Heavy Quarkonia

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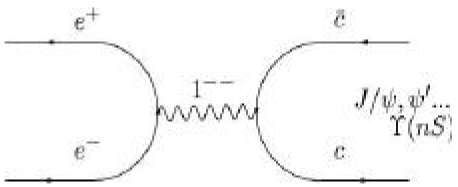
Introduction

- heavy quarkonia – bound states of charm and bottom quarks. They are strong interaction analogs of positronium.

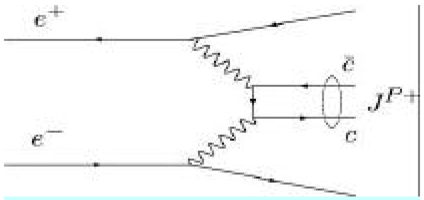
- because charm and bottom quarks have large masses (~1.5 and ~4.5 GeV)
  - velocities of quarks in hadrons are nonrelativistic
  - strong coupling constant α_s (~0.3 for $c\bar{c}$ and ~0.2 for $b\bar{b}$) is small

- therefore heavy quarkonia spectroscopy is a good testing ground for the theories of strong interactions:
  - QCD in both perturbative and non-perturbative regimes
  - QCD inspired purely phenomenological potential models
  - NRQCD and Lattice QCD

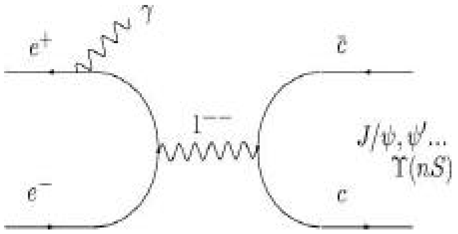
How Quarkonium States are Produced?



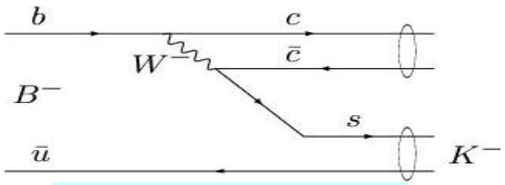
e$^+$e$^-$ annihilation



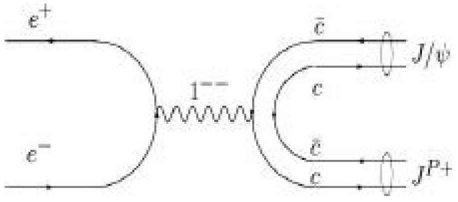
two photon fusion



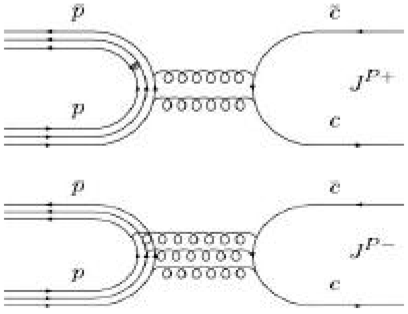
Initial State Radiation (ISR)



B meson decays

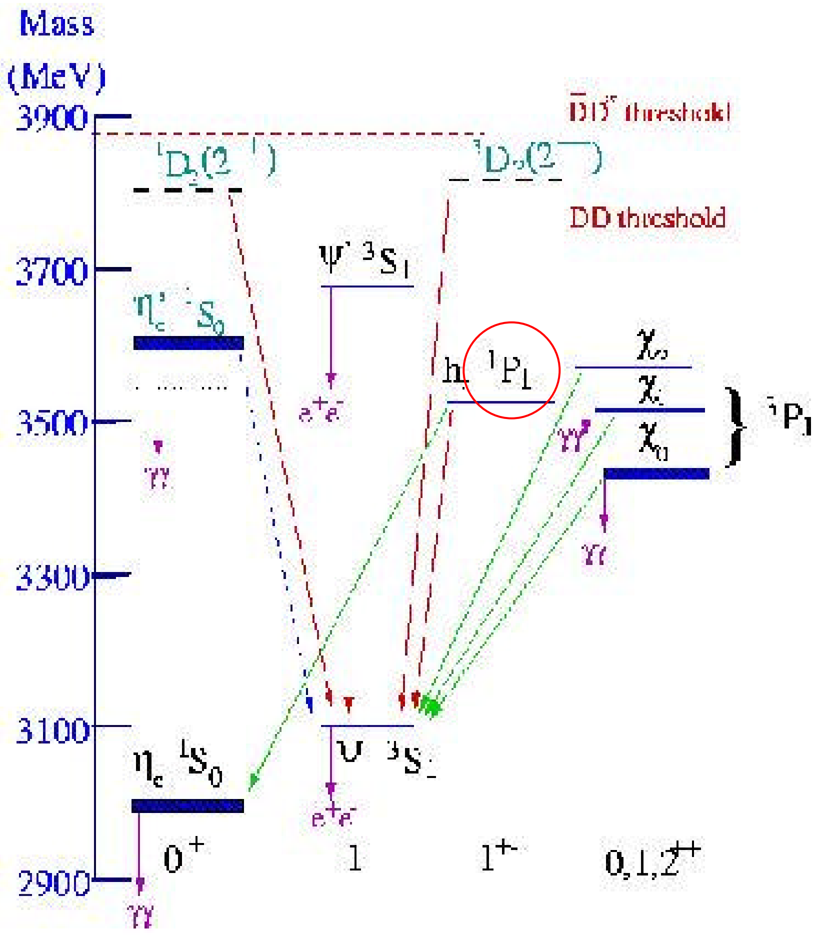


double charm production

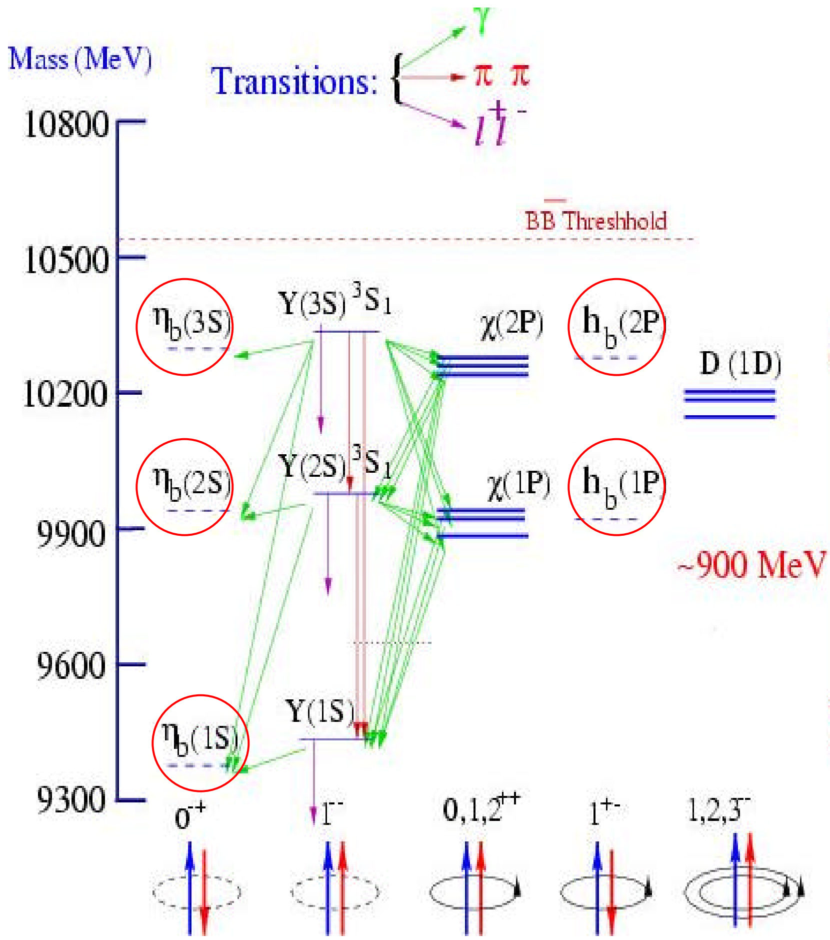


p-pbar annihilation

Charmonium spectroscopy



Bottomonium spectroscopy



J^{PC} $n^{2S+1}L_J$ $\vec{S}=\vec{S}_1+\vec{S}_2$ $\vec{J}=\vec{L}+\vec{S}$ $P=(-1)^{L+1}$ $C=(-1)^{L+S}$

Modern datasets with highest statistics (e^+e^- experiments)

E_{cm}(GeV)	State	#events(10^6)	Experiment
3.10	J/Ψ	8	BES
	J/Ψ	58	BES II
3.69	$\Psi(2S)$	4	BES
	$\Psi(2S)$	14	BES II
	$\Psi(2S)$	3	CLEOc
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

Scope of Talk

- **Upsilon Spectroscopy**
  - $\Upsilon(1^3D_2)$
  - $\Upsilon(nS) \rightarrow \mu^+\mu^-$
  - $\Upsilon(1S) \rightarrow J/\Psi + X$
  - radiative and hadronic transitions from $\Upsilon(3S)$
- **spectroscopy of charmonium region**
  - $\eta_c(2^1S_0)$
  - $\Psi(2S) \rightarrow hh$
  - radiative transitions from $\Psi(2S)$
  - X(3872)

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

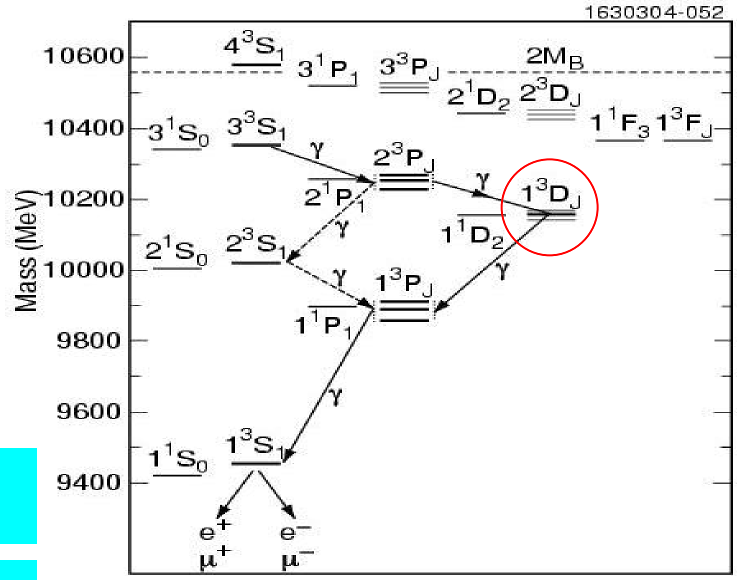
CLEO
Collaboration

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

Y(3S) → γχ(2P) → γY(1D) → γχ(1P) → γY(1S) → $e^+ e^-$, $\mu^+ \mu^-$

i.e. 4 photons and 2 leptons in final state.

- theoretical prediction of the BR by Godfrey and Rosner is **4×10^{-5}**



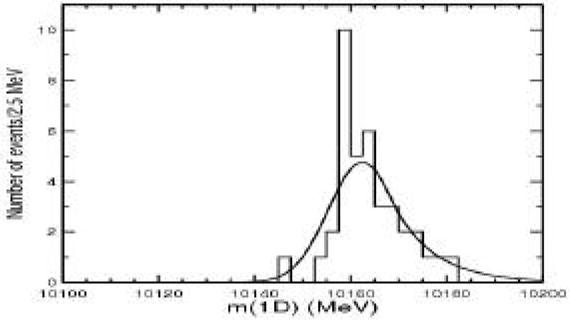
34.5 + – 6.4 signal events were observed.

Significance of the signal = **10.2** σ

M[Y(1D)] = **10161.1 + – 0.6 + – 1.6** (MeV)

$B(\gamma\gamma\gamma\gamma l^+ l^-)_{Y(1D)}$ = (**2.6 + – 0.5 + – 0.5**)x10^{-5}

Consistent with J = 2 assignment Y(1^3D_2)



Mass is consistent with predictions from potential models and Lattice QCD calculations.

Measurement of the **B[Y(nS) → m⁺m⁻]**

CLEO
preliminary

- leptonic (Γ_{ll}) and total widths (Γ) of $Y(n^3S_1)$ resonances are not very well established (4-16% relative errors)
- Γ and Γ_{ee} enter many PQCD calculations
- precise measurement of $B(l^+l^-)$ allows to determine Γ of Y(nS) precisely (also need precise Γ_{ee} measurement, expect from CLEO soon):

$$\Gamma = \Gamma_{ll} / B_{ll} = \Gamma_{ee} / B_{\mu\mu} \quad \text{(assuming lepton universality)}$$

- measure decay rate to muon pairs relative to hadronic decay rate:

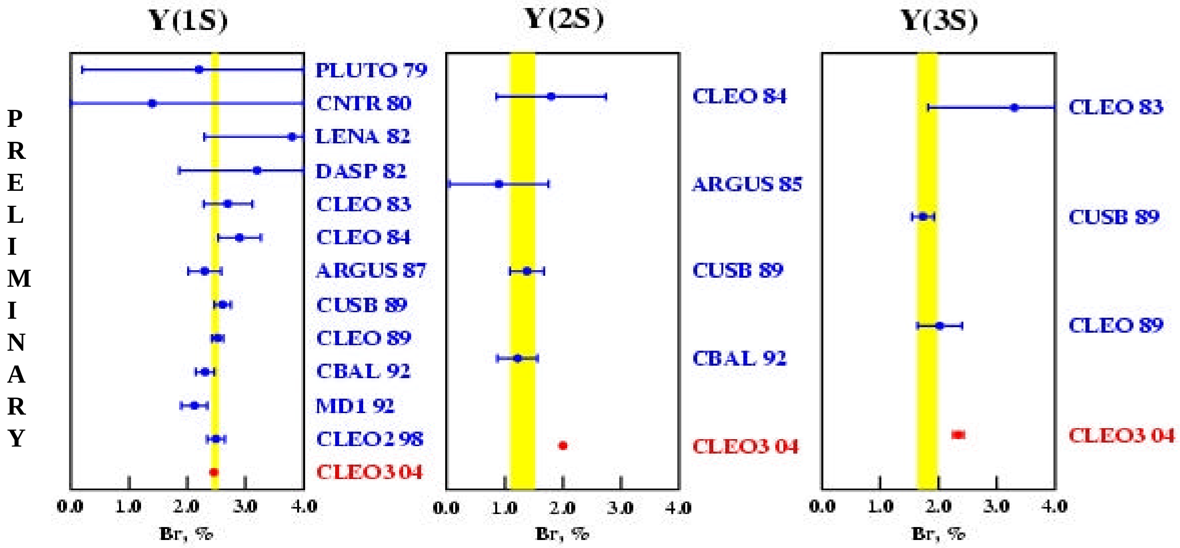
$$\bar{B}_{mm} = \frac{\Gamma_{mm}}{\Gamma_{had}} = \frac{N(Y \to m^+ m^-)/e_{mm}}{N(Y \to hadrons)/e_{had}}$$

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

Measurement of the **B[Y(nS) → m^+m^-]**

CLEO
preliminary

	Y(1S)	Y(2S)	Y(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**



- Y(1S) branching fraction agrees with the PDG average. Significant discrepancy observed in case of Y(2S) and Y(3S).
- The new branching fractions would result in a significantly lower total decay width for Y(2S) and Y(3S).

Production of J/Ψ in Υ(1S) Decays

CLEO
preliminary

- 10 years ago CDF experiment reported anomalously high rates of J/Ψ and Ψ(2S) production in pp collisions.

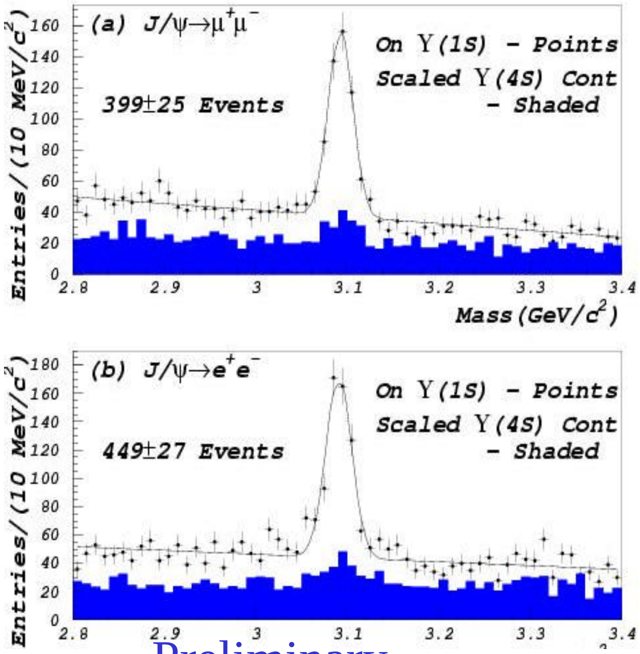
In Υ(1S) data J/Ψ can be produced from:

- Υ(1S) ➔ ggg, Υ(1S) ➔ γ^* ➔ qq
- continuum production $e^+ e^-$ ➔ J/Ψ + X

$B_{\mu\mu}$[Υ(1S) ➔ J/Ψ+X] = (**6.4 + – 0.5**) x 10^{-4}

B_{ee}[Υ(1S) ➔ J/Ψ+X] = (**5.7 + – 0.4**) x 10^{-4}

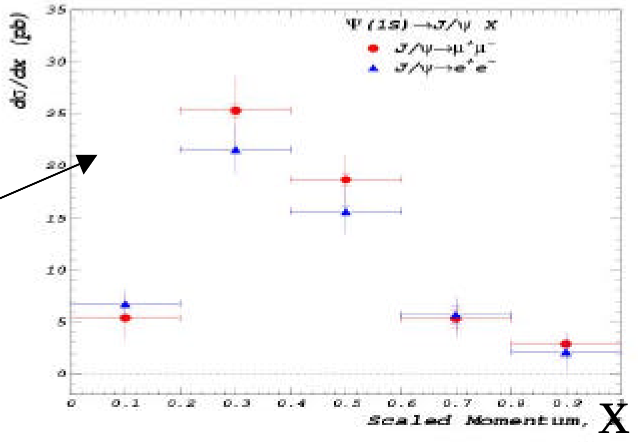
- color octet model (Braaten and Fleming) predictions of BR are in agreement with above preliminary measurements.



Preliminary

Continuum subtracted J/Ψ momentum spectra

- no indication of peaking at large x values, as predicted by color octet model.



Radiative Transitions from Y(nS)

CLEO
preliminary

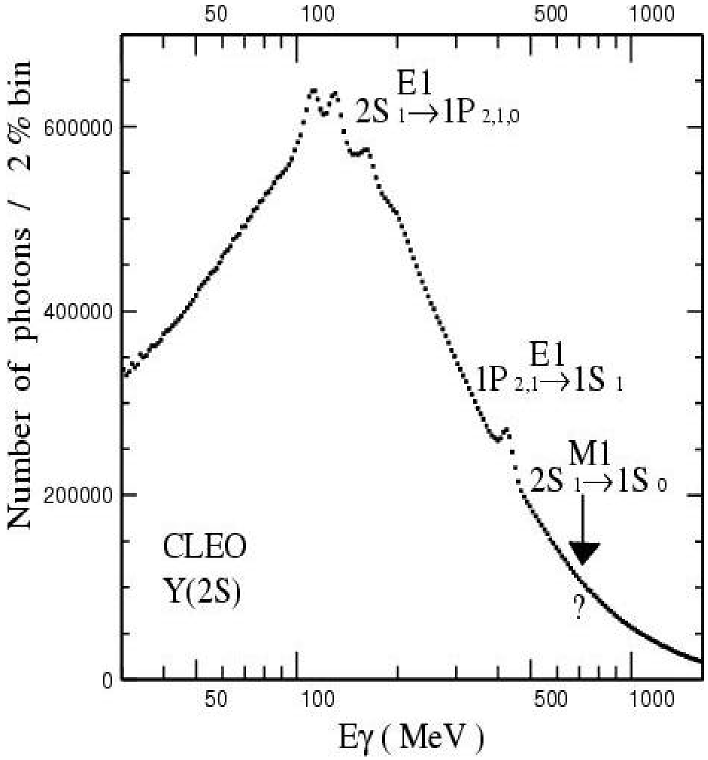
- $\eta_b(1S)$, $\eta_b(2S)$ states were searched in Y(nS) M1 transitions.

- no significant signals were found.

- upper limits on the branching fractions as a function of E_γ were set.

- E1 $Y(3^3S_1) \rightarrow \gamma\chi_b(1^3P_J)$ and $\chi_b(2,1^3P_0) \rightarrow \gamma Y(2,1^3S_1)$ transitions were observed.

- precision measurements are in progress.



Preliminary

$Y(3S) \to \pi^0\pi^0 Y(1S)$ and $Y(3S) \to \pi^0\pi^0 Y(2S)$

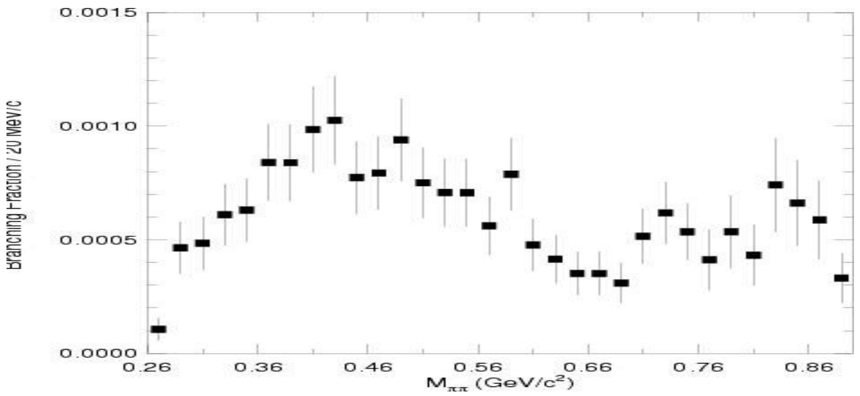
CLEO
preliminary

- branching fractions were measured (preliminary):

$B[Y(3S) \to \pi^0\pi^0 Y(2S)] = \mathbf{2.02} + - \mathbf{0.18} + - \mathbf{0.38}$ (%)

$B[Y(3S) \to \pi^0\pi^0 Y(1S)] = \mathbf{1.88} + - \mathbf{0.08} + - \mathbf{0.31}$ (%)

- $\pi^0\pi^0$ effective mass spectrum from $Y(3S) \to \pi^0\pi^0 Y(2S)$ has the shape consistent with several theoretical predictions.
- $\pi^0\pi^0$ effective mass spectrum from $Y(3S) \to \pi^0\pi^0 Y(1S)$ has "double humped" shape, also observed in the charged pion transitions.



**P
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Latest experimental results on $\eta_c(2S)$

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

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

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

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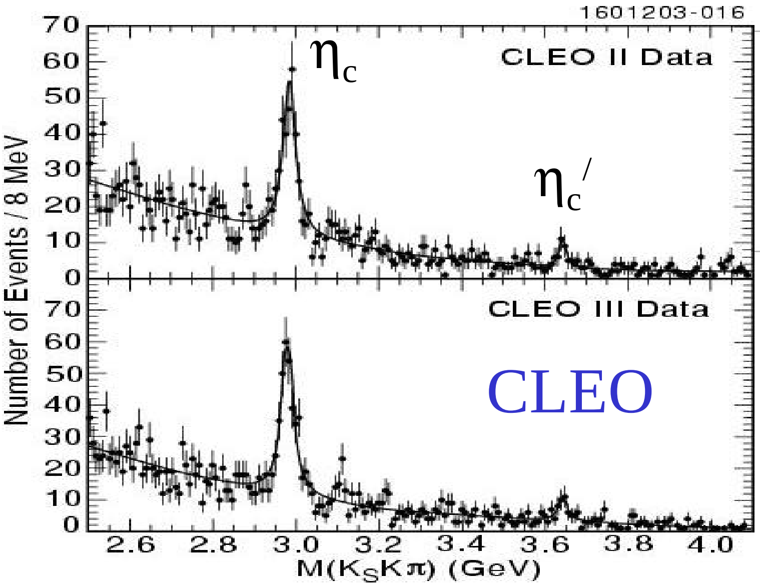
production in two photon fusion processes:

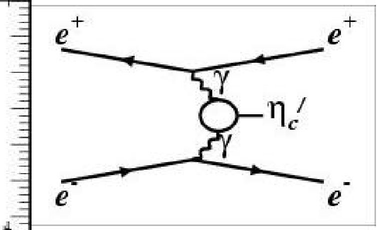
$M = 3642.9 \pm 3.1 \pm 1.5$ (MeV)
$\Gamma < 31$ MeV (90% C.L.)
$\Gamma_{\gamma\gamma} = 1.3 \pm 0.6$ (keV)

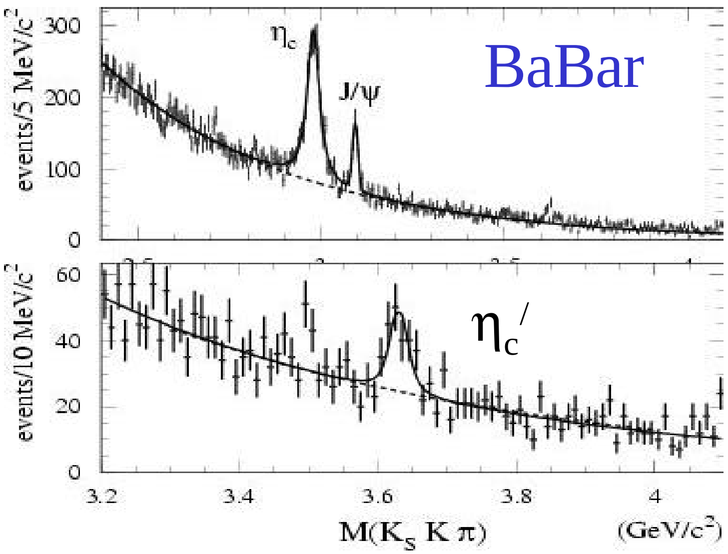
$h_c' \to K_s K^{\pm} p^{\mp}$

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

$\Gamma = 17.0 \pm 8.3 \pm 2.5$ (MeV)







Latest experimental results on $\eta_c(2S)$

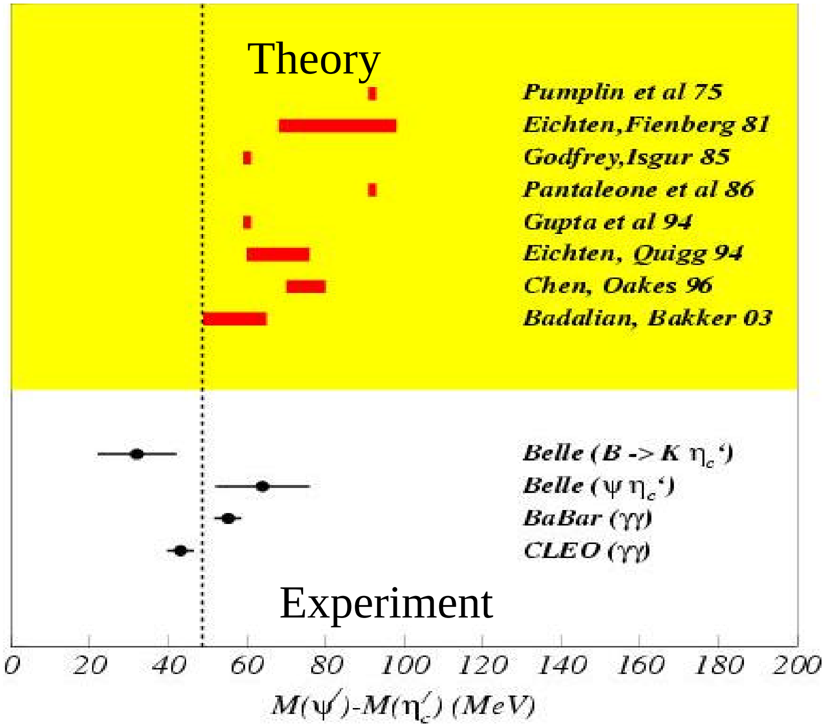
Belle, BaBar, CLEO combined $\eta_c(2S)$ mass value:

$M[\eta_c(2S)] = \mathbf{3637.4 + - 4.4}$ (MeV)

Hyperfine mass splitting

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

to be compared to theoretical predictions.
$\Delta M(1S) = M[\Psi(1S)] - M[\eta_c(1S)] =$
$= 117 + - 2$ (MeV)



$\Delta M(2S)$ is smaller that most theoretical predictions and should lead to a new insight into spin-spin contribution of the confinement part of qq potential.

$\Gamma[\eta_c(1S)] = 24.8 + - 3.4 + - 3.5$ (MeV) CLEO

$\Gamma[\eta_c(1S)] = 34.3 + - 2.3 + - 0.9$ (MeV) BaBar

PDG

$\Gamma[\eta_c(1S)] = 16.0 + 3.6 - 3.2$ (MeV)

Two-body Hadronic Ψ(2S) Decays

- QCD expectation:

$$Q_h \approx \frac{B[\Psi(2S)\rightarrow H]}{B(J/\Psi\rightarrow H)} \approx \frac{B[\Psi(2S)\rightarrow e^+e^-]}{B(J/\Psi\rightarrow e^+e^-)} \approx (12.3\pm 0.9)\%$$

- not taken into account α_s factor for J/Ψ and Ψ(2S)
- not taken into account form factor energy dependence
- interference with continuum?

even with above modifications, agreement within factor two is expected.

- experimentally not justified for many channels. Called as “12% rule” violation, or “ρπ” puzzle;

- many measurements are (were) not available, or poorly measured.

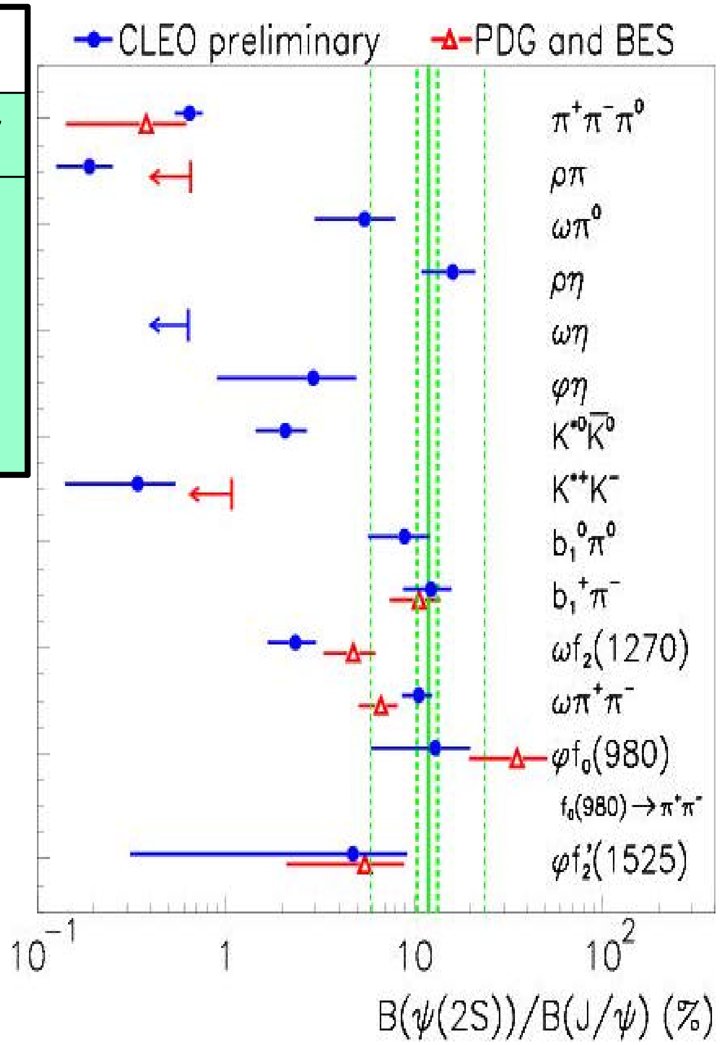
Two-body Hadronic Ψ(2S) Decays

BES,
CLEO preliminary

BES Collaboration

	channel	B[Ψ(2S)→X](x10^{-4})	Q_h(%)
	$K_s^0K_L^0$	1.82 + – 0.04 + –0.13	28.8 + – 3.7
VT	ωf_2	2.05 + – 0.56	4.8 + –1.5
	ρa_2	2.55 + – 0.87	2.3 + –1.1
	$K^*K_2^*$(bar)	1.86 + – 0.54	2.8 + –1.3
	$\phi f_2'$	0.44 + – 0.16	3.6 + –1.5

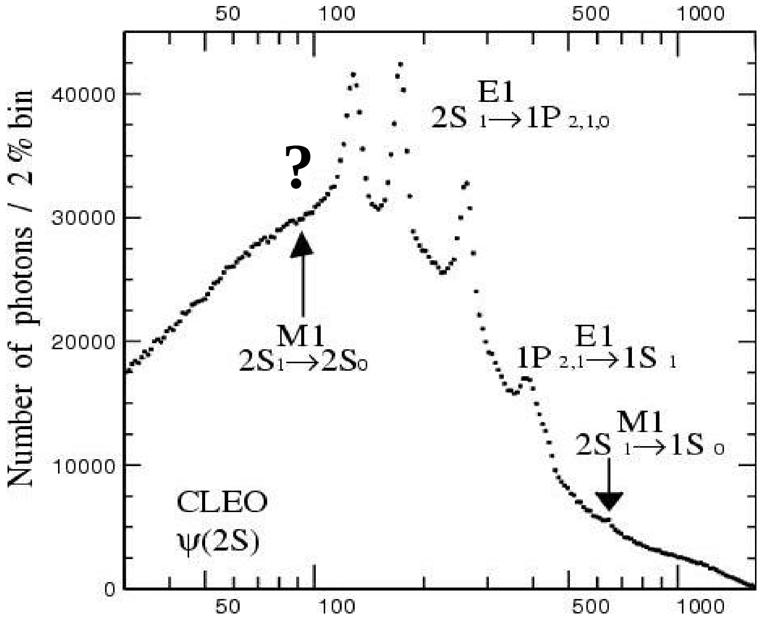
- isospin violating modes ωπ and ρη are not strongly suppressed with respect to 12% rule.
- VT decay modes also violate 12% rule.
- Ψ(2S) decay in $K_s^0K_L^0$ is enhanced by >4σ relative to the 12% rule.



Radiative Transitions from $\Psi(2S)$

CLEO
preliminary

- good agreement with PDG branching ratios.
- M1 transition to $\eta_c(1S)$, observed by CBAL is confirmed.
- no indication of M1 transition to $\eta_c(2S)$, observed by CBAL ~20 years ago.



$B[\Psi(2S) \rightarrow \gamma\chi_c(1P_J)]$ in % $B[\Psi(2S)\rightarrow\gamma\eta_c(1S)]$

	J=2 (E1 line)	J=1 (E1 line)	J=0 (E1 line)	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

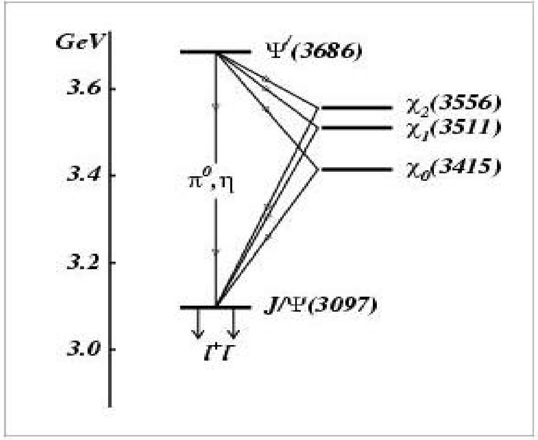
$\Psi\ (2S) \to g\ g\ J/\Psi$

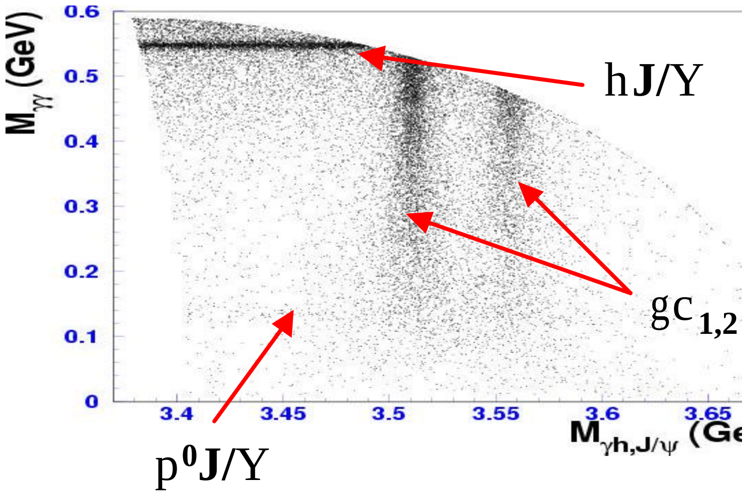
BES Collaboration

$\Psi(2S) \to \gamma\chi_{1,2} \to \gamma\gamma J/\Psi$ $J/\Psi \to \mu^+\mu^-, e^+e^-$

$\Psi(2S) \to \eta J/\Psi$ $\eta \to \gamma\gamma$

$\Psi(2S) \to \pi^0 J/\Psi$ $\pi^0 \to \gamma\gamma$





Expect from CLEOc

channel	$B[\Psi(2S) \to g\, c_2 \to g\, g\, J/\Psi]$	$B[\Psi(2S) \to g\, c_1 \to g\, g\, J/\Psi]$	$B[\Psi(2S) \to g\, c_0 \to g\, g\, J/\Psi]$	$B[\Psi(2S) \to p^0\, J/\Psi]$	$B[\Psi(2S) \to h\, J/\Psi]$
BES (%)	**1.62 + - 0.04 + - 0.12**	**2.81 + - 0.05 + - 0.23**	?	**0.143 + - 0.014+ -0.013**	**2.98 + -0.09 + - 0.25**
PDG (%)	**1.27 + - 0.08**	**2.66 + - 0.15**	**0.089+ -0.015**	**0.096+ -0.021**	**3.13+ -0.21**

New Narrow State X(3872)

- Belle Collaboration observed a narrow state in:

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

  $M = $ **3872.0 + - 0.6 + - 0.5** (MeV), $\Gamma <$ **2.3** MeV (90% CL).

- CDF and D0 Collaborations confirmed in:

  $p\text{-}pbar \rightarrow X(3872) + X$, $X(3872) \rightarrow \pi^+\pi^- J/\Psi$, $J/\Psi \rightarrow \mu^+\mu^-$

  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:
  - a conventional charmonium state ? (Eichten, Lane, Quigg), (Barnes et al)

    many quantum numbers are possible
  - a D^0-D^{*0}(bar) molecule ? (Tornqvist et al)

    $J^{PC} = 1^{++}$ (S-wave), 0^{-+} (P-wave)
  - a charmonium hybrid state ? (Close et al)

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

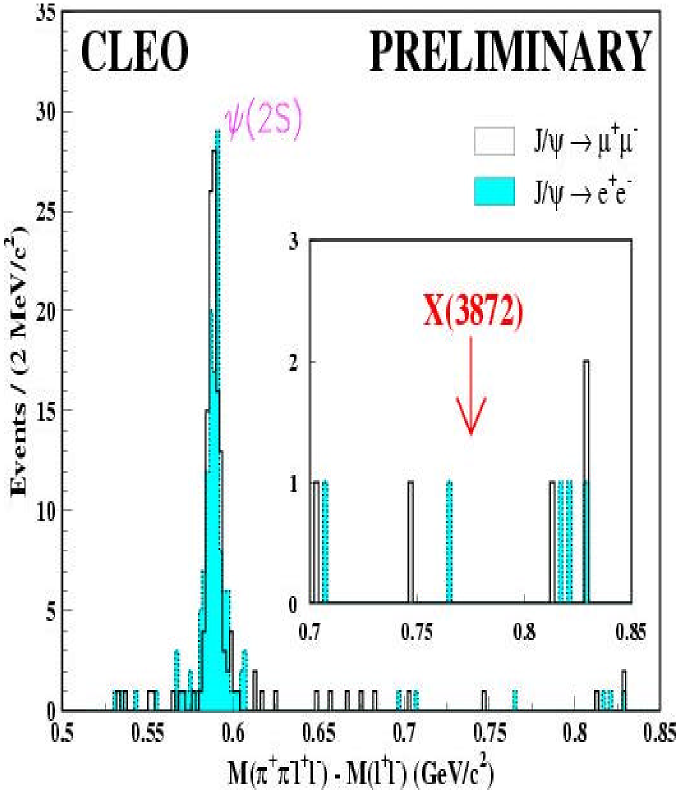
New Narrow State X(3872)

CLEO
preliminary

- CLEO searched for X(3872) state in:
  - untagged γγ 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 $X \rightarrow \pi^+\pi^- J/\Psi,\ J/\Psi \rightarrow l^+l^-$ were analyzed.
- no signal was found.
- following upper limits were set:



Untagged γγ fusion (systematic errors are included):

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

ISR production (systematic errors are included):

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

SUMMARY

- heavy quarkonium physics is still an active field:
  - large data samples collected for quarkonia in e^+e^- annihilation by BES-II ($c\bar{c}$), CLEO III ($b\bar{b}$), CLEOc ($c\bar{c}$).

- many new important experimental observations and measurements are available and many others are expected.

- theory is coming along with progress in NRQCD and Lattice QCD. Many unresolved puzzles still to be understood.

Thank You