SPECTROSCOPY AT CLEO

J. Rosner (U. Chicago) – Beauty 2005 – Perugia, June 23, 2005

We wish to understand nonperturbative techniques, not only for the sake of QCD alone but in the event they are needed for other sectors of high energy physics or even (!) outside our field. A wide range of phenomena from prototypical nonlinear gauge theory.

Hadron spectra sometimes are crucial in separating electroweak physics from strong-interaction effects. The decays of charmed mesons may be one example if final-state resonances are important.

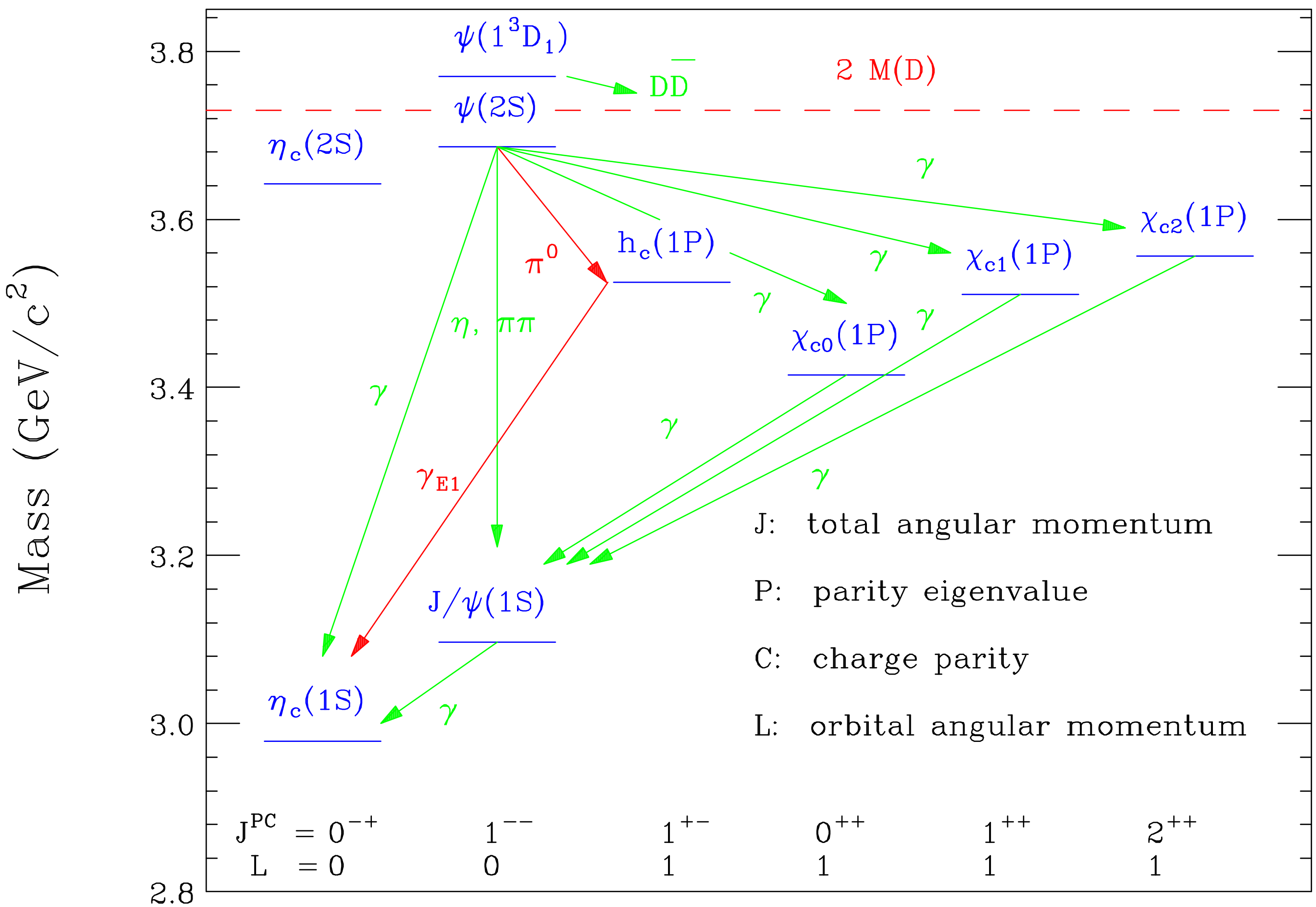
Hadron spectra are beautiful in their own right.

At the quark and lepton level, intricate level structure and transitions among these levels for which we have no fundamental understanding. Sharpening spectroscopic techniques may help solve this problem.

Today: recent spectroscopy contributions from CLEO/CESR utilizing CLEO's excellent particle identification and resolution.

Topics: Charmonium, charm, beauty, upsilons

CHARMONIUM



J/ψ decays: Lepton-pair branching ratio measured better in $\psi(2S) \to J/\psi X$

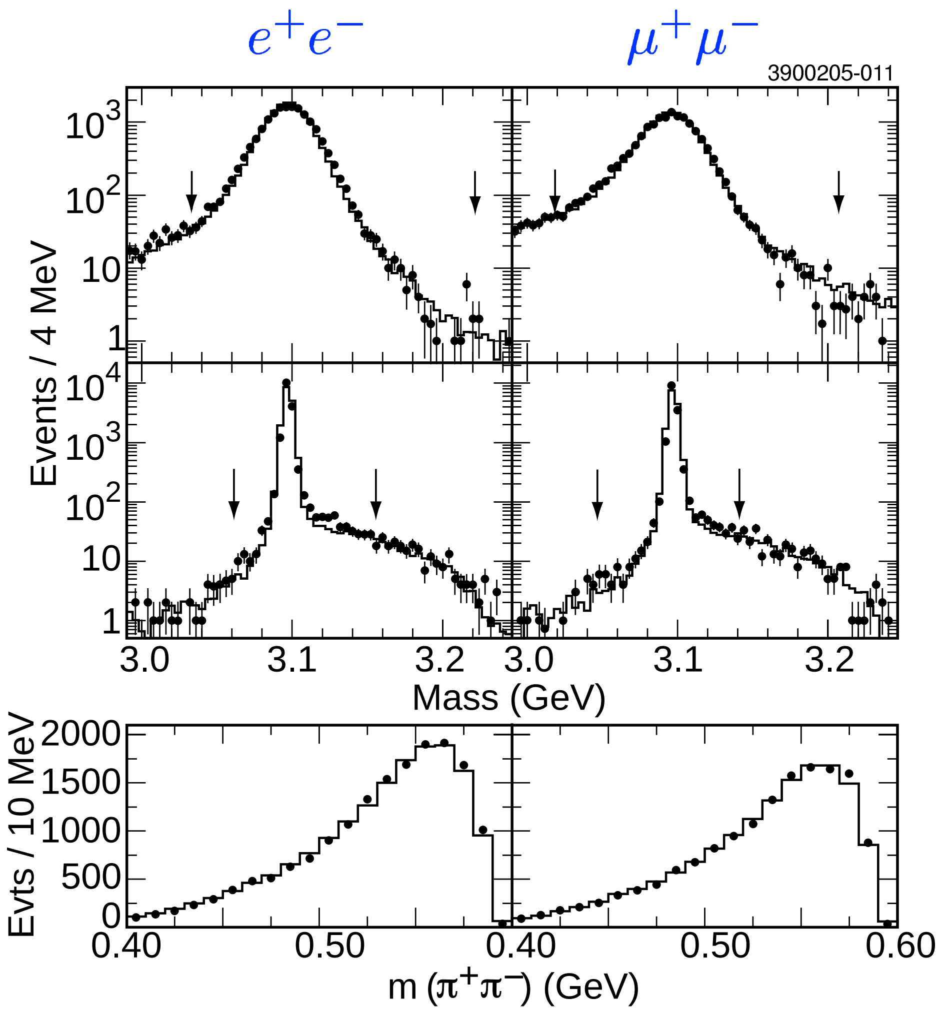
$\psi(2S)$ decays: baryon-antibaryon ("12% rule"), $J/\psi X$, light hadrons, $\pi^0 h_c$

$\Gamma(\chi_{c2} \to \gamma\gamma)$ remeasurement and current status of $gg/\gamma\gamma$ ratio

$\psi(1^3D_1)$ $[\psi''(3770)]$ decays: $\sigma(D\bar{D})$, $\pi\pi J/\psi$, $\gamma\chi_{c1}$, light hadrons

$J/\psi \to \ell^+\ell^-$ BRANCHING RATIO

Compare $\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\ell^+\ell^-)$ with $\mathcal{B}(\psi(2S) \to \pi^+\pi^- X)$



CLNS 05/1914, hep-ex/0503027, accepted in PRD, Rapid Comm.

Reconstructed $M(\ell^+\ell^-)$ at J/ψ peak

Mass recoiling against $\pi^+\pi^-$ shows good resolution

Dipion invariant mass peaked at large values

$\mathcal{B}(J/\psi \to e^+e^-)$=(5.945±0.067±0.042)%, $\mathcal{B}(J/\psi \to \mu^+\mu^-)$=(5.960±0.065±0.050)%

$\mathcal{B}(J/\psi \to \ell^+\ell^-)$=(5.953±0.056±0.042)%, $\mathcal{B}(e^+e^-)/\mathcal{B}(\mu^+\mu^-)$=(99.7±1.2±0.6)%

$\psi(2S) \to$ BARYON-ANTIBARYON

Many final states measured more precisely by CLEO (hep-ex/0505057 $\Rightarrow$ PRL)

Mode	$S_{\psi(2S)}$	$\mathcal{B}(10^{-4})$	Q (%)
$p\bar{p}$	557	2.87±0.12±0.15	13.6±1.1
$\Lambda\bar{\Lambda}$	208	3.28±0.23±0.25	25.2±3.5
$\Sigma^+\overline{\Sigma^+}$	35	2.57±0.44±0.25	–
$\Sigma^0\overline{\Sigma^0}$	58	2.62±0.35±0.21	20.7±4.2
$\Xi^-\overline{\Xi^-}$	63	2.38±0.30±0.21	13.2±2.2
$\Xi^0\overline{\Xi^0}$	19	2.75±0.64±0.61	–
$\Xi^{*0}\overline{\Xi^{*0}}$	2	$0.72^{+1.48}_{-0.62} \pm 0.10$	–
		$(< 3.2$ @90% CL)	–
$\Omega^-\overline{\Omega^-}$	4	$0.70^{+0.55}_{-0.33} \pm 0.10$	
		$(< 1.6$ @90% CL)	–

Expect $Q \equiv \frac{\mathcal{B}[\psi(2S)\to f]}{\mathcal{B}(J/\psi\to f)}$ comparable to $\frac{\mathcal{B}[\psi(2S)\to\ell^+\ell^-]}{\mathcal{B}(J/\psi\to\ell^+\ell^-)}$ $= 12.6 \pm 0.7\%$ ("12% rule") (governed by $|\Psi(0)|^2$)

Q is much smaller than 12% for VP, VT (P=pseudoscalar, V=vector, T=tensor)

$Q(\rho\pi)$=(1.9±0.6)$\times 10^{-3}$, similar for $K^{*\pm}K^{\mp}$

Branching ratios $\sim 50\%$ higher than PDG 2004 averages (based on lower statistics)

Flavor SU(3) seems approximately valid for octet-baryon pair production

Apparent suppression of decuplet-baryon pair production

$\psi(2S) \to J/\psi X$ DECAYS

Channel	$\mathcal{B}$ (%)	$\mathcal{B}/\mathcal{B}_{\pi^+\pi^- J/\psi}$
$\pi^+\pi^- J/\psi$	33.54±0.14±1.10	
$\pi^0\pi^0 J/\psi$	16.52±0.14±0.58	49.24±0.47±0.86
$\eta J/\psi$	3.25±0.06±0.11	9.68±0.19±0.13
$\pi^0 J/\psi$	0.13±0.01±0.01	0.39±0.04±0.01
$\gamma\chi_{c0} \to \gamma\gamma J/\psi$	0.18±0.01±0.02	0.55±0.04±0.06
$\gamma\chi_{c1} \to \gamma\gamma J/\psi$	3.44±0.06±0.13	10.24±0.17±0.23
$\gamma\chi_{c2} \to \gamma\gamma J/\psi$	1.85±0.04±0.07	5.52±0.13±0.13
$X J/\psi$	59.50±0.15±1.90	

CLNS 05/1909, hep-ex/0503028: PRL $\surd$

$\simeq 1/2$: $\surd$ isospin

π^0/η ratio (4.1±0.4±0.1)%

CLEO branching ratios above those of PDG

Combine with inclusive $\mathcal{B}[\psi(2S) \to \gamma\chi_{cJ}]$ [CLEO PRD 70, 112002 (2004)] $\Rightarrow$ $\mathcal{B}(\chi_{c0} \to \gamma J/\psi)$=2.0±0.2±0.2%, $\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$=37.9±0.8±2.1%, $\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$=19.9±0.5±1.2%

$X =$ 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 $\mathcal{B}(\psi(2S) \to \ell^+\ell^-)/\mathcal{B}(J/\psi \to \ell^+\ell^-) = (12.6 \pm 0.7)\%$

$\psi(2S) \Rightarrow$ LIGHT HADRONS

CLEO: Many exclusive multi-body states (hep-ex/0505101). Partial list:

Mode h	N_S	$\mathcal{B}[\psi(2S) \to h]$ (10^{-4})	$\mathcal{B}$ (PDG) (10^{-4})	Q (%)
$2(\pi^+\pi^-)$	308.0	2.2±0.2±0.2	4.5±1.0	5.55±1.53
$2(\pi^+\pi^-)\pi^0$	1702.6	26.1±0.7±3.0	30±8	7.76±1.10
$\omega\pi^+\pi^-$	391.0	8.2±0.5±0.7	4.8±0.9	11.35±1.94
$K^+K^-\pi^+\pi^-$	817.2	7.1±0.3±0.4	16±4	9.85±3.23
$\phi\pi^+\pi^-$	47.6	0.9±0.2±0.1	1.50±0.28	11.07±3.30
$K^+K^-\pi^+\pi^-\pi^0$	711.6	12.7±0.5±1.0	–	10.59±2.81
ωK^+K^-	76.8	1.9±0.3±0.3	1.5±0.4	10.19±2.96
$2(K^+K^-)$	59.2	0.6±0.1±0.1	–	6.71±2.74
ϕK^+K^-	36.8	0.8±0.2±0.1	0.60±0.22	5.14±1.53
$p\bar{p}\pi^+\pi^-$	904.5	5.9±0.2±0.4	8.0±2.0	9.90±1.16
$p\bar{p}\pi^+\pi^-\pi^0$	434.9	7.3±0.4±0.6	–	18.70±5.80
$\eta p\bar{p}$	9.8	0.8±0.3±0.3	–	3.80±2.09
$\omega p\bar{p}$	21.2	0.6±0.2±0.2	0.80±0.32	4.69±2.22
$\Lambda\bar{p}K^+$	74.0	1.0±0.1±0.1	–	10.92±2.93

Mode-by-mode, $\times 2^{\pm 1}$ deviations from 12% rule.

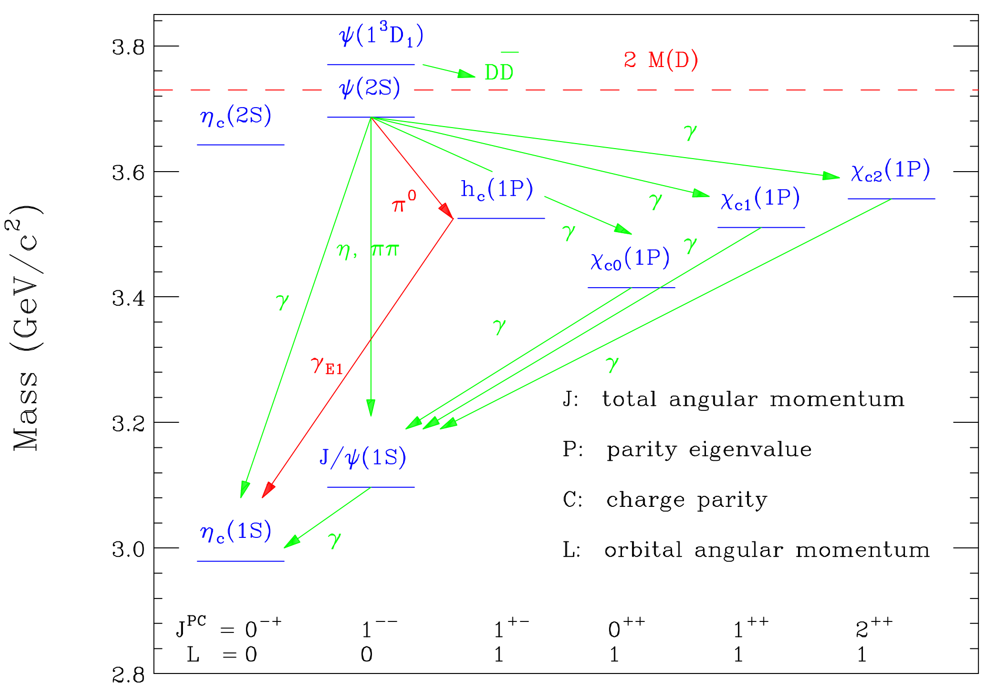
h_c OBSERVATION

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)

Expect $M(h_c) \equiv M(1^1P_1) \simeq \langle M(^3P_J) \rangle = 3525.36 \pm 0.06$ MeV

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



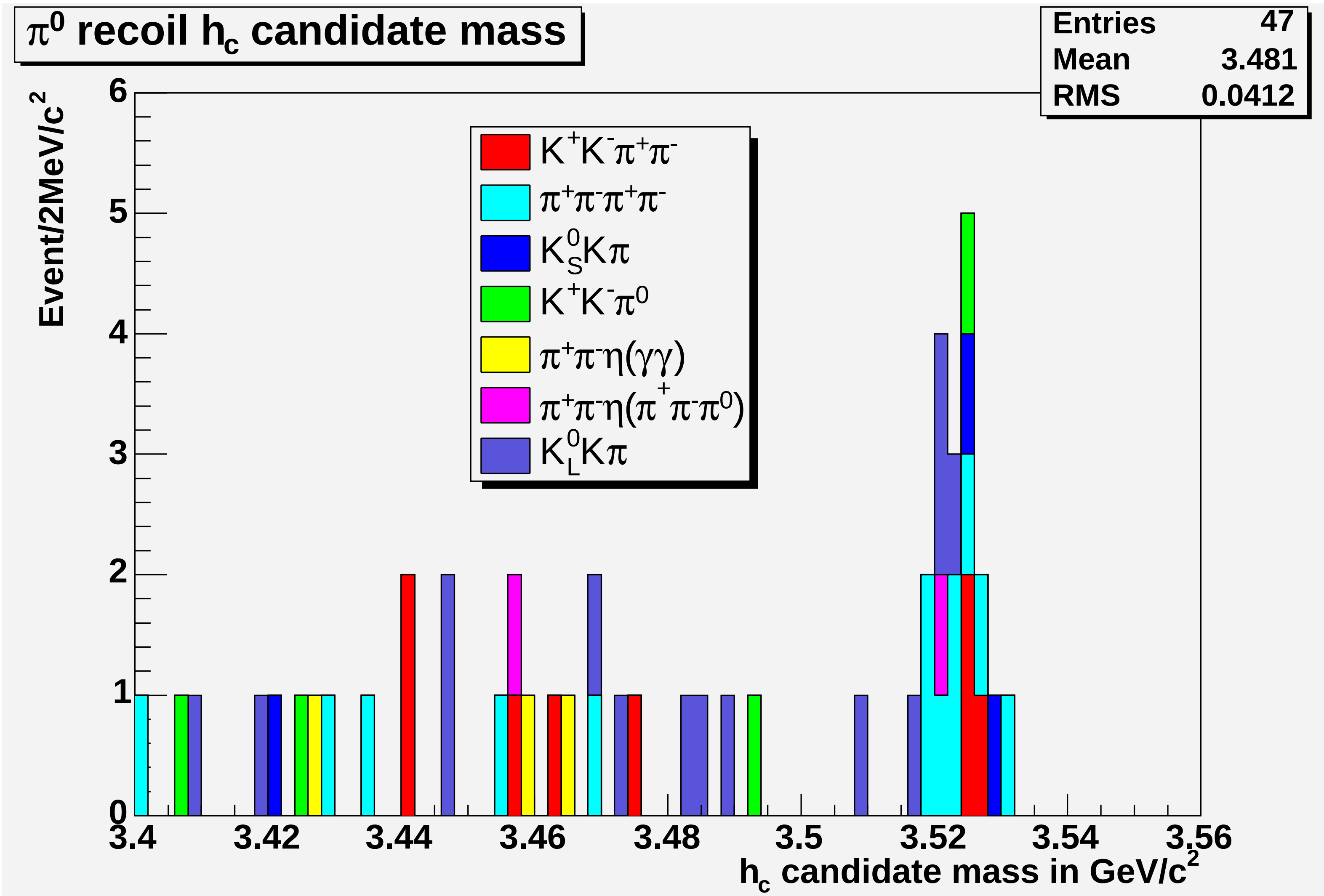
CLEO: Observation in $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma\eta_c$ (red arrows) (CLNS 05/1919,hep-ex/0505073 $\Rightarrow$ PRL)

Inclusive, exclusive analyses see a signal near $\langle M(^3P_J) \rangle$

Exclusive analysis reconstructs η_c in 7 decay modes

Inclusive: No η_c reconstruction.

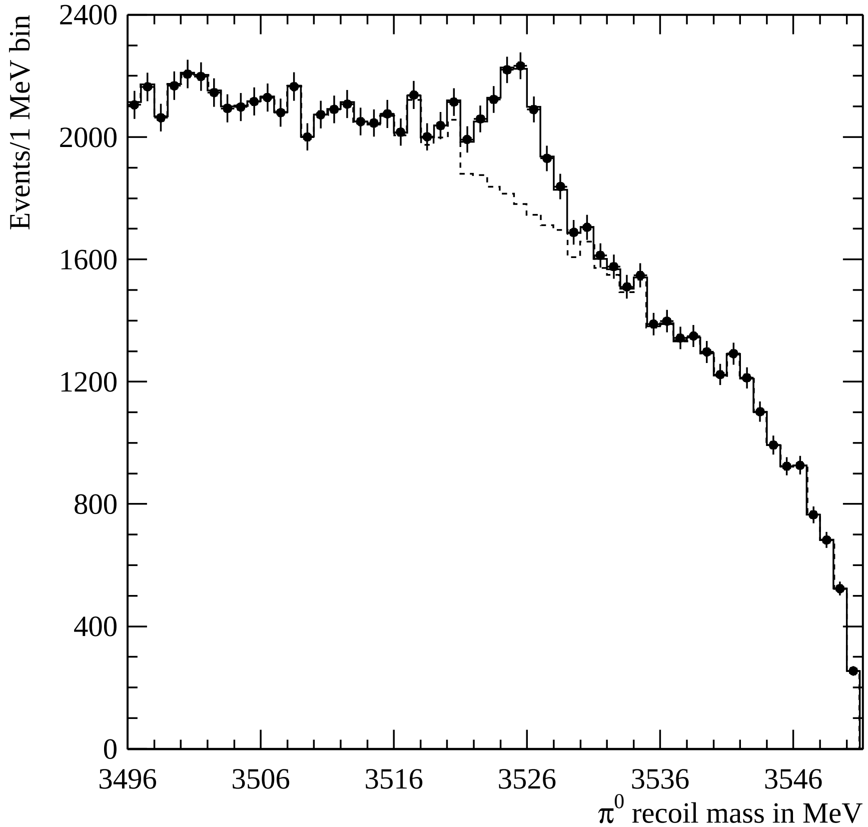
EXCLUSIVE h_c SIGNAL



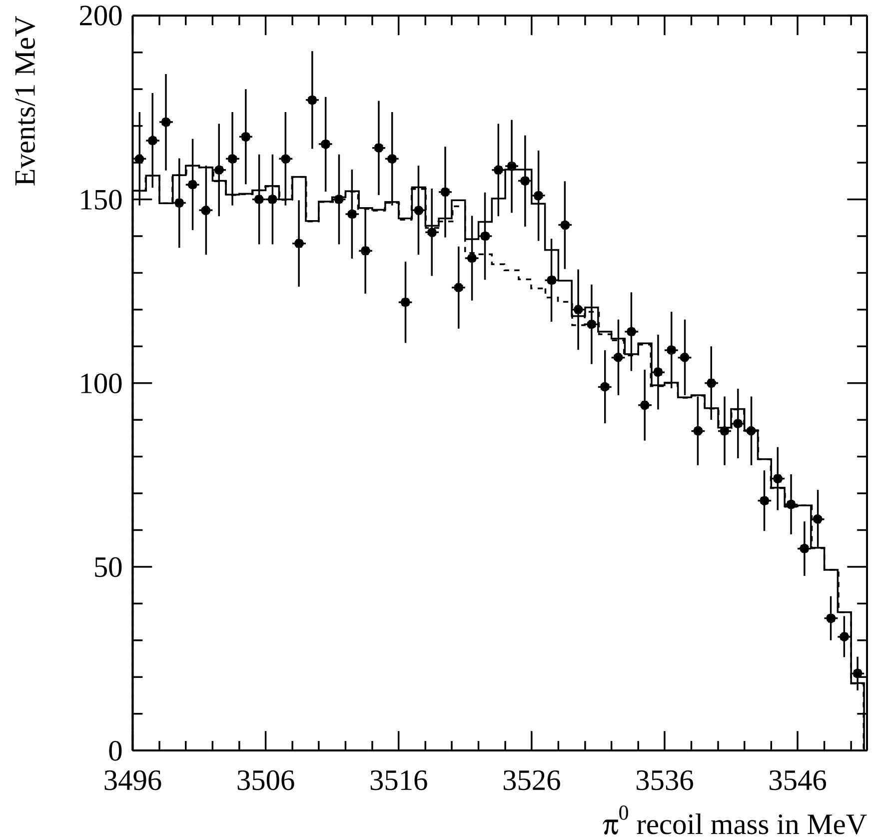
19 candidates identified; 17.5 ± 4.5 events above background. $M(h_c) = (3523.6 \pm 0.9 \pm 0.5)$ MeV; $\mathcal{B}_1(\psi' \to \pi^0 h_c)\mathcal{B}_2(h_c \to \gamma\eta_c) = (5.3 \pm 1.5 \pm 1.0) \times 10^{-4}$

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

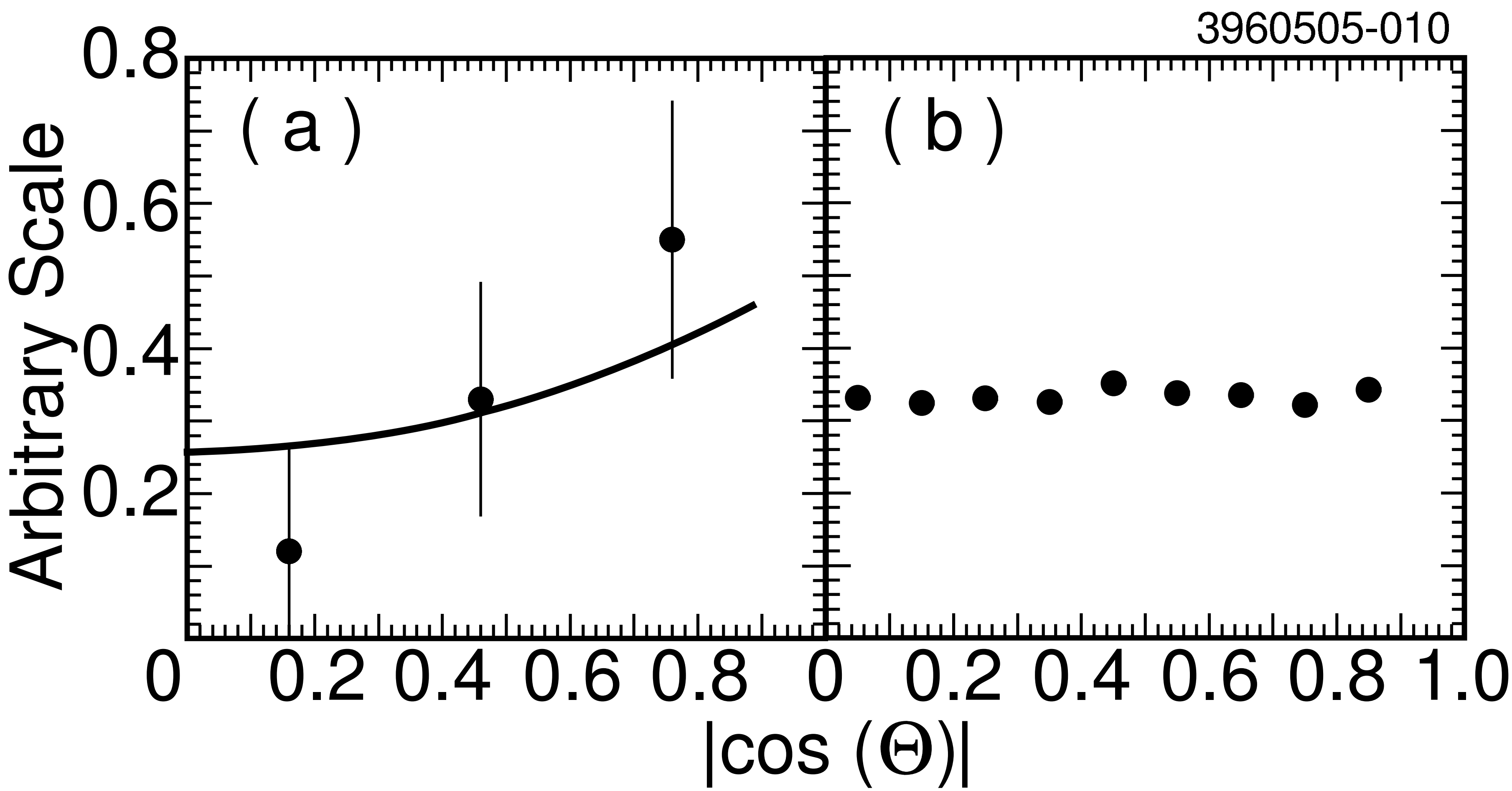
Combined: $M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV, $\mathcal{B}_1\mathcal{B}_2 = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$

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 $(10^{-3} \cdot 0.4)$

ANGULAR DISTRIBUTION

In $\psi(2S) \to \pi^0 h_c$ expect $\psi(2S)$ polarization to be transmitted to the h_c.

In $h_c \to \gamma\eta_c$ one then expects photons $\sim 1+\cos^2\theta$ with respect to beam axis.



(a) Signal; (b) background. Signal distribution is compatible with $1+\cos^2\theta$ (curve).

$\chi_{c2} \equiv \chi_2$ TWO-PHOTON WIDTH

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

Compatible with other measurements when they are corrected for CLEO's new $\mathcal{B}(\chi_2 \to \gamma J/\psi)$ and $\mathcal{B}(J/\psi \to \ell^+\ell^-)$. Errors in Table: stat, sys, br.

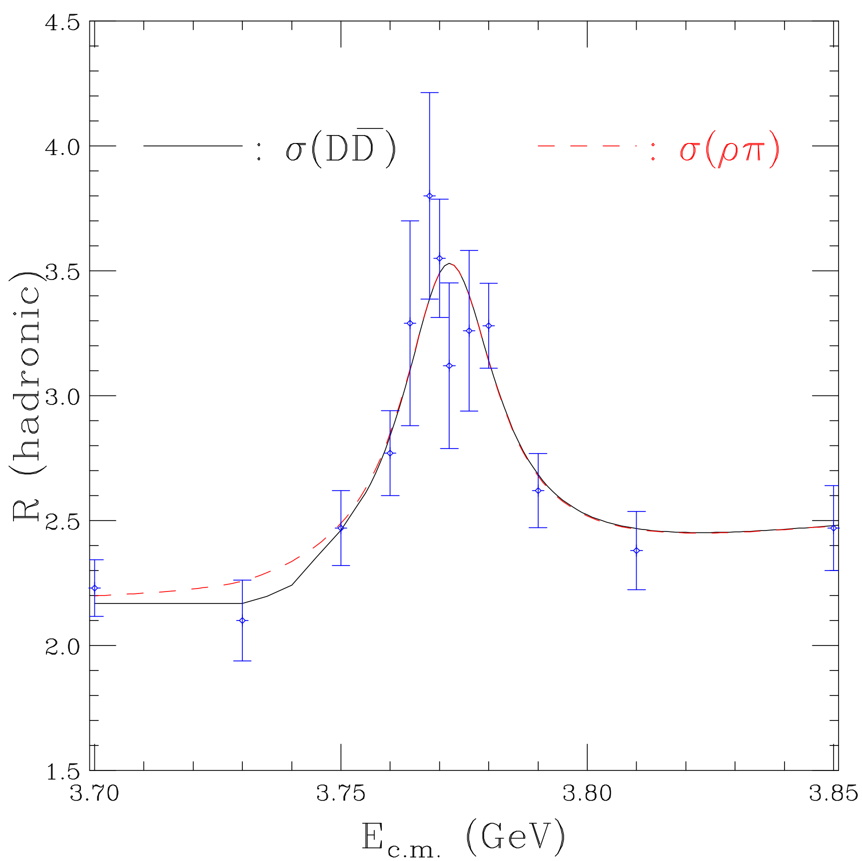
Measurement	$\Gamma_{\gamma\gamma}(\chi_2)$ (eV) (as published)	$\Gamma_{\gamma\gamma}(\chi_2)$ (eV) (after correction)
Present experiment ($\gamma\gamma \to \chi_2 \to \gamma\ell^+\ell^-$)		**559(59)(50)(36)**
Belle PL B **540**, 33 (2002) ($\gamma\gamma \to \chi_2 \to \gamma\ell^+\ell^-$)	850(80)(70)(70)	570(55)(46)(37)
CLEO PRL **87**, 061801 (2001) (($\gamma\gamma \to \chi_2 \to 4\pi$)	530(150)(60)(220)	417(118)(46)(59)
E835 PR D **62**, 052002 (2000) $(\bar{p}p \to \gamma\gamma)/(\bar{p}p \to \gamma J/\psi)$	270(49)(33)	384(69)(47)

$\Gamma(\chi_2) = 1.94 \pm 0.13$ 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 $=$ (2.8±0.5) $\times 10^3$ $\Gamma(\chi_2 \to \gamma\gamma)$, implying $\alpha_S(m_c) = 0.32 \pm 0.03$ vs $\alpha_S(m_\tau) = 0.35 \pm 0.03$ (PDG) if $\Gamma(\chi_2 \to$ hadrons) is dominated by two-gluon width.

$\psi''(3770)$: CHARM + ? FACTORY

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



$\sigma(\psi'')$ seems larger than $\Sigma(D\bar{D})$:

Collaboration	$\sigma(\psi'')$ (nb)
Crystal Ball	6.7 ± 0.9
Lead-Glass Wall	10.3 ± 1.6
Mark II	9.3 ± 1.4
$\Leftarrow$ BES	7.7 ± 1.1
Average	7.9 ± 0.6

What else does ψ'' decay to?

$\pi\pi J/\psi,\ \gamma\chi_{cJ}, \ldots$ at most 1–2%;

Light-hadron modes (CLEO)? $\rho\pi$ *suppressed*

$\psi''(3770) \Rightarrow$ CHARMONIUM

$\psi'' \to XJ/\psi$: CLEO, submitted to LP05 (preliminary):

ψ'' mode	$\mathcal{B}$ (%)
$\pi^+\pi^- J/\psi$	$0.189 \pm 0.022^{+0.007}_{-0.004}$
$\pi^0\pi^0 J/\psi$	$0.087 \pm 0.033^{+0.004}_{-0.003}$
$\eta J/\psi$	$0.067 \pm 0.044^{+0.004}_{-0.003}$
$\pi^0 J/\psi$	< 0.026

$\mathcal{B}[\psi''(3770) \to \pi^+\pi^- J/\psi]$ is about half of BES value [PL B **605**, 63 (2005)]: $(0.34 \pm 0.14 \pm 0.09)\%$

Conservatively sum to $< 1/2\%$

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

Study exclusive process $\psi'' \to \gamma\chi_{c1,2} \to \gamma\gamma J/\psi \to \gamma\gamma\ell^+\ell^-$

Mode	E_γ (MeV)	Predicted (keV) (a)	(b)	(c)	CLEO preliminary
$\gamma\chi_{c2}$	211	3.2	3.9	24 ± 4	
$\gamma\chi_{c1}$	253	183	59	73 ± 9	
$\gamma\chi_{c0}$	341	254	225	523 ± 12	–

No sensitivity to χ_{c0}: small $\mathcal{B}(\chi_{c0} \to J/\psi)$.

Inclusive $\gamma\chi_{c0}$: high bg.

Eichten-Lane-Quigg PR D **69**: (a) without, (b) with coupling to open channels; (c): JLR, hep-ph/0411003, to be published in Ann. Phys. (2005).

Even with maximum likely $\Gamma(\psi'' \to \gamma\chi_{c0})$, $\mathcal{B}(\psi'' \to \gamma\chi_{cJ}) < \mathcal{O}(2\%)$.

$\psi''(3770) \Rightarrow$ LIGHT HADRONS

Many CLEO analyses in progress: $\psi''(3770) \to VP$, $K_L K_S$, multi-body; σ re-check.

Two separate CLEO analyses presented to LP05 (preliminary); no evidence for any light-hadron ψ'' mode above expectations from continuum production except $\phi\eta$.

Upper limits on 26 modes summed $\Rightarrow \mathcal{B}[\psi'' \to$ (light hadrons)] $\leq 1.8\%$. Examples:

Mode	σ(3.67 GeV) (pb) [21 pb^{-1}]	σ(3.77 GeV) (pb) [281 pb^{-1}]
$\rho\pi$	$8.0^{+1.7}_{-1.4}\pm0.9$	$4.4\pm0.3\pm0.5$
$\omega\pi^0$	$14.5^{+2.6}_{-2.3}\pm1.5$	$14.8\pm0.6\pm1.5$
$\rho\eta$	$9.6^{+2.1}_{-1.8}\pm1.0$	$10.4\pm0.5\pm1.0$
$\phi\eta$	< 5.0	$4.5\pm0.5\pm0.5$
$K^{*0}\bar{K}^0$	$23.5^{+4.6}_{-2.4}\pm3.1$	$23.5\pm1.1\pm3.1$
$b_1\pi$	$7.9^{+3.1}_{-2.4}\pm1.8$	$7.6\pm0.7\pm1.8$

If cross sections scale as $1/s$: σ(3.77 GeV)/σ(3.67 GeV) $= 0.95$.

These and other cross sections at 3.77 GeV are consistent with continuum at 3.67 GeV

No "smoking gun" signature of non-$D\bar{D}$ ψ'' decays.

Known modes XJ/ψ, $\gamma\chi_{cJ}$, light hadrons, $\ldots \Rightarrow \Delta\mathcal{B}(\psi'') <$ (few %).

Trying to understand possible discrepancy of 1–2 nb in $\sigma(e^+e^- \to \psi'')$, or $\mathcal{B}(\psi'') =$ 10–20%. Effect of radiative corrections? CLEO σ remeasurement is crucial.

CHARM AT CLEO

Measurement of the D^+ decay constant

CLEO sees 7 events of $D^+ \to \mu^+\nu_\mu$ in ~ 60 pb^{-1} of e^+e^- collisions at $E_{\rm cm} = 3.77$ GeV $\Rightarrow \mathcal{B}(D^+ \to \mu^+) = (3.5 \pm 1.4 \pm 1.6) \times 10^{-4}$ and $f_{D^+} = (202 \pm 41 \pm 17)$ MeV.

Smaller errors to come (S. Stone, 281 pb^{-1}): check lattice QCD predictions.

Recent progress on singly-charmed baryon $\Sigma_c^*(2516, J^P = 3/2^+)$:

Mass differences, widths in MeV remeasured:

State	CLEO PR D **71**, 0551101 (2005)		PDG averages (2004)	
	$M(\Sigma_c^*) - M(\Lambda_c)$	$\Gamma(\Sigma_c^*)$	$M(\Sigma_c^*) - M(\Lambda_c)$	$\Gamma(\Sigma_c^*)$
Σ_c^{*++}	$231.5 \pm 0.4 \pm 0.3$	$14.4^{+1.6}_{-1.5} \pm 1.4$	234.5 ± 1.4	18 ± 5
Σ_c^{*+}	–	–	231.0 ± 2.3	< 17
Σ_c^{*0}	$231.4 \pm 0.5 \pm 0.3$	$16.6^{+1.9}_{-1.7} \pm 1.4$	232.6 ± 1.3	13 ± 5

Isospin mass splittings now quite small, in accord with theoretical expectations

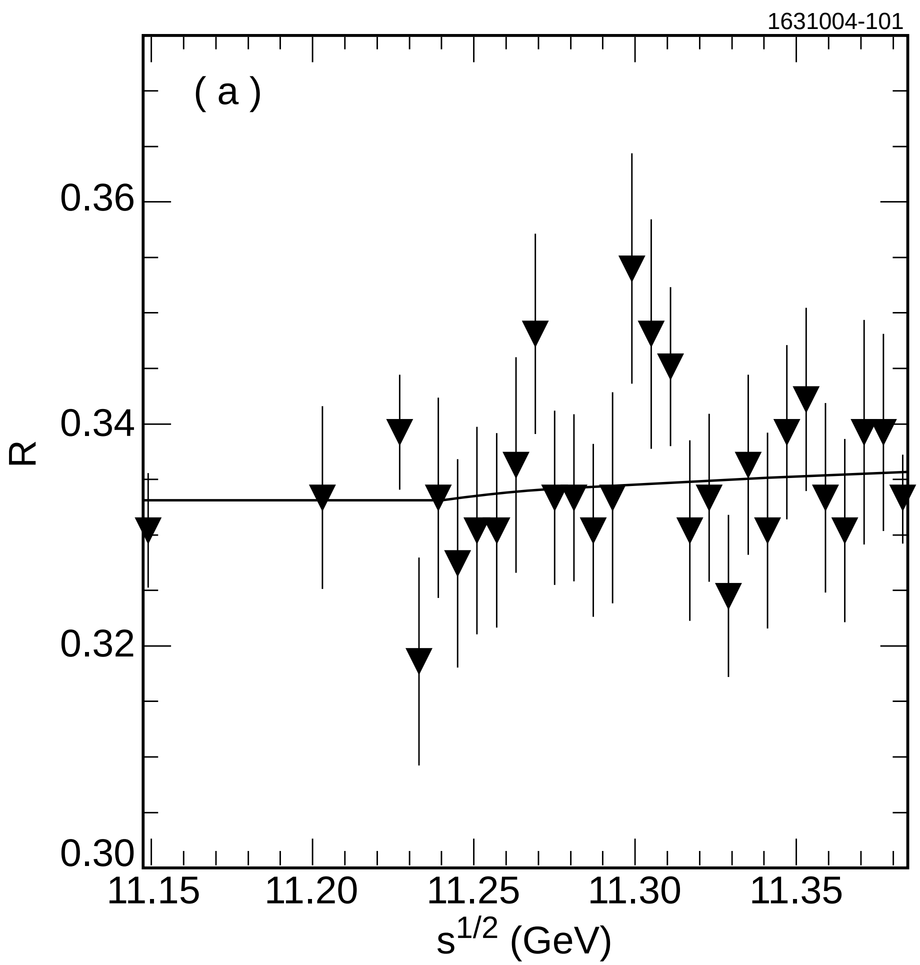
Heavy quark symmetry: $\Gamma(\Sigma_c^{*++})/\Gamma(\Sigma_c^{++}) = \Gamma(\Sigma_c^{*0})/\Gamma(\Sigma_c^{0}) = 7.5 \pm 0.1$

Observe: $\Gamma(\Sigma_c^{*++})/\Gamma(\Sigma_c^{++}) = 6.5 \pm 1.3$, $\Gamma(\Sigma_c^{*++})/\Gamma(\Sigma_c^{++}) = 7.5 \pm 1.7$.

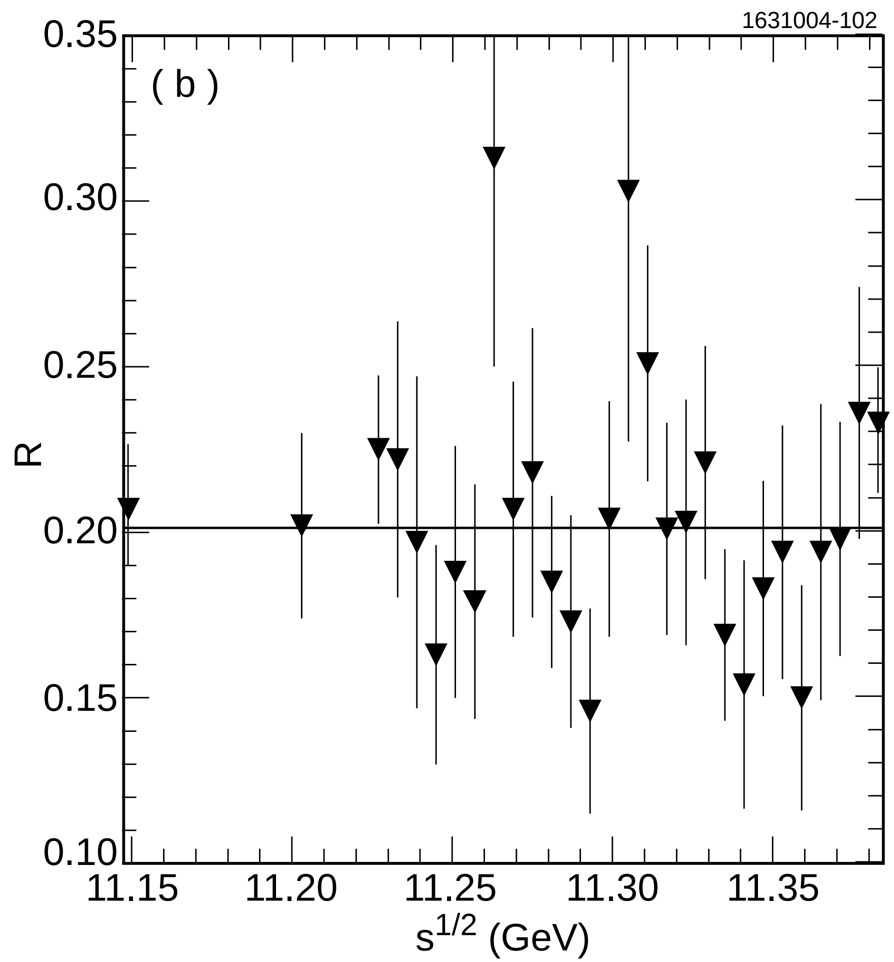
$\Lambda_b\overline{\Lambda}_b$ SEARCH NEAR THRESHOLD

Cross sections normalized by $\sigma(e^+e^- \to \mu^+\mu^-)$ [CLEO, PR D **71**, 012004 (2005):

Events with $\geq 1\bar{p}$

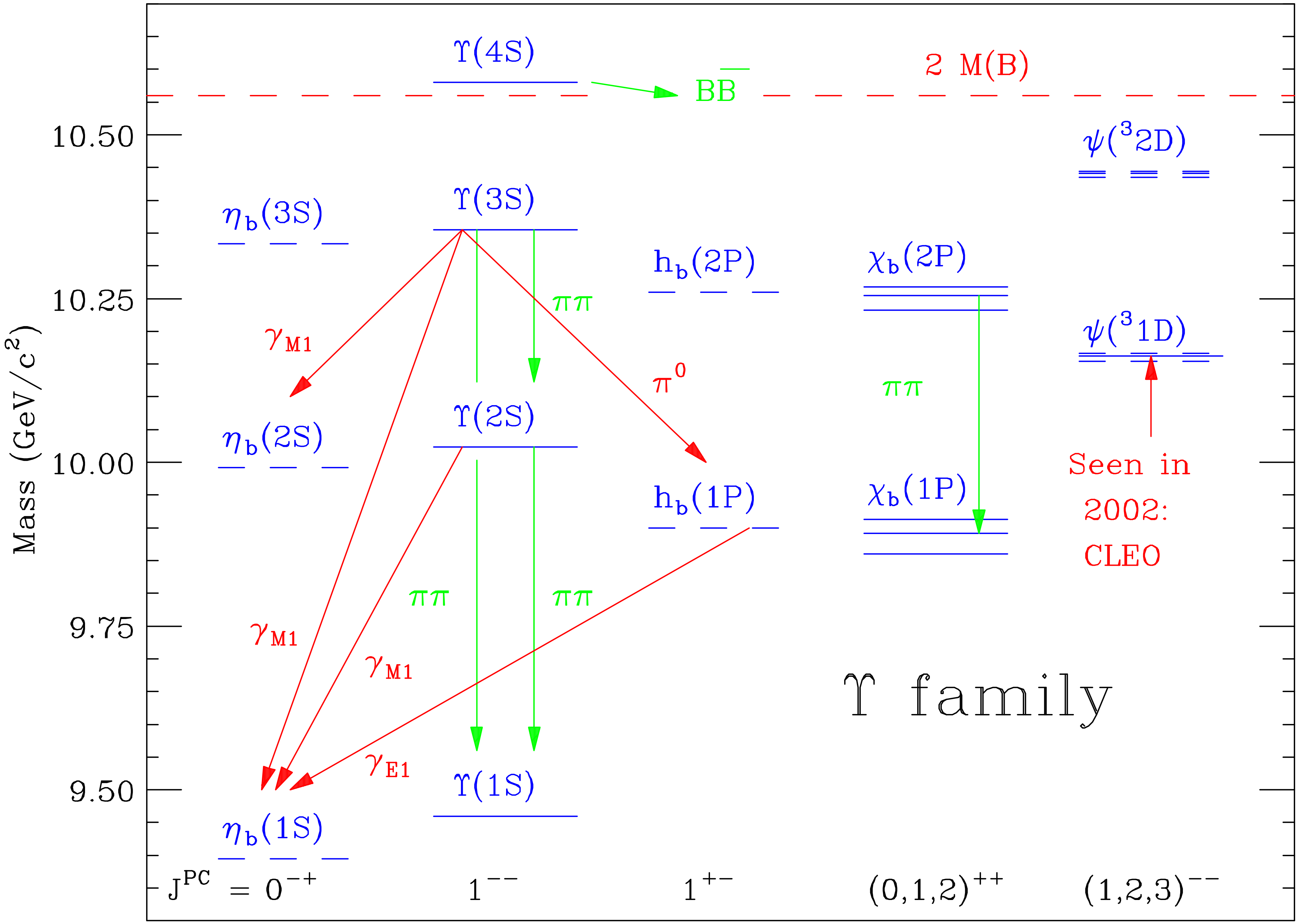


Events with $\geq 1\bar{\Lambda}$



Energy dependence of $\sigma(b\bar{b})$: $R(\Lambda_b\overline{\Lambda}_b) \lesssim 0.04$ (95% c.l.)

Υ STATES



CURRENT Υ ISSUES

New $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-) \Rightarrow$ lower $\Gamma_{\rm tot}(2S, 3S)$ [PRL **94**, 012001]

$\mathcal{B}(1S, 2S, 3S) \to \mu^+\mu^- = (2.39 \pm 0.02 \pm 0.07, 2.03 \pm 0.03 \pm 0.08, 2.39 \pm 0.07 \pm 0.10)\%$

$\Upsilon(2S, 3S) \to \gamma X$ decays [CLEO, PRL **94**, 032001 (2005).]

New measurements of E1 transition rates to $\chi_{bJ}(1P)$, $\chi'_{bJ}(2P)$ states

Searches for $\Upsilon(n'S) \to \gamma\eta_b(nS)$ $(n \neq n')$ 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.

Direct photon spectrum in $1S, 2S, 3S$ decays (CLEO CONF 05-7)

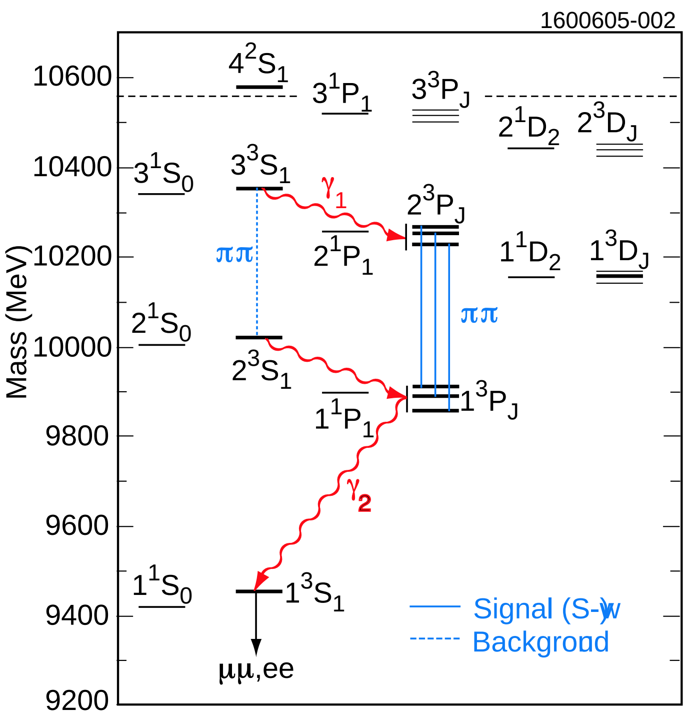
$R_\gamma \equiv \mathcal{B}(gg\gamma)/\mathcal{B}(ggg)$ measured using CLEO III data at & near $1S$, $2S$, $3S$

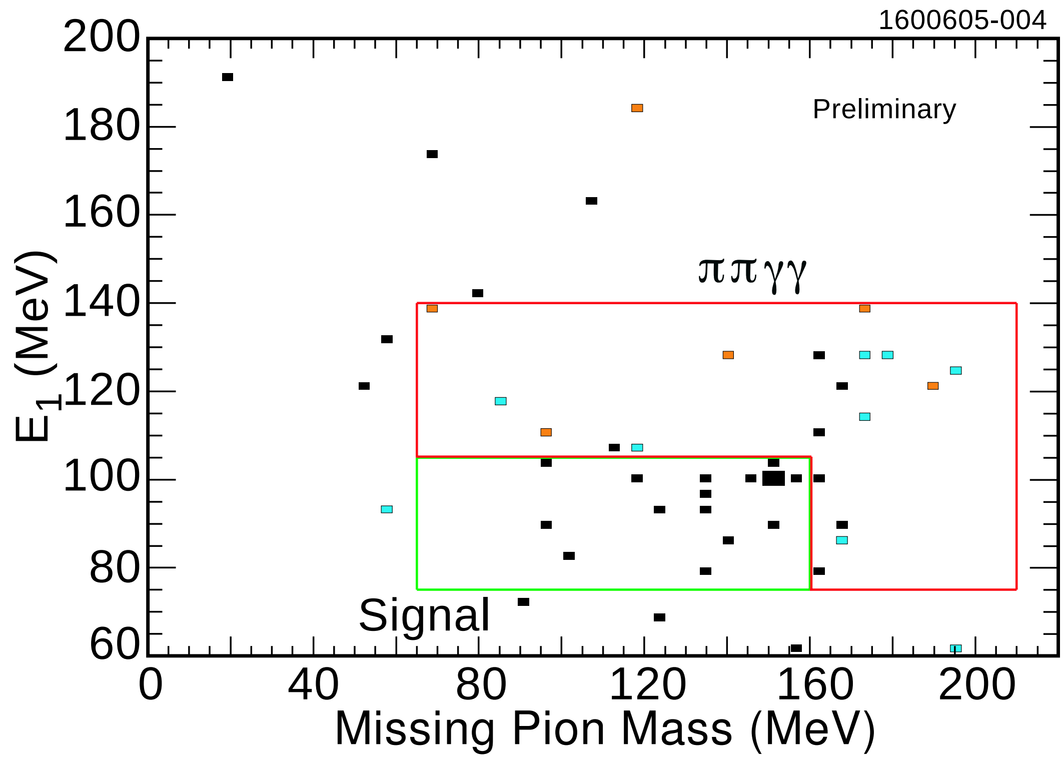
$R_\gamma(1S) = (2.50 \pm 0.01 \pm 0.19 \pm 0.13)\%$, $R_\gamma(2S) = (3.27 \pm 0.02 \pm 0.58 \pm 0.17)\%$,
$R_\gamma(3S) = (2.27 \pm 0.03 \pm 0.43 \pm 0.16)\%$

$R_\gamma(1S)$ consistent with CLEO 1.5 value $(2.54 \pm 0.18 \pm 0.14)\% \Rightarrow \alpha_S$.

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 ($\Uparrow$) 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.

Working now on $\chi_b' \to \pi^0\pi^0\chi_b$.

SUMMARY

Since leaving (most of) B-physics to the B factories, CLEO has made a wide variety of contributions to heavy-quark spectroscopy: charmonium, charm, beauty, $b\bar{b}$.

Present contributions are based on CLEO III data in the Υ and $\psi(2S)$ energy ranges and $\psi(2S)$, continuum, $\psi''(3770)$ data taken with the CLEO-c detector.

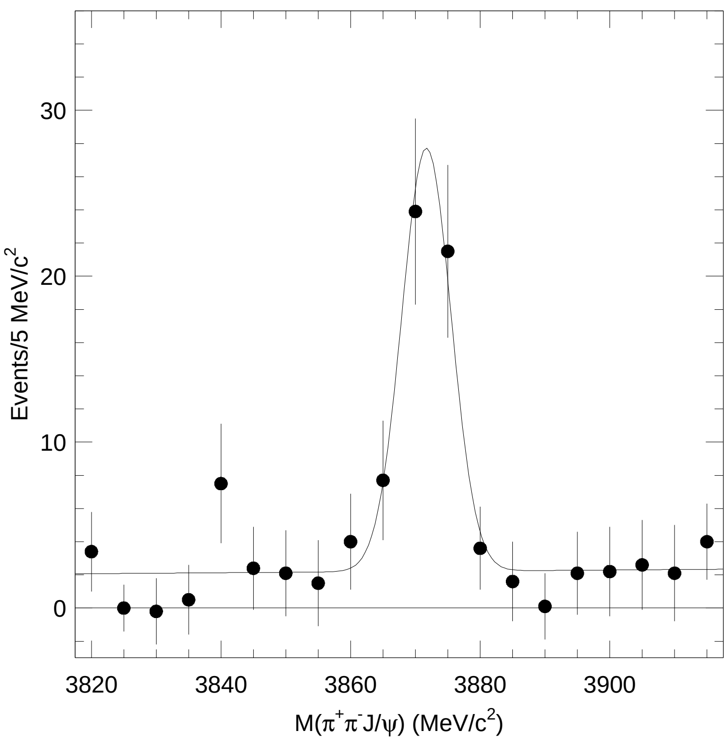
Discoveries include the long-sought h_c, the spin-singlet P-wave ground state of charmonium. Its mass and production rate are not surprising but we don't always need surprises: confirmation of basic ideas about quark confinement and isospin-violating π^0-emission transitions.

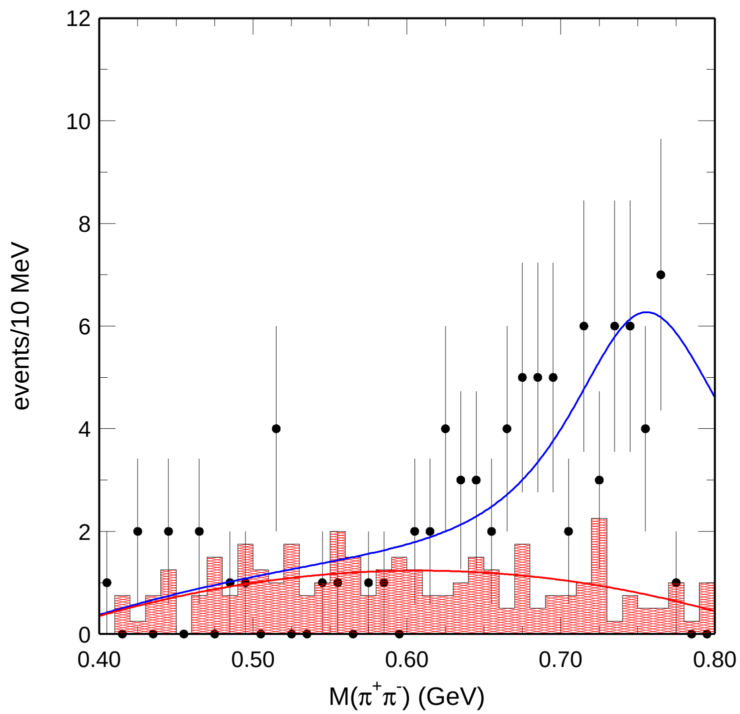
Decays of $\psi''(3770)$ are shedding light on its nature and we look forward to much more data on this state.

A rich CLEO program will include much further spectroscopy: resonances above thresholds for $D\bar{D}$, $D\bar{D}^*$ (+ c.c.), $D^*\bar{D}^*$, corresponding $D_s^{(*)}$ thresholds; D_s studies; $J/\psi \to$ light-quark states.

X(3872): MOLECULAR STATE

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



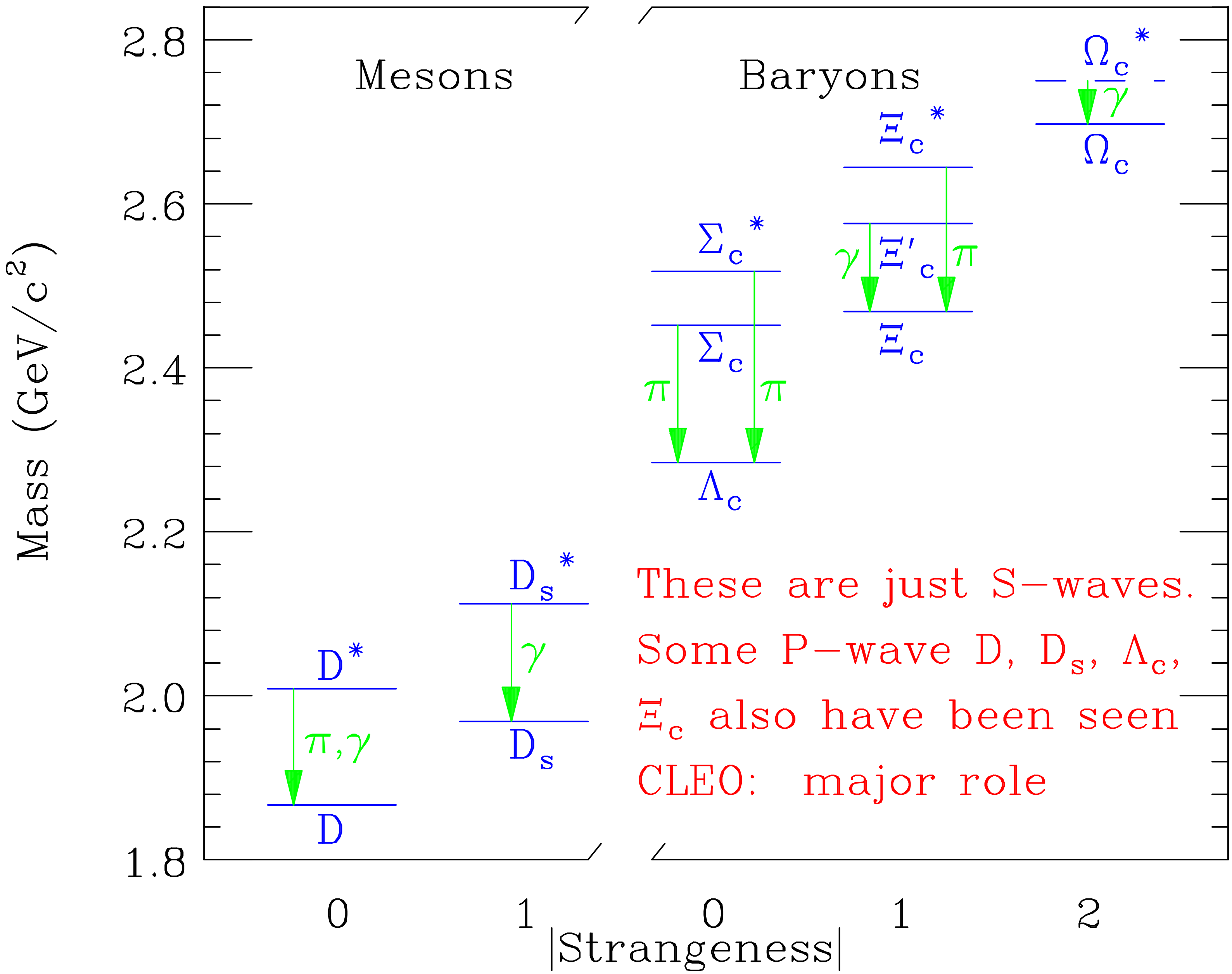


Well above $D\bar{D}$ threshold; favors unnatural $J^P = 0^-, 1^+, 2^-$ ($J \geq 3$ unlikely)

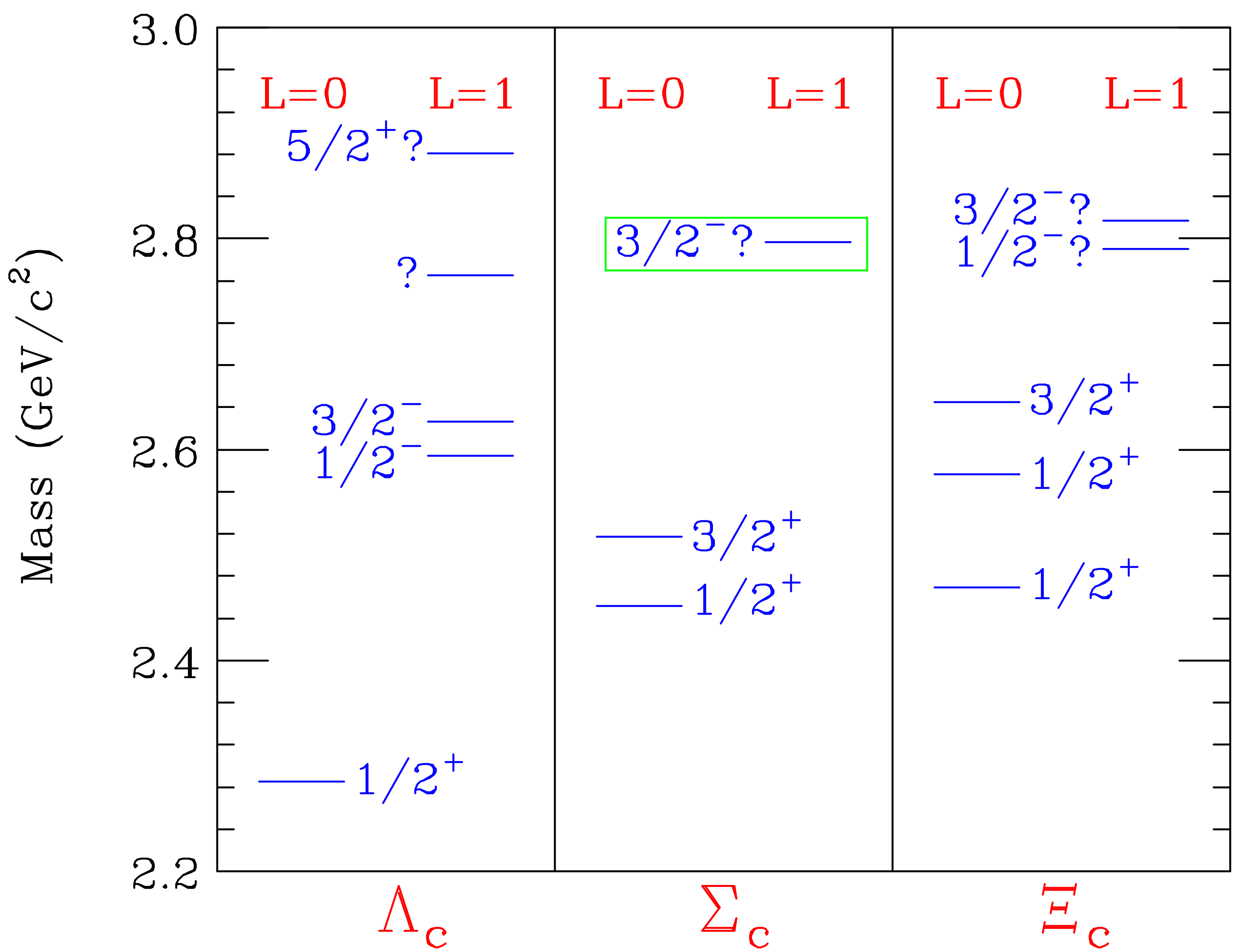
Belle: $J^{PC} = 1^{++}$ strongly favored (angular distributions; $\rho J/\psi$ and $\omega J/\psi$ decays)

Likely an S-wave bound state of $(D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2} \sim c\bar{c}u\bar{u}$ (Törnqvist; Swanson). Doesn't couple to γ^* or $\gamma\gamma$ [CLEO, PRL **94**, 032004 (2005)].

LOW-LYING CHARMED STATES



EXCITED CHARMED BARYONS



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 $5/2^-$.

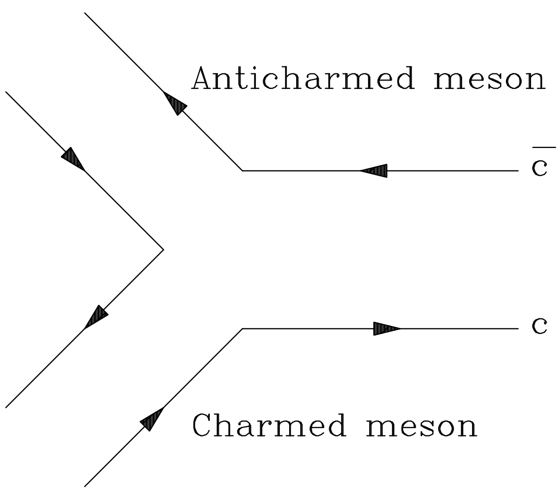
In Σ_c light-quark pair has $S = 1$; adding $L = 1$ allows $J^P \leq 5/2^-$.

OPTIMIZING D_s PRODUCTION

CLEO: best strategy for scanning $E_{\rm cm}$ to optimize D_s production?

What follows: simple phenomenology, not necessarily endorsed by CLEO

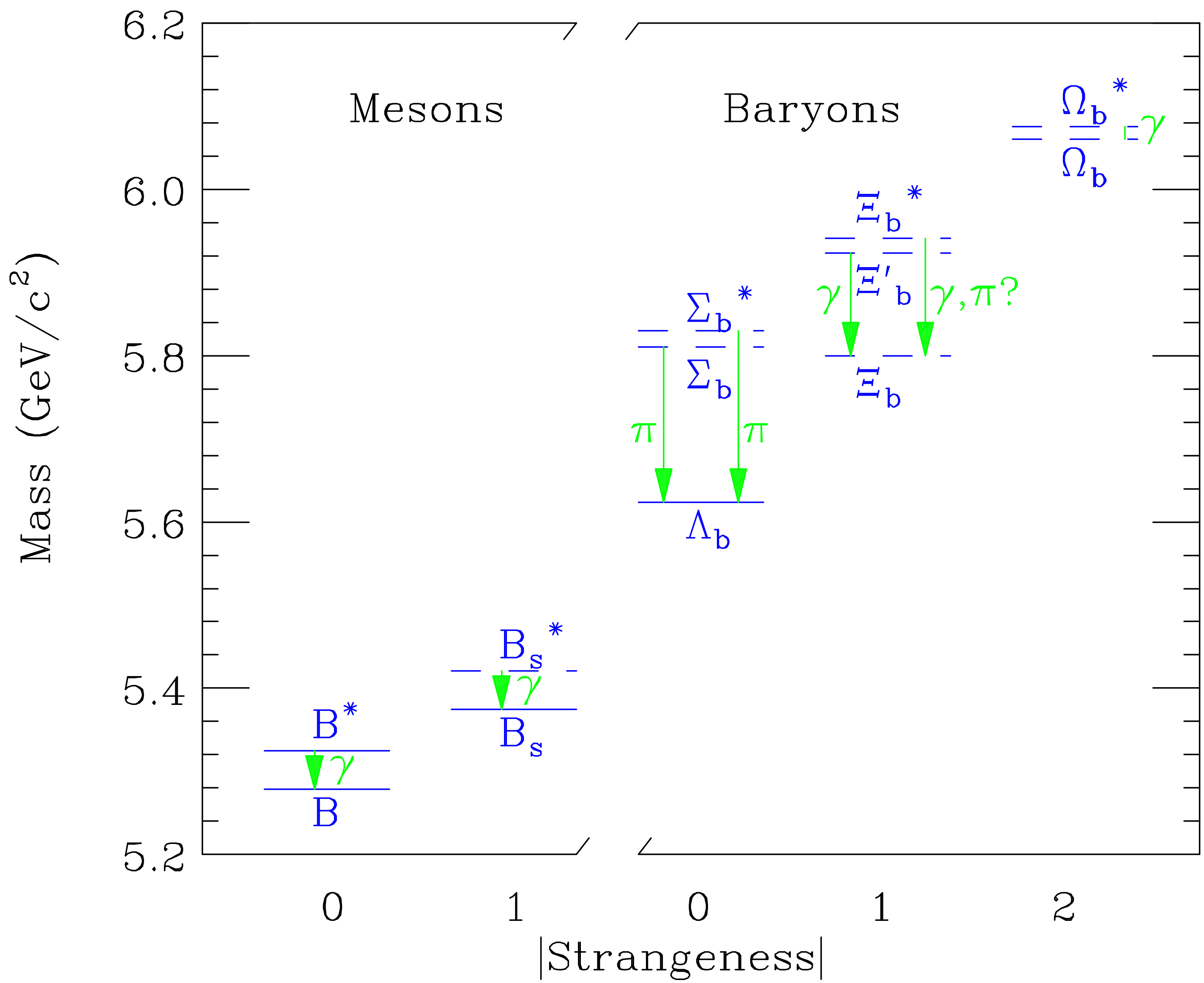
Model for resonance formation [JLR, PR D **6**, 2717 (1972)]: If a meson M_1 and a meson M_2 have quarks which can mutually annihilate, they form at least one resonance when $p_{\rm CM} \le 350$ MeV/c. Denote this resonance mass by $M_{\rm max}$.



Channel	Threshold (MeV)	$M_{\rm max}$ (MeV)	Candidate below $M_{\rm max}$
$D^0\bar{D}^0$	3738.8	3804.3	$\psi''(3770)$
D^+D^-	3729.2	3794.9	$\psi''(3770)$
$D^0\overline{D^{*0}}$+c.c.	3871.3	3934.7	$X(3872)$
$D^+\overline{D^{*+}}$+c.c.	3879.4	3942.6	$X(3940)$
$D^{*0}\overline{D^{*0}}$	4013.4	4075.5	$\psi(3S)$
$D^{*+}\overline{D^{*+}}$	4020.0	4081.0	$\psi(3S)$
$D_s\bar{D}_s$	3936.6	3998.8	?
$D_s\overline{D_s^*}$+c.c.	4080.4	4140.5	?
$D_s^*\overline{D_s^*}$	4224.2	4282.2	?

Detailed estimates by Barnes, Close, Swanson; Byers and Eichten (needs updating!)

BEAUTY HADRONS



Less progress than for charm on baryons or P-waves. Waiting for B_s–$\overline{B}_s$ mixing!
CLEO: No magic energy for $\Lambda_b\overline{\Lambda}_b$ production just above threshold.