MESON SPECTROSCOPY RESULTS

J. Rosner, at "Lattice Meets Experiment," Fermilab, April 26–27, 2010

Some results which can be compared to lattice predictions:

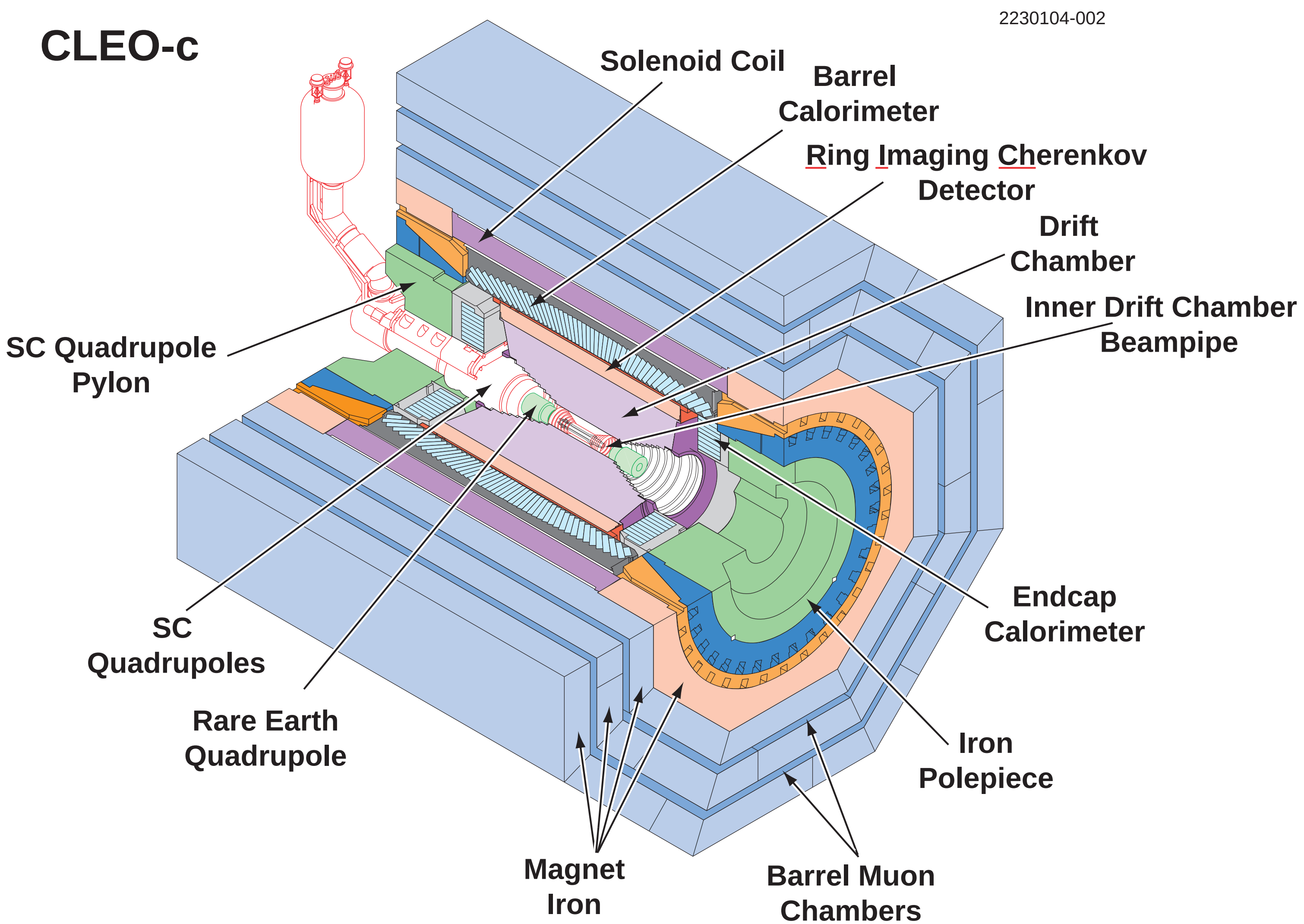
- $1^1P_1(c\bar{c}) \equiv h_c$ mass, production, decays (CLEO, BESIII)
- Magnetic quadrupole (M2) in E1 charmonium transitions: μ_c (CLEO)
- $[J/\psi, \psi(2S)] \to \gamma\eta_c(1S)$ and search for $\psi(2S) \to \gamma\eta_c(2S)$ (CLEO)
- States in the $Y(3940)$ mass range (Belle)
- Observation of the $^3D_1$ bottomonium state (BaBar)
- η_b mass, production rates in $\Upsilon(2S,3S) \to \gamma\eta_b$ (BaBar, CLEO)
- Search for $1^1P_1(b\bar{b}) \equiv h_b$ in $\Upsilon(3S) \to (\pi^0, \pi^+\pi^-)h_b$ with $h_b \to \gamma\eta_b$ (CLEO)
- The B_c meson: precise mass measurement (CDF)

More challenging for lattice QCD:

- Decays $[J/\psi, \psi(2S)] \to \gamma(\eta/\eta')$ ($c\bar{c}$ admixture of η/η'?) (CLEO)
- Low-mass $p\bar{p}$ states in charmonium radiative decays (BESIII)
- Exclusive decays of $\chi_c,\ h_c,\ \chi_b,\ \chi_b'$: Fragmentation (BES,CLEO)

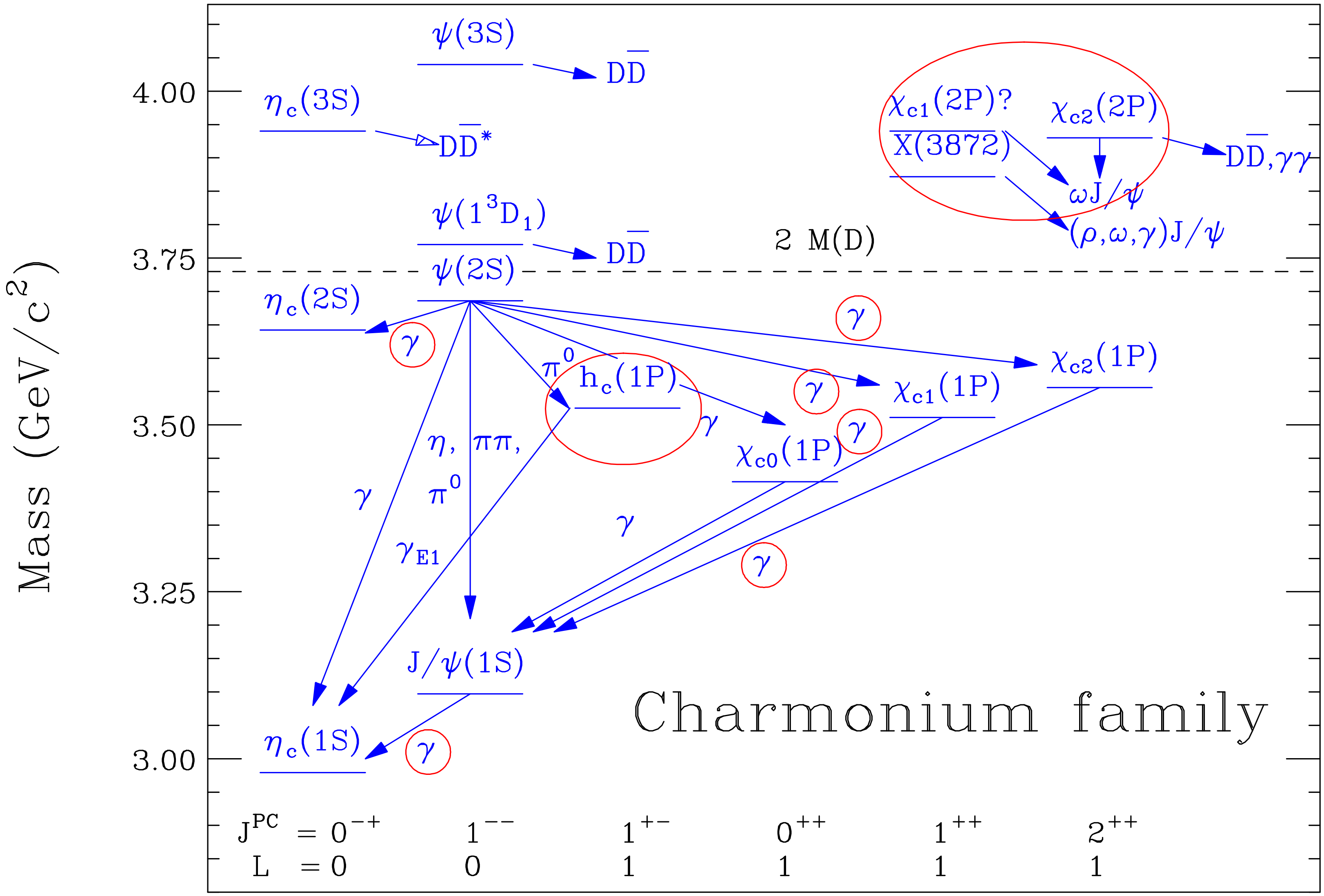
THE CLEO-c DETECTOR

Many of today's results will be as a member of CLEO; thanks to colleagues



Photon $\Delta E/E = (5\%, 2.2\%)$ at (0.1,1) GeV; charged trk. $\Delta p/p = 0.6\%$ at 1 GeV

CHARMONIUM SPECTRUM



Items of interest circled: h_c properties; M2 admixtures in $\psi(2S) \to \gamma\chi_c \to \gamma\gamma J/\psi$ [relevant to M1 transitions $\psi(nS) \to \gamma\eta_c(nS)$]; nature of states near 3.9 GeV.

PROPERTIES OF h_c

Last charmonium state below flavor threshold: $h_c(1P)$, spin-singlet ($J/\psi + 30$ yr!)

Seen in isospin-violating decay $\psi(2S) \to \pi^0 h_c(1P)$ ($\mathcal{B}_1$), $h_c(1P) \to \gamma\eta_c(1S)$ ($\mathcal{B}_2$)

S. Dobbs + (CLEO), PRL **101**, 182003 (2008) [24.5M $\psi(2S)$]:

$M(h_c) =$3525.28±0.19±0.12 MeV, $\langle M(^3P_J)\rangle - M(h_c) =$0.02±0.19±0.13 MeV

M. Ablikim + (BESIII), PRL **104**, 132002 (2010) [106 M $\psi(2S)$]:

$M(h_c) =$3525.40±0.13±0.18 MeV, $\langle M(^3P_J)\rangle - M(h_c) = -$0.10±0.13±0.18 MeV

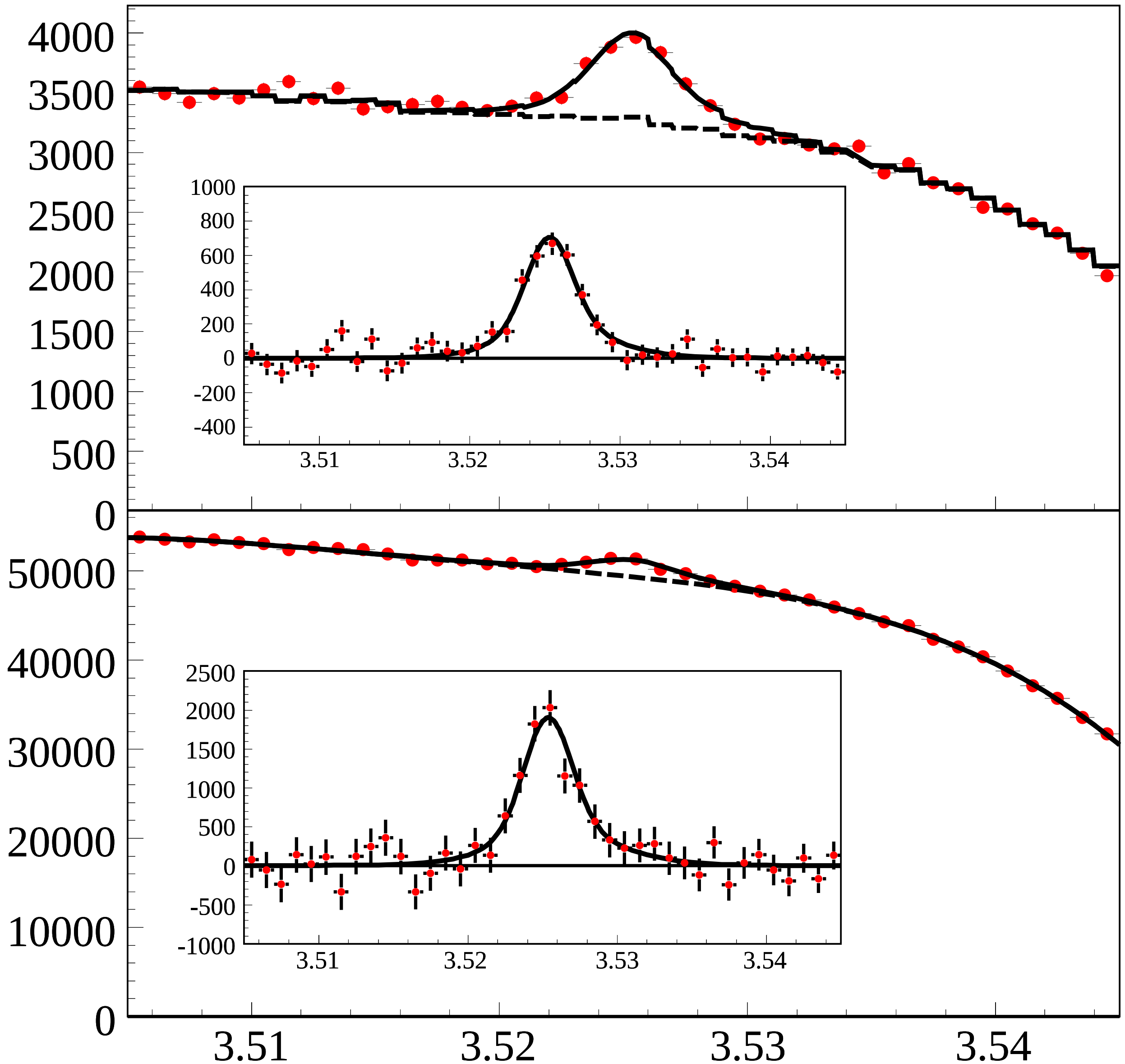
Error $\simeq$ same as CLEO: Smaller statistical but larger systematic

Hyperfine splitting found small between P-wave states; wave function zero at origin

CLEO saw $\eta_c(1S)$ both inclusively [$\mathcal{B}_1\mathcal{B}_2 =$(4.22±0.44±0.22) $\times 10^{-4}$]
and in 15 exclusive modes [$\mathcal{B}_1\mathcal{B}_2$=(4.15±0.48±0.77) $\times 10^{-4}$]

BESIII made separate measurements: $\mathcal{B}_1\mathcal{B}_2 =$ (4.58±0.40±0.50)$\times$ 10^{-4};
$\mathcal{B}_1 = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$; $\mathcal{B}_2 = (54.3 \pm 6.7 \pm 5.2)\%$

BESIII $h_c(1P)$ SPECTRA



Top: π^0 recoil mass; E1-tagged analysis $\psi' \to \pi^0(h_c \to \gamma\eta_c)$

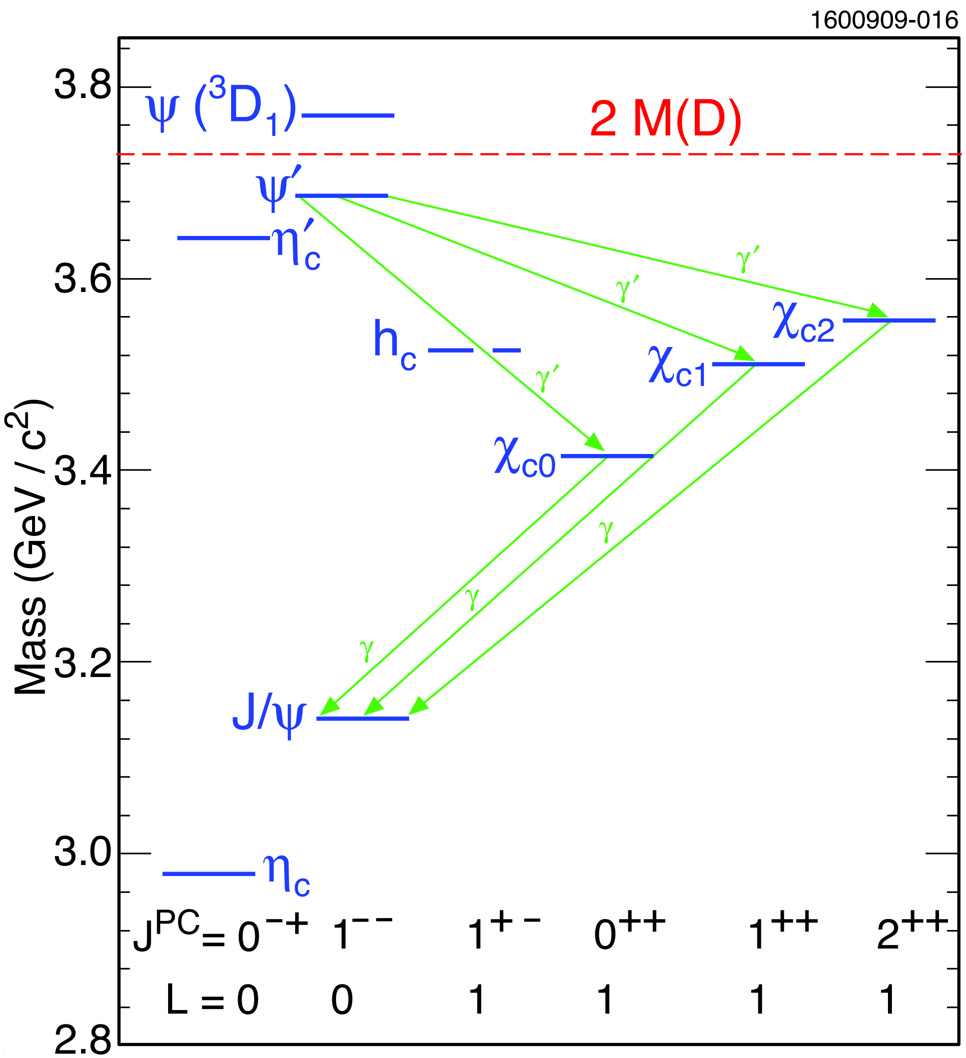
Bottom: Inclusive analysis of $\psi' \to \pi^0 h_c$

$\Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28$ MeV (< 1.44 MeV at 90% confidence)

HIGHER MULTIPOLES IN CHARMONIUM RADIATIVE TRANSITIONS

M. Artuso *et al.*, arXiv:0910.0046 ⇒ PRD 80, 112003 (2009)

Analysis initiated by R. Galik; thesis of James Ledoux (Cornell)



Transitions $\psi' \to \gamma\chi_{cJ} \to \gamma\gamma J/\psi$ dominantly electric dipole (E1)

Higher multipoles allowed: M2 for $J_\chi = 1$; M2 and E3 for $J_\chi = 2$; No E3 for $S \leftrightarrow P$ single-quark trans.

Angular distributions of photons are sensitive to higher multipoles

M2 transition measures charmed quark's total magnetic moment

Relevant to strengths of M1 transitions $\psi(nS) \to \eta_c(nS)$

Prediction of M2 admixture: G. Karl, S. Meshkov, JLR, PRL **45**, 215 (1980)

HELICITY AMPLITUDES AND MULTIPOLES

Five angles describe $\psi' \to \gamma\chi \to \gamma\gamma J/\psi$ decays

Distributions depend on helicity amplitudes $B_{\nu'}$ ("before" χ) and A_ν ("after" χ):

Clebsch-Gordan coeffs. relate helicity amps. A (or B) and multipole amps. $a_{J_\gamma}^{J_\chi}$

M2 amplitudes related to anomalous moment κ_c of charm quark (potl. indep.!):

$$a_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2+M2^2}} = -\frac{E_\gamma}{4m_c}(1+\kappa_c)$$

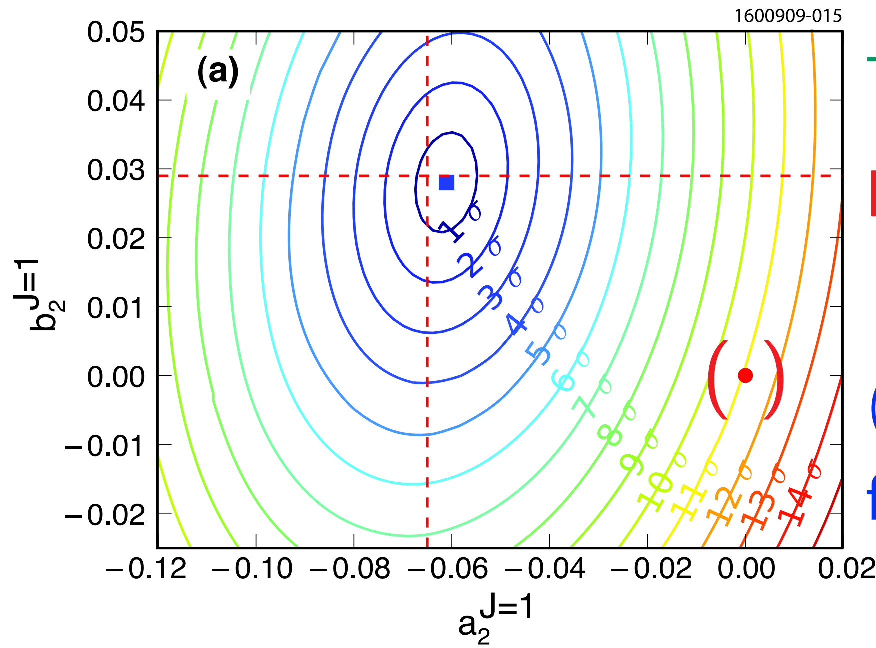
$$a_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2+M2^2+E3^2}} = -\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}(1+\kappa_c)\ ;$$

similarly for b amplitudes with sign change, $E_\gamma \to E_{\gamma'}$. These follow from

$$H_I = -\frac{e_c}{2m_c}(\vec{A}^* \cdot \vec{p} + \vec{p} \cdot \vec{A}^*) - \mu\vec{\sigma} \cdot \vec{H}^* + (\mathrm{spin-orbit\ term})$$

$e_c \equiv \frac{2}{3}|e|$; $\mu \equiv (e_c/2m_c)(1+\kappa_c)$; $\vec{A}^*$ and $\vec{H}^* \equiv \nabla \times \vec{A}^*$ refer to emitted photon

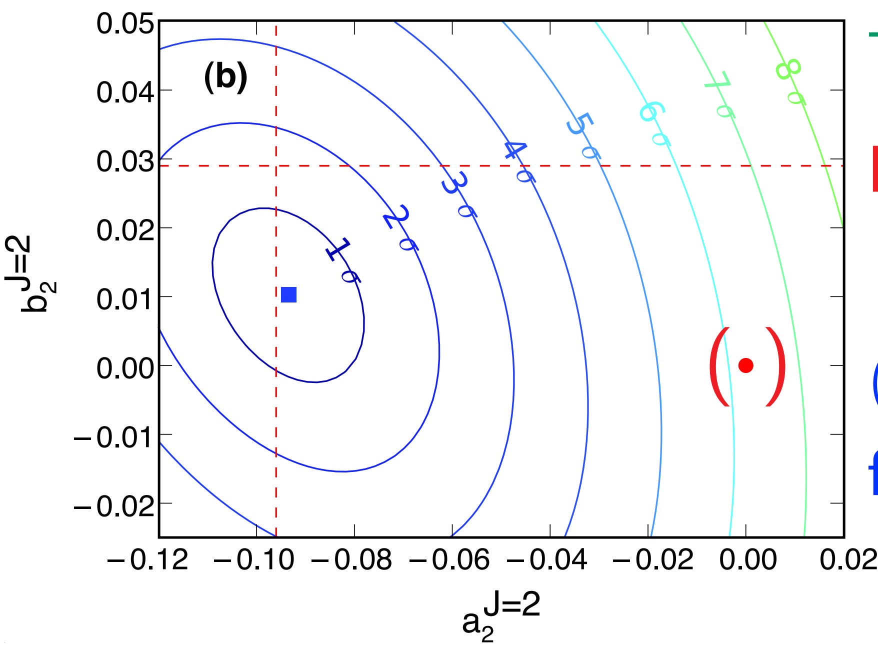
$J_\chi = 1,\ 2$ LIKELIHOODS



Two-parameter fit, $J_\chi = 1$:

Prediction for $\kappa_c = 0$, $m_c = 1.5$ GeV is $(a_2, b_2) = (-0.065, 0.029)$

$(a_2, b_2) = (0, 0)$ (●) is 11.1σ from maximum-likelihood solution (■)

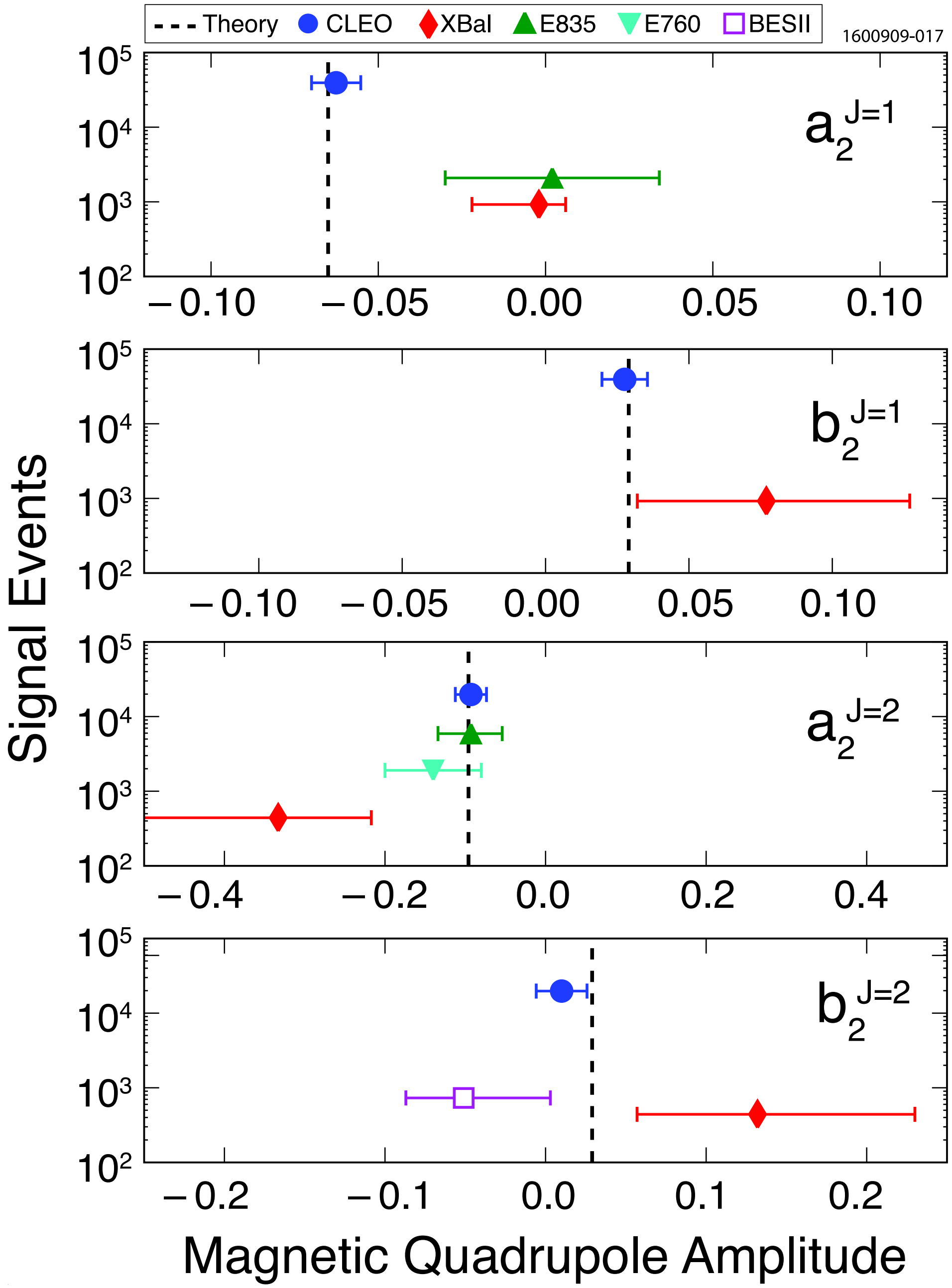


Two-parameter fit, $J_\chi = 2$:

Prediction for $\kappa_c = 0$, $m_c = 1.5$ GeV is $(a_2, b_2) = (-0.096, 0.029)$

$(a_2, b_2) = (0, 0)$ (●) is 6.2σ from maximum-likelihood solution (■)

COMPARISON WITH PREVIOUS RESULTS



CLEO-c: circle (two-parameter fit for J_χ=2); Xtal Ball: diamonds; E760: ∇; E835: Δ; BES-II: square; Th. (m_c=1.5 GeV, $\kappa_c = 0$): dashes

First significant evidence for $a_2^{J=1} \neq 0$; $\surd$ prediction

Multipoles $b_2^{J=1}$ and $a_2^{J=2}$ also significantly non-zero and in accord with prediction

Multipole $b_2^{J=2}$ not significant; error reduced w.r.t. previous

No evidence for E3 transitions

Dudek +, PR D **73**, 075407; **79**, 094504: $a_2^{J=1} = -0.09(7)$; $a_2^{J=2} = -0.39(7)$; $a_3^{J=2} = -0.01(1)$

$[J/\psi, \psi(2S) \to \gamma\eta_c(1S)$; SEARCH FOR $\psi(2S) \to \gamma\eta_c(2S)$

R. E. Mitchell + (CLEO), PRL **102**, 011801 (2009): $\mathcal{B}[J/\psi \to \gamma\eta_c(1S)] =$ (1.98±0.09±0.30)%; scaling $\sim E_\gamma^3 \Rightarrow \mathcal{B}[\psi(2S) \to \gamma\eta_c(2S)] = (4.8 \pm 1.4) \times 10^{-4}$

CLEO (above) also measures $\mathcal{B}[\psi(2S) \to \gamma\eta_c(1S)$ =(4.32±0.16±0.60) $\times 10^{-3}$

PR D **81**, 052002 (2010): CLEO upper limit $\mathcal{B}[\psi(2S) \to \gamma\eta_c(2S)] < 7.6 \times 10^{-4}$

Lattice QCD predicts $\mathcal{B}[(J/\psi, \psi') \to \gamma\eta_c(1S)] =$ (2.7±0.1, 0.13±0.26)%: J. Dudek, R. G. Edwards, and C. E. Thomas, PR D **79**, 074504. How about $\psi(2S) \to \gamma\eta_c(2S)$?

STATES IN 3915–3940 MASS RANGE

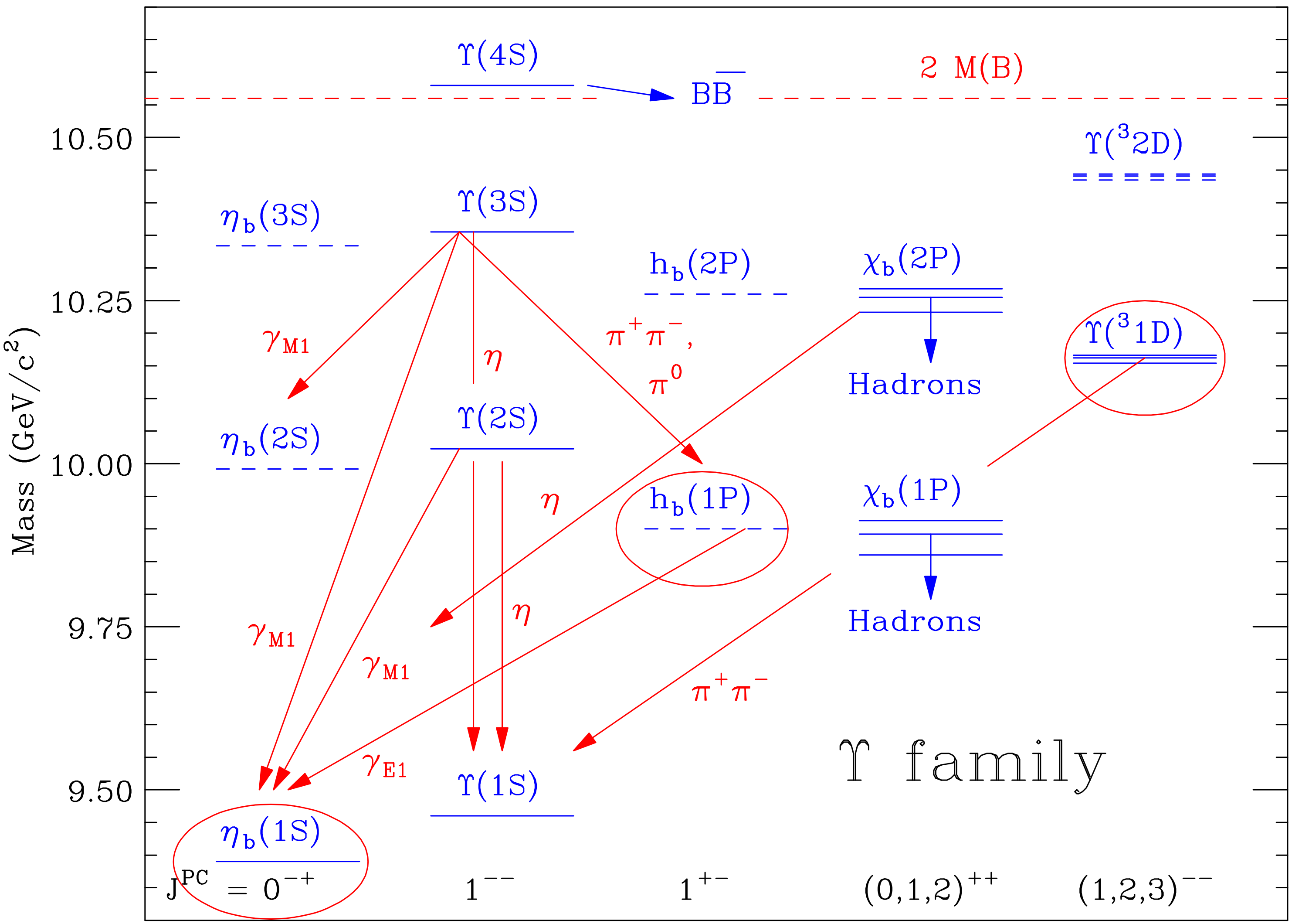
Is Belle's $Y(3940) \to J/\psi\omega$ [S. K. Choi +, PRL **94**, 182002] with M =3943±11±13 MeV, Γ =87±22±26 MeV a 1^{++} state mixing with $X(3872)$?

BaBar [B. Aubert +, PRL **101**, 082001 (2008)] sees $J/\psi\omega$ state at $M = 3914.6^{+3.8}_{-3.4} \pm 2.0$ MeV, $\Gamma = 34^{+12}_{-8} \pm 5$ MeV

BaBar (arXiv:1002.0281) also confirms earlier Belle observation of a 2^{++} candidate in $\gamma\gamma \to \chi'_{c2} \to D\bar{D}$: M = (3926.7±2.7±1.1) MeV, $\Gamma =$ (21.3±6.8±3.6) MeV

Belle sees a candidate for $J^{PC} = 0^{++}$ or 2^{++} in $\gamma\gamma$ collisions [S. Uehara +, PRL **104**, 092001 (2010)]: M =3915±3±2 MeV, Γ =17±10±3 MeV, $\Rightarrow J/\psi\omega$

BOTTOMONIUM SPECTRUM

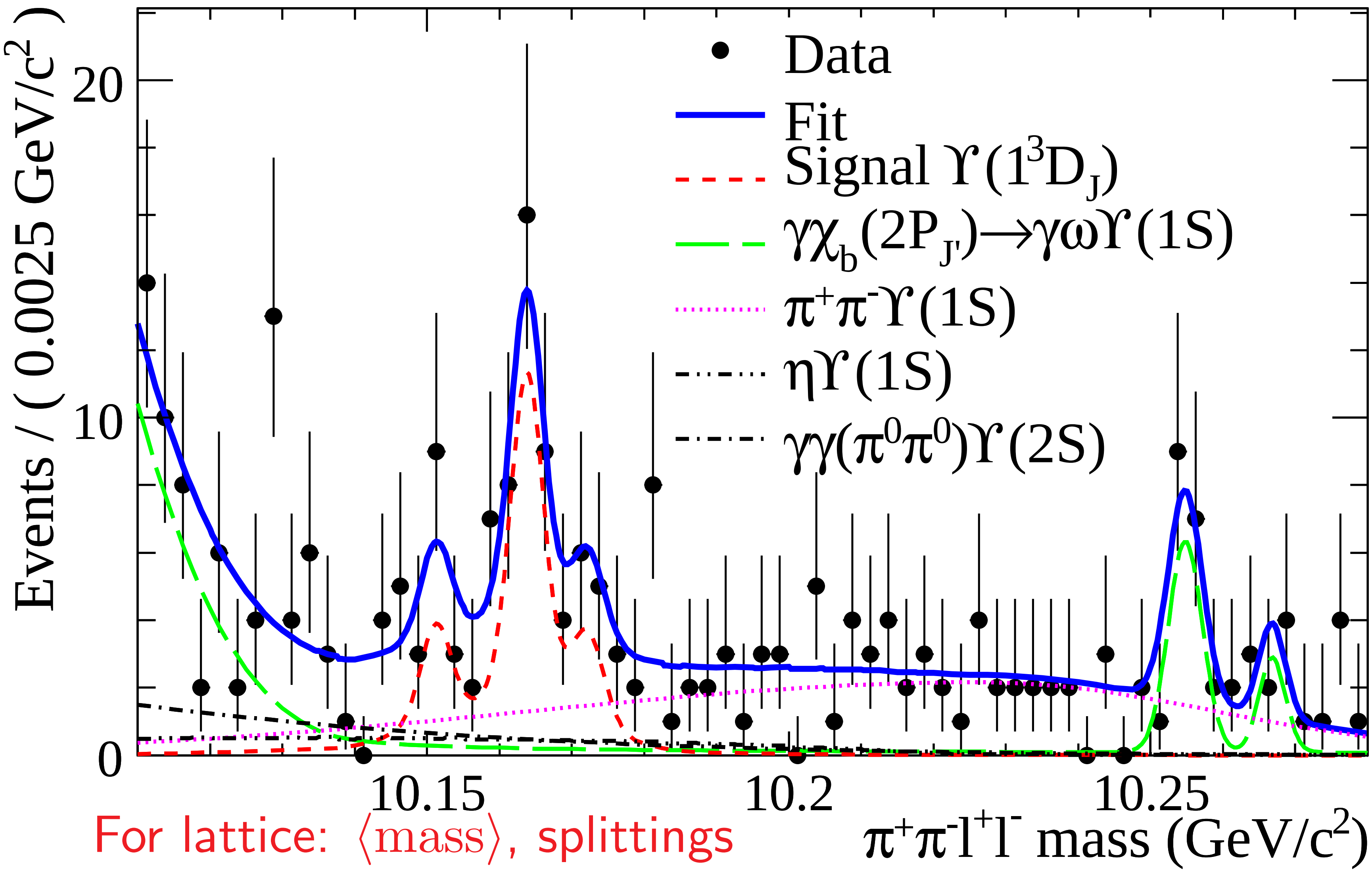


Plus
E1 radiative
transitions
$S \leftrightarrow P \leftrightarrow D$

Observation of $\Upsilon(^3D_J)$ state(s) [BaBar: P. del Amo Sanchez +, arXiv:1004.0175v2]; η_b mass, production rate [BaBar: PRL **101**, 071801 (2008); **103**, 161801 (2009); CLEO: G. Bonvicini +, PR D **81**, 031104(R) (2010)]; $h_b(9900)$ search [CLEO]

CONFIRMATION OF $\Upsilon(1^3D_J)$

BaBar: Fit to region near 10.16 GeV with $M[\Upsilon(1^3D_2) = 10164.5 \pm 0.8 \pm 0.5$ MeV ($33.9^{+8.2}_{-7.5}$ events); $M[\Upsilon(1^3D_1) = 10151.6^{+1.3}_{-1.4} \pm 0.5$ MeV ($10.6^{+5.7}_{-4.9}$ events); $M[\Upsilon(1^3D_3) = 10172.9 \pm 1.7 \pm 0.5$ MeV ($9.4^{+6.2}_{-5.2}$ events) [CLEO: $\Upsilon(1^3D_2)$ only]

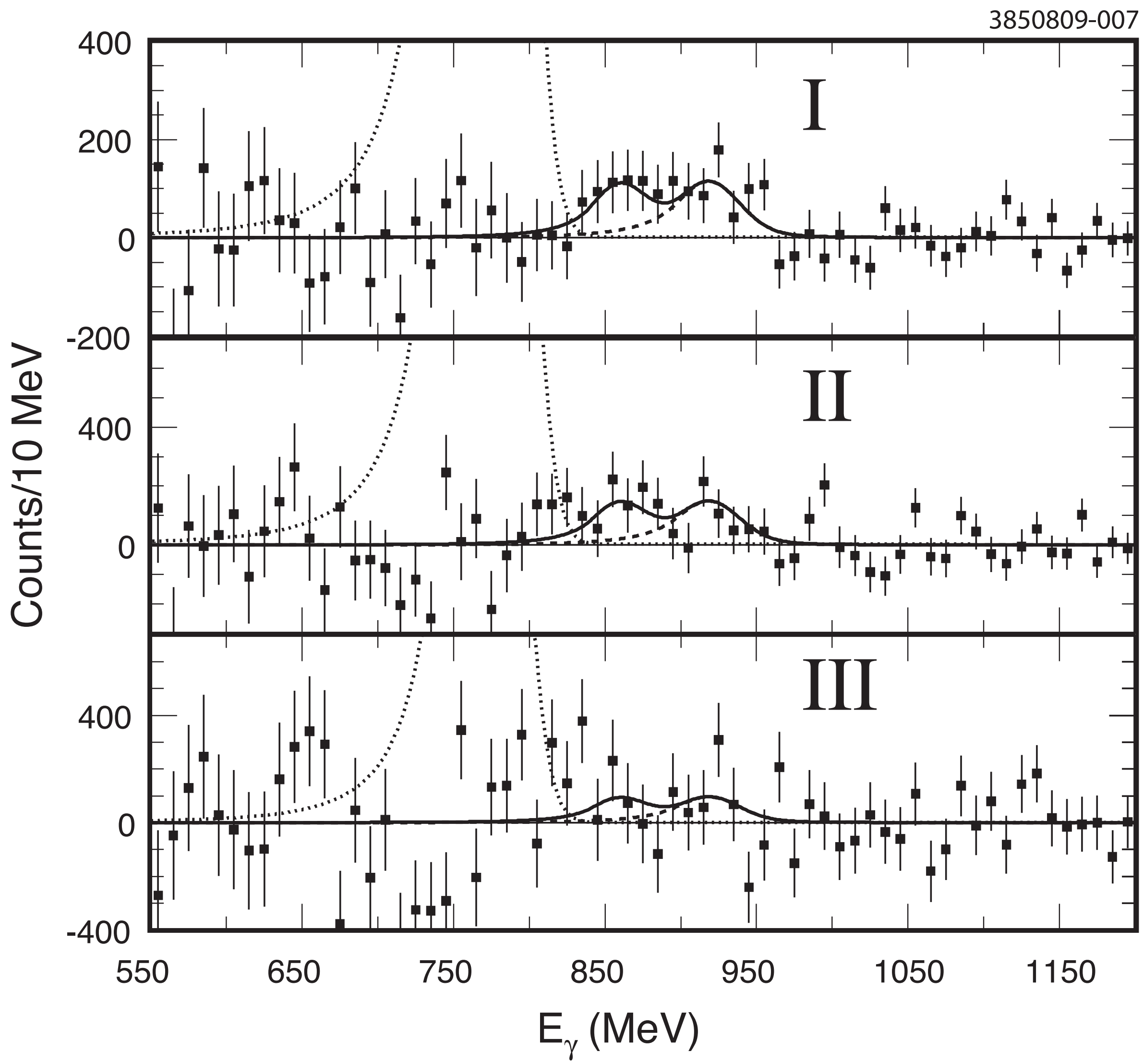


For lattice: $\langle \text{mass} \rangle$, splittings

CLEO $\Upsilon(3S) \to \gamma\eta_b(1S)$ ANALYSIS

New (cf. BaBar): (1) initial-state radiation (ISR) in $e^+e^- \to \gamma(859\ \text{MeV})\Upsilon(1S)$; (2) finite $\Gamma(\eta_b)$ (nominal 10 MeV); (3) angle between $\gamma(920\ \text{MeV})$ and thrust axis [BaBar: $\cos\theta_T < 0.7$; CLEO: bins I(0.0-0.3), II(0.3-0.7), III(0.7-1.0) fit separately]

Subtract large peak (⇓) due to $\chi_b(2P) \to \gamma\Upsilon(1S)$



68.5±6.6±2.0 MeV below Υ

BaBar: $71.4^{+2.3}_{-3.1} \pm 2.7$ MeV

$66.1^{+4.9}_{-4.8} \pm 2.0$ MeV (2S)

Examples of lattice calculations:

HPQCD: 61(14) MeV [PRD **72**, 094507 (2005)]

RBC/UKQCD: 52.5(1.5) MeV [PRD **79**, 094501 (2009)]

FNAL/MILC: $54.0 \pm 12.4^{+1.2}_{-0.0}$ MeV [PRD **81**, 034508 (2010)]

$\mathcal{B}[\Upsilon(3S) \to \gamma\eta_b(1S)] =$

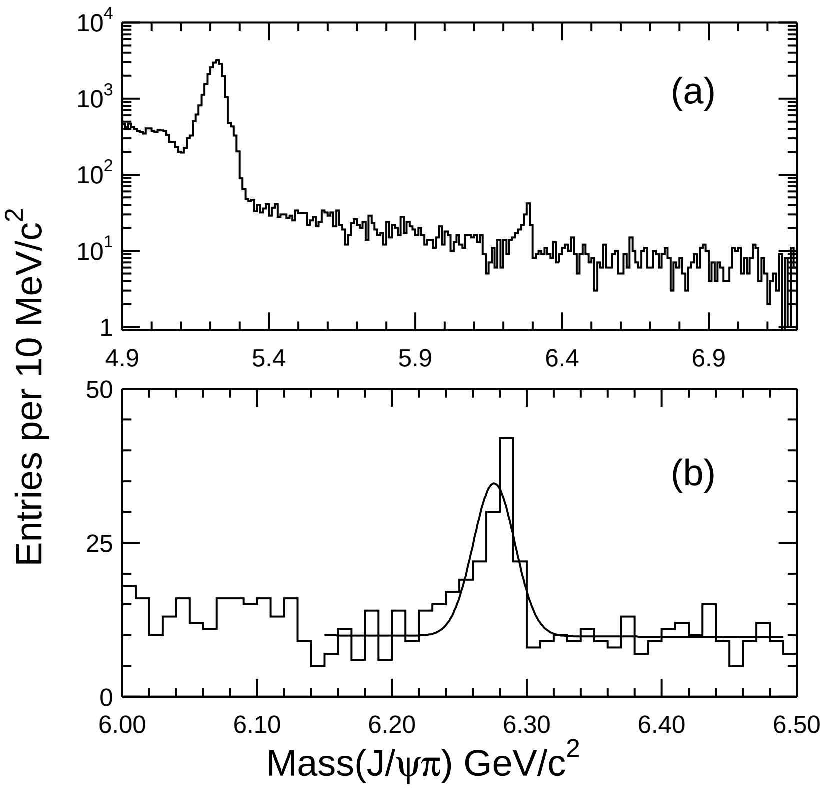
$(4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$ (BaBar)

$(7.1 \pm 1.8 \pm 1.1) \times 10^{-4}$ (CLEO)

THE B_c MESON

Flavor-independence of quarkonium potential (see review by C. Quigg in 1979 Lepton-Photon Symposium, Fermilab) allows estimates of masses of $b\bar{c}$ states, e.g.:

Authors	Reference	$M(B_c)$	$M(B_c^*)$
E. Eichten, C. Quigg	PR D **49**, 5845 (1994)	6264 MeV	6337 MeV
D. Ebert *et al.*	PR D **67**, 014027 (2003)	6270 MeV	6332 MeV
S. Godfrey	Private comm.	6271 MeV	6338 MeV
Lattice (HPQCD/FNAL)	PRL **94**, 172001 (2005)	$6304 \pm 12^{+18}_{-0}$ MeV	—
Lattice (HPQCD)	PRL **104**, 022001 (2010)	$\Delta M_{\rm hf} = 53(7)(2)$ MeV	



Larger peak at left: $B \to J/\psi K^\pm$

CDF measured $M(B_c)$ in $J/\psi\pi^\pm$ mode: $6275.6 \pm 2.9 \pm 2.5$ MeV: T. Aaltonen +, PRL **100**, 182002 (2008)

Eichten-Quigg and Ebert *et al.* quote other predictions

Lattice hyperfine prediction smaller than many others but error needs reduction

Challenge to experiment: γ in $B_c^* \to \gamma B_c$

DECAYS $[J/\psi, \psi(2S)] \to \gamma(\pi^0, \eta, \eta')$

T. K. Pedlar + (CLEO), PR D **79**, 111101 (R) (2009)

$J/\psi \to \gamma\pi^0$ BR gives form factor for $\gamma^* \to \gamma\pi^0$. Below calculation by Chernyak + Zhitnitsky, Phys. Rep. **112**, 173 (1984). Can lattice predict it?

Initial state	$\mathcal{B}$ (10^{-4}) $\gamma\eta$	$\gamma\eta'$	$(p^*_\eta/p^*_{\eta'})^3$
J/ψ	$11.01 \pm 0.29 \pm 0.22$	$52.4 \pm 1.2 \pm 1.1$	1.229
ψ'	< 0.02	$1.19 \pm 0.08 \pm 0.03$	1.153

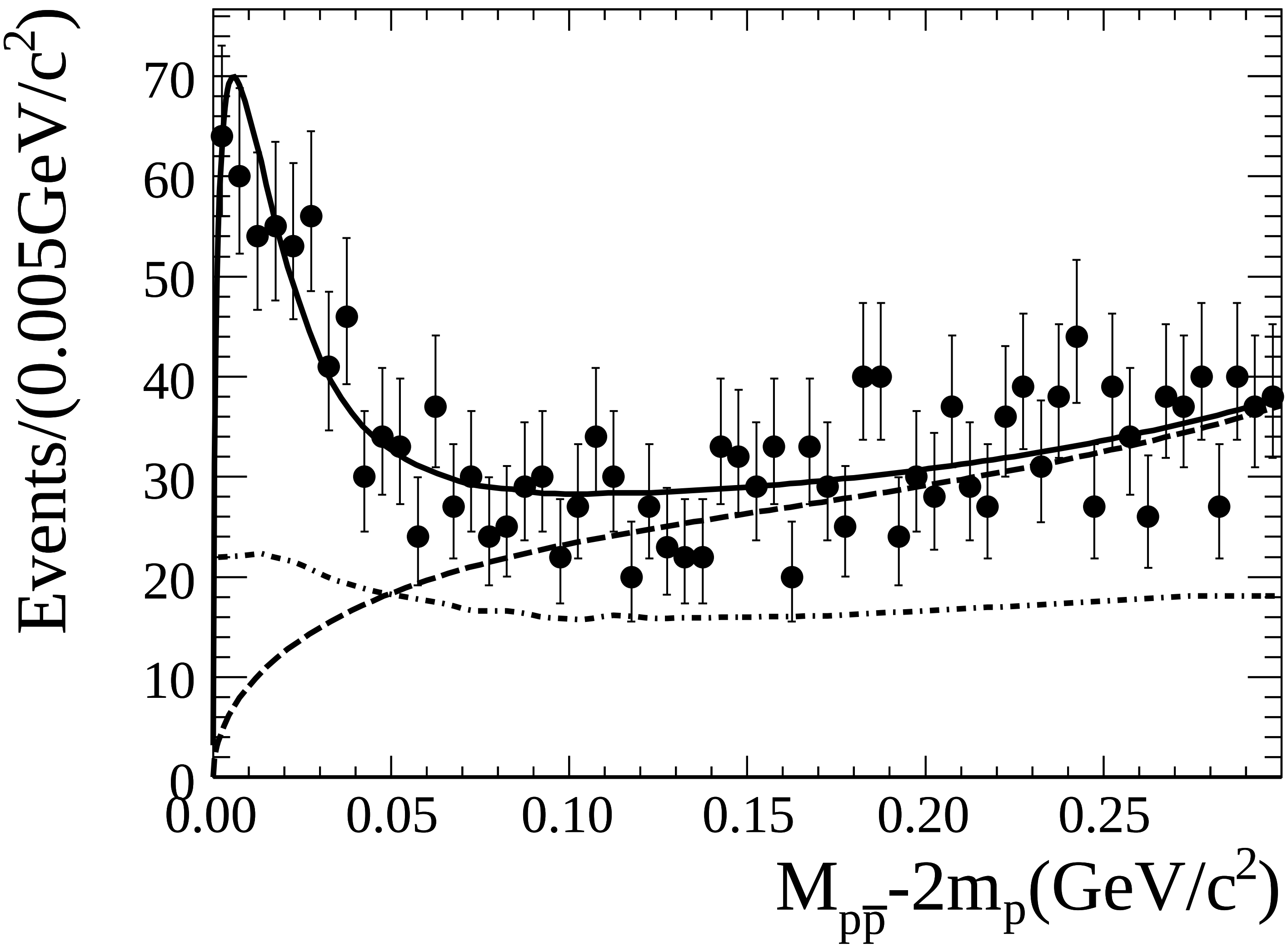
Assuming these decays proceed via $c\bar{c} \to \gamma gg \to \gamma(\eta, \eta')$, the η/η' ratio should give the relative contribution of SU(3) singlet in η and η'

Correcting for p^*3, J/ψ decays give 0.17 ± 0.01 while ψ' gives < 0.02. Typical model gives $\simeq 1/8$ so it is $\mathcal{B}(\psi' \to \gamma\eta')$ that is anomalously low

Reminiscent of strong suppression of certain ψ' decays such as $\rho\pi$; does lattice expect anything unusual about ψ'?

LOW-MASS $p\bar{p}$ STATES

BESIII (M. Ablikim +, arXiv:1001.5328) confirms BES-II (PRL **91**, 022001) low-mass $p\bar{p}$ threshold enhancement in $J/\psi \to \gamma p\bar{p}$ (producing J/ψ in $\psi' \to \pi^+\pi^- J/\psi$)



Not seen in $\psi' \to \gamma p\bar{p}$

$X(1835) \to \eta'\pi^+\pi^-$ may be related

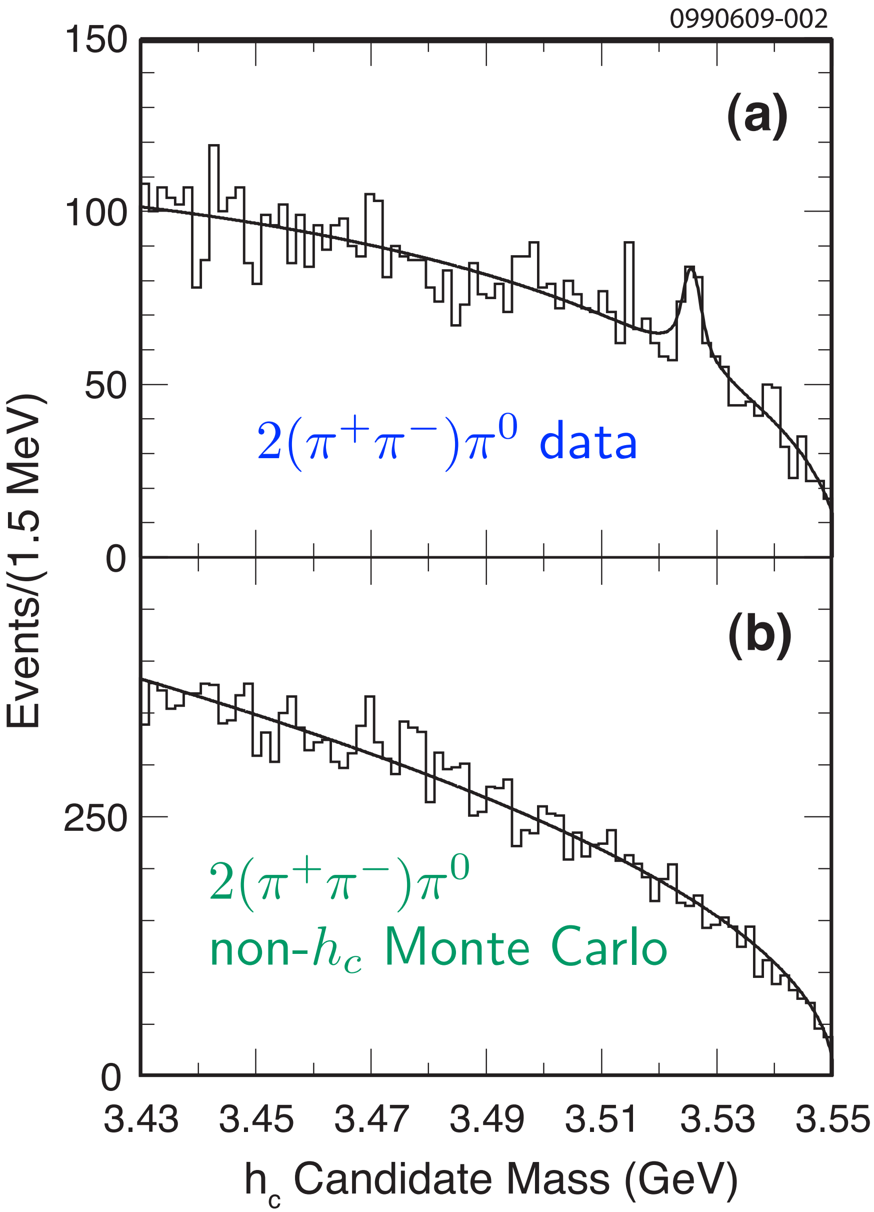
Glueball, baryonium, a mixture, or neither?

CLEO: Enhancement above $M_{p\bar{p}} - 2m_p = 300$ MeV should be considered when fitting threshold enhancement

$M = 1861^{+6+7}_{-13-26}$ MeV, $\Gamma < 38$ MeV. Can lattice say anything about baryon-antibaryon resonances? Early prediction (including exotics): PRL **21**, 950 (1968)

EXCLUSIVE CHARMONIUM DECAYS

$h_c \to 2\pi^+2\pi^-\pi^0$: G. S. Adams *et al.* (CLEO), Phys. Rev. D **80**, 051106(R) (2009)



$$\mathcal{B}[\psi(2S) \to \pi^0 h_c]\mathcal{B}[h_c \to 2(\pi^+\pi^-)\pi^0]$$
$$= (1.88^{+0.48+0.47}_{-0.45-0.30}) \times 10^{-5}$$

$2(\pi^+\pi^-)\pi^0$ estimated to be a few % of all hadronic h_c decays

Can lattice predict inclusive properties such as average multiplicity, dispersion, in decays of a heavy particle?

M. Ablikim + (BESIII), PR D **81**, 052005: (2010): New, more accurate branching fractions for $\chi_{c0,2} \to (\pi^0\pi^0, \eta\eta)$; $\chi_{cJ} \to VV$

Relevant to low-multiplicity tail of fragmentation models such as PYTHIA; what can lattice QCD say?

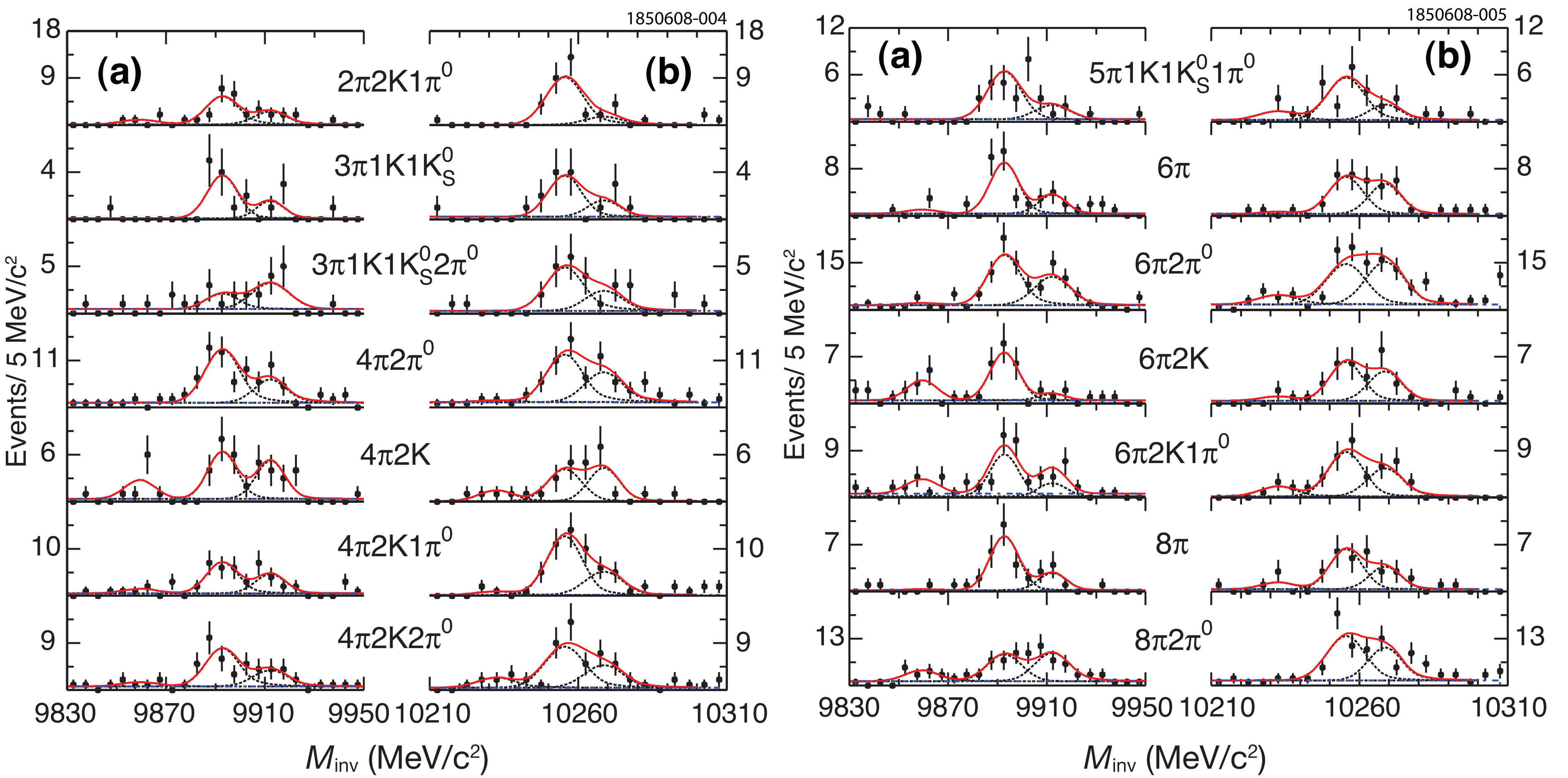
Lower-mass $\pi^0\pi^0, \eta\eta \leftrightarrow$ glueballs?

EXCLUSIVE χ_b, χ_b' DECAYS

D. M. Asner *et al.* [CLEO Collaboration], Phys. Rev. D 79, 072007 (2009).

Identified 14 modes with $> 4\sigma$ signals in at least one χ_{bJ} or χ_{bJ}' decay

$\Upsilon(2S) \to \gamma\chi_b$ $\Upsilon(3S) \to \gamma\chi_b'$ $\Upsilon(2S) \to \gamma\chi_b$ $\Upsilon(3S) \to \gamma\chi_b'$



What do Monte Carlo fragmentation programs (PYTHIA, ...) predict?

CLEO: UNFINISHED BUSINESS

More hadronic transitions in $b\bar{b}$ systems, e.g., $\Upsilon(3S) \to \gamma\chi'_{b0} \to \gamma\eta\eta_b$

Discover $h_b = 1^1P_1(b\bar{b})$ state via $\Upsilon(3S) \to \pi^0 h_b \to \pi^0\gamma\eta_b$ or $\Upsilon(3S) \to \pi^+\pi^- h_b \to \pi^+\pi^-\gamma\eta_b$

Search for $\Upsilon(1S) \to \gamma\eta_b$ summing exclusive η_b modes

Emulate η_b, χ_b, χ'_b decays using PYTHIA to compare with the branching fractions in the 14 observed modes

Map out D^0, D^+ inclusive decays as CLEO has already done for D_s^+ [S. Dobbs +, PR D **79**, 112008 (2009)]. Few (if any) “missing” modes in D_s^+ decays; inclusive study pointed the way to a few more [J. Y. Ge + (CLEO), PR D **80**, 051102(R) (2009)]. Specific missing D^0, D^+ modes predicted by isospin statistical model include $\mathcal{B}(D^+ \to \bar{K}^0\pi^+2\pi^0) \simeq$ (few %)

Can address these and other topics in data from CLEO, BaBar, Belle, CDF, D0, BESIII (forthcoming). Informal CLEO deadline for wrapping up analyses is about a year from now.

CONCLUSIONS

Charm/bottom spectroscopy continues to advance

• h_c is now well-established; how well can lattice predict its mass? Width?

• See M2 amplitudes for $\chi_{c1} \to \gamma J/\psi$, $\chi_{c2} \to \gamma J/\psi$, and $\psi' \to \gamma' \chi_{c1}$; exclude pure E1 by more than $(11, 6)\sigma$ for $J_\chi = (1, 2)$.

• Strengths of these amplitudes agree with predictions to $\mathcal{O}(E_{\gamma^{(\prime)}}/m_c)$ with $m_c = 1.5$ GeV and $\kappa_c = 0$; lattice did not anticipate M2 contributions so well

• B_c came in a bit below lattice predictions; still time to predict B_c^* mass

• η_b has been confirmed; lattice did better than potential models in predicting it

• CLEO's discovery of 1^3D_2 bottomonium state confirmed and extended by BaBar; what can lattice say about mass, 1^3D_J fine structure?

• Many questions in meson spectroscopy may require methods beyond the capability of current lattice approaches; doesn't mean they should be ignored.

Still learning about (c,b) mesons after (35,32) years, with many potential tests of our understanding of low-energy strong interactions