± 3.4	input($|C_1|$)
$\Upsilon(2S) \to \Upsilon(1S) + \pi^+\pi^-$	2.87×10^{-2}	1.19	5.79 ± 0.49	5.9
$\Upsilon(3S) \to \Upsilon(1S) + \pi^+\pi^-$	1.09	2.37×10^{-1}	0.894 ± 0.084	12.9
$\Upsilon(3S) \to \Upsilon(2S) + \pi^+\pi^-$	9.09×10^{-5}	3.70	0.498 ± 0.065	0.26
$\Upsilon(4S) \to \Upsilon(1S) + \pi^+\pi^-$	5.58	9.74×10^{-2}	1.64 ± 0.25	19.9
$\Upsilon(4S) \to \Upsilon(2S) + \pi^+\pi^-$	2.61×10^{-2}	4.64×10^{-1}	1.76 ± 0.34	2.1

OK only if overlap is sizable

Some Puzzles

- The η transitions

Ratio of eta to two pion transition for same quarkonium states at $(M_{\pi\pi} = M_\eta)$

$$R_{Q\bar{Q}}(n \to m) \equiv \frac{\Gamma(n^3S_1 \to m^3S_1 + \eta)}{\Gamma(n^3S_1 \to m^3S_1 + \pi^+\pi^-)} = \frac{8\pi^2}{27}\frac{1}{m_Q^2}(\frac{C_3}{C_1})^2[\frac{[(M_i+M_f)^2 - M_\eta^2)((M_i-M_f)^2 - M_\eta^2)]^{3/2}}{G}]$$

[kinematic factor]

is independent of the details of the intermediate states.

- Comparing theory and experiment

Ratio	theory	experiment
$R^{c\bar{c}}(2 \to 1)$	3.29×10^{-3}	9.78×10^{-2}
$R^{b\bar{b}}(2 \to 1)$	1.16×10^{-3}	1.16×10^{-3}
$R^{b\bar{b}}(3 \to 1)$	4.57×10^{-3}	$< 4.13 \times 10^{-3}$
$R^{b\bar{b}}(4 \to 1)$	2.23×10^{-3}	2.45
$R^{b\bar{b}}(4 \to 2)$	5.28×10^{-4}	

~ 30 > theory

sets $C_3/C_1 = 0.143 \pm 0.024$

~ 1000 > theory

- Large M1-M1 terms for states near threshold?

$$\langle B|\sigma^i\chi^a\mathcal{G}(E_i)\sigma^j\chi_b|A\rangle = \frac{\epsilon^{ijk}\delta^a_b}{E_A - E_{\rm TH}}\langle B|\sigma^k|A\rangle + \cdots$$

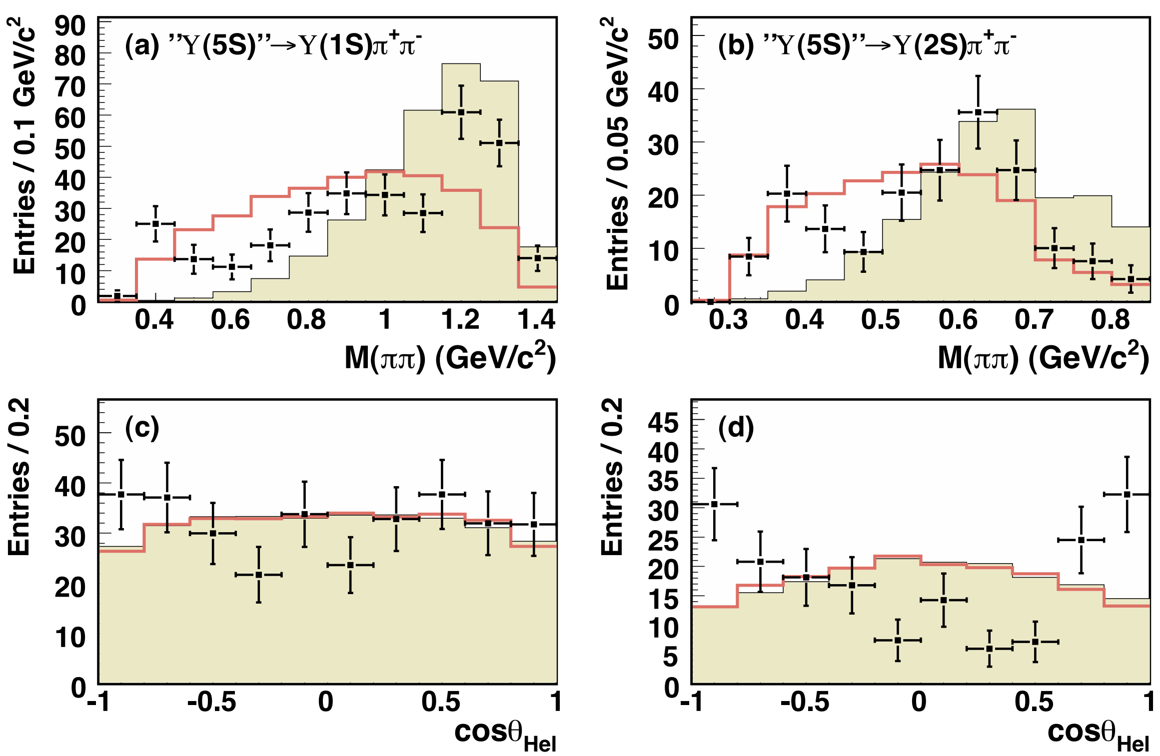
zero as states are orthogonal

Some Puzzles

- The Belle measurements of $\Upsilon(5S) \to \Upsilon(nS) + \pi\pi$ transitions

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 Υ(4S).
- In region of hybrid low-lying states

W. S. Hou [PR D74 (2006) 017504]

Crossing Thresholds

- Usual thresholds - (QQ) -> (Qq) + (qQ) decays -> dominates total widths
  - Strong coupling to virtual decay channels induces spin-dependent forces in charmonium near threshold, because $M_{(Qq)^*} > M_{(Qq)}$
  - Effects are small for states far below threshold

Less that 1 MeV shift ⇒

Reduces ΔM(2S) by 21 MeV ⇒

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	$4\,040^a$		$+22^e$	$+1.0$

ELQ PRD 73:014014 (2006)

- New dynamics in threshold region
  - Hybrids
  - Tetraquark states ?
  - XYZ states

New Neutral States Above Charm Threshold

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle, CDF, D0, BaBar	$3871.2 \pm 0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$, $\gamma\psi'$	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^{++}	$D^0 D^0$, $D^+ D^-$	$\gamma\gamma$
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+}	$D^* D^*$	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(4360)	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)
Y(4660)	Belle	$4664 \pm 11 \pm 5 + i(48 \pm 15 \pm 3)$	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)

Understanding the New XYZ States

- 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
    - $(Qq)(\bar{q}\bar{Q})$ Diquark-Antidiquark
    - $(Q\bar{Q})(\bar{q}q)$ Hadro-charmonium
  - Hybrids - Exciting the gluonic degrees of freedom:
    - valance gluons, string
  - Strong threshold effects:
    - strong interactions, interplay of decay channels

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]

Hybrid States and Lattice QCD

- Heavy quark limit: Born-Oppenheimer approximation

$$-\frac{1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle \boldsymbol{L}^2_{Q\bar{Q}}\rangle}{2\mu r^2}+V_{Q\bar{Q}}(r)\right\}u(r)=E\,u(r) \qquad \Psi_{Q\bar{Q}}(\vec{r}) = \frac{u_{nl}(r)}{r}\mathrm{Y}_{\mathrm{lm}}(\theta,\phi)$$

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	$(\mathbf{R}\times\mathbf{D})^i(\mathbf{R}\times\mathbf{E})^j+(\mathbf{R}\times\mathbf{D})^j(\mathbf{R}\times\mathbf{E})^i$

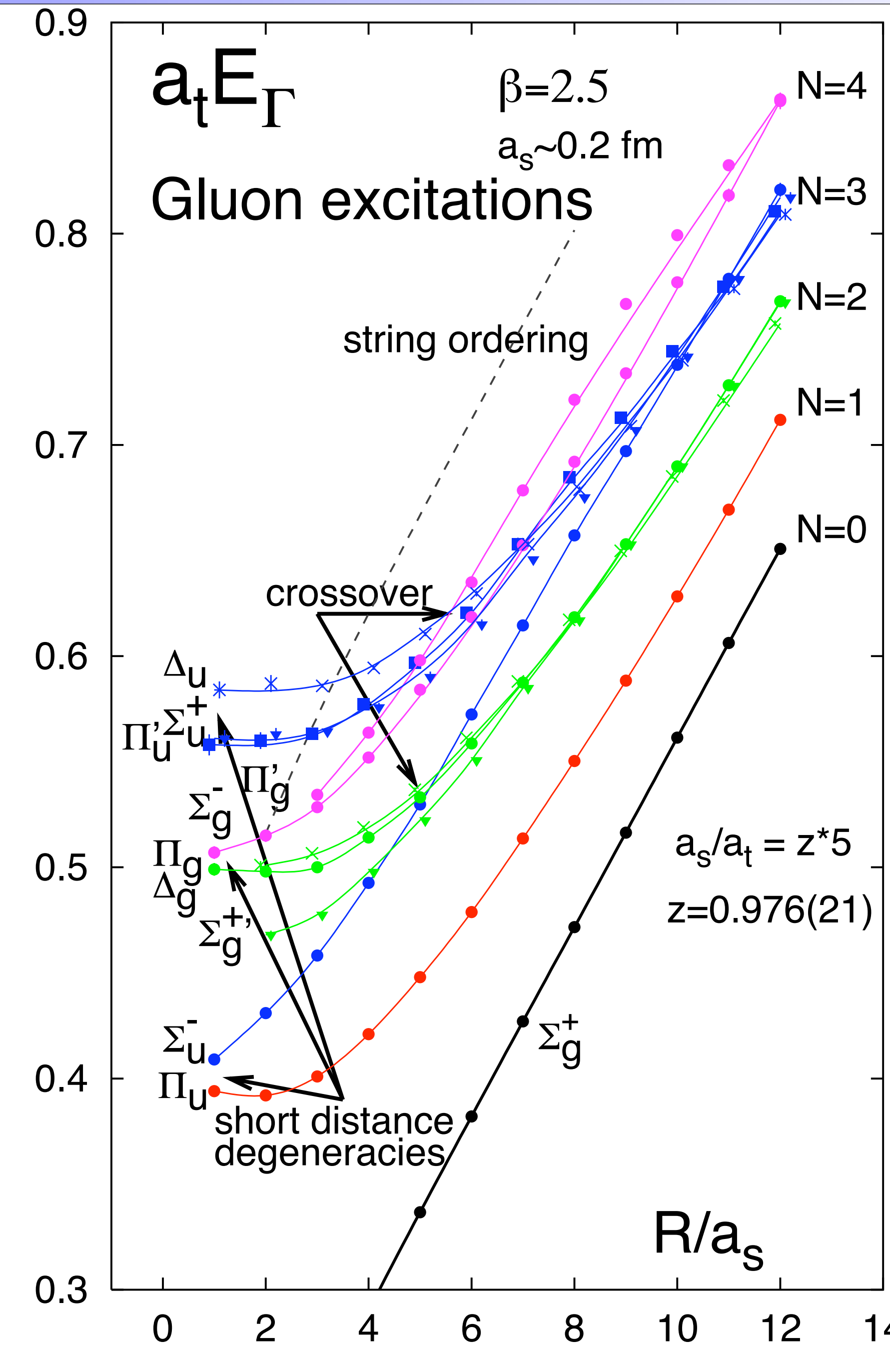


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

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

Low-Lying Spectrum

- No evidence for exotic J^{PC} in new Onia states.
- Mainly interested in non-exotics: $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}, 1^{+-}, \ldots$

$L_{QQ}(L_{QQ} + 1) = L(L+1) - 2\Lambda^2 + J_g(J_g+1)$; $P = \varepsilon(-1)^{L+\Lambda+1}$; $C = \varepsilon\eta(-1)^{L+S+\Lambda}$

$\Lambda = 0$ Σ states

$L = 0 \Rightarrow P = \varepsilon(-1)$ $C = \varepsilon\eta(-1)^S$

$L_{QQ} = J_g$

(S=0) $J^{PC} = 0^{-+}$: $\Sigma^+_g, \Sigma'^+_g, \Sigma''^+_g, \ldots$ (J_g=0, 1, 2,..)

$J^{PC} = 0^{++}$: $\Sigma^-_u, \Sigma'^-_u, \Sigma''^+_u, \ldots$ (J_g=1, 2,..)

(S=1) $J^{PC} = 1^{+-}$: $\Sigma^-_u, \Sigma'^-_u, \Sigma''^-_u, \ldots$ (J_g=1, 2,..)

$J^{PC} = 1^{--}$: $\Sigma^+_g, \Sigma'^+_g, \Sigma''^+_g, \ldots$ (J_g=0,1, 2,..)

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

$L_{QQ} = 1, J_g = 0$

(S=0) $J^{PC} = 1^{+-}$: Σ^+_g

(S=1) $J^{PC} = 1^{+-}$: Σ^+_u ; $J^{PC} = 0^{++}$: Σ^+_g

$L = 2 \Rightarrow P = \varepsilon(-1)$ $C = \varepsilon\eta(-1)^S$

$L_{QQ} = 2, J_g = 0$ (S=1) $J^{PC} = 1^{+-}$: Σ^-_u, Σ''^-_u

$L_{QQ} = 3, J_g = 2$ $J^{PC} = 1^{--}, 1^{++}$: $\Sigma^+_g, \Sigma''^+_g, \Sigma^-_g, \Sigma''^-_g$

Low-Lying Spectrum

$\Lambda = 1$ Π states ($J_g > 0$)

$L = 0$ => $P = \varepsilon(+1)$ $C = \varepsilon\eta(-1)^{S+1}$

$L_{QQ} = 0, J_g = 1$	(S=0)	$J^{PC} = 0^{-+}$: Π_g	(ε =-1)
		$J^{PC} = 0^{++}$: Π_u	(ε =+1)
	(S=1)	$J^{PC} = 1^{++}, 1^{--}$: Π_g	(ε =±1)

$L = 1$ => $P = \varepsilon(-1)$ $C = \varepsilon\eta(-1)^{S}$

$L_{QQ} = J_g$	(S=0)	$J^{PC} = 1^{--}, 1^{++}$: Π_u, Π'_u, ...	(J_g=1, 2,..)	(ε =±1)
		$J^{PC} = 1^{+-}$: Π_g, Π'_g, ...	(J_g=1, 2,..)	(ε = -1)
	(S=1)	$J^{PC} = 0^{++}$: Π_g, Π'_g, ...	(J_g=1, 2,..)	(ε = -1)
		$J^{PC} = 0^{-+}$: Π_u, Π'_u, ...	(J_g=1, 2,..)	(ε = +1)
		$J^{PC} = 1^{--}, 1^{++}$: Π_g, Π'_g, ...	(J_g=1, 2,..)	(ε =±1)
		$J^{PC} = 1^{+-}$: Π_u, Π'_u, ...	(J_g=1, 2,..)	(ε =-1)

$\Lambda = 2$ Δ states ($J_g > 1$)

$L = 2$ => $P = \varepsilon(-1)$ $C = \varepsilon\eta(-1)^{S}$

$L_{QQ} = 2, J_g = 3$ (S=1) $J^{PC} = 1^{--}, 1^{++}$ Λ''_g (ε =±1)

Higher Λ ($J_g > 2$)

$L = 2$ $S = 1$

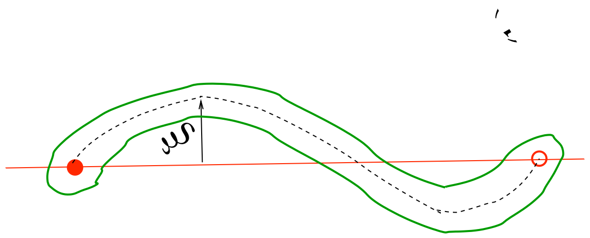
$L_{QQ}(L_{QQ} + 1) = 6 - 2\Lambda^2 + J_g(J_g+1)$ [$\Lambda = 3, J_g = 8$]; [$\Lambda = 4, J_g = 15$], ...

- Need Hybrid potentials for: Σ'^{+}_g, Σ^{-}_g, Π_g, Σ^{+}_u, Π_u, Δ_g

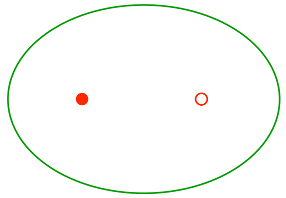
Determining the Hybrid Potentials

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

Long distance: String
$\sigma\, r + \pi N/r$ NG string behaviour



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 behaviour with lattice
calculations in the region [0.25 fm < R < 2 fm]

Determining the Hybrid Potentials

- Long distance (R > 2 fm)

Solution for the energy spectrum of the Nambu-Goto (NG) string action

$$V_n(R) = \sigma R \sqrt{1 + \frac{2\pi}{\sigma R^2}(n - \frac{1}{24}(d-2))}$$

O. Alvarez, Phys. Rev. D24, 440 (1981).
J. F. Arvis, Phys. Lett. B127, 106 (1983).

n is string excitation mode -- consistent in d = 26 dimensions

The leading correction for large R is expected to be universal.

$$d = 4$$

J. Polchinski and A. Strominger, Phys. Rev. Lett. 67, 1681 (1991)
M. Luscher and P. Weisz, JHEP 07, 049 (2002),

$$V_n(R) = \sigma R + \frac{\pi}{R}(n - \frac{1}{12}) + \ldots$$

This behavior is confirmed by lattice calculations in (d=3,4) and (SU(2),SU(3))

G. S. Bali, Phys. Rept. 343, 1 (2001)
C. Bernard et al. (MILC), Nucl. Phys. Proc. Suppl. 119, 598 (2003)
K. J. Juge, J. Kuti and C. J. Morningstar, Nucl. Phys. Proc. Suppl. 63, 326 (1998)
K. J. Juge, J. Kuti and C. Morningstar, Phys. Rev. Lett. 90, 161601 (2003).

Thus the excitation spectrum of hybrids at large R is determined completely
the behavior of the ground state system (the usual quarkonium potential)
$\sqrt{\sigma} \approx 430$ MeV --> $E_n - E_{n-1} \approx 210$ MeV (at R = 3 fm)

Determining the Hybrid Potentials

- Short distance (R < 0.25 fm)

The Q Qbar Singlet(S) and Octet(O) potentials have been calculated in pNRQCD:

$$V^{[S,O]}(R) = [-C_F, (\frac{C_A}{2} - C_F)] \frac{4\pi\alpha_s(R)}{R} \times \left(1 + \sum_{n=1}^{\infty} a_n^{[S,O]} \left[\frac{\alpha_s(R)}{4\pi}\right]^n\right)$$

[Fischler:1977] [Billoire:1979]. $a_1^S = a_1^O = \frac{31}{9} C_A - \frac{10}{9} n_l + 2\gamma_E \beta_0$

The two-loop coefficient, a_2^S, has been found more recently [Peter:1997][Schroder:1998] [Kniehl:2001]
In this order $a_2^O \neq a_2^S$ differ and it is known
The non-logarithmic third-order term, a_3, is still unknown

The leading behavior has the usual QCD coulomb coefficients: -4/3 (S); +1/6 (O)

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)

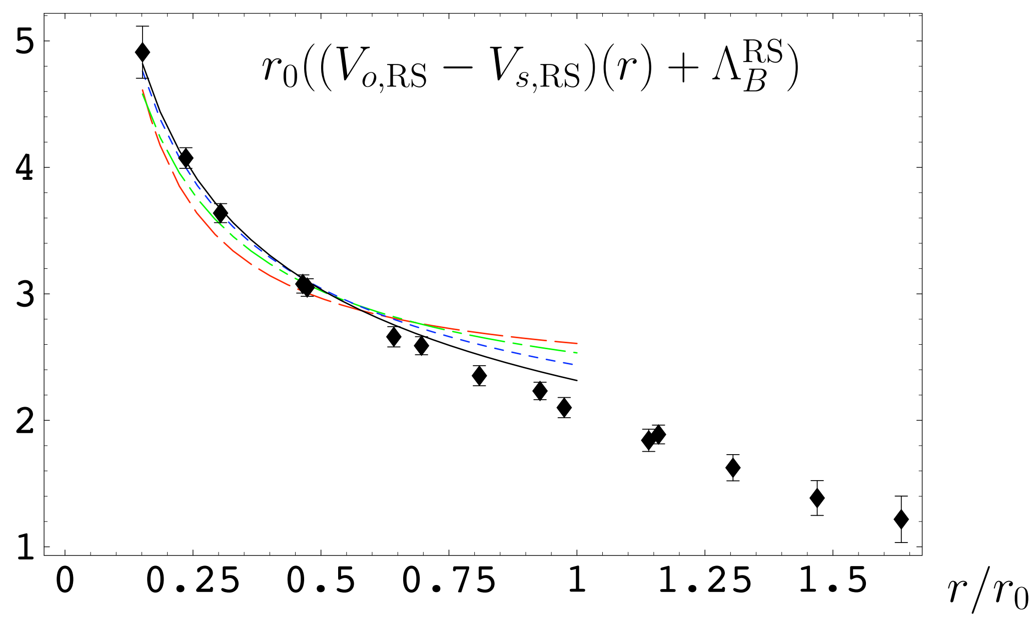
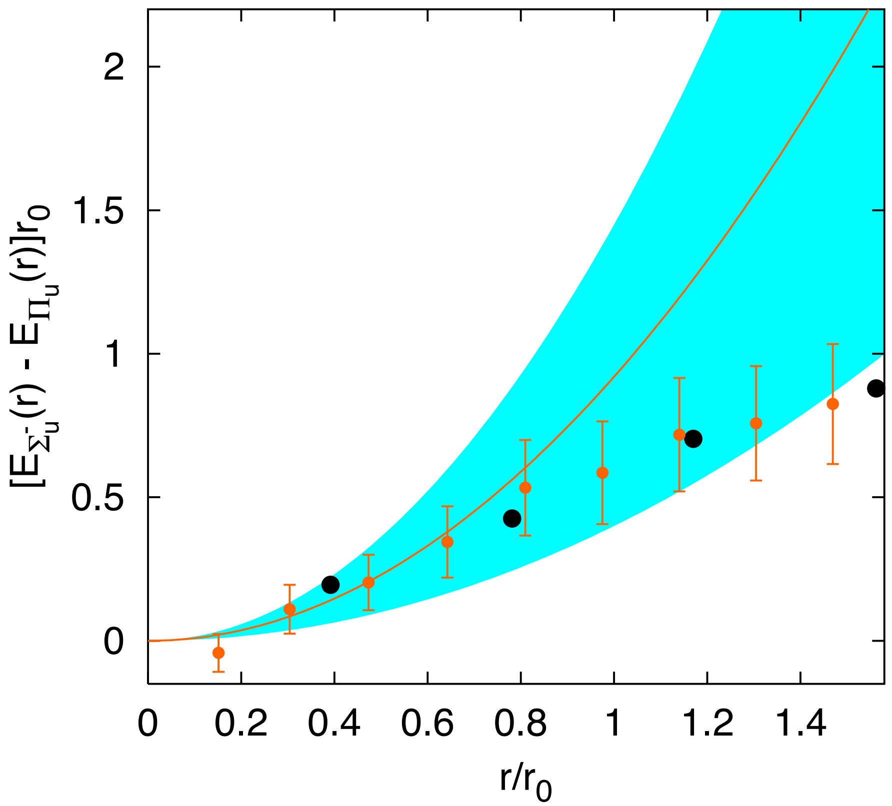


Figure 12: *Splitting between the Π_u and the Σ_g^+ potentials and the comparison with Eq. (65) for $\nu = \nu_i$ [see Eq. (16)] at $\nu_f = 2.5\, r_0^{-1}$. $r_0[(V_{o,\mathrm{RS}} - V_{s,\mathrm{RS}})(r) + \Lambda_B^{\mathrm{RS}}]$ is plotted at tree level (dashed line), one-loop (dashed-dotted line),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

A. Pineda [hep-lat/0702019]



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)

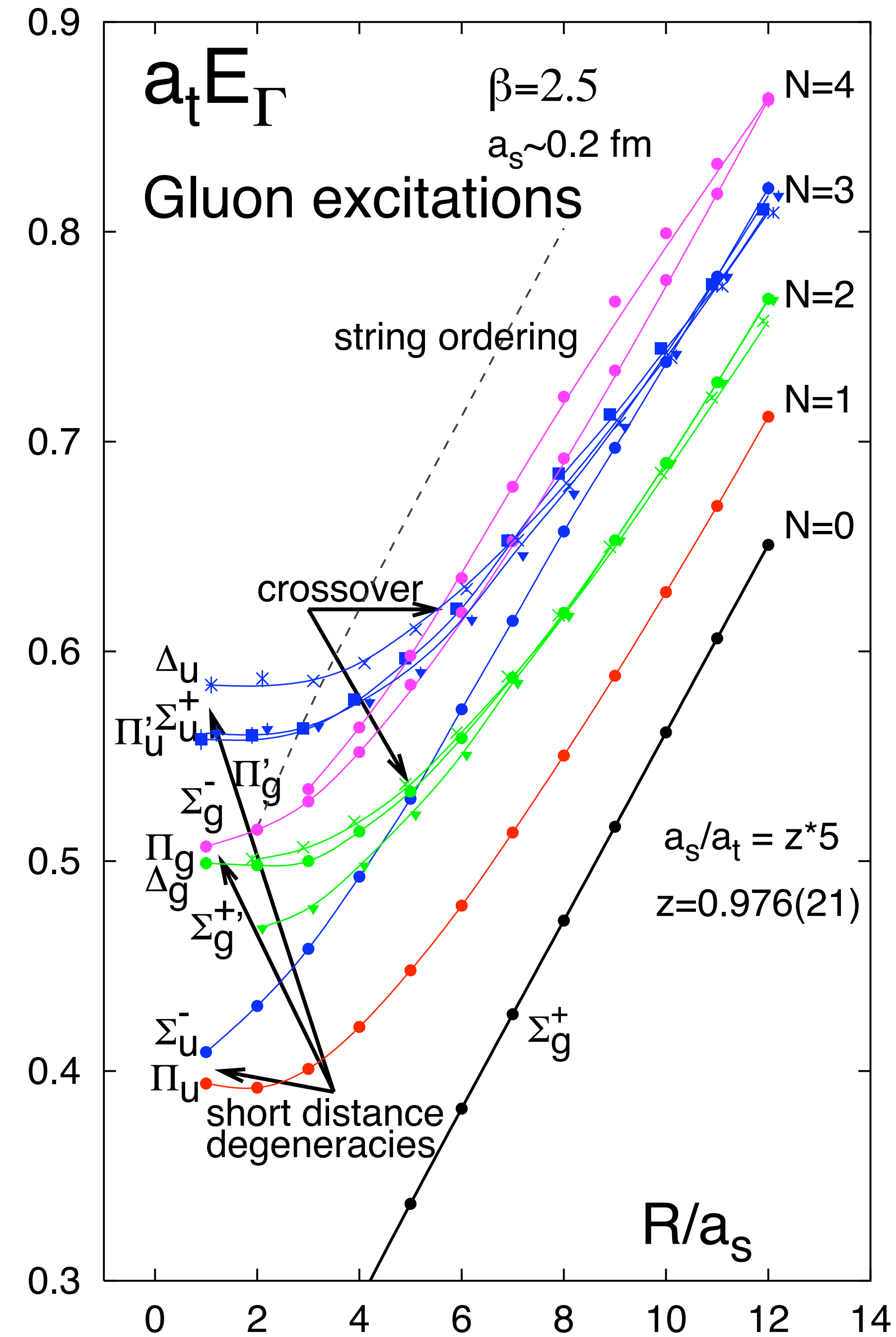
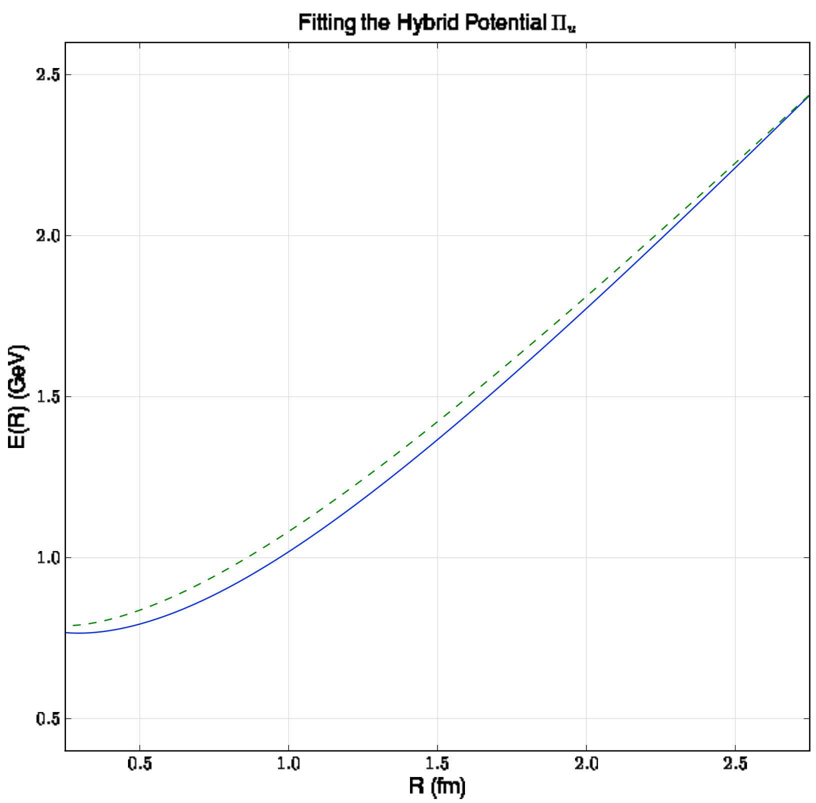
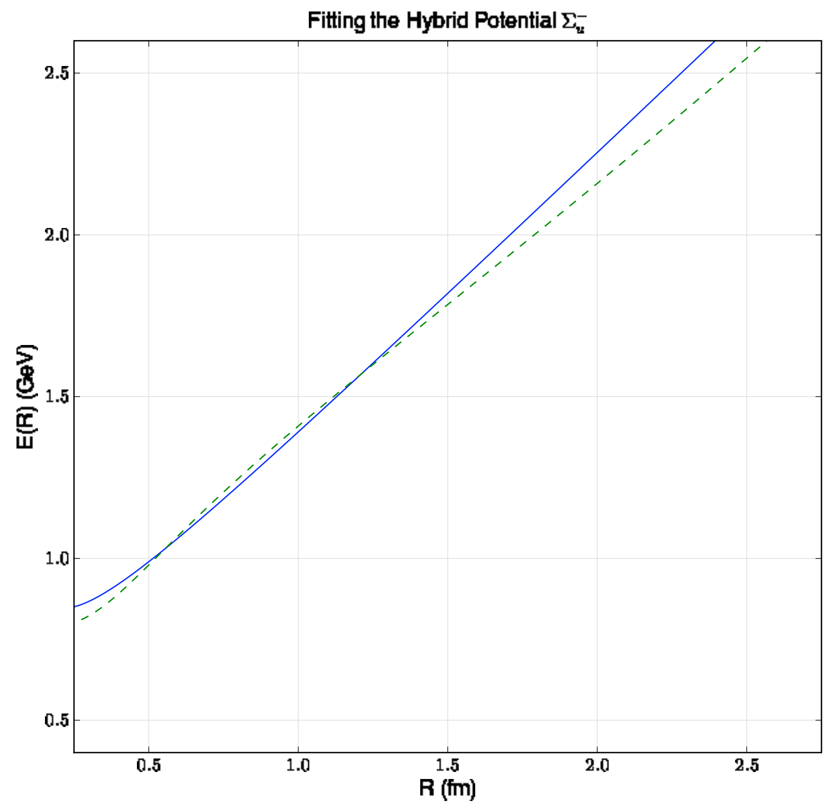
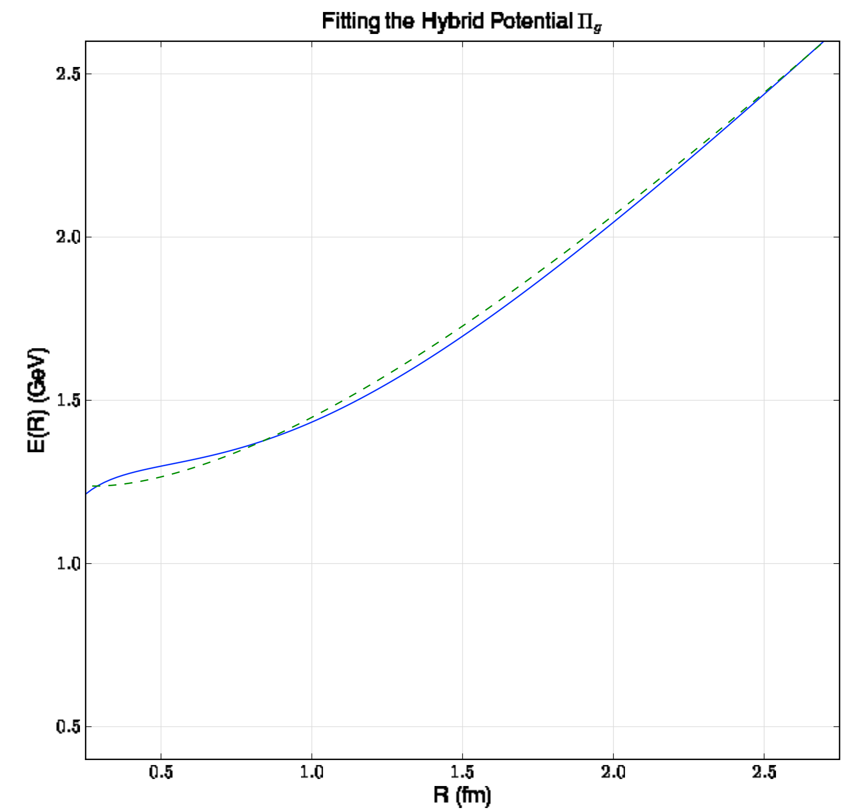


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Comparing Toy Model to Lattice Results



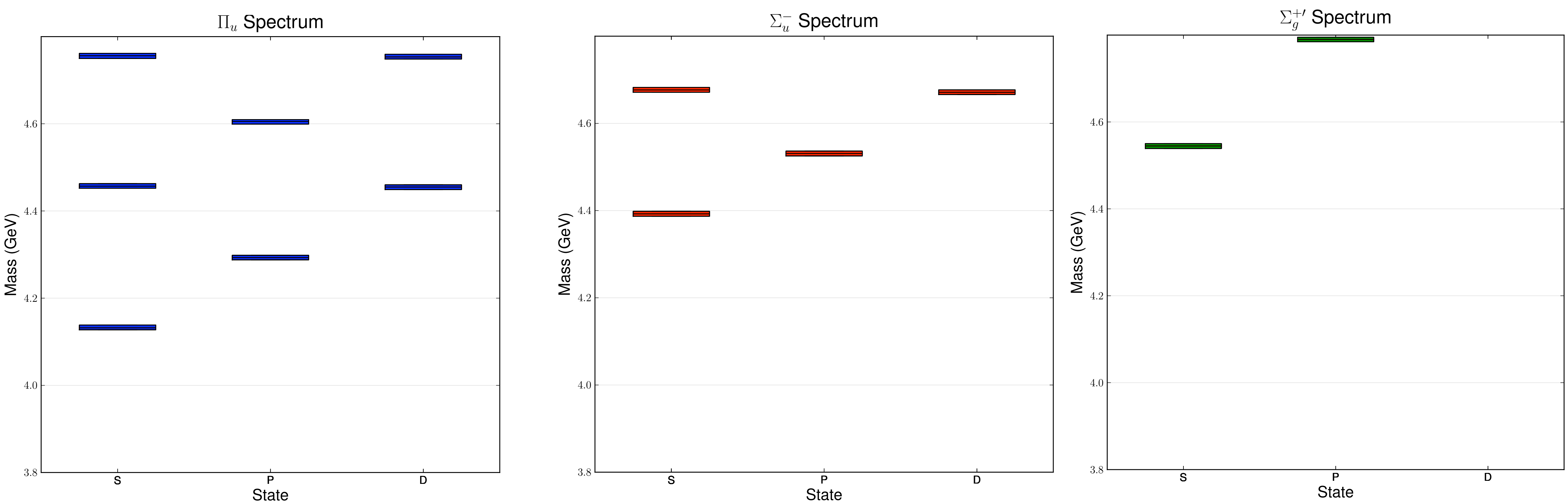




Comparing this model (dashed lines) to the parameterization of The fits to Juge, Kuti and Morningstar lattice results (thanks to Juge) (solid lines) one finds fairly good agreement in the region (0.25 fm < R < 2 fm)

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)

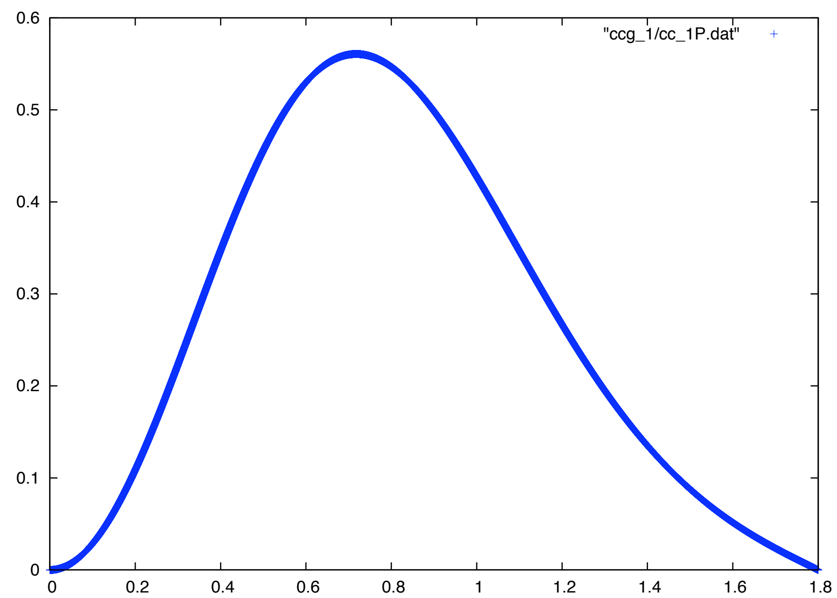


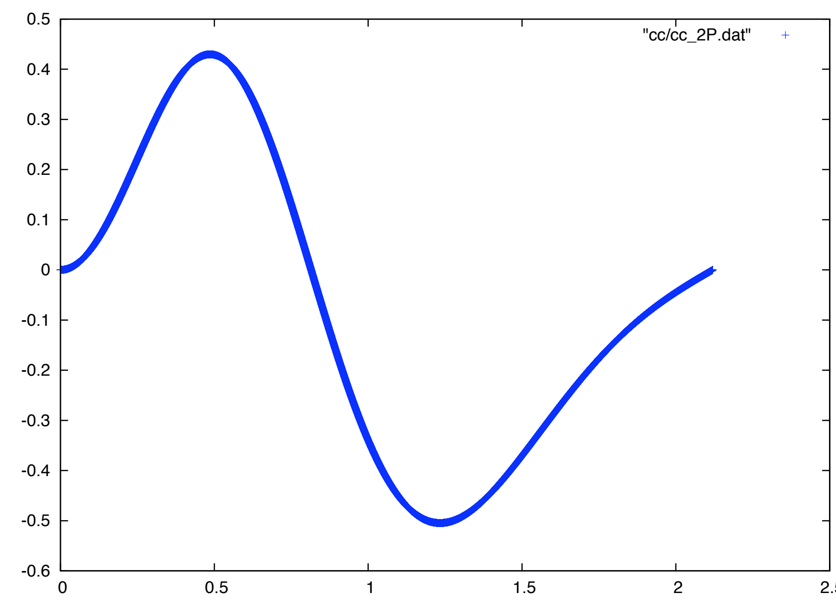
- Only Π_u, Σ_u^-, and $\Sigma_g^{+\prime}$ systems have sufficiently light states.

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.

Spectrum of Low-Lying Hybrid States

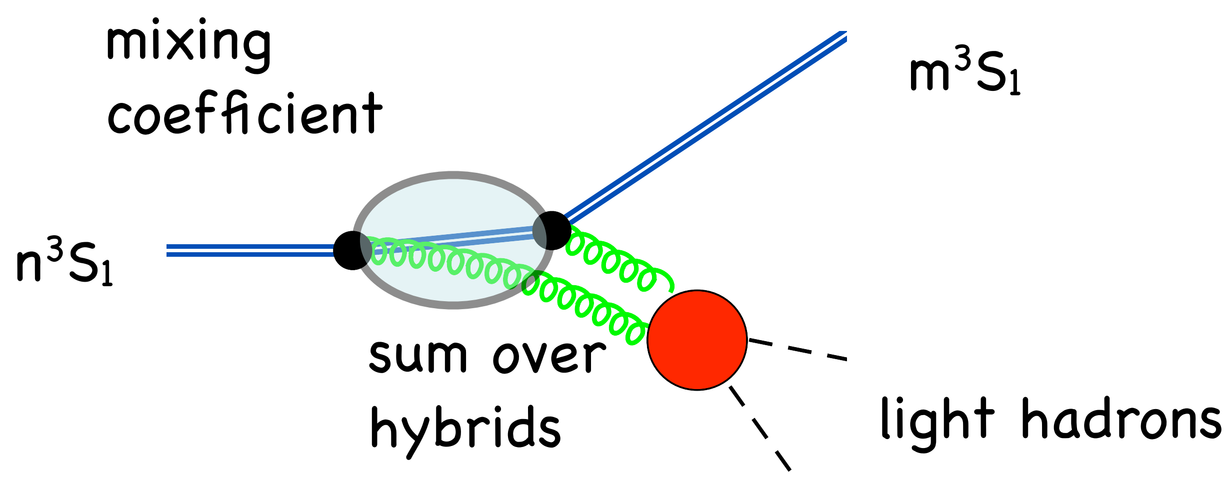
- The spectrum of bottomonium hybrids is completely predicted as well
- For the Π_u states

(cc)	L	n	mass(GeV)
	0	1	4.132580
	0	2	4.454556
	0	3	4.752947
	0	4	5.032962
	0	5	5.298250
	0	6	5.551412
✓	1	1	4.293717
	1	2	4.604123
	1	3	4.893249
	1	4	5.165793
	1	5	5.424925
	2	1	4.454768
	2	2	4.753368
	2	3	5.033384

(bb)	L	n	mass(GeV)
	0	1	10.783900
	0	2	10.982855
	0	3	11.172408
	0	4	11.353469
	0	5	11.527274
	0	6	11.694851
	0	7	11.856977
	0	8	12.014256
✓	1	1	10.877928
	1	2	11.073672
	1	3	11.259766
	1	4	11.437735
	1	5	11.608810
	1	6	11.773931
	1	7	11.933823
	2	1	10.976071
	2	2	11.167070
	2	3	11.349124
	2	4	11.523652
	2	5	11.691737
	2	6	11.854216

Hybrid Decays and Hadronic Transitions

- Information from hadronic transitions might be used to estimate decay rates for a hybrid 1^{--} state (H) to a (QQ) state (ψ(nS)) + light hadrons.



- Branching ratios: BR(H->ψ' + $\pi^+\pi^-$)/BR(H->J/ψ + $\pi^+\pi^-$) calculable.

- Mixing between (QQ) states and hybrid (QQg) states can be calculated using Lattice QCD.

Summary

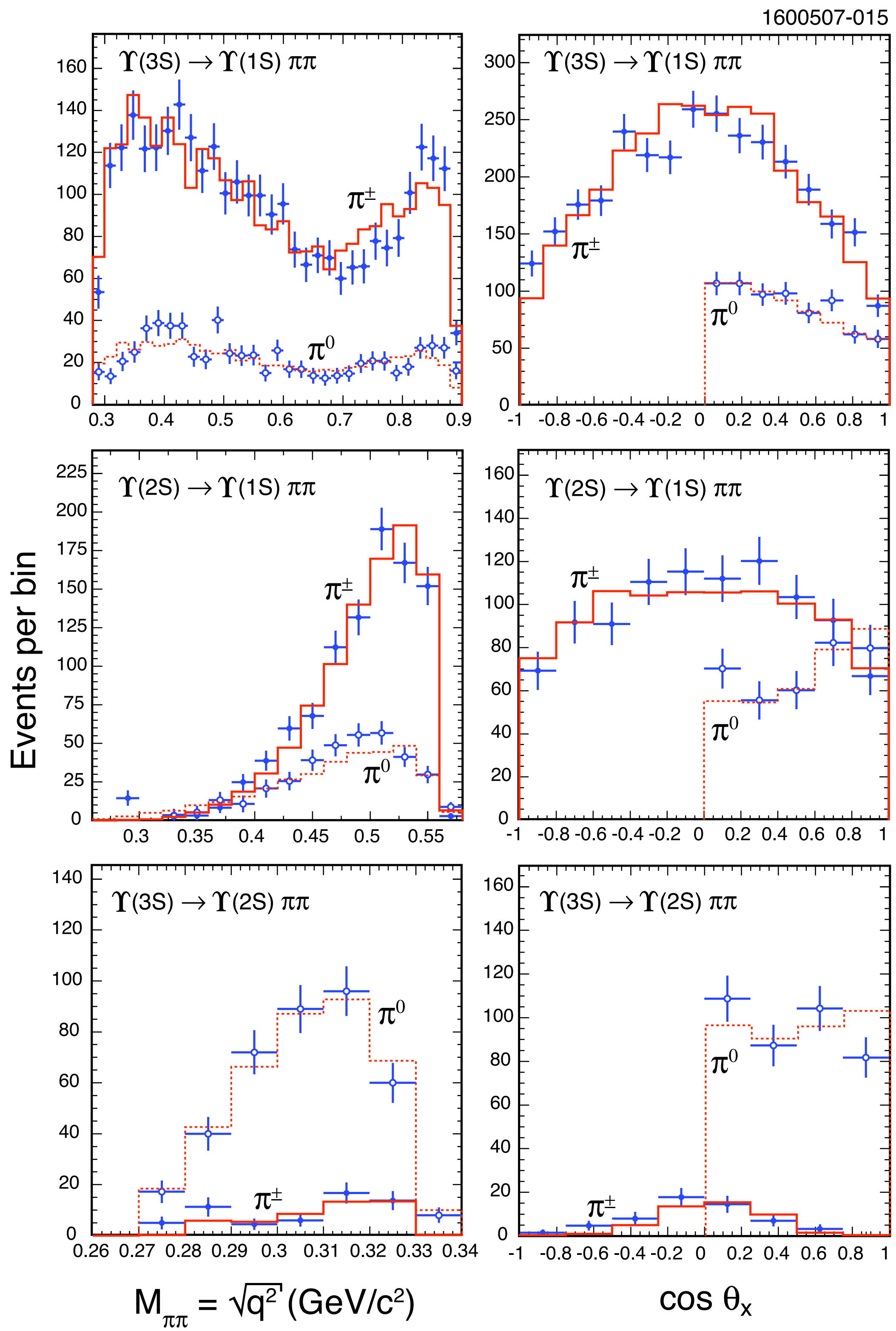
- The wealth of precision data brings the QCDME approach for hadronic transitions into sharp focus.
- Although there are many successes for the Kuang-Yan model. Some puzzling issues remain:
  - Υ(nS) -> Υ(mS) +2π transitions for (n,m)=(3,1);(4,2);(5,m)
  - ψ' -> J/ψ + η; Υ(nS) -> Υ(mS) + η transitions
  - 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:
  - The states in the 4160 region with C=+ may contain hybrid states.
  - The Y(4260) and related 1^{--} new states. Hybrid states?
  - For any XYZ state that is a hybrid, its decays to quarkonium states may be related to the standard hadronic transitions.

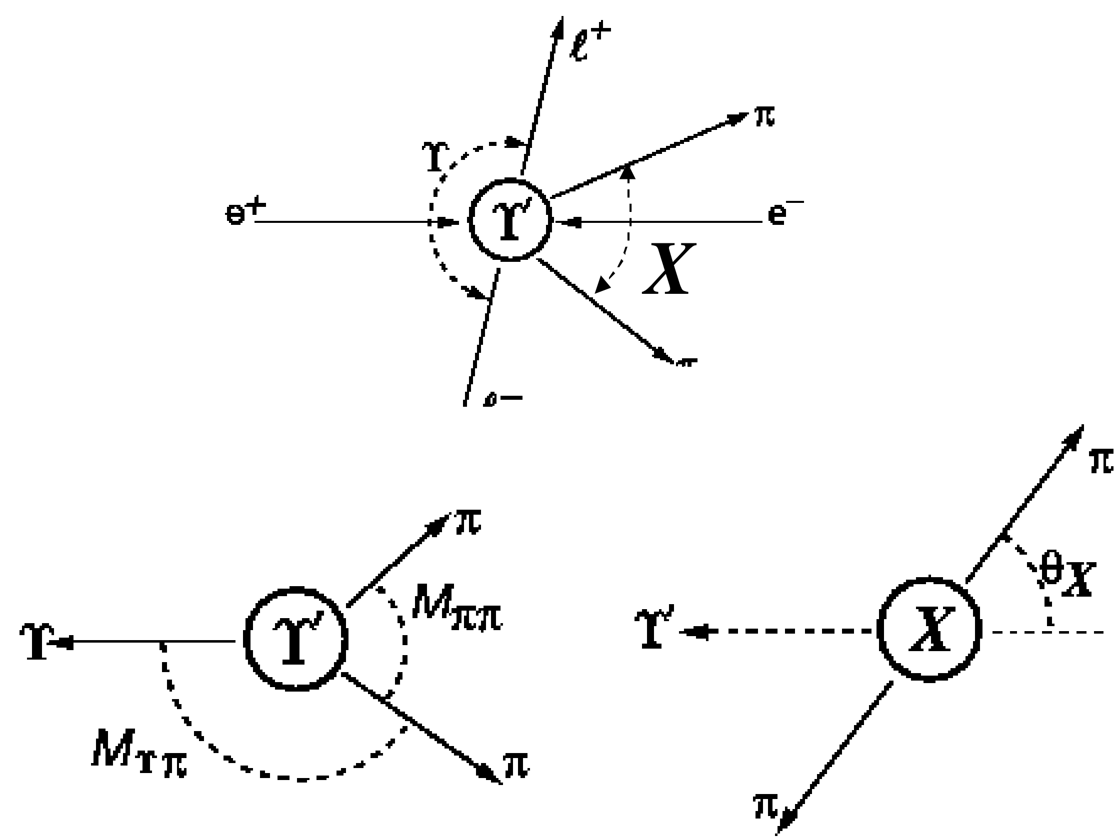
Outlook

- 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.
  - Disentangle the relation to unexpectedly large hadronic transition rates: $\Upsilon(5S) \to \Upsilon(nS)+2\pi$ (n=1,2,3); etc
- Future prospects
  - NRQCD and HQET allows scaling from c to b systems. This will eventually provide critical tests of our understanding of hadronic transitions..
  - 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.*

Backup Slides

$\Upsilon(3S) \to \Upsilon(1S) + \pi\pi$





$$q^2 = M_{\pi\pi}^{\ 2}$$

$$r^2 = M_{\Upsilon\pi}^{\ 2}$$

$$\cos\theta_X = \frac{M_{\Upsilon(2S)}^{\ 2} + M_{\Upsilon(1S)}^{\ 2} + 2m_\pi^{\ 2} - q^2 - 2r^2}{\sqrt{\Lambda_3(M_{\Upsilon(2S)}^{\ 2}, M_{\Upsilon(1S)}^{\ 2}, q^2)\,\frac{q^2 - 4m_\pi^{\ 2}}{q^2}}}$$

CLEO

Detailed study

$$\mathcal{M} = S\,(\epsilon_1 \cdot \epsilon_2) + D_1\,\ell_{\mu\nu}\,\frac{P^\mu P^\nu}{P^2}\,(\epsilon_1 \cdot \epsilon_2) + D_2\,q_\mu\,q_\nu\,\epsilon^{\mu\nu} + D_3\,\ell_{\mu\nu}\,\epsilon^{\mu\nu}\ .$$

Voloshin [PR D74:054022(2006)]

S-wave

$$S(\psi_2 \to \pi^+\pi^-\psi_1) = \tag{25}$$
$$-\frac{4\pi^2}{b}\,\alpha_0^{(12)}\left[(1-\chi_M)\,(q^2+m^2) - (1+\chi_M)\,\kappa\left(1+\frac{2m^2}{q^2}\right)\left(\frac{(q\cdot P)^2}{P^2} - \frac{1}{2}\,q^2\right)\right](\psi_1\cdot\psi_2)\ ,$$

$$P_\mu = M_A \delta^0_\mu$$

$$r_\mu = (k_{1\mu} - k_{2\mu})$$

and three D-waves

$$D_1(\psi_2 \to \pi^+\pi^-\psi_1) = -\frac{4\pi^2}{b}\,\alpha_0^{(12)}\,(1+\chi_M)\,\frac{3\kappa}{2}\,\frac{\ell_{\mu\nu}P^\mu P^\nu}{P^2}\,(\psi_1\cdot\psi_2)\ ,$$

spin independent

$$D_2(\psi_2 \to \pi^+\pi^-\psi_1) = \frac{4\pi^2}{b}\,\alpha_0^{(12)}\,\left(\chi_2 + \frac{3}{2}\,\chi_M\right)\,\frac{\kappa}{2}\,\left(1+\frac{2m^2}{q^2}\right)\,q_\mu q_\nu \psi^{\mu\nu}$$

spin dependent

$$D_3(\psi_2 \to \pi^+\pi^-\psi_1) = \frac{4\pi^2}{b}\,\alpha_0^{(12)}\,\left(\chi_2 + \frac{3}{2}\,\chi_M\right)\,\frac{3\kappa}{4}\,\ell_{\mu\nu}\psi^{\mu\nu}$$

$$\psi^{\mu\nu} = \psi_1^\mu \psi_2^\nu + \psi_1^\nu \psi_2^\mu - (2/3)\,(\psi_1\cdot\psi_2)\,(P^\mu P^\nu/P^2 - g^{\mu\nu})$$

$$\ell_{\mu\nu} = r_\mu r_\nu + \frac{1}{3}\left(1 - \frac{4m^2}{q^2}\right)(q^2\,g_{\mu\nu} - q_\mu q_\nu)$$

magnetic

$$\chi_M = \frac{\alpha_M}{\alpha_0}\ ,$$

$O(v^2)$

S-D mixing

$$\chi_2 = \frac{\alpha_2}{\alpha_0}$$

$O(v^2)$

If <M1-M1> term significant,
expect noticeable presence of D2 and D3 in Υ(3S) ->Υ +ππ

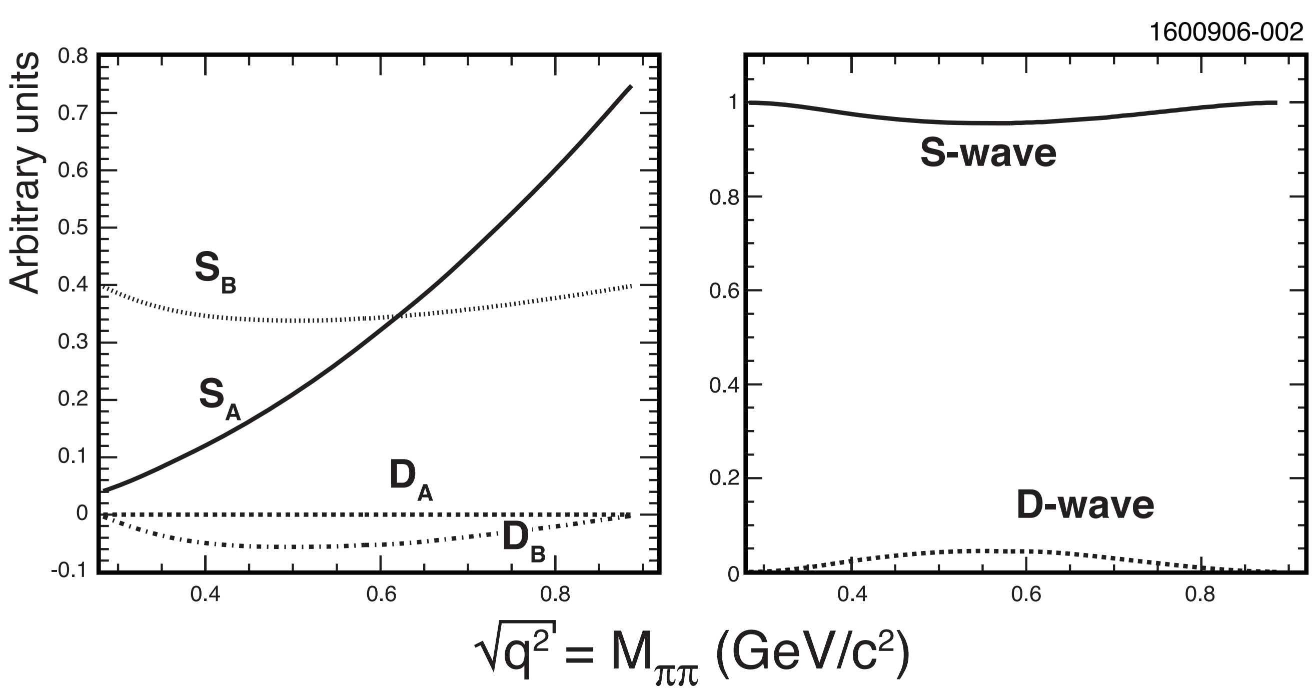
$$M = A(\varepsilon'\cdot\varepsilon)(q^2 - 2m_\pi^{\ 2}) + B(\varepsilon'\cdot\varepsilon)E_1E_2 + C\left[(\varepsilon'\cdot q_1)(\varepsilon\cdot q_2) + (\varepsilon'\cdot q_2)(\varepsilon\cdot q_1)\right]$$

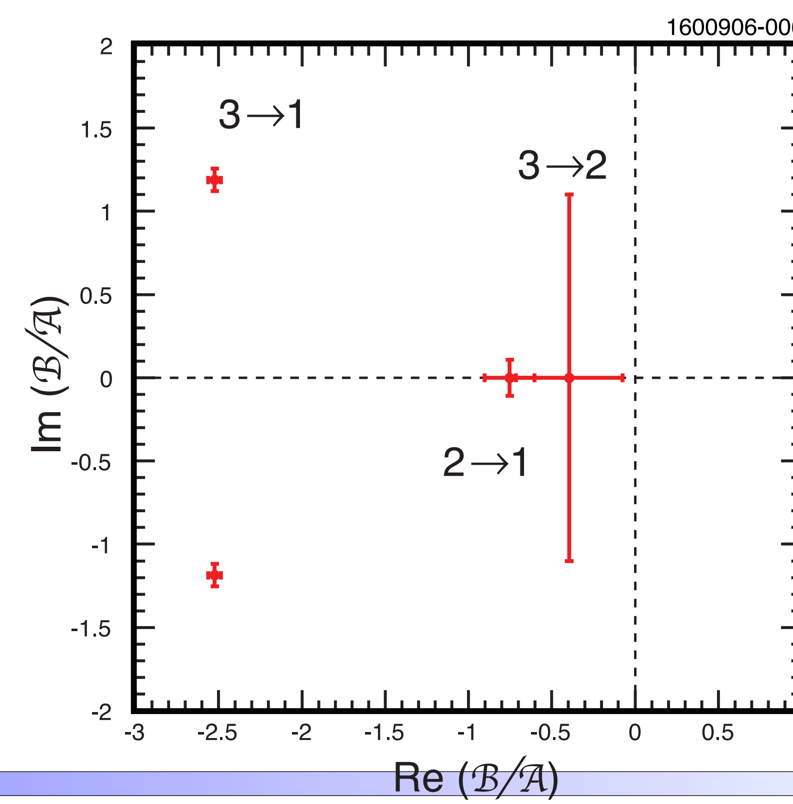
- Hindered M1-M1 term => C≈0. Consistent with CLEO results.
- Small D-wave contributions
- Useful to look at polarization info.
  Dubynskiy & Voloshin [hep-ph/0707.1272]

CLEO

Fit, No $\mathcal{C}$			stat.	effcy. ($\pi^\pm$)	effcy.(π^0)	bg. sub.
$\Upsilon(3S)\to\Upsilon(1S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-2.523	±0.031	±0.019	±0.011	±0.001
	$\Im(\mathcal{B}/\mathcal{A})$	±1.189	±0.051	±0.026	±0.018	±0.015
$\Upsilon(2S)\to\Upsilon(1S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-0.753	±0.064	±0.059	±0.035	±0.112
	$\Im(\mathcal{B}/\mathcal{A})$	0.000	±0.108	±0.036	±0.012	±0.001
$\Upsilon(3S)\to\Upsilon(2S)\pi\pi$	$\Re(\mathcal{B}/\mathcal{A})$	-0.395	±0.295		±0.025	±0.120
	$\Im(\mathcal{B}/\mathcal{A})$	±0.001	±1.053		±0.180	±0.001
Fit, float $\mathcal{C}$			stat.	effcy. ($\pi^\pm$)	effcy.(π^0)	bg. sub.
$\Upsilon(3S)\to\Upsilon(1S)\pi\pi$	$\lvert\mathcal{B}/\mathcal{A}\rvert$	2.89	±0.11	±0.19	±0.11	±0.027
	$\lvert\mathcal{C}/\mathcal{A}\rvert$	0.45	±0.18	±0.28	±0.20	±0.093

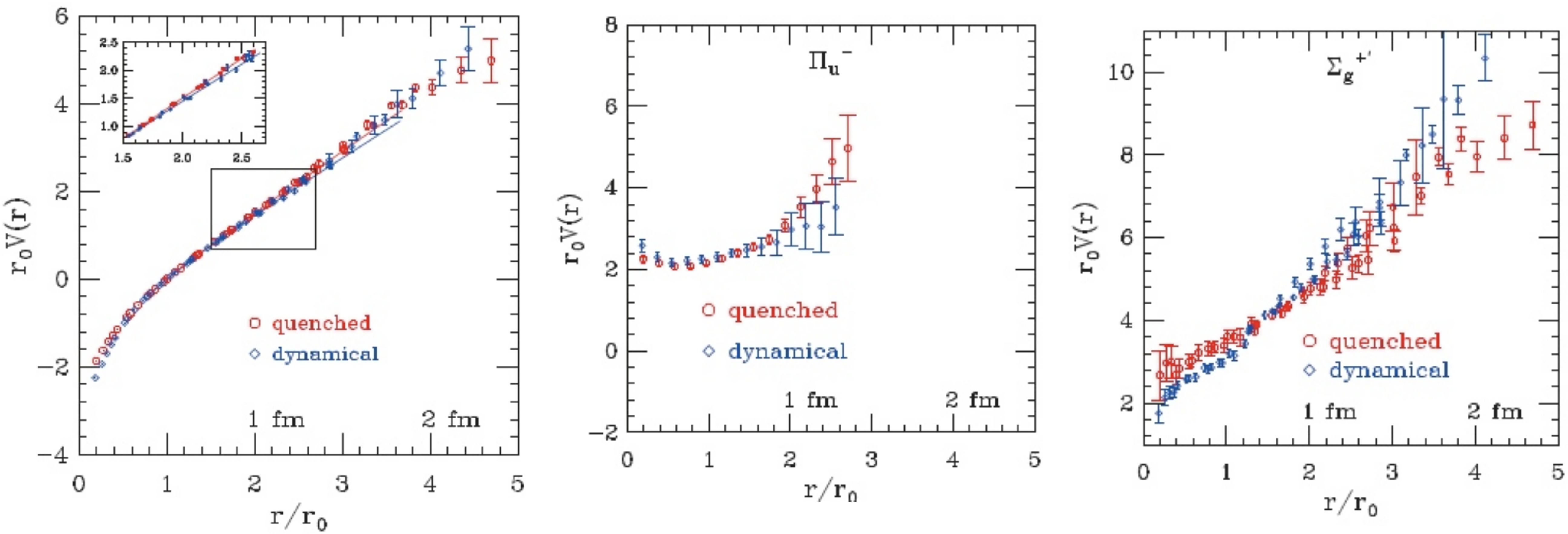
3S->1S





Comment on Quenched versus Full QCD

- Only observed effects at R < 2.0 fm in $\alpha_s(R)$ running and a slight slope change.



C. Bernard, et al.; (MILC) NP Proc. Suppl. 119, 5 98(2003) [hep – lat/0209051]

E1-E1

Model results:

$M(\Sigma_g^{+\prime}(1P)) \approx 4.55\ (c\bar{c})$
$10.80\ (b\bar{b})$

$\Sigma_g^{+\prime}(nP)$ n	$(M(n)-M(n-1))$ (MeV)	$<\lvert r\rvert>$ (fm)	$<v^2>$
$c\bar{c}$ 1	-	0.85	0.37
2	360	1.20	0.74
$b\bar{b}$ 1	-	0.45	0.09
2	300	0.64	0.18
3	265	0.80	0.25
4	240	0.96	0.31
5	225	1.09	0.37

Full overlap calculations gives:

$$\mathcal{F}(\text{full}) = \sum_n < i|r|X(n) >< X(n)|r|f > \frac{E_i - E_{X(0)}}{E_i - E_{X(n)}}$$

Transition	$\lvert\mathcal{F}\rvert$(full) (GeV^{-2})
$\psi(2S) \to J/\psi$	3.82
$\Upsilon(2S) \to \Upsilon(1S)$	1.37
$\Upsilon(3S) \to \Upsilon(1S)$	1.33×10^{-1}
$\Upsilon(3S) \to \Upsilon(2S)$	3.70
$\Upsilon(4S) \to \Upsilon(1S)$	1.17×10^{-1}
$\Upsilon(4S) \to \Upsilon(2S)$	2.71×10^{-1}

	$<\Sigma_g^{+\prime}(mP)\lvert r\rvert\Upsilon(nS)>$ (GeV^{-1})				
n	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$
1	0.874	0.460	0.283	0.196	0.142
2	-2.12	0.871	0.481	0.291	0.196
3	0.811	-3.14	0.99	0.531	0.314
4	0.082	1.23	-3.98	1.14	0.585

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

BUT - In addition to the suppression of the M1-M1 term by $<v^2>$ relative to the dominate E1-E1 term:

Radial overlap amplitude:

$$\sum_{n,l} \frac{< f|\Psi_{nl}) >< \Psi_{nl}|i >}{E_i - E_{X(nl)}}$$

with the hybrid states

$$\Psi_{nl} = \Pi_u^+(nP)$$

Again below lowest intermediate state threshold

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

In this limit the overlap vanishes since <f|i>=0 (i≠f)

A complete calculation yields:

Transition	$\lvert\mathcal{F}\rvert$(full) (GeV^{-2})
$\psi(2S) \to J/\psi$	1.81×10^{-1}
$\Upsilon(2S) \to \Upsilon(1S)$	3.04×10^{-1}
$\Upsilon(3S) \to \Upsilon(1S)$	1.70×10^{-1}
$\Upsilon(3S) \to \Upsilon(2S)$	1.74×10^{-1}
$\Upsilon(4S) \to \Upsilon(1S)$	1.06×10^{-1}
$\Upsilon(4S) \to \Upsilon(2S)$	0.92×10^{-1}

	$< \Pi_u^+(mP)\lvert r\rvert\Upsilon(nS) >$ (GeV^{-1})				
n	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$
1	0.705	0.470	0.346	0.274	0.226
2	−0.851	0.358	0.306	0.239	0.200
3	: 0.027	−0.934	0.263	0.254	0.199
4	−0.006	0.024	−0.968	0.220	0.227

The M1-M1 term is highly suppressed !

Transition Ratio	Belle
$R(2,1)$	$1.47 \pm 0.15 \pm 0.20$
$R(3,1)$	$0.91 \pm 0.35 \pm 0.15$

$$R(n,m) \equiv \frac{\Gamma(\Upsilon(5S) \to \pi^+\pi^- + \Upsilon(nS))}{\Gamma(\Upsilon(5S) \to \pi^+\pi^- + \Upsilon(mS))}$$

phase space (GeV^{-7})

$$\Gamma(\Upsilon(5S) \to \pi^+\pi^- + \Upsilon(nS)) \propto G(n)|f(n)|^2$$

$$\text{with } f(n) = \sum_l \frac{< \Upsilon(5S)|r|\Sigma_g^{+'}(lP) >< \Sigma_g^{+'}(lP)|r|\Upsilon(nS) >}{M_{\Upsilon(5S)} - E_l(\Sigma) + i\Gamma_l(\Sigma)}|^2$$

$$G(n) = 28.7,\ 0.729,\ 1.33 \times 10^{-2}$$

for $n = 1, 2, 3$

theory - hadronic transition rates

- If lowest hybrid mass near Υ(5S) a few states dominate sum. Results sensitive to mass value.
- If hybrid mass 10.75 + i(0.1) (GeV), obtain R(2,1)≈1.1 and R(3,1)≈0.08.
- Overall scale of transitions nearly two orders of magnitude larger than low-lying transitions.