Spectroscopy of Heavy Quarkonia

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Why Spectroscopy of Heavy Quarkonia?

Heavy quarkonia – bound states of two charm and two bottom quarks – are still a very rich exploration site:

- No $b\bar{b}$ singlet states are known
- Only very few hadronic and radiative decays are known

Charm and bottom quarks have large masses (~1.5 and ~4.5 GeV)

- velocities of quarks in hadrons are non-relativistic
- strong coupling constant α_s is small (~0.3 for $c\bar{c}$ and ~0.2 for $b\bar{b}$).

Hence, heavy quarkonia provide the best means of testing the theories of strong interaction:

- QCD in both pertubative and non-pertubative regimes
- QCD inspired purely phenomenological potential models
- NRQCD and LatticeQCD

Topics

Bottomonium Spectroscopy

New $\Upsilon(1^3D_2)$ State

Branching Ratio $\mathbf{B}(\Upsilon(nS) \to \mu^+\mu^-)$

$\Upsilon(1S) \to J/\psi + X$

Hadronic Transitions from $\Upsilon(3S)$

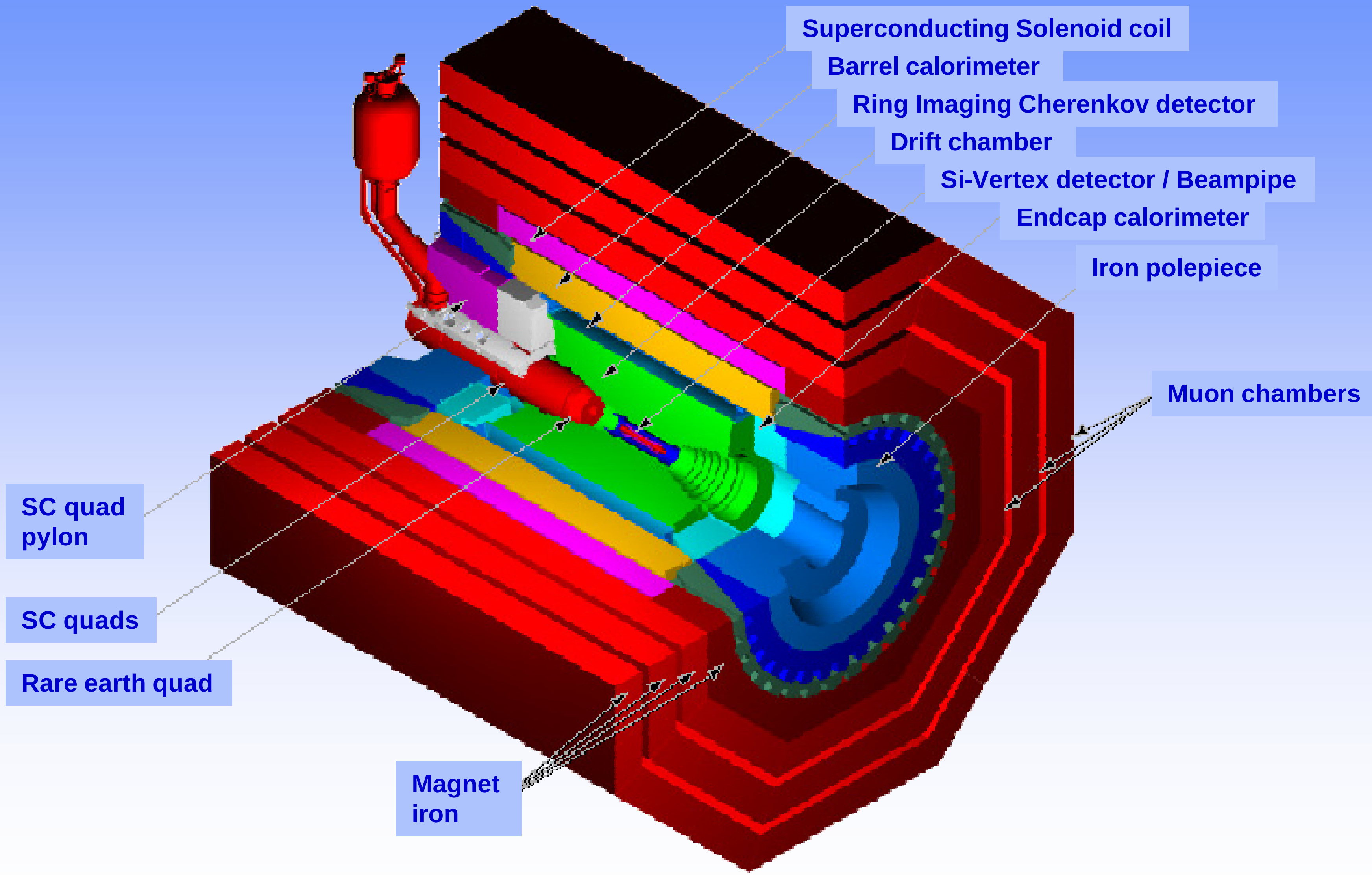
Charmonium Spectroscopy

Latest Results from $\eta_c(2S)$

Radiative Transitions from $\psi(2S)$

X(3872)

The CLEO III Detector



CLEO Data Sets

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

Observation of ¡(1D) State of Bottomonium

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

¡(3S) → g c**(2P)** → g ¡**(1D)** → g c**(1P)** → g ¡**(1S)** → **e⁺ e⁻,** m⁺ m⁻

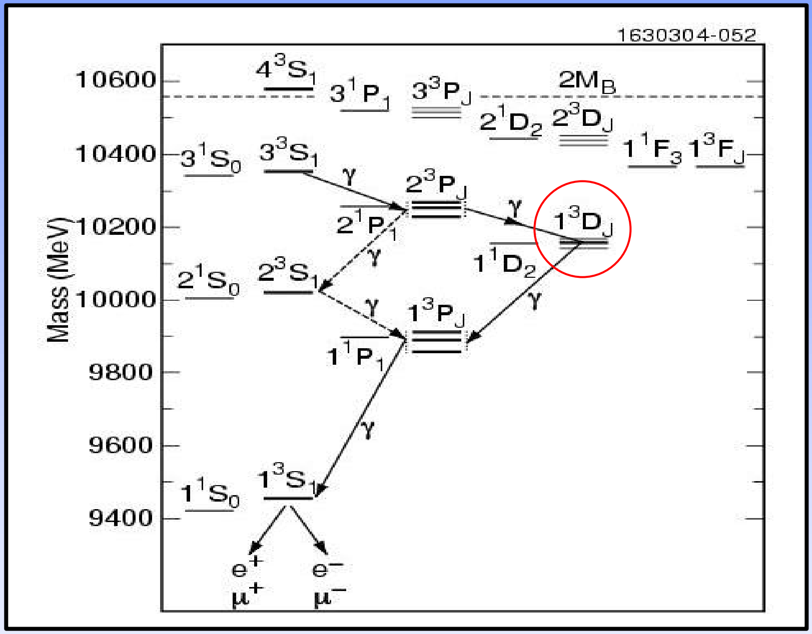
34.5 ± 6.4 signal events were observed

Significance of the signal is **10.2** s

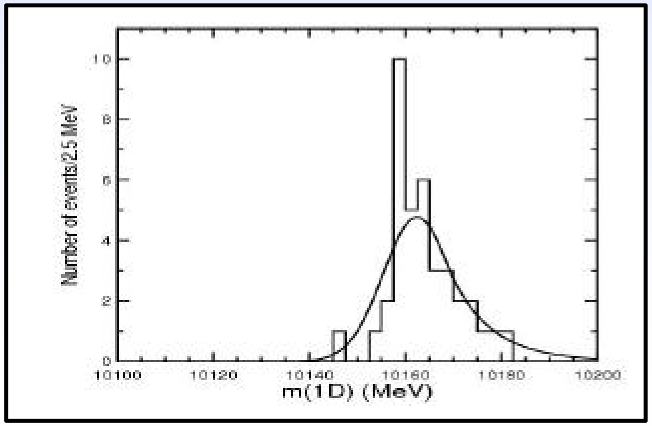
Consistent with J = 2 assignment → $\Upsilon(1^3D_2)$

M(¡(1D)) = 10161.1 ± 0.6 ± 1.6 MeV

B(gggg**l⁺l⁻**)$_{¡(1D)}$ **= (2.6 ± 0.5 ± 0.5) x 10^{-5}**



Theoretical prediction of the branching ratio by Godfrey and Rosner: **4x10^{-5}**



Mass is consistent with predictions from potential models and LatticeQCD calculations

Measurement of B(¡ (nS) → m^+m^-)

Leptonic (Γ_{ll}) and total widths (Γ) of $\Upsilon(n^3S_1)$ resonances are not very well established. They have 4 - 16% relative errors.

Γ and Γ_{ee} are used in many PQCD calculations

Precise measurement of **B**(l^+l^-) allows to determine Γ of Υ(nS) precisely (precise Γ_{ee} measurement is also needed, expected soon from CLEO):

$\Gamma = \Gamma_{ll} / \mathbf{B}_{ll} = \Gamma_{ee} / \mathbf{B}_{\mu\mu}$ (assuming lepton universality)

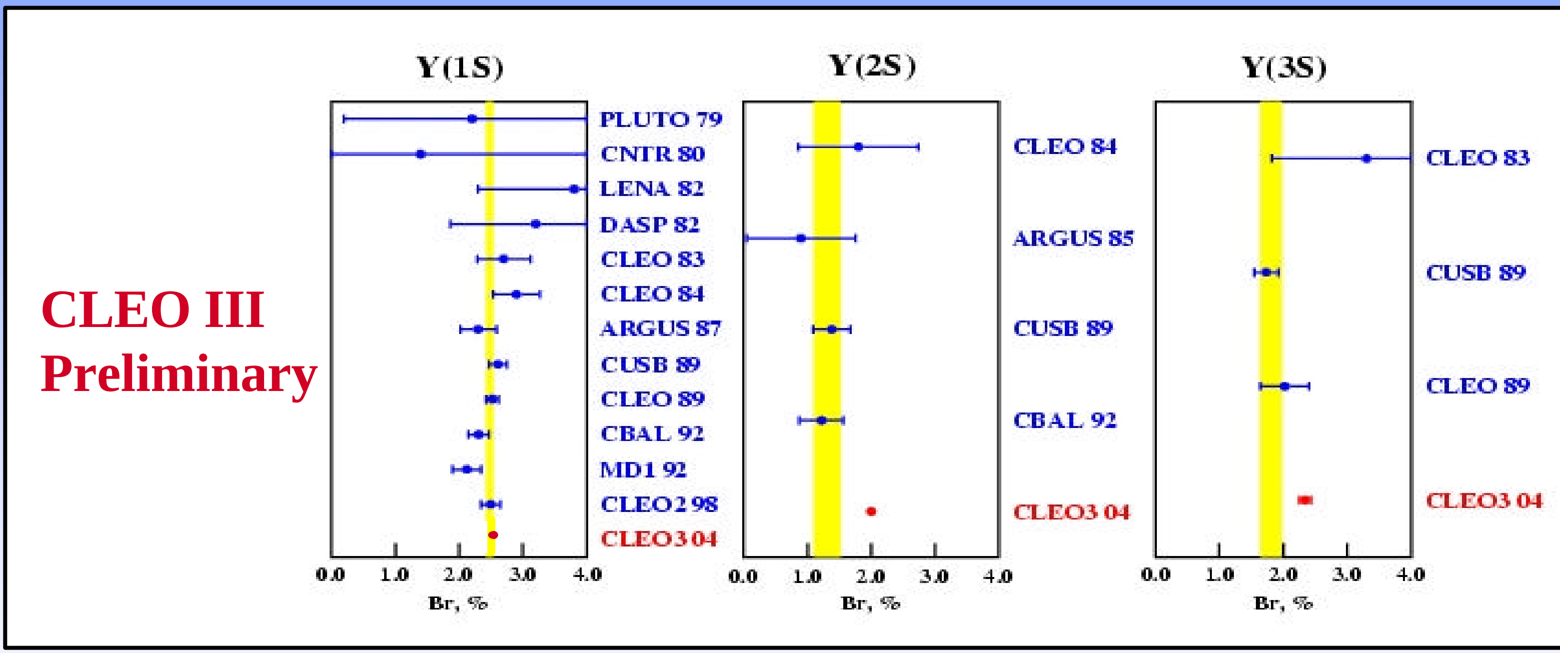
→ Measure decay rate to muon pairs relative to hadronic decay rate:

$$\overline{\mathbf{B}}_{mm} = \frac{\Gamma_{mm}}{\Gamma_{had}} = \frac{N(Y \rightarrow m^+ m^-)/e_{mm}}{N(Y \rightarrow hadrons)/e_{had}}$$

$$\mathbf{B}_{mm} = \frac{\Gamma_{mm}}{\Gamma} = \frac{\Gamma_{mm}}{\Gamma_{had}(1+3\Gamma_{mm}/\Gamma_{had})} = \frac{\overline{\mathbf{B}}_{mm}}{1+3\overline{\mathbf{B}}_{mm}}$$

Measurement of B(¡ (nS) → m^+m^-)

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



ϒ(1S) branching ratio agrees with the PDG average.

Significant discrepancy observed for ϒ(2S) and ϒ(3S). The new branching ratios would result in a significantly lower total decay width for ϒ(2S) and ϒ(3S)

Production of J/y in ¡(1S) Decays

10 years ago the CDF experiment reported anomalously high rates of J/ψ and ψ(2S) production in $p\bar{p}$ collisions.

In ϒ(1S) data a J/ψ can be produced by:

- ϒ(1S) → ggg, ϒ(1S) → γ^* → $q\bar{q}$
- continuum production $e^+ e^-$ → J/ψ + X

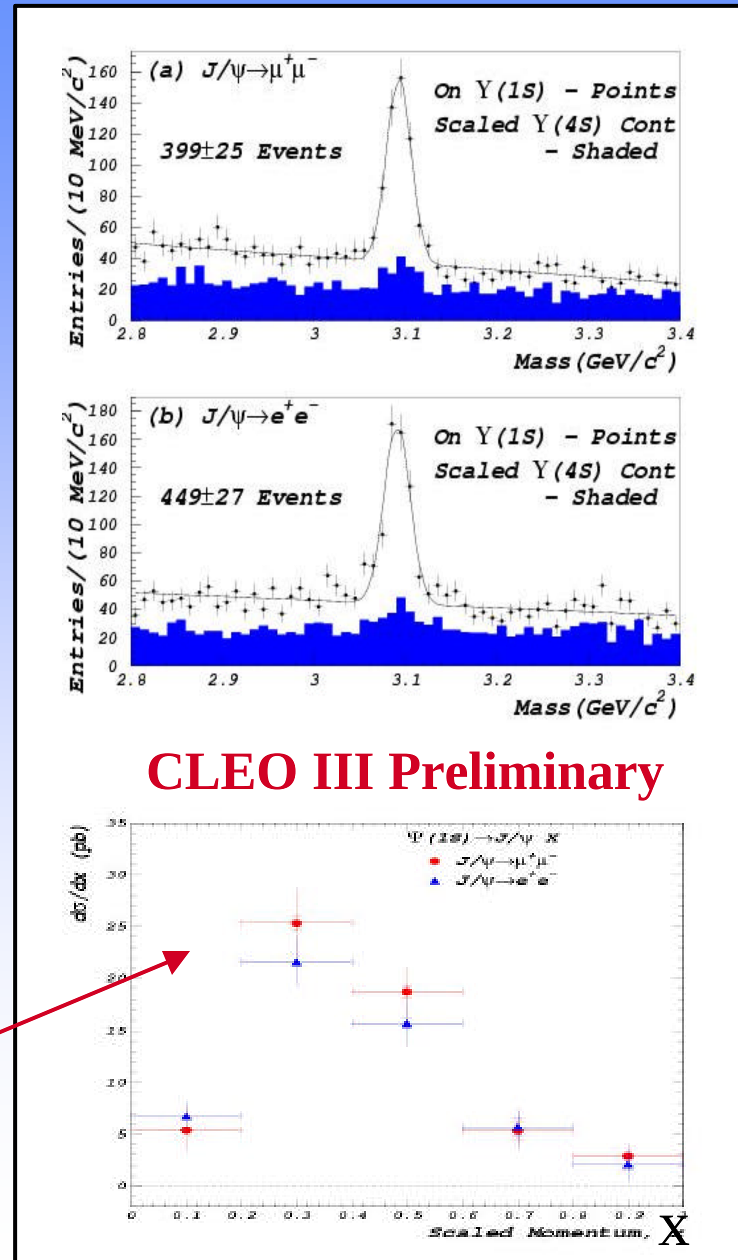
B_{mm}(¡(1S) → J/y + X) = (6.4 ± 0.5) x 10^{-4}

B_{ee}(¡(1S) → J/y + X) = (5.7 ± 0.4) x 10^{-4}

Branching ratio predictions of the color octet model by Braaten and Fleming are in agreement with the above preliminary measurements.

Continuum subtracted J/ψ momentum spectra

No indication of peaking at large x values, as predicted by color octet model



Di-Pion Transitions from ¡ (3S)

Preliminary ranching ratio measurements for ϒ(2S) and ϒ(3S):

B(¡ (3S) → p^0p^0 ¡ (2S)) = 2.02 ± 0.18 ± 0.38 %

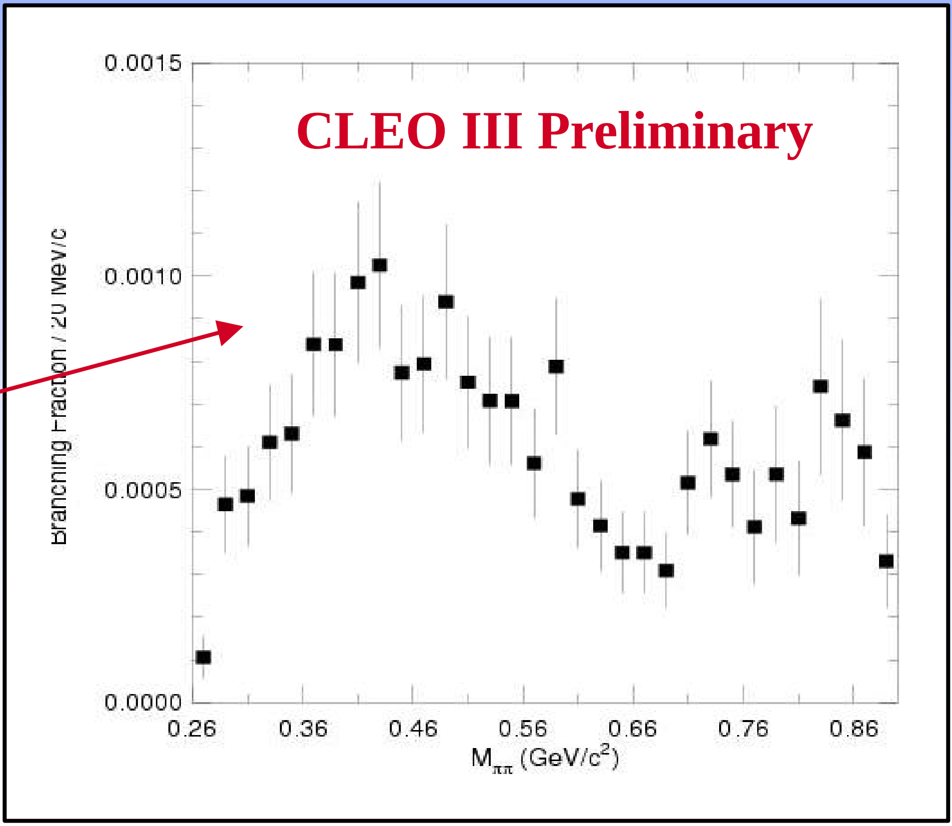
B(¡ (3S) → p^0p^0 ¡ (1S)) = 1.88 ± 0.08 ± 0.31 %

ϒ(3S) → $\pi^0\pi^0$ ϒ(2S):

$\pi^0\pi^0$ effective mass spectrum has a shape consistent with several theoretical predictions

ϒ(3S) → $\pi^0\pi^0$ ϒ(1S):

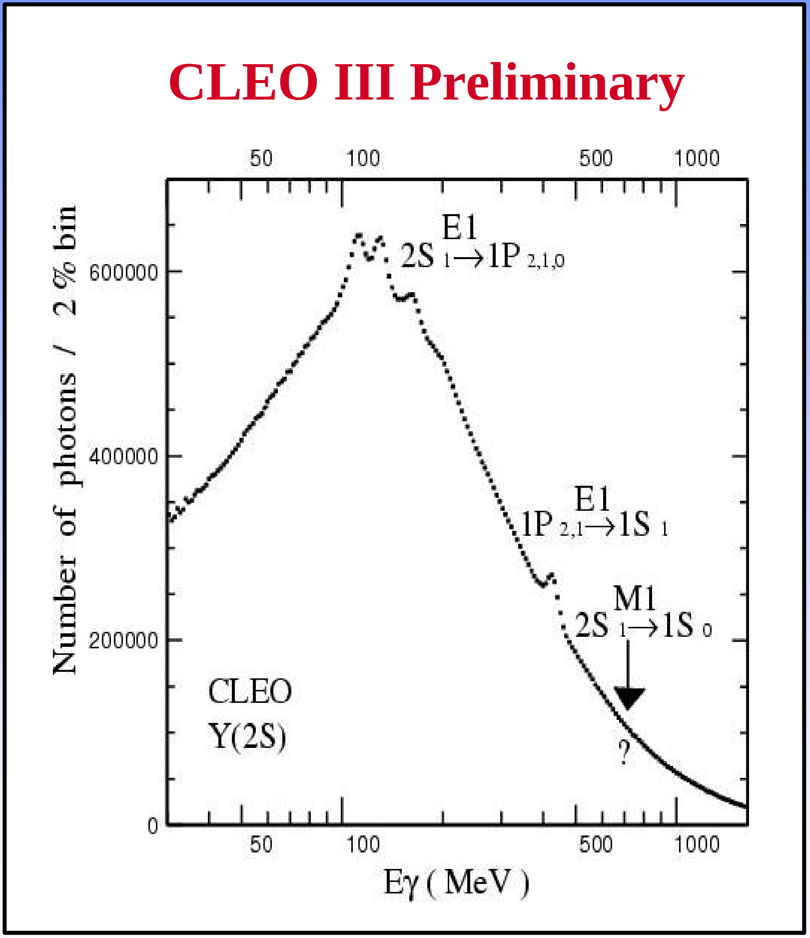
$\pi^0\pi^0$ effective mass spectrum has "double humped" shape, also observed in the charged pion transitions



Radiative Transitions from ¡ (nS)

M1 Transitions:

CLEO searched for $\eta_b(1S)$ and $\eta_b(2S)$ states. No significant signals were found. Upper limits for branching ratios as a function of E_γ were determined.



E1 Transitions:

The following transitions were observed:

$$¡\,(3^3S_1) \rightarrow g\ c_b(1^3P_J)$$

$$c_b(2,1^3P_0) \rightarrow g\ ¡\,(2,1^3S_1)$$

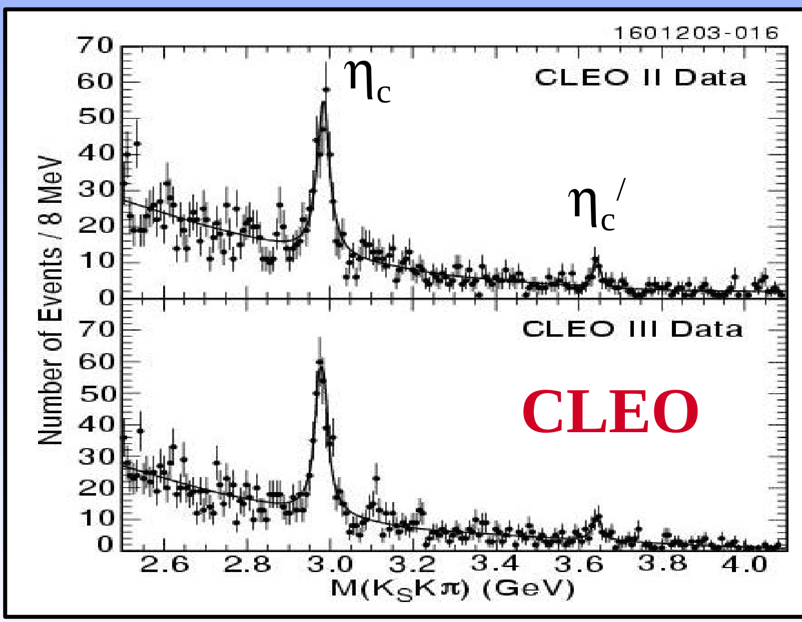
Further precision measurements are in progress.

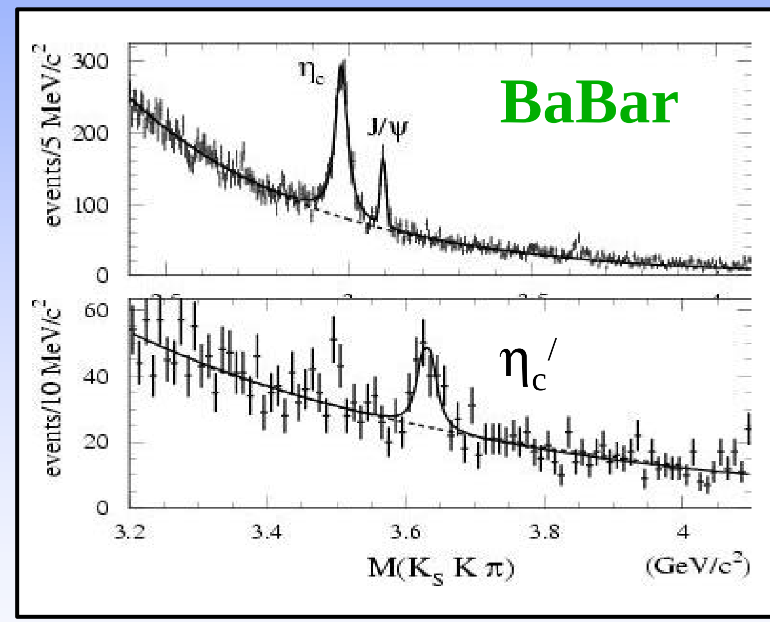
Latest Experimental Results on $h_c(2S)$

Belle observed the $\eta_c(2S)$ in two different channels:

$B^\pm \to K^\pm\,(h_c')\to K^\pm\,(K_s K^\pm p^\pm)$	$M(h_c') = 3654 \pm 6 \pm 8$ MeV
$e^+e^- \to J/y\ h_c'$	$M(h_c') = 3622 \pm 12$ MeV

CLEO and BaBar have observed the $\eta_c(2S)$ in two-photon fusion processes:





$M = 3642.9 \pm 3.1 \pm 1.5$ MeV

$G < 31$ MeV (90% CL)

$G_{gg} = 1.3 \pm 0.6$ keV

$h_c' \to K_s K^\pm p^\mp$

$M = 3630.8 \pm 3.4 \pm 1.0$ MeV

$G = 17.0 \pm 8.3 \pm 2.5$ MeV

Latest Experimental Results on $h_c(2S)$

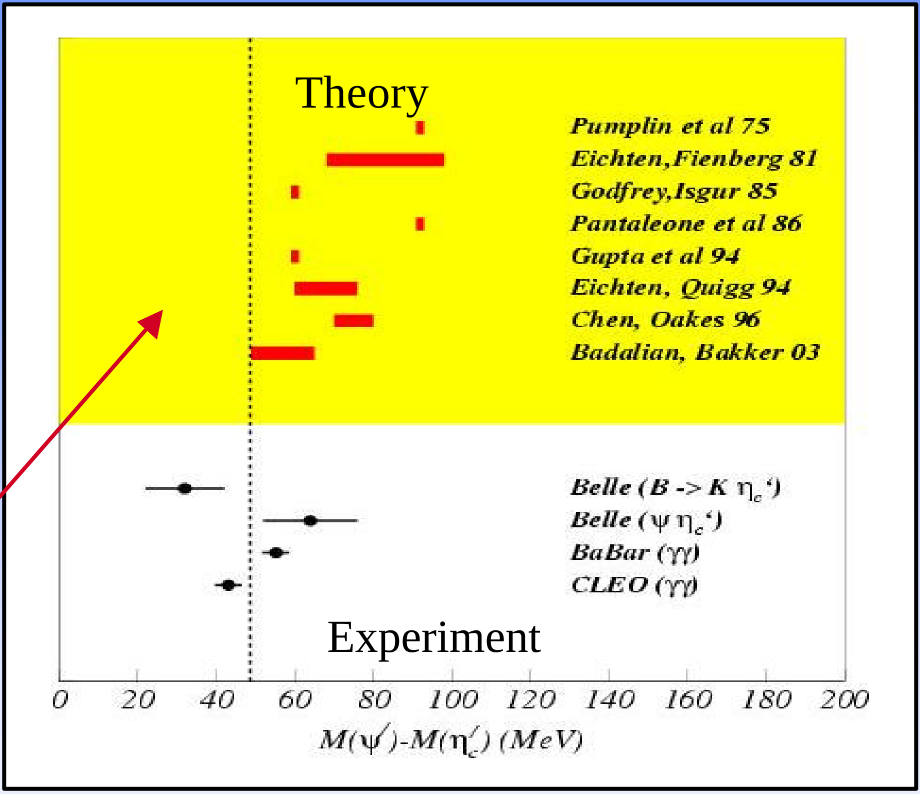
Combined $\eta_c(2S)$ mass value
(Belle, BaBar, CLEO):

$M(h_c(2S)) = 3637.4 \pm 4.4$ MeV

Hyperfine mass splitting:

DM(2S) = M(y(2S)) – M(h_c(2S))
= 48.6 ± 4.4 MeV

Comparison to theoretical predictions



DM(1S) = M(y(1S)) – M(h_c(1S))
= 117 ± 2 MeV

The measured ΔM(2S) is much smaller than most theoretical predictions.

This should lead to a new insight into coupled channel effects and spin-spin contribution of the confinement part of $q\bar{q}$ potential.

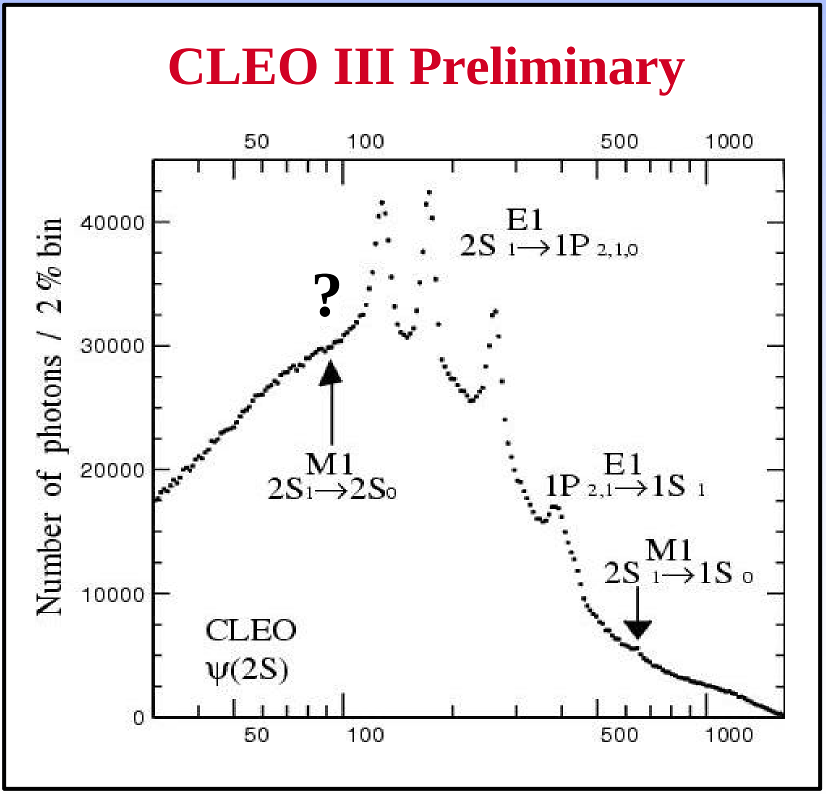
Radiative Transitions from y (2S)

B (%)	$\psi(2S) \to \gamma\,\chi_c(1P_J)$ J=2 (E1 line)	J=1 (E1 line)	J=0 (E1 line)	$\psi(2S) \to \gamma\,\eta_c(1S)$ J=0 (M1 line)
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**

Good agreement with PDG branching ratios.

Crystal Balls observation of M1 transition to $\eta_c(1S)$ confirmed.

No indication of M1 transition to $\eta_c(2S)$ which was observed by Crystal Ball ~20 years ago.



New Narrow State X(3872)

Belle collaboration observed a narrow state in:

$B^{\pm} \rightarrow K^{\pm}$ X(3872), X (3872) $\rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$

M = 3872.0 ± 0.6 ± 0.5 MeV , G < 2.3 MeV (90% CL)

CDF and D0 collaborations confirmed narrow state in:

$p\,\bar{p} \rightarrow$ X(3872) + X , X(3872) $\rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$

M = 3871.3 ± 0.7 ± 0.4 MeV	CDF Collaboration
M = 3871.8 ± 3.1 ± 3.0 MeV	D0 Collaboration

Identification of the quantum numbers is important to understand the structure:

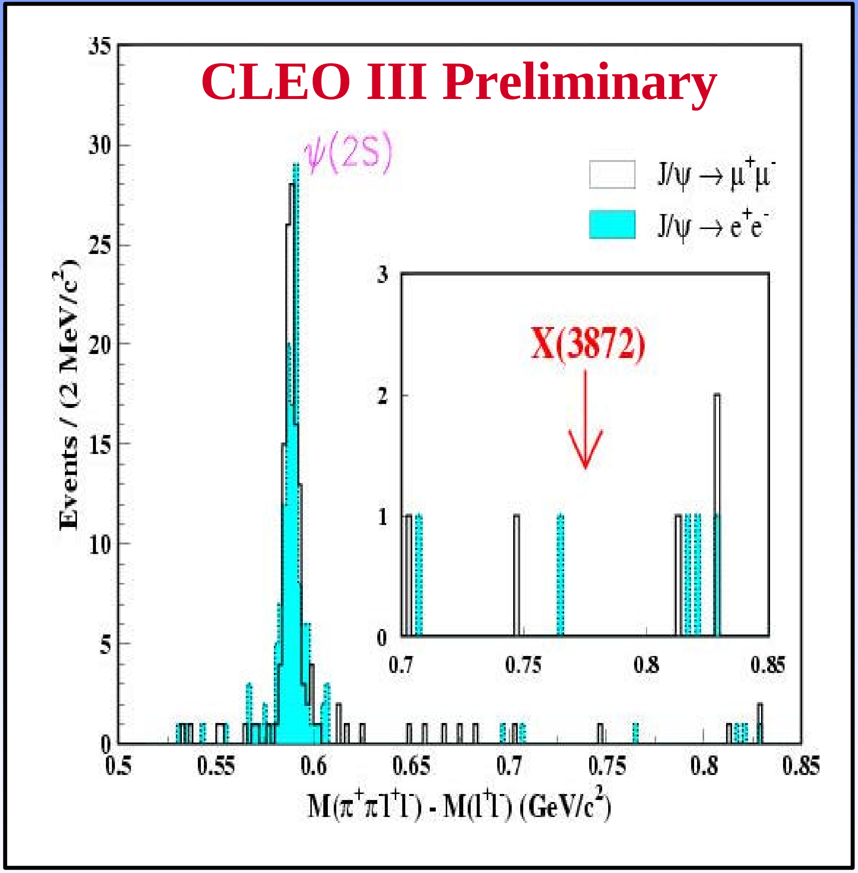
- Conventional charmonium state? (Eichten, Lane, Quigg), (Barnes et al)
  many quantum numbers are possible
- $D^0\,\bar{D}^{*0}$ molecule? (Tornqvist et al)
  $J^{PC} = 1^{++}$ (S-wave), 0^{-+} (P-wave)
- Charmonium hybrid state? (Close et al)

X(3872) decays to $\chi_{c1}\,\gamma$ (if state is $^3D_2$) or $\chi_{c2}\gamma$ (if state is $^3D_3$) or $J/\psi\,\gamma$ (if state is χ_{cJ}'). D^0D^0 (if state is molecular) were searched for. Only upper limits were set.

New Narrow State X(3872)

CLEO searched with ~15 fb^{-1} of CLEO III data for X(3872) state in:

- untagged $\gamma\gamma$ fusion: C+ parity, $J^{PC} = 0^{++}, 0^{-+}, 2^{++}, 2^{-+}, \ldots$
- ISR production: $J^{PC} = 1^{--}$



Exclusive channels X → $\pi^+\pi^-$ J/ψ with J/ψ → l^+l^- were analyzed.

No signal was found, but upper limits were set

Untagged $\gamma\gamma$ fusion:

$(2J+1)G_{gg}$ B(X → p^+p^- J/y) < 16.7 eV (90% CL)

ISR production:

G_{ee} B(X → p^+p^- J/y) < 6.8 eV (90% CL)

(systematic errors are included)

Summary

Spectroscopy of heavy quarkonia is a very active field.

Collections of large data samples are now available:

- CLEO III ($b\bar{b}$)
- BES II ($c\bar{c}$)
- CLEO-c ($c\bar{c}$)

Many new important experimental observations and measurements emerged – many more are expected.

Theoretical side (LatticeQCD, NRQCD) is catching up. But many questions still remain open and need to be answered.