QUARKONIUM - THEORY

J. Rosner, FPCP, Ma'ale Hachamisha, Israel, May 23, 2011

Moving beyond the $Q\bar{Q}$ picture of mesons

- What do the scalar mesons below 1 GeV tell us?
- Importance of coupled channels and mesonic degrees of freedom
- Are $Q\bar{Q}q\bar{q}$ exotics really tetraquarks?
- Feshbach resonances, cusps, thresholds
- Are there exotic baryon-antibaryon resonances?
- Challenges to lattice QCD

Some progress on bottomonium transitions (CLEO)

Compendium of references: QWG, EPJ C **71**, 1534 (2011)

Common sense: D. Bugg, arXiv:0806.3566, 1101.1659

SCALAR MESONS

$I = 0$: $\sigma(\sim 500) \leftrightarrow \pi\pi$ prominent in many Dalitz plots

$I = 1/2$: $\kappa(\sim 750) \leftrightarrow K\pi$ also appears frequently

Another $I = 0$: $f_0(980)$ closely correlated with $K\bar{K}$ threshold

$I = 1$: $a_0(980)$ couples to $\eta\pi$ and $K\bar{K}$

All properties closely linked to coupled channels

$\sigma(500)$ is dynamically generated; consequence of current algebra, crossing, unitarity, and assumption of a ρ in $I = J = 1$ $\pi\pi$ channel: See R. L. Goble +, PR D **39**, 3264 (1989); earlier references therein

Expect similar dynamics to generate a κ in the $I = 1/2$ $K\pi$ channel

$f_0(980)$ decays mainly to $\pi\pi$ but is produced largely from $s\bar{s}$ initial state, e.g., in $B_s \to J/\psi s\bar{s}$

Proposed nonet structure (diquark-antidiquark) misses couplings to meson-meson channels

OLD CHESTNUT: $\Lambda(1405)$

Low-energy $I = 0$ S-wave Σ-π resonance PRL **6**, 698 (1961)

Strong coupling to $I = 0$ S-wave $\bar{K}N$; ~ 27 MeV below threshold

Interaction between closed and open channels studied extensively by Dalitz and Tuan in the early 1960s; realization of *Feshbach resonance*

Opening of S-wave channels $\Rightarrow$ cusps in scattering amplitudes

Fits SU(6) $\otimes$ O(3) quark model as a $(70,\ L = 1\ uds)$ with $J^P = 1/2^-$

Fine-structure splitting from state $\Lambda(1520)$ with $J^P = 3/2^-$ understood through coupled-channel interaction (Isgur and Karl)

Now studied on lattice: M. Lage *et al.*, PL B **681**, 439 (2009); viewed as $\bar{K}N$ molecule: T. Hyodo *et al.*, arXiv:1104.4474

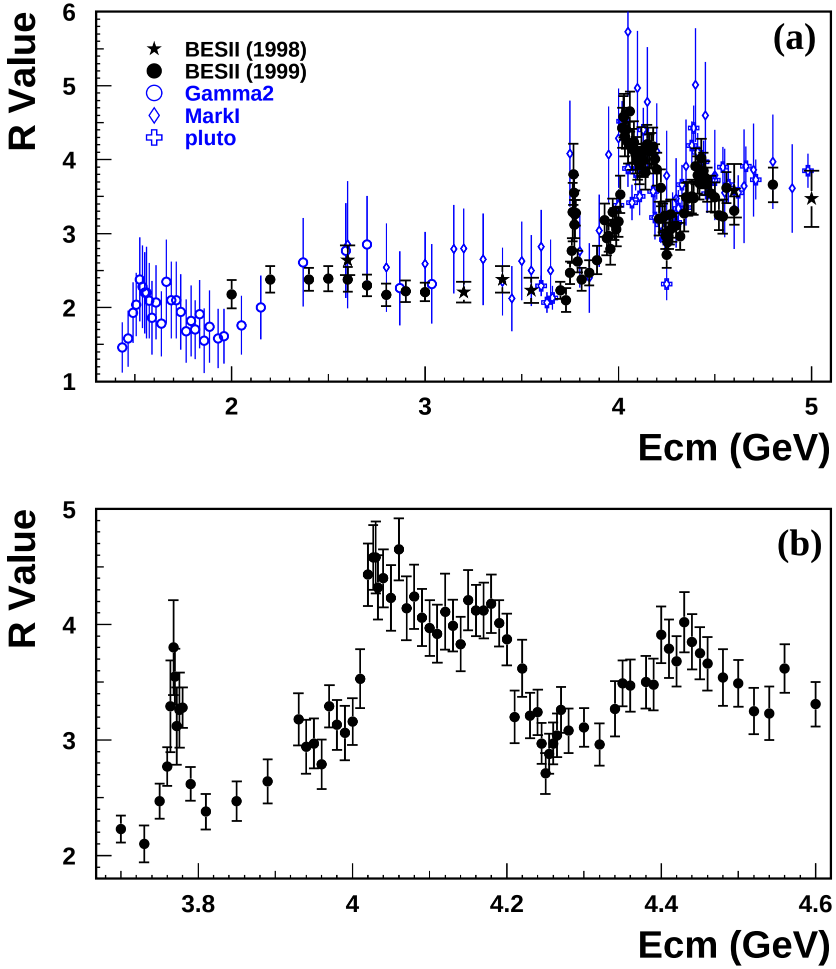
Analog: $D_{s0}(2317)$ as KD state with ~ 42 MeV binding energy

More on S-wave thresholds [JLR, PR D **74**, 076006 (2006)]: cusps in $M(\pi^0\pi^0)$ at $\pi^+\pi^-$ threshold and in $M(\pi^0 p)$ at $\pi^+ n$ threshold; sharp dips in $R_{e^+e^-}$ just below S-wave charm-anticharm threshold (4285 MeV) and in $M(3\pi^+3\pi^-)$ at $\bar{p}p$ threshold. (See also: D. Bugg)

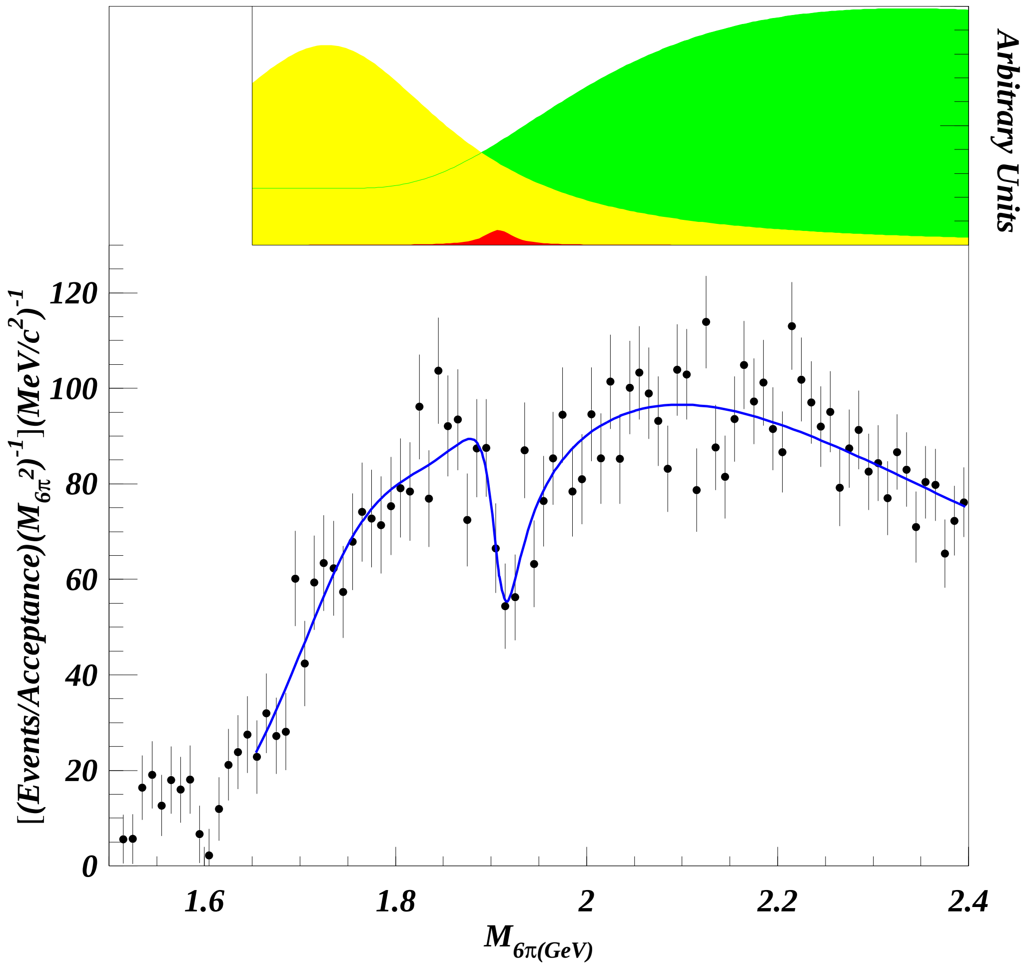
SHARP DIPS

If an elastic phase shift goes though 180°, the scattering amplitude vanishes: *Ramsauer–Townsend effect*. Leads to atomic or nuclear transparency at specific energies; utilized for making monochromatic neutrons

$e^+e^- \to$ hadrons



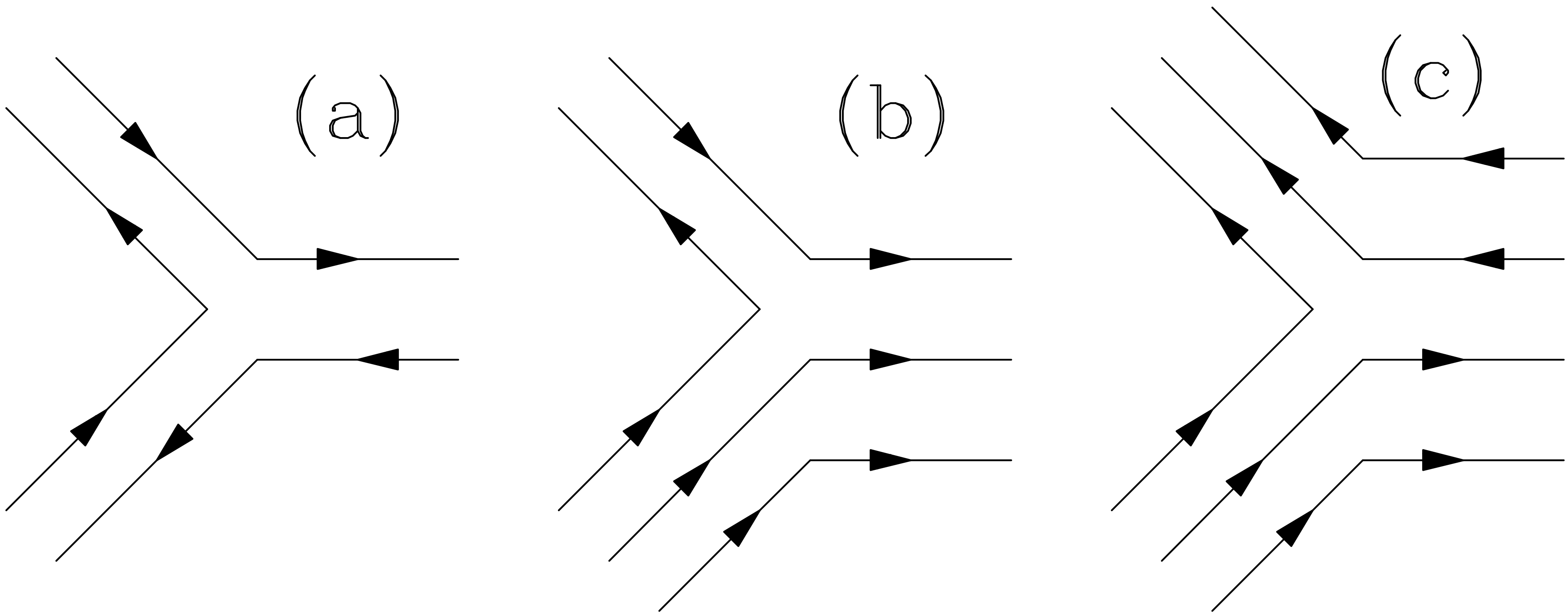
Photoproduction of $3\pi^+3\pi^-$



EXOTIC BARYONIUM?

PRL **21**, 950 (1968) $\Rightarrow$ $qq\bar{q}\bar{q}$ couple to baryon-antibaryon

Ordinary meson Ordinary baryon Exotic meson



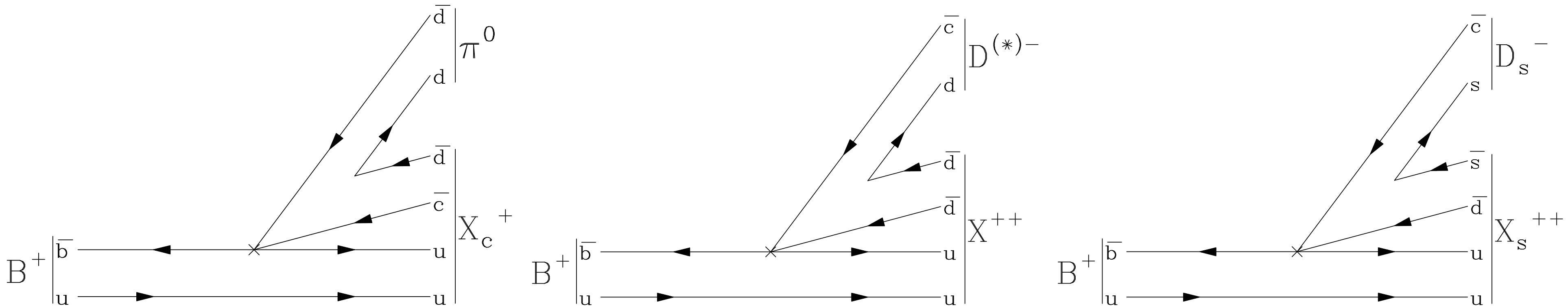
B decays offer numerous exotic final states: e.g., $b\bar{d} \to c\bar{u}d\bar{d}$

Suggestions for seeing exotics at B factories: PR D **69**, 094014 (2004)

B DECAYS WITH EXOTICS

Production examples; look for baryon-antibaryon final state

$X_c^+ = uu\bar{c}\bar{d}$ $\qquad$ $X^{++} = uu\bar{d}\bar{d}$ $\qquad$ $X^{++} = uu\bar{d}\bar{s}$



$\Rightarrow p\bar{\Lambda}_c^- \pi^+$ $\qquad$ $\Rightarrow p\bar{n}\pi^+$ $\qquad$ $\Rightarrow p\bar{\Lambda}\pi^+$

Bet with P. Freund (1972): Exotic baryonium would not be found in two years (he bet it would). He bought dinner in 1974; still waiting.

Can also look for exotic baryons ("pentaquarks"); none seen so far

See also: K. Terasaki, arXiv:1102.3750

LARGE h_b PRODUCTION

Belle (arXiv:1103.3419; Bondar): large cross section for $e^+e^- \to (\Upsilon(5S)?) \to \pi^+\pi^- h_b(1P)$ or $\pi^+\pi^- h_b'(2P)$

This is reminiscient of CLEO's observation of a large cross section for $e^+e^- \to \psi(4170) \to \pi^+\pi^- h_c$ [T. K. Pedlar *et al.*, CLNS 11/2073, arXiv:1104.2073 $\Rightarrow$ PRD; details on May 25]

Earlier, BaBar [B. Aubert +, PRL **96**, 232001 (2006); PR D **78**, 112002 (2008)] and Belle [A. Sokolov +, PR D **75**, 071103 (2007)] reported $\pi^+\pi^-$ and η transitions to lower Υ states from $\Upsilon(4S)$ states; Belle [K. F. Chen +, PRL **100**, 112001 (2008)] saw $\Gamma[\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1S)] = (0.59 \pm 0.04 \pm 0.09)$ MeV, $\Gamma[\Upsilon(5S) \to \pi^+\pi^-\Upsilon(2S)] = (0.85 \pm 0.07 \pm 0.16)$ MeV, more than $10^2\times$ nS rate for $n \le 4$

Lipkin-Tuan [PL B **206**, 349 (1988)]; Moxhay [PR D **39**, 3497 (1989)]: rescattering from $B^{(*)}\bar{B}^{(*)}$ important; recent calculations by Meng and Chao [PR D **77**, 074003 (2008); **78**, 034022, 074001 (2009)] and by Simonov and Veselov [PL B **671**, 55 (2009); **673**, 211 (2009)]

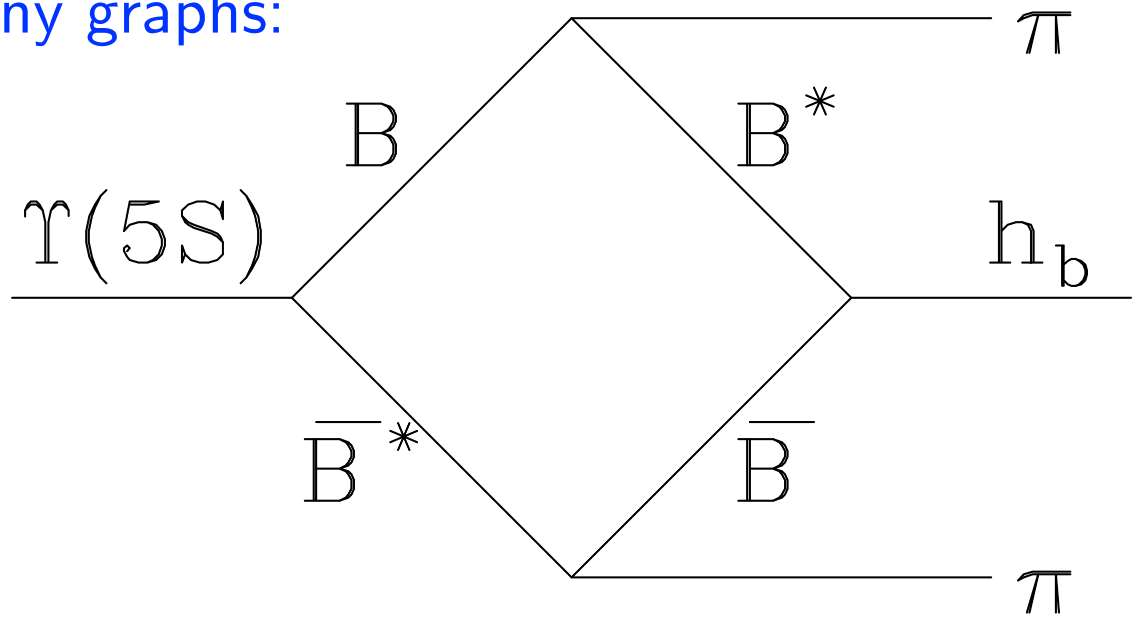
T. J. Burns, arXiv:1105.2533: small hyperfine splitting of P-wave mesons evades large loop corrections

OPEN FLAVOR RESCATTERING

D. Bugg, arXiv:1101.1659: $\Upsilon(5S) \to B\overline{B}^*, \ldots \to \pi^+\pi^- h_b$

Must be above $B\overline{B}^*$ threshold to produce some $J^P(b\bar{b})$ values.

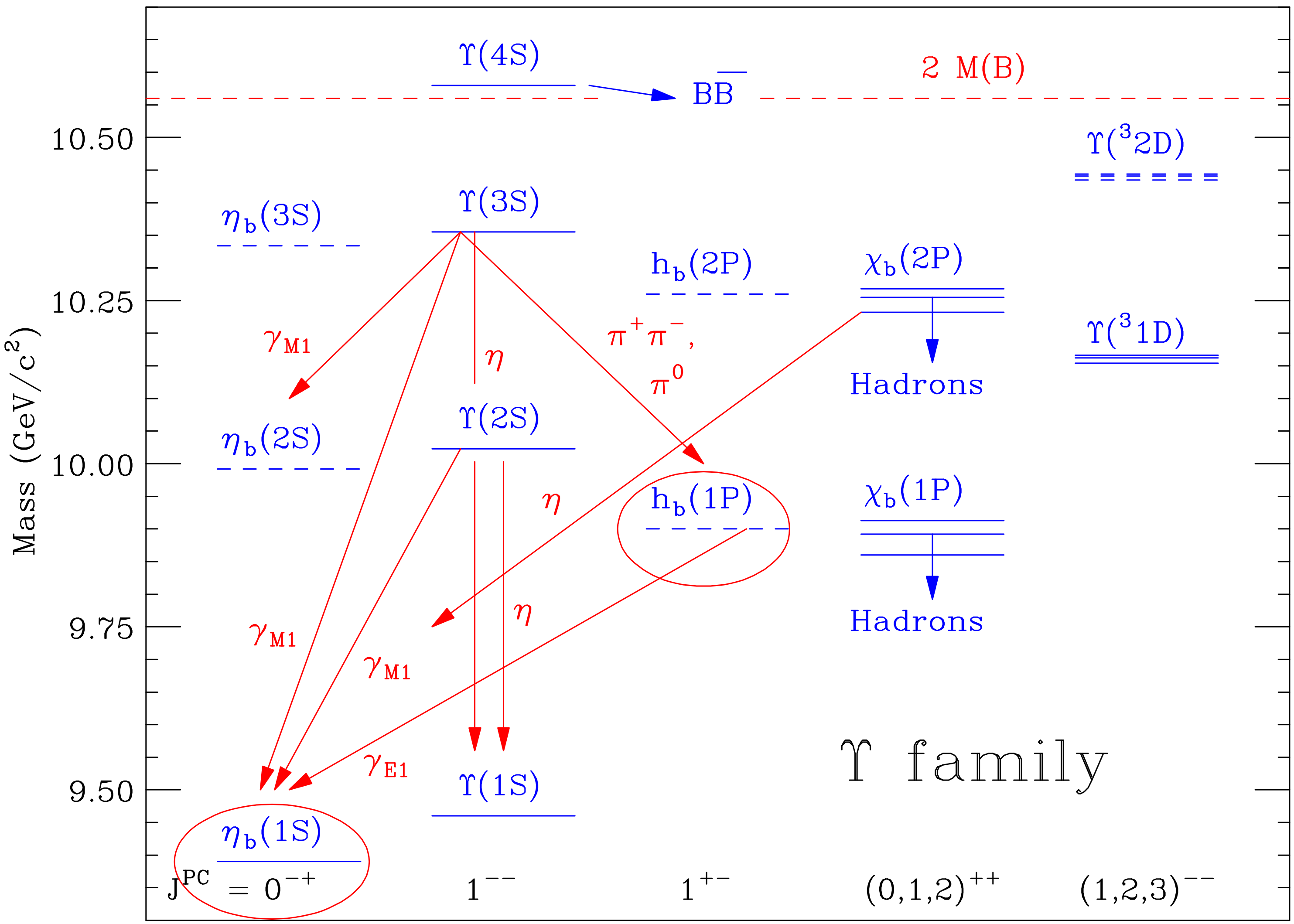
One of many graphs:



Selection rules for which bottomonium states are favorably produced?

Rescattering through flavored pairs flips the $b\bar{b}$ spin in $\Upsilon(5S) \to \pi^+\pi^- h_b(1P, 2P)$ (triplet to singlet). Suppressed in perturbative QCD.

BOTTOMONIUM SPECTRUM



Plus
E1 radiative
transitions
S $\leftrightarrow$ P $\leftrightarrow$ D

Some recent transitions; CLEO searching for $\Upsilon(3S) \rightarrow \pi^+\pi^- h_b,\ \pi^0 h_b,\ h_b \rightarrow \gamma\eta_b$

Background to h_b search from radiative $\Upsilon(3S) \rightarrow \gamma\chi_b(1P) \rightarrow \gamma\gamma\Upsilon(1S)$ led to more detailed study of these suppressed E1 transitions

RADIATIVE $\chi_{bJ}(1P)$ TRANSITIONS

M. Kornicer *et al.* **(CLEO), arXiv:1012.0589 $\Rightarrow$ PR D 83, 054003 (2011)**

In search for $\Upsilon(3S) \to \pi^0 h_b \to \pi^0 \gamma \eta_b$, photons in the transitions $\Upsilon(3S) \to \gamma\chi_b(1P)$ and $\chi_b \to \gamma\Upsilon(1S)$ are in the 400–500 MeV range and can be a problematic background

Electric dipole matrix elements for $3S \to 1P$ are forbidden for a harmonic oscillator potential and highly suppressed for realistic quarkonium potentials (A. K. Grant *et al.*, PR D **53**, 2742 (1996)).

Previously known branching fractions involving $\chi_b(1P)$ states:

Transition	E_γ (MeV)	$\mathcal{B}$ (%)	Comments
$\Upsilon(3S) \to \gamma\chi_{b0}(1P)$	483.9	0.30 ± 0.11	CLEO, PR D **78**, 091103
$\Upsilon(3S) \to \gamma\chi_{b1}(1P)$	452.1	< 0.17	First reported here
$\Upsilon(3S) \to \gamma\chi_{b2}(1P)$	433.5	< 1.9	First reported here
$\Upsilon(2S) \to \gamma\chi_{b0}(1P)$	162.5	3.8 ± 0.4	Dominated by CLEO:
$\Upsilon(2S) \to \gamma\chi_{b1}(1P)$	129.6	6.9 ± 0.4	M. Artuso *et al.*,
$\Upsilon(2S) \to \gamma\chi_{b2}(1P)$	110.4	7.15 ± 0.35	PRL **94**, 032001 (2005)
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	391.1	< 6	Main χ_{b0} decay hadronic
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	423.0	35 ± 8	Latest measurement
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	441.6	22 ± 4	in 1986!

UNFOLDING 420–450 MeV PHOTONS

Overlap of photon energies meant it was easiest to quote

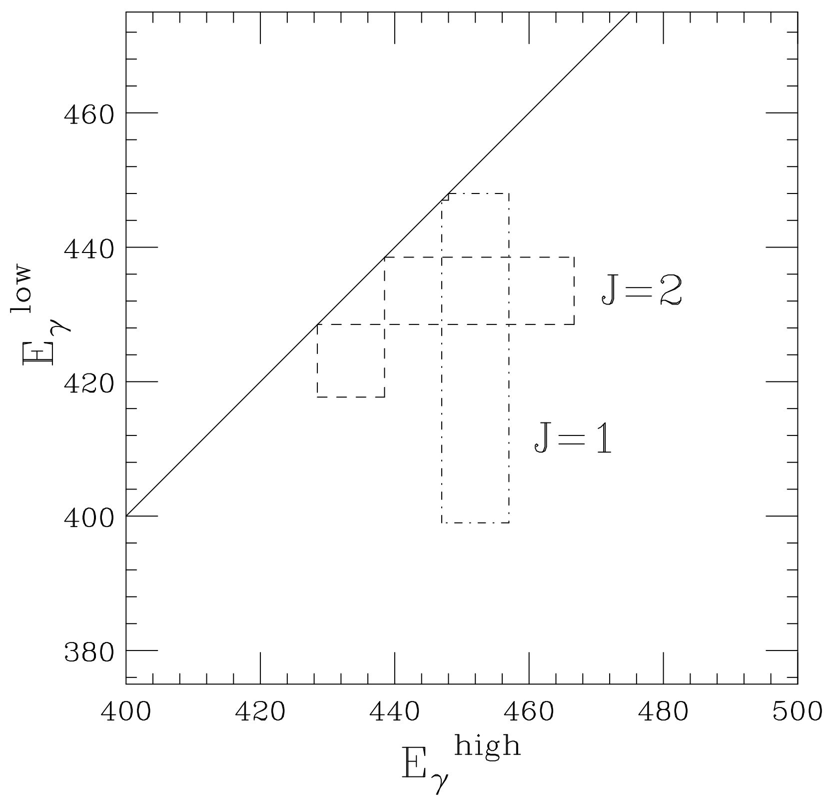
$$\mathcal{B}_{\rm sum} = \sum_{J=1,2} \mathcal{B}[\Upsilon(3S) \to \gamma\chi_{bJ}(1P)] \times \mathcal{B}[\chi_{bJ}(1P) \to \gamma\Upsilon(1S)]$$

$= (1.2^{+0.4}_{-0.3} \pm 0.09) \times 10^{-3}$ (CUSB, PR D **46**, 1928 (1992))

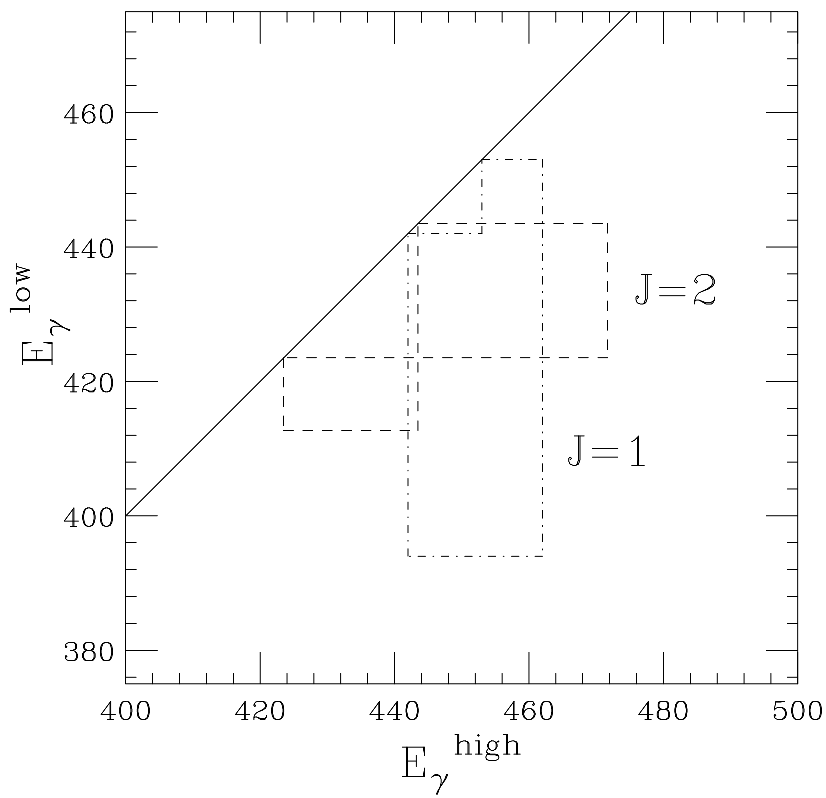
$= (2.14 \pm 0.22 \pm 0.21) \times 10^{-3}$ (CLEO, T. Skwarnicki, ICHEP 2002, Amsterdam)

To unfold $J = 1$ and $J = 2$ use Doppler broadening:

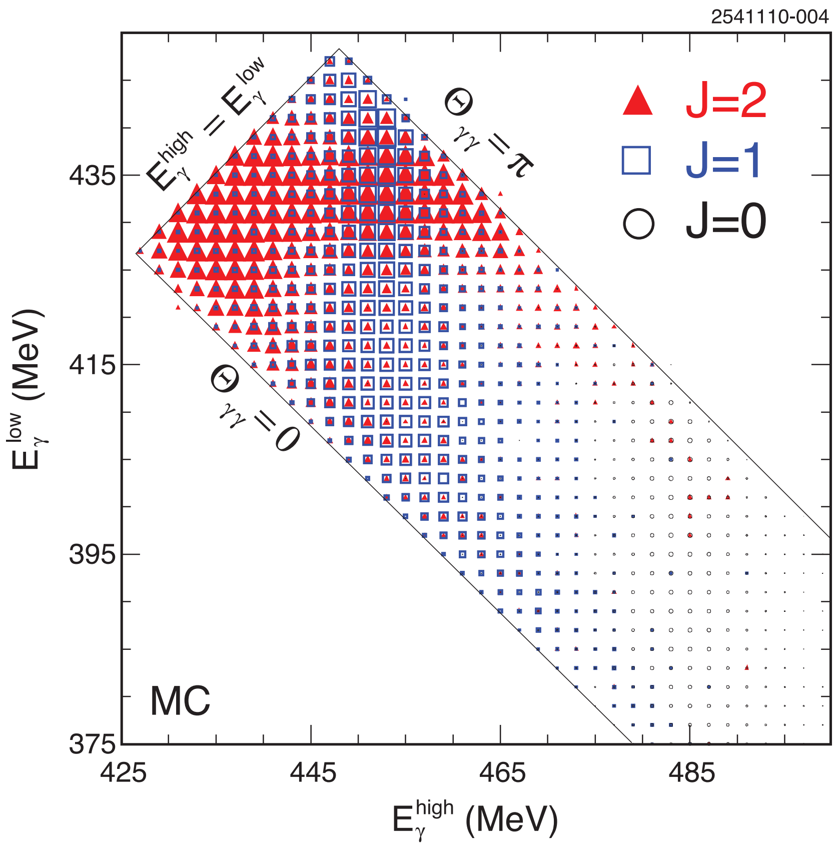
Photon resolution ± 5 MeV

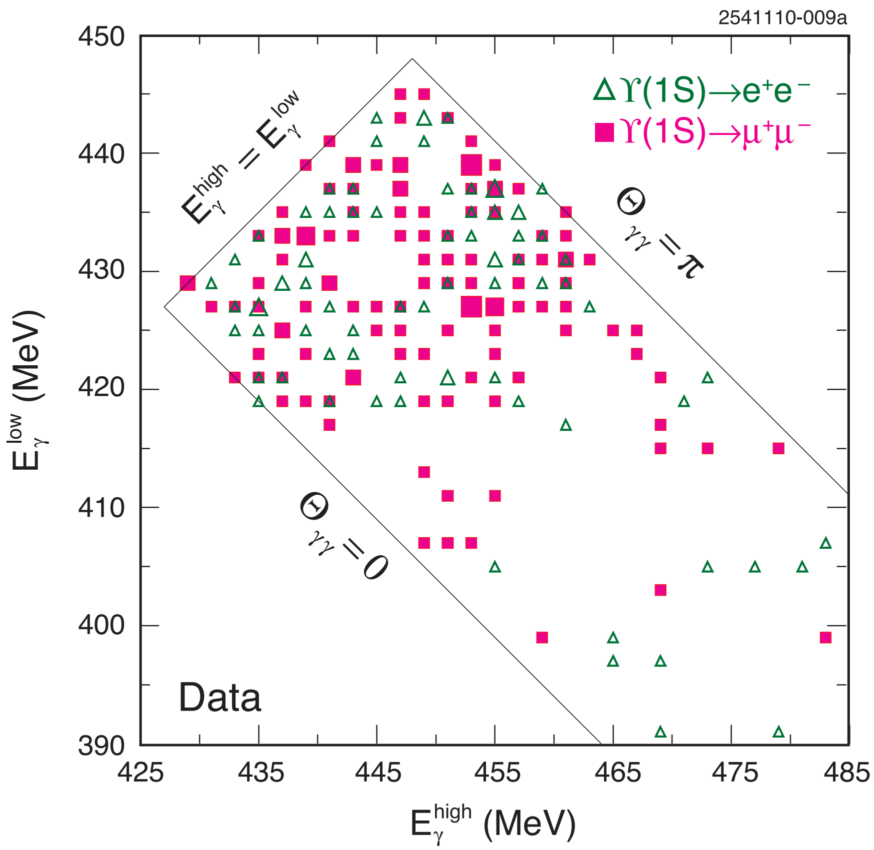


Photon resolution ± 10 MeV



$\Upsilon(3S)$ MONTE CARLO AND DATA





Monte Carlo, $\Upsilon(1S) \to \mu^+\mu^-$ Data, $\Upsilon(1S) \to e^+e^-$ (Δ) or $\mu^+\mu^-$ ($\square$)

Two-dimensional fit: best sensitivity to $J = 1$ and $J = 2$ components

$\mathcal{B}1 \equiv \mathcal{B}[\Upsilon(3S) \to \gamma\chi_{bJ}(1P)]$; $\mathcal{B}2 \equiv \mathcal{B}[\chi_{bJ}(1P) \to \gamma\Upsilon(1S)]$; $\mathcal{B}3 \equiv \mathcal{B}[\Upsilon(1S) \to \ell^+\ell^-]$.

Take $\mathcal{B}2$(J=1) $= (33.0 \pm 0.5)\%$, $\mathcal{B}2$(J=2) $= (18.5 \pm 0.5)\%$
from new fit to $\Upsilon(2S)$ data; $\mathcal{B}3 = (2.48 \pm 0.05)\%$

EXTRACTED BRANCHING FRACTIONS

For the sum of $J = 1$ and $J = 2$, find $\sum \mathcal{B}1 \times \mathcal{B}2 = (2.00 \pm 0.15 \pm 0.22 \pm 0.04) \times 10^{-3}$, agreeing well with 2002 CLEO value

Determinations for individual values of J:

	$J = 1$	$J = 2$
$\mathcal{B}1 \times \mathcal{B}2$ (10^{-4})	$5.38 \pm 1.20 \pm 0.94 \pm 0.11$	$14.35 \pm 1.62 \pm 1.66 \pm 0.29$
$\mathcal{B}1$ (10^{-3})	$1.63 \pm 0.36 \pm 0.28 \pm 0.09$	$7.74 \pm 0.88 \pm 0.88 \pm 0.38$

Portions of table presented earlier now look like this:

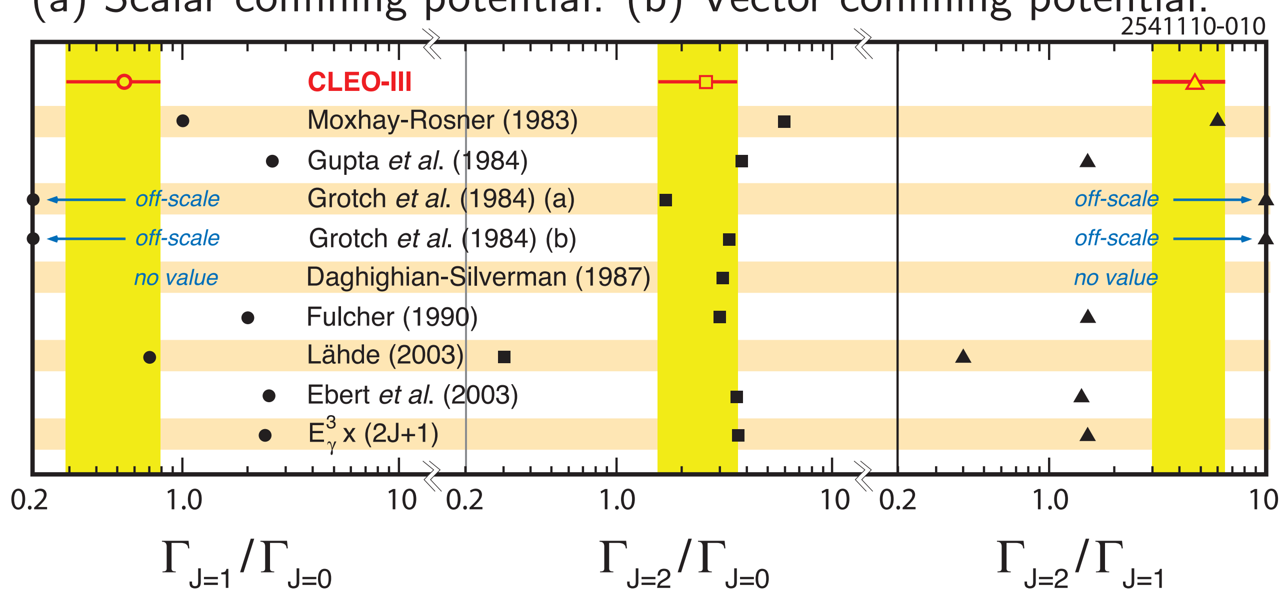
Transition	$\mathcal{B}$ (%)		
	Previous	CLEO now	Babar*
$\Upsilon(3S) \to \gamma\chi_{b0}(1P)$	0.30 ± 0.11	0.30 ± 0.11	$0.27 \pm 0.04 \pm 0.02$
$\Upsilon(3S) \to \gamma\chi_{b1}(1P)$	< 0.17	0.163 ± 0.046	$0.05 \pm 0.03^{+0.02}_{-0.01}$ (< 1.1)
$\Upsilon(3S) \to \gamma\chi_{b2}(1P)$	< 1.9	0.774 ± 0.130	$1.06 \pm 0.03 \pm 0.06$
$\chi_{b0}(1P) \to \gamma\Upsilon(1S)$	< 6	1.73 ± 0.35	$2.3 \pm 1.5^{+1.0}_{-0.7} \pm 0.2$ (< 4.6)
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	35 ± 8	33.0 ± 2.6	$36.2 \pm 0.8 \pm 1.7 \pm 2.1$
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	22 ± 4	18.5 ± 1.4	$20.2 \pm 0.7^{+1.0}_{-1.4} \pm 1.0$

*J. P. Lees *et al.*, arXiv:1104.5254, using converted photons

$\Gamma[\Upsilon(3S) \to \gamma \chi_{bJ}(1P)]$: EXPT VS THEORY

	$\Gamma_{J=0}$ (eV)	$\Gamma_{J=1}$ (eV)	$\Gamma_{J=2}$ (eV)
This analysis	–	33 ± 10	157 ± 30
Inclusive CLEO expt.	61 ± 23	–	–
Moxhay–Rosner (1983)	25	25	150
Gupta *et al.* (1984)	1.2	3.1	4.6
Grotch *et al.* (1984) (a)	114	3.4	194
Grotch *et al.* (1984) (b)	130	0.3	430
Daghighian–Silverman (1987)	42	–	130
Fulcher (1990)	10	20	30
Lähde (2003)	150	110	40
Ebert *et al.* (2003)	27	67	97

(a) Scalar confining potential. (b) Vector confining potential.



Note

log

scale

$\Upsilon(3S) \to \gamma \chi_{bJ}(1P)$ rates differ from expected $\sim E_\gamma^3(2J+1)$ pattern.

THEORY COMPARISONS, CONTINUED

Deviations from expected $\sim E_\gamma^3(2J+1)$ pattern test models of relativistic corrections

Worth revisiting some of the old calculations within newer frameworks, e.g., NRQCD

Comparison of results for $\mathcal{B}[\chi_{bJ}(1P) \to \gamma\Upsilon(1S)]$ with theoretical predictions (%):

Reference	$J=0$	$J=1$	$J=2$
CLEO-III	1.73 ± 0.35	33.0 ± 2.6	18.3 ± 1.4
Moxhay–Rosner (1983)	3.8	50.6	22.3
Gupta *et al.* (1984)	4.1	56.8	26.7
Grotch *et al.* (1984) (a)	3.1	41.9	19.4
Grotch *et al.* (1984) (b)	3.3	43.9	20.3
Daghighian–Silverman (1987)	2.3	31.6	16.6
Kwong–Rosner (1988)	3.2	46.1	22.2
Fulcher (1990)	3.1	39.9	18.6
Lähde (2003)	3.3	45.7	21.1
Ebert *et al.* (2003)	3.7	51.5	23.6

(a) Scalar confining potential. (b) Vector confining potential.

Increase of $\alpha_S(m_b)$ in Kwong-Rosner calculation from 0.18 to 0.214 ± 0.006 leads to agreement; consistent with compilation by Bethke, EJPC 64, 689 (2009)

CONCLUSIONS

Heavy quarkonium theory now must confront light-quark degrees of freedom

We have been living with this since the dawn of hadron spectroscopy

Scalar mesons' properties governed by $\pi\pi$, $K\pi$, $K\bar{K}$ channels

Effects of S-wave thresholds are ubiquitous

Still waiting for definitive evidence for tetraquark exotics

Large h_b production from bottomonium above flavor threshold serves as a challenge to our understanding of hadron interactions

Progress in study of bottomonium electromagnetic transitions