Heavy Quarkonia ($c\bar{c}$, $b\bar{b}$)
- Results from CLEO -

Kamal K. Seth
Northwestern University

LATTICE 2004
Fermilab, June 21 – 25, 2004

Introduction

- Heavy quarkonia ($c\bar{c}$ charmonium, $b\bar{b}$ bottomonium) provide the best means of testing QCD, both
  - the validity of perturbative QCD and potential models, and
  - lattice QCD calculations.

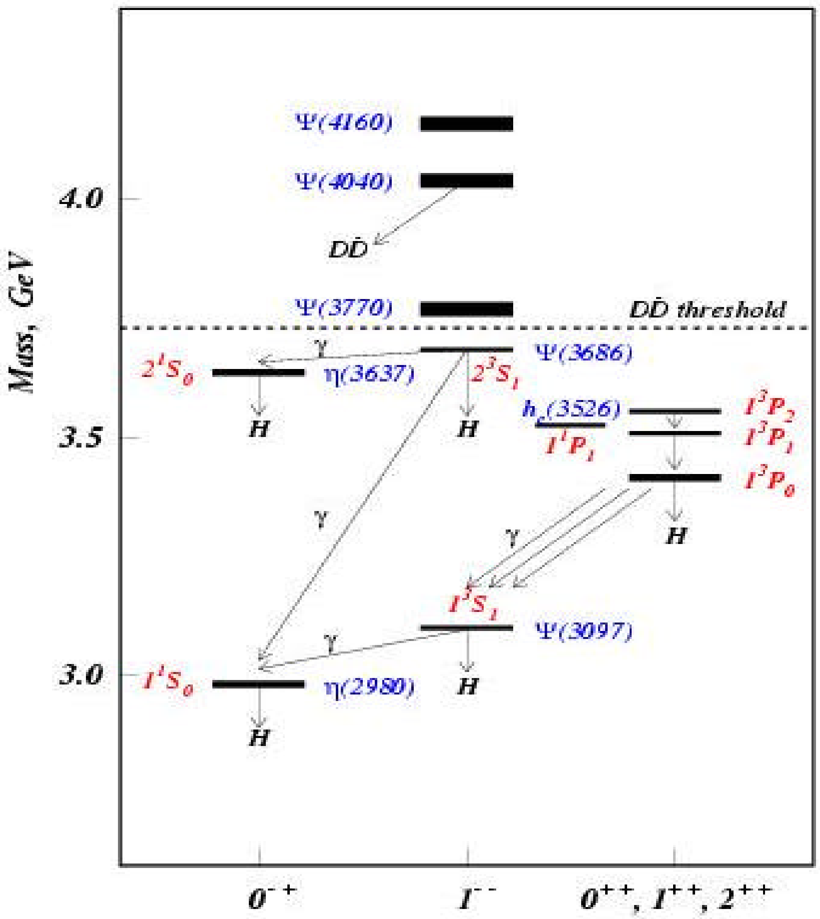
- Bottomonium ($b\bar{b}$) is better then charmonium ($c\bar{c}$), both because it has smaller relativistic problems ($\langle v^2/c^2 \rangle \approx 0.1$ versus ≈ 0.2) and smaller coupling constant ($\alpha \approx 0.2$ versus ≈ 0.35), but much less high precision spectroscopic information is available for bottomonium.

- No $b\bar{b}$ singlet states are known, and very few hadronic and radiative decays are known. Nevertheless, progress is being made through recently taken $\Upsilon(nS)$ data with CLEO III.

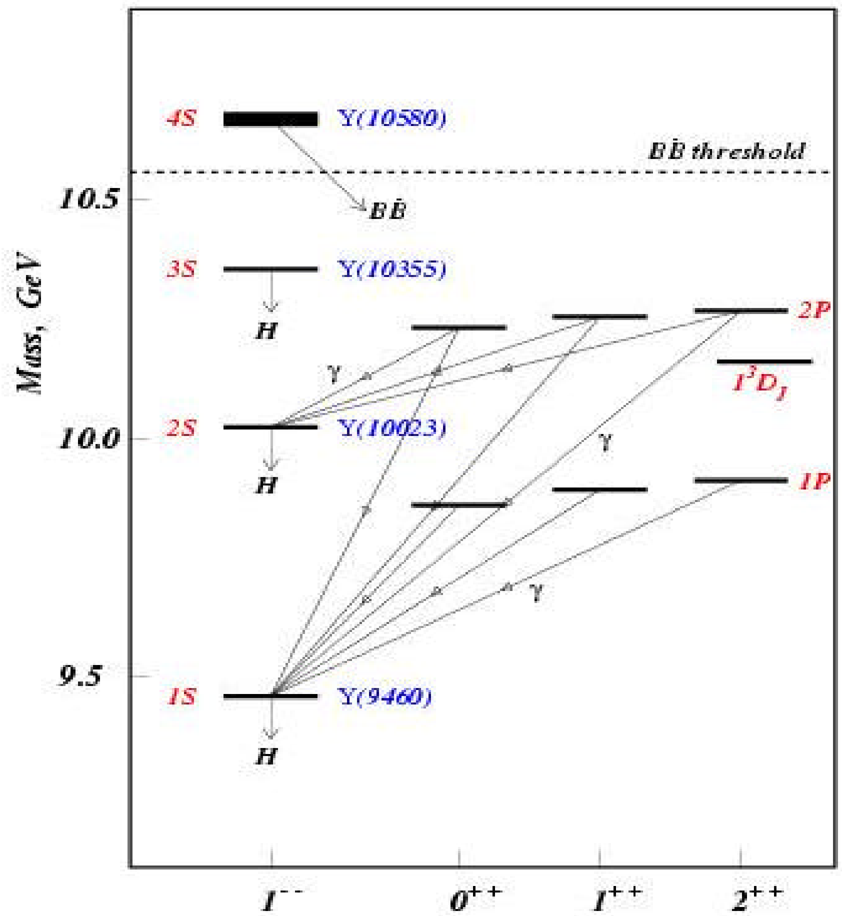
- With the beginning of the CLEO-c program, interesting new results are being produced in the charmonium region.

A Text Book Picture

Charmonium



Bottomonium



Scope of Talk

- New in **Upsilon** **Spectroscopy**
  - $\Upsilon(1^3D_2)$
  - $\Upsilon(nS) \rightarrow \mu^+\mu^-$
  - $\Upsilon(1S) \rightarrow J/\Psi + X$
  - hadronic transitions from $\Upsilon(3S)$

- New in **Charmonium** **Spectroscopy**
  - $\gamma\gamma \rightarrow \eta_c^/(2^1S_0)$
  - $\Psi^/(2S) \rightarrow$ hadrons
  - radiative transitions from $\Psi^/(2S)$
  - $\gamma\gamma \rightarrow X(3872)$, ISR$\rightarrow X(3872)$

CLEO (e^+e^-) Data Sets

E_{cm}(GeV)	State	#events(10^6)	Experiment
9.46	$\Upsilon(1S)$	**2**	CLEO II
	$\Upsilon(1S)$	**20**	CLEO III
10.02	$\Upsilon(2S)$	**0.5**	CLEO II
	$\Upsilon(2S)$	**10**	CLEO III
10.36	$\Upsilon(3S)$	**0.5**	CLEO II
	$\Upsilon(3S)$	**5**	CLEO III
3.69	$\Psi^{/}(2S)$	**3**	CLEO III CLEOc

First Observation of New Υ(1D) State of Bottomonium

Υ(1D) state was observed in the following 4 photon cascade:

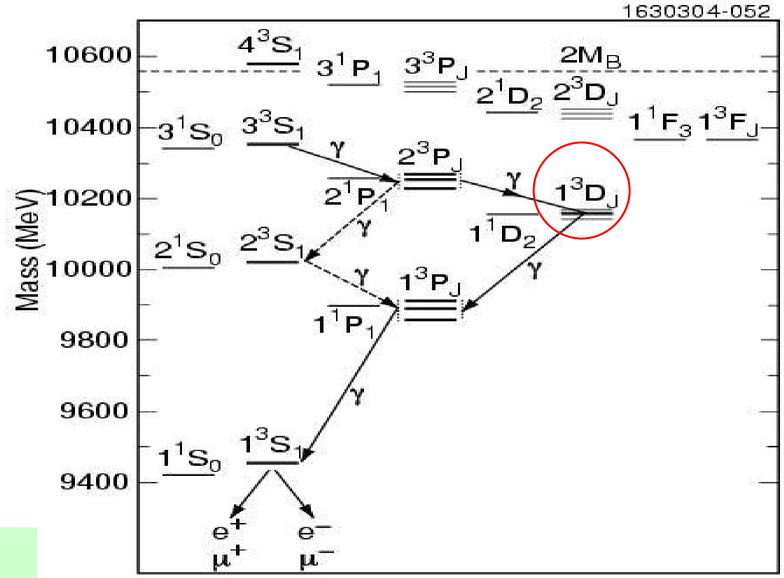
$\Upsilon(3S) \rightarrow \gamma_1 \chi(2P)$

$\downarrow \gamma_2$ **¡ (1D)**

$\downarrow \gamma_3 \chi(1P)$

$\downarrow \gamma_4\, \Upsilon(1S)$

$\downarrow e^+e^-, \mu^+\mu^-$

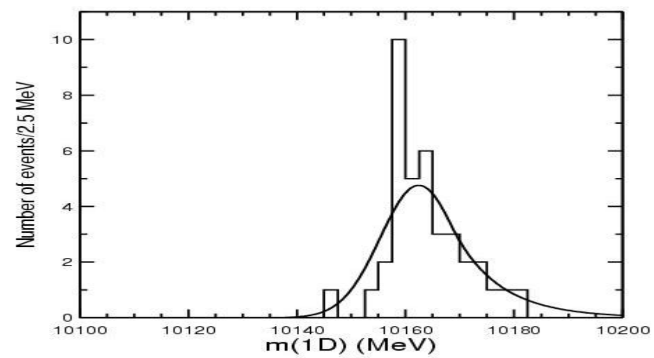


34.5 ± 6.4 signal events were observed.

Significance of the signal = **10.2** σ

$M[\Upsilon(1^3D_2)] = \mathbf{10161.1 \pm 0.6 \pm 1.6}$ (MeV)

$B(\gamma\gamma\gamma\gamma l^+l^-)_{\Upsilon(1D)} = (\mathbf{2.6 \pm 0.5 \pm 0.5}) \times 10^{-5}$



- Mass is consistent with predictions from potential models and Lattice QCD calculations.
- Cascade assignment $\chi_1(2^3P_1) \rightarrow \mathbf{1^3D_2} \rightarrow \chi_1(1^3P_1) \rightarrow \Upsilon(1S)$ and the measured product branching ratio are consistent with the predictions of Godfrey and Rosner.

Measurement of the B[ϒ(nS) → μ⁺μ⁻]

preliminary

• The important parameters of ϒ(2S) and ϒ(3S) resonances - leptonic widths, Γ_{ee} and total widths, Γ are not well established.

• Measurement of ϒ(nS) decay to muon pairs relative to hadrons near resonance peaks gives:

$$\bar{B}_{mm} = \frac{\Gamma_{mm}}{\Gamma_{had}} = \frac{N(Y \to m^{+}m^{-})/e_{mm}}{N(Y \to hadrons\;)/e_{had}}$$

• Assuming lepton universality,

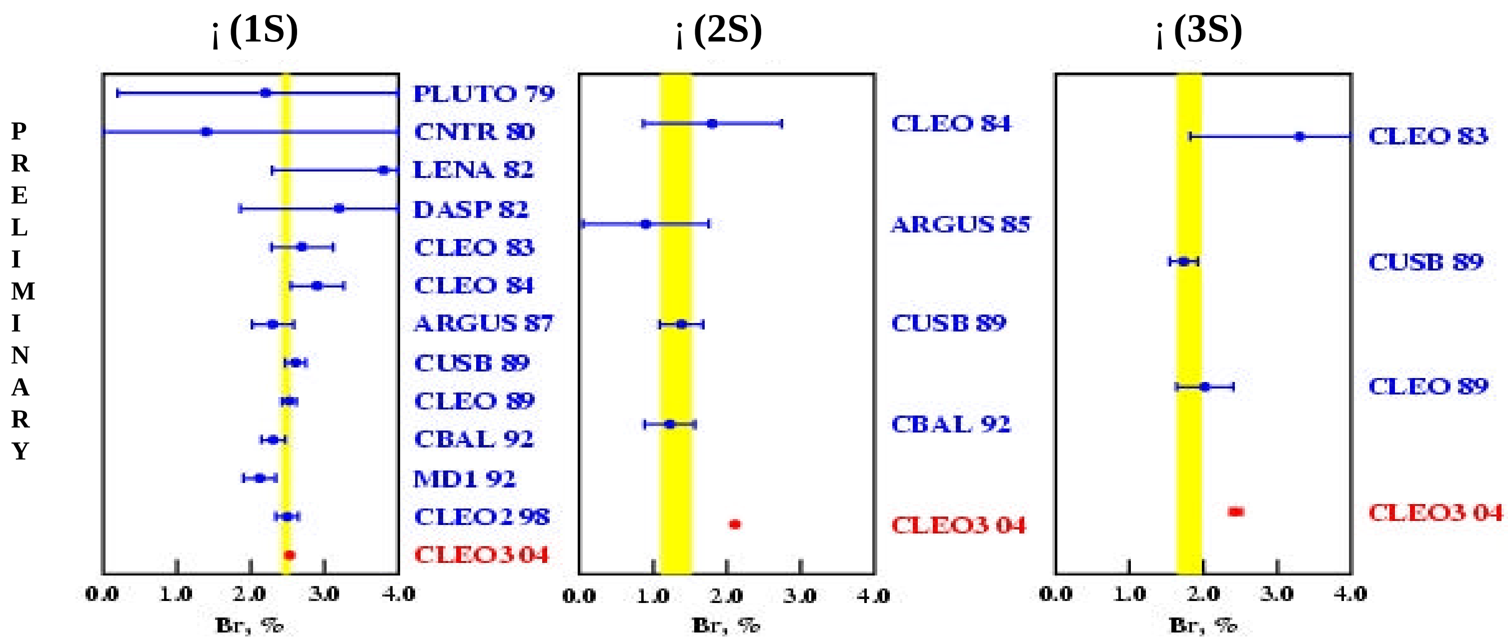
$$B_{mm} = \frac{\Gamma_{mm}}{\Gamma} = \frac{\bar{B}_{mm}}{1+3\bar{B}_{mm}}$$

• Analysis of CLEO III resonance scans (in progress) will provide separate measurements of Γ_{ee} and therefore lead to precision measurements of $\Gamma=\Gamma_{ee}/B_{\mu\mu}$.

Measurement of the $B[\Upsilon(nS) \to \mu^+\mu^-]$

preliminary

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
$B_{\mu\mu}(\%)$ CLEO	**2.53 ± 0.02 ± 0.05**	**2.11 ± 0.03 ± 0.05**	**2.44 ± 0.07 ± 0.05**
$B_{\mu\mu}(\%)$ PDG	**2.48 ± 0.06**	**1.31 ± 0.21**	**1.81 ± 0.17**



Good agreement for $\Upsilon(1S)$ Large discrepancy for $\Upsilon(2S,3S)$

$\Upsilon(1S)$ Decays to Charmonia

preliminary

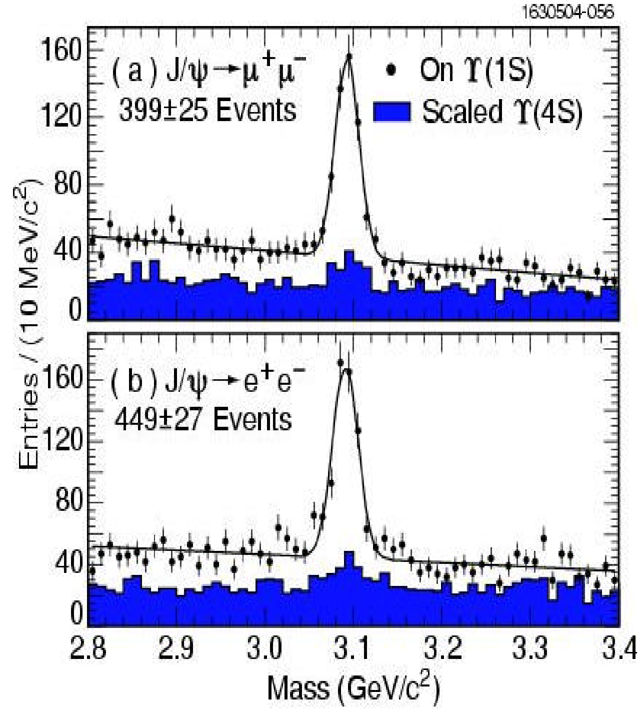
- $\Upsilon(1S)$ decays to J/Ψ, Ψ', and $\chi_{c1,c2}$ have been measured.

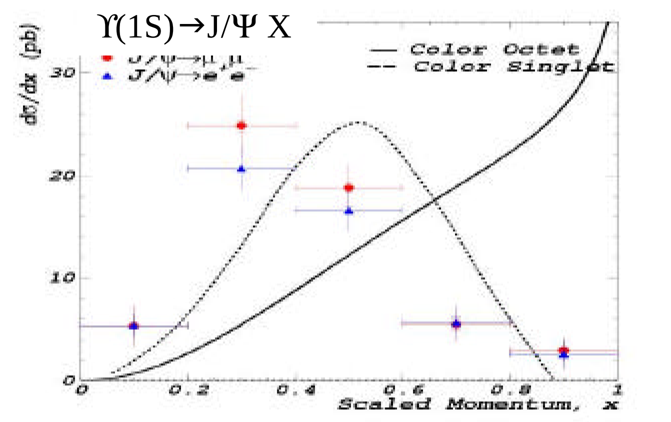
- The decay $\Upsilon(1S) \to J/\Psi\ X$, $J/\Psi \to e^+e^-, \mu^+\mu^-$ leads to

$$B_{\mu\mu}[\Upsilon(1S) \to J/\Psi + X] = (\mathbf{6.4} \pm \mathbf{0.5}) \times 10^{-4}$$

$$B_{ee}[\Upsilon(1S) \to J/\Psi + X] = (\mathbf{5.7} \pm \mathbf{0.4}) \times 10^{-4}$$

- J/Ψ momentum distribution is found to be in clear disagreement with the prediction based on the color octet model (Cheung et al., PRD 54(1996)929), and in qualitative agreement with color singlet model.



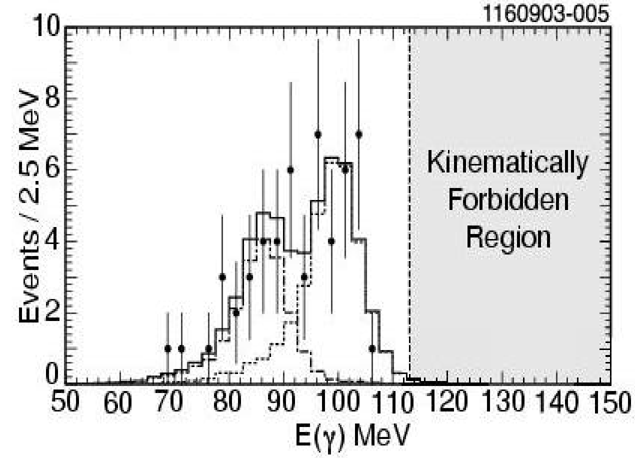


First Observation of $\chi_b^{/}(2P) \rightarrow \omega\Upsilon(1S)$

- For the first time in a bottomonium system a hadronic transition, other than $\Upsilon(nS) \rightarrow \Upsilon(n^{/}S)\pi\pi$ has been observed, with

$B[\chi_{b1}(2P) \rightarrow \omega\Upsilon(1S)] = \mathbf{(1.63 \pm 0.38)}\ \%$

$B[\chi_{b2}(2P) \rightarrow \omega\Upsilon(1S)] = \mathbf{(1.10 \pm 0.34)}\ \%$

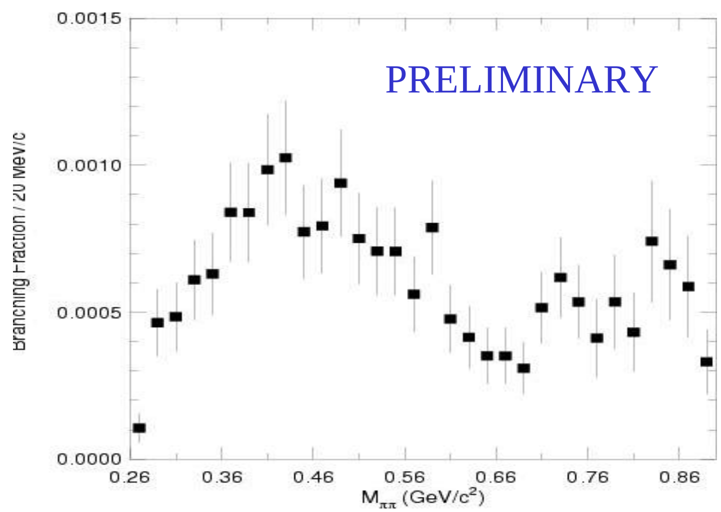


Dipion Decays of $\Upsilon(3S)$

- The decays $\Upsilon(3S) \rightarrow \pi^0\pi^0\ \Upsilon(1S,2S)$ are found to have dipion mass distributions in agreement with those observed for corresponding $\pi^+\pi^-$ dipion decays.

$B[\Upsilon(3S) \rightarrow \pi^0\pi^0\ \Upsilon(2S)] = \mathbf{2.02 \pm 0.18 \pm 0.38}\ \ (\%)$

$B[\Upsilon(3S) \rightarrow \pi^0\pi^0 Y(1S)] = \mathbf{1.88 \pm 0.08 \pm 0.31}\ \ (\%)$



PRELIMINARY

Discovery of $\eta_c'(2S)$

- Belle experiment observed $\eta_c'(2S)$ in two different channels:

$B^{\pm} \to K^{\pm}(\eta_c') \to K^{\pm}(K_s K^{\pm} \pi^{\mp})$ $M(\eta_c') = \mathbf{3654} \pm \mathbf{6} \pm \mathbf{8}$ (MeV)

$e^+e^- \to J/\Psi \eta_c'$ $M(\eta_c') = \mathbf{3622} \pm \mathbf{12}$ (MeV)

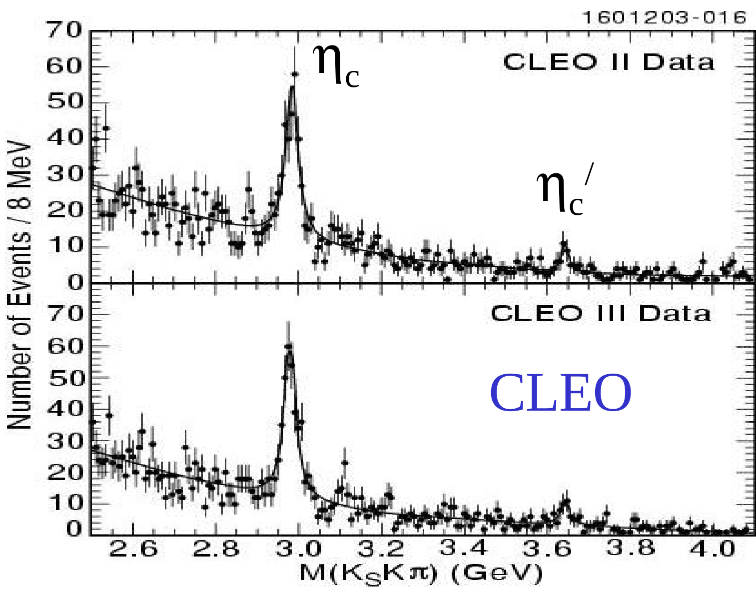
CLEO and BaBar have observed $\eta_c'(2S)$ in two photon fusion

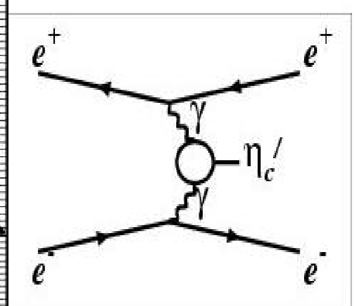
$M = \mathbf{3642.}9 \pm 3\mathbf{.}1 \pm 1\mathbf{.5}$ (MeV)
$\Gamma < \mathbf{31}$ MeV (90% C.L.)
$\Gamma_{\gamma\gamma} = \mathbf{1.}3 \pm 0\mathbf{.6}$ (keV)

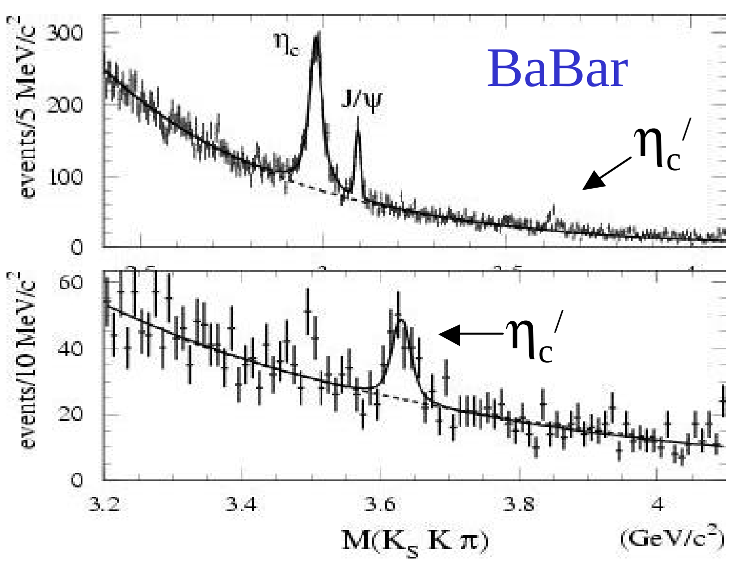
$h'_c \to K_s K^{\pm} p^{\mp}$

$M = \mathbf{3630.}8 \pm 3\mathbf{.}4 \pm 1\mathbf{.0}$ (MeV)

$\Gamma = \mathbf{17.}0 \pm 8\mathbf{.}3 \pm 2\mathbf{.5}$ (MeV)







Discovery of $\eta_c^{/}(2S)$

- The average of Belle, BaBar, CLEO is

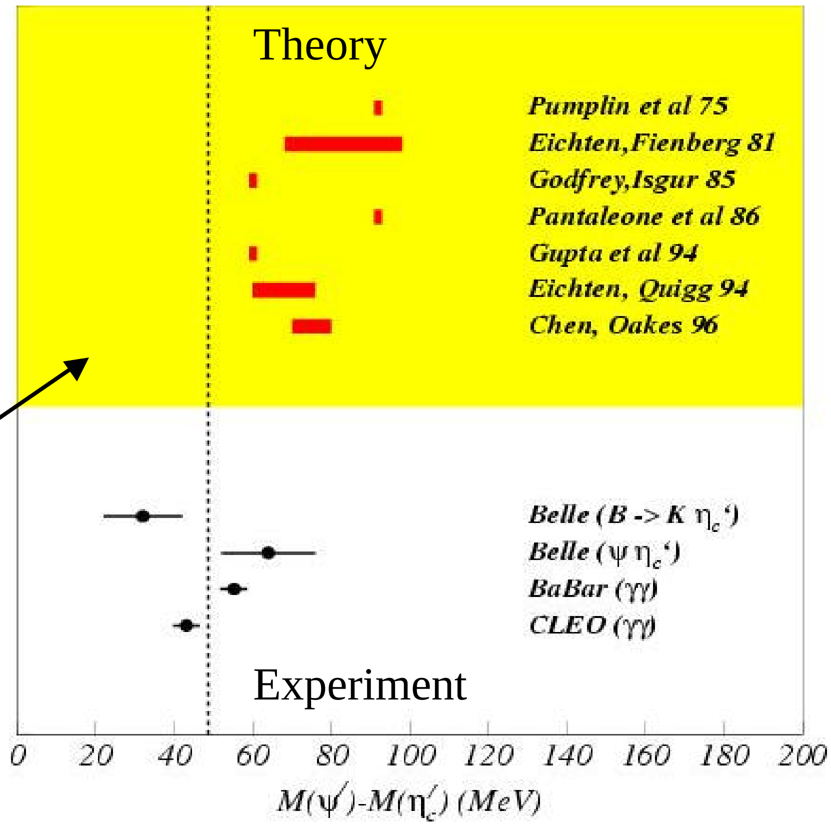
$$M[\eta_c^{/}(2S)] = \mathbf{3637.4 \pm 4.4} \quad (\text{MeV})$$

- Hyperfine mass splitting

$$\Delta M(2S) = M[\Psi^{/}(2S)] - M[\eta_c^{/}(2S)] = \\ = \mathbf{48.6 \pm 4.4} \ (\text{MeV})$$

Compare to theoretical predictions, and

$$\Delta M(1S) = M[\Psi(1S)] - M[\eta_c(1S)] = \\ = 117 \pm 2 \ (\text{MeV})$$



- The measured $\Delta M(2S)$ is much smaller than most of the theoretical predictions .

  It should lead to a new insight into coupled channel effects and spin-spin

  contribution of the confinement part of $q\bar{q}$ potential.

Two-body Hadronic Decays of $\Psi^{/}(2S)$

preliminary

- PQCD expectation [assuming $\alpha_s(\Psi^{/}(2S)) = \alpha_s(J/\Psi)$]

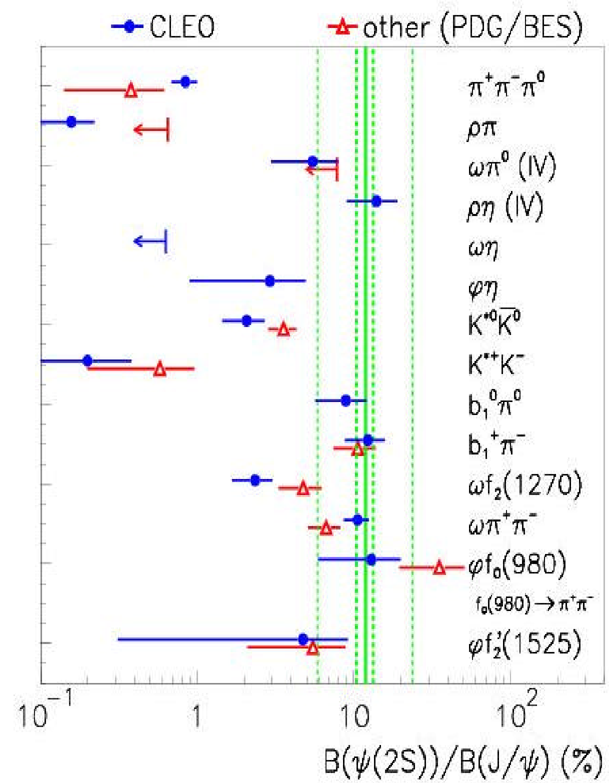
$$Q_{LH} \approx \frac{B[\Psi^{/}(2S) \to LH]}{B(J/\Psi \to LH)} \approx \frac{B[\Psi^{/}(2S) \to e^+e^-]}{B(J/\Psi \to e^+e^-)} \approx (13 \pm 1)\%$$

(LH- Light Hadrons)

As a matter of fact $Q(\Sigma\, LH)_{expt} \approx (17 \pm 3)\ \%$. However, for individual hadronic decays this "13% rule" is found to be badly broken ($Q_{LH} \approx 0.2\%$-20%)

- BES measured a large number of hadronic decays. CLEO has now added many more, and found many more examples of strong violation of this rule.

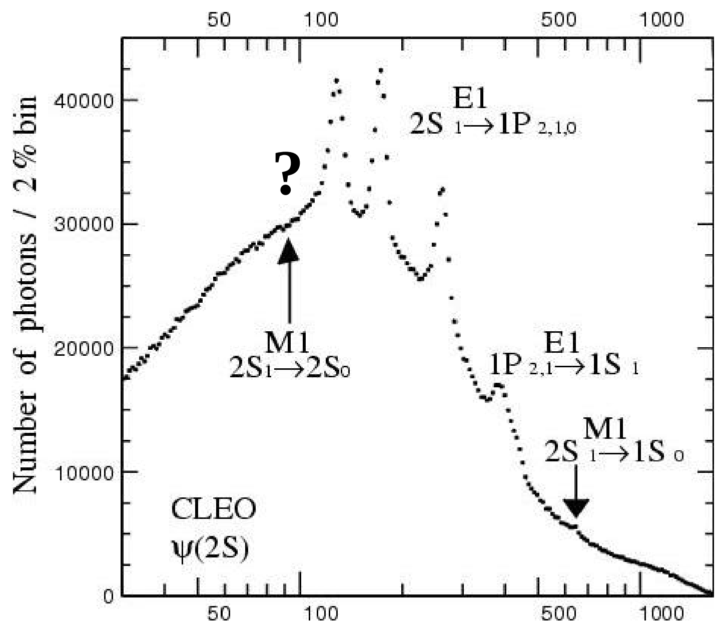
- Many possible theoretical explanations have been offered, but there is no consensus.



Radiative Transitions from $\Psi^{/}(2S)$

preliminary

- general agreement with PDG branching ratios.
- M1 transition to $\eta_c(1S)$, observed by CBAL is confirmed.
- M1 transition to $\eta_c^{/}(2S)$, claimed by CBAL is not observed.

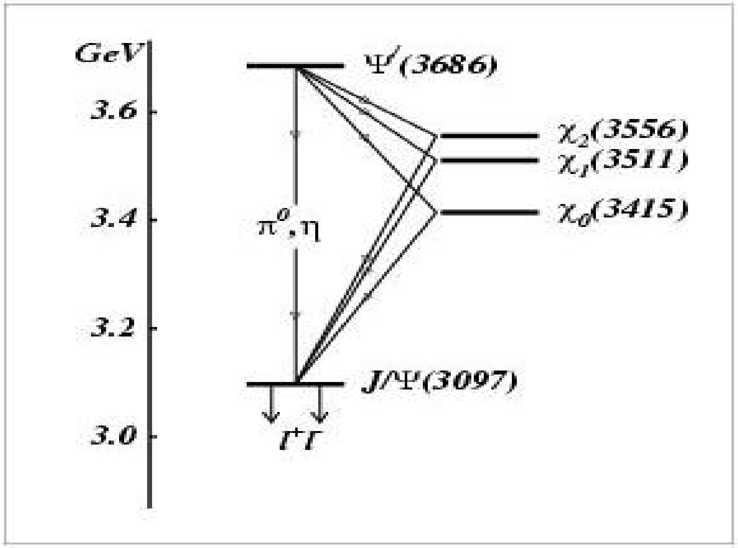


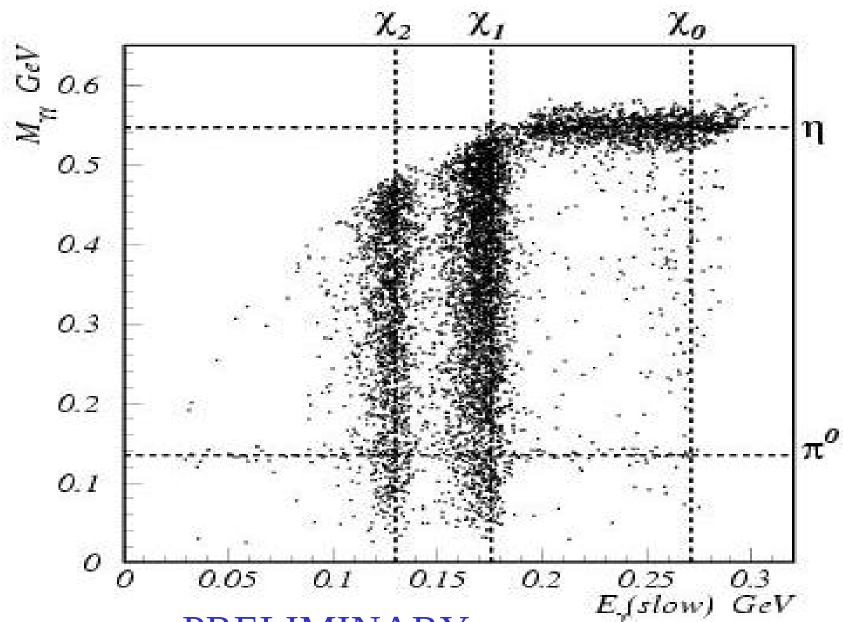
Branching ratios in %

	$\Psi^{/}(2S)\to\gamma\chi_2$	$\Psi^{/}(2S)\to\gamma\chi_1$	$\Psi^{/}(2S)\to\gamma\chi_0$	$\Psi^{/}(2S)\to\gamma\eta_c$
CLEO	**9.75±0.14±1.17**	**9.64±0.11±0.69**	**9.83±0.13±0.87**	**0.278±0.033±0.049**
PDG	**7.8 ± 0.8**	**8.7 ± 0.8**	**9.3 ± 0.8**	**0.28 ± 0.06**

$\Psi^{/}(2S) \rightarrow \gamma\gamma J/\Psi$

preliminary





PRELIMINARY

With ~3 million $\Psi^{/}$ decays precision determination of branching ratios for the following decay channels are being determined from two photon cascades:

$B(\chi_{cJ} \rightarrow \gamma J/\Psi)$, $B(\Psi^{/} \rightarrow \eta J/\Psi)$, $B[\Psi^{/}(2S) \rightarrow \pi^0 J/\Psi)]$

New Narrow State X(3872)

- Belle Collaboration observed a narrow state in:

$$B^{+-} \to K^{+-} X(3872), \quad X(3872) \to \pi^+\pi^- J/\Psi, \quad J/\Psi \to l^+l^-$$

M = **3872.0** ± **0.6** ± **0.5** (MeV),	Γ < **2.3** MeV	Belle (2003)
M = **3873.4** ± **1.4** (MeV),	Γ < **3.1** ± **0.2** (MeV)	BaBar (2004)

- CDF and D0 Collaborations confirmed in:

$$p\bar{p} \to X(3872) + X, \quad X(3872) \to \pi^+\pi^- J/\Psi, \quad J/\Psi \to \mu^+\mu^-$$

M = **3871.3** ± **0.7** ± **0.4** (MeV),	Γ < **4.9** ± **0.7** (MeV)	CDF	(2003)
M = **3871.8** ± **3.1** ± **3.0** (MeV),	Γ < **17** ± **3** (MeV)	D0	(2004)

- Identification of the quantum numbers is important to understand the structure:
  - a conventional charmonium state ? (Eichten, Lane, Quigg), (Barnes et al)
    many quantum numbers are possible
  - a D^0-$\bar{D}^{*0}$ molecule ? (Tornqvist et al)
    $J^{PC} = 1^{++}$ (S-wave), 0^{-+} (P-wave)
  - a charmonium hybrid state ? (Close et al)

- X(3872) decays to various charmonium states and $D^0\bar{D}^0$ states have been searched and upper limits have been set.

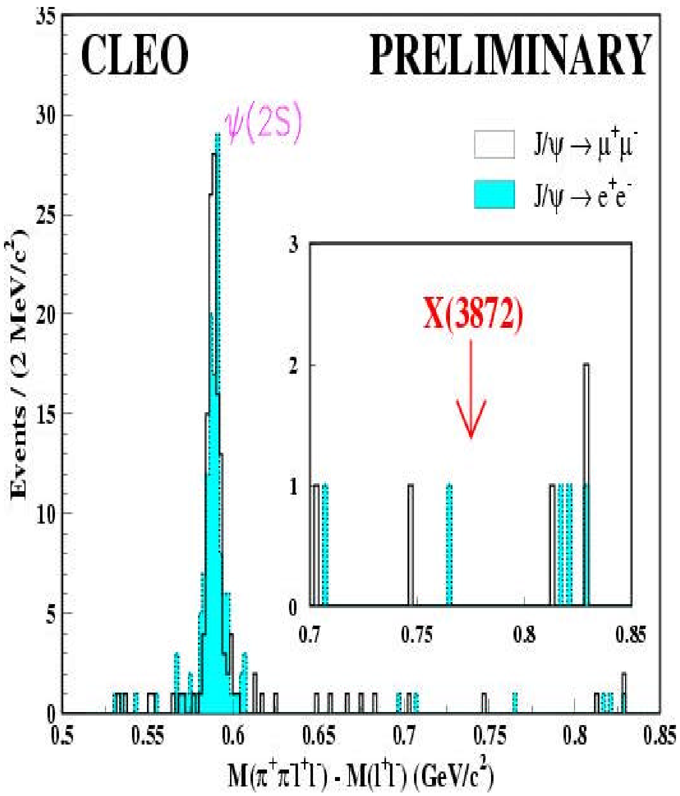
New Narrow State X(3872)

preliminary

- CLEO searched for X(3872) state in:
  - untagged $\gamma\gamma$ fusion: +C parity, $J^{PC} = 0^{++}, 0^{-+}, 2^{++}, 2^{-+}, \ldots$
  - ISR production: $J^{PC} = 1^{--}$

  with ~15 fb^{-1} of CLEO III data.

- exclusive channels $X \to \pi^+\pi^- J/\Psi$, $J/\Psi \to l^+l^-$ were analyzed.
- no signal was found.
- following upper limits were set:



Untagged $\gamma\gamma$ fusion (systematic errors are included):

$$(2J+1)\Gamma_{\gamma\gamma}B(X \to \pi^+\pi^- J/\Psi) < \mathbf{16.7}\ \text{eV} \quad (90\%\ \text{CL})$$

ISR production (systematic errors are included):

$$\Gamma_{ee}B(X \to \pi^+\pi^- J/\Psi) < \mathbf{6.8}\ \text{eV} \quad (90\%\ \text{CL})$$

SUMMARY

- Heavy quarkonium spectroscopy continues to produce precision results.
  With CLEOc, look forward to …
  - observation of charmonium $^1P_1(h_c)$ state
  - search for charmonium 2P and 1D states
  - improved understanding of D decays of $\Psi^{//}(3770)$, $\Psi^{///}(4040)$ …
  - glueballs and other exotics.

- Hopefully, LATTICE can use these precision results for calibration.
  We are promised this for bottomonium, and look forward to similar success with charmonium.