HEAVY QUARK SPECTRA

CLEO (+ some other) results and prospects

Thanks to collaborators E. Eichten, S. Godfrey, H. Mahlke (hep-ph/0701208)

J. Rosner – University of Chicago – 12/10/07 at Fermilab Lattice Workshop

Heavy quarks Q provide an exceptional window into tests of QCD:
(1) Through perturbative description of $Q\bar{Q}$ decays;
(2) As "nuclei" for $Q\bar{q}$ and Qqq hadrons ($q =$ light quark u, d, s) where many interesting questions involve non-perturbative effects.

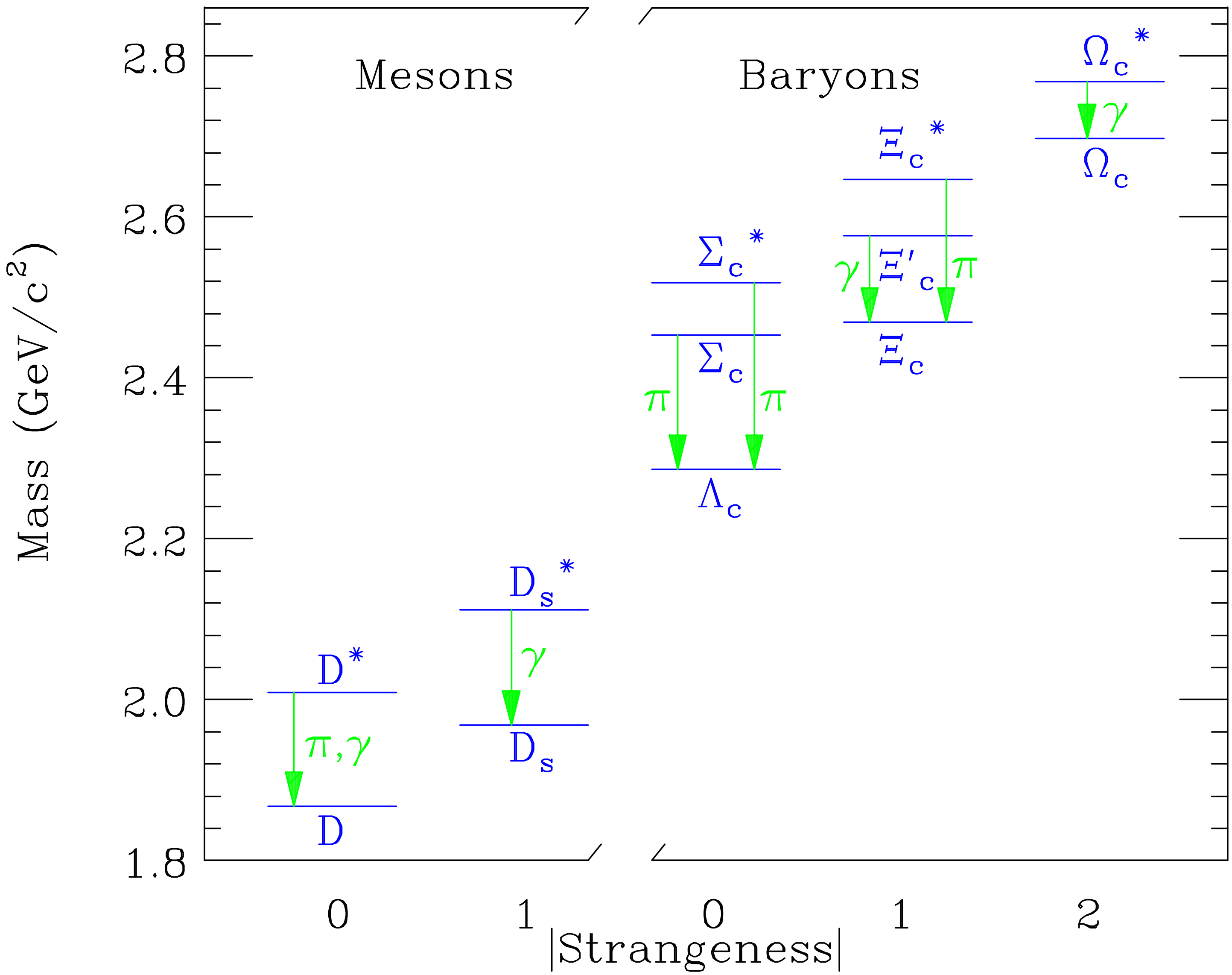
Many hadrons discovered recently require that one understand nearby thresholds: see Fano (1935), Wigner (1948), Feshbach (1958).

Hadron spectra often are crucial in separating electroweak physics from strong-interaction effects.

QCD may not be the only instance of important non-perturbative effects: Composite Higgs? Composite quarks/leptons??

Today's topics (with challenges to lattice QCD):
Charmed and beauty hadrons, heavy quarkonium ($c\bar{c}$, $b\bar{b}$), future

CHARMED STATES



Today: D^0 mass and $X(3872)$; excited D_{sJ} and light quarks

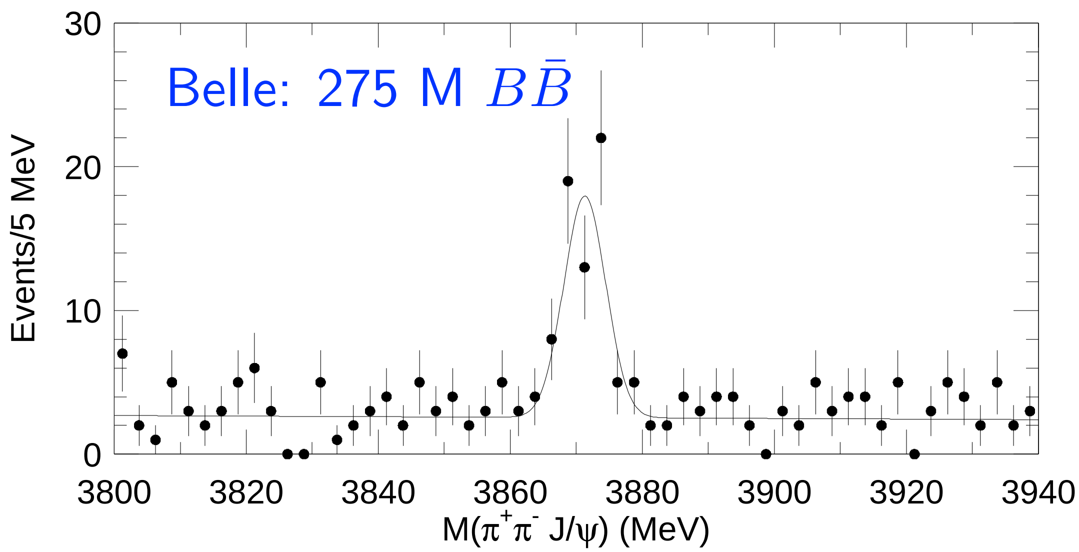
BaBar: Ω_c^* 70.8±1.0±1.1 MeV above Ω_c: $\surd$ quark models

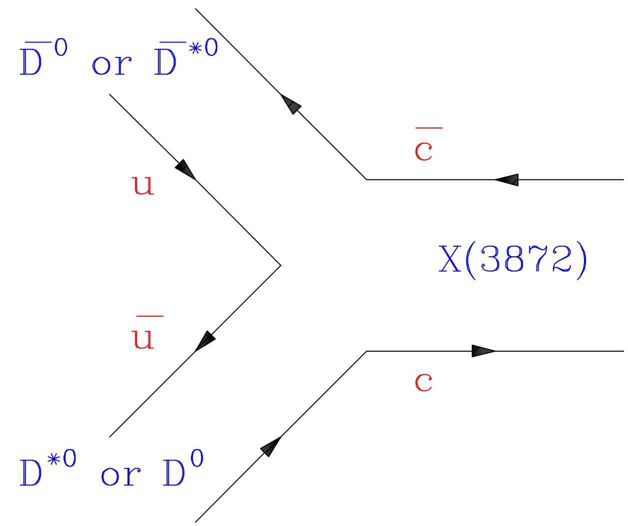
D^0 MASS MEASUREMENT

Relevant to $X(3872)$ as possible $D^0\bar{D}^{*0}$ + c.c. bound state or molecule

$M(D^0) = 1864.847 \pm 0.150 \pm 0.095$ MeV using $D^0 \to \bar{K}^0\phi$ [C. Cawlfield *et al.* [CLEO], Phys. Rev. Lett. **98**, 092002 (2007)] implies $M(D^0\bar{D}^{*0}) = 3871.81 \pm 0.36$ MeV, so $M(X) = 3872.4 \pm 0.6$ MeV is 0.6 ± 0.6 MeV heavier. Bound state?

Belle saw $X(3872) \to \pi^+\pi^- J/\psi$ in $B \to KX(3872)$ (BaBar, CDF, D0, ... $\surd$)





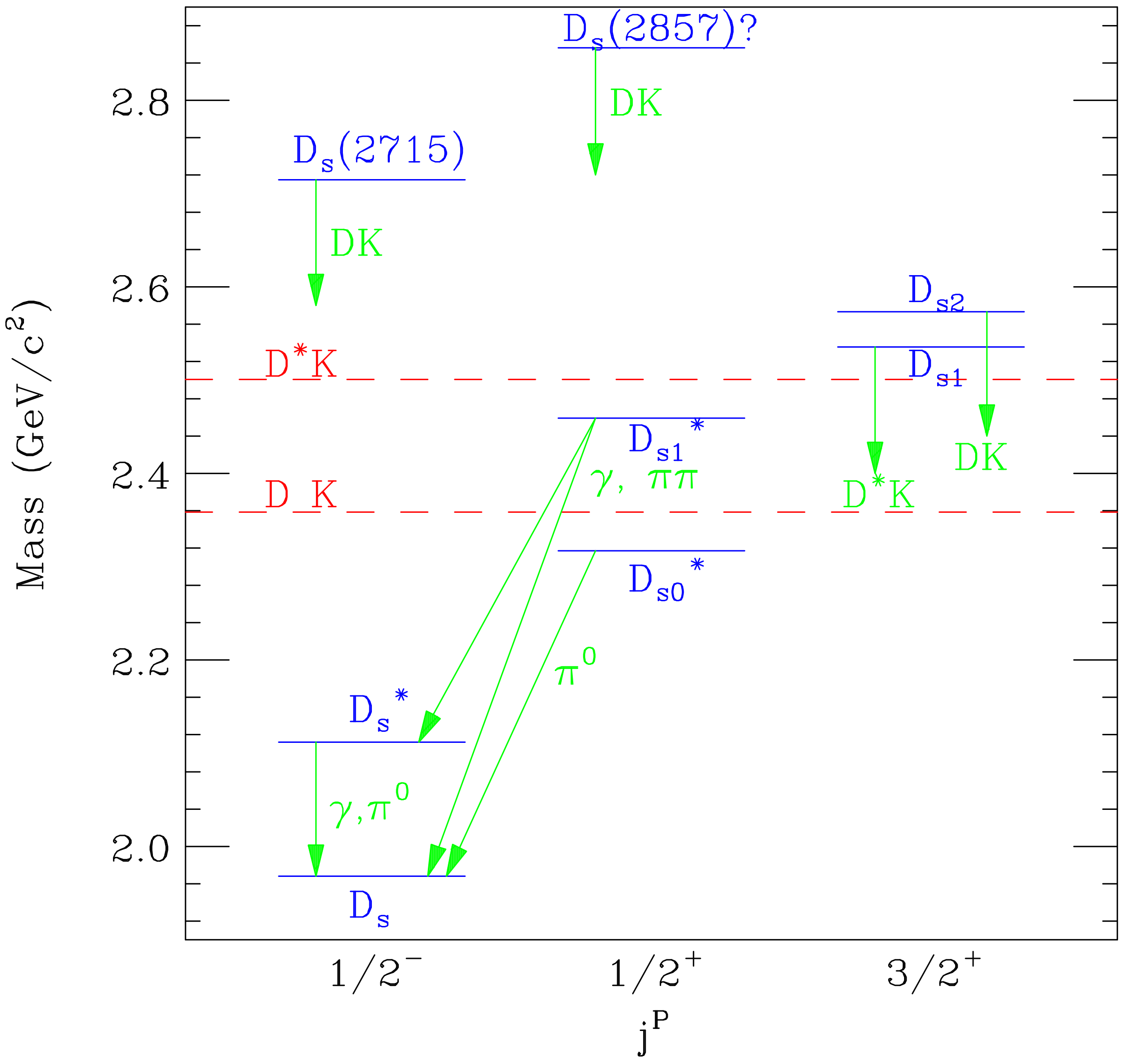
$J^{PC} = 1^{++}$ favored (angular dists.; $\rho J/\psi$ and $\omega J/\psi$ decays)

Could be S-wave bound state of $(D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2} \sim c\bar{u}u\bar{c}$; $c\bar{d}d\bar{c}$ channel closed. Decays to $\gamma J/\psi \Rightarrow$ some $c\bar{c}$ in wave function.

Can lattice QCD tell us about binding/molecular dynamics?

UNEXPECTEDLY LIGHT D_s

Two orbitally-excited $c\bar{s}$ mesons were lighter than expected (by most)



j^P: light-quark angular momentum ($\vec{S}_q + \vec{L}$), parity

D^*_{s0} below DK threshold;

D^*_{s1} below D^*K threshold

Allows EM and I-violating transitions to dominate

Low masses of $D^*_{s0,1}$ suggested by chiral models as parity-doublets of $D_s^{(*)}$ ($\Delta M \simeq 350$ MeV)

Bound states of $D^{(*)}K$?

$(c\bar{q})(q\bar{s}) \leftrightarrow (c\bar{s})$: Binding energy $\simeq 41$ MeV; similarly for $\bar{B}^{(*)}K$?

EXCITED D_s AND D STATES

D_s state at 2708 MeV

Seen in $M(D^0K^+)$ spectrum in $B^0 \to \bar{D}^0 D^0 K^+$ [Belle arXiv:0707.3491 for PRL]

$M = (2708 \pm 9^{+11}_{-10})$ MeV; $\Gamma = (108 \pm 23^{+36}_{-31})$ MeV

$J^P = 1^-$, 596 ± 14 MeV above $D_s^*(2112)$ vs M(2S)–M(1S) = 681±20 MeV for $s\bar{s}$ and 589 MeV for $c\bar{c}$: Good $c\bar{s}(2^3S_1)$ candidate. BaBar also sees similar state.

D_s state at 2857 MeV

Seen decaying to D^0K^+ and D^+K_S [BaBar PRL **97**, 222201 (2006)]

$M = (2856.6 \pm 1.5 \pm 5.0)$ MeV; $\Gamma = (48 \pm 7 \pm 10)$ MeV

Interpreted as first radial excitation of $D_{s0}(2317)$ (shown) or $J^P = 3^-(^3D_3)$ state

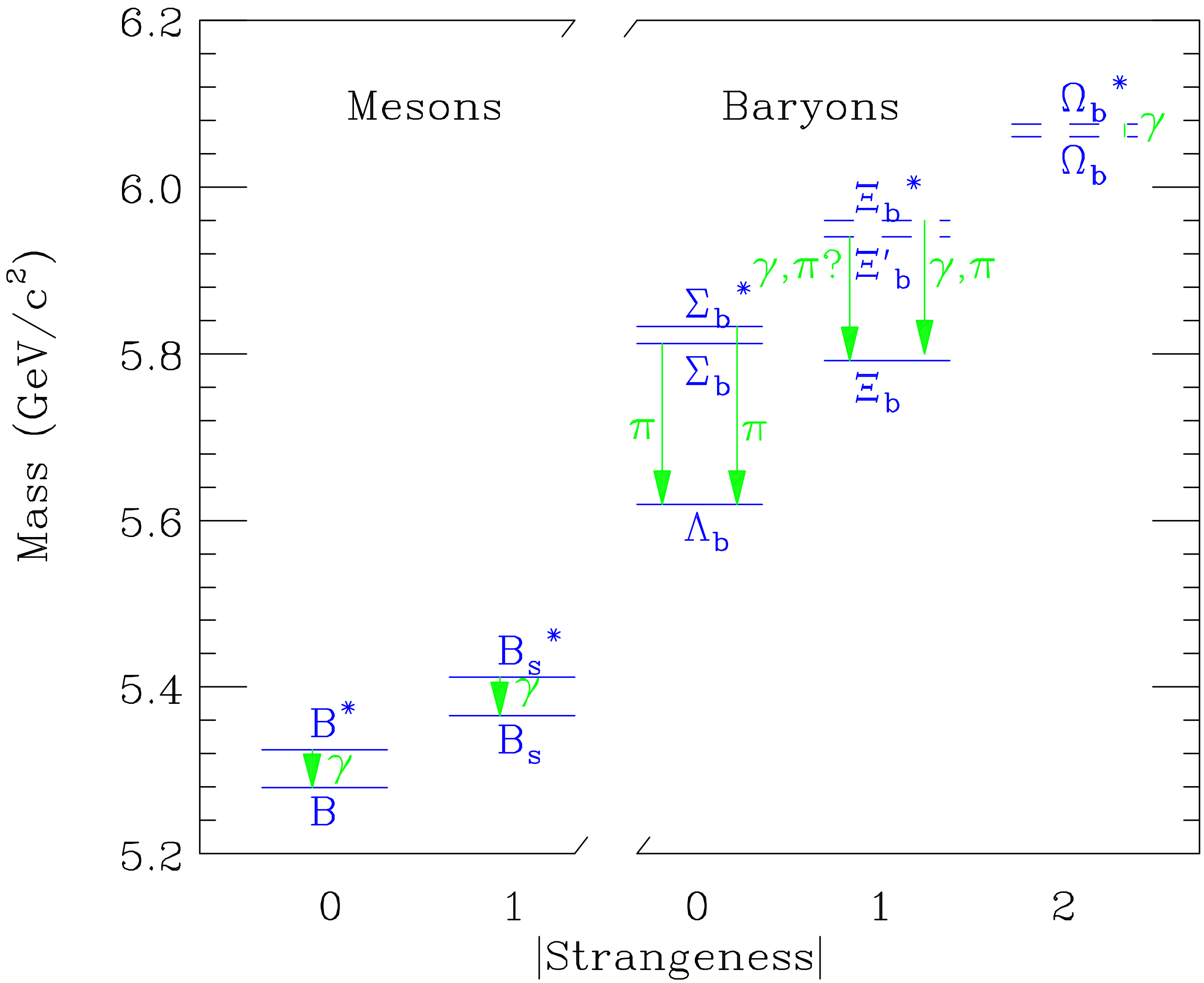
Excited charmed-nonstrange states

Established: $j^P = 3/2^+$ states (narrow); candidates: $j^P = 1/2^+$ states (broad)

Broad $J^P = 1^+$ candidates: CLEO, Belle in range 2420-2460 MeV
Broad $J^P = 0^+$ candidates: Belle, FOCUS in range 2300-2400 MeV

What can lattice say about radial, orbital excitations?

BEAUTY HADRONS



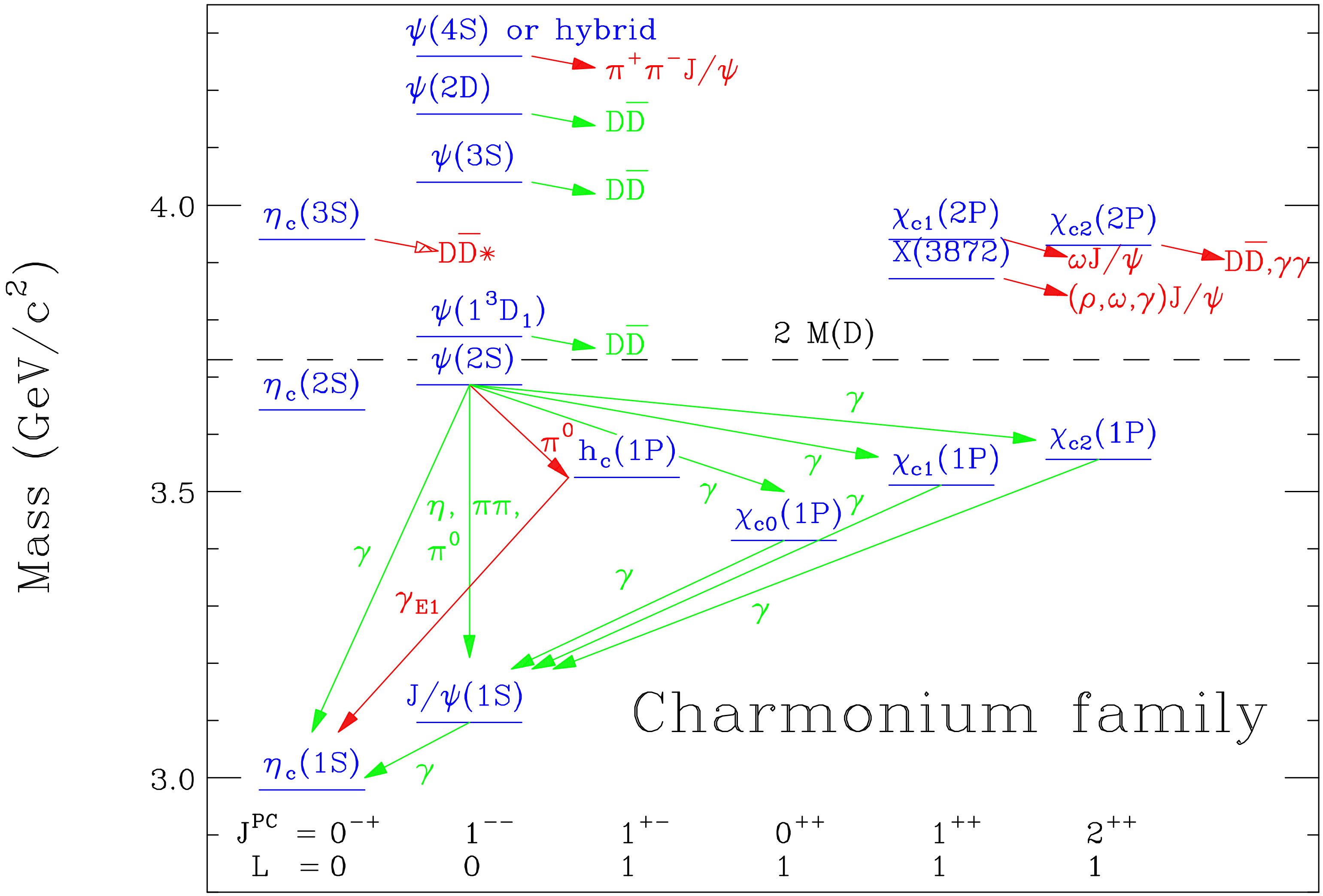
CLEO: O. Aquines *et al.*, PRL **96**, 152001: $\Rightarrow B_s^* - B_s = 45.9 \pm 1.2$ MeV

Almost same as $B^* - B = 45.78 \pm 0.35$ MeV: Can lattice explain this?

$Q\bar{Q}$ CLEO/LATTICE ISSUES

Hyperfine mass splittings	S-waves	$c\bar{c}$	$J/\psi - \eta_c$	Lattice value?
		$b\bar{b}$	$\Upsilon(1S) - \eta_b$	Lattice value?
	P-waves	$c\bar{c}$	$\langle\chi_c(^3P_J)\rangle - h_c$	Expect $\simeq 0$
		$b\bar{b}$	$\langle\chi_b(^3P_J)\rangle - h_b$	Expect $\simeq 0$
EM transition rates	Allowed M1	$c\bar{c}$	$J/\psi \to \gamma\eta_c$	Rate too small?
		$b\bar{b}$	$\Upsilon(1S) \to \gamma\eta_b$	Expected rate?
	Forbidden M1	$c\bar{c}$	$\psi(2S) \to \gamma\eta_c$	Lattice prediction?
		$b\bar{b}$	$\Upsilon(2S,3S) \to \gamma\eta_b$	Lattice prediction?
	E1; M2/E1	$c\bar{c}$	$\psi(2S) \to \gamma\chi_{cJ}$; $\chi_{cJ} \to \gamma J/\psi$	Quark model makes predictions
		$b\bar{b}$	$\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$	Rate > prediction
Hadronic transition rates (mostly CLEO)	$\pi\pi$	$c\bar{c}$	$\psi(2S) \to \pi\pi J/\psi$	$\pi^0\pi^0/\pi^+\pi^- = 1/2$
		$b\bar{b}$	$\Upsilon(2S,3S) \to \pi\pi\Upsilon(1S)$	Spectrum shapes?
			$\chi'_{bJ}(2P) \to \pi\pi\chi_{bJ}(1P)$	Rates?
	η	$c\bar{c}$	$\psi(2S) \to \eta J/\psi$	η mass, BRs
		$b\bar{b}$	$\Upsilon(2S,3S) \to \eta\Upsilon(1S)$	See $\Upsilon(2S) \to \eta\Upsilon(1S)$
			$\chi'_{b0}(2P) \to \eta\eta_b$	Search (Voloshin)
	π^0	$c\bar{c}$	$\psi(2S) \to \pi^0 J/\psi$	π^0 rate high?
			$\psi(2S) \to \pi^0 h_c$	h_c properties
		$b\bar{b}$	$\Upsilon(2S,3S) \to \pi^0\Upsilon(1S,2S)$	Upper limits
			$\Upsilon(3S) \to \pi^0 h_b$	h_b search

CHARMONIUM STATUS



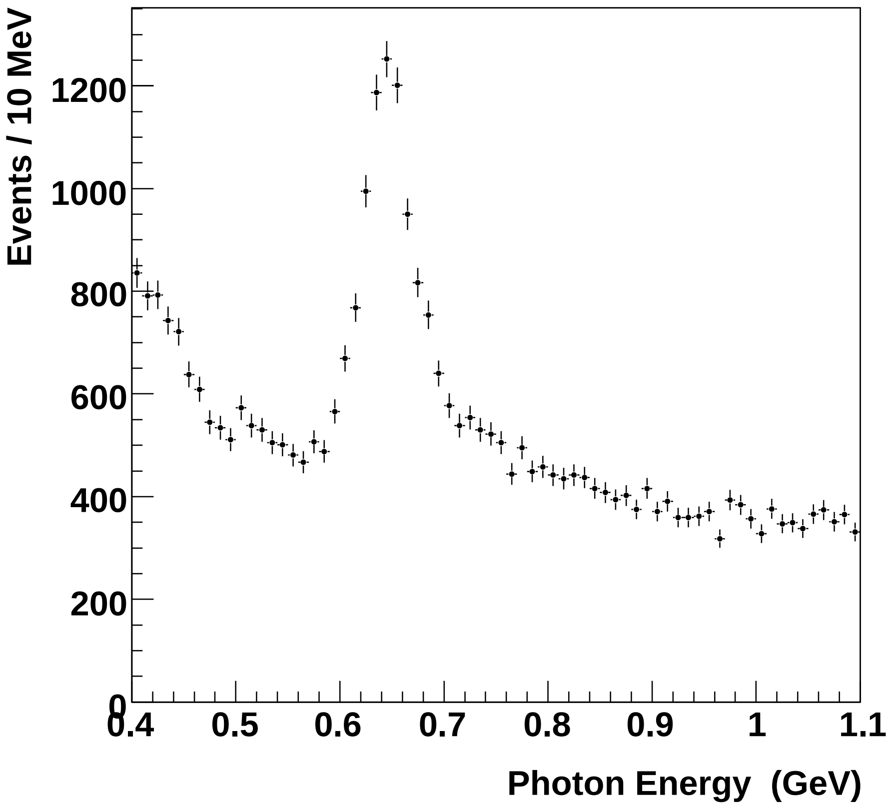
Spectroscopy of states above $D\bar{D}$ threshold is making progress. Even though states can decay to charm pairs in some cases, other modes are being seen.

BES, CLEO: specific χ_{cJ}, $\psi(2S)$ decays including wealth of multi-body modes

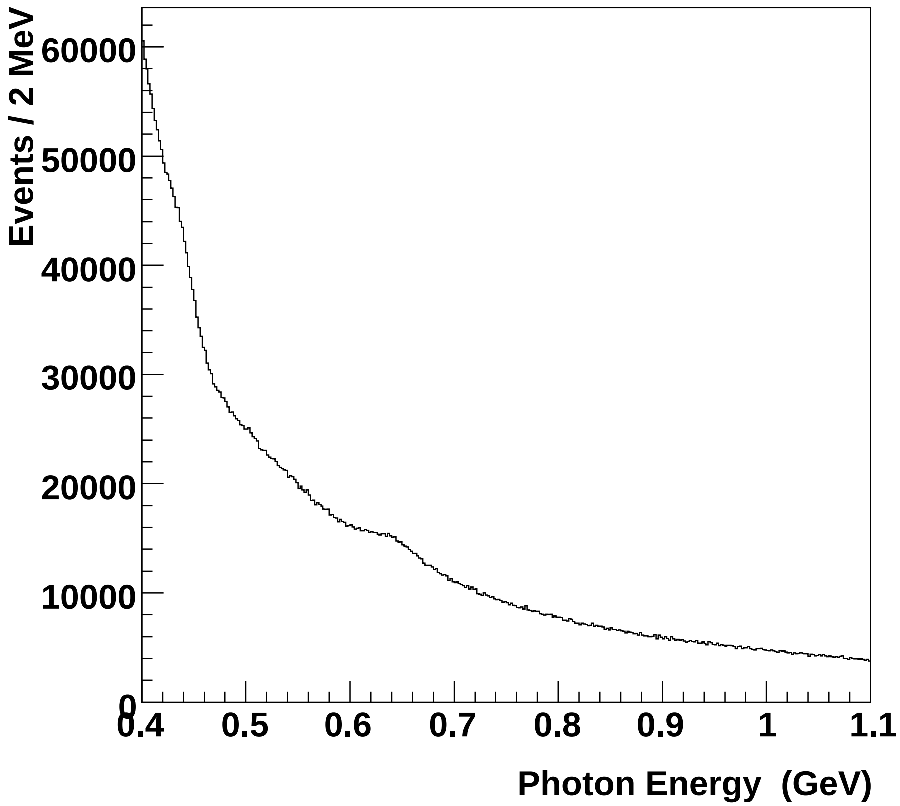
DECAY $\psi(2S) \to \gamma\eta_c$

CLEO is studying exclusive and inclusive $\psi(2S) \to \gamma\eta_c$

Exclusive:



Inclusive:



Measure $\mathcal{B}[\psi(2S) \to \gamma\eta_c] = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$ (preliminary)

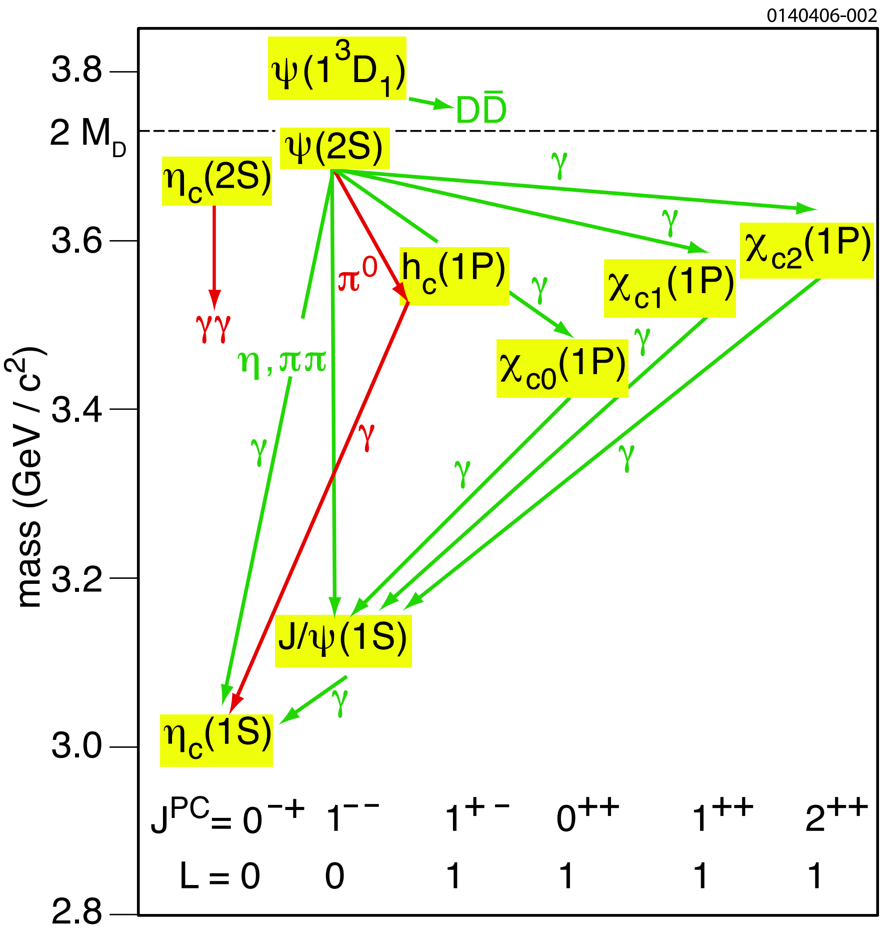
Unusual η_c line shape: enhancement at large E_γ. Can lattice reproduce this?

h_c OBSERVATION

Hyperfine splittings test spin-dependence and spatial behavior of $Q\bar{Q}$ force

S-wave ΔM's: $M(J/\psi) - M(\eta_c) \simeq 115$ MeV (1S), $M(\psi') - M(\eta'_c) \simeq$49 MeV (2S).

Expect $\leq$ few MeV P-wave splittings (Coulombic vector $c\bar{c}$ interaction; $\surd$ lattice)



CLEO: Observation in $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$) [PRL **95**, 102003 (2005); PRD **72**, 092004 (2005)]

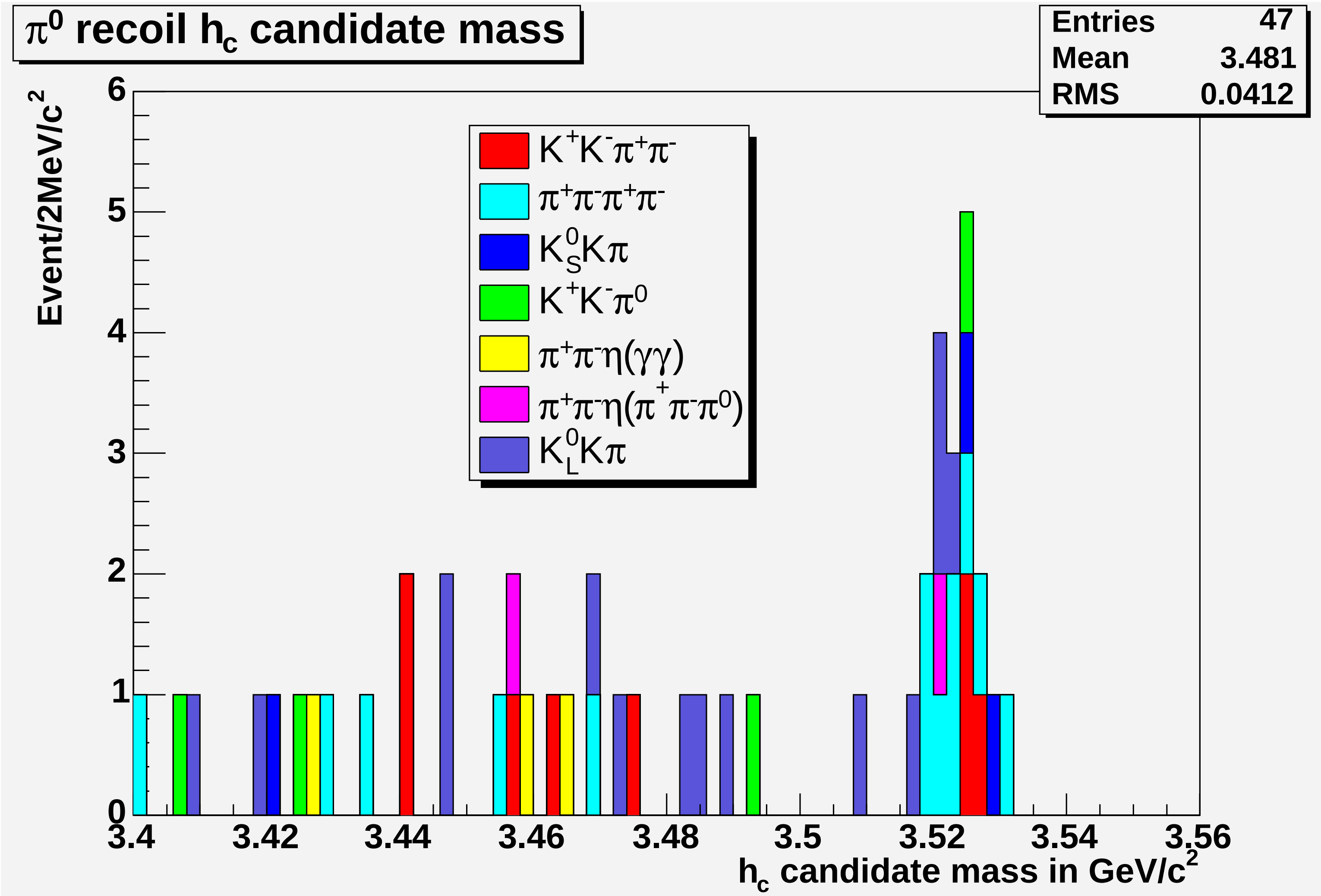
Inclusive, exclusive analyses saw a signal near $\langle M(^3P_J)\rangle = 3525.36 \pm 0.06$ MeV$/c^2$

Exclusive analysis reconstructed η_c in 7 decay modes ($\sim 10\%$ of all η_c decays)

Inclusive: No η_c reconstruction: better statistics but more background

Small P-wave ΔM favored local $\nabla^2 V_V(r)$

EXCLUSIVE h_c SIGNAL



19 candidates identified; 17.5 ± 4.5 events above background.

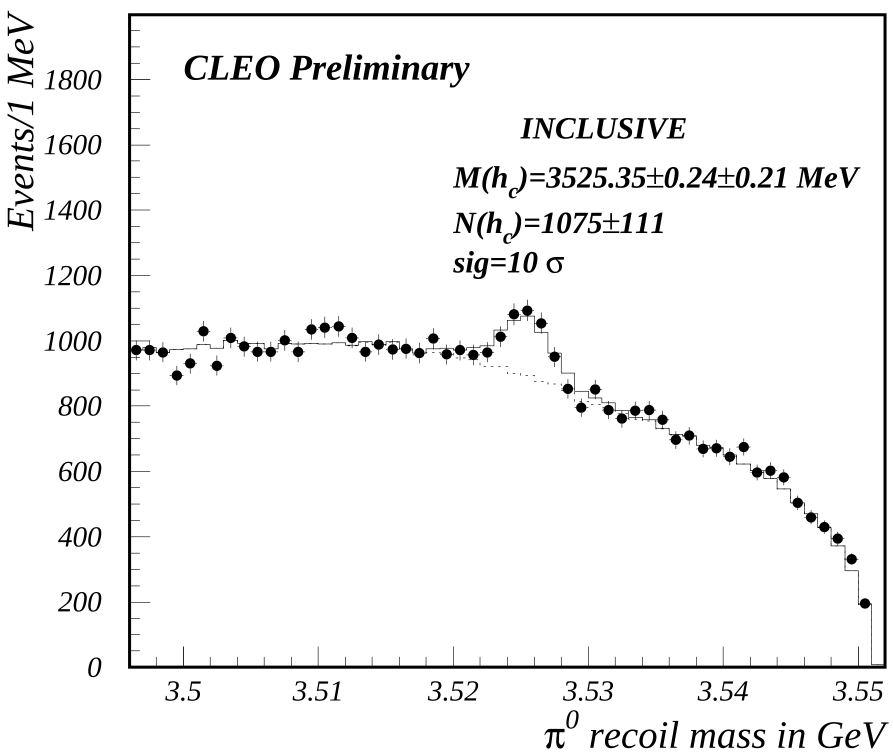
Excl.+incl.: $M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV, $\mathcal{B}_1\mathcal{B}_2 = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$

Mass was $(1.0 \pm 0.6 \pm 0.4)$ MeV below $\langle M(^3P_J)\rangle$; $\mathcal{B}_1\mathcal{B}_2$ $\surd$ theory $(10^{-3} \cdot 0.4)$

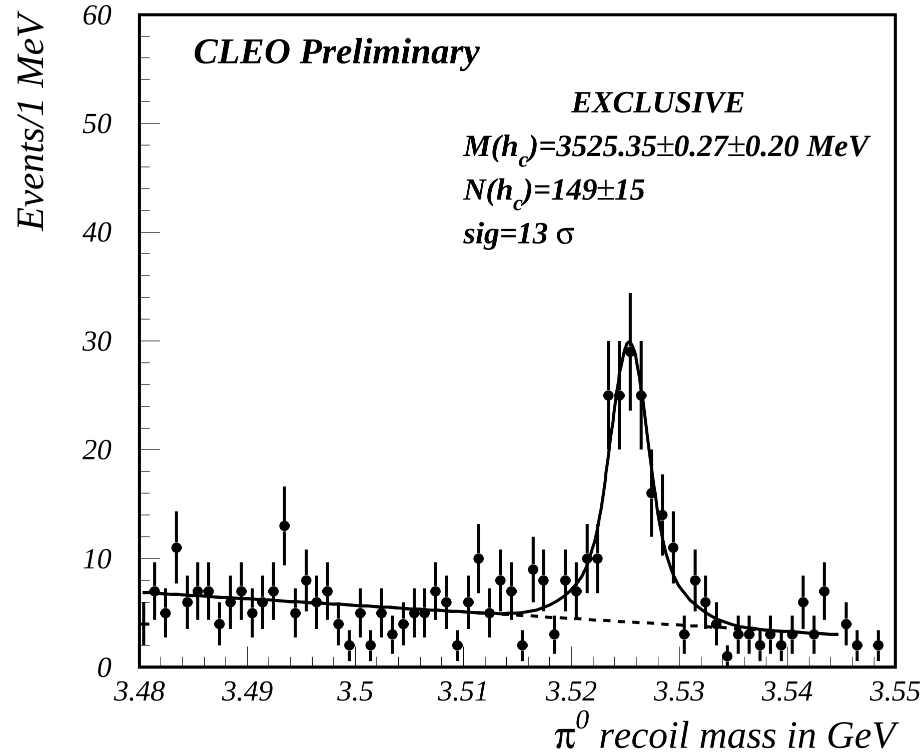
NEW h_c RESULTS

Earlier results were based on 3 M $\psi(2S)$; now 24.5 M additional

Inclusive:



Exclusive (18 modes):



New results confirm negligible $\langle ^3P_J \rangle - h_c$ splitting

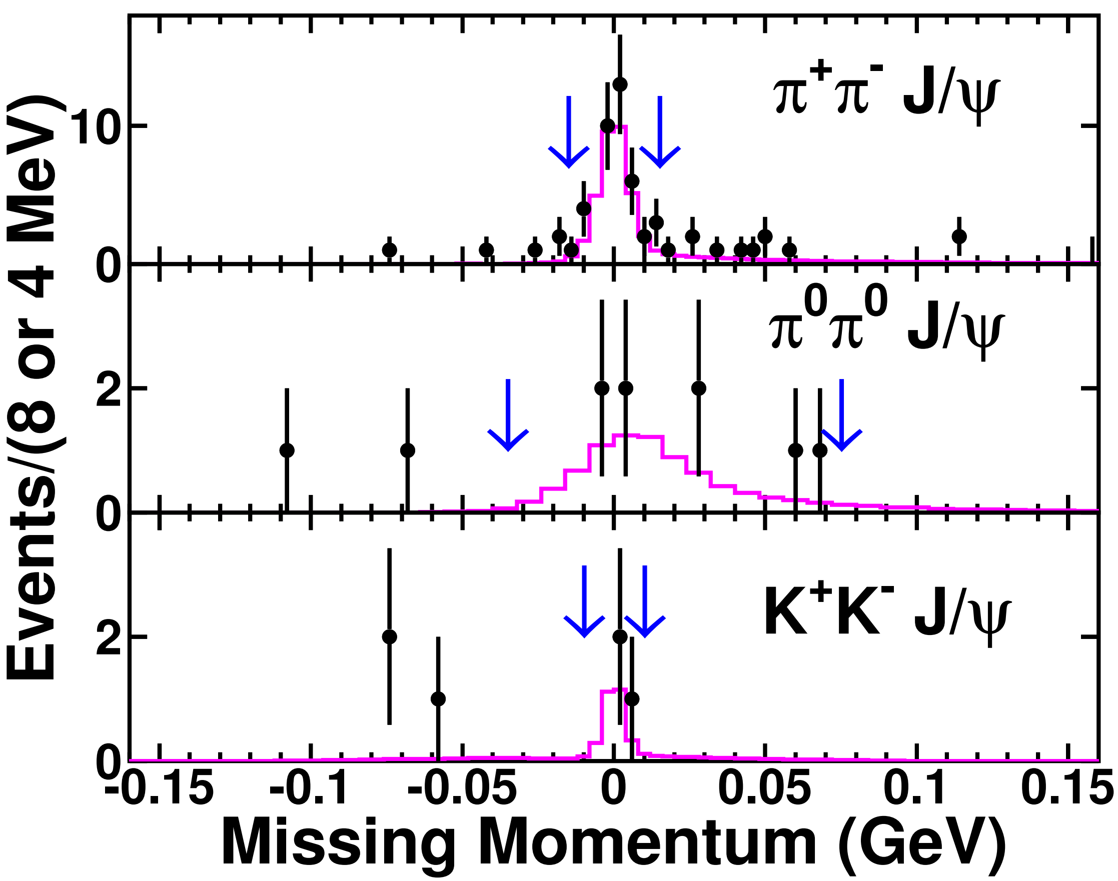
Inclusive process yields product of branching ratios (preliminary)
$\mathcal{B}[\psi(2S) \to \pi^0 h_c]\mathcal{B}[h_c \to \gamma\eta_c] = (3.96 \pm 0.41 \pm 0.55) \times 10^{-4}$

Y(4260): HYBRID?

BaBar: Y(4260) in radiative return to $\pi^+\pi^- J/\psi$: PRL **95**, 142001 (2005).

CLEO (Q. He +, PR D **74**, 091104), Belle (PRL **99**, 182004): $\surd$ radiative return

CLEO evidence for $Y(4260)$ in direct scan:



$Y(4260) \to \pi^+\pi^- J/\psi$ (11σ)
$\pi^0\pi^0 J/\psi(5.1\sigma)$, $K^+K^- J/\psi(3.7\sigma)$

$\psi(4160) \to \pi^+\pi^- J/\psi$ (3.6σ), $\pi^0\pi^0 J/\psi$ (2.6σ), consistent with $Y(4260)$ tail

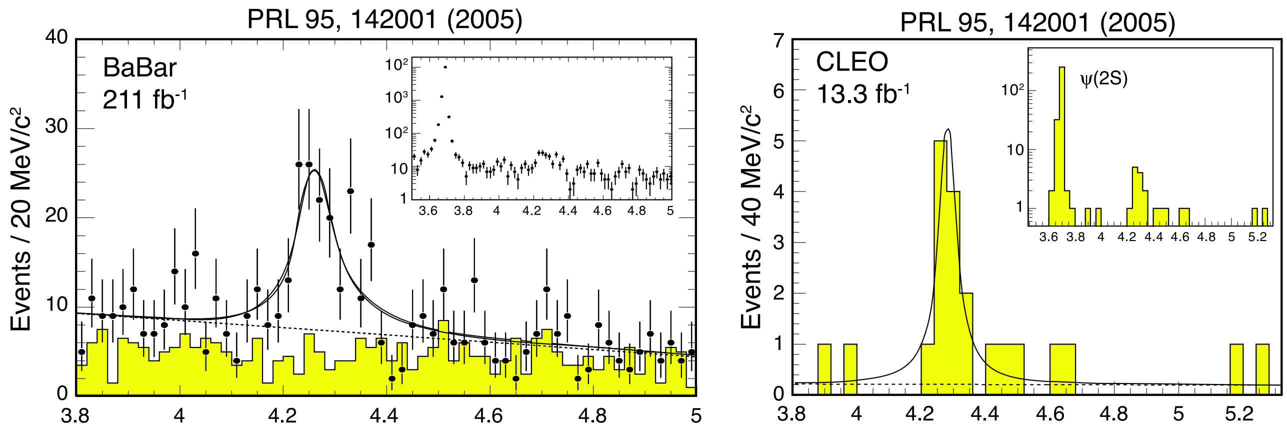
$\psi(4040) \to \pi^+\pi^- J/\psi$ (3.3σ)

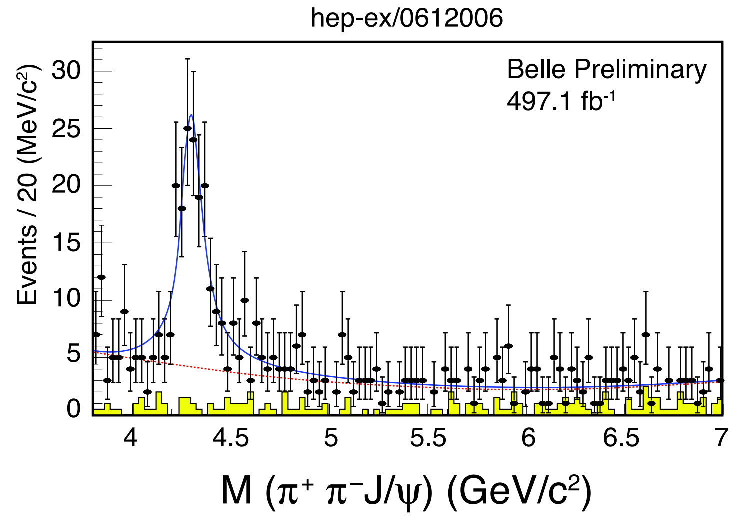
T. E. Coan +, PRL **96**, 162003: $\pi^0\pi^0 J/\psi$: not $\rho^0 J/\psi$ molecule

Small ΔR: not likely 4S state

$cq\bar{c}\bar{q}$ also proposed; how to tell from hybrid $c\bar{c}g$?

$Y(4260)$ SIGNALS





Update based on 547 fb^{-1}:

PRL **99**, 182004 (2007)

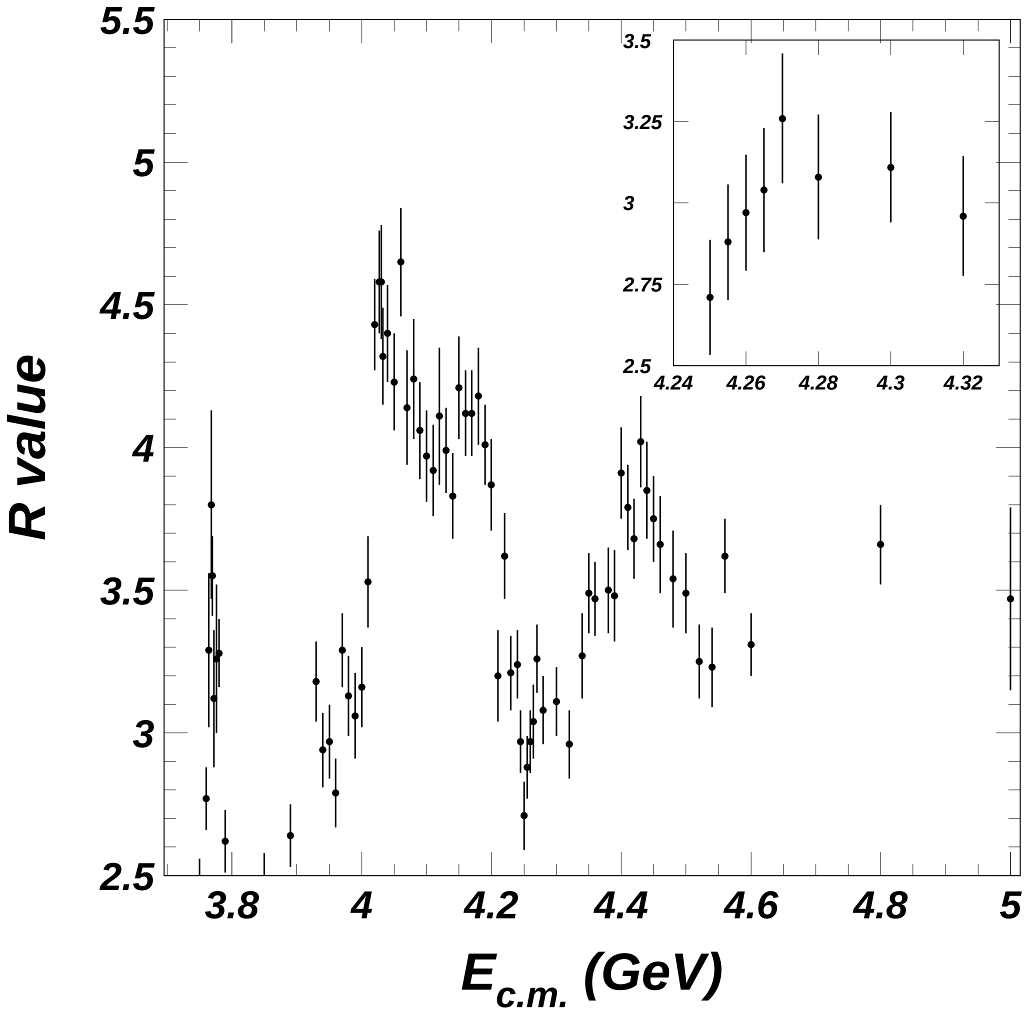
arXiv: 0707.2541

If $Y(4260)$ is a hybrid ($c\bar{c}+$ gluon), one expects it to couple to $D\bar{D}_1+$ c.c., where D_1 is a P-wave $c\bar{q}$ pair. *Dip* in $R_{e^+e^-}$ just below threshold!

$D\bar{D}_1$ threshold is ~ 4287 MeV: $Y(4260)$ a $D\bar{D}_1(\to D\pi\bar{D}^*)$ "molecule"?

B. Lang [for CLEO], arXiv:0710.0165: No $D\pi\bar{D}^*$ enhancement at 4260 MeV

DIP IN R AT 4250 MeV



Dip is just below threshold of lowest-mass charmed meson pair $D^0\bar{D}_1^*$ produced in an S-*wave*.
(Lower thresholds: P-wave production.)

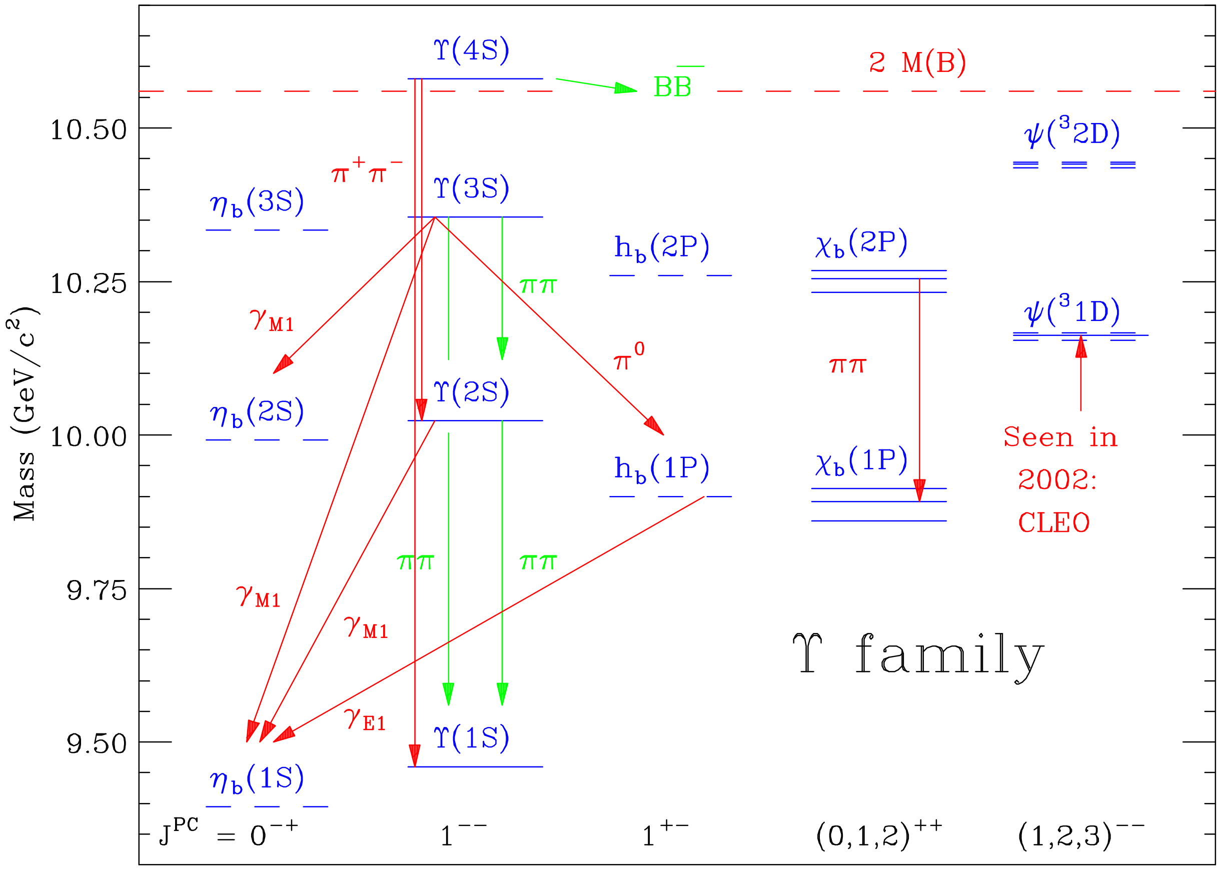
This channel is the expected decay of $Y(4260)$ if it is a hybrid. But it is closed, so other modes (such as $\pi\pi J/\psi$) may be favored instead.

Many other dips are correlated with thresholds [e.g., in $\pi\pi$ S-wave near $2M(K)$; $\gamma^* \to 6\pi$ near $2M(p)$; see PR D **74**, 076006 (2006).]

Dip in $e^+e^- \to D^*\bar{D}^*$ (major charm channel) [Belle PRL **98**, 092001] at 4250 MeV

$Y(4320) \to \pi^+\pi^-\psi(2S)$ [BaBar PRL **98**, 212001]: M=4324±24, Γ=172±33 MeV

Υ STATES



Masses $\surd$ unquenched lattice QCD [G. P. Lepage, Ann. Phys. **315**, 193 (2005)].

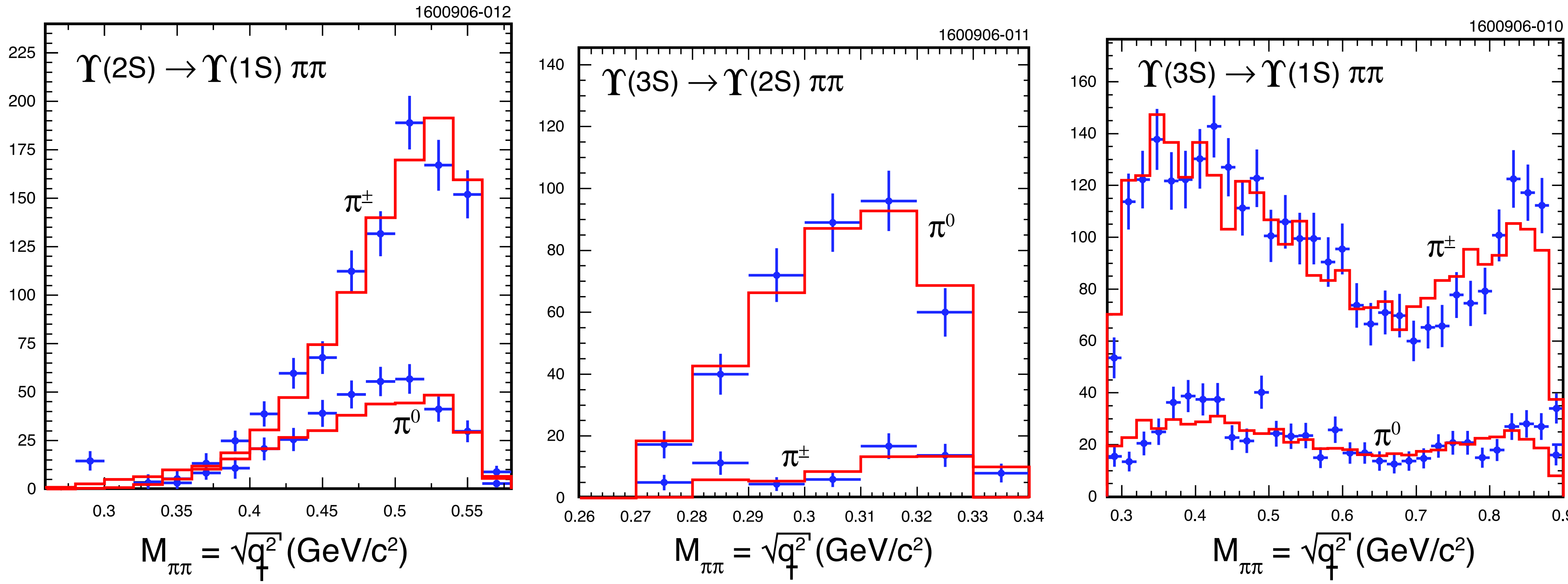
Transitions $\chi_b(2P) \to \pi\pi\chi_b(1P)$ [PR D **73**, 012003 (2006)]. Lattice: rates?

BaBar, PRL **96**, 232001 (2006): $\Gamma[\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)] = (1.8 \pm 0.4)$ keV; $\Gamma[\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)] = (1.7 \pm 0.5)$ KeV with CLEO $\mathcal{B}_{\mu\mu}(2S)$ [$M_{\pi\pi}$: camel]

Belle, hep-ex/0512034: $\mathcal{B}[\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)] = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$

$M(\pi\pi)$ SPECTRA (CLEO)

PR D **76**, 072001 (2007)



Typical spectra in $\psi(2S) \to \pi\pi J/\psi$, $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ are peaked at high $M(\pi\pi)$

This has usually been ascribed to an "Adler zero" associated with couplings of soft pions to other matter with factors p_π/f_π which vanish as $p_\pi \to 0$.

However, $M(\pi\pi)$ spectrum in $\Upsilon(3S) \to \pi\pi\Upsilon(1S)$ has a double-hump ("camel") structure. Nodes in wave functions; coupled channels?

This appears to be so for $\Upsilon(4S) \to \pi\pi\Upsilon(2S)$ whereas $\Upsilon(4S) \to \pi\pi\Upsilon(1S)$ spectrum peaks at high $M(\pi\pi)$. $\Upsilon(5S) \to \pi\pi\ (1S, 2S, 3S), K\bar{K}\ 1S$: Belle, arXiv:0710.2517

CLEO Υ REMEASUREMENTS

New $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$ [PRL **94**, 012001]; $\Gamma_{ee}(nS)$ values [PRL **96**, 092003] agree with lattice *ratios* (absolute values?); lead to lower $\Gamma_{\rm tot}(2S, 3S)$:

State	$B_{\mu\mu}(\%)$	$\Gamma_{ee}(\mathrm{keV})$	$\Gamma_{\rm tot}(\mathrm{keV})$
$\Upsilon(1S)$	$2.49 \pm 0.02 \pm 0.07$	$1.354 \pm 0.004 \pm 0.020$	$54.4 \pm 0.2 \pm 0.8 \pm 1.6$
$\Upsilon(2S)$	$2.03 \pm 0.03 \pm 0.08$	$0.619 \pm 0.004 \pm 0.010$	$30.5 \pm 0.2 \pm 0.5 \pm 1.3$
$\Upsilon(3S)$	$2.39 \pm 0.07 \pm 0.10$	$0.446 \pm 0.004 \pm 0.007$	$18.6 \pm 0.2 \pm 0.3 \pm 0.9$

Potential models do better with Γ_{ee} ratios than with absolute values

Combine with new $\Upsilon(2S, 3S) \to \gamma\chi_{bJ}(1P, 2P)$ branching ratios [CLEO, PRL **94**, 032001] for E1 transition rates (a); vs. NR prediction of PR D **38**, 3179 (b):

	Γ (keV), $2S \to 1P_J$ transitions			Γ (keV), $3S \to 2P_J$ transitions		
	$J = 0$	$J = 1$	$J = 2$	$J = 0$	$J = 1$	$J = 2$
(a)	1.14±0.16	2.11±0.16	2.21±0.16	1.26±0.14	2.71±0.20	2.95±0.21
(b)	1.39	2.18	2.14	1.65	2.52	2.78

$J = 0$ suppression 10–20% agrees with relativistic predictions [PR D **28**, 1132; *ibid.* **28**, 1692]; can lattice calculate such effects?

$\Gamma(3S \to 1P_0) = 64 \pm 23$ eV, 9× prediction: less suppressed than anticipated.

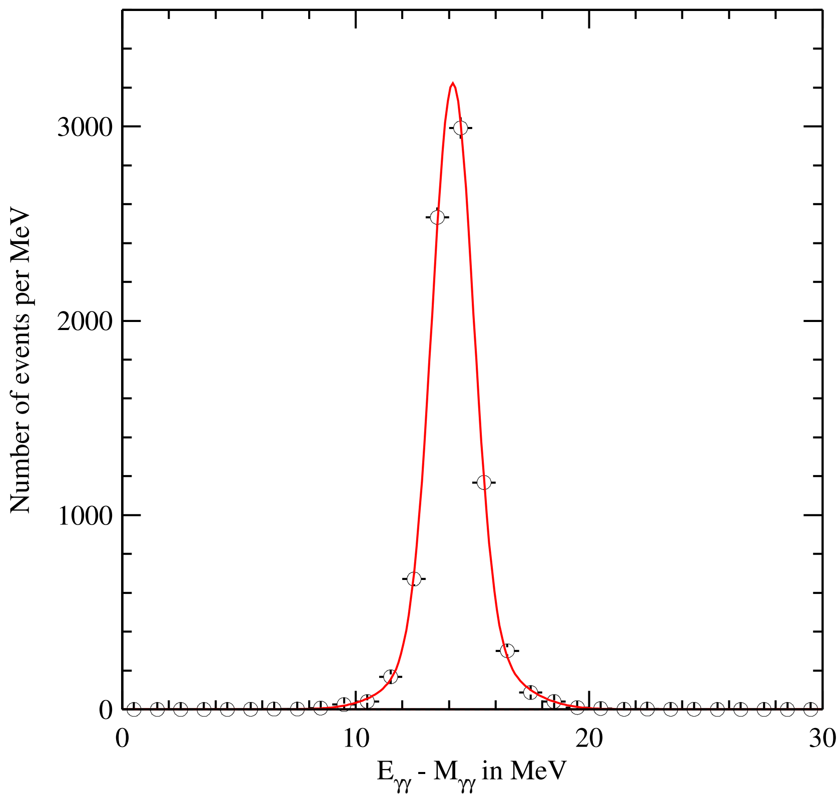
$\Upsilon(2S) \to (\eta, \pi^0)\Upsilon(1S)$

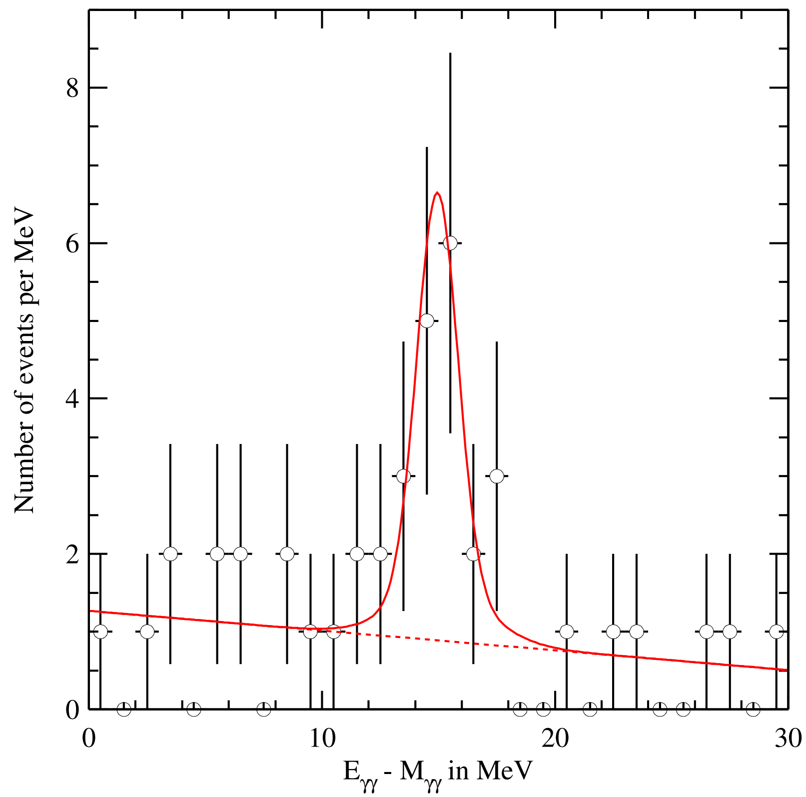
Using scaling laws $\Gamma \sim (p^*)^3/m_Q^4$, Yan 1980, Kuang 2006 predict

$$R' \equiv \frac{\Gamma[\Upsilon(2S)\to\eta\Upsilon(1S)]}{\Gamma[\psi(2S)\to\eta J/\psi(1S)]} = 0.0025 \ , \quad R'' \equiv \frac{\Gamma[\Upsilon(3S)\to\eta\Upsilon(1S)]}{\Gamma[\psi(2S)\to\eta J/\psi(1S)]} = 0.0013 \ ,$$

$\mathcal{B}[\Upsilon(2S,3S) \to \eta\Upsilon(1S)] = (8.1 \pm 0.8,\ 6.7 \pm 0.7) \times 10^{-4}$

$\Upsilon(2S) \to \eta(\to \gamma\gamma)\Upsilon(1S)$ Monte Carlo: Data (CLEO preliminary):





Rate $\simeq$ 1/4 of Yan/Kuang prediction. $\mathcal{B}[\Upsilon(2S) \to \pi^0\Upsilon(1S)] < 1.6 \times 10^{-4}$

$b\bar{b}$ SPIN SINGLETS

No $b\bar{b}$ spin-singlets have been seen yet.

Lattice: predict (i) hyperfine splittings and rates for (ii) allowed M1 transitions; (iii) forbidden M1 transitions; (iv) hadronic transitions (many listed below)

Expect 1S, 2S, 3S hyperfine splittings to be approximately 60, 30, 20 MeV; Lowest P-wave singlet state ("h_b") expected to be near $\langle M(1^3P_J)\rangle \simeq 9900$ MeV/c^2

Several searches have been performed or are under way in 1S, 2S, 3S CLEO data

Searches for $\eta_b(nS)$

Direct search using allowed (soft) M1 photon in $\Upsilon(1S) \to \gamma\eta_b(1S)$: Reconstruct exclusive final states in $\eta_b(1S)$ decays. Likely to be high-multiplicity.

Searches for suppressed M1 photons in $\Upsilon(n'S) \to \gamma\eta_b(nS)$ $(n \neq n')$

η_b searches using sequential processes $\Upsilon(3S) \to \pi^0 h_b(1^1P_1) \to \pi^0\gamma\eta_b(1S)$, $\Upsilon(3S) \to \gamma\chi'_{b0} \to \gamma\eta\eta_b(1S)$, and $\Upsilon(3S) \to \omega\eta_b(1S)$

Additional searches for h_b

$\Upsilon(3S) \to \pi^+\pi^- h_b$ [typical upper bound $\mathcal{O}(10^{-3})$], possible $h_b \to \gamma\eta_b$ (40%).

FUTURE PROSPECTS

CLEO has about 800 pb^{-1} at 3770 MeV and hopes to have 650 pb^{-1} at 4170 MeV by end of running in March 2008

24.5 million $\psi(2S)$ (about 8 times the previous CLEO sample) were collected in summer 2006; analyses of 21M $\Upsilon(1S)$, 9M $\Upsilon(2S)$, 6M $\Upsilon(3S)$ still in progress.

Belle has taken 2.9 fb^{-1} of data at $\Upsilon(3S)$ for "invisible" decays of $\Upsilon(1S)$ [CLEO search] tagged via $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ but potentially valuable for spectroscopy. BaBar is considering a 3S run. CLEO has (1.1, 1.2, 1.2) fb^{-1} at 1S, 2S, 3S.

Spectroscopy at $\psi(2S)$ bears further rich promise:

- M2/E1 ratios in $\chi_{c1,2} \to \gamma J/\psi \Rightarrow$ charmed quark magnetic moment
- Exclusive χ_c decays: potentially fertile ground for hybrids, glueballs
- One (tagged via $\pi^+\pi^-$) J/ψ decay for every 4–5 $\psi(2S)$: Simultaneously study exclusive decays of J/ψ and $\psi(2S)$ to same final states, guard against kinematic reflections.

SUMMARY

Hadron spectroscopy is providing both long-awaited states like h_c and surprises like low-lying P-wave D_s mesons and $c\bar{c}$ states with light-quark admixtures like X(3872).

Many states are more understandable when light-quark degrees of freedom are included. Evidence for molecules, 3S, 2P, 4S or hybrid charmonium, interesting decays of states above flavor threshold.

QCD may not be the only strongly coupled theory with which we have to deal. Electroweak symmetry breaking or quark/lepton structure may require related techniques.

Although lattice QCD probably cannot say much, a big gap in our understanding is how heavy hadrons fragment to multiparticle states. For example, how does η_b decay?

Lattice gauge theories will have to cope with interplay of light- and heavy-quark degrees of freedom to satisfactorily describe the variety of phenomena in heavy quark spectra. Progress in unquenched lattice QCD is a good sign that this effort is under way.

$\psi''(3770)$ DECAYS

Cross sections (nb) for charm production at $\psi''(3770)$:

Collaboration	$\sigma(D^+D^-)$	$\sigma(D^0\bar{D}^0)$	$\sigma(D\bar{D})$
BES-II	$2.56 \pm 0.08 \pm 0.26$	$3.58 \pm 0.09 \pm 0.31$	$6.14 \pm 0.12 \pm 0.50$
CLEO	$2.79 \pm 0.07^{+0.10}_{-0.04}$	$3.60 \pm 0.07^{+0.07}_{-0.05}$	$6.39 \pm 0.10^{+0.17}_{-0.08}$
Mark III	2.1 ± 0.3	2.9 ± 0.4	5.0 ± 0.5

$\sigma(\psi'')$ seemed $> \Sigma(D\bar{D})$ [see also BES, PL B**641**, 145 and PRL **97**, 121801]; CLEO [PRL **96**, 092002] says $\sigma(\psi'') = (6.38 \pm 0.08^{+0.41}_{-0.30})$ nb $\simeq \sigma(D\bar{D})$.

$\psi'' \to XJ/\psi$: CLEO, PRL:

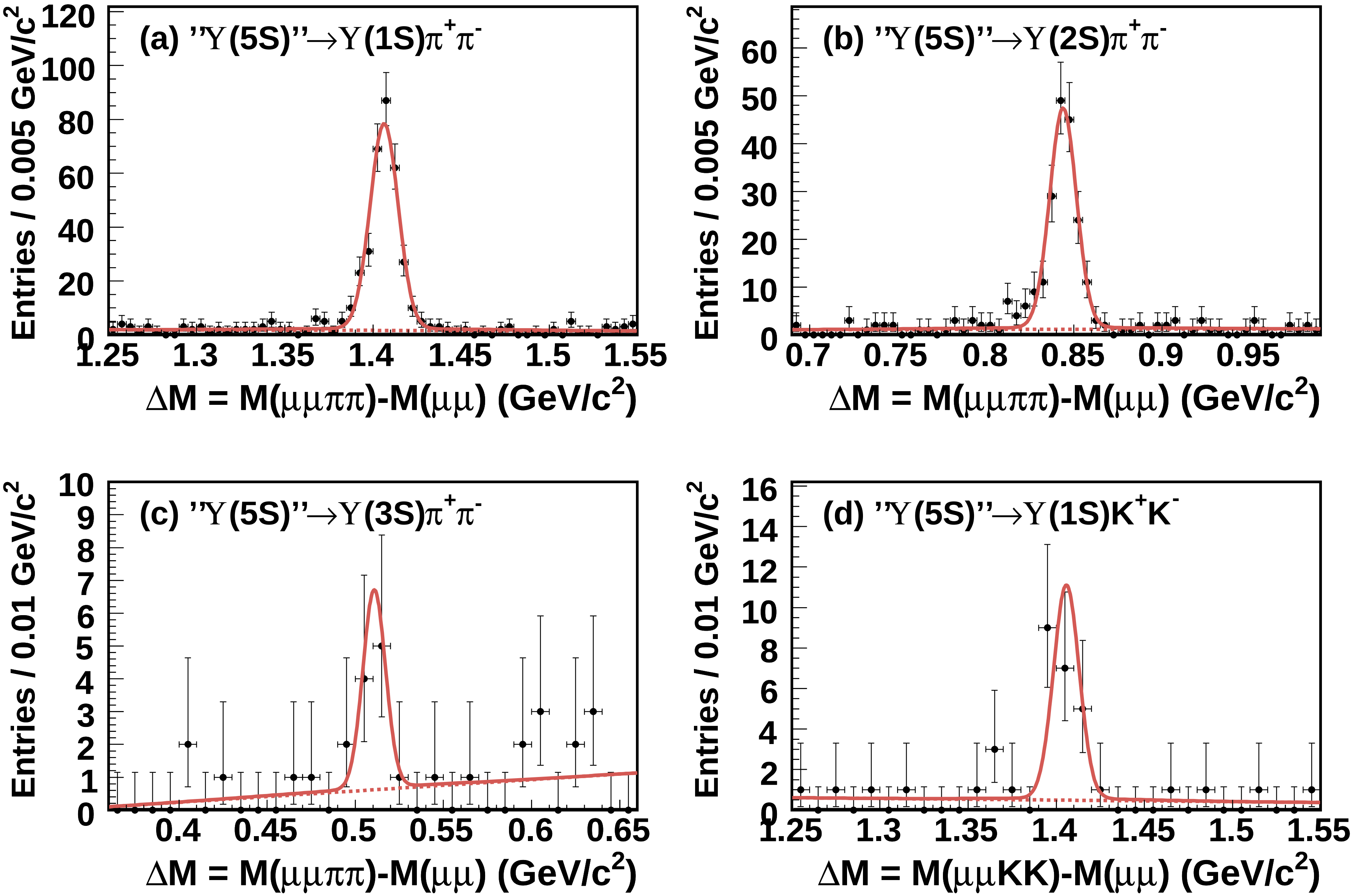
ψ'' mode	$\mathcal{B}$ (%)
$\pi^+\pi^-J/\psi$	0.189±0.020±0.020
$\pi^0\pi^0J/\psi$	0.080±0.025±0.016
$\eta J/\psi$	0.087±0.033±0.022
π^0J/ψ	< 0.028

$\psi'' \to \gamma\chi_{cJ}$ partial widths:

Mode	Predicted (keV) (a)	(b)	(c)	CLEO (PRD **74**, 031106)
$\gamma\chi_{c2}$	3.2	3.9	24±4	< 21
$\gamma\chi_{c1}$	183	59	73 ± 9	75 ± 18
$\gamma\chi_{c0}$	254	225	523±12	172 ± 30

Eichten-Lane-Quigg PR D **69**: (a) without, (b) with coupling to open channels; (c): JLR, Ann. Phys. **319**, 1 (2005). Non-$D\bar{D}$ modes at most a percent or two: negative exclusive searches [Yelton; PR D **73**, 012002; PRL **96**, 032003 (2006)]

$\Upsilon(5S)$ TRANSITIONS (BELLE)



Rates are much greater than anticipated; role of open channels?