HADRON SPECTROSCOPY

J. Rosner (U. Chicago) – CIPANP – June 1, 2006

Dedicated to the memory of R. H. Dalitz

QCD is our theory of the strong interactions. However, we are far from understanding how it works in many important cases.

Many hadrons discovered recently have puzzling properties.

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: Be prepared for LHC surprises.

At the quark and lepton level: An intricate level structure and a set of transitions among these levels for which we have no fundamental understanding. Sharpening spectroscopic techniques may help.

Today's topics:
Light-quark (and no-quark) states, charmed and beauty hadrons, heavy quarkonium ($c\bar{c}$, $b\bar{b}$), future prospects.

LIGHT-QUARK STATES

The QCD scale is ~ 200 MeV (momentum) or ~ 1 fm (distance). At this scale perturbation theory cannot be used. Non-perturbative methods include:

- Lattice gauge theories (discrete space-time) $\Leftarrow$ eventual tool of choice
- Chiral dynamics (soft pions; chiral solitons; parity doubling [Jaffe])
- Heavy quark symmetry (hadrons with one charm or beauty quark as QCD "hydrogen" or "deuterium" atoms)
- Correlations among quarks (e.g., diquarks); new states they imply (Karliner-Lipkin $bq\bar{c}\bar{q}'$; Jaffe-Wilczek; Selem-Wilczek)
- Potential descriptions (with relativistic corrections, coupled channels)
- QCD sum rules (a means of averaging over resonances)

I will describe phenomena to which these methods might be applied.

LIGHT-QUARK ISSUES

1) Nature of the low-energy S-wave $\pi\pi$ and $K\pi$ interactions

An S-wave $\pi\pi$ low-mass correlation in the $I = 0$ channel ("σ") has been used to describe nuclear forces. Is it a resonance? What is its quark content?

Is there a corresponding low-energy $K\pi$ correlation ("κ")?

What can we learn about σ, κ from charm and beauty decays? [Oller PR D **71**]

2) Can we understand $dips$ as well as bumps?

Seen frequently when new channel opens (e.g., $\pi\pi$ S-wave at $K\bar{K}$ threshold).

Other examples occur in Dalitz plots for charmed and beauty meson decays.

Thresholds may play a role in "molecule" or bound state formation.

3) QCD predicts gluonic excitations. Can we see them?

Zero-quark states: "glueballs". States with quarks and gluons: "hybrids"

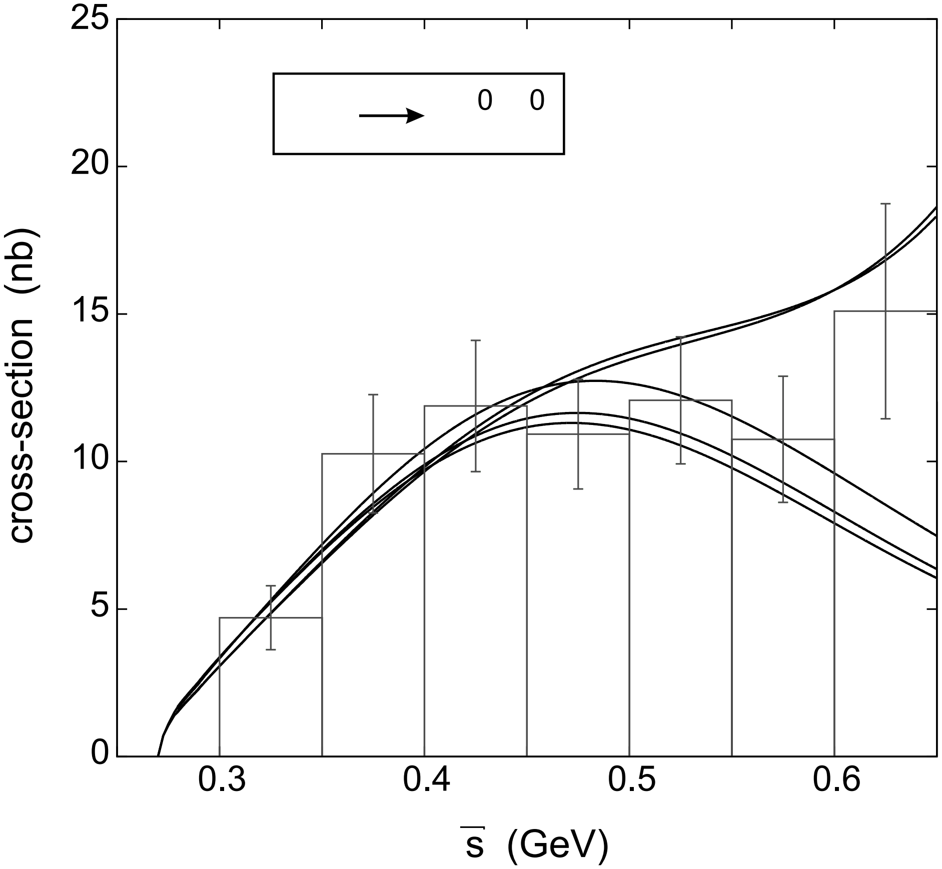
Glueballs can mix with $q\bar{q}$, $qq\bar{q}\bar{q}, \ldots$ configurations; must understand them.

Hybrids (e.g. $q\bar{q}g$) may have distinctive J^{PC} properties, decay modes.

LOW-ENERGY $\pi\pi$ S WAVE

$\sigma = f_0(600)$ and its interpretation

Dynamical $I = J = 0$ resonance in $\pi\pi \to \pi\pi$ from current algebra, crossing symmetry, unitarity (Brown & Goble 1971). Pole with large imaginary part occurs at or below m_ρ. Effects differ in $\pi\pi \to \pi\pi$ (Adler zero) and (e.g.) $\gamma\gamma \to \pi\pi$ [R. Goble and JLR, PR **D5** (1972); R. Goble, R. Rosenfeld, and JLR, PR D **39** (1989)].



M. Pennington (hep-ph/0604212): Crossing symmetry implemented *à la* S. M. Roy [PL **36B** (1971)]

σ pole at $441 - i272$ MeV

Obtain $\Gamma(\sigma \to \gamma\gamma) = (4.1 \pm 0.3)$ keV

M. P. interprets as ordinary $q\bar{q}$ state (or just $\pi\pi$ dynamical resonance?)

FNAL E-791: $D^+ \to \sigma\pi^+ \to \pi^+\pi^-\pi^+$

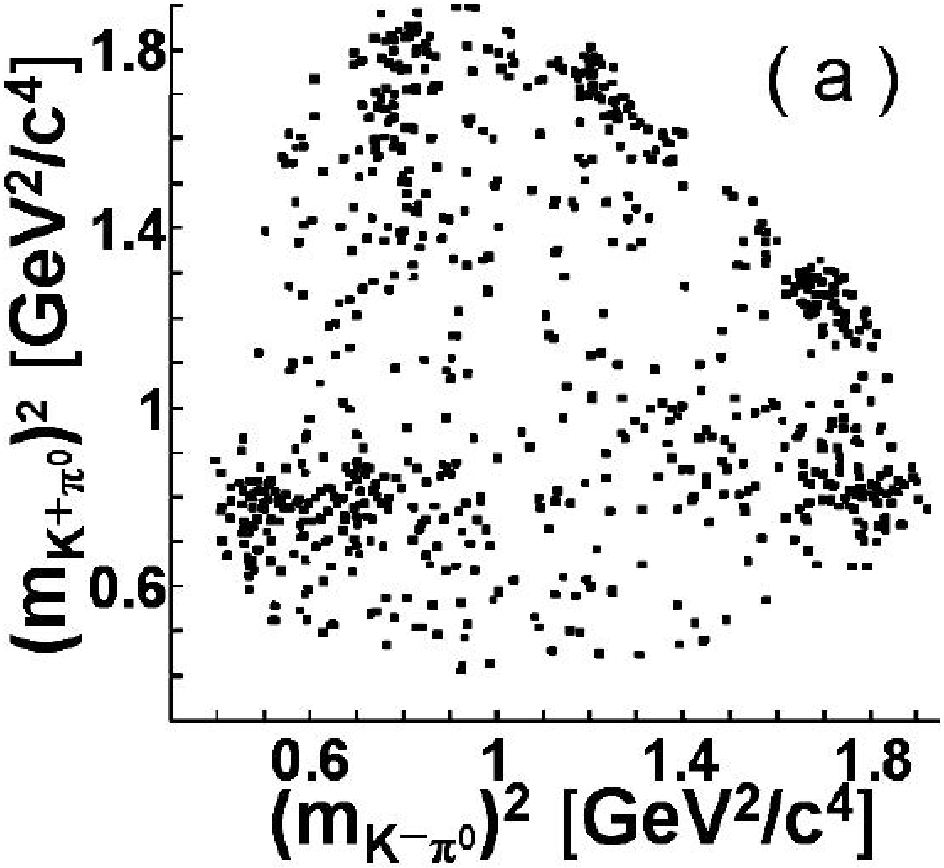
BES: $J/\psi \to \omega\pi^+\pi^-$ $(M - i\Gamma/2 = 541 - i252$ MeV [PL B **598**, 149]

Many final states can be fit *without* σ: depends on production.

LOW-ENERGY $K\pi$ S-WAVE

Can $I = 1/2$, $J = 0$ resonance be generated dynamically in $K\pi$ system? Low-energy chiral interaction is favorable; same sign of scattering length as $I = J = 0$ $\pi\pi$.

Fermilab E791 [PR D **73**, 032004 (2006)]: $D^+ \to K^-\pi^+\pi^+ \Rightarrow M_\kappa = 780 \pm 15$ MeV, $\Gamma_\kappa = 371 \pm 36$ MeV $(I = 1/2,\ J = 0)$ in an isobar fit (☹ Watson's Theorem). BES sees $\kappa(878)$ in $J/\psi \to \bar{K}^* K^+ \pi^-$: PL B **633**, 681 (2006).



κ optional in recent fit to $D^0 \to K^+K^-\pi^0$ Dalitz plot: P. Naik, April 2006 APS Mtg

Bands: Vert. K^{*-}; hor. K^{*+}; diag. ϕ

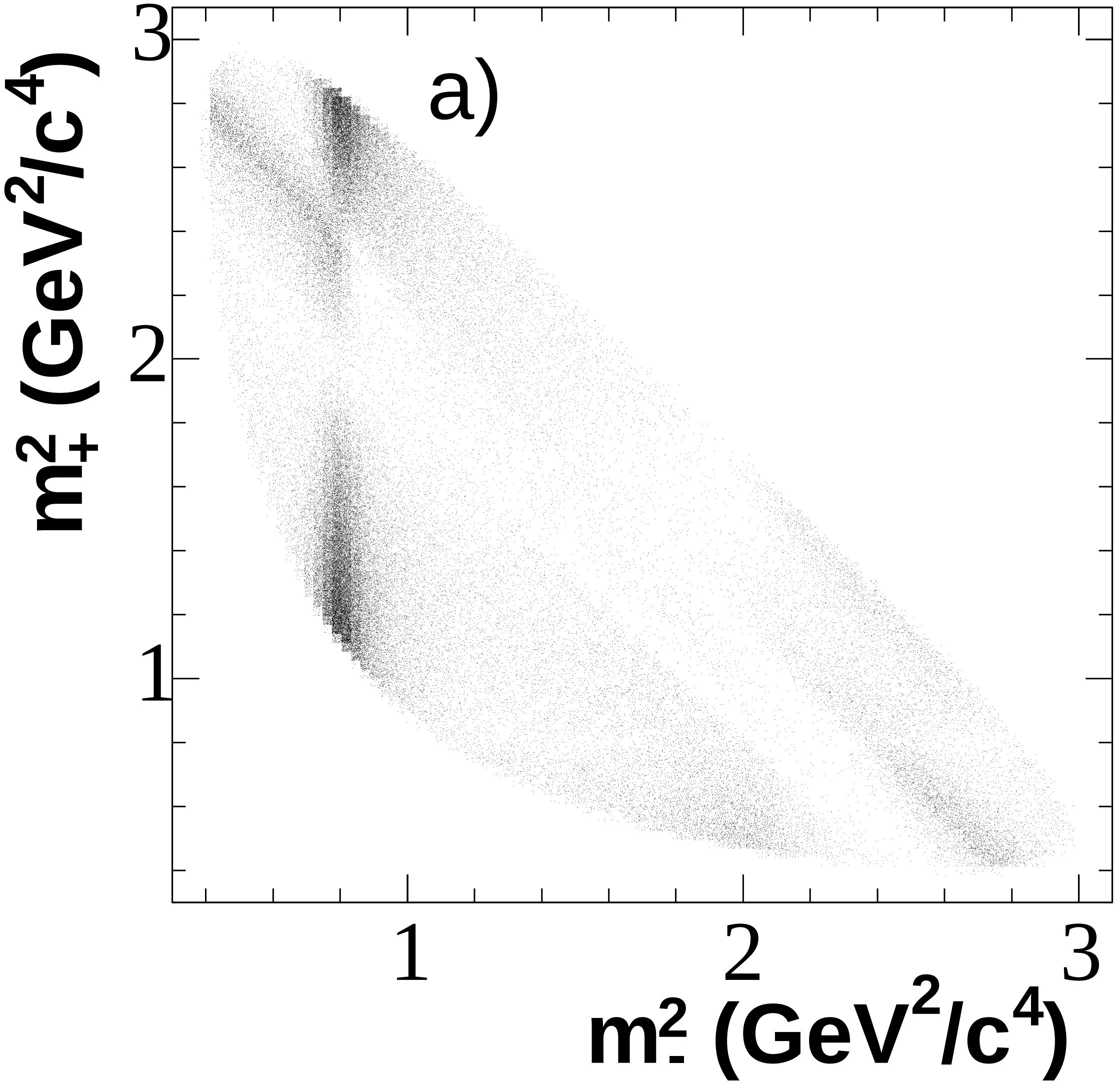
S-wave (NR or κ), interfering with K^{*+} and K^{*-} with opposite signs (e.g., on left and bottom) of plot

Depopulated regions at $m(K^\pm\pi^0) \simeq$ 1 GeV$/c^2$ may be due to $K\pi^0 \to K\eta$.

Need a $D^0 \to K^+K^-\eta$ Dalitz plot.

DIPS AND EDGES

$D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot: BaBar, PRL **95**, 121802 (2005); hep-ex/0507101 [see also Belle, Moriond 2006; CLEO PR D **70**, 091101(R) (2004)]:



Vertical band: K^{*-}; diagonal: ρ^0

Note sharp edges (diagonals) in $\pi^+\pi^-$ spectrum, due to S-wave $\pi^+\pi^- \leftrightarrow K^+K^-$

Depopulation just below $m_{\pi\pi} = 1$ GeV$/c^2$ followed by strong band (diagonal) around 1 GeV$/c^2$

Rapid amplitude variation occurs when new S-wave channel opens.

More dips: $\gamma \to 6\pi$ photoprod. at $\bar{p}p$ threshold; $R_{e^+e^-}$ below 4260 MeV; $B^\pm \to K^\pm K^\mp K^\pm$ (BaBar, hep-ex/0605003): $K^*\bar{K}^*$?

GLUEBALL PROPERTIES

Quarkless states from pure-glue configurations: $F^a_{\mu\nu}$ = gluon field-strength tensor (a = color index); form $J^{PC} = 0^{++}$ states as $F^a_{\mu\nu}F^{a\mu\nu}$, 0^{-+} as $F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$, higher spin with derivatives or > 2 gluon fields.

All such states should be flavor-singlet (isospin $I = 0$; but Chanowitz argues $s\bar{s}$ may be favored).

KLOE $\mathcal{B}(\phi \to \eta'\gamma) \Rightarrow \eta'$ is gluonic $(8 \pm 2)\%$ of the time [S. Giovanella, Tues.]

Lattice QCD: Lowest "glueball" state is 0^{++} with $M \simeq 1.7$ GeV.

At this mass there are many other $I = 0$ levels with which such a state can mix, e.g., $q\bar{q}$, $q\bar{q}g$ (g = gluon), $qq\bar{q}\bar{q}$, etc.

Study $I = 0$ levels, mesonic couplings to separate out glueball, $(u\bar{u} + d\bar{d})/\sqrt{2}$, and $s\bar{s}$ components. Understanding the *flavored* $q\bar{q}$ spectrum for the same J^P is crucial.

Best 0^{++} candidates are at 1370, 1500, 1700 MeV; explore flavor structure via their $\gamma(\rho, \omega, \phi)$ decays (Close-Zhao). CLEO search in $\Upsilon(1S) \to \gamma X$: no evidence.

HYBRIDS AND CANDIDATES

What quantum numbers are forbidden for $q\bar{q}$ but allowed for $q\bar{q}g$?

For $q\bar{q}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, so $CP = (-1)^{S+1}$

Forbidden $q\bar{q}$ states are then 0^{--} and 0^{+-}, 1^{-+}, $2^{+-}, \ldots$

Quenched lattice QCD: Lightest exotic hybrids have $J^{PC} = 1^{-+}$ and $M(n\bar{n}g) \simeq 1.9$ GeV, $M(s\bar{s}g) \simeq 2.1$ GeV, with errors 0.1–0.2 GeV. Unquenched QCD must treat mixing with $qq\bar{q}\bar{q}$ and meson pairs.

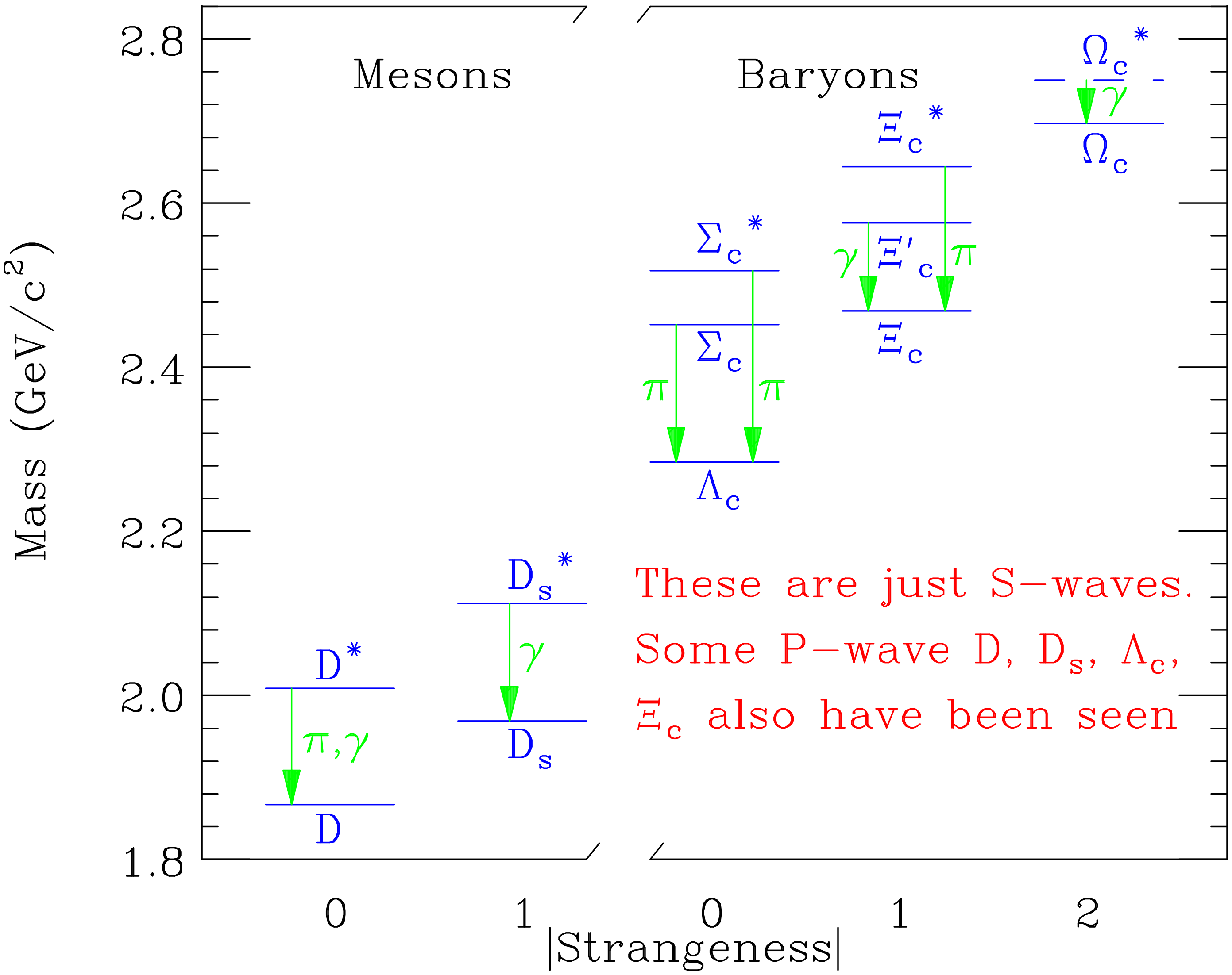
Candidates include $\pi_1(1400)$ (seen in some $\eta\pi$ final states, e.g., in $p\bar{p}$ annihilations) and $\pi_1(1600)$ (seen in 3π, $\rho\pi$, $\eta'\pi$).

Partial wave analysis by A. Dzierba $+$, PR D **73**, 072001 [BNL E-852 subset] does not require $\pi_1(1600)$ if a $\pi_2(1670)$ contribution [orbital excitation of the $\pi(140)$] is assumed.

Favored decays are to $q\bar{q}(L = 0) + q\bar{q}(L = 1)$, e.g., $\pi b_1(1235)$.

Review of glueballs and hybrids: C. Meyer, this Conference.

CHARMED STATES

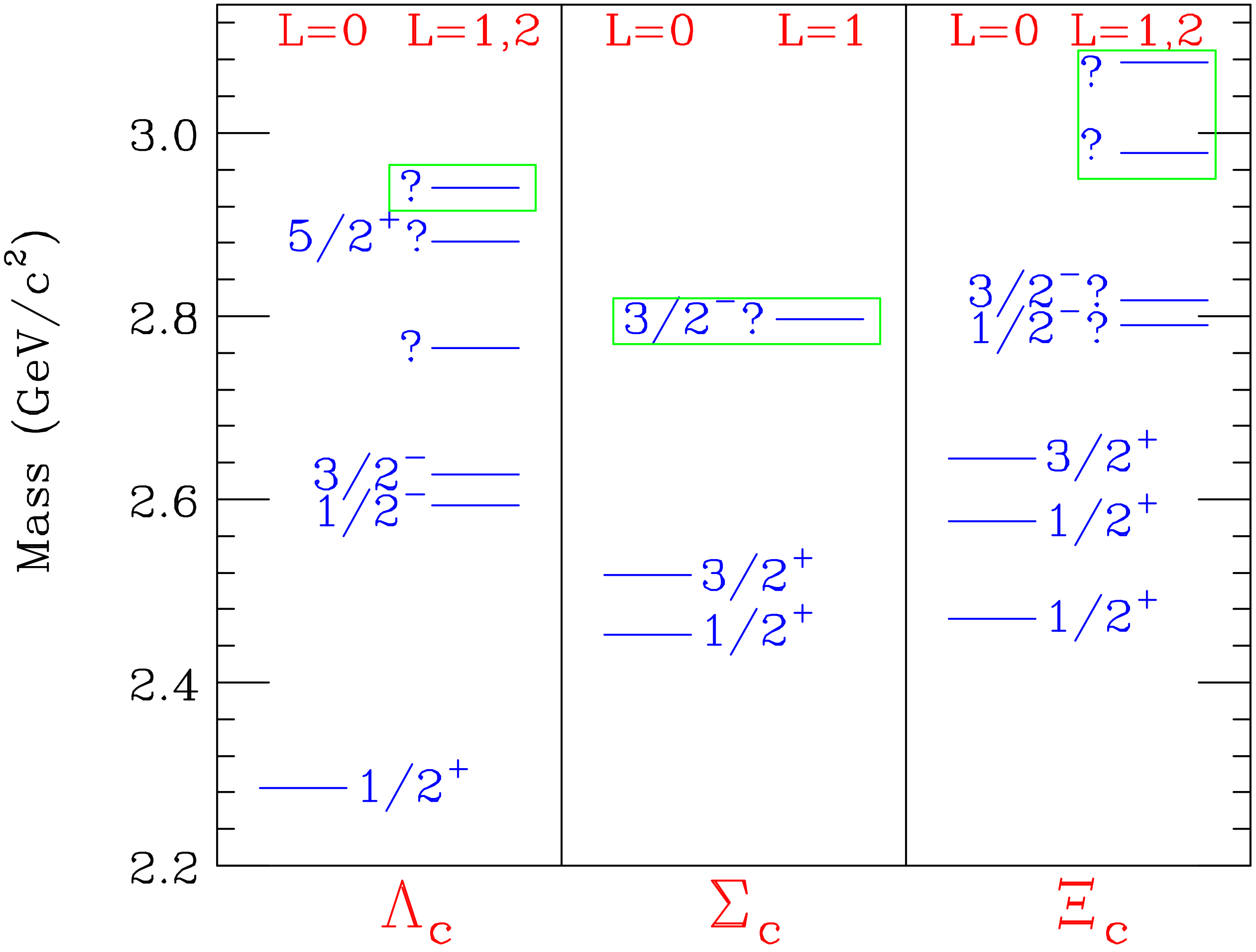


These are just S−waves. Some P−wave D, D_s, Λ_c, Ξ_c also have been seen

Today: charmed baryons; D_{sJ} remarks; skip D and D_s decay constants

⇑ U. Mallik (BaBar); T. Tsuboyama (Belle) ⇑ R. Briere

CHARMED $L > 0$ BARYONS



Many CLEO states

Highest Σ_c, Ξ_c: Belle [462 fb^{-1}, Moriond06]

Highest $\Lambda_c \to D^0 p$: BaBar, hep-ex/0603052

J^P assignments with "?" are speculative (diquark ideas helpful) need J^P analyses

Narrower for higher L?

$\Delta L = 1$: ~ 300 MeV

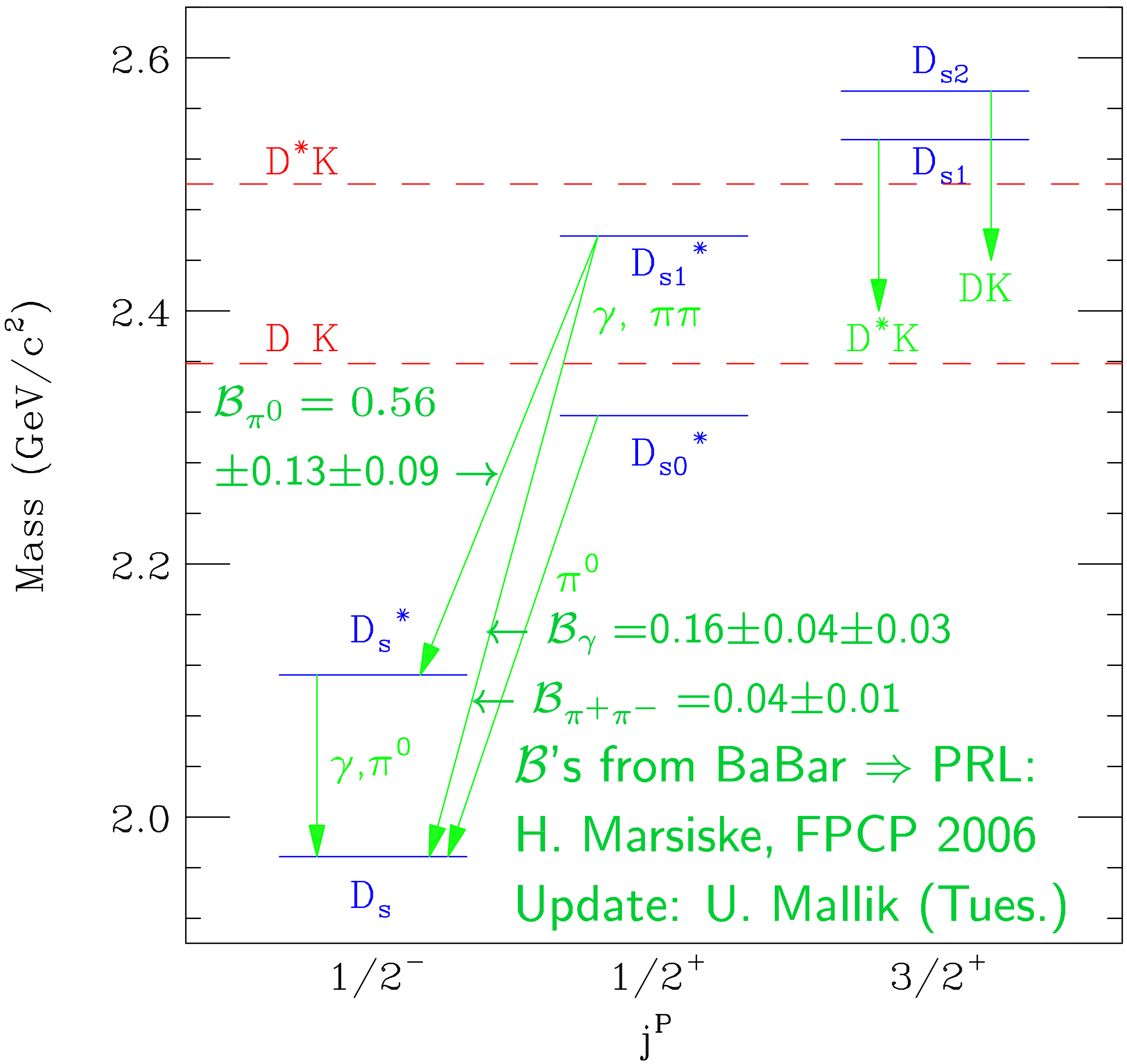
Λ_c and Ξ_c first excitations similar, scale well from first Λ excitations $\Lambda(1405, 1/2^-)$ and $\Lambda(1520, 3/2^-)$: $\sim$ same ΔL cost; $L \cdot S$ splitting scales $\sim 1/m_s$ or $1/m_c$.

Higher Λ_c states: excite spin-zero $[ud]$ pair to $S = L = 1$? Many J^P up to $5/2^-$.

In Σ_c light-quark pair has $S = 1$; adding $L = 1$ allows $J^P \leq 5/2^-$.

REMARKS ON D_{sJ}

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



$\mathcal{B}_{\pi^0} = 0.56$
$\pm$0.13$\pm$0.09 →

← $\mathcal{B}_\gamma$ =0.16$\pm$0.04$\pm$0.03

← $\mathcal{B}_{\pi^+\pi^-}$ =0.04$\pm$0.01

$\mathcal{B}$'s from BaBar ⇒ PRL:
H. Marsiske, FPCP 2006
Update: U. Mallik (Tues.)

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-viol. 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

Light-quark degrees of freedom are important in heavy-quark systems!

D^+, D_s DECAY CONSTANTS

CLEO D^+ decay constant [PRL **95**, 251801 (2005)]: $f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV vs. lattice prediction [PRL **95**, 122002 (2005)]: $201 \pm 3 \pm 17$ MeV

PDG (2004): $f_{D_s} = 267 \pm 33$ MeV, so $f_{D_s}/f_D = 1.20 \pm 0.17$. BaBar value $279 \pm 17 \pm 6 \pm 19$ MeV uses $\mathcal{B}(D_s \to \phi\pi^+) = (4.8 \pm 0.4 \pm 0.5)\%$. May be smaller if $\mathcal{B}(D_s \to \phi\pi^+) = (3.49 \pm 0.39)\%$ (S. Stone, FPCP 2006) is right.

Lattice [PRL **95**, 122002]: $f_{D_s} = 249 \pm 3 \pm 16$ MeV, $f_{D_s}/f_D = 1.24 \pm 0.01 \pm 0.07$.

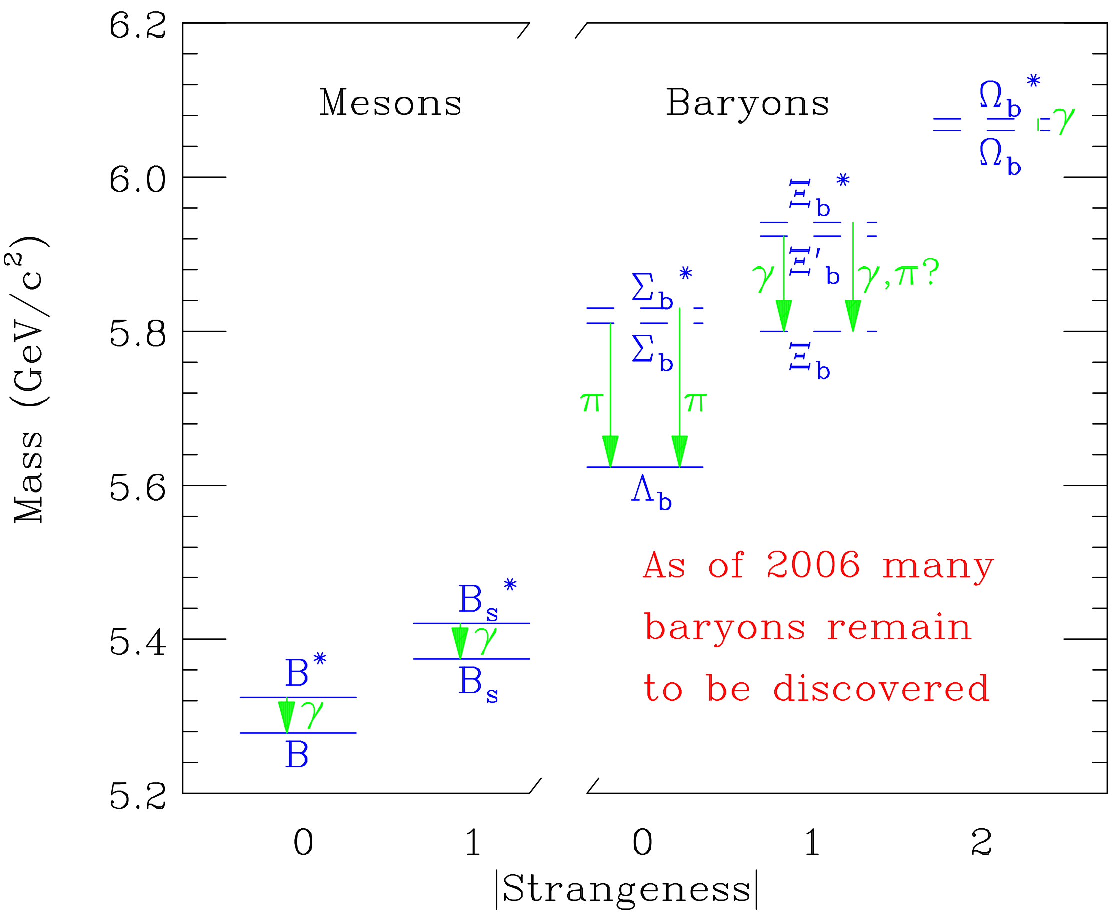
Expect $f_{B_s}/f_B \simeq f_{D_s}/f_D$ so better measurements of f_{D_s} and f_D by CLEO will help validate lattice calculations and provide input for interpreting B_s mixing.

Desirable error on $f_{B_s}/f_B \simeq f_{D_s}/f_D$ is $\leq 5\%$ for useful determination of CKM element ratio $|V_{td}/V_{ts}|$, needing errors ≤ 10 MeV on f_{D_s} and f_D.

$|V_{td}/V_{ts}| = 0.208^{+0.008}_{-0.007}$ from CDF result on B_s–$\overline{B}_s$ mixing combined with B–$\overline{B}$ mixing and $\xi \equiv (f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B}) = 1.21^{+0.047}_{-0.035}$ from lattice (Okamoto +).

Simple scaling argument from quark model anticipated $f_{D_s}/f_D \simeq f_{B_s}/f_B \simeq \sqrt{m_s/m_d} \simeq 1.25$, where $m_s \simeq 485$ MeV and $m_d \simeq 310$ MeV are constituent quark masses: JLR, PR D **42**, 3732 (1990).

BEAUTY HADRONS



As of 2006 many baryons remain to be discovered

CDF: $B_c \to J/\psi\pi^\pm$, M=6275.2±4.3±2.3 MeV. Lattice predicts $6304\pm12^{+18}_{-0}$.

B_s–$\overline{B}_s$ mixing ($D0$: hep-ex/0603029; CDF: $17.33^{+0.42}_{-0.21}\pm 0.07$ ps^{-1}) gives f_{B_s}.

$B \to \tau\nu_\tau \Rightarrow f_B|V_{ub}| = (7.73^{+1.24+0.66}_{-1.02-0.58})\times 10^{-4}$ GeV $\Rightarrow |V_{ub}| = (4.05\pm 0.89)\times 10^{-3}$ using $f_{B_d} = (191\pm 27)$ MeV (Höcker and Ligeti, hep-ph/0605217).

New CDF $\tau(\Lambda_b) = 1.59\pm 0.08\pm 0.03$ ps: A. Kryemadhi (Wed.)

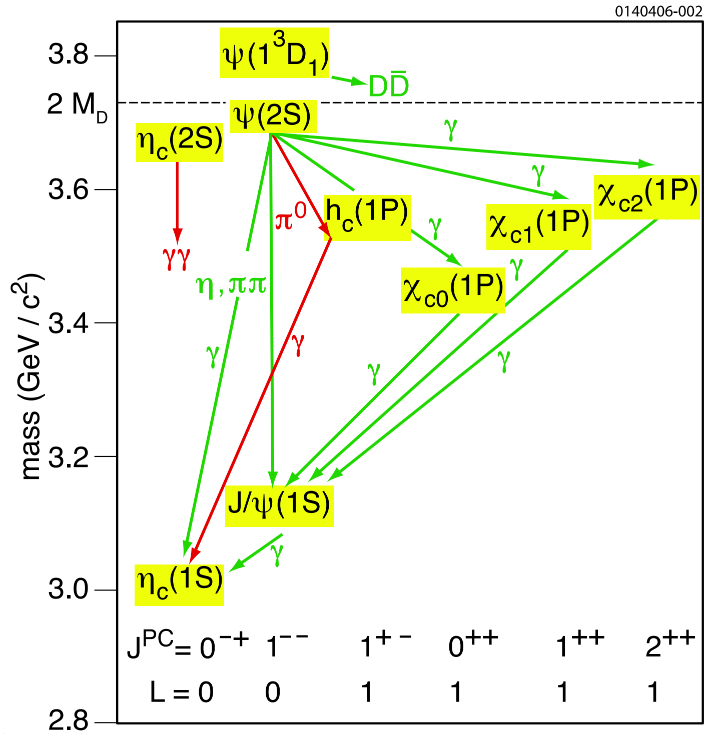
h_c OBSERVATION

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)

Earlier searches: ($\bar{p}p$ direct channel): (1) CERN ISR R704: few evts, 3525.4 ± 0.8 MeV; (2) Fermilab E760: $3526.2 \pm 0.15 \pm 0.2$ MeV → $\pi^0 J/\psi$, not confirmed by (3) Fermilab E835, state at $3525.8 \pm 0.2 \pm 0.2$ MeV → $\gamma\eta_c$ with $\eta_c \to \gamma\gamma$.



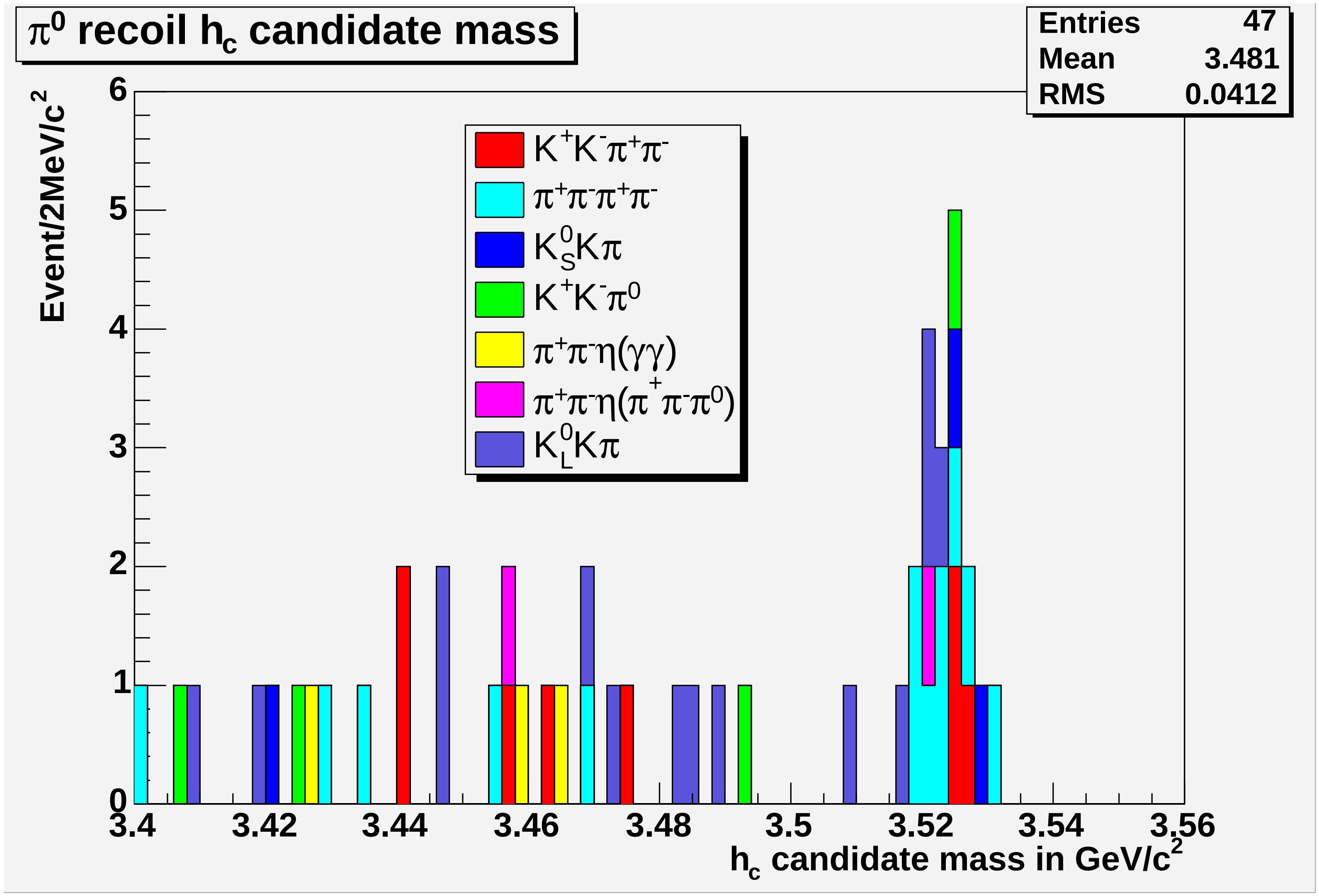
CLEO: Observation in $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ [PRL **95**, 102003 (2005); PRD **72**, 092004 (2005)]

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

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

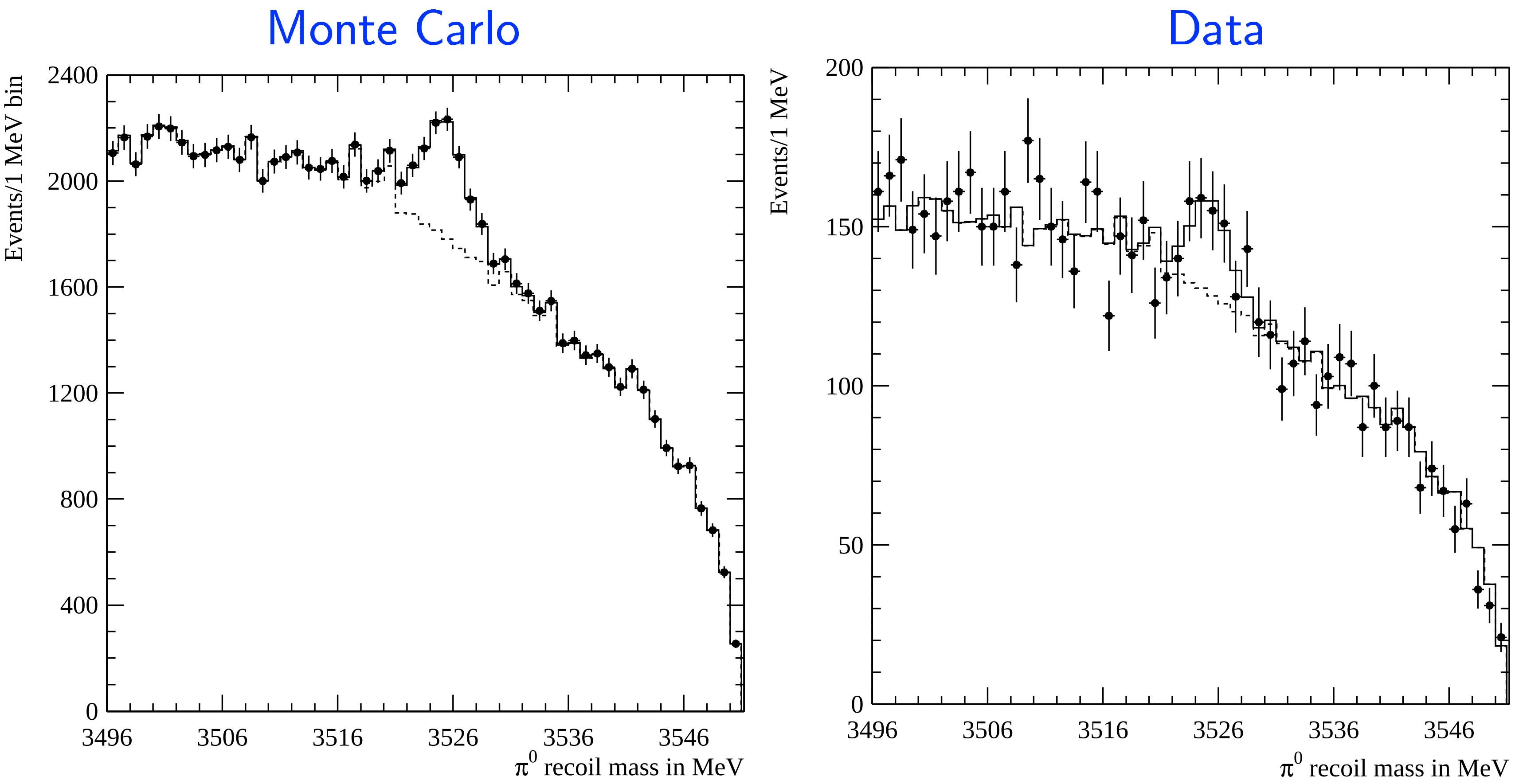
Inclusive: No η_c reconstruction: better statistics but more background

EXCLUSIVE h_c SIGNAL



19 candidates identified; 17.5 ± 4.5 events above background. $M(h_c) = (3523.6 \pm 0.9 \pm 0.5)$ MeV; $\mathcal{B}_1(\psi' \to \pi^0 h_c)\mathcal{B}_2(h_c \to \gamma\eta_c) = (5.3 \pm 1.5 \pm 1.0) \times 10^{-4}$

INCLUSIVE h_c SIGNAL


Monte Carlo

Data

h_c spectra for $M(\eta_c) = 2980 \pm 35$ MeV. Parallel analysis: $E_{\gamma,E1} = 503 \pm 35$ MeV.

$M(h_c) = (3524.9 \pm 0.7 \pm 0.4)$ MeV, $\mathcal{B}_1\mathcal{B}_2 = (3.5 \pm 1.0 \pm 0.7) \times 10^{-4}$

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

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

Martin-Stubbe: Reasonable (nonrelativistic) assumptions $\Rightarrow M(h_c) \geq \langle M(^3P_J)\rangle$.

$\psi''(3770)$ DECAYS

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

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 larger than $\Sigma(D\bar{D})$ [see also BES, hep-ex/060510(5,7)] but new CLEO measurement [PRL **96**, 092002] ⇒ $\sigma(\psi'') = (6.38 \pm 0.08^{+0.41}_{-0.30})$ 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:

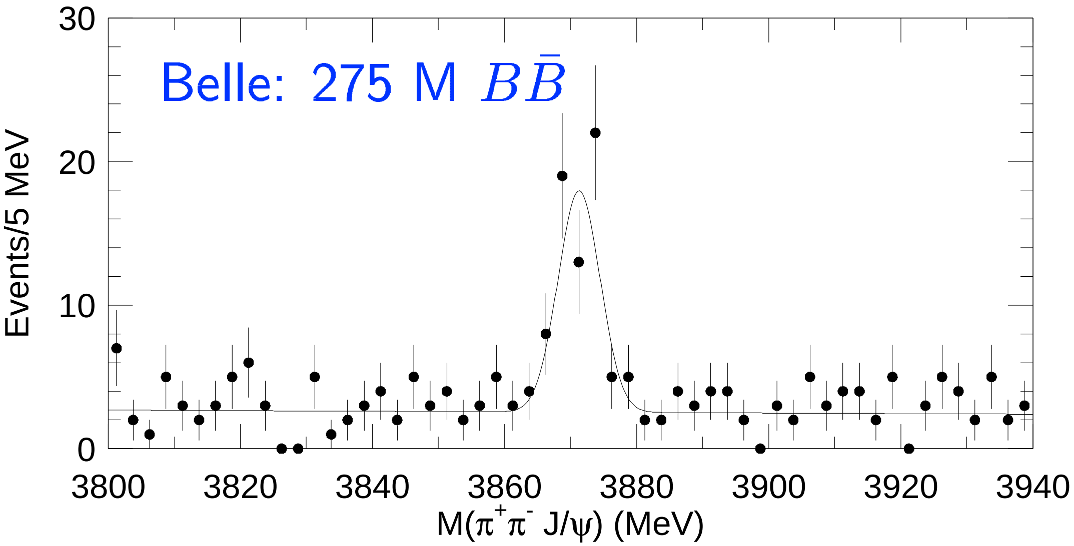
Mode	Predicted (keV)			CLEO (hep-ex/0605070)
	(a)	(b)	(c)	
$\gamma\chi_{c2}$	3.2	3.9	24±4	< 21
$\gamma\chi_{c1}$	183	59	73 ± 9	75 ± 18
$\gamma\chi_{c0}$	254	225	523±12	172 ± 30

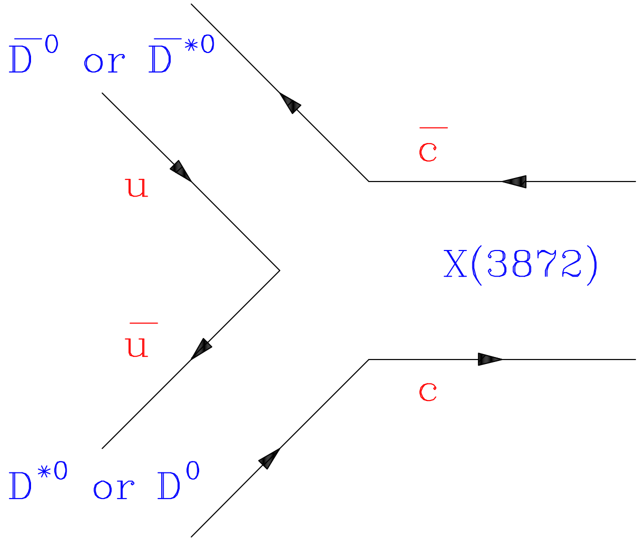
Eichten-Lane-Quigg PR D **69**: (a) without, (b) with coupling to open channels; (c): JLR, Ann. Phys. **319**, 1 (2005). Non-$D\bar{D}$ modes at most a percent or two.

X(3872): 1^{++} MOLECULE

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

Details of J^{PC} conclusion: H. Marsiske, FPCP 2006; E. Swanson (Tues.)





Well above $D\bar{D}$ threshold; favors unnatural $J^P = 0^-, 1^+, 2^-$ ($J \geq 3$ unlikely)

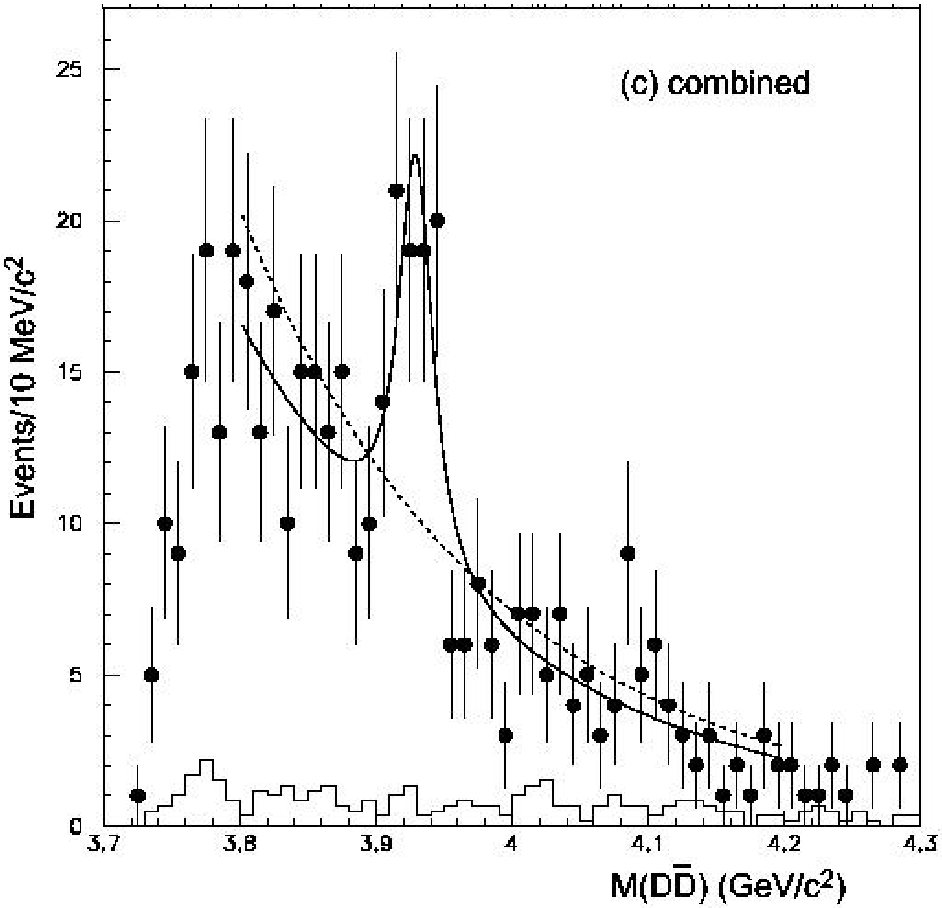
hep-ex/0505038: $J^{PC} = 1^{++}$ favored (angular dists.; $\rho J/\psi$ and $\omega J/\psi$ decays)

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 $\gamma J/\psi$ (hep-ex/0505037) $\Rightarrow$ some $c\bar{c}$ in wave function. BaBar [PRL **96**, 052002 (2006)] finds $\mathcal{B}(\pi^+\pi^- J/\psi) > 0.042$ (90% c.l.).

Two mesons sharing $q, \bar{q}$ always form ≥ 1 resonance below $p_{\rm cm} = 350$ MeV.

EVIDENCE FOR $\chi_{c2}(3931)$

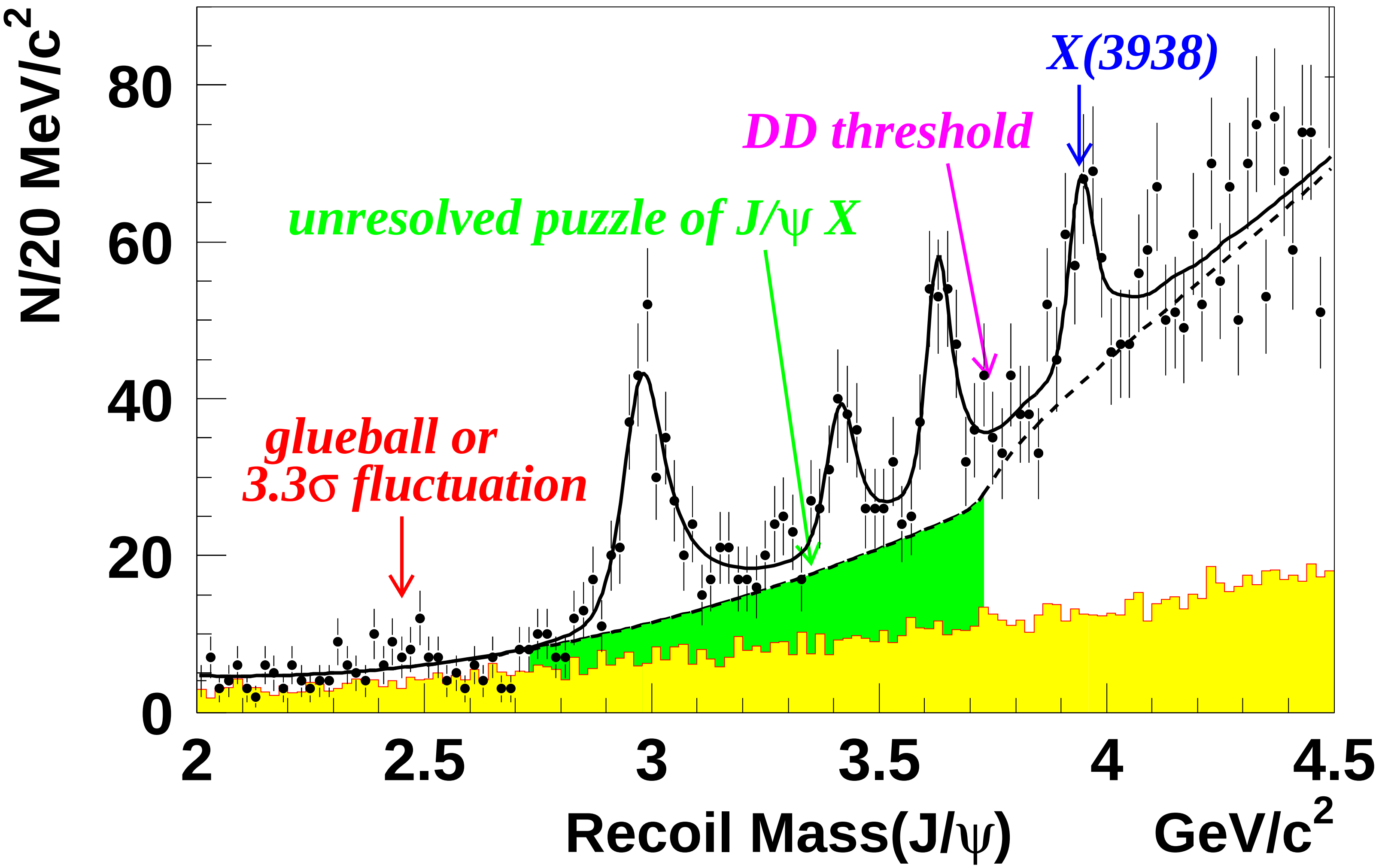
Belle [PRL **96**, 082003 (2006)]: Combined $\gamma\gamma \to D^0\bar{D}^0,\ D^+D^-$ spectrum:



Angular distribution consistent with $\sin^4\theta^*$ $(J = 2, \lambda = \pm 2)$

M =3929±5±2 MeV, Γ =29±10±2 MeV, $\Gamma_{ee}\mathcal{B}(D\bar{D})$ =0.18±0.05±0.03 keV

STATES NEAR 3940 MeV

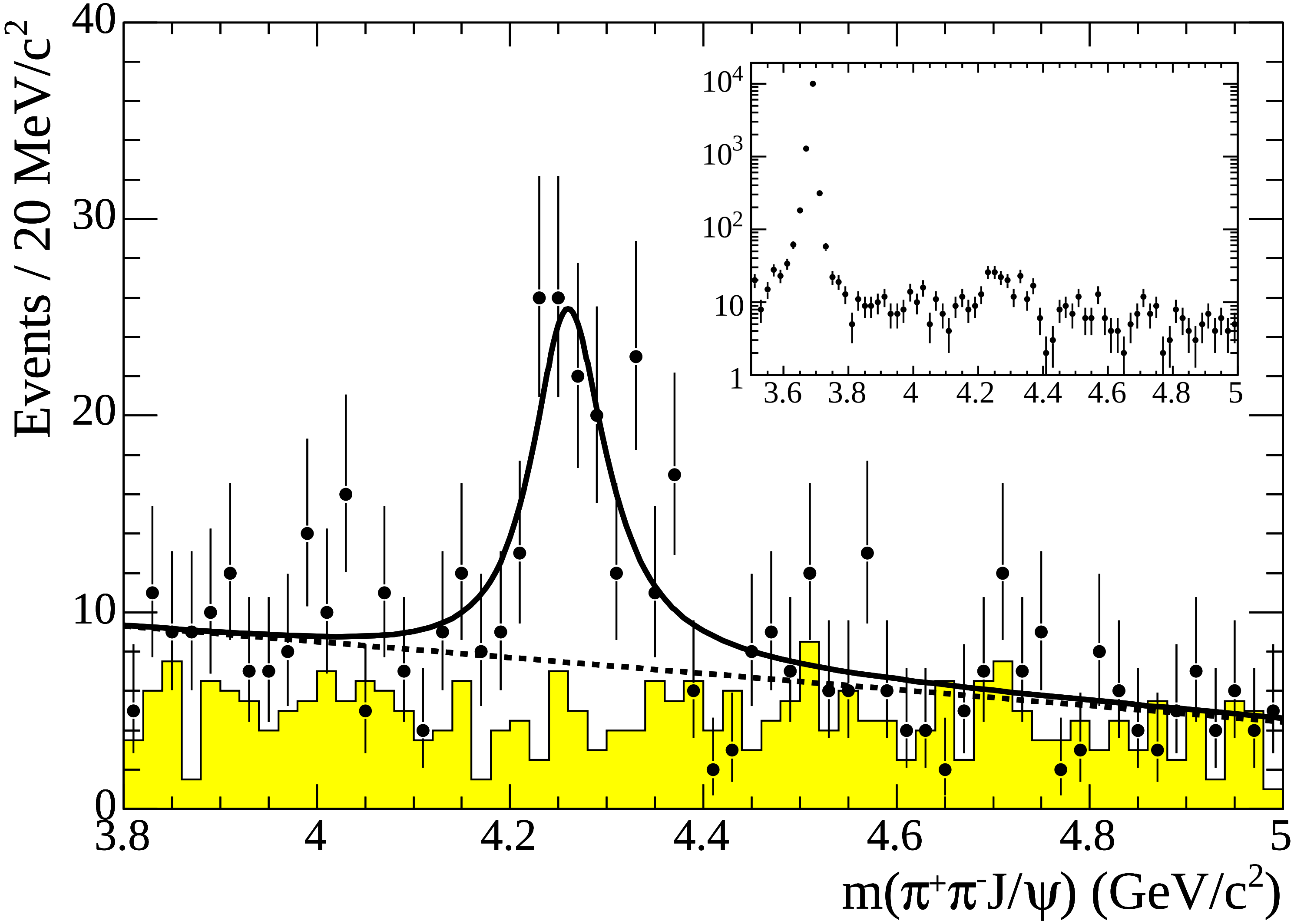


Belle, EPS 2005, PoS (HEP2005) 090; hep-ex/0507019; L. Hinz (Tues.):

X(3940) recoiling against J/ψ decays to $D\bar{D}^* +$ c.c., not $\omega J/\psi$: $\eta_c(3S)$

$B \to KY(3940) \to K\omega J/\psi$ [PRL **94**, 182002]: $\chi_{c1}(2P)$ [cf. $\chi_b' \to \omega\Upsilon$]

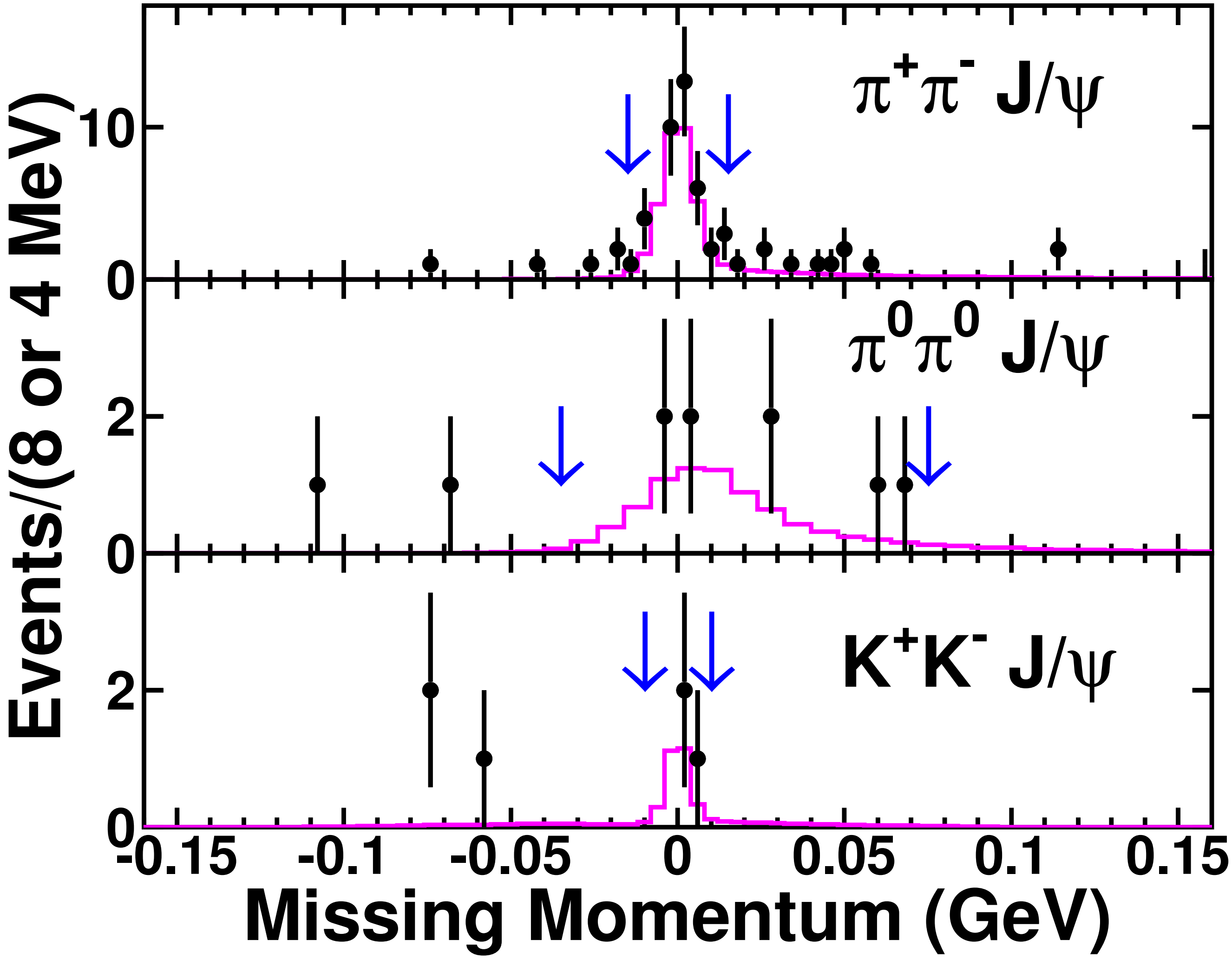
ORIGINAL Y(4260) SIGNAL



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

CLEO confirms radiative return signal in 9.5–10.6 GeV data (S. Blusk, Tues.)

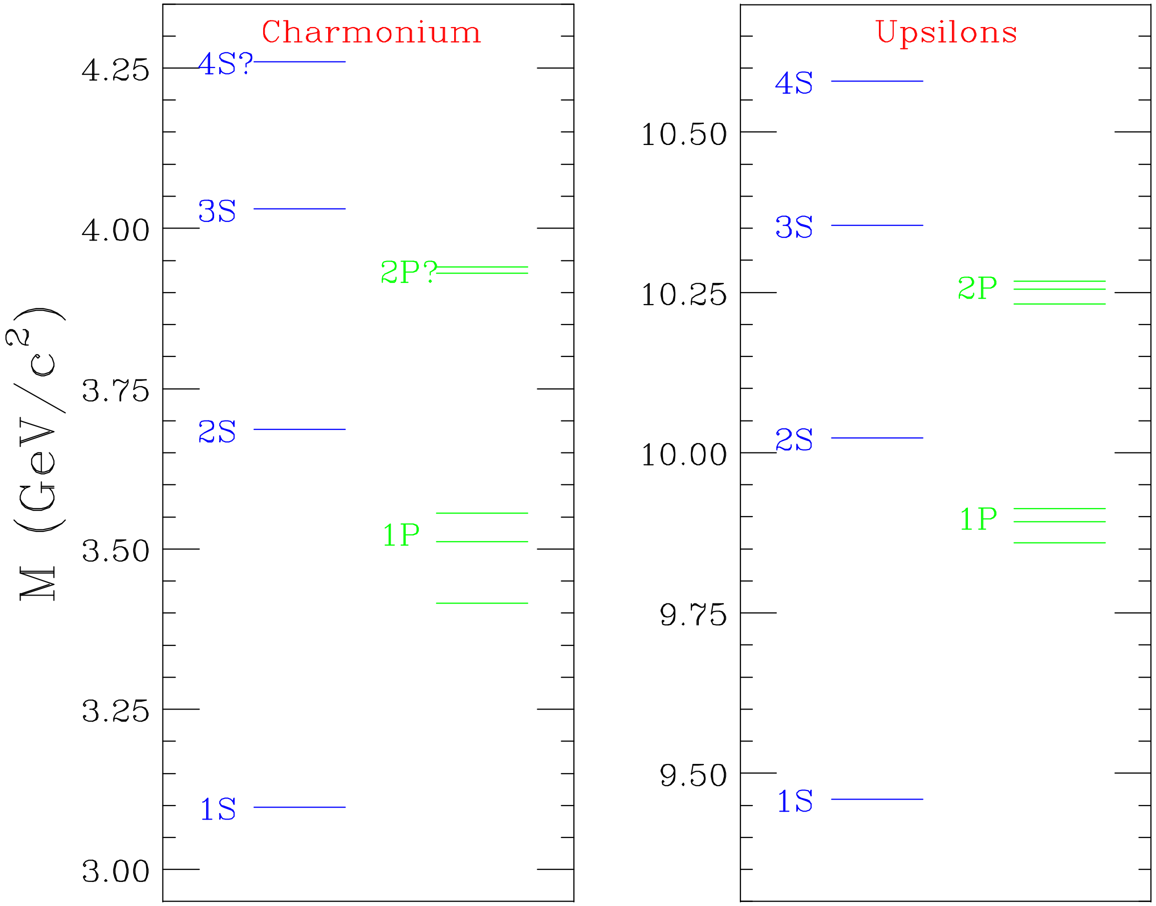
Y(4260) IN CLEO SCAN



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

Also $\psi(4160) \to \pi^+\pi^- J/\psi$ (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 (2006); S. Blusk

COMPARING SPECTRA

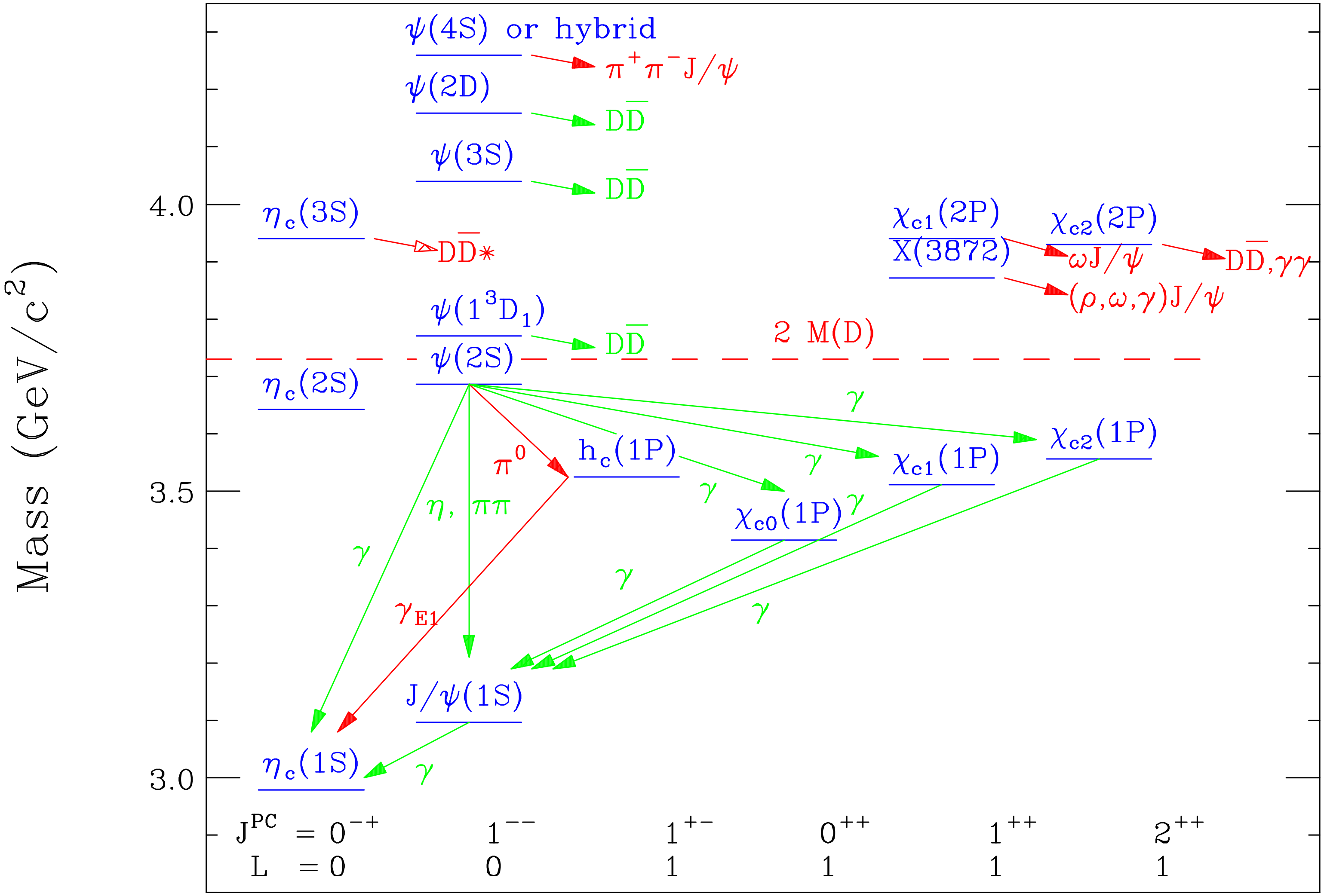


Congruence of spectra (C. Quigg + JLR): Effective $V(r) \sim \log(r)$ interpolates between $-1/r$ at short distance and r at long distance.

$Y(4260)$ also could be a hybrid ($c\bar{c}+$ gluon), in which case one expects it to decay 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"?

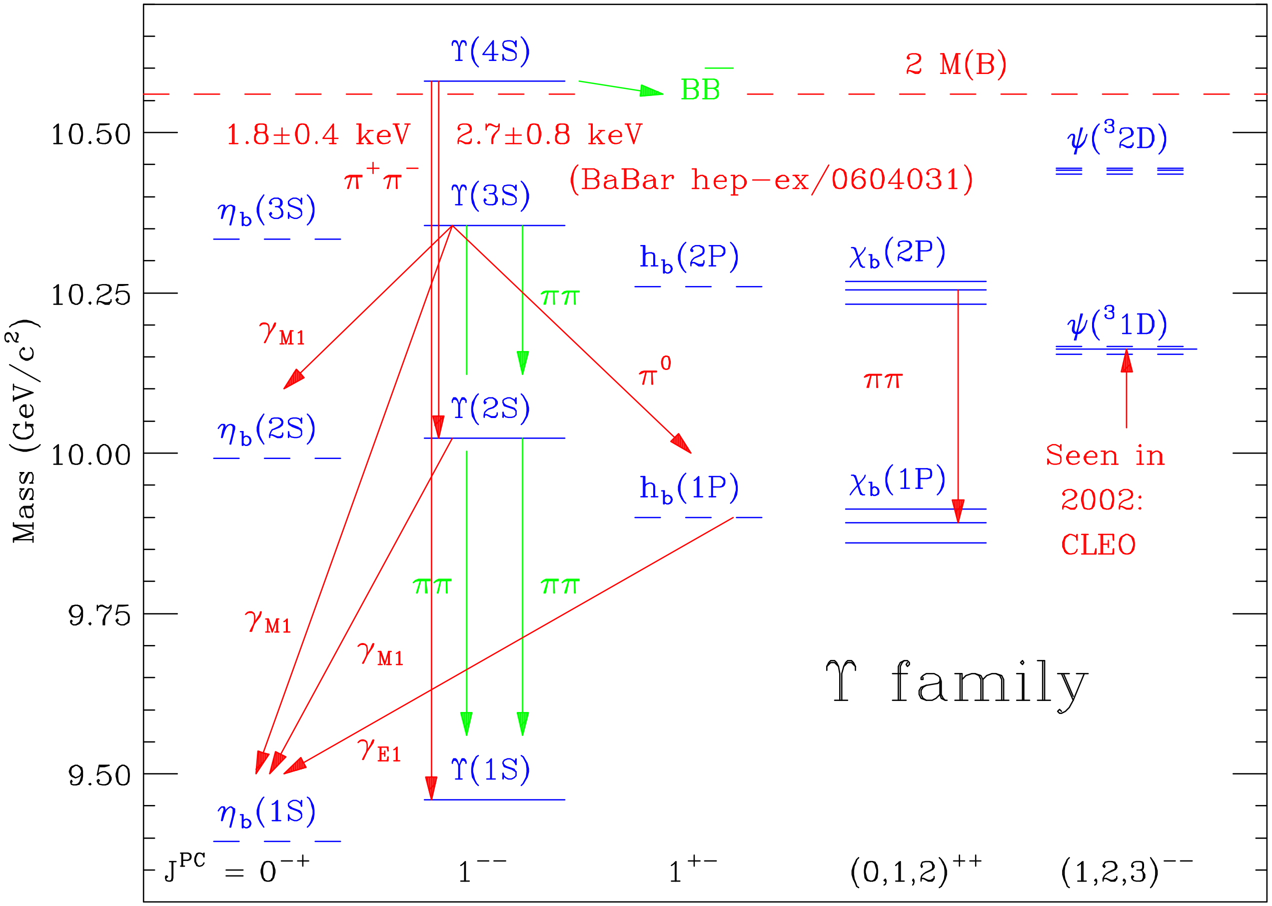
CHARMONIUM: UPDATED



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 strong-EM int. in $\pi\pi, K\bar{K}$

Υ STATES



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

Direct photons in $1S, 2S, 3S$ decays (hep-ex/0512061); transitions $\chi_b(2P) \to \pi\pi\chi_b(1P)$ [PR D **73**, 012003 (2006)]: G. Tatishvili, this conference

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

E1 photon transitions $S \leftrightarrow P \leftrightarrow D$ not shown.

CLEO Υ REMEASUREMENTS

New $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$ [PRL **94**, 012001 (2005)]; $\Gamma_{ee}(nS)$ values [PRL **96**, 092003 (2006)] $\surd$ lattice ratios (G. Tatishvili); lead to lower $\Gamma_{\rm tot}(2S, 3S)$:

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

Combine with updated $\Upsilon(2S, 3S) \to \gamma\chi_{bJ}(1P, 2P)$ branching ratios [CLEO, PRL **94**, 032001 (2005)] for new E1 transition rates (a); compare with nonrelativistic prediction (b) of W. Kwong + JLR, PR D **38**, 3179 (1988):

	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 of P. Moxhay and JLR, PR D **28**, 1132 (1983) and R. McClary and N. Byers, *ibid.* **28**, 1692 (1983).

$\Gamma(3S \to 1P_0) = 56 \pm 20$ eV, 8× prediction: suppressed, but not as anticipated.

$b\bar{b}$ SPIN SINGLETS

No $b\bar{b}$ spin-singlets have been seen yet [more lattice tests!]

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 (but 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 $\Upsilon(n'S) \to \gamma\eta_b(nS)$ $(n \neq n')$ already exclude many models. Strongest upper limit: $n' = 3$, $n = 1$, $\mathcal{B} \leq 4.3 \times 10^{-4}$ (90% c.l.).

η_b searches using sequential processes $\Upsilon(3S) \to \pi^0 h_b(1^1P_1) \to \pi^0\gamma\eta_b(1S)$ and $\Upsilon(3S) \to \gamma\chi'_{b0} \to \gamma\eta\eta_b(1S)$ are being conducted but no results yet.

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

Reduced CLEO luminosity makes original goals of 3 fb^{-1} at $\psi(3770)$, 3 fb^{-1} above D_s pair threshold, and 10^9 J/ψ unrealistic

It was agreed to focus CLEO on 3770 and 4170 MeV, split roughly equally, yielding about 750 pb^{-1} at each energy if current luminosity projections hold

Best possible determination of f_D, f_{D_s}, and form factors for semileptonic D and D_s decays will provide incisive tests for lattice gauge theories and measure CKM factors V_{cd} and V_{cs} with unprecedented precision.

30 million $\psi(2S)$ (about 10 times the current number) envisioned, with at least 10 million to be taken this summer

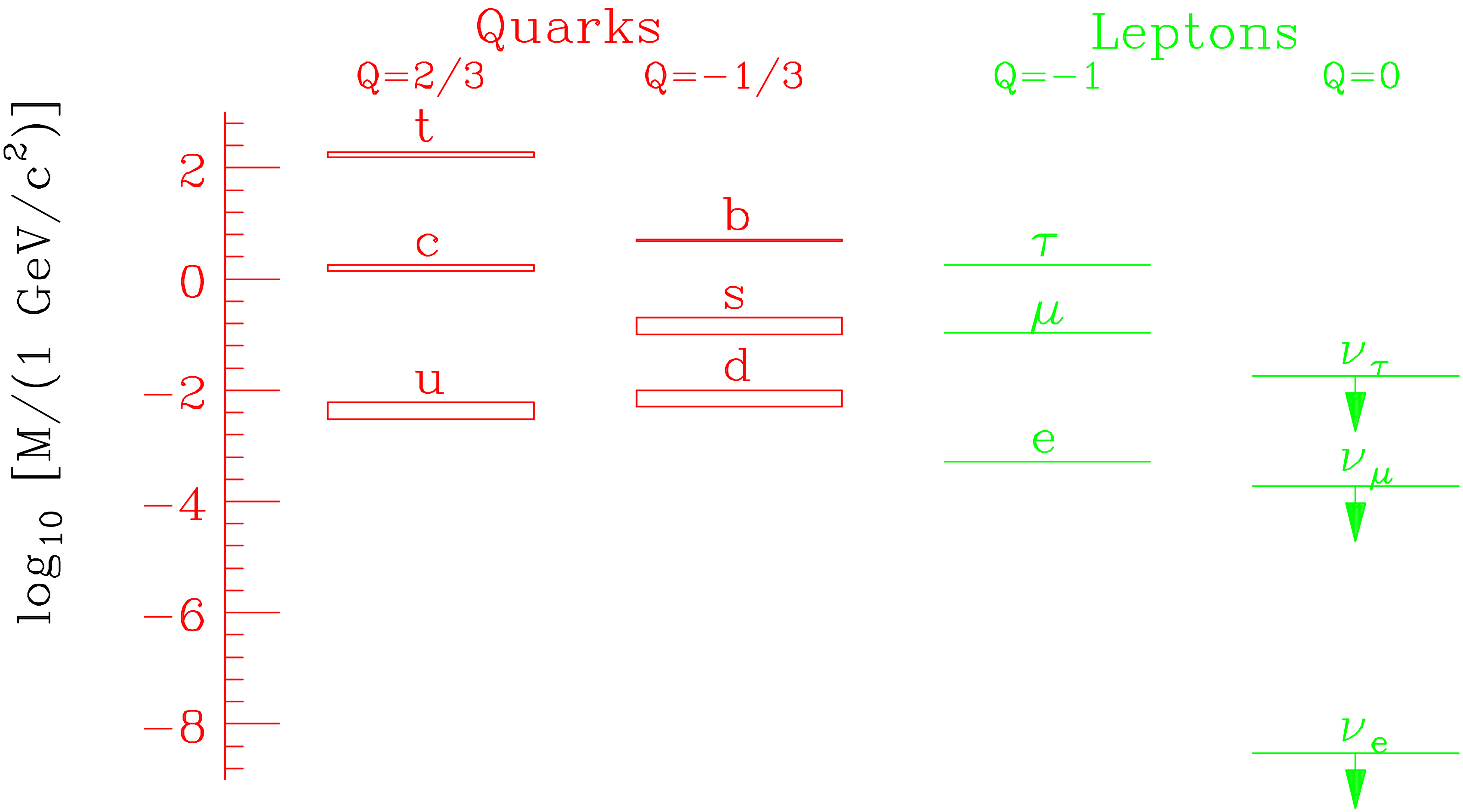
Some flexibility to explore new phenomena will be maintained

CLEO-c running will end at the end of March 2008; BES-III and PANDA thereafter

Belle has taken 3 fb^{-1} of data at $\Upsilon(3S)$; anyone's guess what they will find with such a fine sample. CLEO has (1.1, 1.2, 1.2) fb^{-1} at 1S, 2S, 3S.

Both BaBar and Belle have shown interest in hadron spectroscopy; well-positioned to study it. Contributions from CDF and D0 as well.

THE NEXT LEVEL DOWN



Mendeleev spotted gaps in his periodic table by dealing out elements on cards. Are we playing with a full deck of quarks and leptons? Does our “periodic table” have gaps? Can we understand it as fundamentally as we understand Mendeleev’s?

Exercise: *Explain* the pattern of masses and transitions!

SUMMARY

Hadron spectroscopy is providing both long-awaited states like h_c (whose mass and production rate confirm theories of quark confinement and isospin-violating π^0-emission transitions) and surprises like low-lying P-wave D_s mesons, X(3872), X(3940), Y(3940), Z(3940) and Y(4260). Decays of $\psi''(3770)$ shed light on its nature: D-wave $c\bar{c}$, some S-wave.

Upon reflection, some properties may be less surprising but we are continuing to learn about properties of QCD in the strong-coupling regime. Evidence for molecules, 3S, 2P, 4S or hybrid charmonium, interesting decays of states above flavor threshold.

QCD may not be the last strongly coupled theory with which we have to deal. The mystery of electroweak symmetry breaking or the very structure of quarks and leptons may require related techniques.

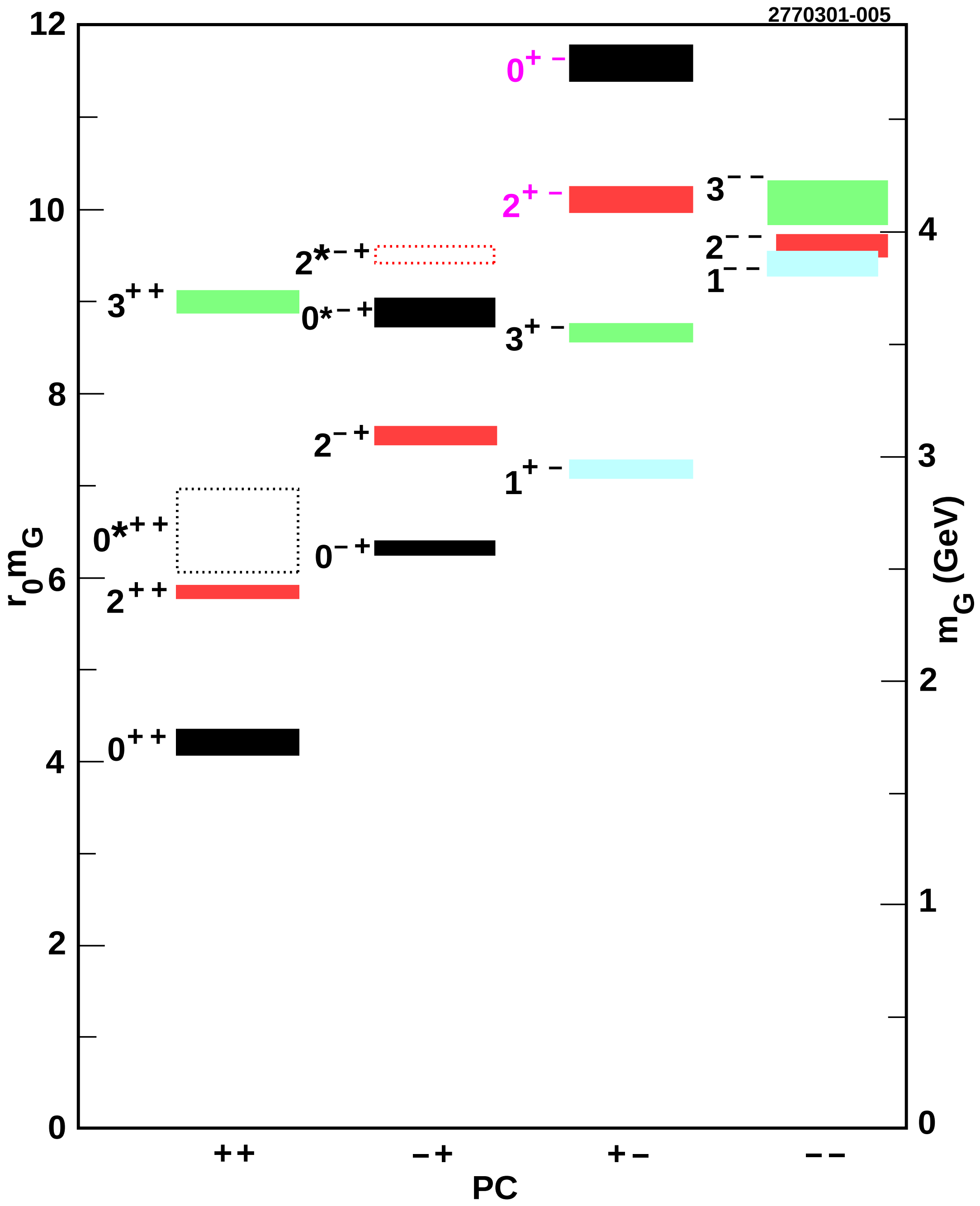
These insights are coming to us in general from experiments at the frontier of intensity and detector capabilities rather than energy, and illustrate the importance of a diverse approach to the fundamental structure of matter.

L'ENVOI

We thank R. H. Dalitz for teaching us that in order to learn about fundamental physics (such as parity violation in the weak interactions or the existence of quarks) it is often necessary to deal with phenomenological techniques of strong-interaction physics (such as "phase space plots" or baryon resonance descriptions).

Let us keep Dalitz's legacy alive in our approach to particle physics.

GLUEBALLS: LATTICE MASSES



From CLNS-01/1742: M.S. thesis, M. Campbell, Univ. Glasgow, 1997

$r_0 \simeq 0.42$ GeV: scale factor

G. P. Lepage, LP 2003: Lattice predictions for glueballs aren't easy!

Mixing with decay channels, $q\bar{q}$ configurations one reason

Best prospects are to sort out $J^{PC} = 0^{++}$ mesons

Next best: $J^{PC} = 2^{++}$

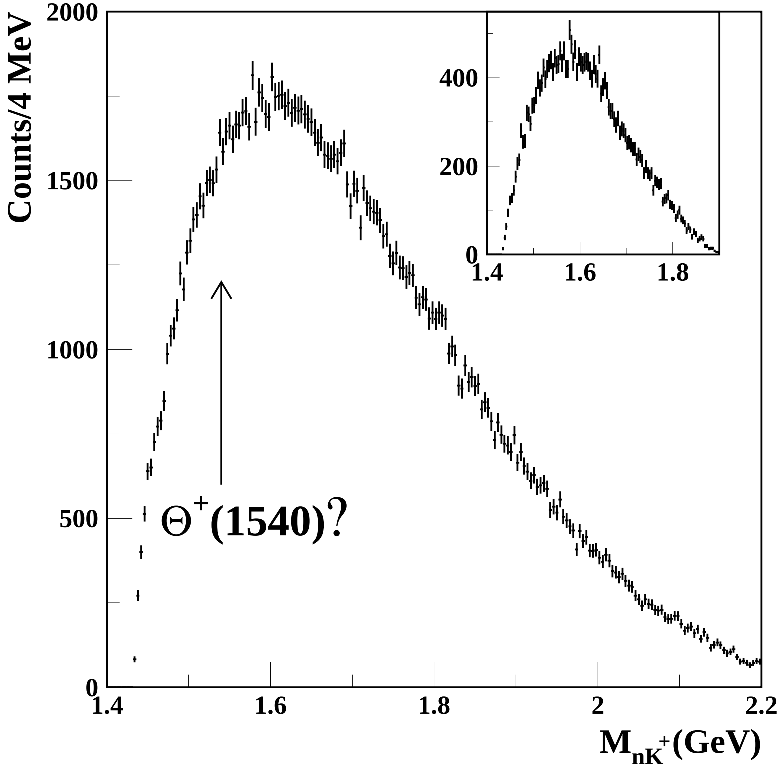
PENTAQUARK SEARCHES

Exotic candidate $\Theta^+ = uudd\bar{s}$ at 1540 MeV, predicted in chiral soliton model and seen in many experiments. References: CLAS, M. Battaglieri +, PRL **96**, 042001 (2006); V. Kubarovsky (yesterday); reviews by K. Hicks, A. Dzierba

Many channels previously displaying signals now do not, with increased statistics.

HERA: H1 sees $\Theta_c(3100)$, not Θ^+; ZEUS: vice versa.

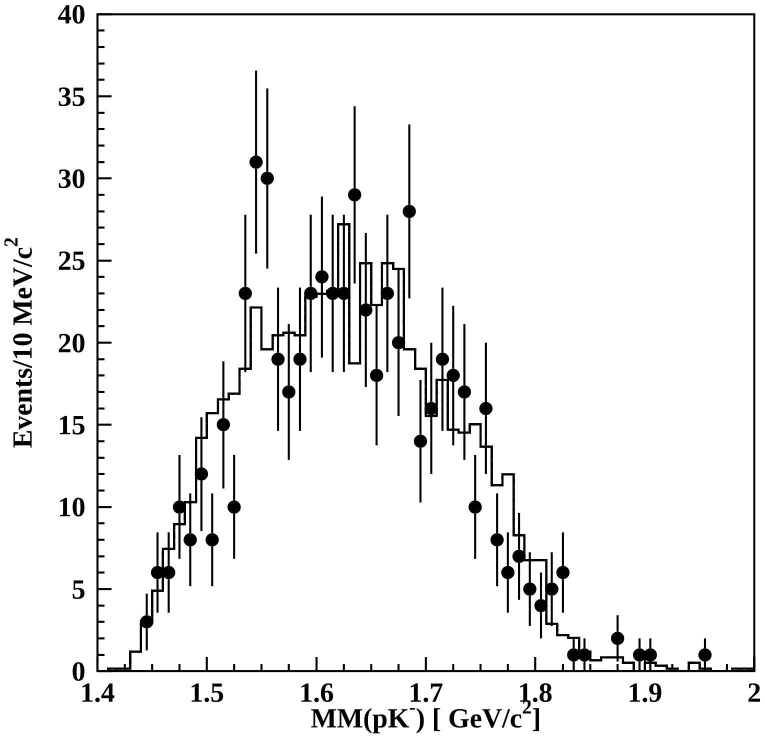
$\gamma p \to \bar{K}^0 K^+ n$ (PRL **96**, 042001)



$M(nK^+)$ distribution after cuts.

Inset: cuts of SAPHIR analysis

$\gamma d \to p K^- K^+ n$ (hep-ex/0603028)

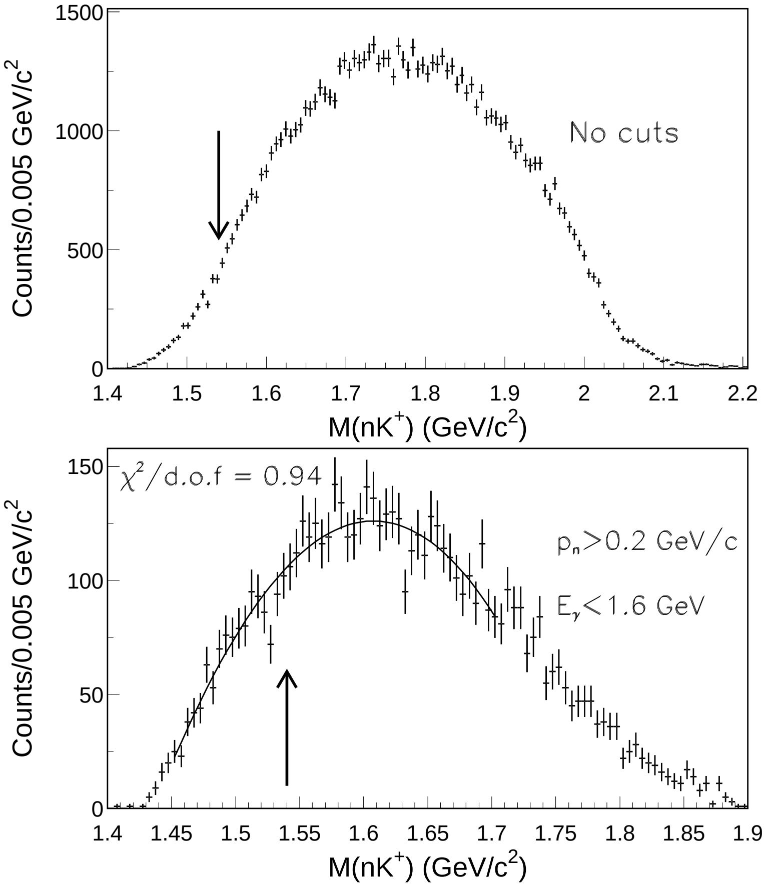


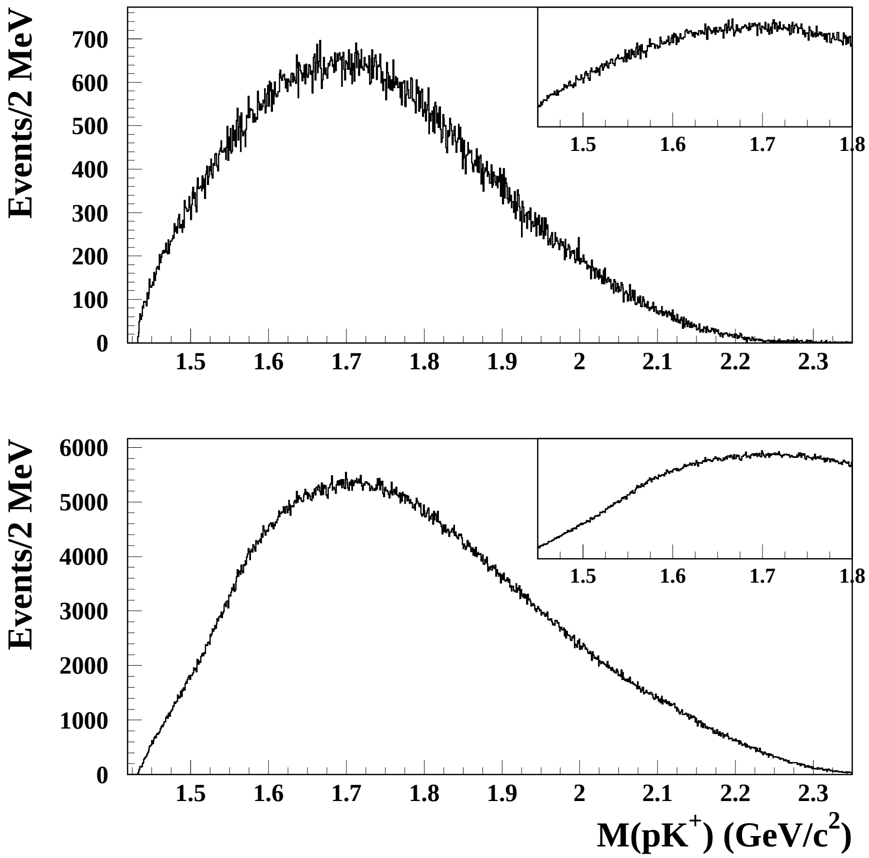
Points: previously published; histogram: present CLAS result (normalized)

RELATED SEARCHES

Many other searches by BaBar, Belle, HERA, . . .: `FIND TI SEARCH AND TI PENTAQUARK AND D AFTER 2004` → 44 entries on SPIRES

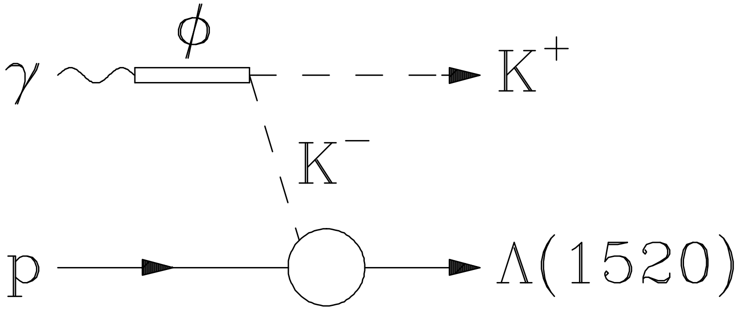
Two examples by CLAS Collaboration: $\gamma d \to \Lambda n K^+$ (left, hep-ex/0604047) and $\gamma p \to K^+ K^- p$ (right, hep-ex/0605001, looking for Θ^{++})





Non-exotic $K^- p$ channel shows prominent $\Lambda(1520)$ resonance

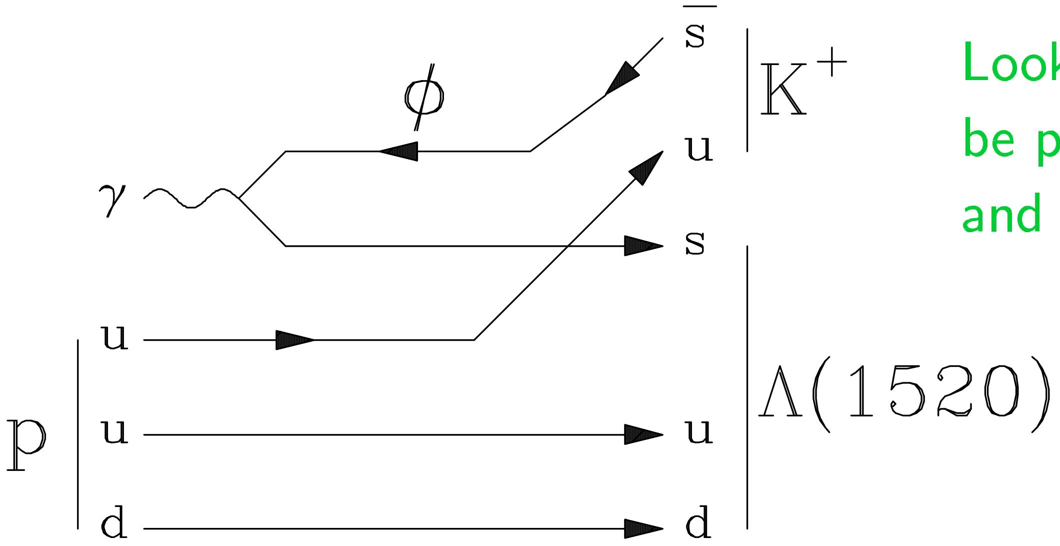
ϕ PHOTOPRODUCTION



Be careful of kinematic correlations:
If K^- can resonate with proton, and
K^+ has nearly same velocity as K^-,
it will appear to resonate with spectators

Test for this: What is the momentum distribution of K^+ in low-energy (~ 3 GeV) inclusive γp reactions? If it has a peak at $p_K \simeq 450$ MeV$/c$, watch out!

At the quark level:

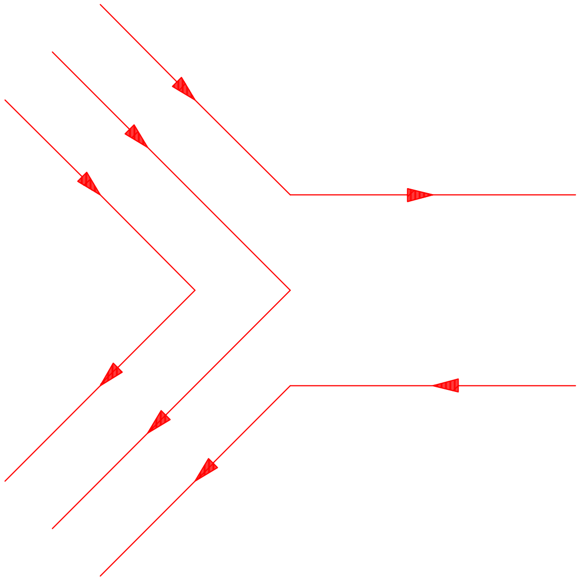


Looks like $s\bar{s}uud$ correlation may be possible with simultaneous ϕN and $K^+\Lambda(1520)$ substates

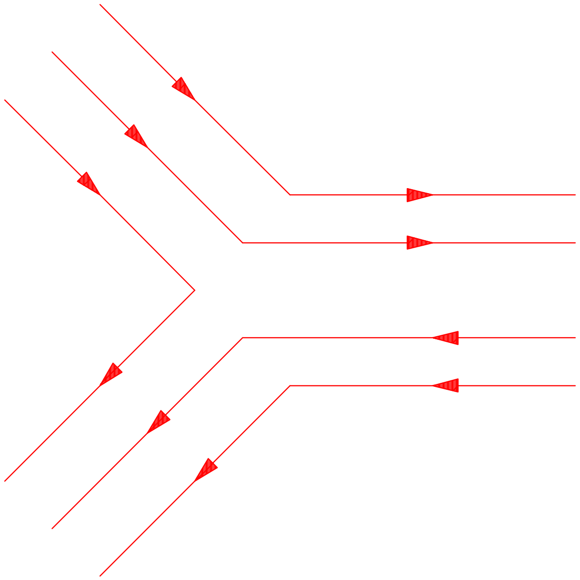
Need to understand more about 3-body systems

BARYONIUM FORMATION

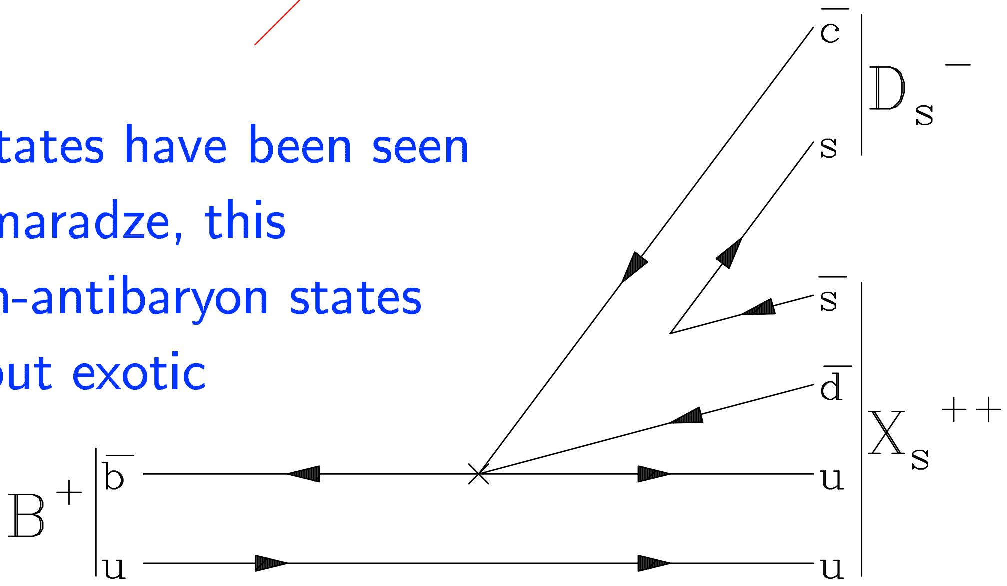
Non-exotic:



Exotic:

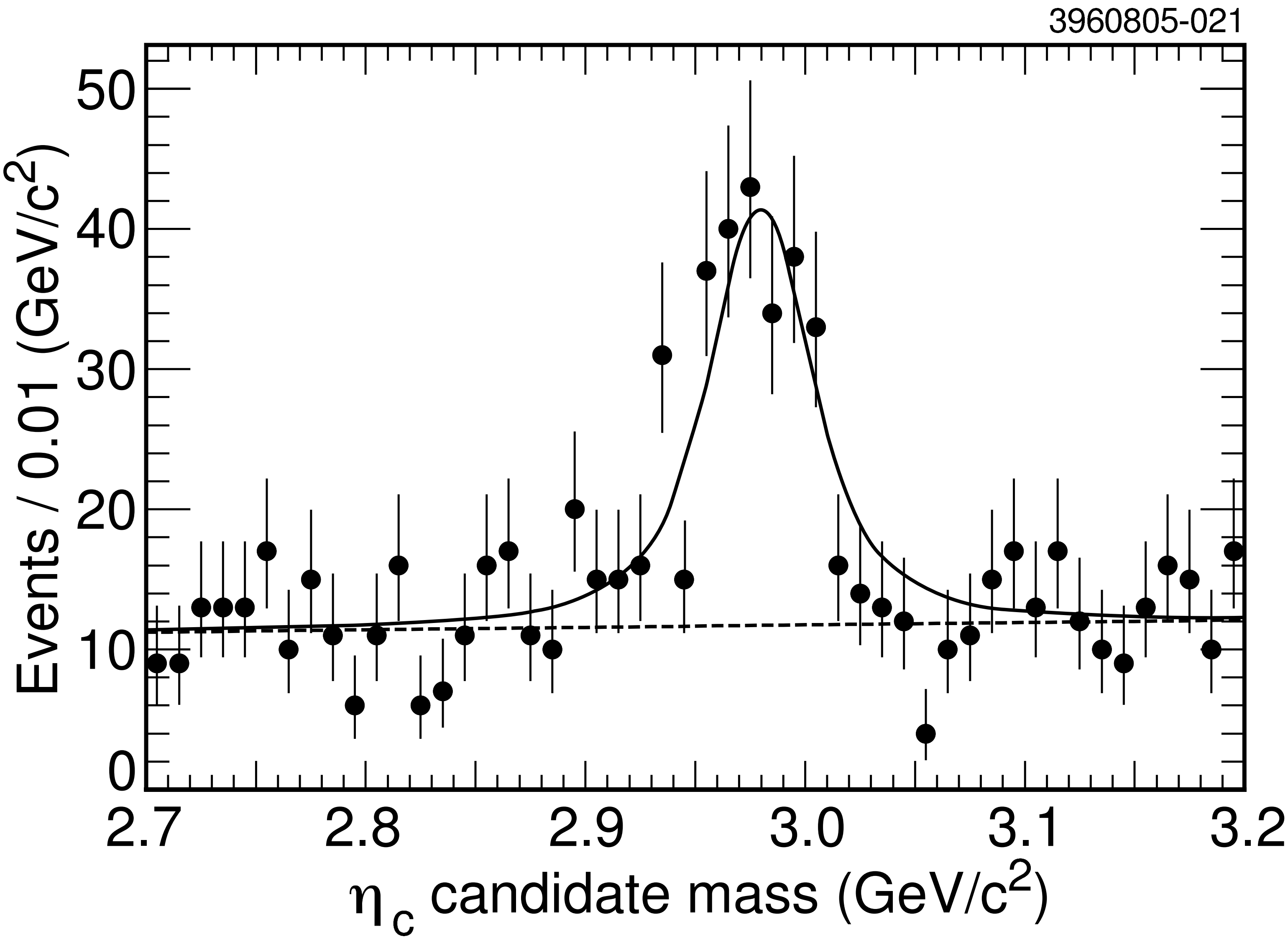


Many non-exotic baryon-antibaryon states have been seen near threshold in J/ψ decays (A. Tomaradze, this conference) and B decays. No baryon-antibaryon states with $qq\bar{q}\bar{q}$ numbers have been seen, but exotic mesons ($qq\bar{q}\bar{q}$) and baryons ($qqqq\bar{q}$) are accessible in B decays, e.g.:



Look for $X_s^{++} \to \bar{\Lambda} p \pi^+$. More suggestions: PR D **69**, 094014 (2004).

CALIBRATION: $\psi(2S) \rightarrow \gamma\eta_c(1S)$



See 220 ± 22 events in the seven inclusive channels

TWO-PHOTON WIDTHS

Remarks on $\eta_c(2S) \to \gamma\gamma$:

Expect $\Gamma_{\gamma\gamma}(2S)/\Gamma_{\gamma\gamma}(1S) \simeq |\Psi_{2S}(0)/\Psi_{1S}(0)|^2 \simeq \Gamma_{ee}[\psi(2S)]/\Gamma_{ee}[J/\psi(1S)] \simeq 0.4$.

CLEO finds $\Gamma_{\gamma\gamma}(2S)\mathcal{B}[\eta_c(2S) \to K_S K^{\pm}\pi^{\mp}]$ is only $0.18 \pm 0.05 \pm 0.02$ times the corresponding ratio for $\eta_c(1S)$.

Most likely explanation: The heavier $\eta_c(2S)$ has more available decay modes, lower $\mathcal{B}$ to any individual final state.

Remarks on $\chi_{c2} \to \gamma\gamma$:

CLEO: 15 fb^{-1} of e^+e^- data at $\sqrt{s} = 9.46$–11.30 GeV

CLEO: $\Gamma(\chi_2 \to \gamma\gamma) = 559(57)(45)(36)$ eV (A. Tomaradze, this conference)

$\surd$ other measurements corrected for CLEO's $\mathcal{B}(\chi_2 \to \gamma J/\psi)$, $\mathcal{B}(J/\psi \to \ell^+\ell^-)$.

$\Gamma(\chi_2) = 1.94 \pm 0.13$ MeV [E835, NP **B 717**, 34 (2005)] and $\mathcal{B}(\chi_2 \to \gamma J/\psi) =$ (19.9±0.5±1.2)% $\Rightarrow$ $\Gamma(\chi_2 \to$ hadrons) = 1.55±0.11 MeV = (2.75±0.41) $\times 10^3$ $\Gamma(\chi_2 \to \gamma\gamma)$, implying $\alpha_S(m_c) = 0.290 \pm 0.013$ if $\Gamma(\chi_2 \to$ hadrons) is dominated by two-gluon width. Compatible with $\alpha_S(m_c)$ from other charmonium decays.

$\psi' \equiv \psi(2S)$ DECAYS

Decays $\psi' \to \gamma X$ [CLEO, S. B. Athar +, PRD **70**, 112002 (2004)]

Decay	CLEO $\mathcal{B}$ (%)	PDG $\mathcal{B}$ (%)
$\psi' \to \gamma\chi_{c2}$	$9.33 \pm 0.14 \pm 0.61$	6.4 ± 0.6
$\psi' \to \gamma\chi_{c1}$	$9.07 \pm 0.11 \pm 0.54$	8.4 ± 0.8
$\psi' \to \gamma\chi_{c0}$	$9.22 \pm 0.11 \pm 0.46$	8.6 ± 0.7
$\psi' \to \gamma\chi_{cJ}$	$27.6 \pm 0.3 \pm 2.0$	23.4 ± 1.2
$\psi' \to \gamma\eta_c$	$0.32 \pm 0.04 \pm 0.06$	0.28 ± 0.06

Inclusive $\psi' \to \gamma\chi_{cJ}$ rates above those of PDG 2004

$\psi' \to \gamma\eta_c$ a calibration for $\psi' \to \pi^0 h_c \to \pi^0\gamma\eta_c$

Decays $\psi' \to J/\psi X$ (CLEO, N. E. Adam +, hep-ex/0503028)

$X = \pi\pi$: CLEO $\pi^0\pi^0/\pi^+\pi^-$ ratio closer to $1/2$ ($\surd$ isospin) vs. PDG, BES $> 1/2$

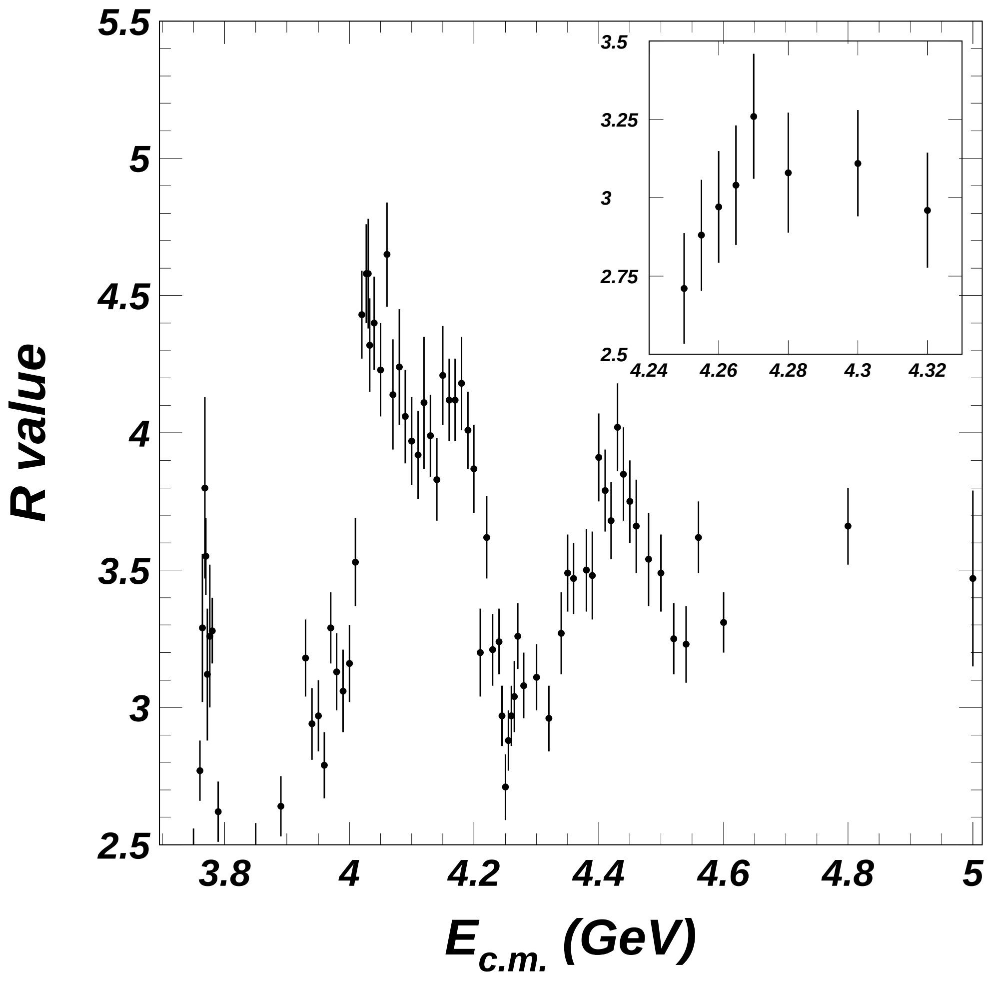
$X = \gamma\chi_{cJ} \to \gamma\gamma J/\psi$: CLEO branching ratios above those of PDG

$X =$ all: $\mathcal{B} = (59.50 \pm 0.15 \pm 1.90)\%$ vs. sum of known modes $(58.9 \pm 0.2 \pm 2.0)\%$

Results imply $\mathcal{B}(\psi' \to \text{light hadrons}) = (16.9 \pm 2.6)\%$, 2.2σ above $\mathcal{B}(\psi \to \ell^+\ell^-)/\mathcal{B}(J/\psi \to \ell^+\ell^-) = (12.6 \pm 0.7)\%$ (the "12% rule")

Suppression of hadronic ψ' final states confined to certain species (such as $\rho\pi$, $K^*\bar{K}$)

DIP IN R at 4250 MeV



Dip is just below threshold $\simeq 4287$ MeV for production of lowest-mass charmed meson pair $D^0\bar{D}_1^*$ in an S-$wave$. (Lower thresholds: P-wave production.)

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

DOUBLY CHARMED BARYONS

Expect $X_{cc}^{+} = ccd$ and $X_{cc}^{++} = ccu$ with masses 3.5–3.8 GeV/c^2

SELEX Collaboration [M. Mattson +, PRL **89**, 112001 (2002); A. Ocherashvili +, PL B **628**, 18 (2005)] sees X_{cc}^{+} at $M = (3518.7 \pm 1.7$ MeV/c^2, decaying to $\Lambda_c^+ K^- \pi^+$ and pD^+K^-. Produced in Σ^- beam.

SELEX, ICHEP 2002 (J. S. Russ): X_{cc}^{++} at $M = 3.46$ GeV/c^2, decaying to $\Lambda_c^+ K^- \pi^+ \pi^+$. Isospin splitting from X_{cc}^{+} expected to be a few MeV/c^2, not 60.

FOCUS Collaboration [S. P. Ratti +, NP Proc. Supp. **115**, 33 (2003)] sees no X_{cc} states in photoproduction although they have nearly 12 times as many Λ_c^+ as SELEX.

New BaBar result (hep-ex/0605075): see no decays $X_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$, $\Xi_c^0 \pi^+$ or $X_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_c^0 \pi^+ \pi^+$. Consult for theory refs.

PROSPECTS WITH $3 \times 10^7 \psi'$

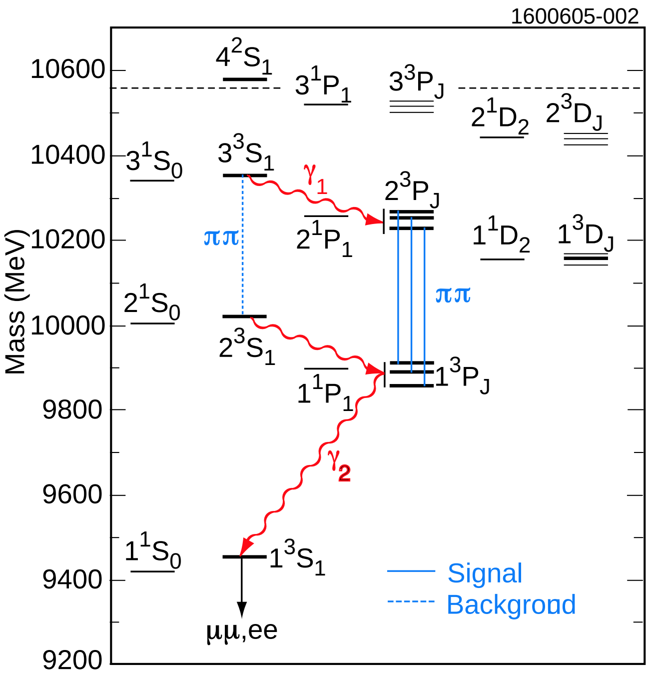
Spectroscopy at $\psi(2S)$ bears rich promise. With $10\times$ present 3M:

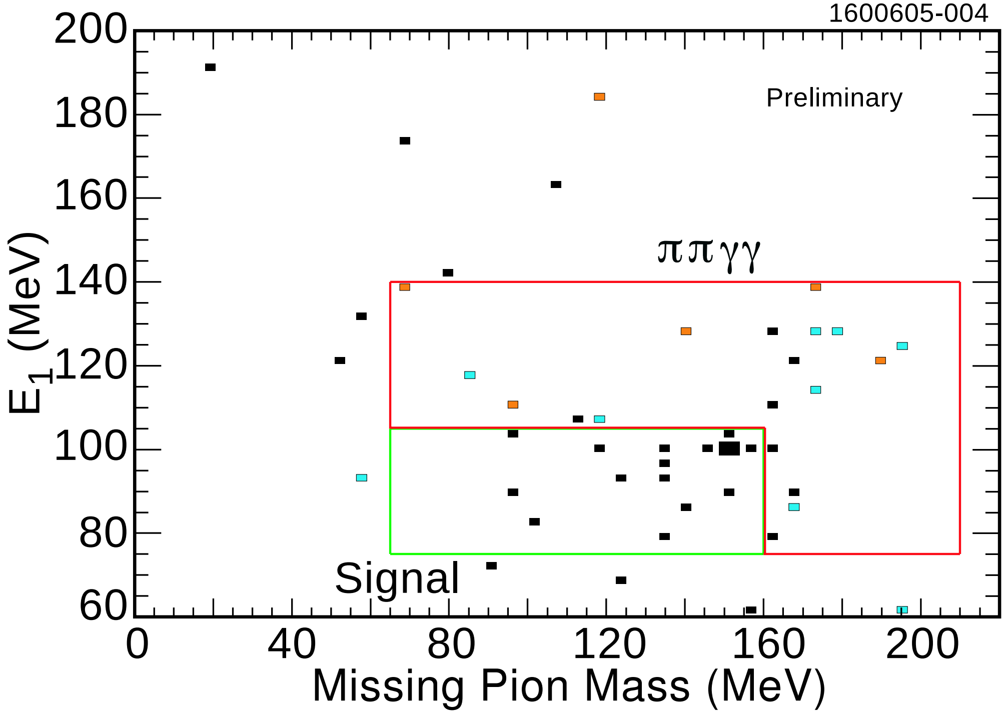
- Nearly 200 events of $\psi(2S) \to \pi^0 h_c \to \pi^0 \gamma \eta_c$ with exclusive η_c decay $\Rightarrow \Delta M_{\rm stat} < 0.3$ MeV to match $\Delta M_{\rm sys}$
- M2/E1 ratios in $\chi_{c1,2} \to \gamma J/\psi \Rightarrow$ charmed quark magnetic moment
- Exclusive χ_c decays: potentially fertile ground for hybrids, glueballs
- One (tagged via $\pi^+\pi^-$) J/ψ decay for every four $\psi(2S)$: Simultaneously study exclusive decays of J/ψ and $\psi(2S)$ to same final states, guard against kinematic reflections.

Modest (30M) sample of $\psi' = \psi(2S)$ data, possibly to be taken in summer 2006, will give much new information. More may be warranted if results are promising.

OBSERVATION OF $\chi_b' \to \pi^+\pi^-\chi_b$

Look for $\Upsilon(3S) \to \gamma \to \gamma\pi^+\pi^- \to \gamma\pi^+\pi^-\gamma\Upsilon(1S)$ in CLEO III data (5.8 M)





Use events with (both,one) soft pions. Missing pion mass (⇑) vs. lower E_γ.

2π: 7 events seen, 0.6±0.2 background. 1π: 17 events seen, 2.2±0.6 background.

Measure $\Gamma(\chi_{b1}' \to \pi^+\pi^-\chi_{b1}) = \Gamma(\chi_{b2}' \to \pi^+\pi^-\chi_{b2}) = (0.80 \pm 0.21^{+0.23}_{-0.17})$ keV.

Published: PR D **73**, 012003 (2006); $\chi_b' \to \pi^0\pi^0\chi_b$ results forthcoming.

Kuang-Yan: Predict $\Gamma(2^3P_J \to 1^3P_J\pi\pi) = 0.3$–0.4 keV.

A PAGE OF BIBLIOGRAPHY

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