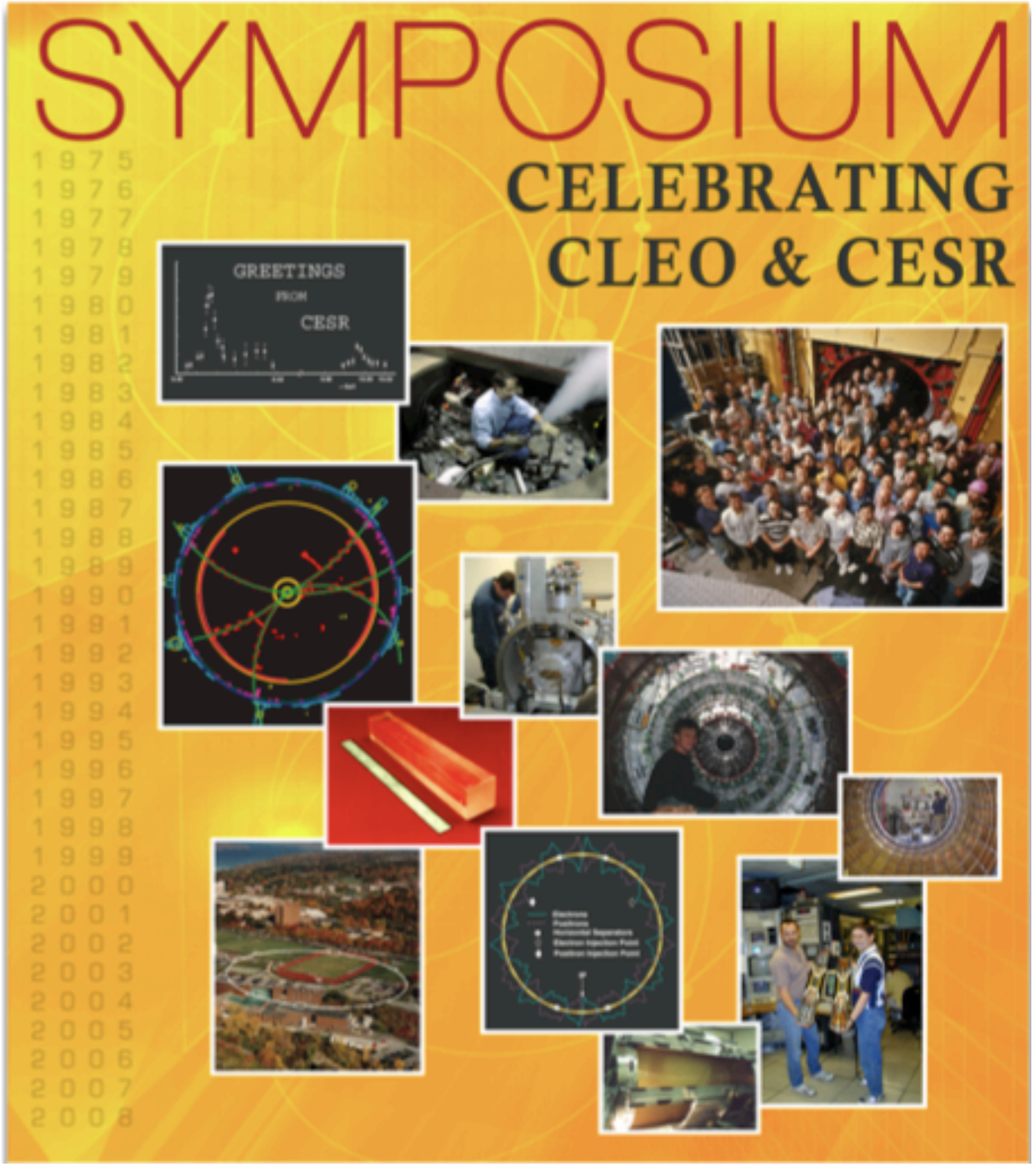
Charmonium and Bottomonium at CLEO

Estia Eichten

- (8) Spectroscopy
- (41) Direct Decays
- (19) Transitions
- (27) Above Threshold



Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E.
[hep-ph/0701208]

Plan of Talk

- Narrow States
  - Spin singlets
  - Direct decays
  - EM transitions
- Why it works so well
- Hadronic transitions
  - Two pions
- Above Threshold
  - Heavy flavor factories
  - New states

Spectroscopy

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

NRQCD v

- The NRQCD approach:

Kinetic — Potential — Static Energy

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

relativistic corrections

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

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

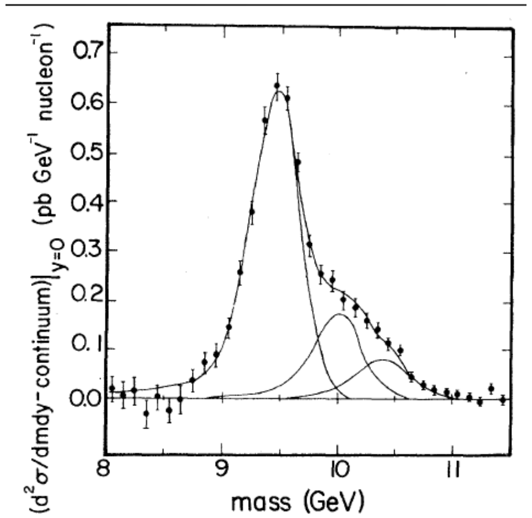
where $j_a^0 = Q^\dagger g t_a Q + g^2 f^{abc}\mathbf{E}_b\cdot\mathbf{A}_c + \ldots$

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

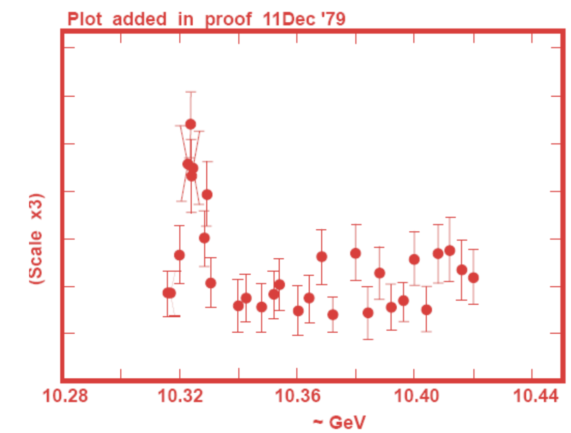
- CLEO played a major role in validating the NRQCD approach

D. Andrews, et al. PRL **44**:1108 (1980)

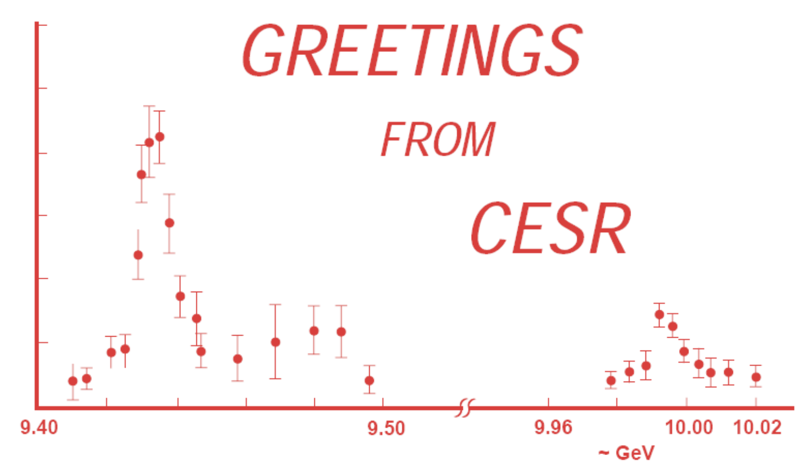
- Υ, Υ' and Υ'' confirmed



S. Herb et al., PRL **39**:252 (1977)
C. Berger et al., Phys. Lett. **76B**, 243 (1978)
C. W. Darden et al., Phys. Lett. **76B**, 246 (1978); ibid, **78B**, 364 (1978)
J. K. Bienlein et al., Phys. Lett. **78B**, 360 (1978)
K. Ueno et al., PRL **42**:486 (1979)



Xmas card 1979



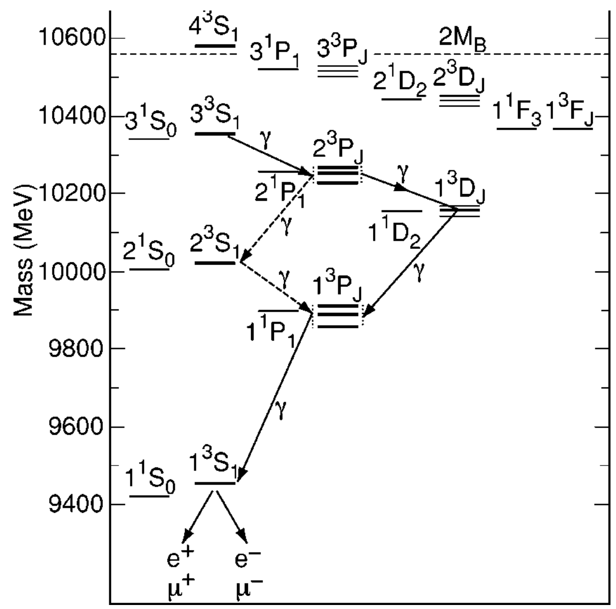
- Spin triplet states
  - $\Upsilon(4S)$
  - $\Upsilon(5S)$
  - $\chi_b(1^3P_J)$, $\chi_b(2^3P_J)$
  - 1^3D_2 $(b\bar{b})$

D. Andrews et al., PRL **45**:219 (1980)

D. Besson et al., PRL **54**:381 (1985)

CUSB, CLEO, Crystal Ball, Argus
M. Artuso et al., PRL **94** 032001 (2005)

$\Upsilon(3S) \to \gamma\chi_b(2P)$
$\chi_b(2P) \to \gamma\Upsilon(1D)$
$\Upsilon(1D) \to \gamma\chi_b(1P)$
$\chi_b(1P) \to \gamma\Upsilon(1S)$

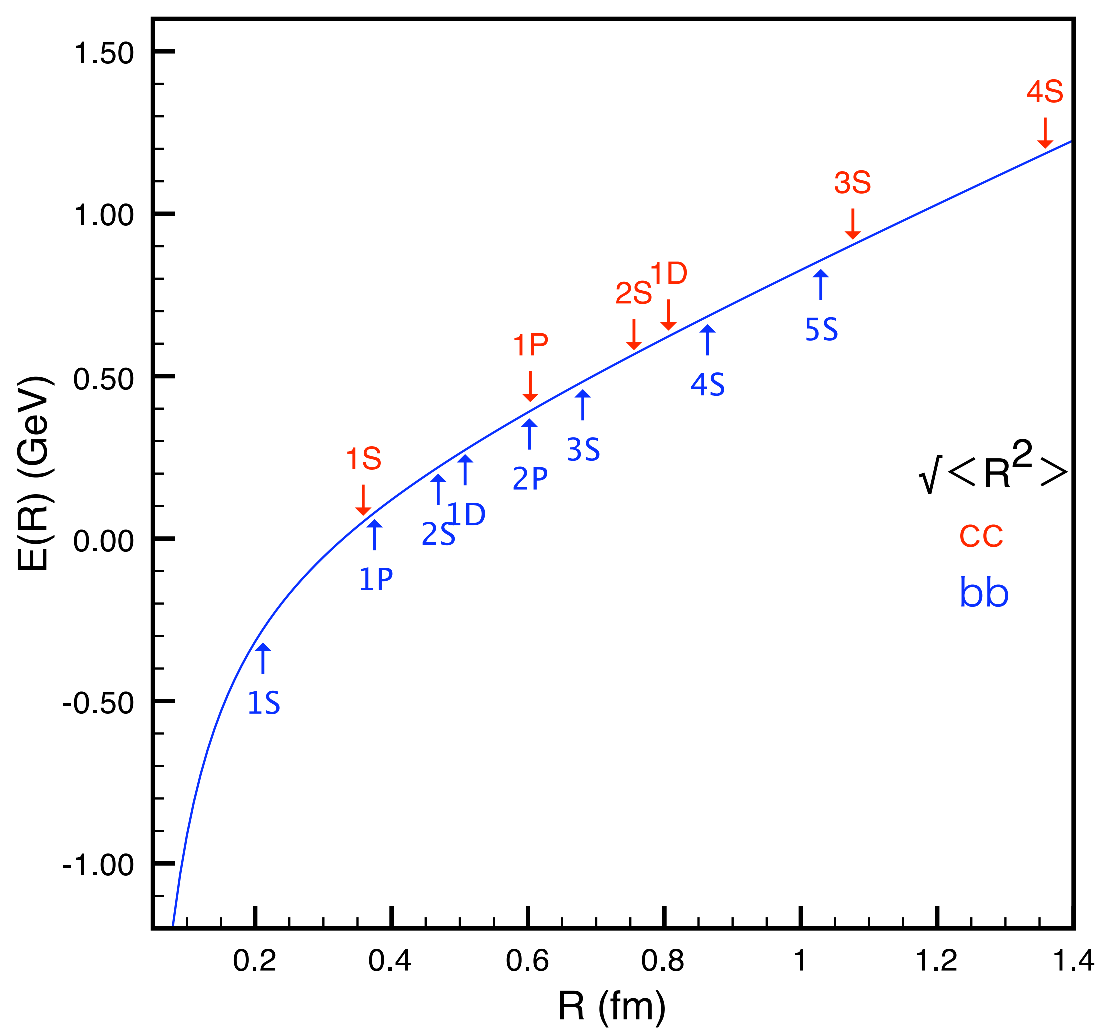


D. Andrews et al., PR D**70** 032001 (2004)
$M = 10161.1 \pm 0.6 \pm 1.6$ MeV$/c^2$

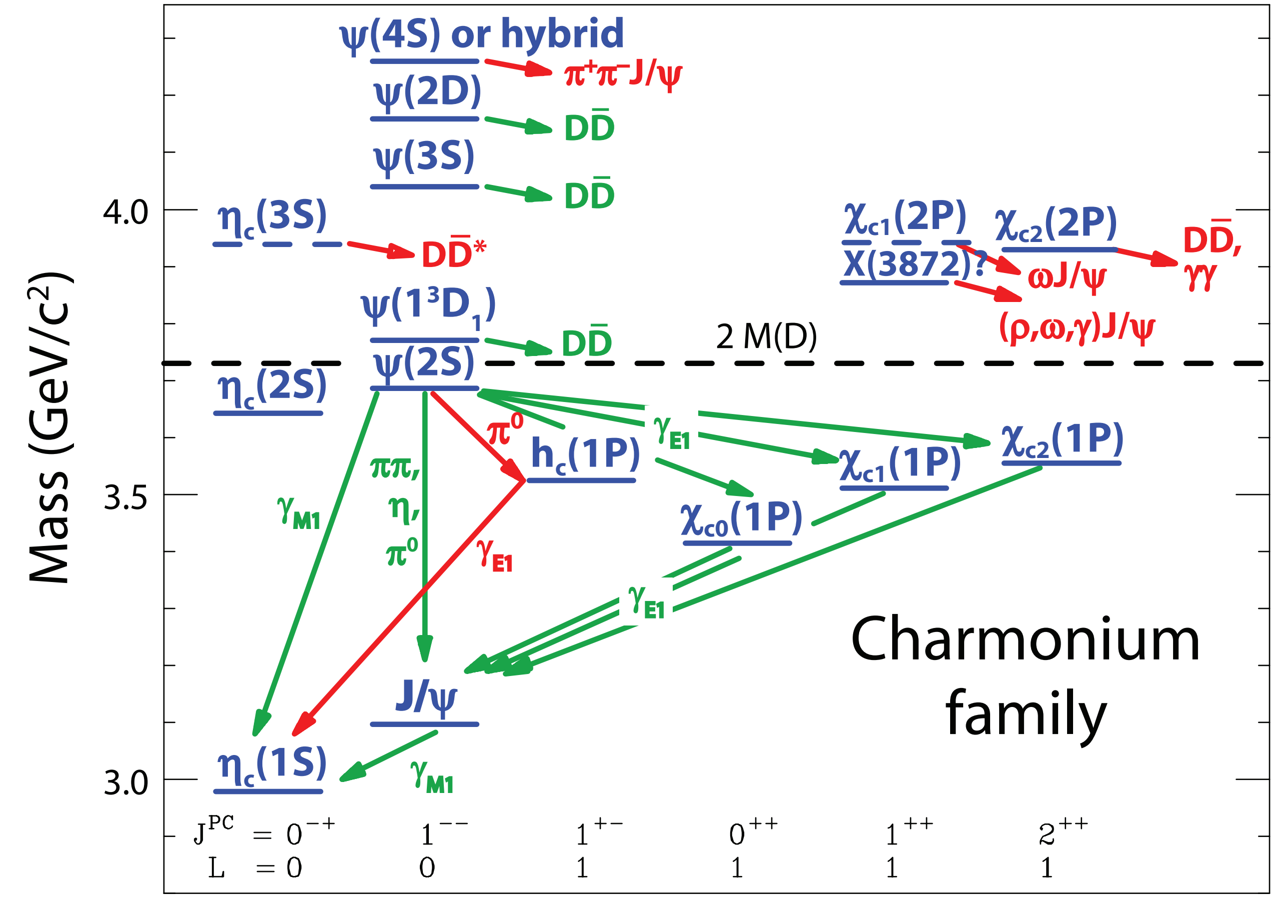
- Consistency between $(b\bar{b})$ and $(c\bar{c})$ systems validates NRQCD approach.
  - masses
  - spin splittings
  - EM transitions
  - hadronic transitions
  - direct decays

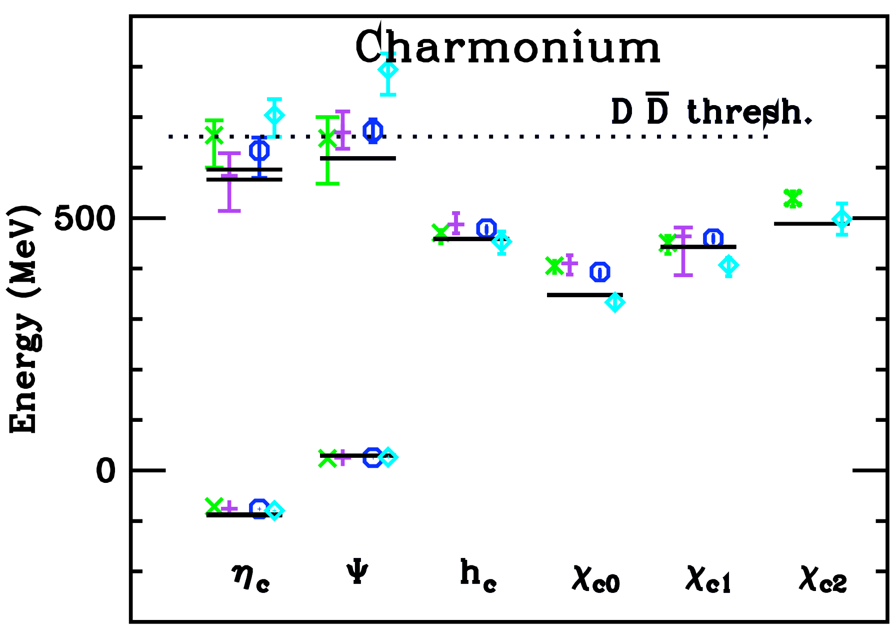
$$< \frac{v^2}{c^2} > \approx 0.24 \quad (c\bar{c})$$
$$\approx 0.08 \quad (b\bar{b})$$

Potential model



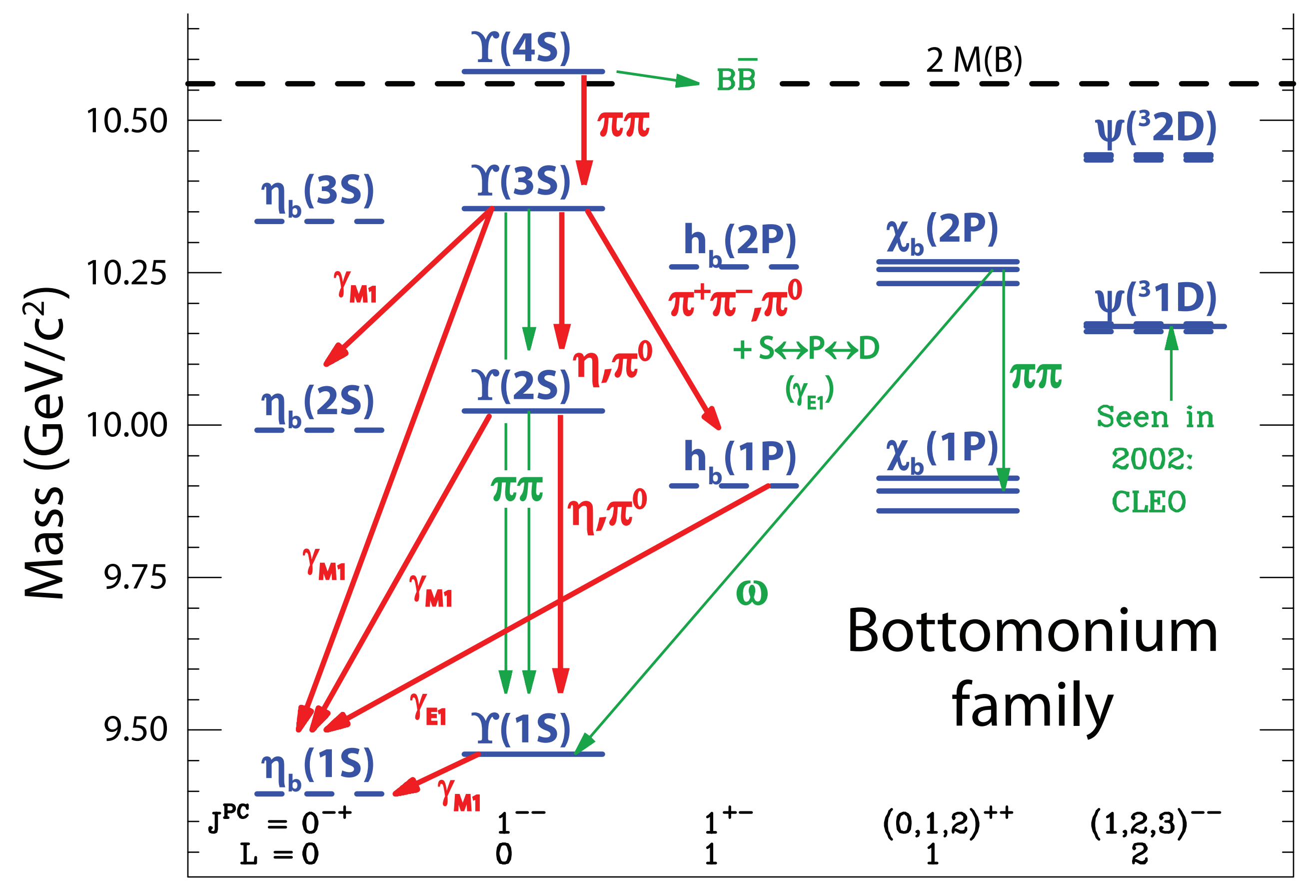
- Below threshold for heavy flavor meson pair production
  - Narrow states allow precise experimental probes of the subtle nature of QCD.
  - Lattice QCD supports and will supplant potential models
  - A variety of lattice approaches





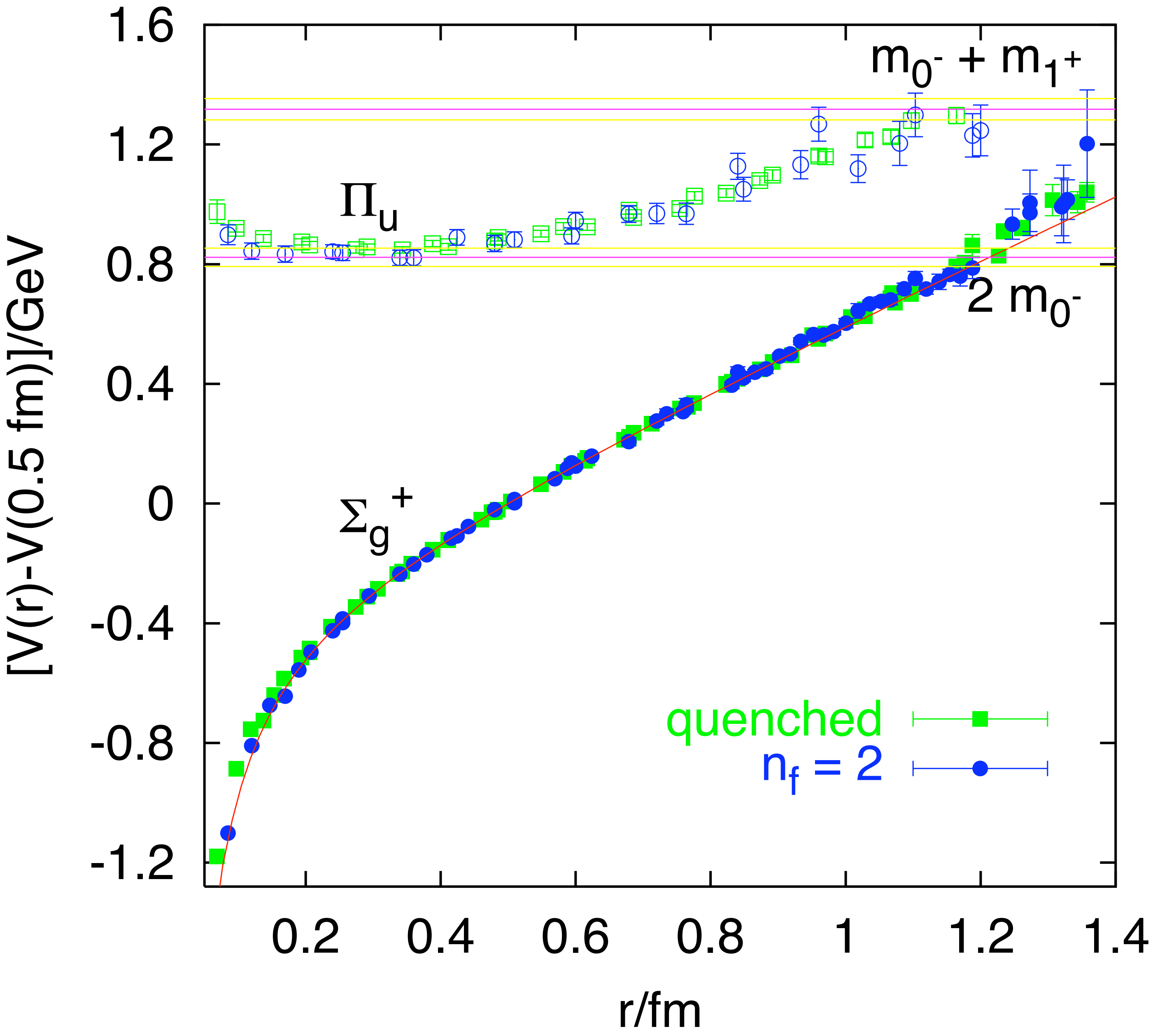
S. Gottlieb et al., PoS LAT2006

Figure 5: Summary of charmonium spectrum.



QCD Static Energy

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

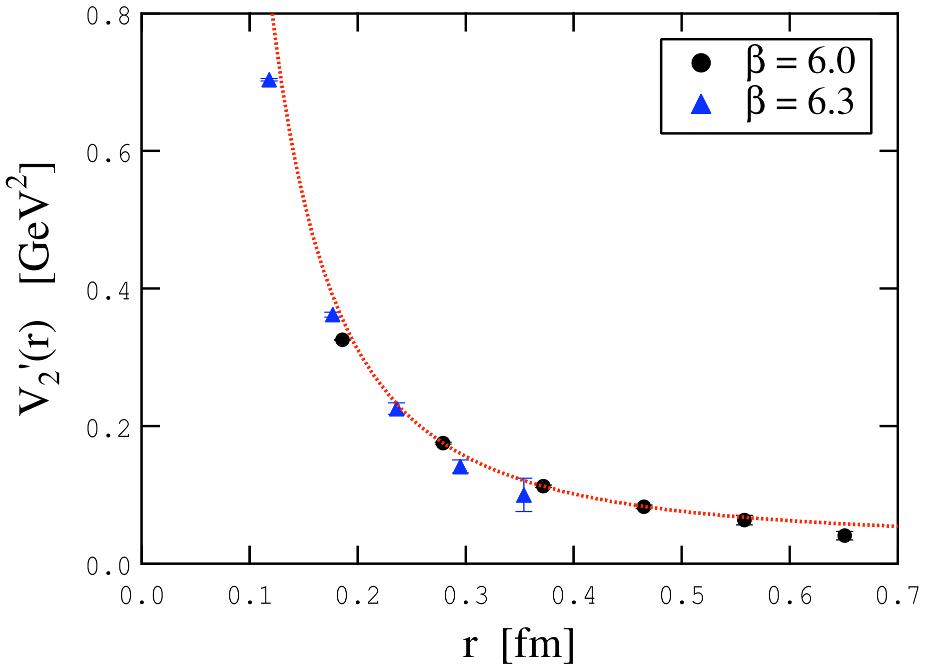


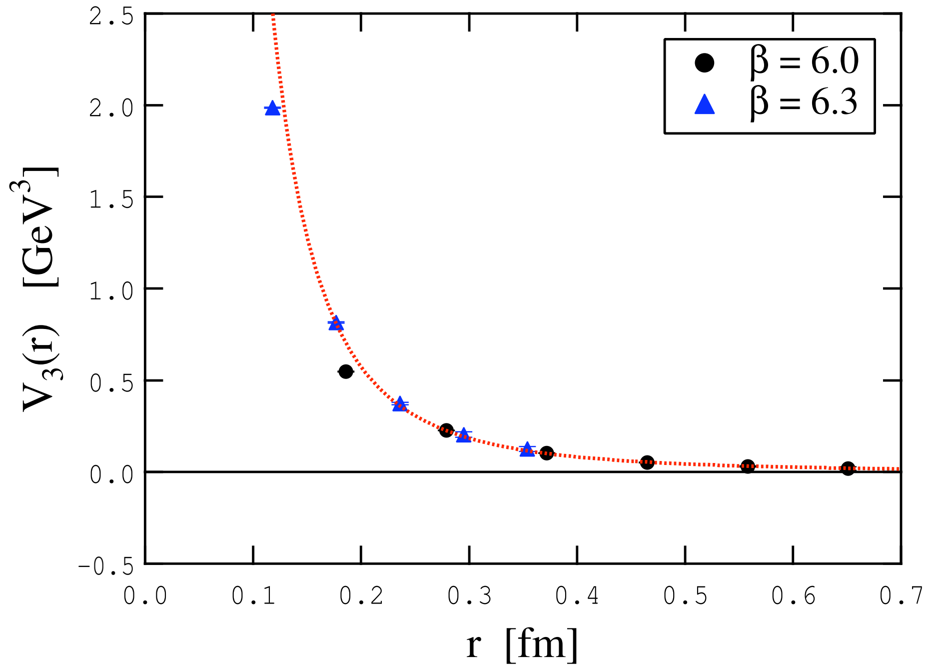
Multi-level algorithm allows lattice determination of potentials with unprecedented precision

Y. Koma, M. Koma and H. Wittig

[PRL 97 (2006) 122003]

Quenched





Heavy quark potential

To $O(1/m^2)$

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

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

Long range component

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

Short range

Fine and hyper-fine splitting

Spin Singlet States

- h_c
  - Observation E835, CLEO $e^+e^- \to \psi(2S) \to \pi^0 h_c, \quad h_c \to \gamma\eta_c, \quad \pi^0 \to \gamma\gamma.$

$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4$$
$$\mathcal{B}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}(h_c \to \gamma\eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$$

TABLE I. Results for the inclusive and exclusive analyses for the reaction $\psi(2S) \to \pi^0 h_c \to \pi^0 \gamma\eta_c$. First errors are statistical, and the second errors are systematic, as described in the text and Table II.

	Inclusive	Exclusive
Counts	150 ± 40	17.5 ± 4.5
Significance	$\sim 3.8\sigma$	6.1σ
$M(h_c)$ (MeV)	$3524.9 \pm 0.7 \pm 0.4$	$3523.6 \pm 0.9 \pm 0.5$
$\mathcal{B}_\psi \mathcal{B}_h$ (10^{-4})	$3.5 \pm 1.0 \pm 0.7$	$5.3 \pm 1.5 \pm 1.0$

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

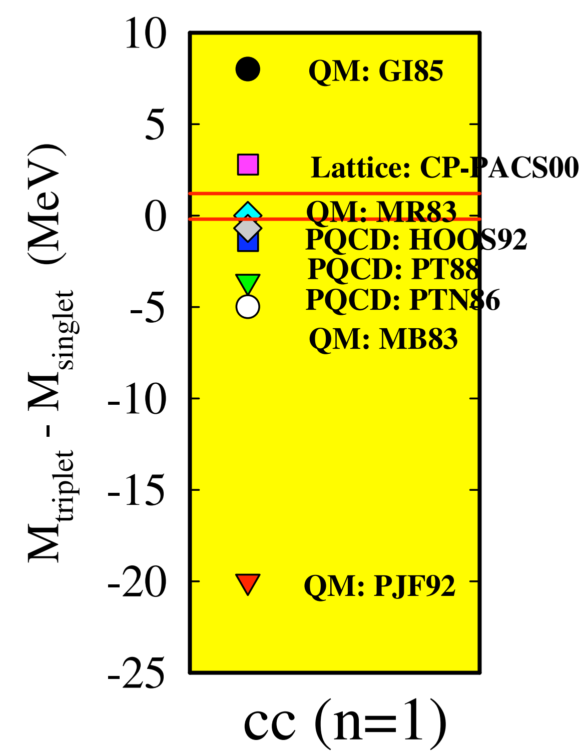
  - Partial widths and decay modes:

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

  - 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

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

$$\mathcal{M}_{if} = \int r^2 dr\, R_{n_i L_i}(r) j_0(\frac{rk}{2}) R_{n_f L_f}(r)$$

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

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

$$\Gamma(J/\psi \to \eta_c\gamma) = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}(1 + \kappa_c)[1 + o(v^2)]$$

  - $J/\psi \to \gamma + \eta_c$ M1 transition

1.19 ± 0.33 keV Exp [CUSB] half the naive theoretical result

  - LQCD $\Gamma(J/\psi \to \eta_c + \gamma) = 2.0 \pm 0.1 \pm 0.4$

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

  - 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

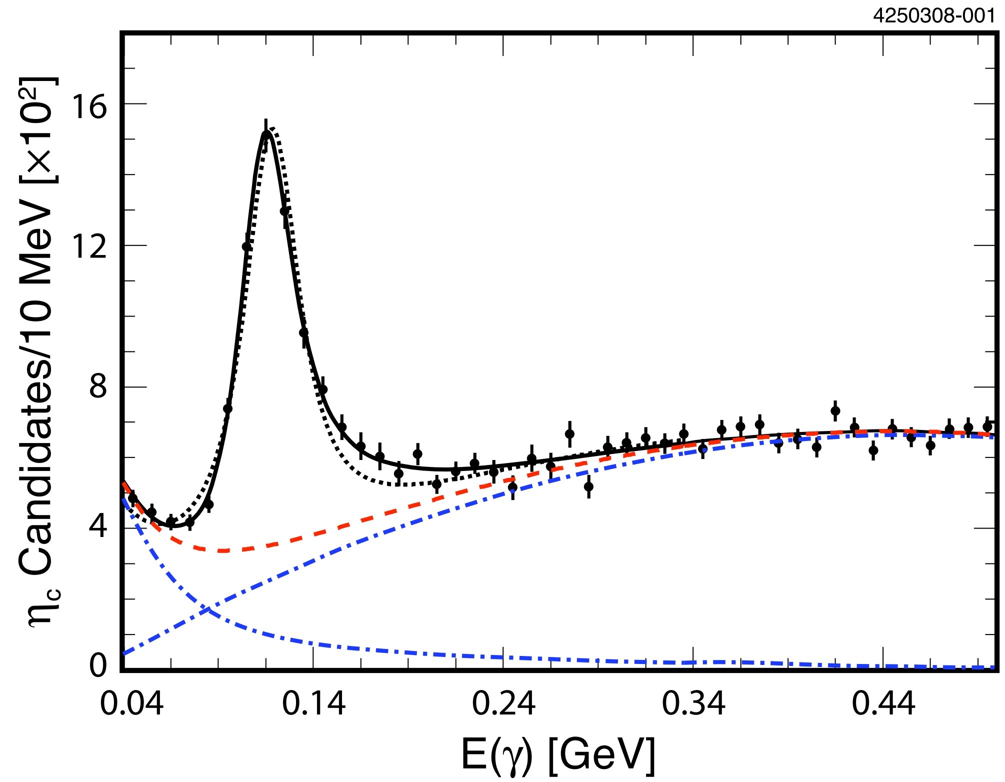
No scalar long range interaction

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

- New 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

$$M(\eta_c) = 2976.7 \pm 0.6 \text{ MeV}/c^2 \quad \text{Breit – Wigner}$$
$$= 2982.2 \pm 0.6 \text{ MeV}/c^2 \quad \text{Modified Breit – Wigner}$$

long tail

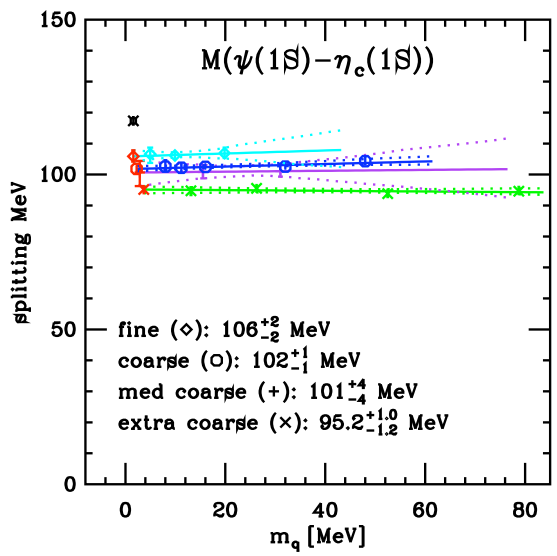
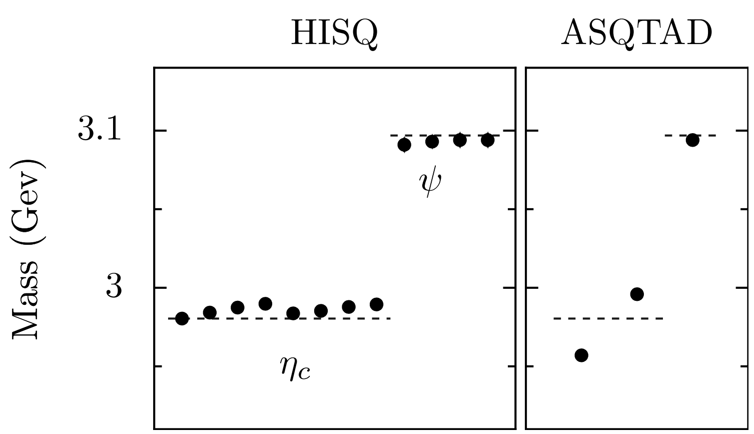
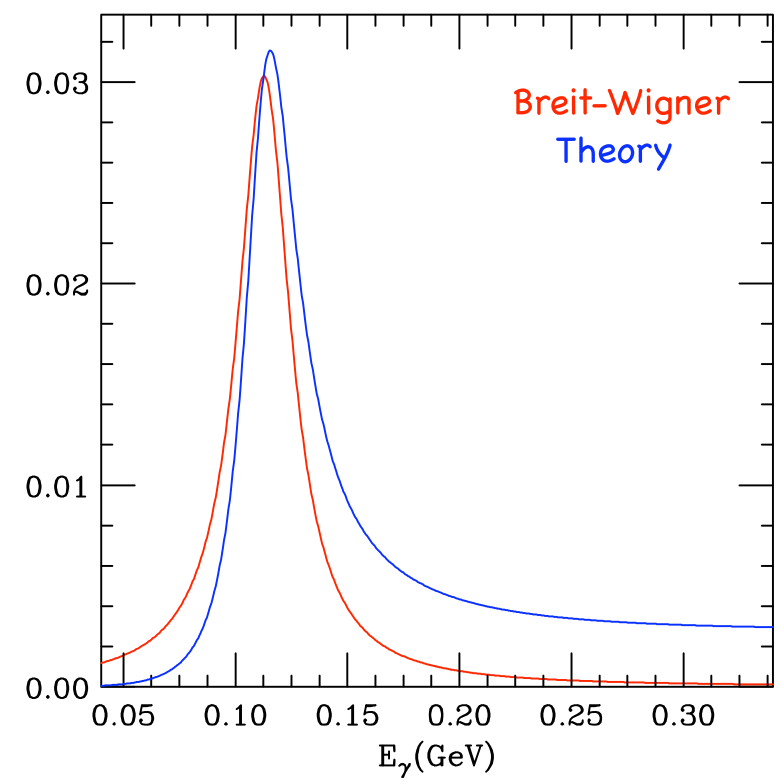


Figure 4: Hyperfine splitting of the 1S states.

S. Gottlieb et al., PoS LAT2006



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



η_c':

D. M. Asner et al., PRL 92, 142001 (2004)

$$M(\eta_c') = 3642.9 \pm 3.1 \pm 1.5 \text{ MeV}/c^2; \quad \Delta M = 43.1 \pm 3.4 \text{ MeV}/c^2$$

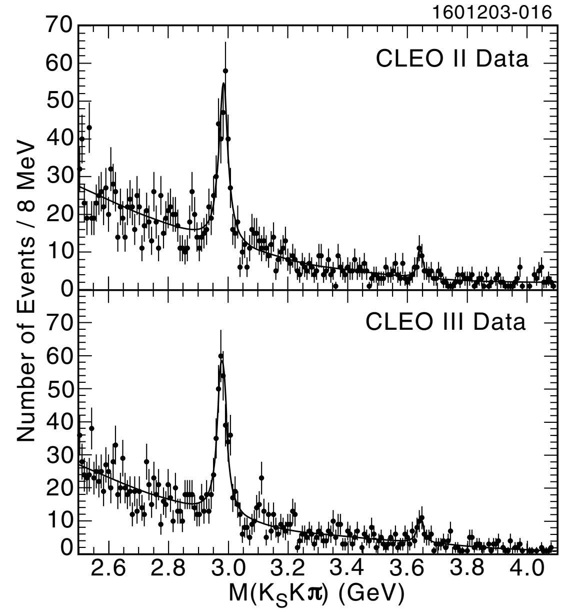


FIG. 1. Invariant mass distributions for $K_S^0 K^\pm \pi^\mp$ events from (top) the CLEO II data and (bottom) the CLEO III data. The curves in the figures are results of fits described in the text.

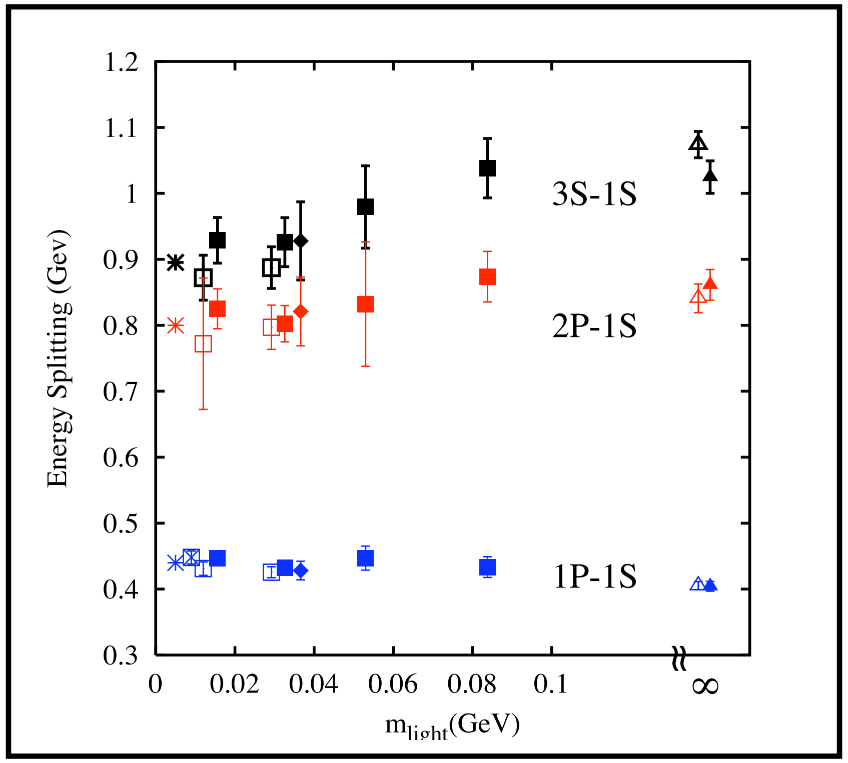
- Spin splitting

$$\Delta M = M(\Upsilon(2S)) - M(\eta_c') = 49 \pm 4 \text{ MeV}/c^2 \quad \text{PDG 2007}$$

Too small - scaling from 1S; most models.

Are we seeing threshold effects?

- Effects of light quark loops



Effects on spectrum seen in LQCD

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

- Dual approach using heavy flavor mesons virtual/real pairs

Phenomenological approach based on Cornell coupled channel model (CCCM):

$$\mathcal{H}_I = \frac{3}{8}\sum_a \int : \rho_a(\mathbf{r}) V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}') : d^3r\, d^3r'$$
$$\rho^a = \bar{c}\gamma^0 t^a c + \bar{q}\gamma^0 t^a q$$

Calculate pair-creation amplitudes, eg $<^3D_2|\mathcal{H}_I|D\bar{D}^\star>$

Solve coupled-state system for ω and ψ

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

where

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

ψ_0: $\bar{c}c$ ψ_2: $\bar{D}D$

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

- Spin dependent shifts small far below threshold

ELQ PRD 73:014014 (2006)

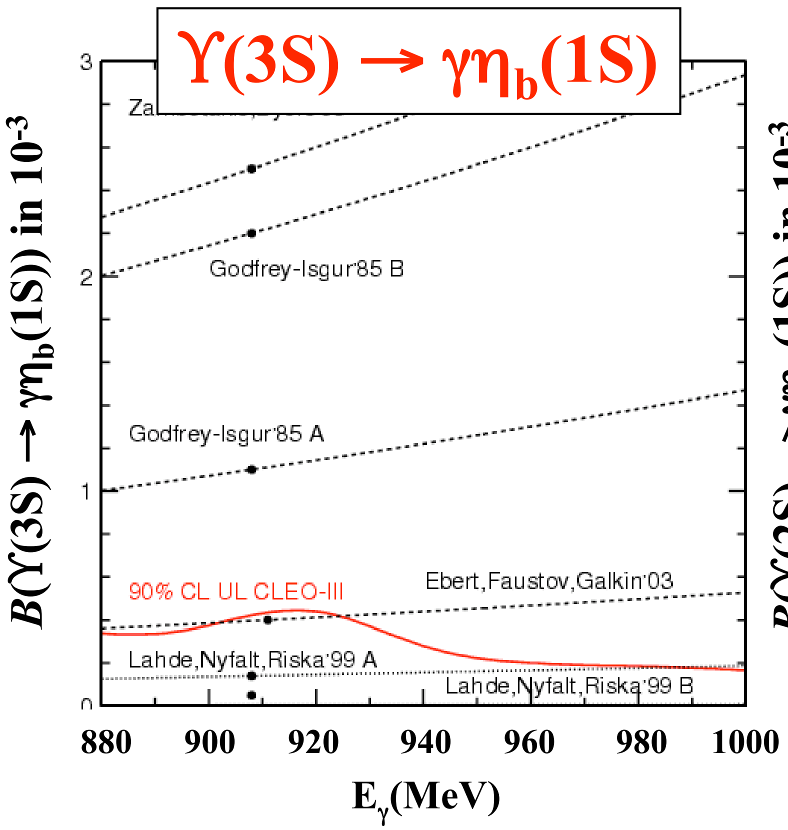
Less that 1 MeV shift ⇒

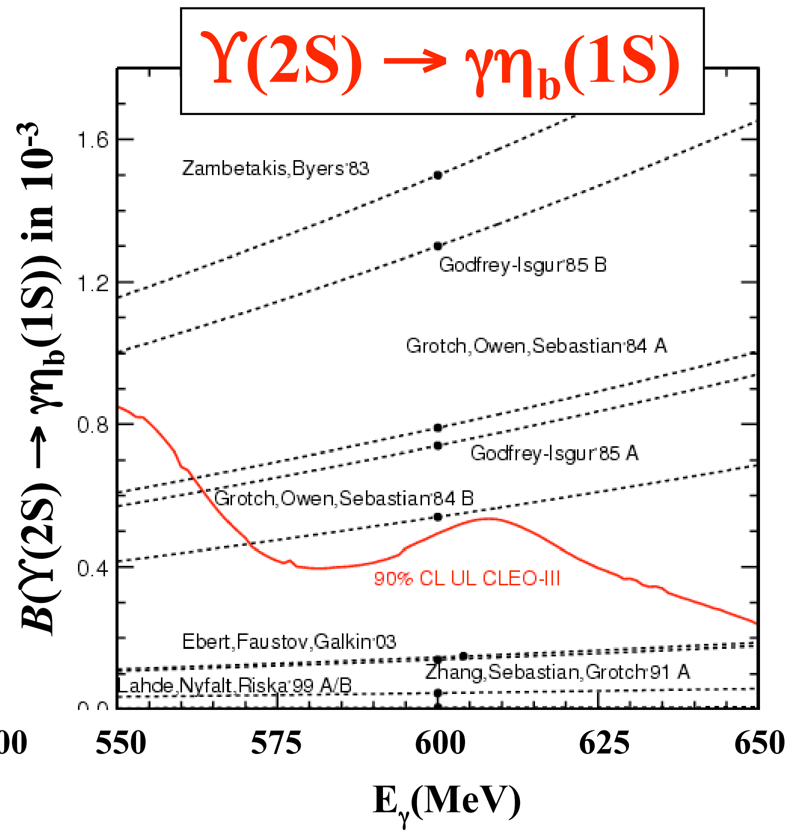
Reduces ΔM(2S) by 21 MeV ⇒

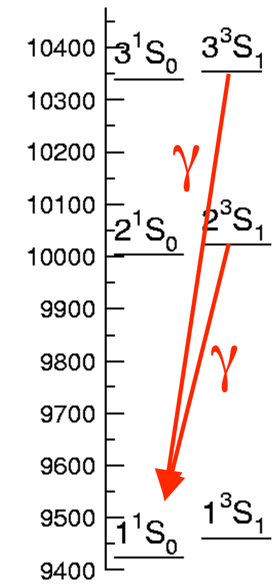
State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5^e	$+2.8$
1^3S_1	$3\,096.9^a$		$+30.2^e$	-0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
1^1P_1	$3\,524.4^f$		$+0.6^e$	$+0.5$
1^3P_2	$3\,556.2^a$		$+31.9^e$	-0.3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

Search for the at η_b CLEO

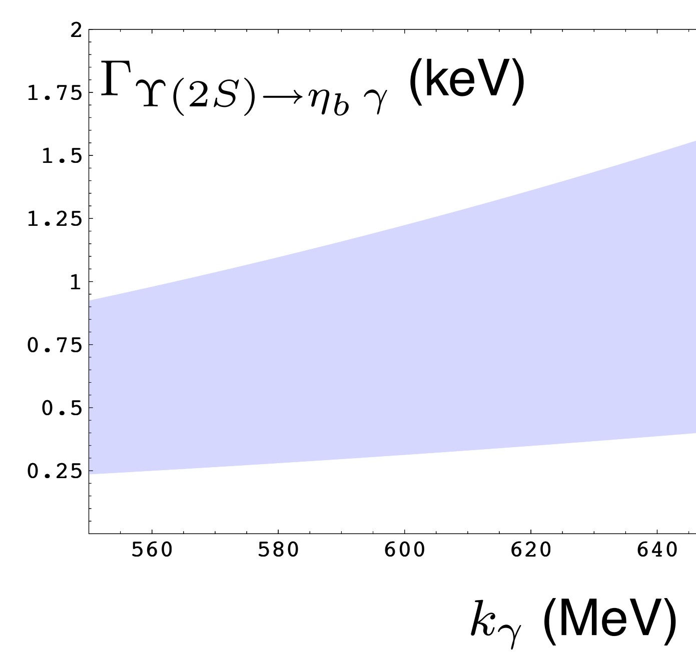
- Hindered M1 transitions
  - $\Upsilon(3S) \to \eta_b$ and $\Upsilon(2S) \to \eta_b$







- Phenomenological model results vary greatly due to poorly understood relativistic corrections.
- pNRQCD expectation



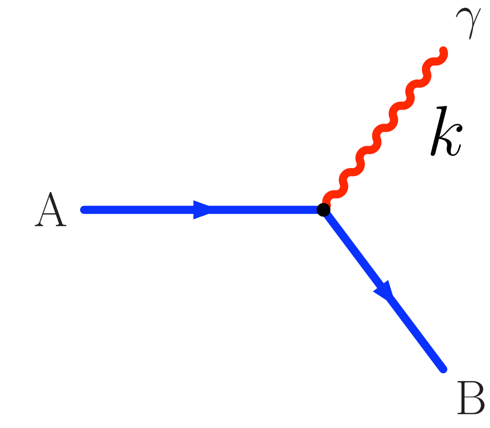
CLEO < 0.14 keV (90%c.l.)

Narrow states still missing

- Charmonium - 3 - $^1D_2$, $^3D_2$, and $^3D_3$
- Bottomonium - 24 - 1^3D_0, 1^3D_1, 1^3F_J, 2^3D_J, 1^3G_J, 3^3P_J, 1^1S_0, 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

Photon Transitions

Multipole Expansion

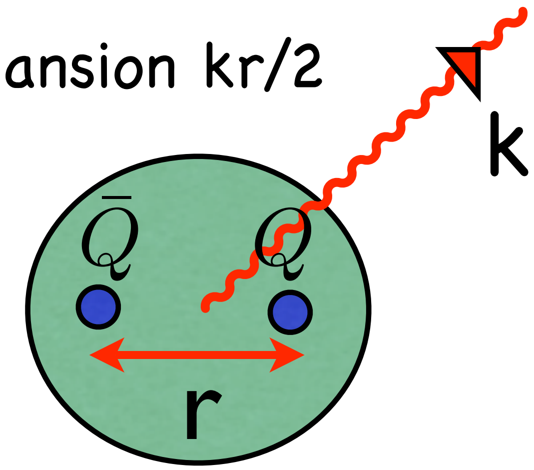


- Including EM interactions

$$\mathcal{H}_I = ie_Q\psi^\dagger\left(\frac{\mathbf{D}\cdot e\mathbf{A} + e\mathbf{A}\cdot\mathbf{D}}{2m_Q}\right)\psi + \frac{c_F e_Q}{2m_Q}\psi^\dagger\boldsymbol{\sigma}\cdot e\mathbf{B}\psi + \ldots$$

Electric　　　　Magnetic

- Theory of quarkonium transitions relies on the multipole expansion



$$\mathbf{A}(R_{\rm cm}, r, t) = \mathbf{A}(R_{\rm cm}, t) + \mathbf{x}\cdot\nabla\mathbf{A}(R_{\rm cm}, t) + \ldots$$

Electric $$\frac{1}{m_Q}\{\mathbf{p}, \mathbf{A}(R_{\rm cm}, r, t)\} = \mathbf{r}\cdot\mathbf{E}(R_{\rm cm}, t) + \cdots$$

Magnetic $$\frac{c_F e_Q}{2m_Q}\psi^\dagger\boldsymbol{\sigma}\cdot e\mathbf{B}\psi$$

- Higher order terms E1, E2, E3, ... M1, M2, M3, ...

Selection Rules $$e^{\frac{i\mathbf{r}\cdot\mathbf{k}}{2}} = \sum_n \frac{1}{n!}\left(\frac{i\mathbf{r}\cdot\mathbf{k}}{2}\right)^n$$

Electric S <-> P $$r \to \frac{3}{k}\left[\frac{kr}{2}j_0(\frac{kr}{2}) - j_1(\frac{kr}{2})\right] = r\left[1 - \frac{(kr)^2}{24} + \ldots\right]$$

Magnetic S <-> S $$1 \to j_0(\frac{kr}{2})$$

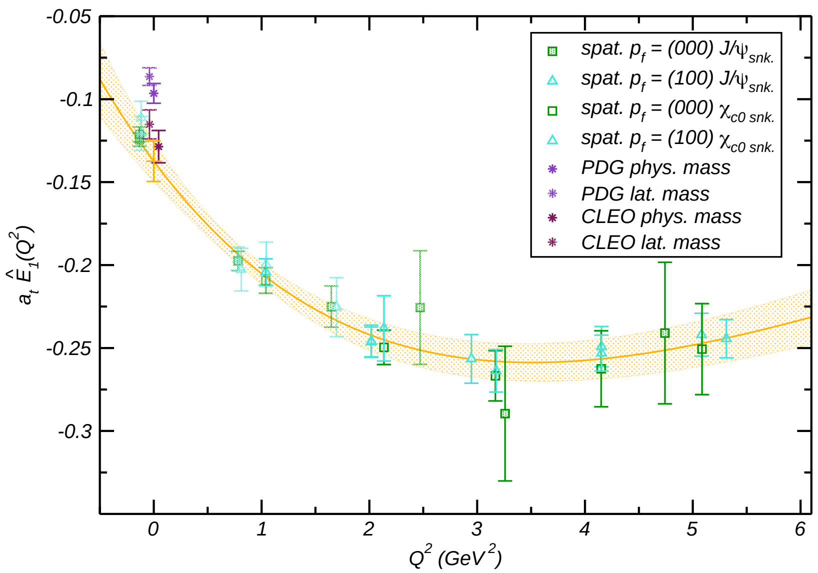
expansion coefficients small: $$\frac{1}{(2n+1)!!}$$

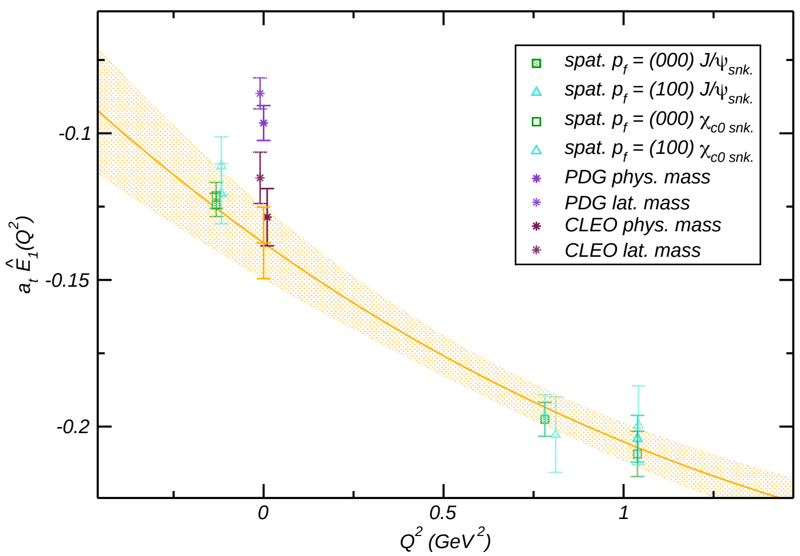
Other approaches

- Lattice

  Direct calculation - Extrapolate to Q^2=0

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





- pNRQCD

  Systematic Effective Lagrangian approach.
  Higher states an issue

  See review:
  Heavy Quarkonium
  Physics Cern-2005-005

E1 Transitions

$$\Gamma(i \xrightarrow{\text{E1}} f + \gamma) = \frac{4\alpha e_Q^2}{3}(2J_f + 1)\text{S}_{if}^{\text{E}} k^3 |\mathcal{E}_{if}|^2$$

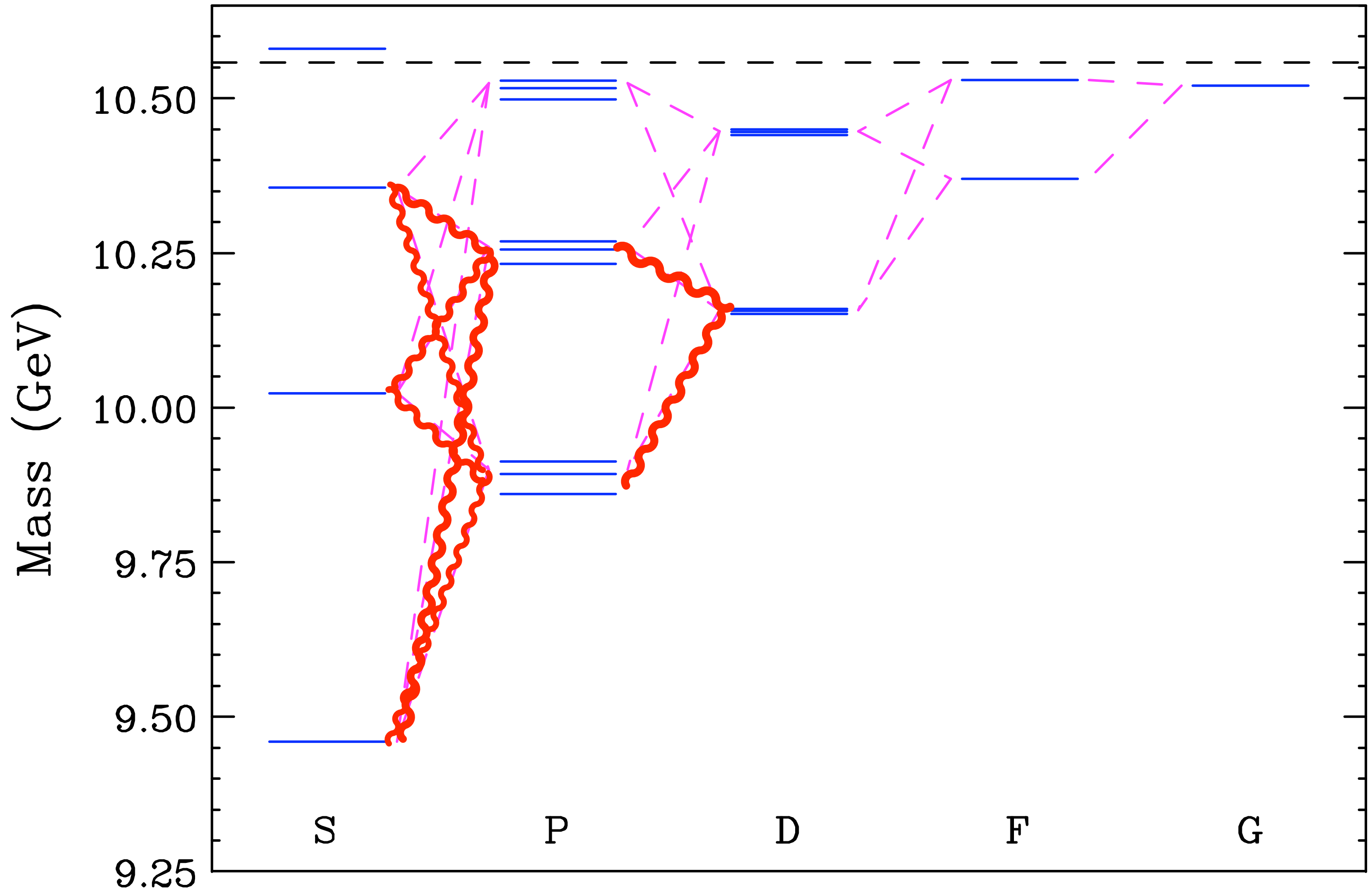
CG factor $\text{S}_{if}^{\text{E}} = \max(L_i, L_f) \begin{Bmatrix} J_i & 1 & J_f \\ L_f & S & L_i \end{Bmatrix}^2$

Overlap

$$\mathcal{E}_{if} = \int r^2 dr\, R_{n_i \text{L}_i}(r) r R_{n_f \text{L}_f}(r)$$

Sensitive to detailed dynamics for transitions involving radially excited states

$b\bar{b}$ spin triplets



S states -> P states

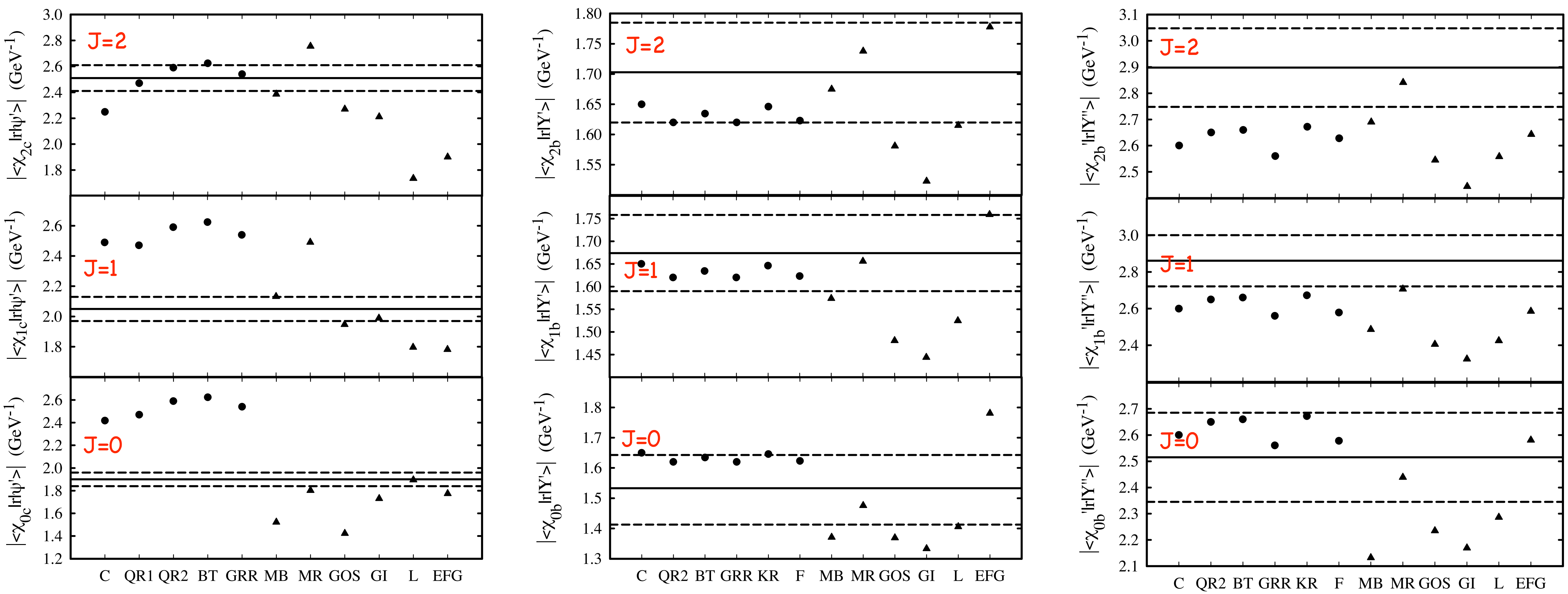
$\mathcal{E}_{if}$

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

$c\bar{c}$		
State	$< \lvert r \rvert >$ (fm)	$< v^2 >$
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	$< \lvert r \rvert >$ (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

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



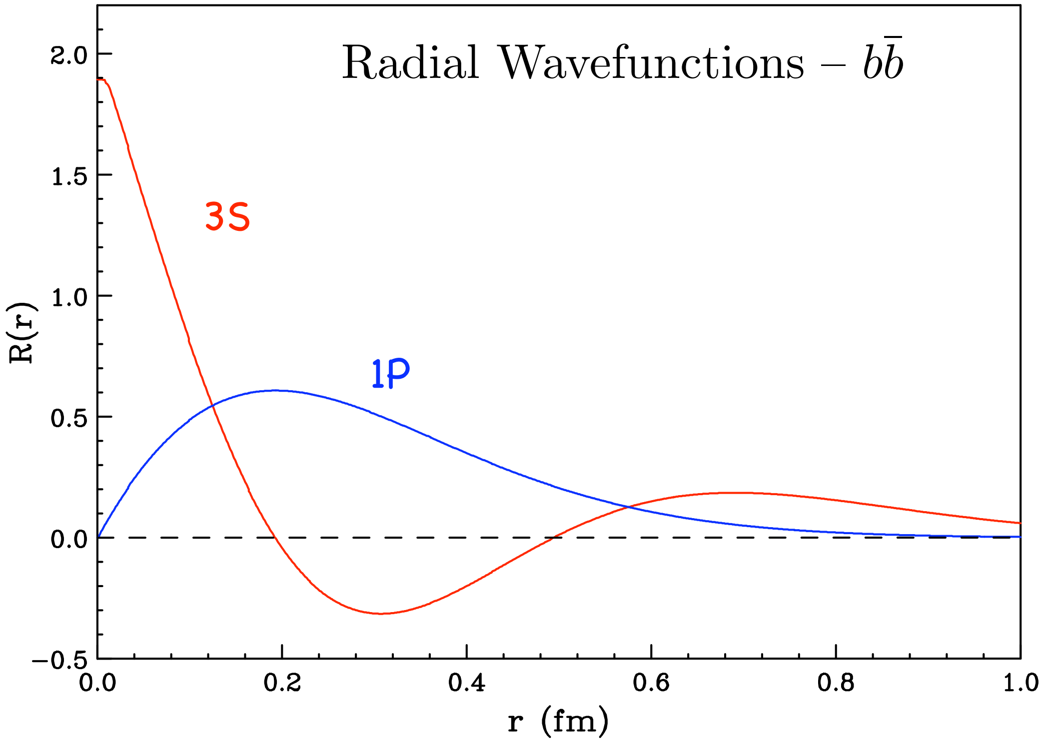
E.E., S. Godfrey, H. Mahlke and J. Rosner [hep-ph/0701208]

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

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

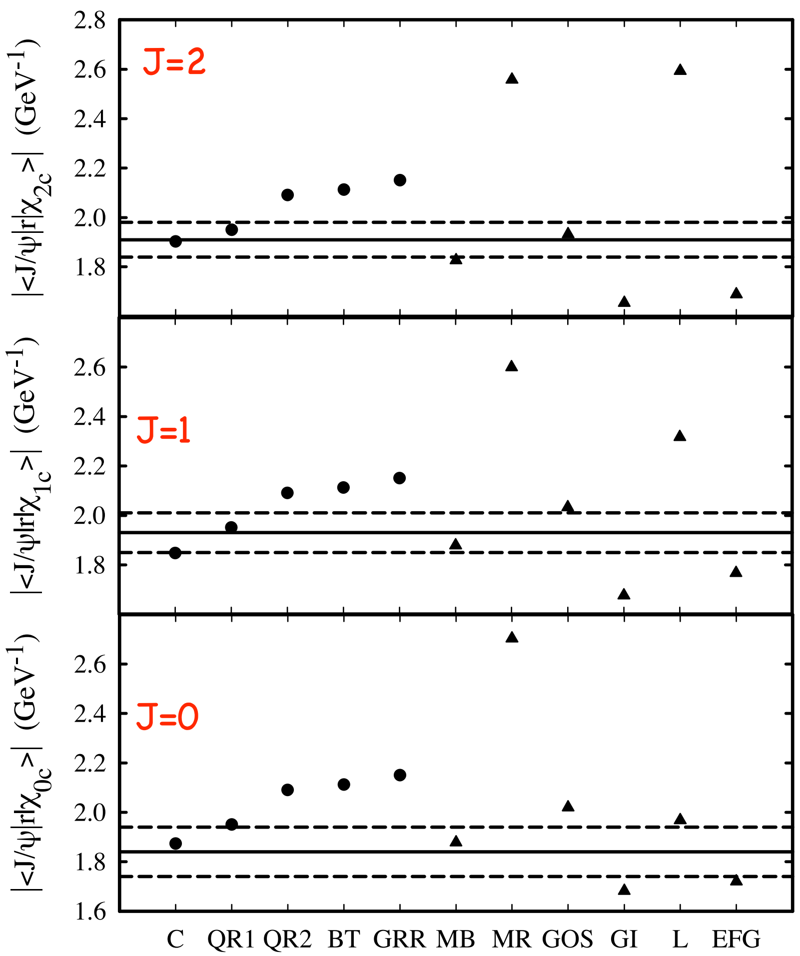
Exp

GI Model



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

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

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

$b\bar{b}$ Transition	initial state node < 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

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

	$\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ 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

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

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

Direct Decays

A wealth of results

- Partial and total widths:
  - Leptonic widths

$$\Gamma_{e^+e^-}(n^3S_1) = \frac{16\pi\alpha^2 e_q^2}{M^2}|\Psi_{nS}(0)|^2(1 - \frac{16\alpha_s}{3\pi})$$

Lattice calculations needed

Branching ratios and total widths

Z. Li et al., PRD 71, 111103(R) (2005)

$$B(J/\psi \to e^+e^-) = 5.945 \pm 0.067 \pm 0.042$$

TABLE II. The results of $\Gamma_{ee}\Gamma_{\text{had}}/\Gamma_{\text{tot}}$ for the three resonances, the dielectron widths Γ_{ee}, and their ratios. The first uncertainty is statistical and the second is systematic.

$\Gamma_{ee}\Gamma_{\text{had}}/\Gamma_{\text{tot}}(1S)$	$1.252 \pm 0.004 \pm 0.019$ keV
$\Gamma_{ee}\Gamma_{\text{had}}/\Gamma_{\text{tot}}(2S)$	$0.581 \pm 0.004 \pm 0.009$ keV
$\Gamma_{ee}\Gamma_{\text{had}}/\Gamma_{\text{tot}}(3S)$	$0.413 \pm 0.004 \pm 0.006$ keV
$\Gamma_{ee}(1S)$	$1.354 \pm 0.004 \pm 0.020$ keV
$\Gamma_{ee}(2S)$	$0.619 \pm 0.004 \pm 0.010$ keV
$\Gamma_{ee}(3S)$	$0.446 \pm 0.004 \pm 0.007$ keV
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$0.457 \pm 0.004 \pm 0.004$
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$0.329 \pm 0.003 \pm 0.003$
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$	$0.720 \pm 0.009 \pm 0.007$

Check lepton universality

TABLE II. Final results on the ratio of branching fractions to $\tau^+\tau^-$ and $\mu^+\mu^-$ final states, and the absolute branching fraction for $\Upsilon \to \tau^+\tau^-$. Included are both statistical and systematic uncertainties, as detailed in the text. Results from Ref. [3] are used in deriving the final absolute branching fractions.

	$\mathcal{R}^{\Upsilon}_{\tau\tau}$	$B(\Upsilon \to \tau^+\tau^-)$ (%)
$\Upsilon(1S)$	$1.02 \pm 0.02 \pm 0.05$	$2.54 \pm 0.04 \pm 0.12$
$\Upsilon(2S)$	$1.04 \pm 0.04 \pm 0.05$	$2.11 \pm 0.07 \pm 0.13$
$\Upsilon(3S)$	$1.05 \pm 0.08 \pm 0.05$	$2.52 \pm 0.19 \pm 0.15$

$$\Gamma(\Upsilon(1S)) = 54.4 \pm 0.2 \pm 0.8 \pm 1.6 \text{ keV}$$
$$\Gamma(\Upsilon(2S)) = 30.5 \pm 0.2 \pm 0.5 \pm 1.3 \text{ keV}$$
$$\Gamma(\Upsilon(3S)) = 18.6 \pm 0.2 \pm 0.3 \pm 0.9 \text{ keV}$$

D. Besson et al., PRL 98, 052002 (2007)

G. S. Adams, PRL 94, 012001 (2005)
J. L. Rosner et al., PRL 96, 092003 (2006)

Measure α_s and other QCD tests

A recent result

$$\psi(2S) \to \gamma_1 \chi_{cJ}, \quad \chi_{cJ} \to \gamma_2 \gamma_3,$$

K. M. Ecklund et al. [arXiv:0803.2869] [hep-ex]

$$\Gamma(\chi_{c0} \to \gamma\gamma) = (2.53 \pm 0.37 \pm 0.26) \text{ keV}$$
$$\Gamma(\chi_{c2} \to \gamma\gamma) = (0.60 \pm 0.06 \pm 0.06) \text{ keV}$$
$$\mathcal{R} = \frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \gamma\gamma)} = 0.237 \pm 0.043 \pm 0.034$$

Widths depend on $|R'_P(0)|^2$

Dependence cancels in ratio -> measure α_s

BUT (as is typical) first order α_s corrections are large -> large theoretical uncertainties

More work for theorists

Partial list of theory expectations (cc)

$$\Gamma(n^3S_1 \to 3g) = \frac{10}{81}\frac{(\pi^2-9)}{\pi}\frac{\alpha^3(m_Q)}{m_Q^2}|R_{nS}(0)|^2(1-\frac{3.7\alpha_s}{\pi})$$
$$\frac{\Gamma(n^1S_0 \to \gamma\gamma)}{\Gamma_{ee}(n^3S_1)} = 3e_Q^2[1+\frac{\alpha_s}{3\pi}(\pi^2-4)]$$
$$\frac{\Gamma(n^3S_1 \to ggg)}{\Gamma_{ee}(n^3S_1)} = \frac{10}{81}\frac{(\pi^2-9)}{\pi}\frac{\alpha_s^3(m_Q)}{e_Q^2\alpha^2}[1+1.6\frac{\alpha_s}{\pi}]$$
$$\frac{\Gamma(n^3S_1 \to \gamma gg)}{\Gamma_{ee}(n^3S_1)} = \frac{8}{9}\frac{(\pi^2-9)}{\pi}\alpha_s^2(m_Q)[1-1.3\frac{\alpha_s}{\pi}]$$
$$\Gamma(n^3P_0 \to \gamma\gamma) = \frac{27e_Q^4\alpha^2}{m_Q^4}|R'_{nP}(0)|^2[1+\frac{\alpha_s}{3\pi}(\pi^2-\frac{28}{3})]$$
$$\Gamma(n^3P_2 \to \gamma\gamma) = \frac{36e_Q^4\alpha^2}{5m_Q^4}|R'_{nP}(0)|^2[1-\frac{16\alpha_s}{3\pi}]$$
$$\frac{\Gamma(n^3P_2 \to \gamma\gamma)}{\Gamma(n^3P_0 \to \gamma\gamma)} = \frac{4}{15}[1-\frac{\alpha_s}{3\pi}(\pi^2+\frac{20}{3})]$$
$$\frac{\Gamma(n^1S_0 \to gg)}{\Gamma(n^1S_0 \to \gamma\gamma)} = \frac{2}{9}|\frac{\alpha_s(m_q)}{e_Q^2\alpha}|^2(1+8.2\frac{\alpha_s}{\pi})$$
$$\frac{\Gamma(n^3P_0 \to gg)}{\Gamma(n^3P_0 \to \gamma\gamma)} = \frac{2}{9}|\frac{\alpha_s(m_q)}{e_Q^2\alpha}|^2(1+9.3\frac{\alpha_s}{\pi})$$
$$\frac{\Gamma(n^3P_2 \to gg)}{\Gamma(n^3P_2 \to \gamma\gamma)} = \frac{2}{9}|\frac{\alpha_s(m_q)}{e_Q^2\alpha}|^2(1+3.1\frac{\alpha_s}{\pi})$$

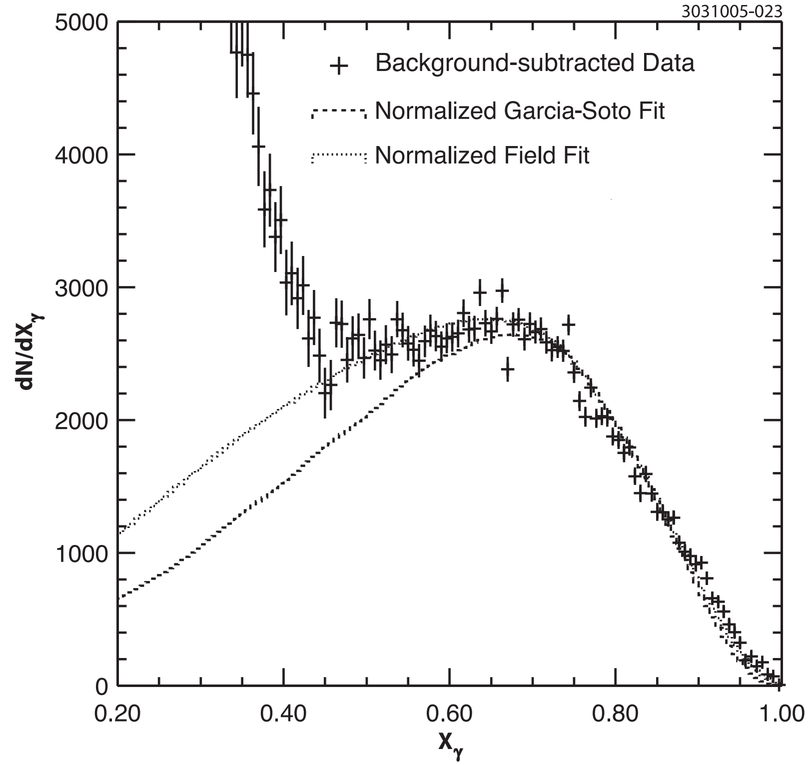
- Inclusive $\Upsilon(n^3S_1) \to \gamma + X$

Fleming and Leibovich;
Garcia and Soto

The differential photon spectrum dN/dx_γ for $0.4 \leq x_\gamma \leq 0.95$ is determined in NRQCD (+SCET)

$$\mathcal{R}_n = \frac{\Gamma(\Upsilon(n^3S_1) \to \gamma gg)}{\Gamma(\Upsilon(n^3S_1) \to ggg)} = \frac{4}{5}\frac{\alpha}{\alpha_s(m_Q)}[1 + 2.2\frac{\alpha_s}{\pi}]$$

$\Upsilon(1S) \to \gamma + X$



D. Besson et al., PRD 74 012003 (2006)

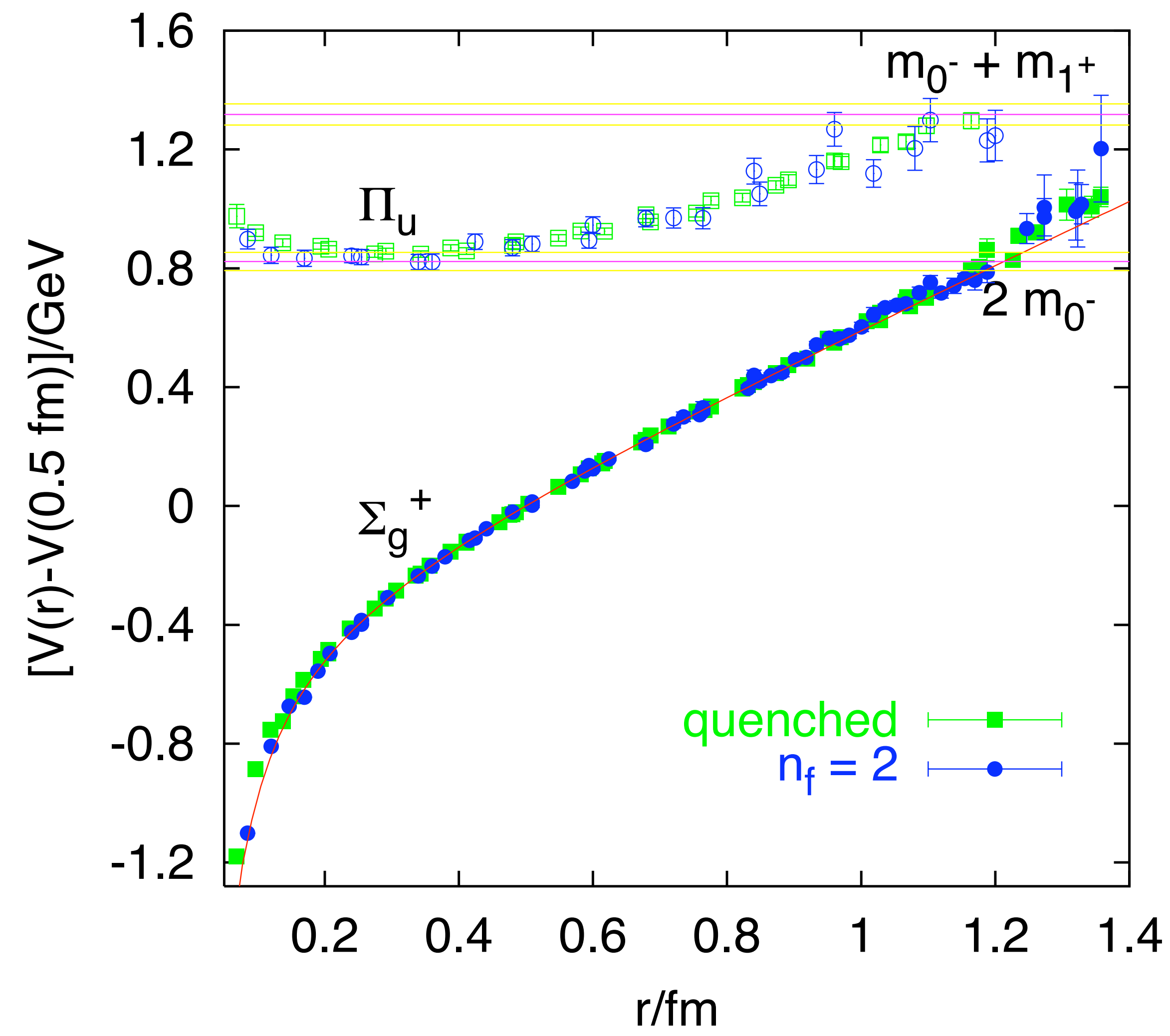
$$\mathcal{R}_1 = (2.70 \pm 0.01 \pm 0.13 \pm 0.24)\%$$
$$\mathcal{R}_2 = (3.18 \pm 0.04 \pm 0.22 \pm 0.41)\%$$
$$\mathcal{R}_3 = (2.72 \pm 0.06 \pm 0.32 \pm 0.37)\%$$

- Factory mode:
  - Access to known lighter states.
  - Search for new states: glueballs, axions, light a^0 (SUSY), narrow resonances, ...

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



Hybrid states and Lattice QCD

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

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

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

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

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

$$< J_g^2 >= 0, 2, 6, \ldots$$

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, ...

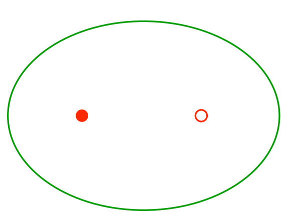
η= ±1 (symmetry under combined charge conjugation and spatial inversion) denoted g(+1) or u(-1).

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

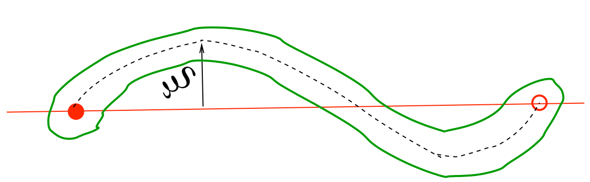
Potentials computed by lattice QCD

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

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



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



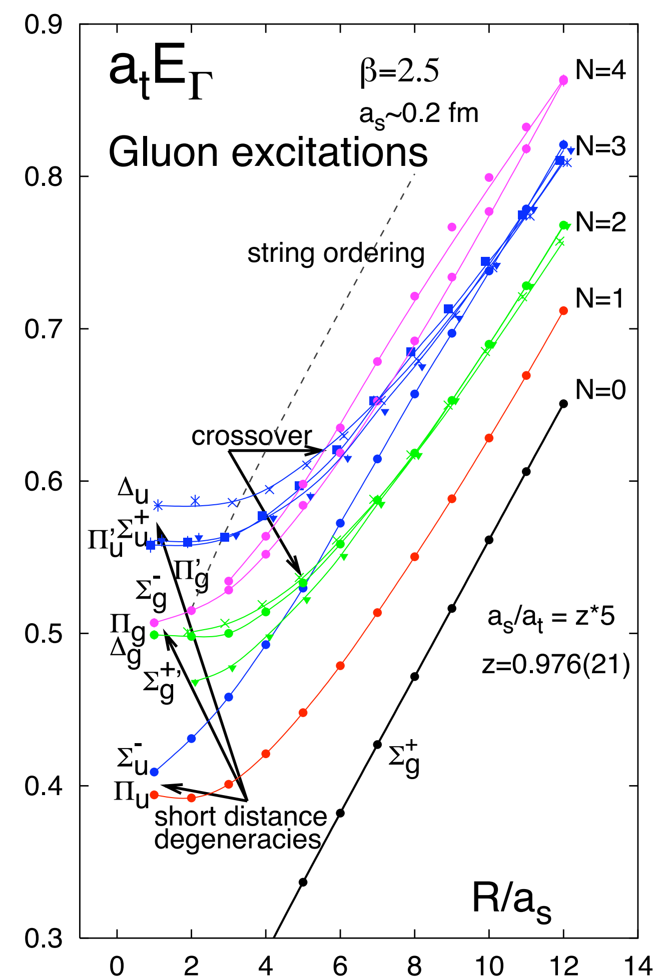


FIG. 2: Short-distance degeneracies and crossover in the spectrum. The solid curves are only shown for visualization. The dashed line marks a lower bound for the onset of mixing effects with glueball states which requires careful interpretation.

Hadronic Transitions

- **Multipole expansion**

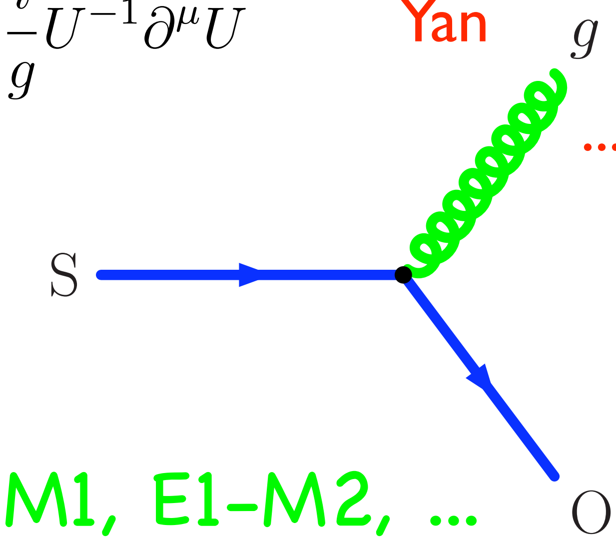
  For lowest order gluon emission: Gottfried

$$\mathcal{H}_I = i\psi^{\dagger\prime}\frac{\mathbf{r}}{\mathbf{2}}\cdot\mathbf{g}\mathbf{E}'_{\mathbf{a}}\mathbf{t}^{\mathbf{a}}\psi' + \frac{\mathbf{c_F}}{\mathbf{m_Q}}\psi^{\dagger\prime}\mathbf{s_Q}\cdot\mathbf{g}\mathbf{t}^{\mathbf{a}}\mathbf{B}'_{\mathbf{a}}\psi' + [\mathbf{Q}->\bar{\mathbf{Q}}] + \cdots$$

Voloshin

with dressed fields $\psi' = U^{-1}\psi \qquad \mathbf{t^a}\mathbf{A}'^{\mu}_{\mathbf{a}} = U^{-1}\mathbf{t^a}\mathbf{A}^{\mu}_{\mathbf{a}}U - \frac{i}{g}U^{-1}\partial^{\mu}U$ Yan

But single emission takes color singlet state (S) to unphysical octet state (O).



Double transitions dominate: E1-E1, E1-M1, M1-M1, E1-M2, ...

- **Factorization**

E1-E1 $\quad \frac{g_E^2}{8} < B|\mathbf{r_i}gt^a\mathcal{G}\mathbf{r_j}gt^b|A> \qquad \overset{\delta_{ab}}{<\pi\pi|\mathbf{E^i_a}\mathbf{E^i_b}|\mathbf{0}>}$

electric polarizability — chiral methods — Brown & Cahn, ...

model $\quad \mathcal{G} = (\mathrm{E_A} - \mathcal{H}^0_{\mathrm{NR}})^{-1} = \sum_{\mathrm{KL}} \frac{|\mathrm{KL}><\mathrm{KL}|}{\mathrm{E_A}-\mathrm{E_{KL}}} \quad (Q\bar{Q}\ \mathrm{octet})$ Kuang & Yan

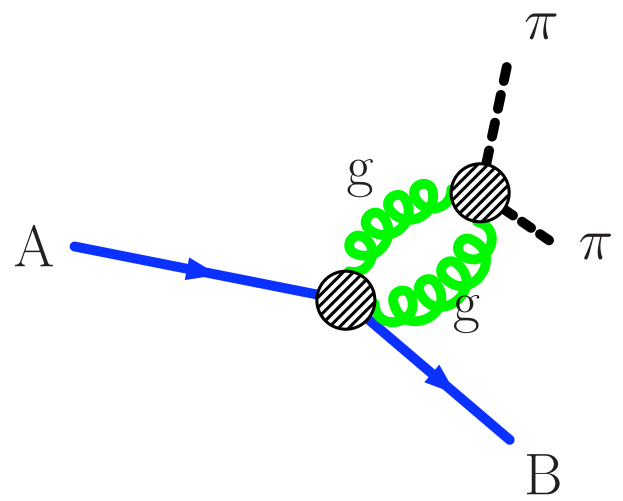
quark confining string

Two pion transitions

Factorization

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

$$\alpha_{AB}^{EE}$$



Model: Kuang & Yan
[PR D24, 2874 (1981)]

Hadronize

S-wave D-wave

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

S state -> S state

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

$$\Gamma = \mathrm{G}\ |\alpha_{\mathrm{AB}}^{\mathrm{EE}}\ \mathrm{C}_1|^2$$

Phase Space

Overlap - Vibrating String Model

$\psi(2S) \to \pi\pi + J/\psi$

H. Mendez et al. [arXiv:0804.4432] [hep-ex]

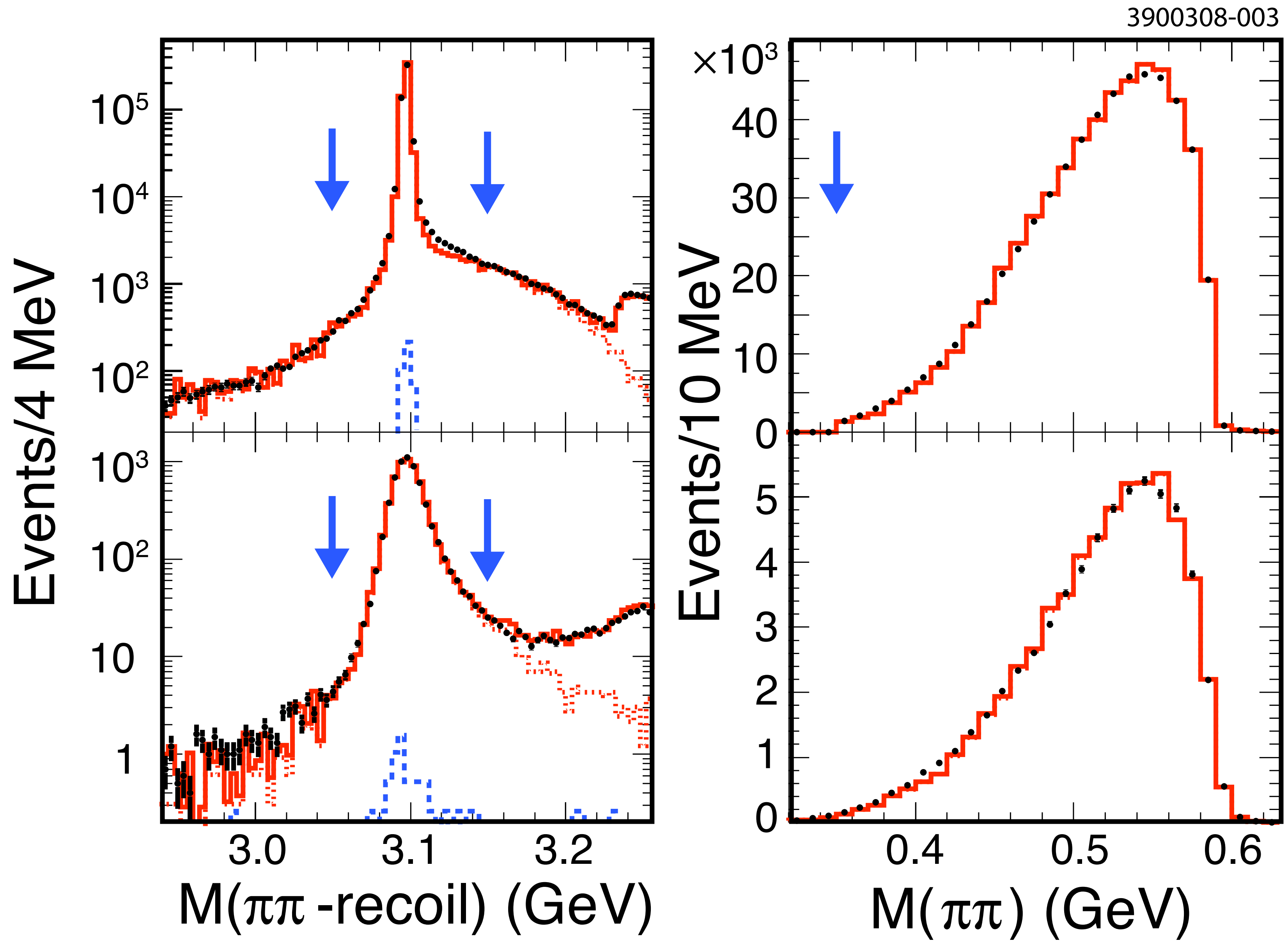


FIG. 2: Plots relevant to the decay $\psi(2S) \to \pi^+\pi^- J/\psi$ (top) and $\psi(2S) \to \pi^0\pi^0 J/\psi$ (bottom). The left plots show the dipion recoil mass spectrum and the right plots the dipion mass spectrum. The J/ψ candidates in the continuum sample arise from the tail of the $\psi(2S)$. Symbols are as in Fig. 1.

D state -> S state

Determines

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

CLEO [N. E. Adam et al., PRL 96, 082004 (2006)]

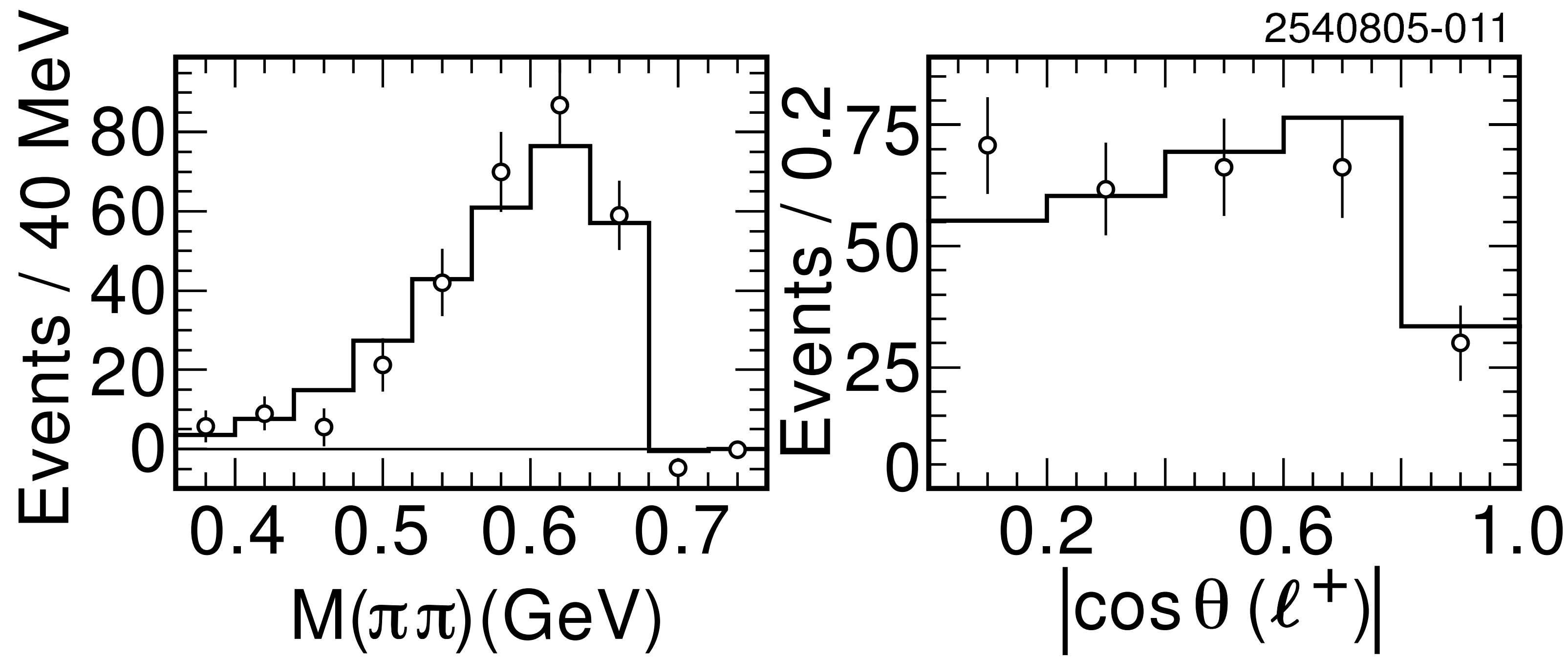


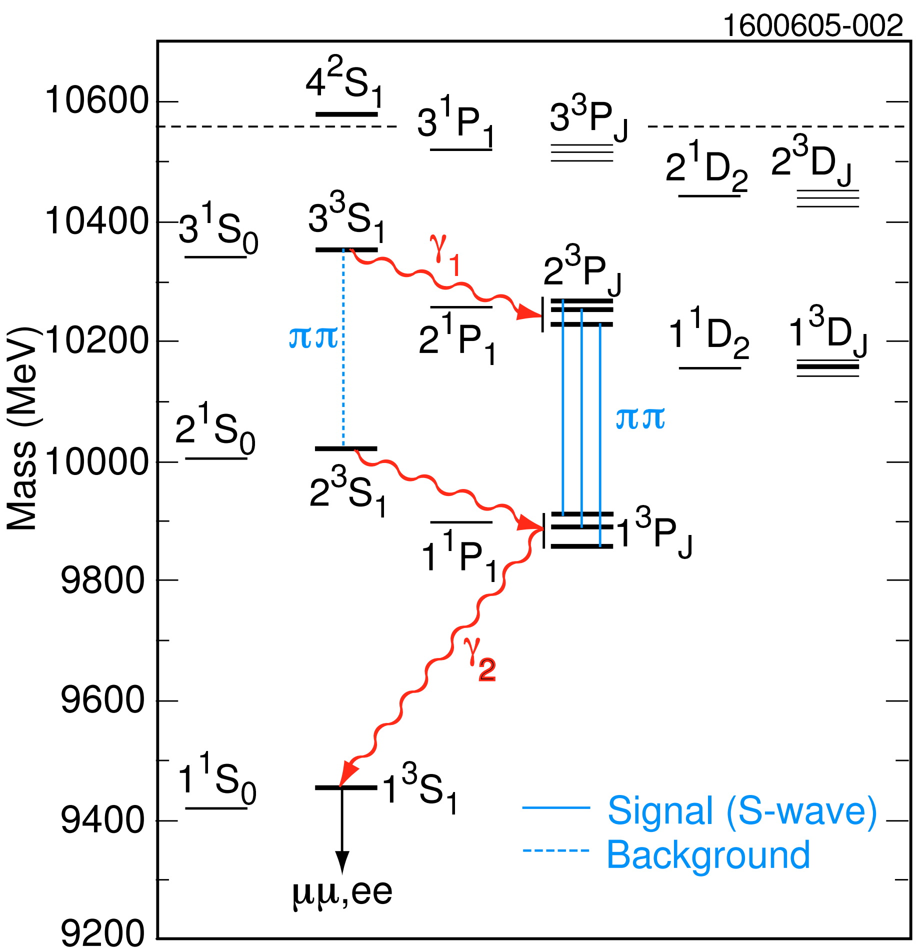
FIG. 4: Distributions in $\pi^+\pi^-\ell^+\ell^-$ events of the $\pi^+\pi^-$ mass (left) and polar angle (right) of the positively charged lepton from data (open circles) and MC (solid line line).

P state -> P state

Assume only S wave term => J = J'

$$\Gamma_{\pi\pi} = (0.83 \pm 0.22 \pm 0.08 \pm 0.19)\ \mathrm{keV}$$

CLEO [C. Cawfield et al.,PR D73, 012003 (2006)]



$2P_J \rightarrow 1P_{J'} + 2\pi$ - First observation[CLEO]

Results agree with Kuang and Yan (1988)

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

=> $|C_1| = 8.87\times10^{-3}$

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

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

Puzzle

$$\Upsilon(3S) \rightarrow \Upsilon + \pi\pi$$
$$\Upsilon(4S) \rightarrow \Upsilon(2S) + \pi\pi$$

don't show leading (S-wave) two pion invariant mass distribution

Many proposals for explaining the Υ(3S)->Υ transition but most don't survive results for Υ(4S):

- Final State Interactions

  Problem: Compare Υ(4S)->Υ(2S), Υ(2S)->Υ(1S) and ψ(2S) -> J/ψ essentially the same phase space but different distributions.

- Coupling to decay channels

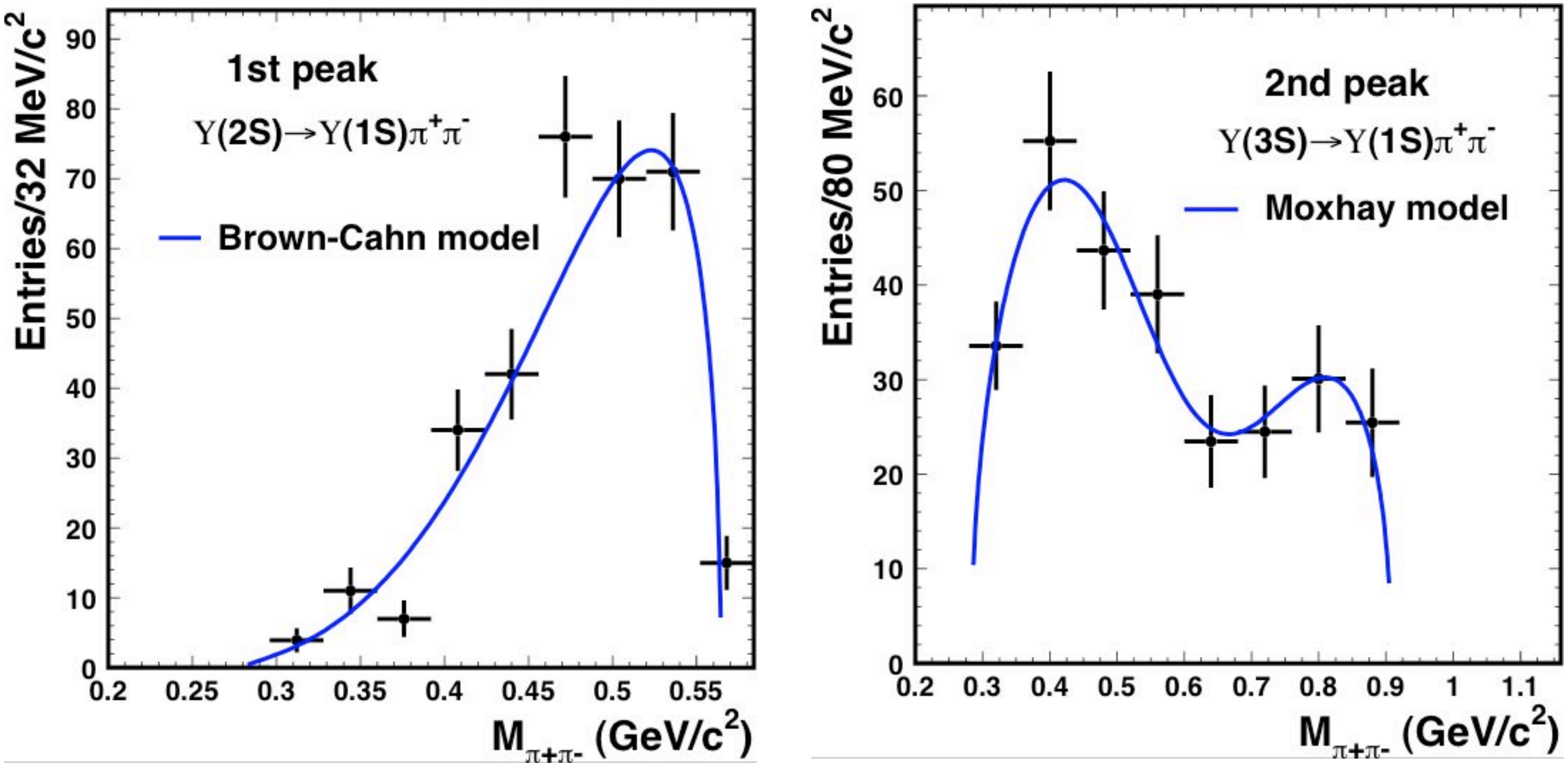
  Problem: Compare Υ(3S)->Υ(1S) to ψ(2S)->J/ψ, Υ(4S)->Υ(1S) Coupled channel effects should be larger in second set.

- 4 quark intermediate state

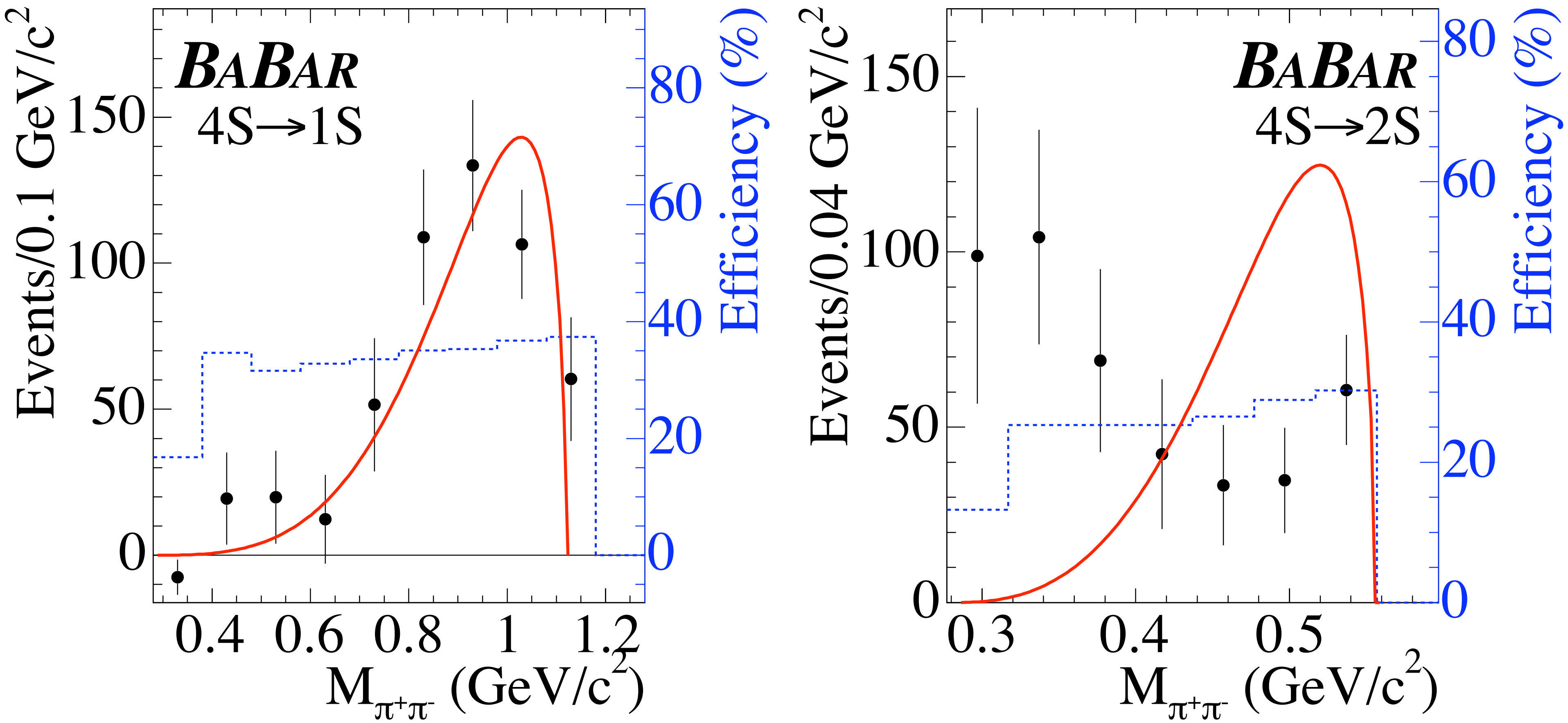
  Problem: Compare Υ(4S)->Υ(2S), Υ(3S)->Υ(1S) similiar distributions but shifted masses

- dynamical accident - suppress the leading E1 E1 term ⇒

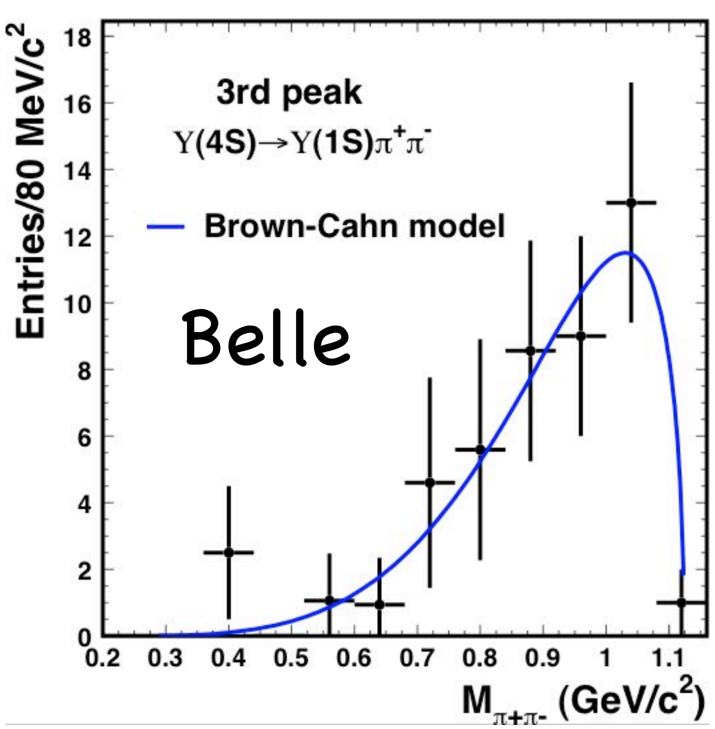
$M_{\pi\pi}$ distributions



ϒ(2S) and ϒ(3S)→ϒ(1S) are well described by Brown-Cahn and Moxhay models. → consistent with CLEO measurement(PRD58 052004, PRD49 40).



$M_{\pi\pi}$ distributions(cont.)



$\Upsilon(4S) \to \Upsilon(1S)$ is consistent with Brown-Cahn model.

Like the E1 case ?

$\Delta n = 2$ overlap suppressed.

Predicted for $\Upsilon(3S) \to \Upsilon(1S)$

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:

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

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

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

Hence transition rates fairly insensitive to intermediate states details

Transition	G (GeV^7)	$\lvert < i\lvert r^2\rvert f > \rvert$ (GeV^{-2})	$G< i\lvert r^2\rvert f >^2$ $\times 10^2$
$\psi(2S) \to J/\psi$	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?

Detailed study: S-wave

Voloshin [PR D74:054022(2006)]

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

S-wave

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

and three D-waves

$$P_\mu = M_A \delta_\mu^0 \qquad r_\mu = (k_{1\mu} - k_{2\mu})$$

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

spin independent

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

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

spin dependent

magnetic	S-D mixing
$\chi_M = \frac{\alpha_M}{\alpha_0}\ ,$	$\chi_2 = \frac{\alpha_2}{\alpha_0}$
O(v^2)	O(v^2)

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

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

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

BUT - In addition to the suppression of the M1-M1 term by $\langle v^2 \rangle$ 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

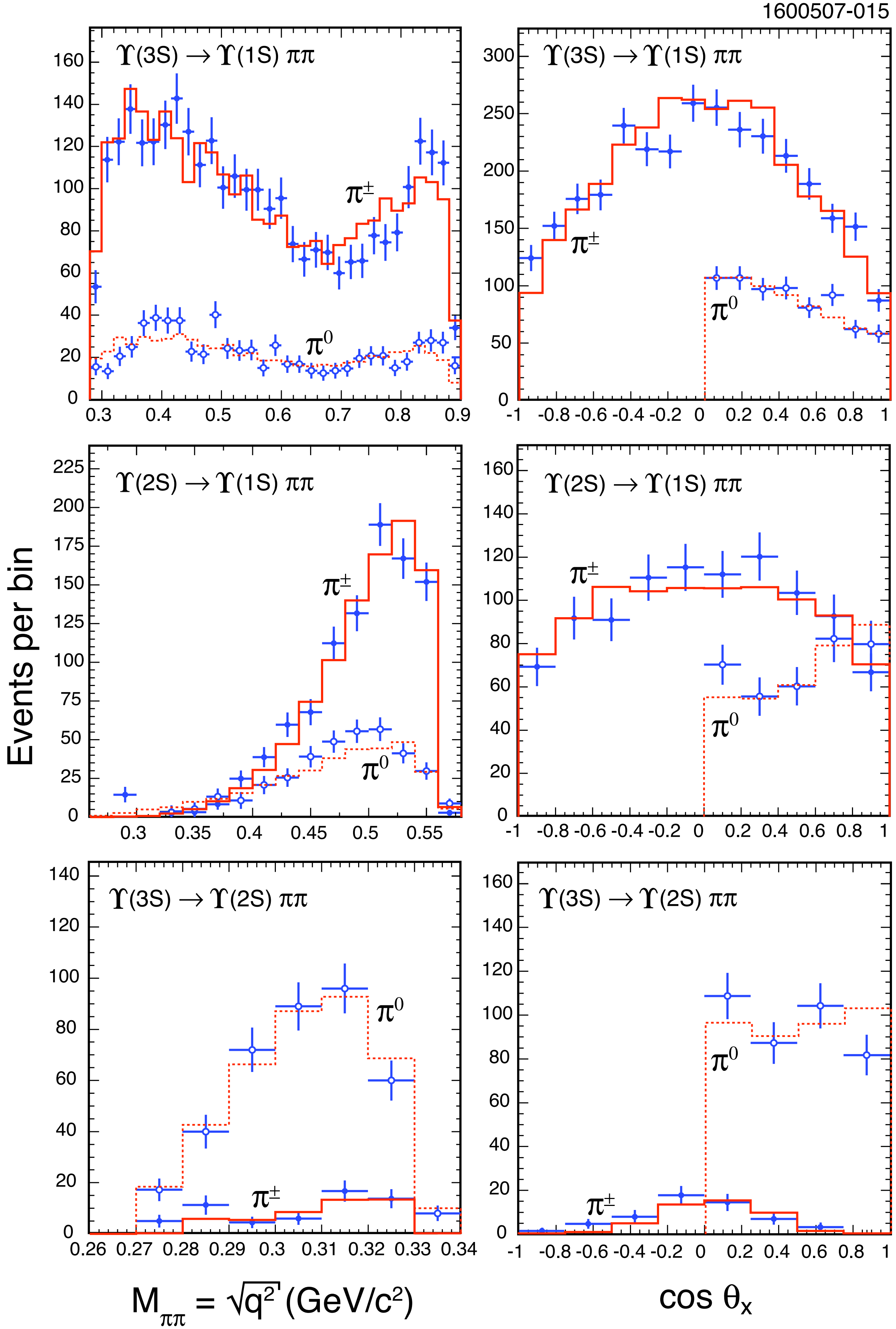
$$\Psi_{nl} = \Pi_u^+(nP)$$

Again below lowest intermediate state threshold

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

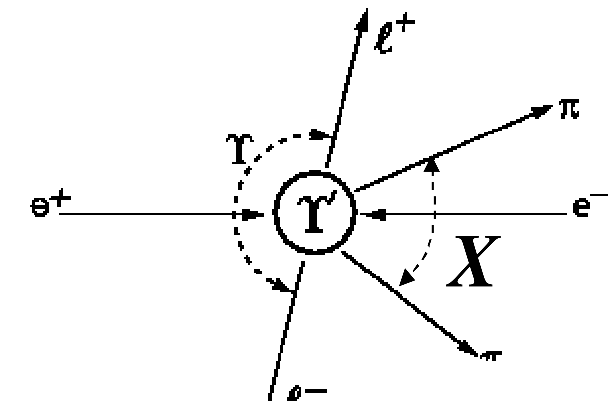
In this limit the overlap vanishes since $\langle f|i \rangle = 0$ ($i \neq f$)

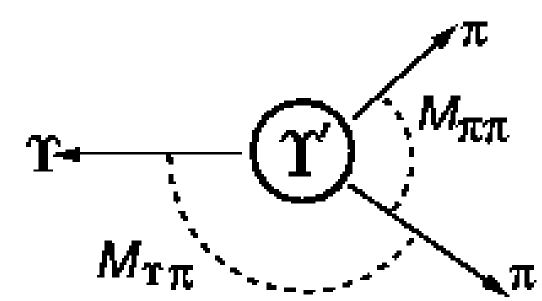
The M1-M1 term is highly suppressed !

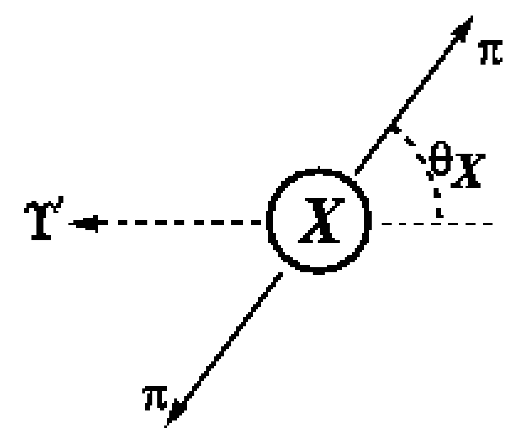


CLEO

[D. Cronin-Hennessy et al., PRD 76:072001 (2007)]







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

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

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

$QQ(n^3S_1) \to QQ(m^3S_1) + \pi^+\pi^-$

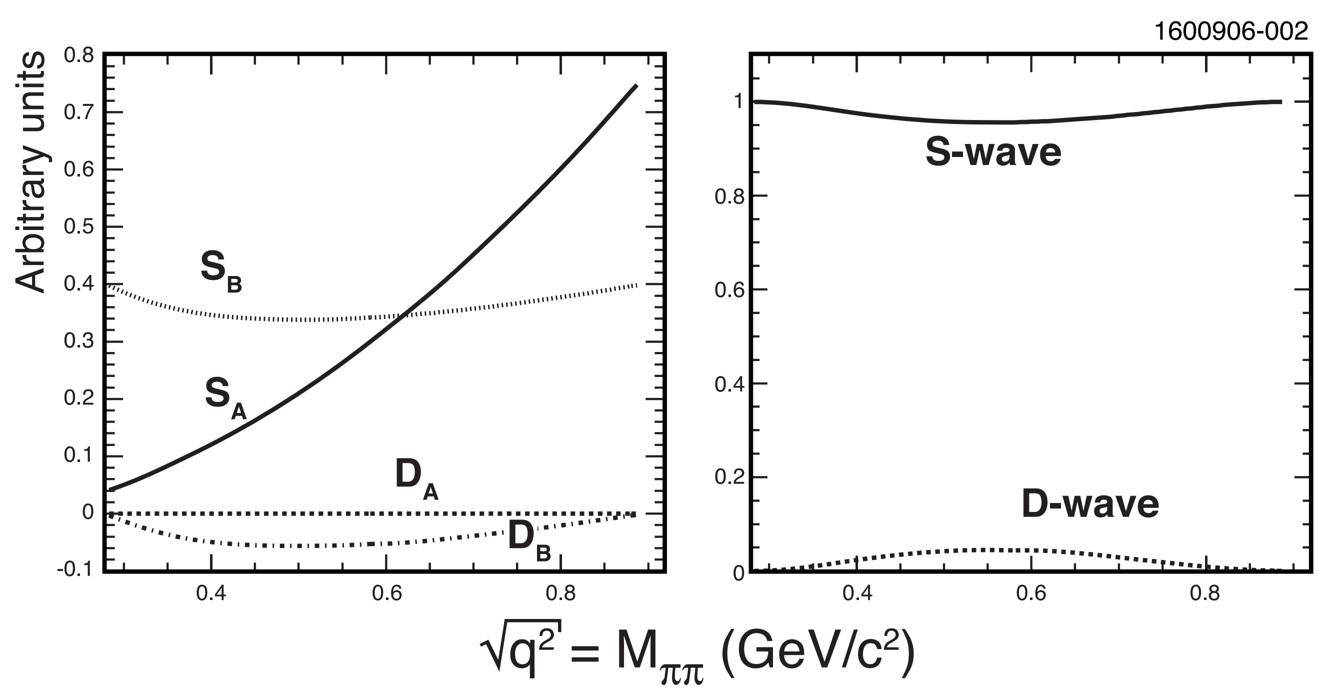
$$M = \mathrm{A}(\varepsilon'\cdot\varepsilon)(q^2 - 2m_\pi^{\;2}) + \mathrm{B}(\varepsilon'\cdot\varepsilon)E_1E_2 + \mathrm{C}\left[(\varepsilon'\cdot q_1)(\varepsilon\cdot q_2) + (\varepsilon'\cdot q_2)(\varepsilon\cdot q_1)\right]$$

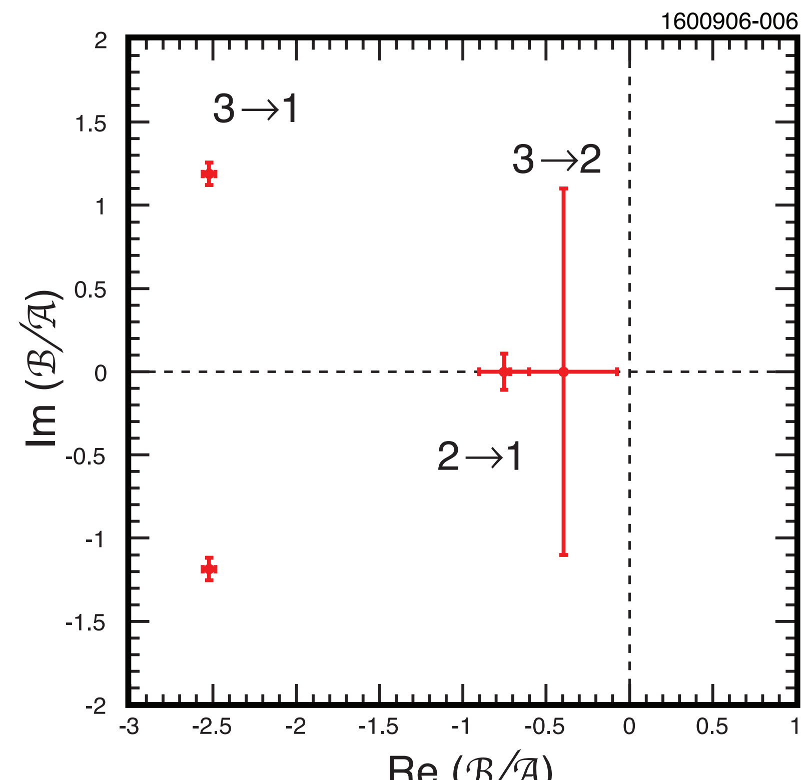
- Hindered M1-M1 term => C≈0. Consistent with CLEO results.
- Small D-wave contributions
- Useful to look at polarization info.
  Dubynskiy & Voloshin [hep-ph/0707.1272]

CLEO [D. Cronin-Hennessy et al., PRD 76:072001 (2007)]

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





Single hadron transitions

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

$C_i C_f = -1 \qquad +1$

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

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

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

chiral effective theory:

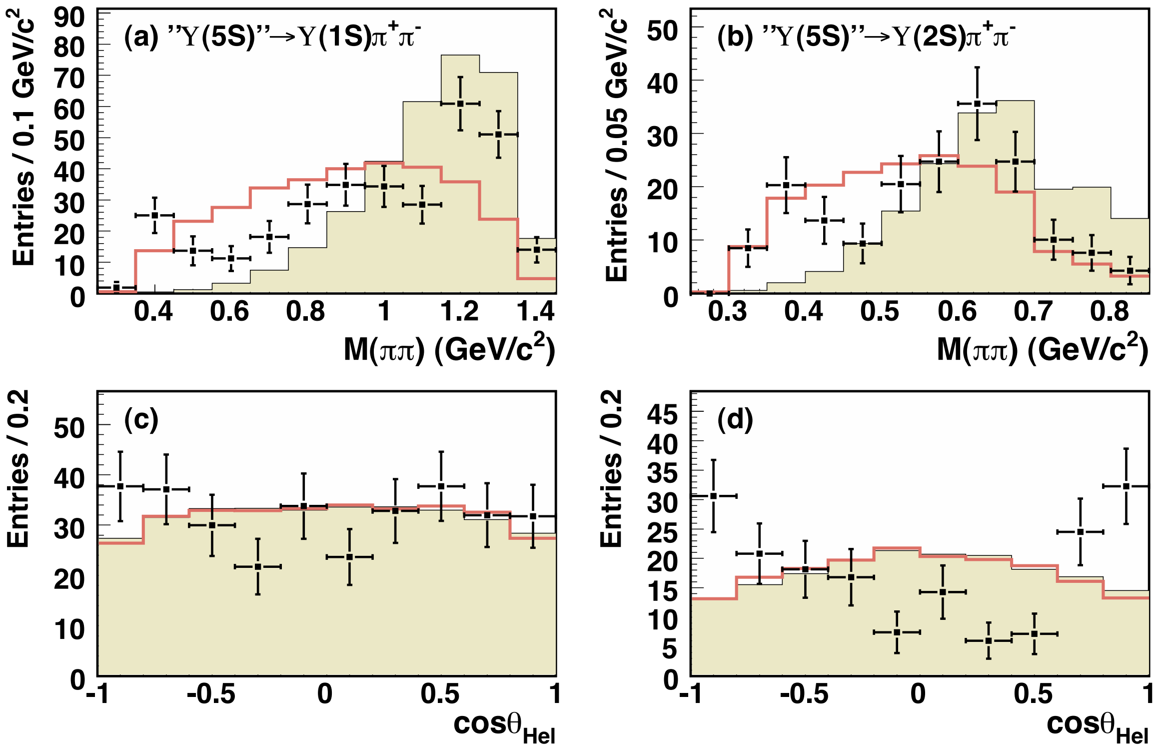
$$\epsilon = \frac{(m_d - m_u)\sqrt{3}}{4(m_s - \frac{m_u + m_d}{2})}, \qquad \epsilon' = \frac{\tilde{\lambda}(m_d - m_u)}{\sqrt{2}(m_{\eta'}^2 - m_{\pi^0}^2)}, \qquad \theta = \sqrt{\frac{2}{3}}\,\frac{\tilde{\lambda}\left(m_s - \frac{m_u + m_d}{2}\right)}{m_{\eta'}^2 - m_\eta^2}.$$

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.

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



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

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

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

phase space (GeV^{-7})

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

$$G(n) = 28.7,\ 0.729,\ 1.33 \times 10^{-2}$$
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 more than an order of magnitude larger than theory expects.

Above Threshold

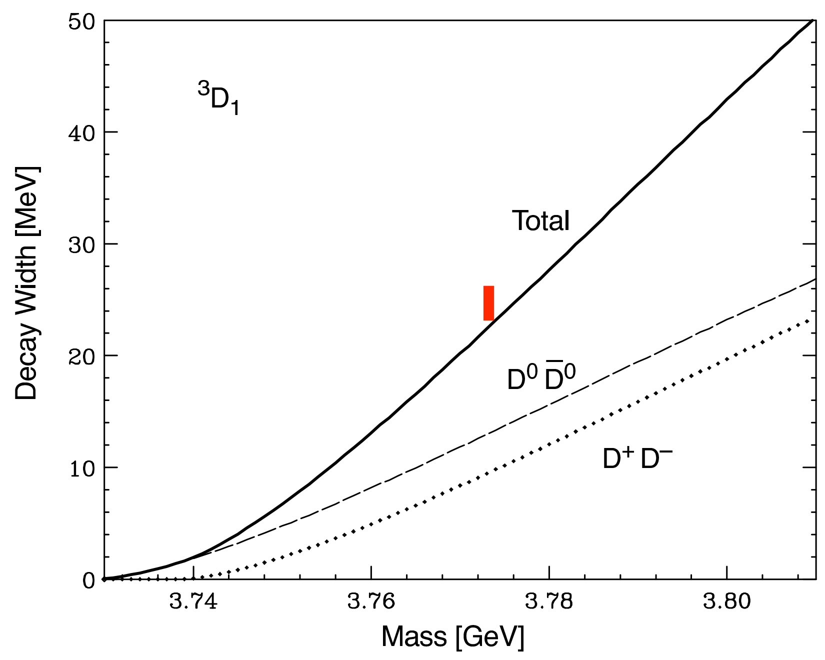
Heavy Flavor Factories

- $\Upsilon(4S)$ ideal for study of $B^{\pm}$, B^0 mesons
  $\Upsilon(5S)$ ideal for study of $B_s^{\pm}$ mesons

- $\psi(3770)$ **Mass *m*** = 3772.4 ± 1.1 MeV , (S = 1.8)
  Full width Γ = 25.2 ± 1.8 MeV

  - Ideal for D^+, D^0 studies. CLEO has exploited this for f_D, D decays and m_D (572 pb^{-1})

  - Decays into charmed mesons



Decay width in good agreement with theory (CCCM)

More details

- Charged/neutral ratios

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

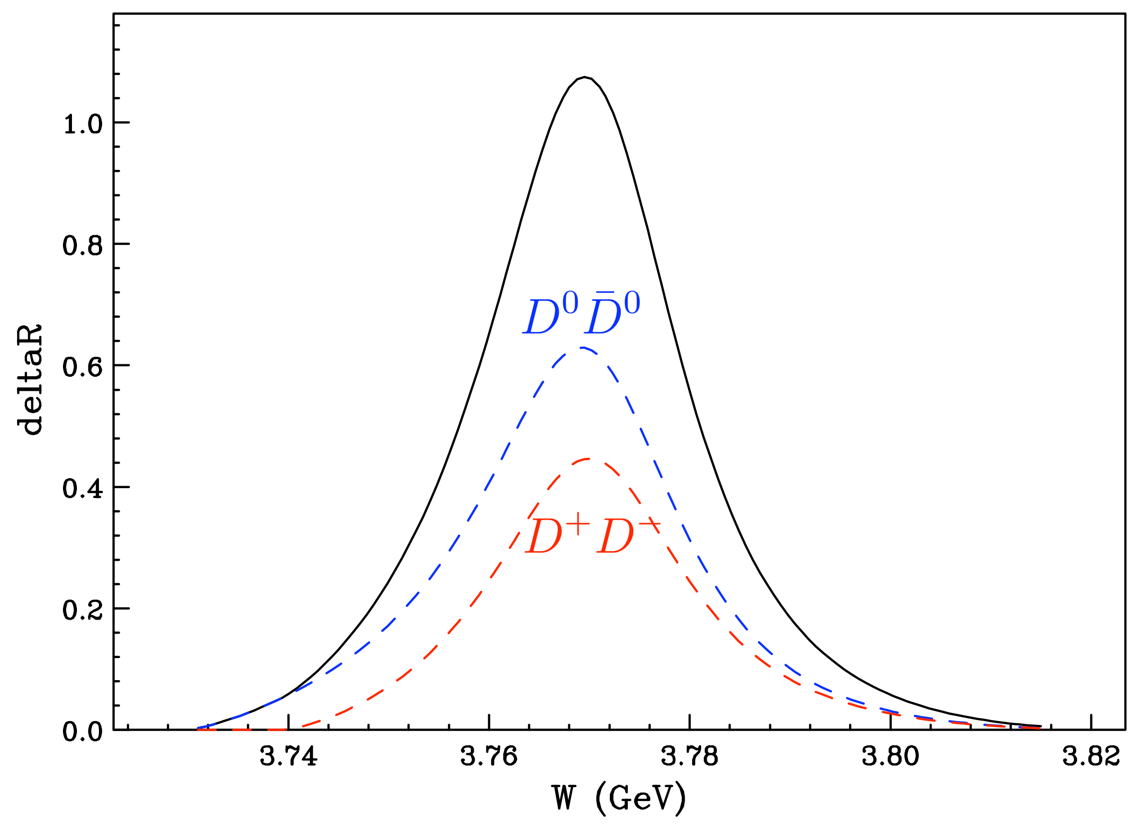
(a) up-down mass difference

(b) EM interactions

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

-> different final state interactions

CCC Model



- Shape of resonance

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

(1) width Γ(p) not pure p wave

(2) interference with 2S state.

$R^{0/+}$

PDG07	p^3	CCCM
1.28 ± 0.14	1.47	1.36

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

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

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

- Mixing with ψ(2S)

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

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

(a) Expansion of EM current

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

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

(b) S-D mixing terms - short range

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

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

- Two important measurement:

(1) Resonance shape in each channel

(2) Ratio of charge to neutral DD final states over the whole resonance region

phase shifts

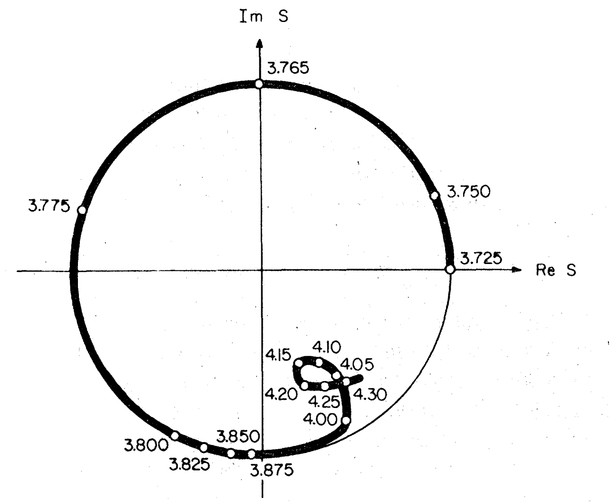


FIG. 9. Argand plot of the $D\bar{D}$ S matrix in the 1^{--} state. The rather narrow elastic $^3D_1$ resonance ψ (3772) is clearly in evidence, as is an inelastic resonance at ~4.15 GeV due to the $3\,^3S\ c\bar{c}$ state. The parameters are the same as in Figs. 7 and 8.

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

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

- X J/ψ

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

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

- $\gamma\chi_{cJ}$

Good agreement with theory expectations including relativistic effects

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

- light hadrons

No evidence for direct decays to light hadrons seen yet.

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

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

No evidence of unexpected rates for non DD decays

ΔR - Total

ΔR - Exclusive channels

- First: a caution

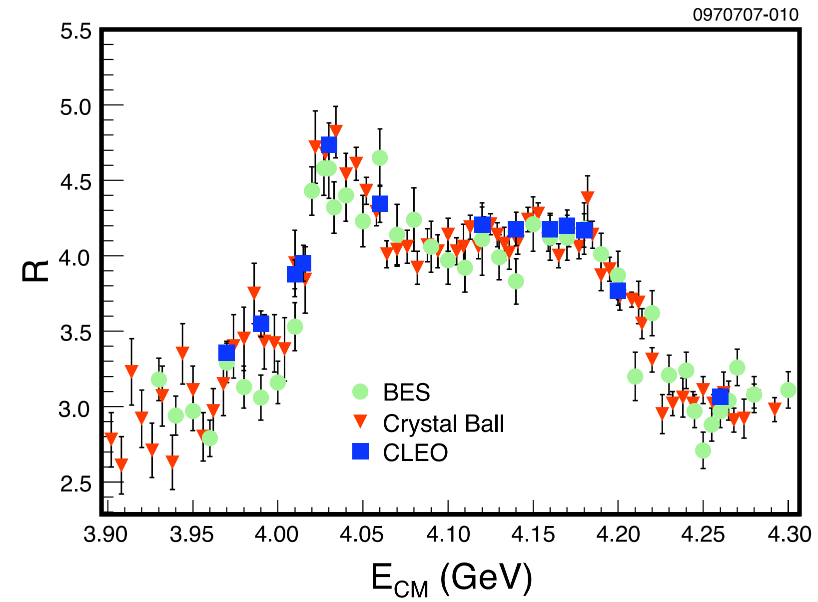
This rich structure arises simply from the 3S and 2D states

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

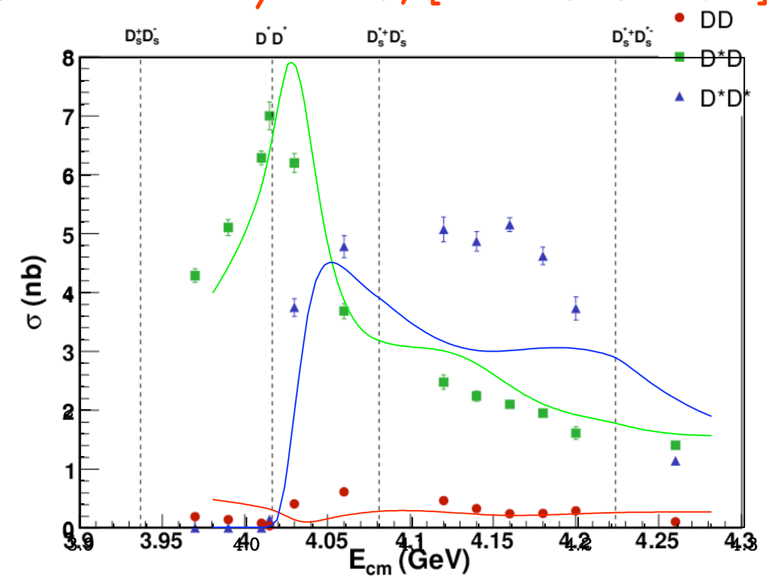
Decay amplitudes for radially excited states have oscillatory structure

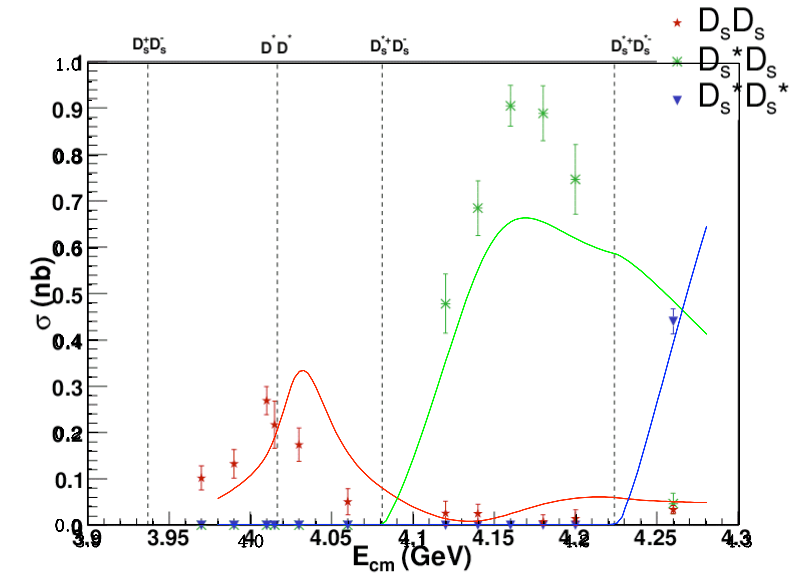
The peaks for individual final states do not coincide

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



D. Cronin-Hennessy et al., [arXiv:0801.3418] [hep-ex]





Updated Cornell Coupled Channel Model

- CLEO - ψ(4170) an excellent D_s factory

  Study f_{Ds}, D_s decays, M_{Ds} with 314 pb^{-1}

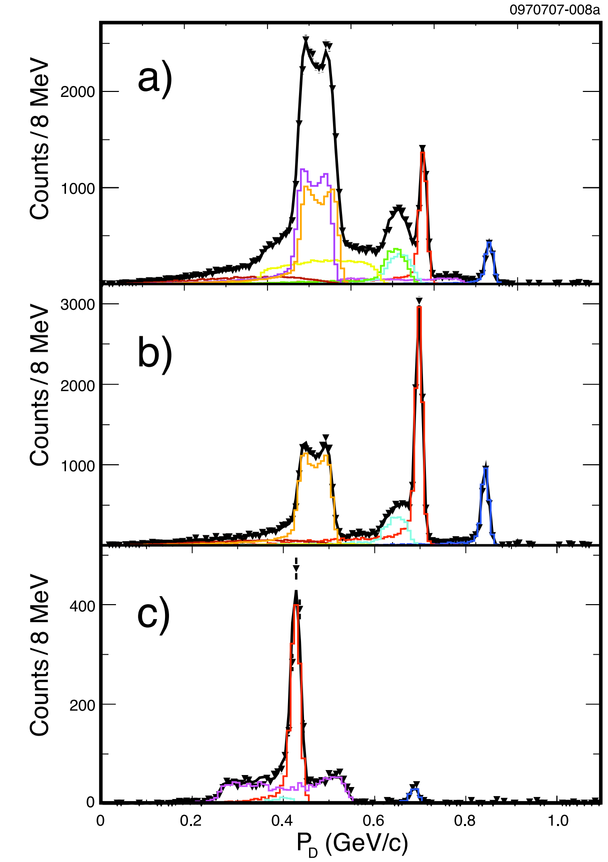
- Opening of the $DD\pi$ channels$_{New}$

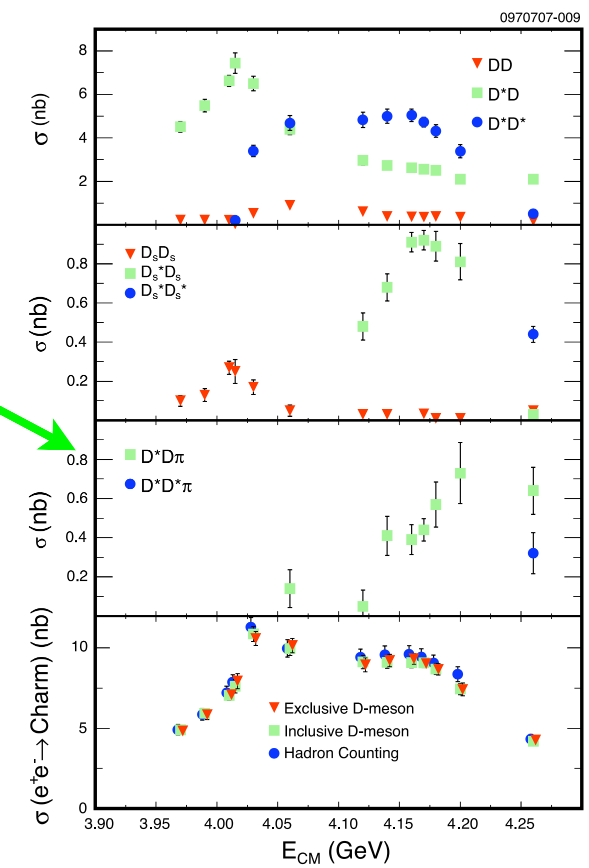
  These channels are small
  for $E_{cm} \leq 4.26$ GeV
  But will become very
  significant at the ψ(4S)

- Surprises in existing data

  Discovery of $D_{s1}(2460)$
  in 13 pb^{-1}
  data collected from 1990-1998

  Besson et al., PR D68, 032002 (2003)





New States Near Charm Threshold

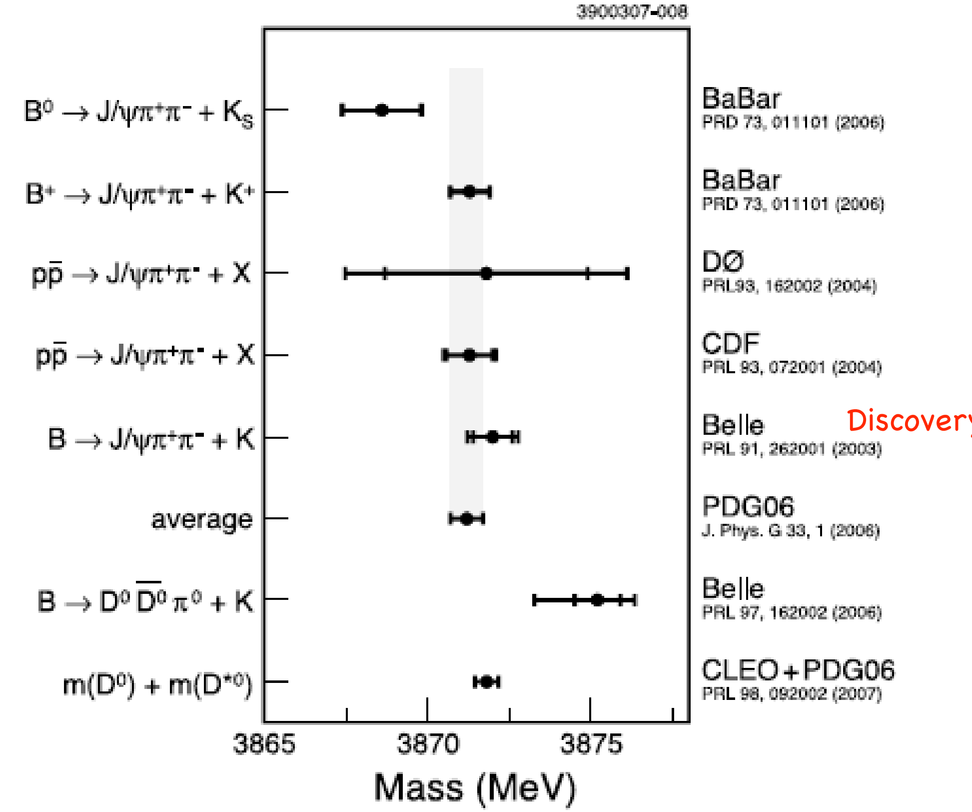
State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, BaBar	$3871.2\pm0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\Upsilon J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	$3929\pm5\pm2 + i(29\pm10\pm2)$	2^{++}	D^0D^0, D^+D^-	$\Upsilon\Upsilon$
Y(3940)	Belle BaBar	$3943\pm11\pm13 + i(87\pm22\pm26)$ $3914.3^{+3.8}_{-3.4} \pm1.6 + i(33^{+12}_{-8} \pm0.60)$	1^{--}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6}\pm6 + i(37^{+26}_{-15}\pm8)$	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008\pm40^{+72}_{-28} + i(226\pm44^{+87}_{-79})$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20}\pm15 + i(139^{+111}_{-61}\pm21)$	J^{P+}	D^*D^*	B decays
Y(4260)	BaBar Cleo Belle	$4259\pm8^{+8}_{-6} + i(88\pm23^{+6}_{-4})$ $4284^{+17}_{-16} \pm4 + i(73^{+39}_{-25}\pm5)$ $4247\pm12^{+17}_{-32} + i(108\pm19\pm10)$	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324\pm24 + i(172\pm33)$ $4361\pm9\pm9 + i(74\pm15\pm10)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	$4433\pm4\pm1 + i(44^{+17}_{-13}{}^{+30}_{-11})$	J^P	$\pi^+\psi(2S)$	B decays
Y(4660)	Belle	$4664\pm11\pm5 + i(48\pm15\pm3)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

Basic Questions:

Is it a new state?
What are its properties?
Charmonium or not?
If not what? New spectroscopy?

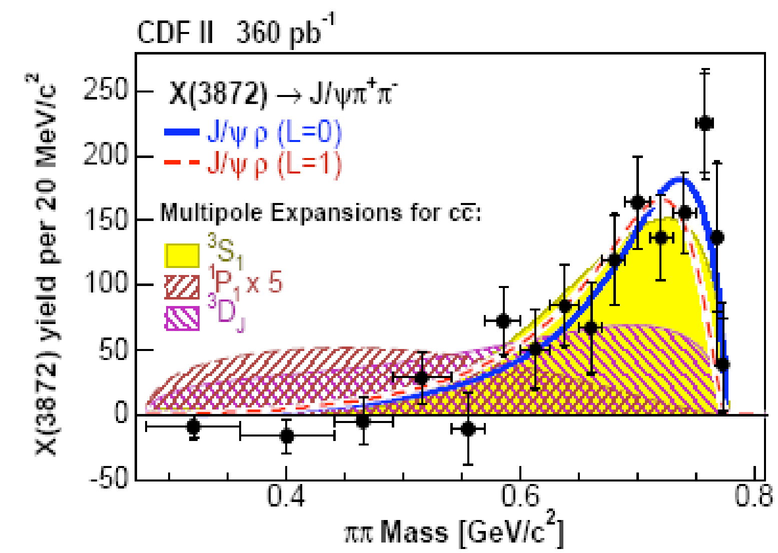
X(3872)

Mass = 3871.2 ± 0.6
Width < 2.3 90% cl



Decay Modes

- X(3872) -> $\pi^+\pi^-$ + J/ψ (Γ_0) (ρ like)
  (Belle, CDF, D0, BaBar)

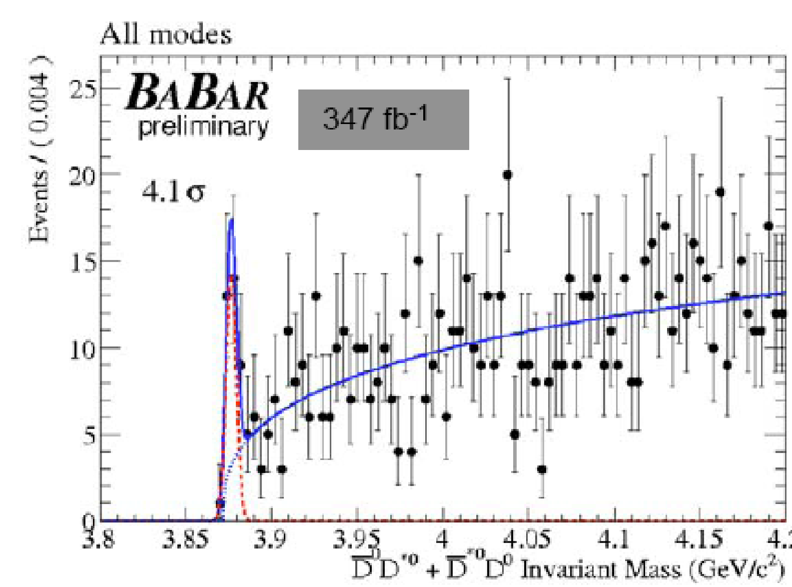


- Γ(X(3872)->\` ω\`+J/ψ)/Γ_0 = 1.0±0.4±0.3
  ⇒ Isospin violating (Belle)

- Γ(X(3872->ϒ+J/ψ)/Γ_0 = 0.14±0.05
  ⇒ C=+ (Belle, BaBar)

- $J^{PC} = 1^{++}$ Strongly favored (Belle, CDF)

- Γ(X(3875)->$D^0D^{*0}+D^{*0}D^0$)/Γ_0 = $12.2 \pm 3.1 {}^{+2.3}_{-3.0}$
  (Belle, BaBar)



Same state ? M = $3875.4^{+1.2}_{-2.0} \pm 0.7$ Mev/c^2

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

  $\Rightarrow$ $M(X) - M(D^0) - M(D^{0*}) = -0.6 \pm 0.6$ 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. 2^3P_1 charmonium state (χ'_{c1}) expected 50 MeV higher and isosinglet.

Requires S-wave threshold;
Decay into two very narrow hadrons
Nearby state ($|M_S - M(\text{threshold})| \leq \Gamma_S$)
with strong coupling to decay channel.

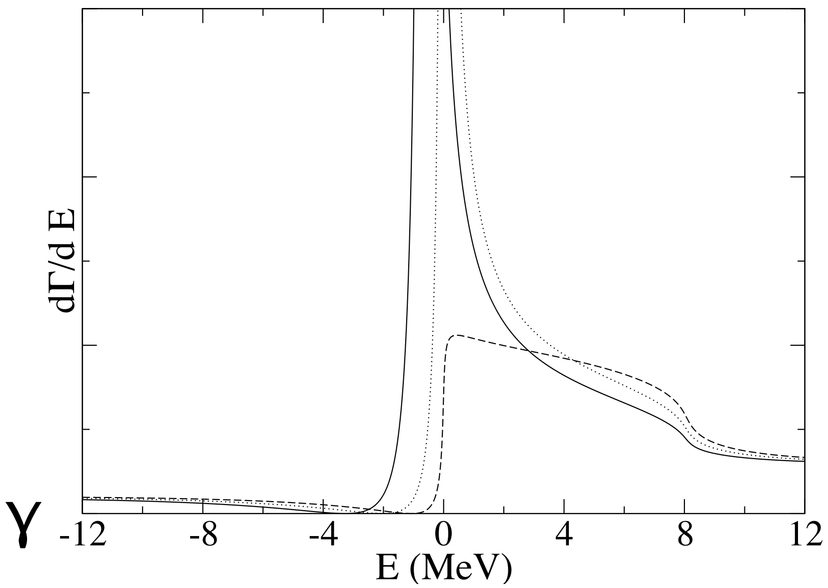
- D^0D^{*0} molecule with binding provided mainly by nearby χ'_{c1} most likely possibility.

- 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)]

  Dependence of $d\Gamma/dE$ on inverse scattering length γ

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



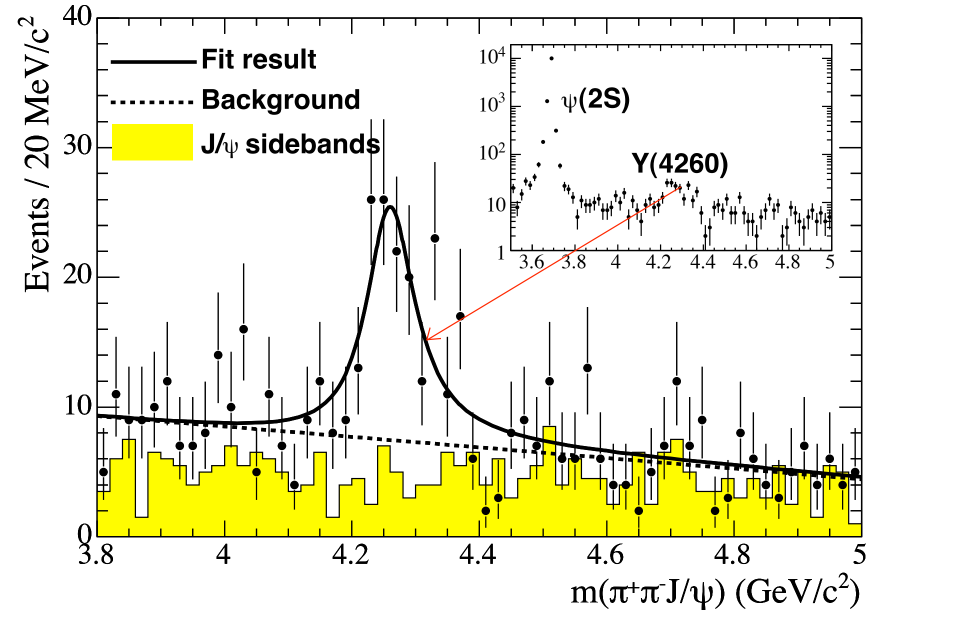
Y(4260) and beyond

- **Y(4260) discovery**

  Seen by BaBar in ISR production

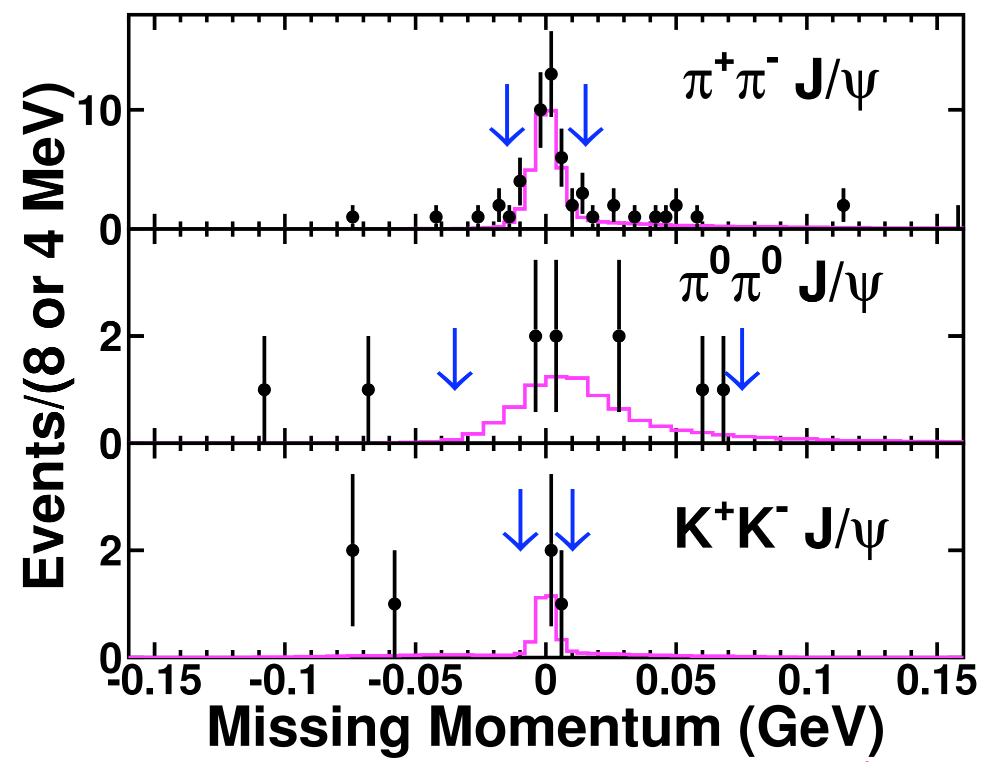
  confirmed by CLEO and Belle $\Rightarrow J^{PC} = 1^{--}$

  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



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

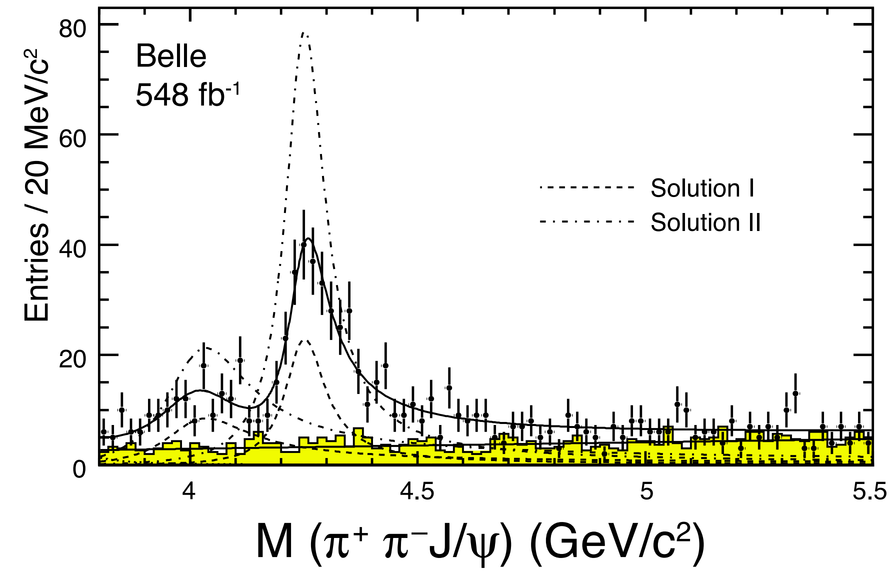
- **Not a charmonium state**
  - Small ΔR - 4^3S_1 state at 4.26 would have ΔR≈2.5
  - 1^3D_1 state ψ(4160)

X(4008)

Mass = $4008 \pm 40 ^{+72}_{-28}$ MeV/c^2
Width = $226 \pm 44 ^{+87}_{-79}$ MeV
Seen by Belle in $\pi^+\pi^-$ + J/ψ final state

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

PRL 99, 182004 (2007)



Y(4350)

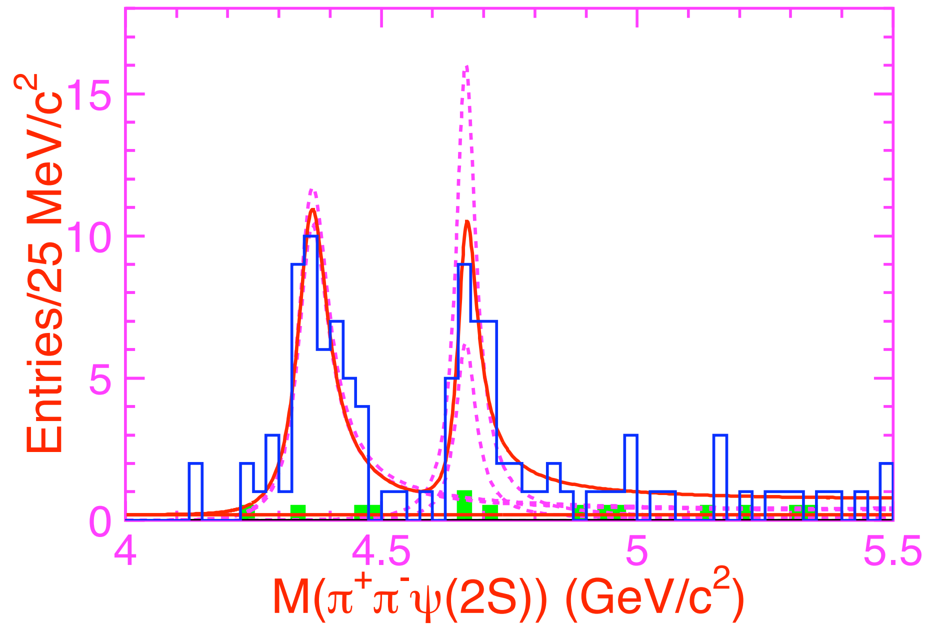
Mass = $4361 \pm 9 \pm 9$ MeV/c^2
Width = $74 \pm 15 \pm 10$ MeV
Seen by BaBar, Belle in $\pi^+\pi^-$ + $\psi(2S)$ final state

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

Y(4660)

Mass = $4664 \pm 11 \pm 5$ MeV/c^2
Width = $48 \pm 15 \pm 3$ MeV
Seen by Belle in $\pi^+\pi^-$ + $\psi(2S)$ final state

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

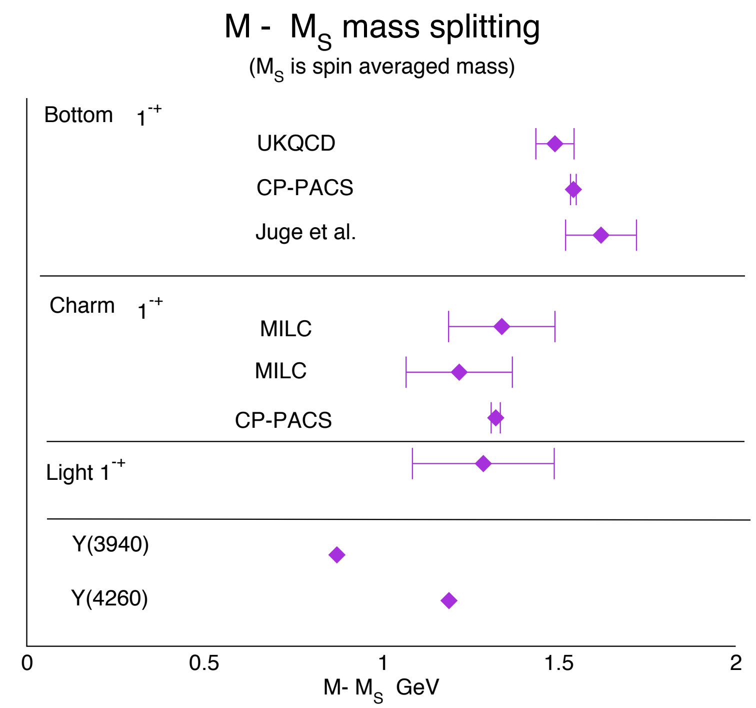


X. L. Wang, et al. PRL **99**:142002 (2007)

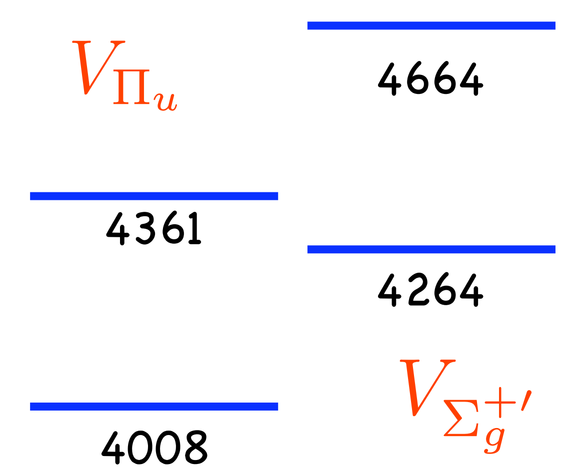
What are the X(4008), Y(4260), Y(4350) and Y(4660)?

- Various options - see Stephen Godfrey, Hanna Mahlke, Jonathan L. Rosner and E.E. [hep-ph/0701208]

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

- CLEO has been in the forefront of quarkonium physics from beginning to end. 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. Phenomenological models inadequate. Need lattice QCD and pNRQCD.
- Below threshold - puzzling exceptions are resolved:
  - By new CLEO measurement: $J/\psi \to \gamma+\eta_c$ M1 rate
  - 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

- CLEO has exploited quarkonium resonances 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:
  - Unexpected large hadronic transition rates: $\Upsilon(5S) \to \Upsilon(nS) + 2\pi$ (n=1,2,3)
  - New states and possibly a new spectroscopy: X(3872), X(4008), Y(4260), Y(4350), Y(4660)
  - 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.