Upsilon(1S,2S,3S) Studies at CLEO

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Studies of Υ(1S,2S,3S): Outline

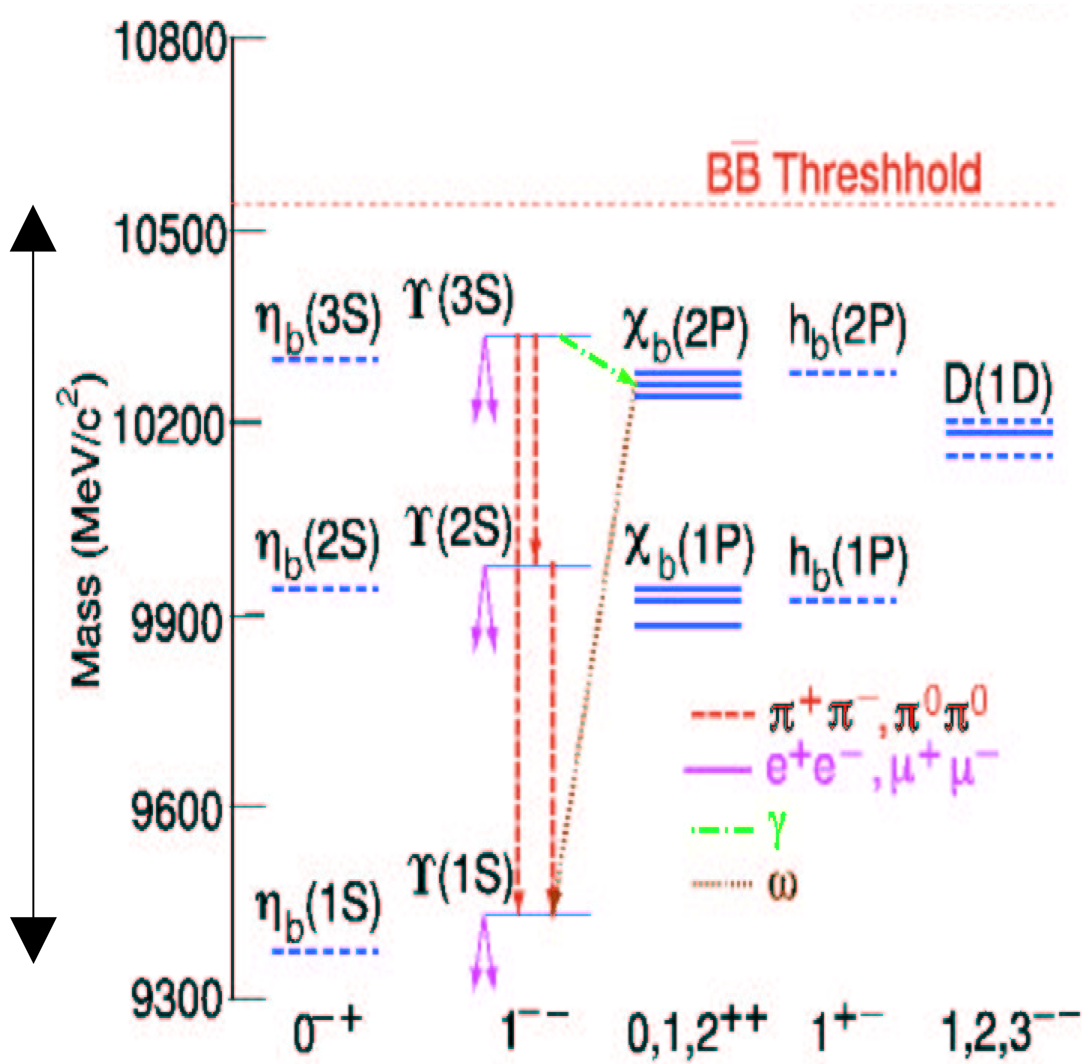
- Motivation for studying Quarkonium
- CLEO III detector, data sample and quality
- Measurement of $B_{\mu\mu}(\Upsilon(nS))$ (n=1,2,3)
- Hadronic transitions within Upsilon states
- E1 and M1 Photon transitions
- Upsilon decays to Charmonium states
- Conclusion

Motivation for Studying Quarkonium

- Simplest strongly interacting system
- QCD equivalent of positronium
- Non-relativistic for heavy quarks ($Q\bar{Q}$)

  Q=c: $\beta^2 \sim 0.25$; Q=b: $\beta^2 \sim 0.08$
- Tests potential models, $V(r) = -4/3\ \alpha_s/r + k\ r$
- Tests Lattice QCD calculations

The Upsilon System: Bottomium

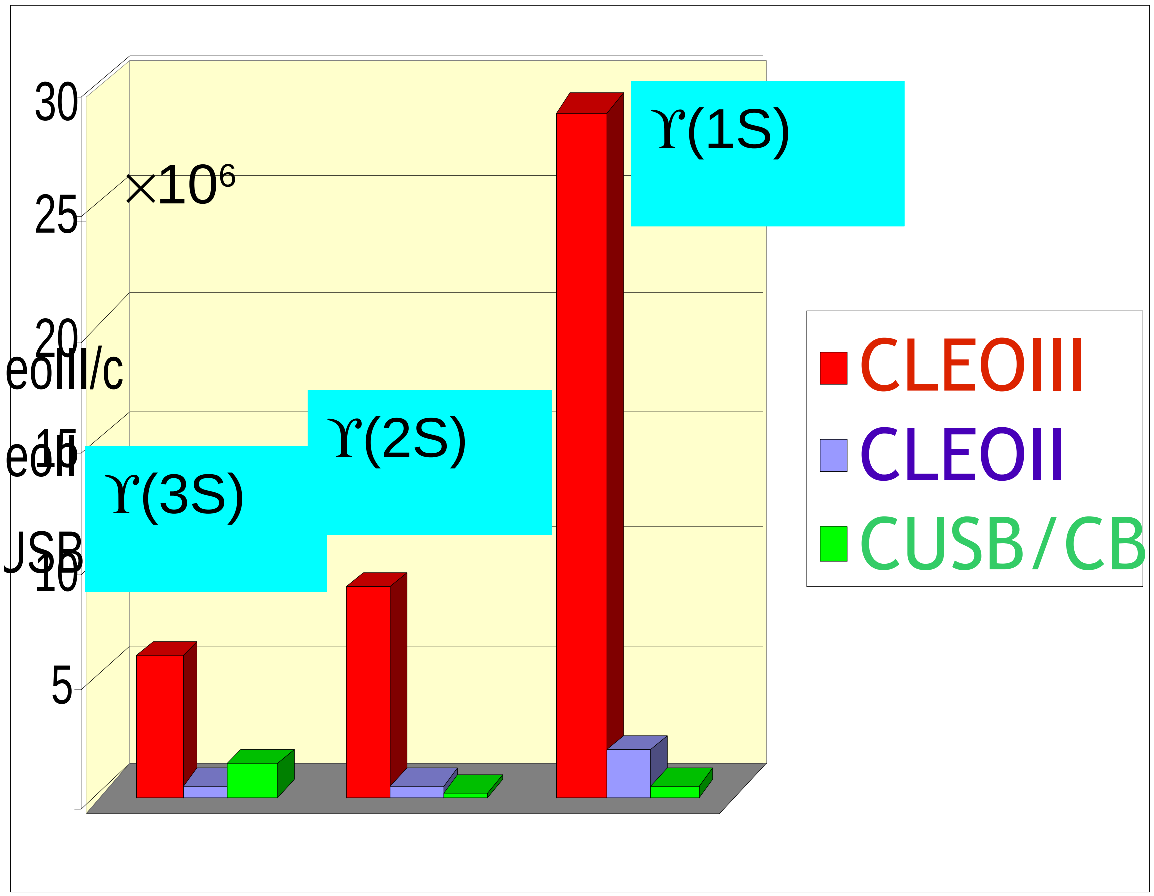


Rich spectroscopy,

many transitions - hadronic, photonic

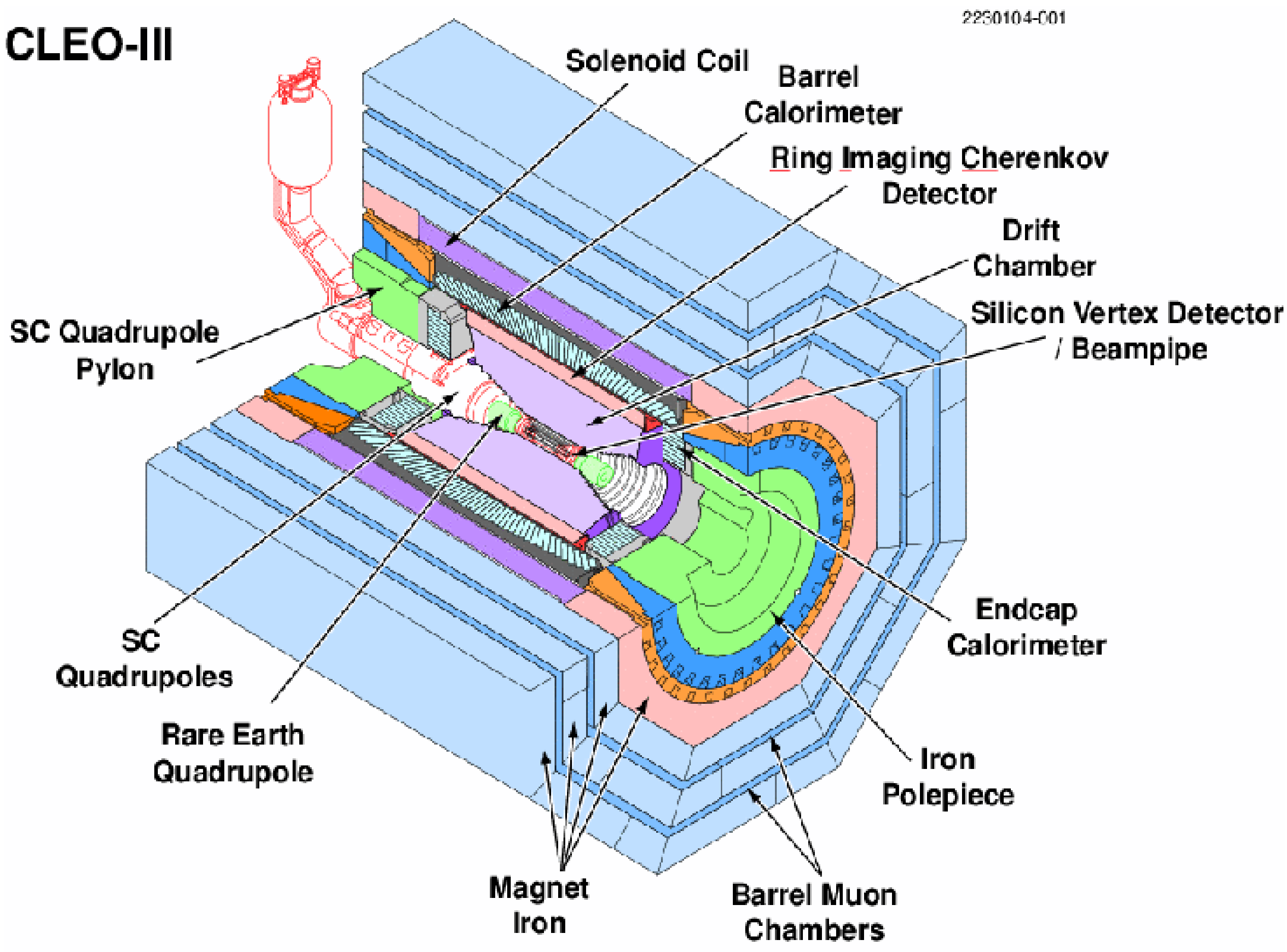
Y(1S,2S,3S) directly produced in e+e- annihilation

CLEO III Data Sample on $\Upsilon(1S,2S,3S)$



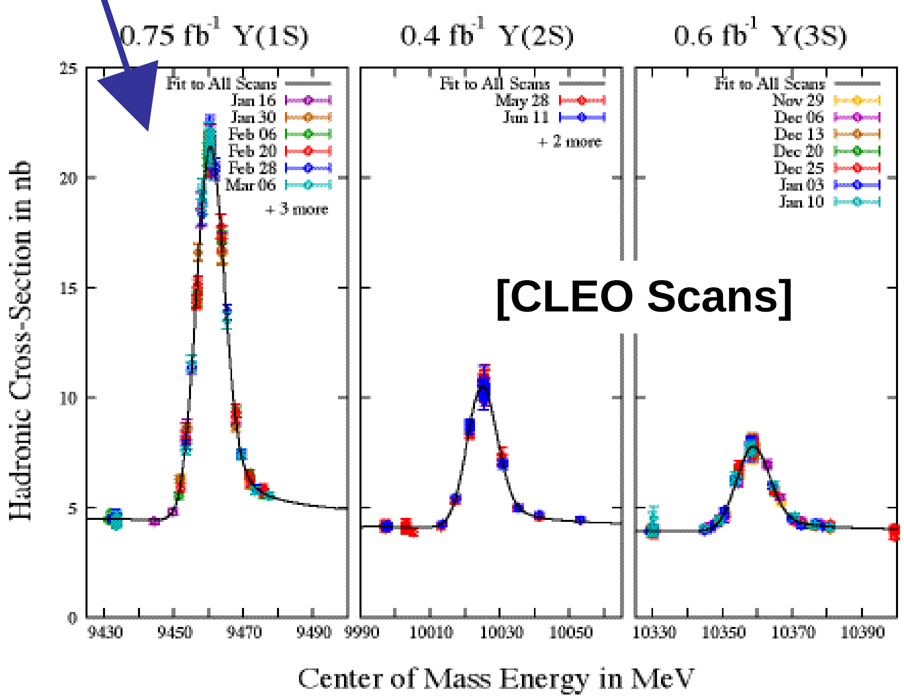
Orders of magnitude improvement in statistics, plus a much more powerful detector!

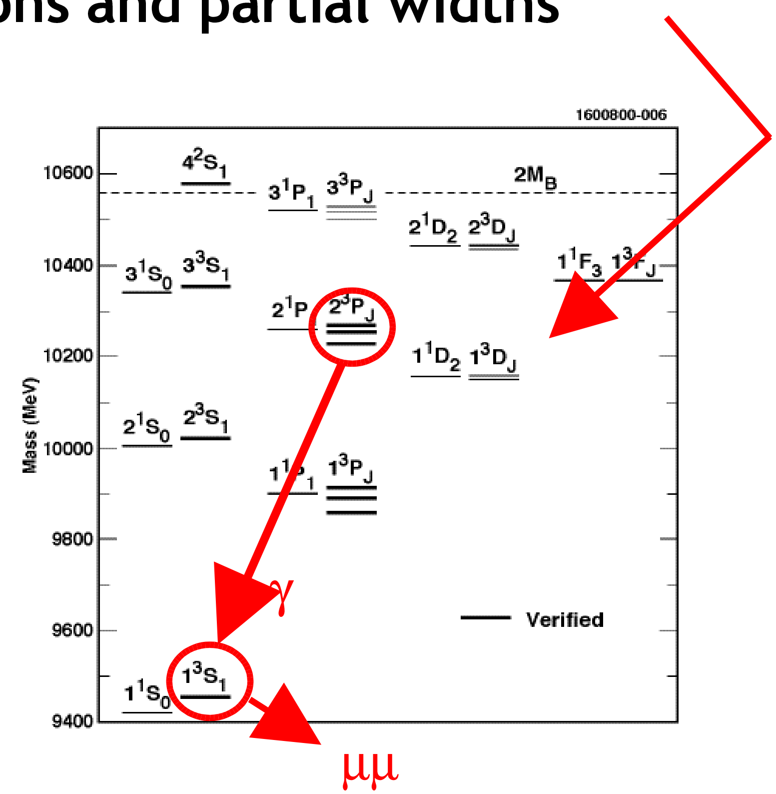
The CLEO III Detector



$B_{\mu\mu}$ for the Υ States

- Importance beyond knowing $B(\Upsilon(nS) \to \mu^+\mu^-)$
- Needed to get Γ_{tot} for narrow resonances from Γ_{ee}
- CLEO hopes to measure Γ_{ee} to a few percent
- Many analyses use the $\mu^+\mu^-$ final state for cleanliness
- $B_{\mu\mu}$ affects many branching fractions and partial widths





$B_{\mu\mu}$ for the Υ States

Measurement of $B(\Upsilon(nS) \rightarrow \mu^+\mu^-)$

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 $\Upsilon(nS)$ precisely (precise Γ_{ee} measurement is also needed, expected soon from CLEO):

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

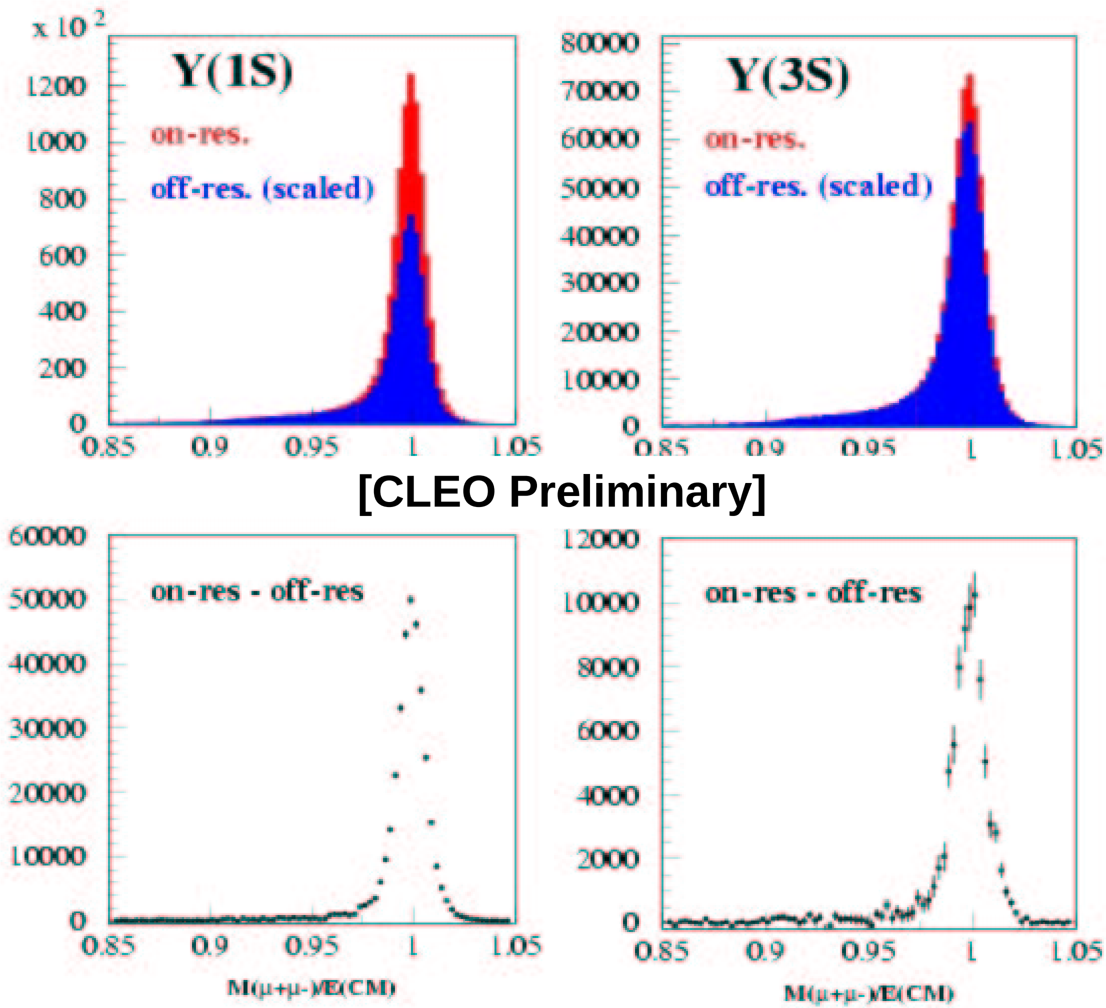
→ Measure decay rate to muon pairs relative to hadronic decay rate:

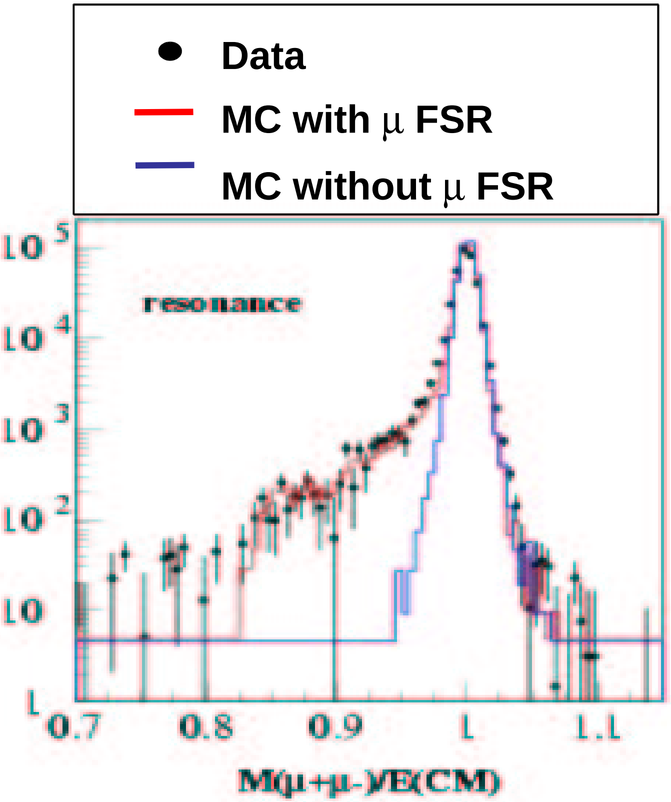
$$\bar{B}_{\mu\mu} = \frac{\Gamma_{\mu\mu}}{\Gamma_{had}} = \frac{N(\Upsilon \rightarrow \mu^+\mu^-)/\varepsilon_{\mu\mu}}{N(\Upsilon \rightarrow hadrons)/\varepsilon_{had}}$$

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

Large signals in $m_{\mu\mu}/\sqrt{s}$ after continuum subtraction at the $\Upsilon(1S)$, $\Upsilon(2S)$, and even $\Upsilon(3S)$ …

$B_{\mu\mu}(\Upsilon(nS))$





… and details such as muon FSR allow for high precision.

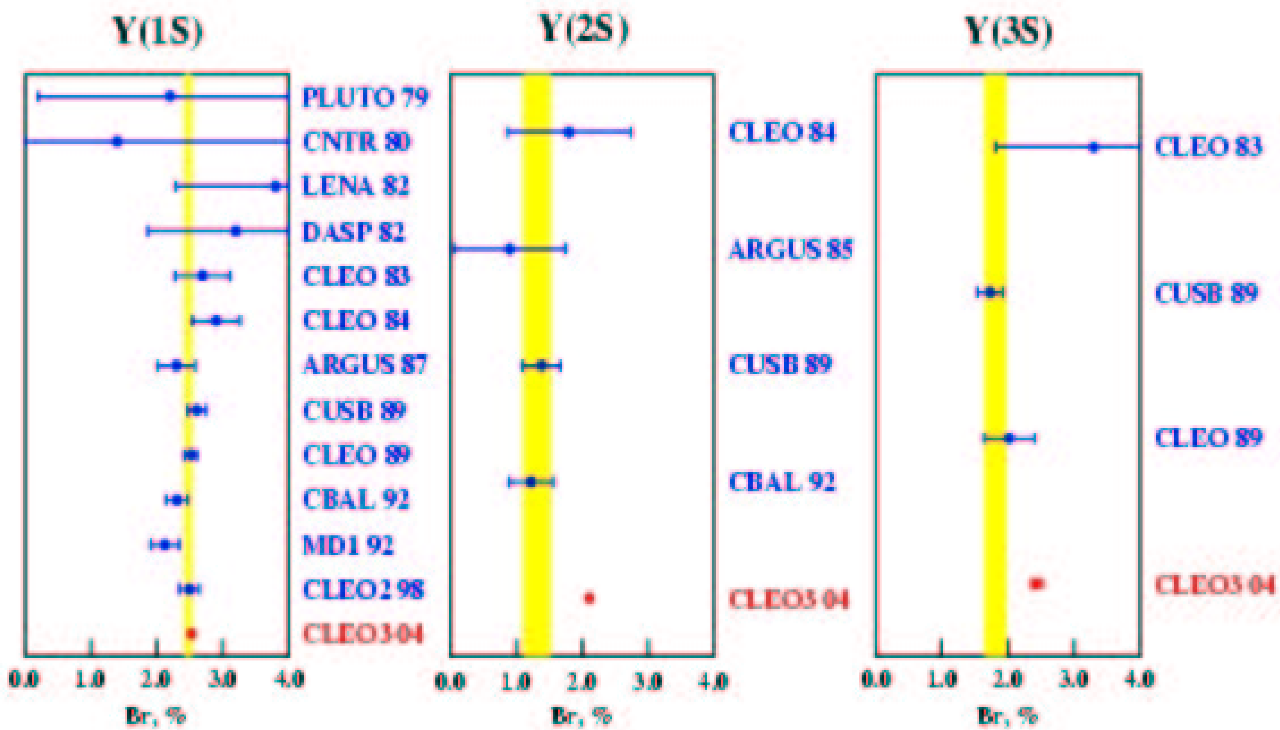
$B_{\mu\mu}$ for the Bound Υ States [CLEO, submitted to PRL]

	$B_{\mu\mu}$ (%)		Γ_{tot} (keV)	
	CLEO *preliminary*	PDG	CLEO *preliminary*	PDG
Υ(1S)	2.53 ± 0.02 ±0.05	2.48 ± 0.06	52.1 ± 1.5	52.5 ± 1.8
Υ(2S)	**2.11** ± 0.03 ±0.05	**1.31** ± 0.21	**28.0** ± 1.4	**44** ± 7
Υ(3S)	2.44 ± 0.07 ±0.05	1.81 ± 0.17	19.9 ± 2.0	26.3 ± 3.5

Few % precision reached !

$B_{\mu\mu}(\Upsilon(2,3S))$ significantly higher than prior results

Await CLEO Γ_{ee} !



Hadronic Transitions between Upsilon States

Di-Pion Transitions from Υ(3S)

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

$B(\Upsilon(3S) \rightarrow \pi^0\pi^0\,\Upsilon(2S)) = 2.02 \pm 0.18 \pm 0.38\ \%$

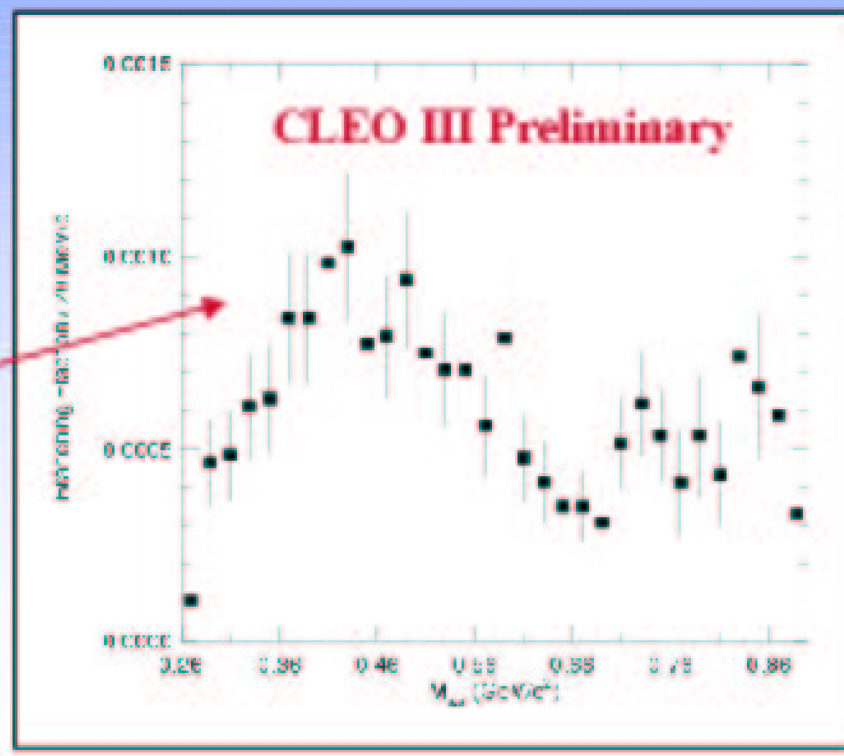
$B(\Upsilon(3S) \rightarrow \pi^0\pi^0\,\Upsilon(1S)) = 1.88 \pm 0.08 \pm 0.31\ \%$

$\Upsilon(3S) \rightarrow \pi^0\pi^0\,\Upsilon(2S)$:

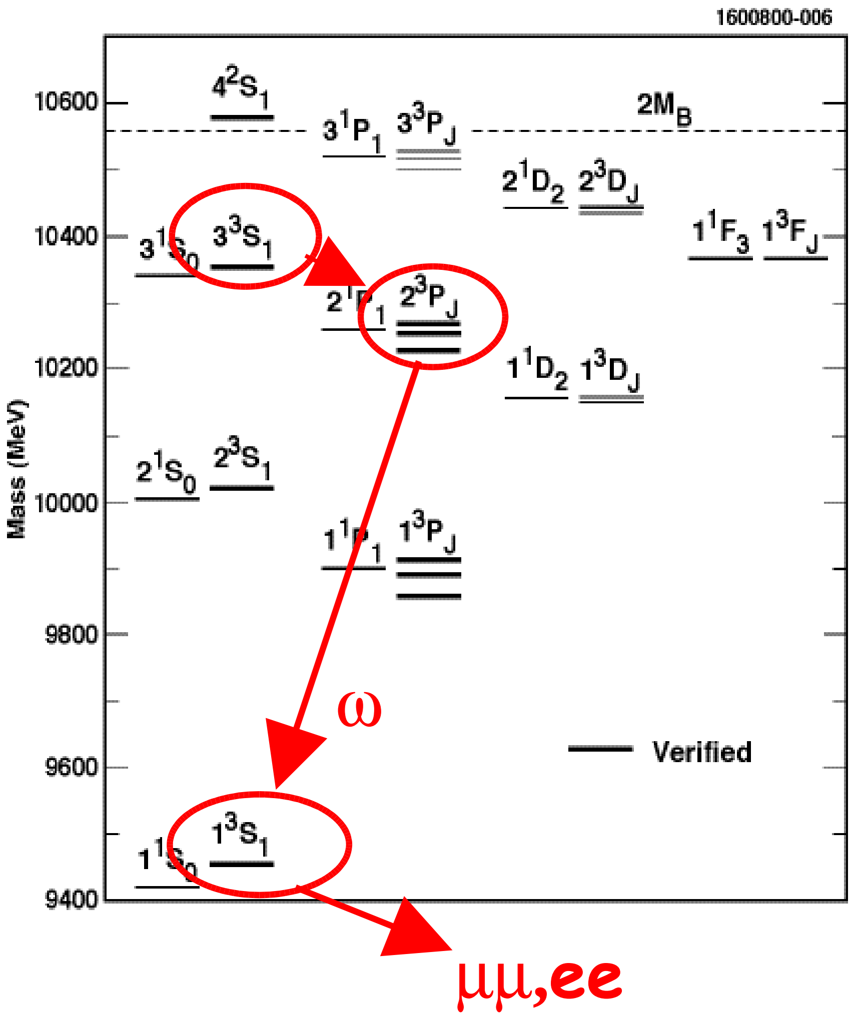
$\pi^0\pi^0$ effective mass spectrum has a shape consistent with several theoretical predictions

$\Upsilon(3S) \rightarrow \pi^0\pi^0\,\Upsilon(1S)$:

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



NEW: Observation of $\chi_b(2P) \to \omega\Upsilon(1S)$



New Υ hadronic transition - **not $\pi\pi$!**

First hadronic transition for χ_b states!

Fully reconstructed exclusive channel: Cascade starts with E1 γ from $\Upsilon(3S)$; ends with $\Upsilon(1S)$ to lepton pairs

Preliminary results reported in 2003; now final, with full $\Upsilon(3S)$ data sample

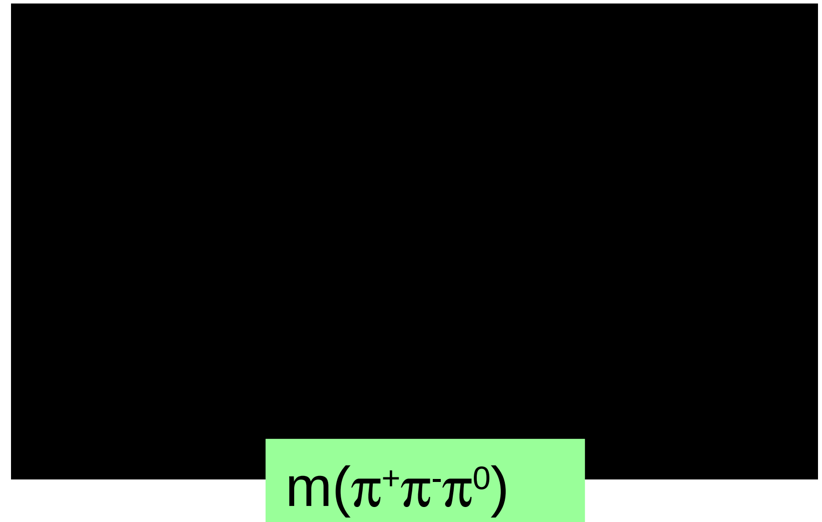
$\chi_b(2P) \rightarrow \omega\Upsilon(1S)$

Final Results:

$$B(\chi_{b1}'\rightarrow\omega\Upsilon(1S)) = (\mathbf{1.63}^{+0.35}_{-0.31}{}^{+0.16}_{-0.15})\%$$

$$B(\chi_{b2}'\rightarrow\omega\Upsilon(1S)) = (\mathbf{1.10}^{+0.32}_{-0.28}{}^{+0.11}_{-0.10})\%$$

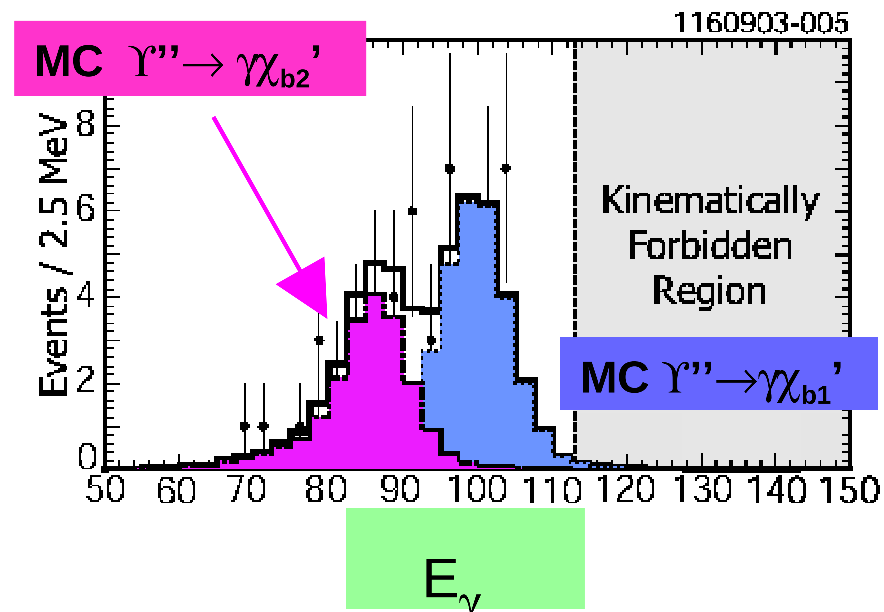
J = 0 kinematically forbidden!



Roughly equal for J = 1 and 2

$r_{2/1}$ predicted to be 1.3 ± 0.3

[Voloshin - hep-ph/0304165]

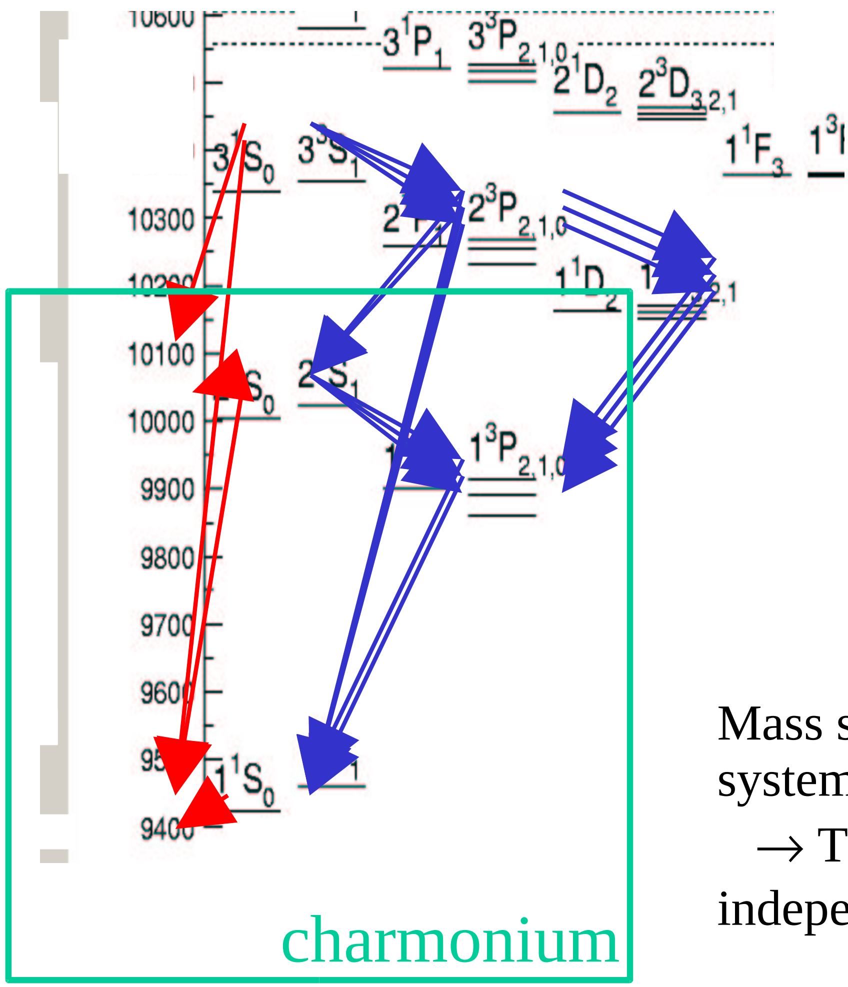


[hep-ex/0311043, accepted by PRL]

Very large rate considering limited phase space!

E1 and M1 Photon Transitions

Bottomonium



Typical λ_γ ~0.3-2fm ≥ mean quark separation ~0.3~0.8fm

Lowest multipoles dominate:

E1: $\Delta L=1, \Delta S=0$

M1: $\Delta L=0, \Delta S=1$

$(\Gamma_{M1} << \Gamma_{E1})$

Mass splitting are very similar between cc and bb systems

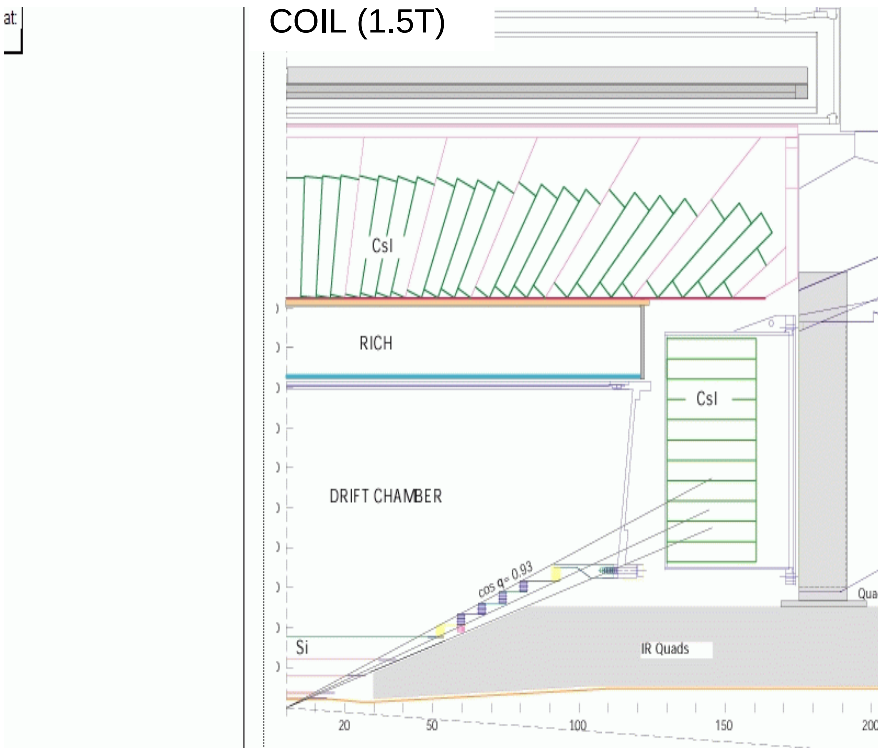
→ The responsible inter-quark force is flavor independent.

Detecting Photon Transitions

- EM calorimeter - Essential for photon spectroscopy
  - ~8000 CsI(Tl) crystals + photodiodes
  - First crystal calorimeter in magnetic field

·Excellent charged particle detection

·Large solid angle coverage

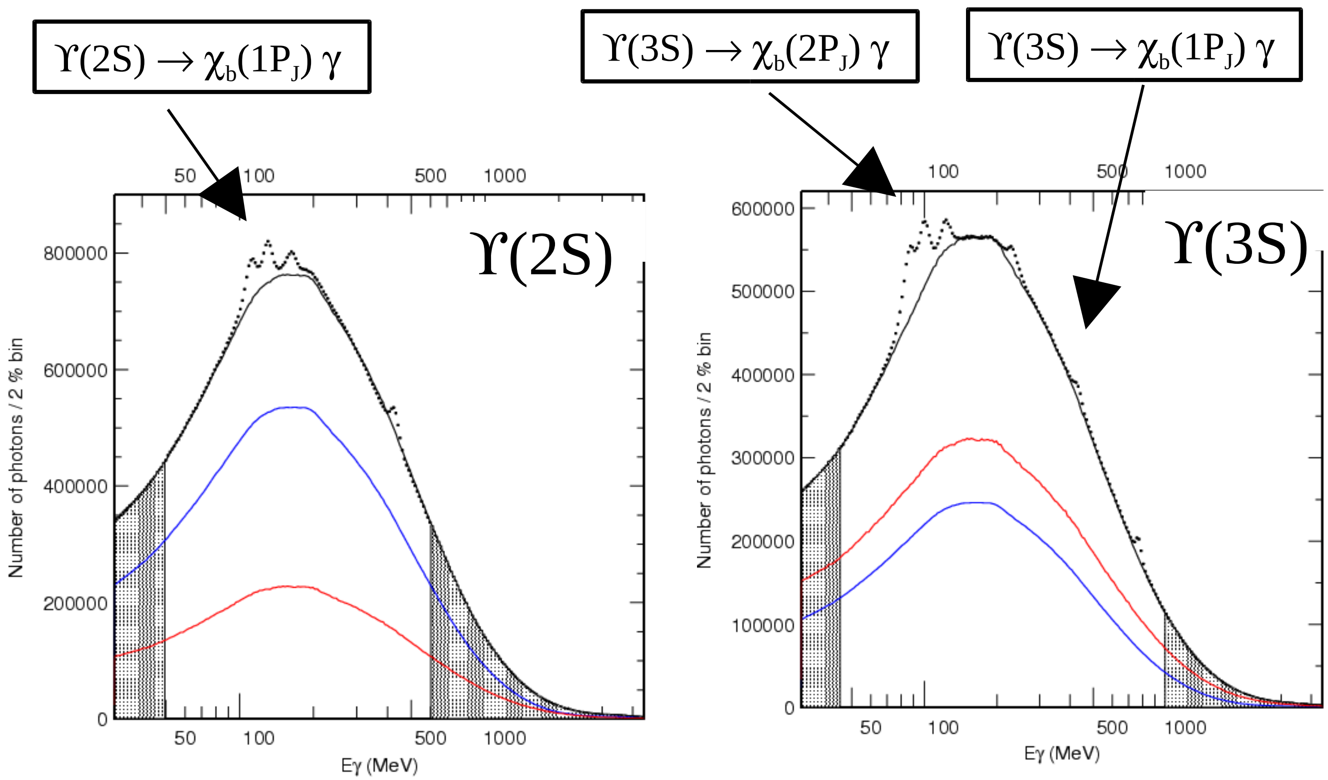


Detector	Calorimeter crystals	$\sigma_{E\gamma}$ resolution at $E\gamma$=100 MeV
CLEO III	CsI(Tl)	4.5 MeV
CUSB II	BGO	4.2 MeV
Crystal Ball	NaI(Tl)	4.8 MeV
BESII	Not a crystal calorimeter	70 MeV

Photon Transitions

Analysis procedure

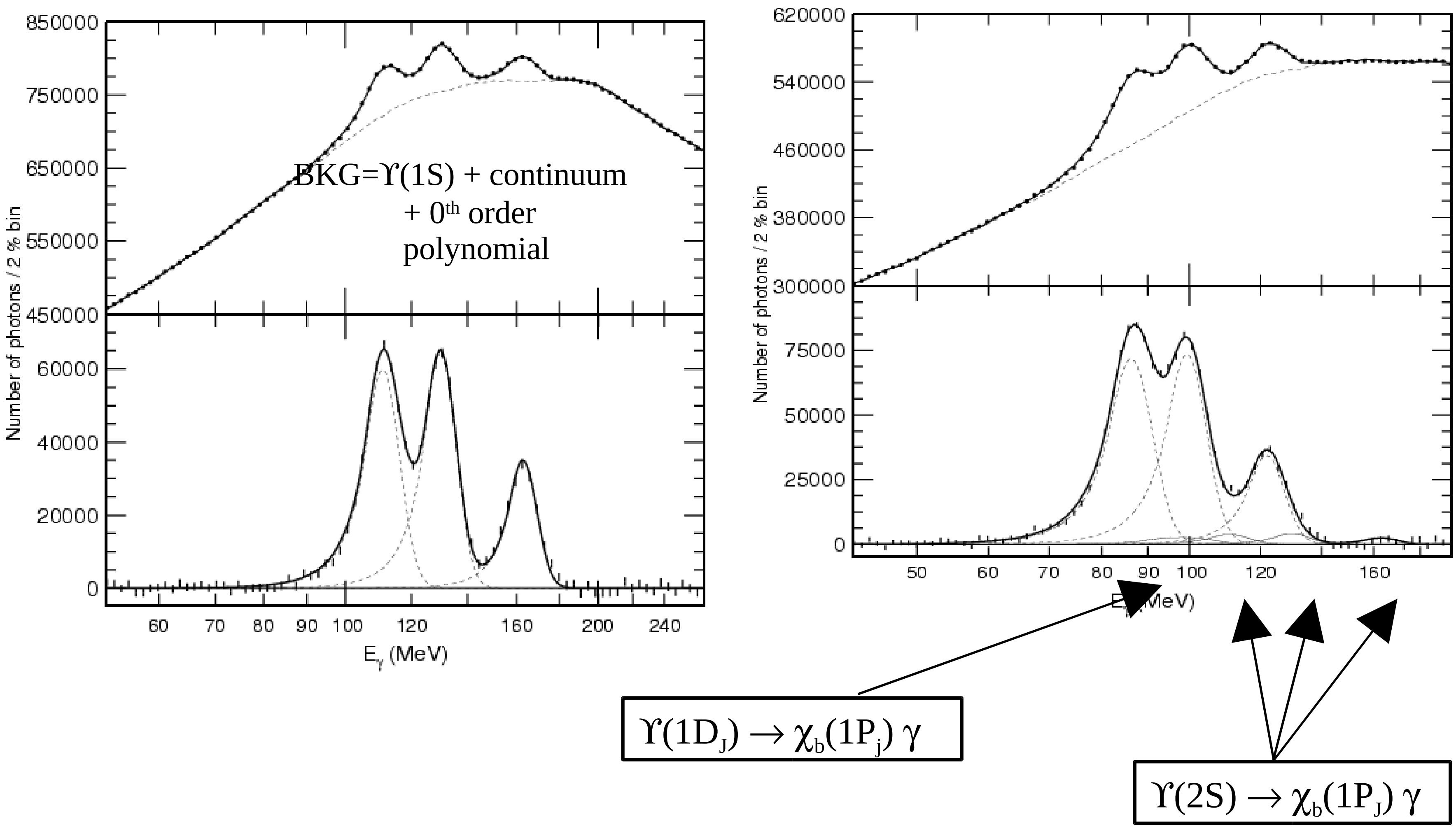
- Same photon selection as in $\psi(2s)$ analysis (veto tracks pointing at shower, E9/E25, suppress hot crystals
- Suppress photons from π^0 ($\cos\theta_{\gamma\gamma}$>0.7) for analysis of high energy photons only
- Use $\Upsilon(1S)$+continuum+(low order polynomial) for BKG parametrization (E_γ<200MeV)



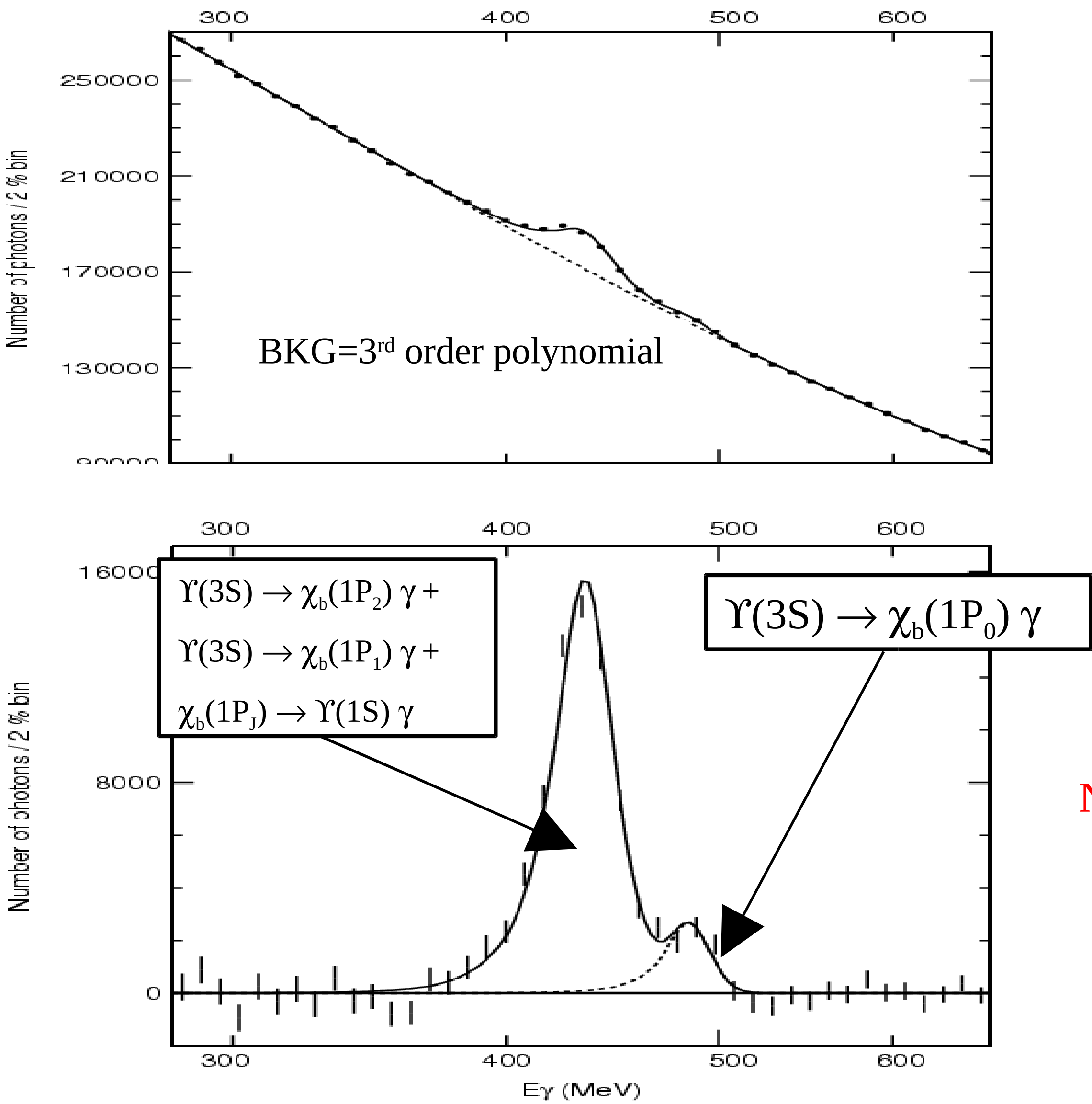
total fitted background
fitted $\Upsilon(1S)$ spectrum
fitted continuum spectrum

Photon Transitions

$\Upsilon(2S) \rightarrow \chi_b(1P_J)\ \gamma$ and $\Upsilon(3S) \rightarrow \chi_b(2P_J)\ \gamma$



$\Upsilon(3S) \rightarrow \chi_{bJ}(1P_J)\ \gamma$

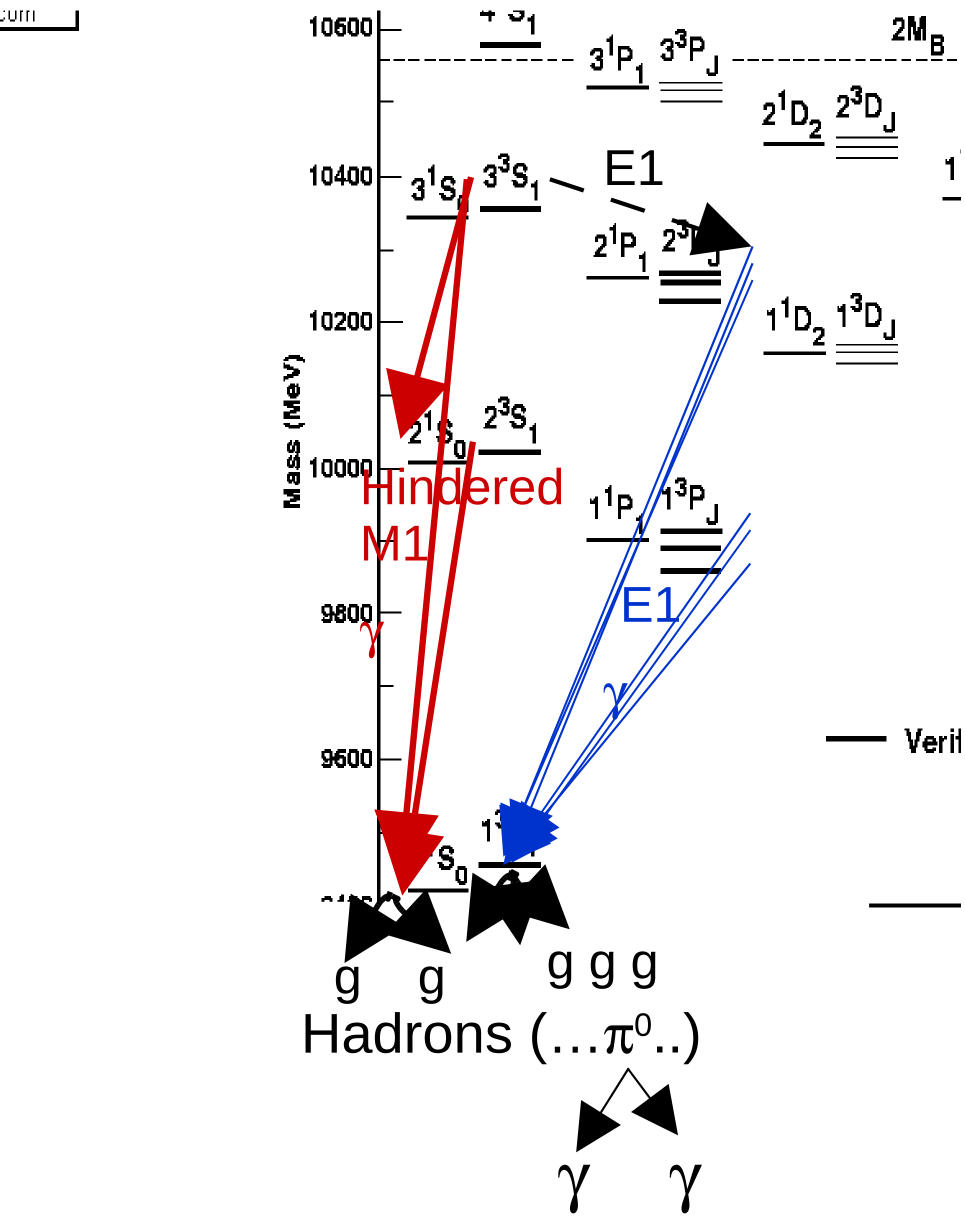


We were able to extract
BR($\Upsilon(3S) \rightarrow \chi_b(1P_0)\ \gamma$)

whose photon peak is isolated

Notice also that there is no significant enhancement around E~350MeV which would correspond to $\Upsilon(3S) \rightarrow \eta_b(2S)\ \gamma$

Search for $\eta_b(1^1S_0)$, $\eta_b(2^1S_0)$

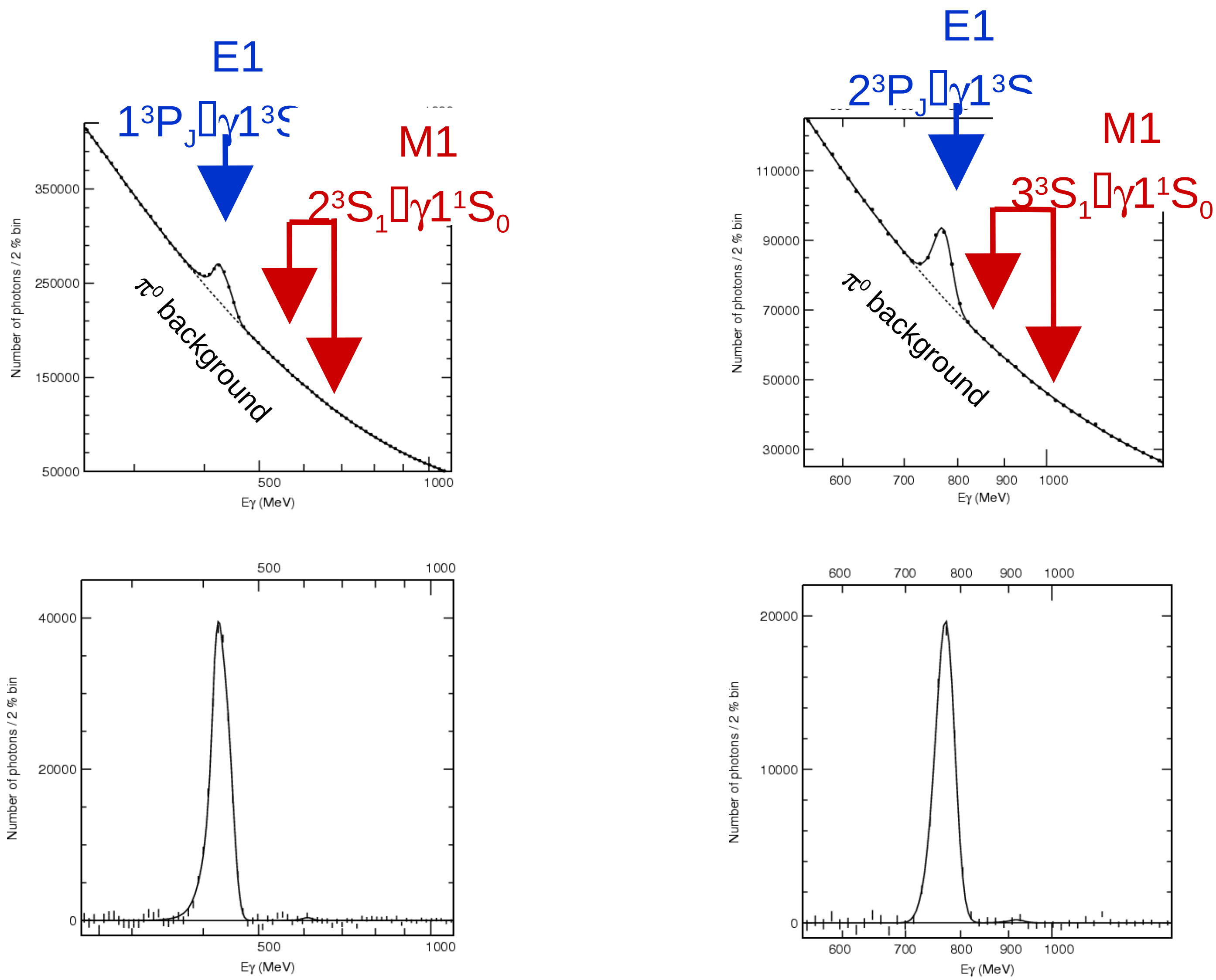


Hindered M1 transitions

Rates strongly suppressed compared to E1

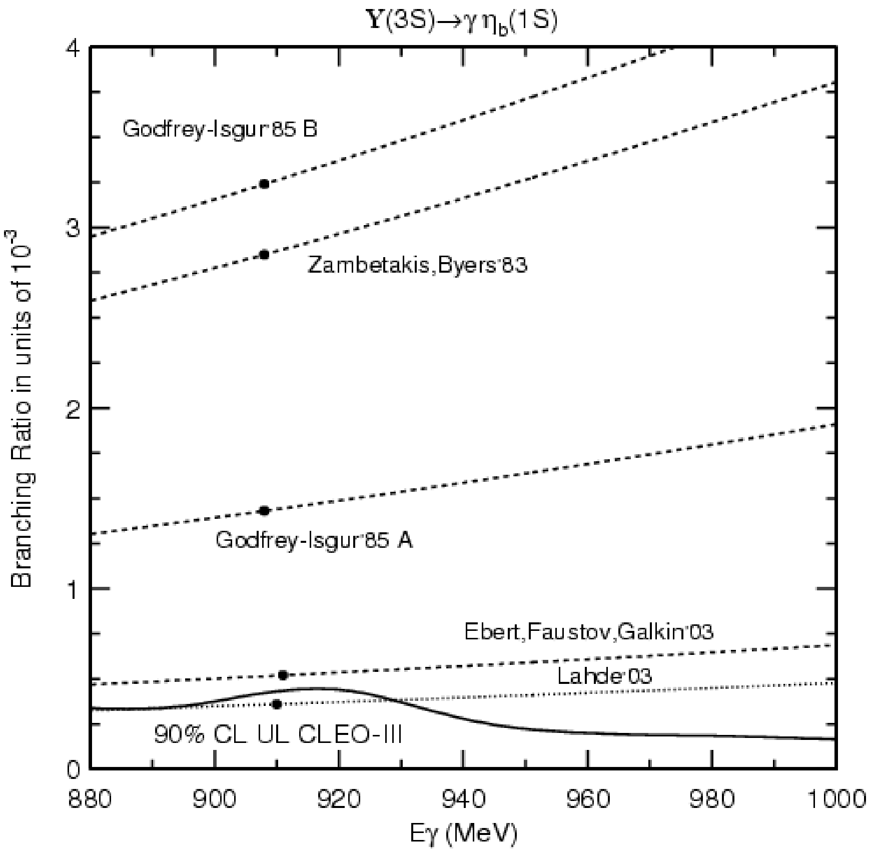
Also, masses of singlet states not known experimentally

Fitting to $\Upsilon(3S) \rightarrow \eta_b(1S)\ \gamma$ and $\Upsilon(2S) \rightarrow \eta_b(1S)\ \gamma$



The UL's are looser in lower energy region due to higher background (dominated by π^0's)

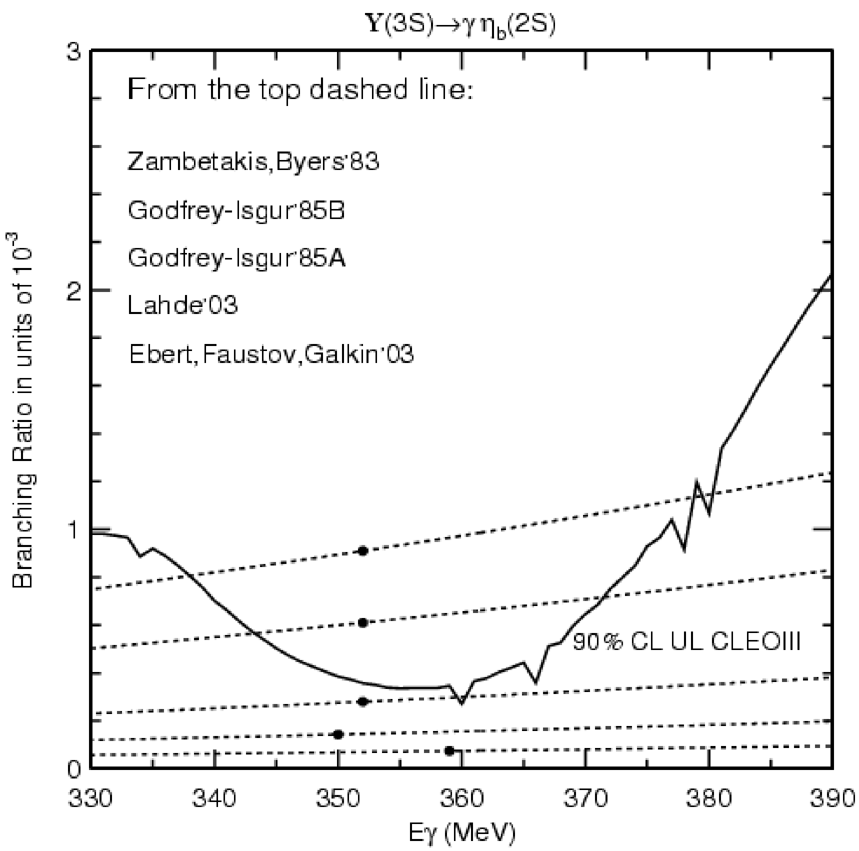
- **Test potential model predictions for Γ_{M1}**

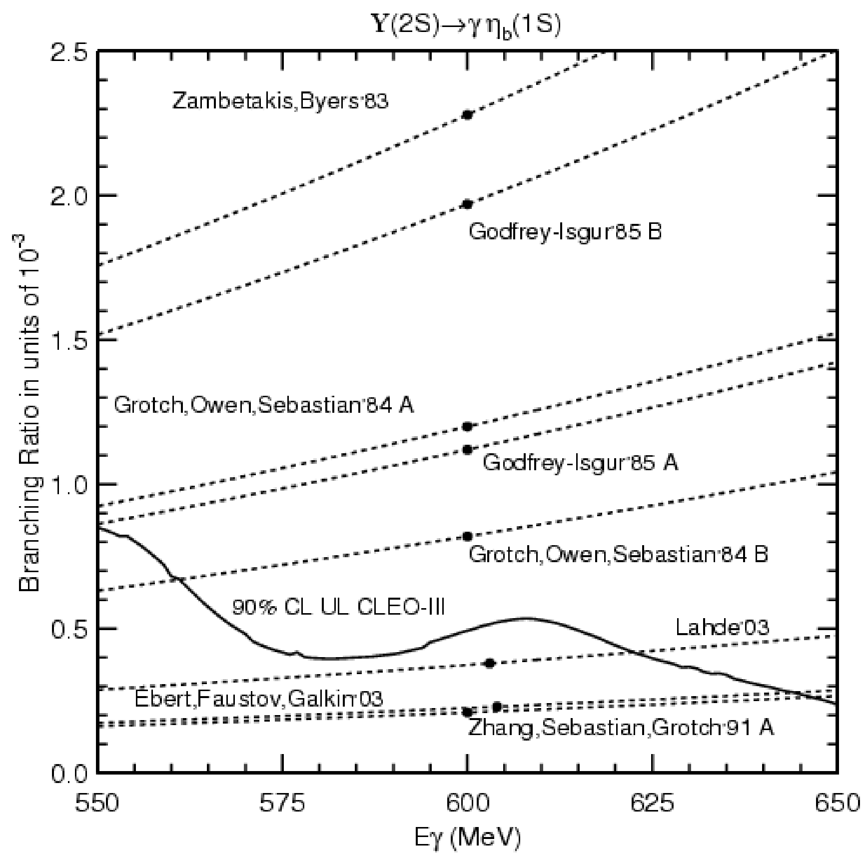


Models from the compilation by Godfrey&Rosner PR D64, 074011 (2001); Ebert,Faustov, and Galkin, PRD67, 014027(2003); Lahde NP A714, 183(2003) [scaled here by phase-space]

- Many calculations are ruled out!

- **Test potential model predictions for Γ_{M1}**





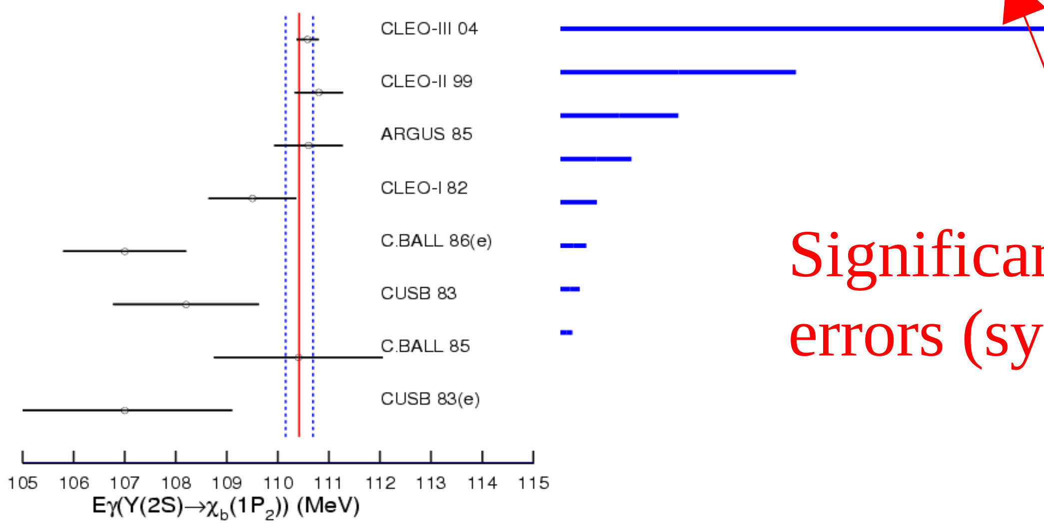
Results on E1 Transitions in the Upsilon System

	CLEO III (2004)	CLEO II (1998)	PDG (average of observed photon energies)
$BR(\Upsilon' \to \chi_{b0}\ \gamma)$	3.75±0.12±0.47%	3.4±0.5±0.6 %	3.8±0.6 %
$BR(\Upsilon' \to \chi_{b1}\ \gamma)$	6.93±0.12±0.41%	6.9±0.5±0.9 %	6.8±0.7 %
$BR(\Upsilon' \to \chi_{b2}\ \gamma)$	7.24±0.11±0.40%	7.4±0.5±0.8 %	7.0±0.6 %
$E_\gamma(\Upsilon' \to \chi_{b0}\ \gamma)$	162.56±0.19±0.42MeV	162.0±0.8±1.2 MeV	162.1±1.0 MeV
$E_\gamma(\Upsilon' \to \chi_{b1}\ \gamma)$	129.58±0.09±0.29MeV	128.8±0.4±0.6 MeV	129.8±0.5 MeV
$E_\gamma(\Upsilon' \to \chi_{b2}\ \gamma)$	110.58±0.08±0.30MeV	110.8±0.3±0.6 MeV	110.1±0.5 MeV

	This measurement	CLEO2 (1991)	PDG
$BR(\Upsilon'' \to \chi_{b0}'\ \gamma)$	6.77±0.20±0.65%	$4.9^{+0.3}_{-0.4}\pm0.6$ %	5.4±0.6 %
$BR(\Upsilon'' \to \chi_{b1}'\ \gamma)$	14.54±0.18±0.73%	$10.5^{+0.3}_{-0.2}\pm1.3$ %	11.3±0.6 %
$BR(\Upsilon'' \to \chi_{b2}'\ \gamma)$	15.79±0.17±0.73%	13.5±0.3±1.7 %	11.4±0.8 %
$BR(\Upsilon'' \to \chi_{b0}\ \gamma)$	0.30±0.04±0.10%	-	-
$E_\gamma(\Upsilon'' \to \chi_{b0}'\ \gamma)$	121.55±0.16±0.46MeV	122.3±0.3±0.6 MeV	122.8±0.5 MeV
$E_\gamma(\Upsilon'' \to \chi_{b1}'\ \gamma)$ From excl. (CBX02-20)	99.15±0.07±0.25MeV 99.08±0.17±0.34MeV	99.5±0.1±0.5 MeV	99.90±0.26 MeV
$E_\gamma(\Upsilon'' \to \chi_{b2}'\ \gamma)$ From excl. (CBX02-20)	86.04±0.06±0.27MeV 86.09±0.30±0.29MeV	86.4±0.1±0.4 MeV	86.64±0.23 MeV

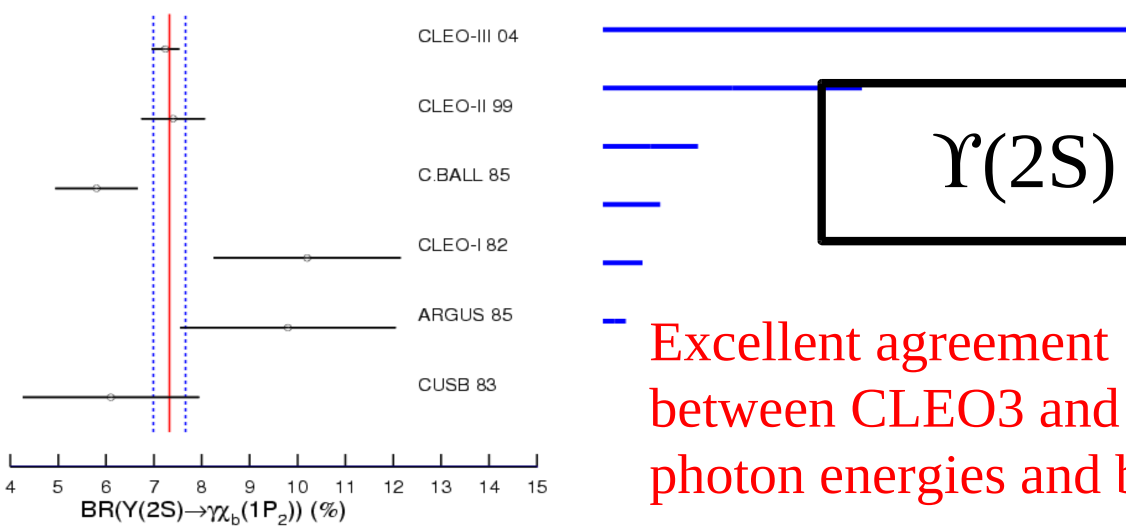
E1 Transitions: Impact of CLEO III Results

Weight in new world average:



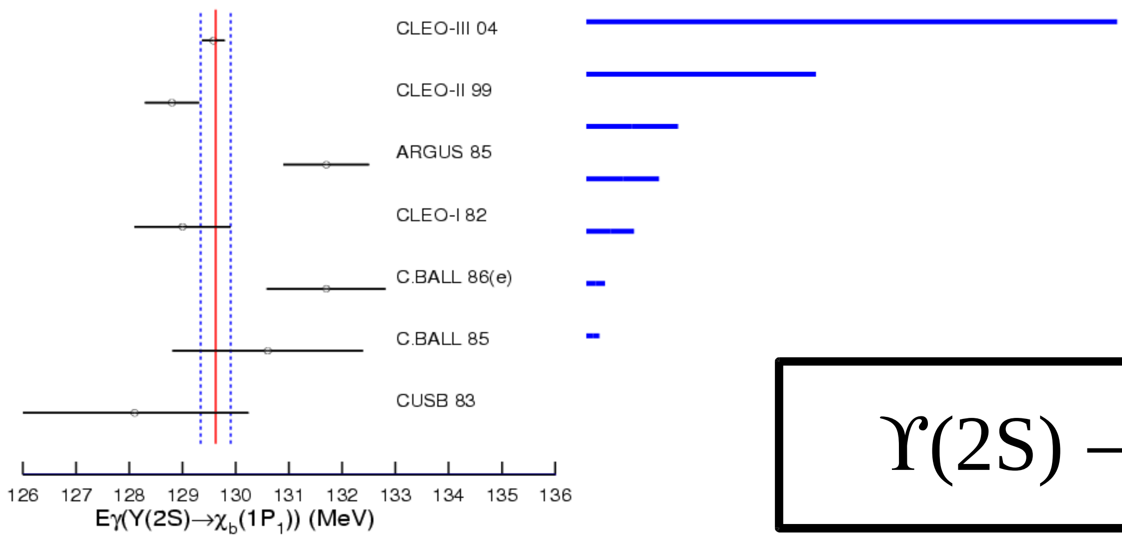
Significantly improved errors (systematics dominated)

$$\Upsilon(2S) \rightarrow \chi_{bJ}(1P_2)\ \gamma$$

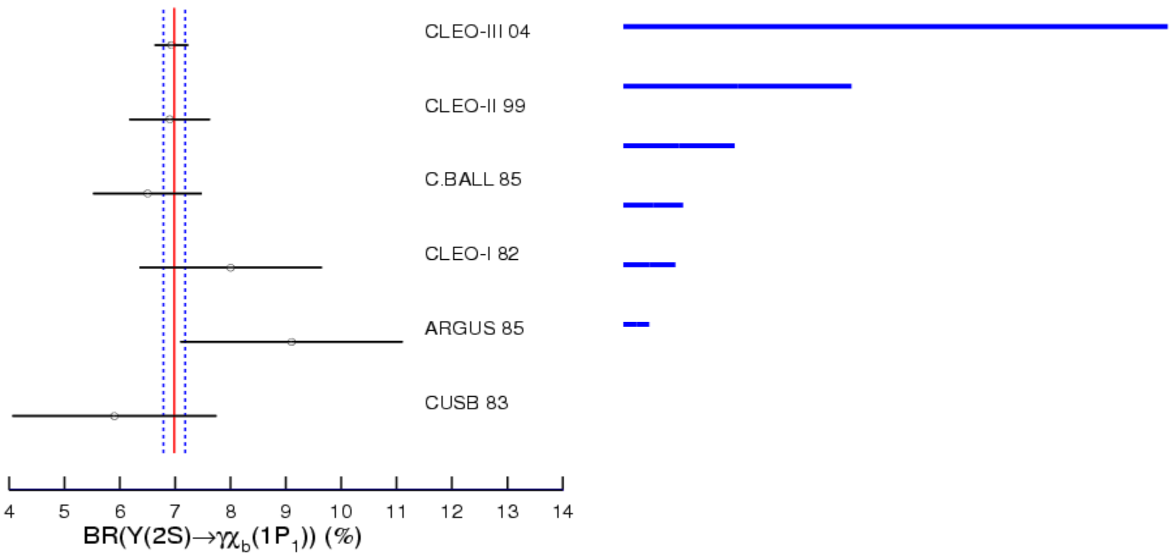


Excellent agreement
between CLEO3 and previous measurements of photon energies and branching ratios

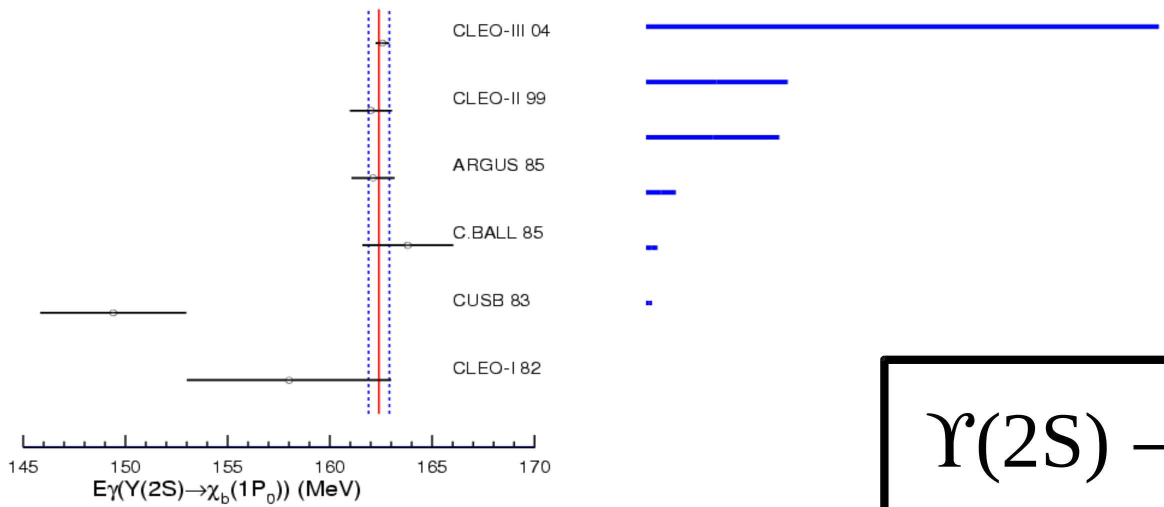
E1 Transitions: Impact of CLEO III Results



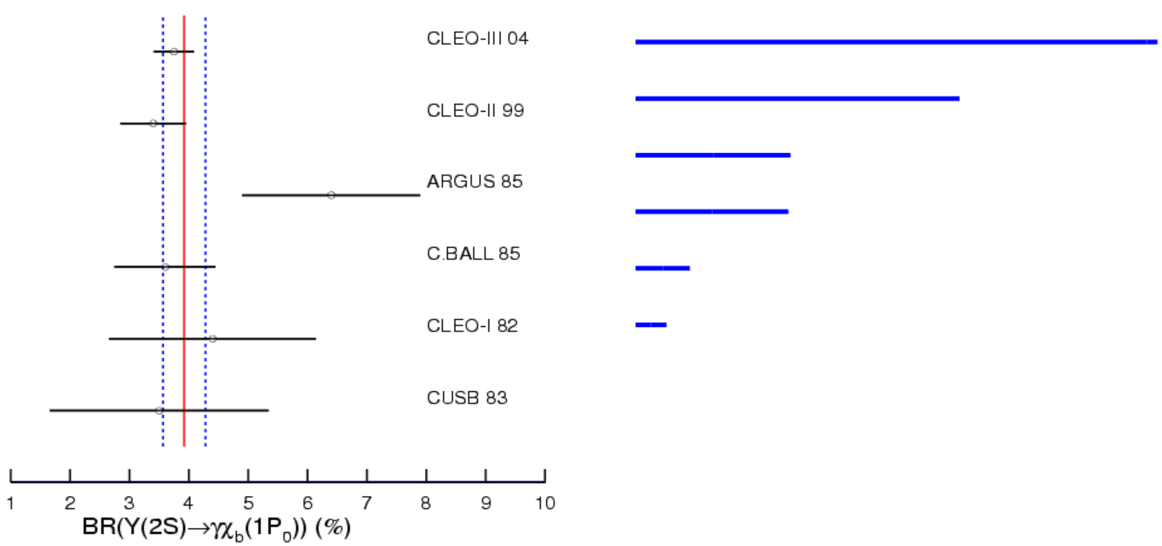
$$\Upsilon(2S) \to \chi_{bJ}(1P_1)\ \gamma$$



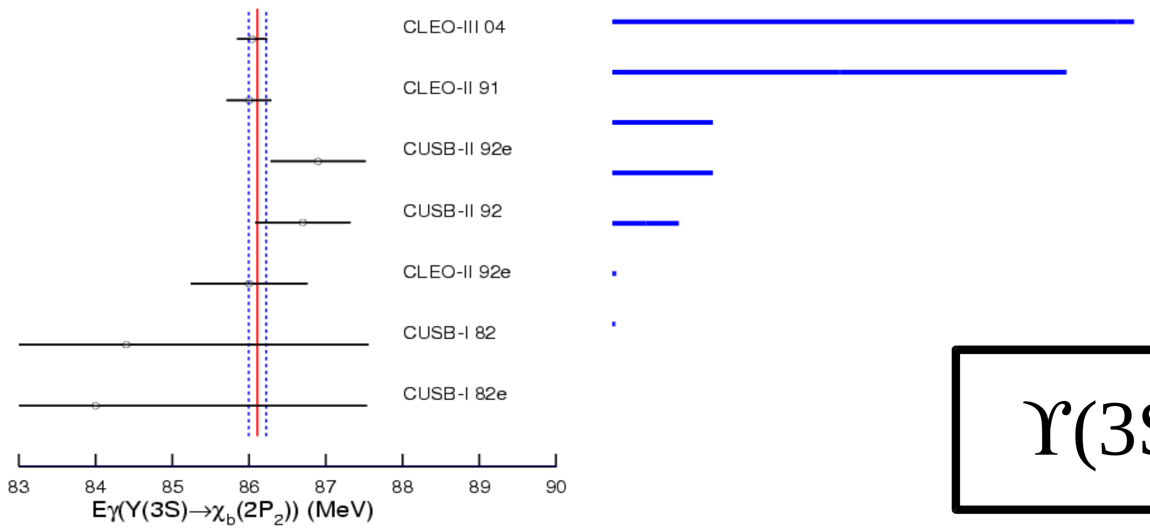
E1 Transitions: Impact of CLEO III Results



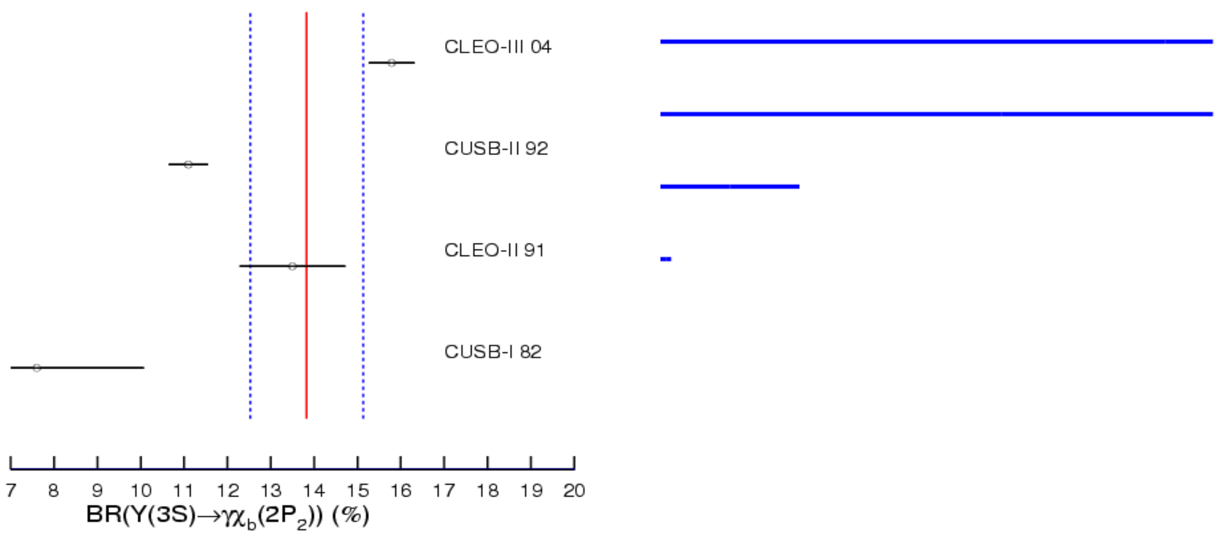
$$\Upsilon(2S) \to \chi_{bJ}(1P_0)\ \gamma$$



E1 Transitions: Impact of CLEO III Results



$$\Upsilon(3S) \rightarrow \chi_{bJ}(2P_2)\ \gamma$$



E1 Transitions:

Fine splitting in 1P and 2P

The fine structure splitting can be quantified by **r = (m2-m1)/(m1-m0)**

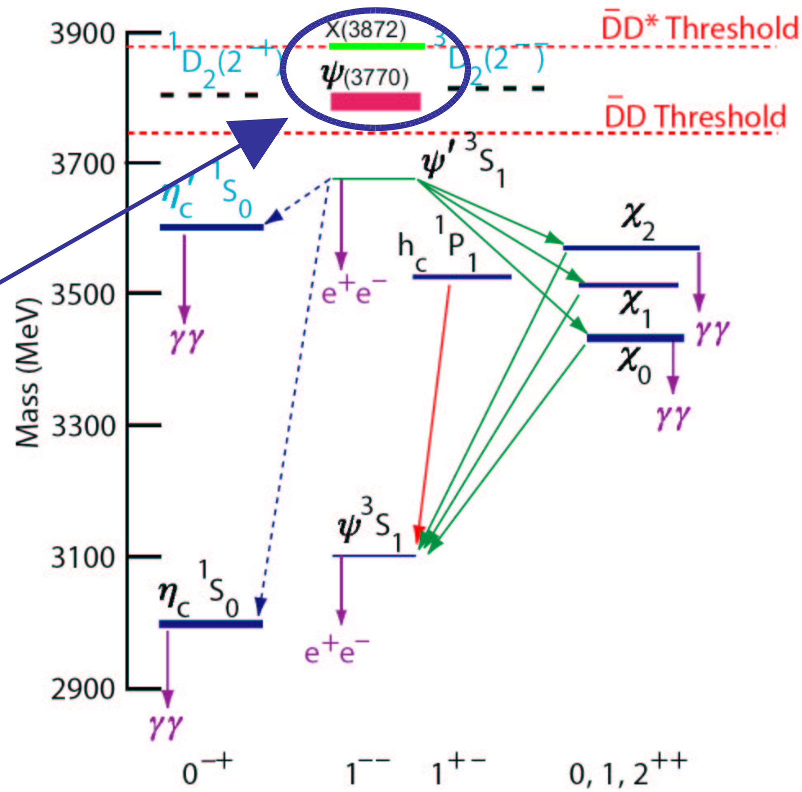
r gives properties of Lorentz transformation (scalar and/or vector) of the confining potentials.

	CLEOIII	CLEO2
r(1P)	0.57±0.01±0.01	0.54±0.02±0.02
r(2P)	0.58±0.01±0.01	0.57±0.01±0.01

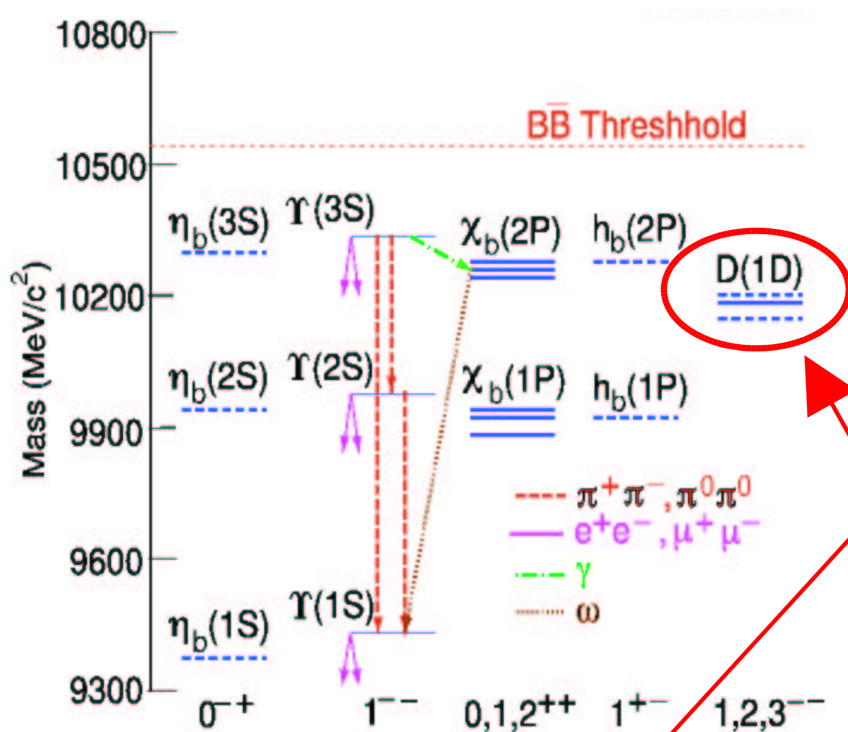
- Our results indicate that there is no difference between the different radial excitations of the P waves in bb.

The L=2 (“D”) States in Quarkonium

Charmonium



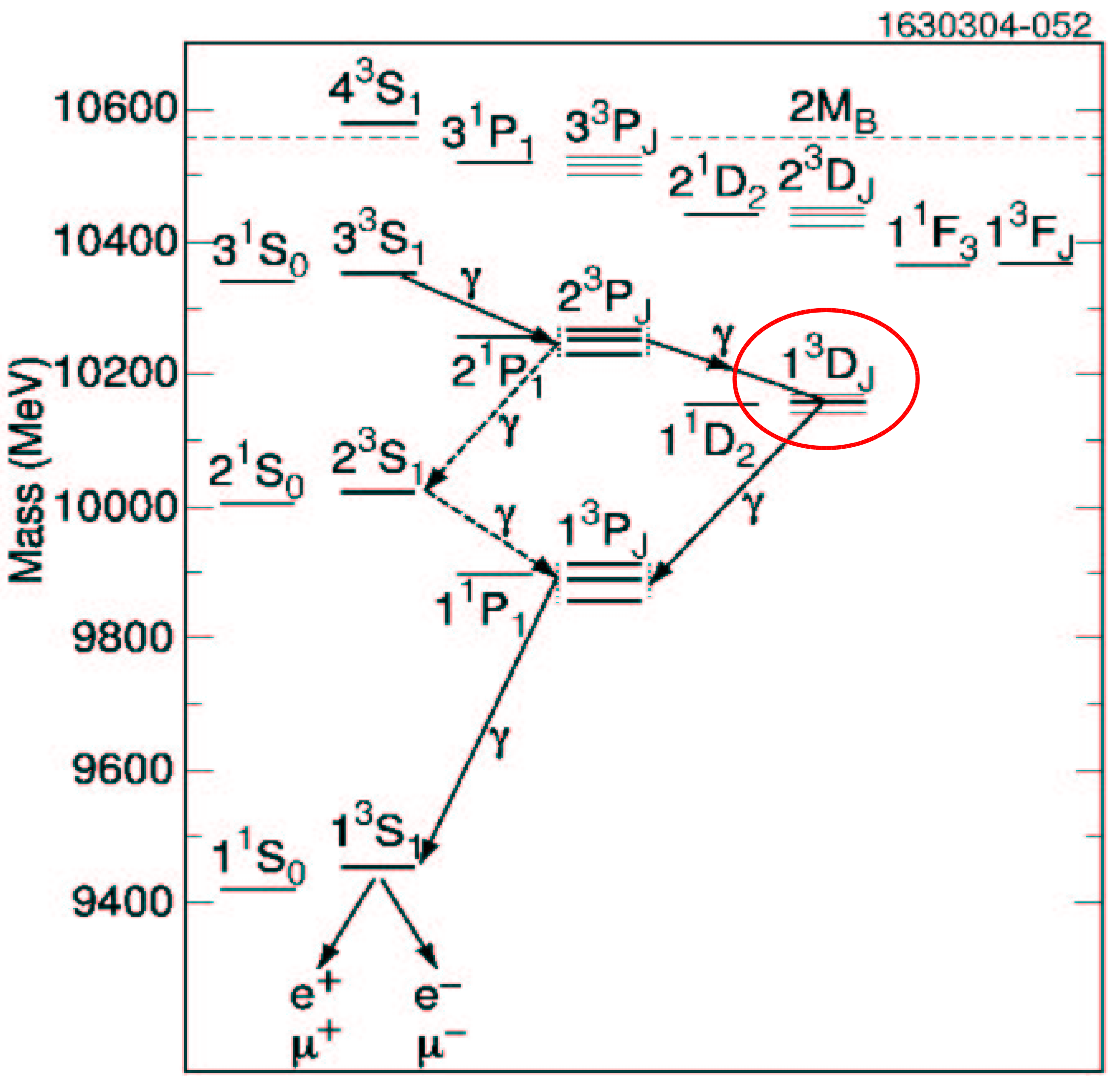
Bottomonium



ψ(3770): $^3S_1 - {}^3D_1$ mixing? Molecule?

ϒ(1D): stable - tests models and LQCD at high L !!

Photon Transitions to $\Upsilon(1D)$ [CLEO]



Four γ cascade; exclusive $\Upsilon(1S)$ channel

Background thru 2^3S_1

First reported at ICHEP02 with 80% of data.
Now final

Accepted by PRD
[hep-ex/0404021]

Final Υ(1D) Analysis Results [CLEO]

>10 σ significance

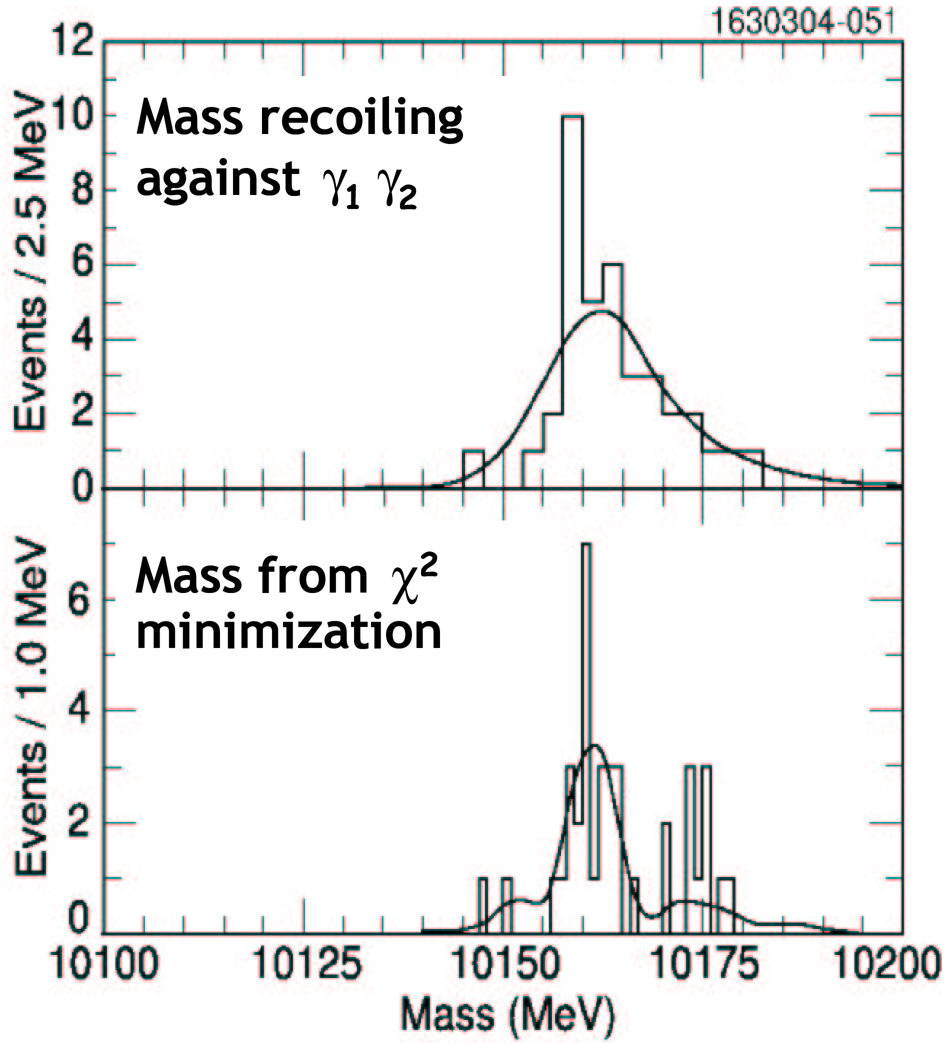
M = **10161.1±0.6±1.6** MeV

Consistent with 1^3D_2

$B(\Upsilon(3S) \to \gamma_1 \gamma_2 \gamma_3 \gamma_4 l\, l)$ =
(2.5 $\pm$ 0.5 $\pm$ 0.5) x 10^{-5}

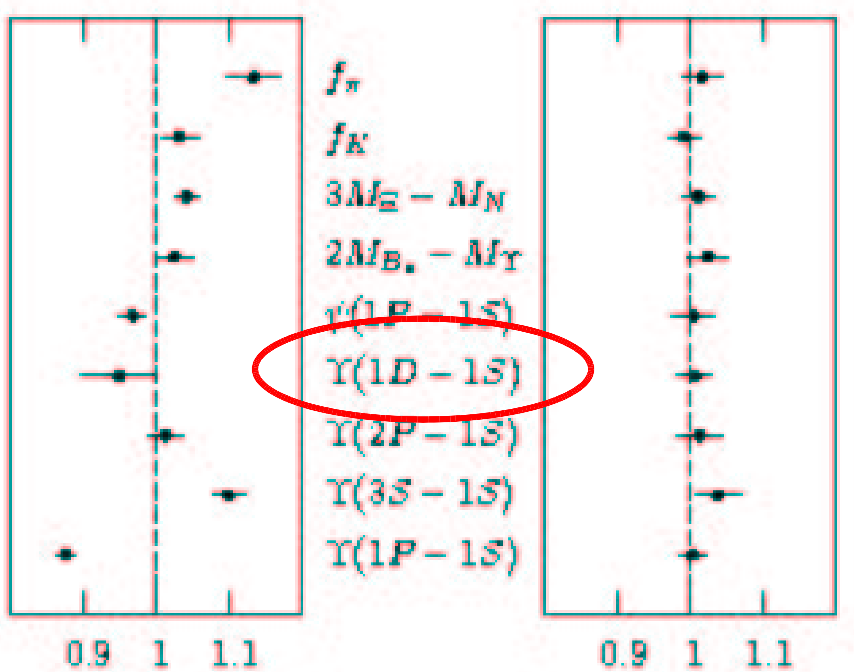
Rate consistent with theory estimates

[hep-ex/0404021; accepted by PRD]



“D” State Impact on LQCD

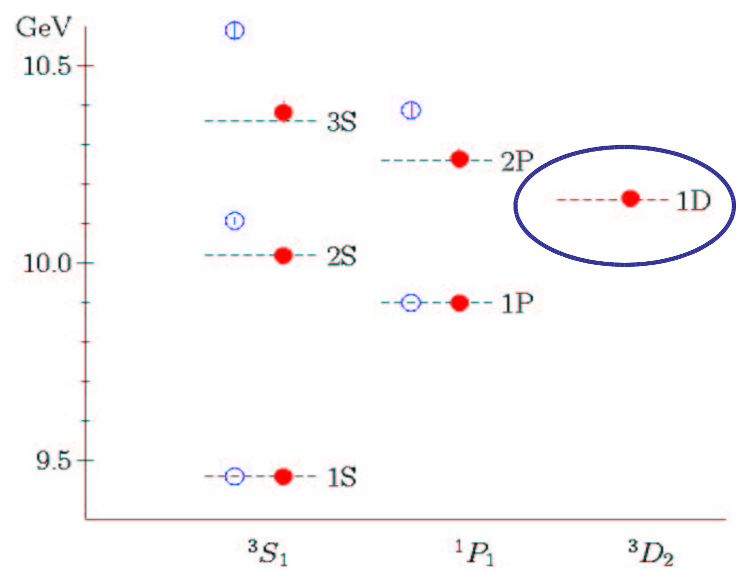
Ratio = LQCD/Expt



Quenched **Unquenched (n_f=3)**

[CTH Davies et al., PRL **92**:022001 (2004)]

ϒ Spectrum

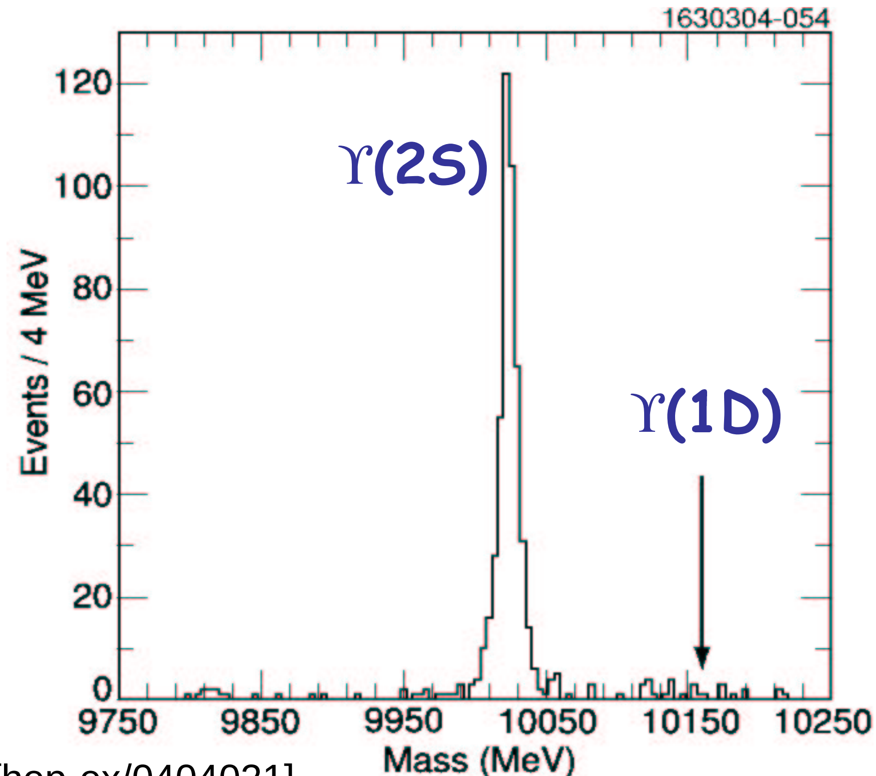


○ **Quenched**

● $m_u = m_d = m_s/5$

[Courtesy: G.P. Lepage]

$\Upsilon(1D)$: What is NOT seen !!!



[hep-ex/0404021]

Search for $\Upsilon(1D) \to \pi^+\pi^-\Upsilon(1S)$

Large signal from $\Upsilon(2S)$ is consistent with known rates

No events observed from $\Upsilon(1D)$; upper limits set

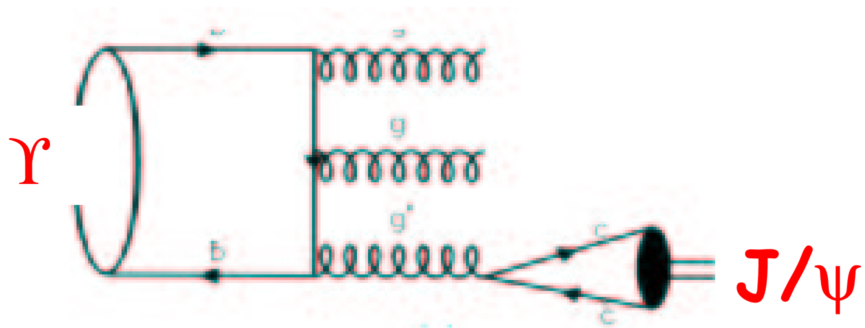
Limits ~7 times lower than predicted by Kuang-Yan model; ~3 times higher than Ko model

[J.L.Rosner PRD67, 097504 (2003)]

Also see no evidence for enhancement of $\Upsilon(1D) \to \eta\Upsilon(1S)$ as postulated by Voloshin [PL **B562,** 68 (2003)]

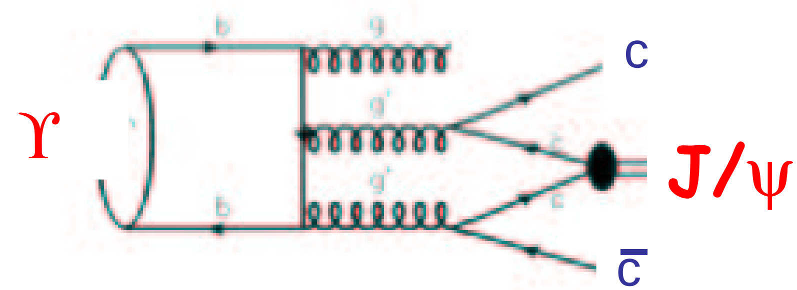
Upsilon Decay to Charmonium: $\Upsilon(1S) \rightarrow (c\bar{c})\, X$

- onia production and onia decay
- test of color-octet v. color-singlet models
- similar rate predictions: B ~ 6 x 10^{-4}
- very different momentum spectra
- may have some relevance to cccc production



color-octet

[Chueng, Keung, Yuan: PRD 54, 929 (1996)]



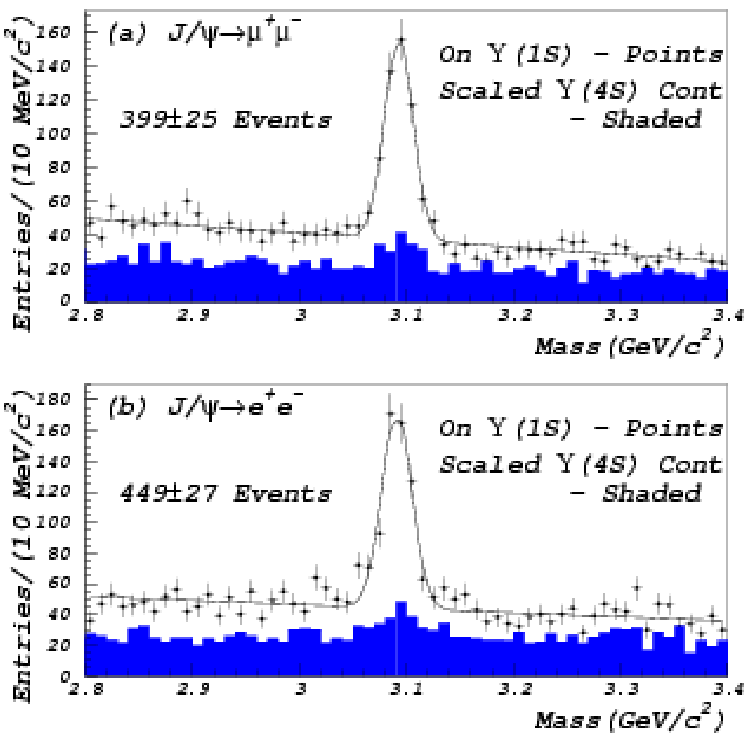
color-singlet

[Li, Xie, Wang: PLB 482, 65 (2000)]

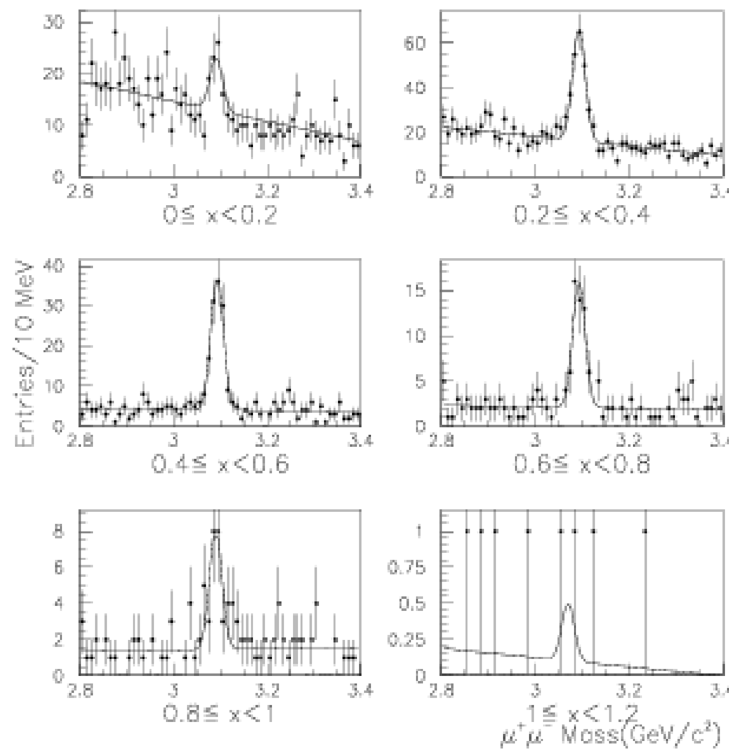
Upsilon(1S) Decay to Charmonium

The J/ψ Signal

All events passing cuts for $\mu^+\mu^-$ and for e^+e^-



$\mu^+\mu^-$ events binned in $x \equiv p_{J/\psi}/p_{\max}$



$\Upsilon(1S) \rightarrow J/\psi\, X$

p/p_{max} much too soft for octet model

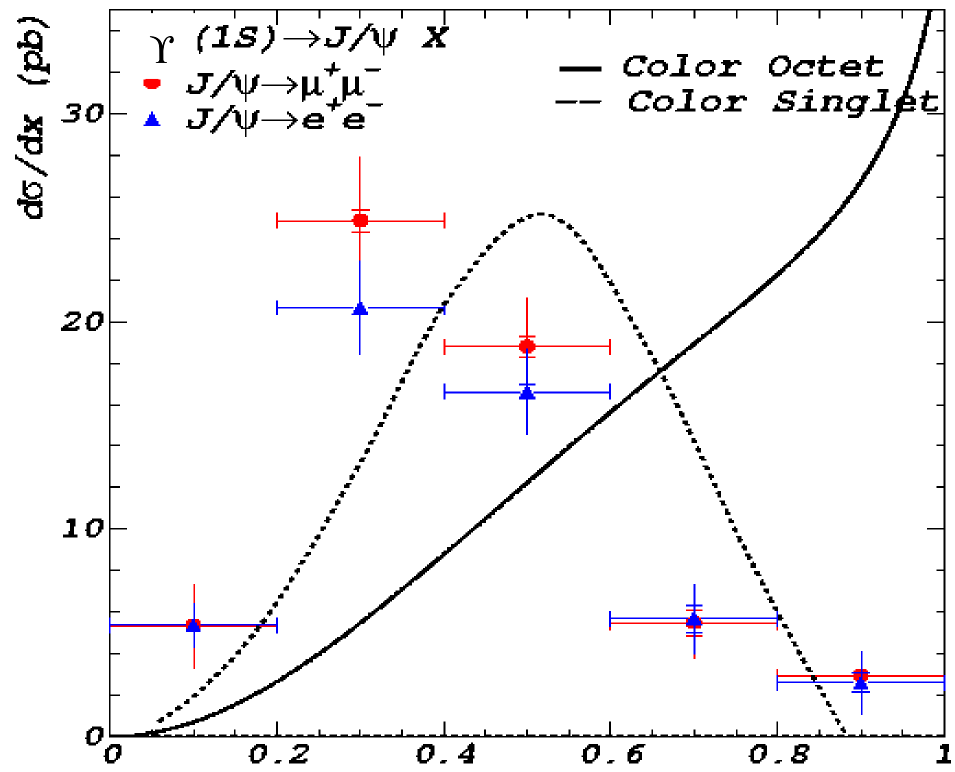
$B(\Upsilon(1S) \rightarrow J/\psi\, X)$ =
$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$

This includes feed-down from other charmonia

Rate consistent with either octet or singlet model

Production and helicity angular distributions also determined

CLEO hep-ex/0407030

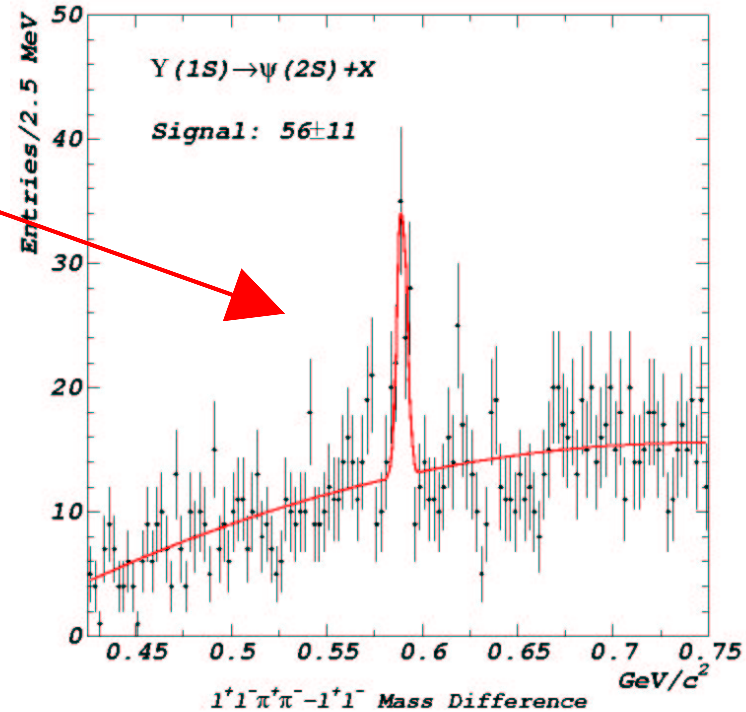


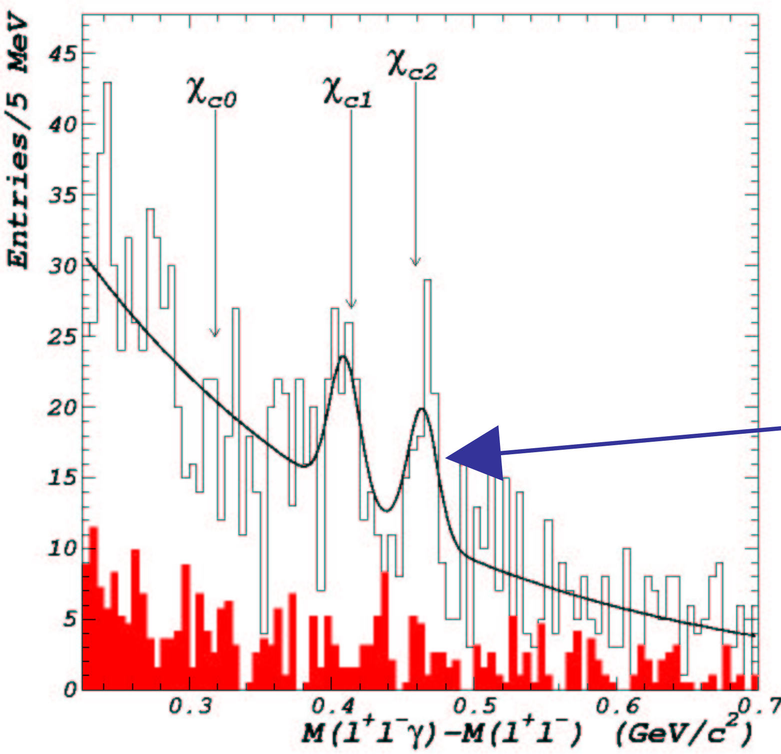
Scaled Momentum (p/p_{max})
(ggg component only!)

$\Upsilon(1S) \rightarrow (c\bar{c})\ X$

Also: first observation of $\psi'X$ ...

$B(\Upsilon\rightarrow\psi'X)/B(\Upsilon\rightarrow J/\psi\ X) = (41\pm\ 11\pm\ 8)\%$





... and evidence for the two χ_c states with large Γ_{E1}

$B(\Upsilon\rightarrow\ \chi_{c2}X)/B(\Upsilon\rightarrow J/\psi\ X) = (52\ \pm\ 12\pm\ 9)\%$

$B(\Upsilon\rightarrow\ \chi_{c1}X)/B(\Upsilon\rightarrow J/\psi\ X) = (35\ \pm\ 8\pm\ 6)\%$

All larger than the octet predictions.

Υ(1S) Decay to Charmonium (hep-ex/0407030)

Final state	Branching Ratio	Feed-down to J/ψ
J/ψ	$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$	-
$\psi(2S)$	$0.41 \pm 0.11 \pm 0.08$	$0.24 \pm 0.06 \pm 0.05$
χ_{c_0}	<7.4	<0.082
χ_{c_1}	$0.35 \pm 0.08 \pm 0.06$	$0.11 \pm 0.03 \pm 0.02$
χ_{c_2}	$0.52 \pm 0.12 \pm 0.09$	$0.10 \pm 0.02 \pm 0.02$

The issue of color octet versus color singlet remains unresolved. The ball is back in the theorist's court.

Suggestion to Fleming, et al., that they apply same softening mechanism they used for continuum production.

More experimentation suggested: Perhaps search for $D\bar{D}$ in association with charmonium, in e^+e^- and at CDF/D0.

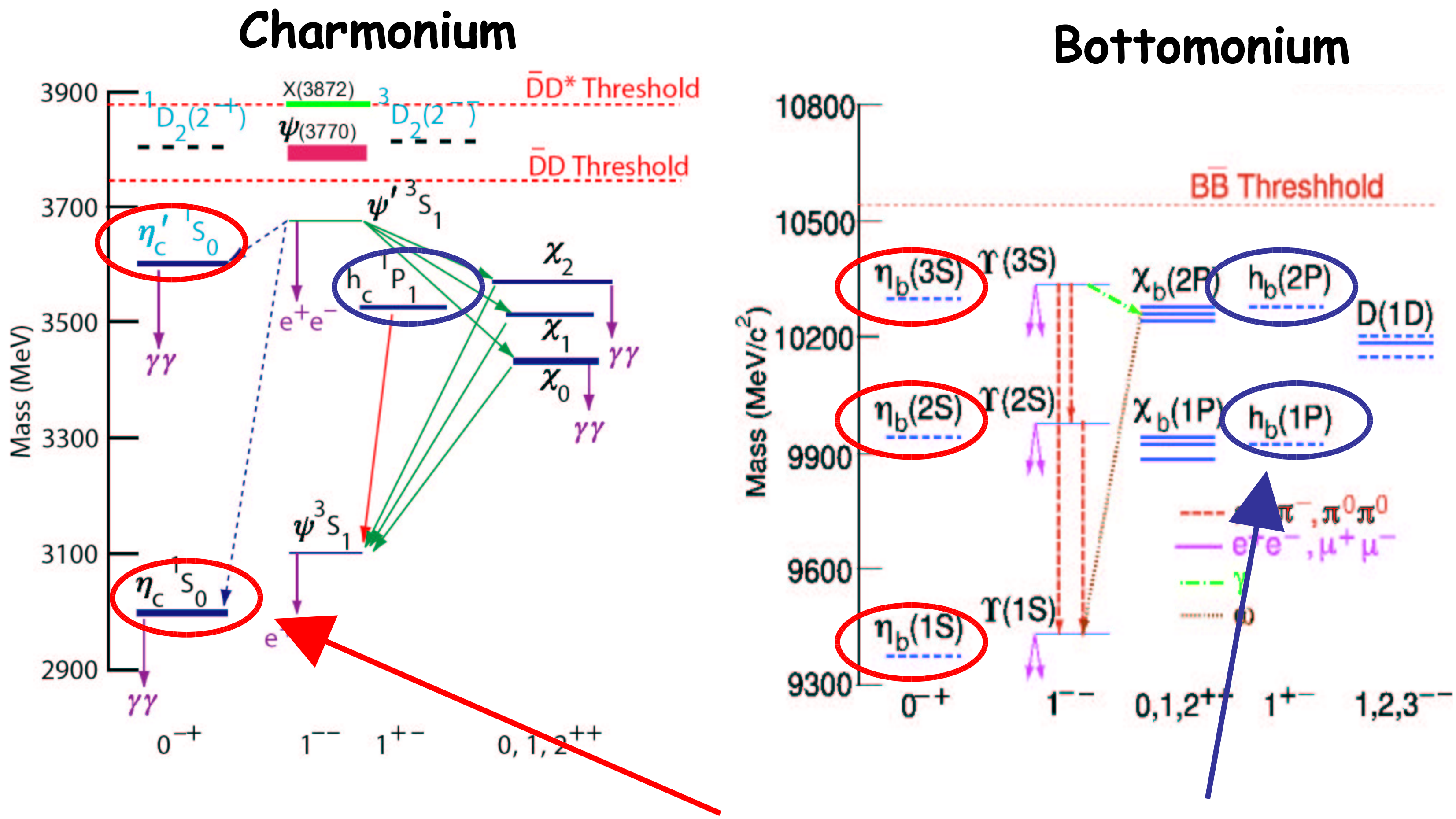
Summary

- Upsilon Spectroscopy revitalized after ~20 years!
- Vastly increased data sample + CLEO III detector!
- Precision scans, $B(\mu\mu)$, Γ(tot) of Υ(1S,2S,3S)
- Improved precision in dipion transitions
- First observation of internal ω transition
- First observation of the 1 D (L=2) state
- Precision measurement of E1 photon transitions
- Meaningful upper limits on hindered M1 transitions
- Precision measurements of Y(1S) decay to (cc)
- Generated considerable theoretical interest:
  potential models, LQCD, color octet/color singlet

...and, by the way, we also do Charmonium!
Join the QWG! (meets next week in Beijing!)

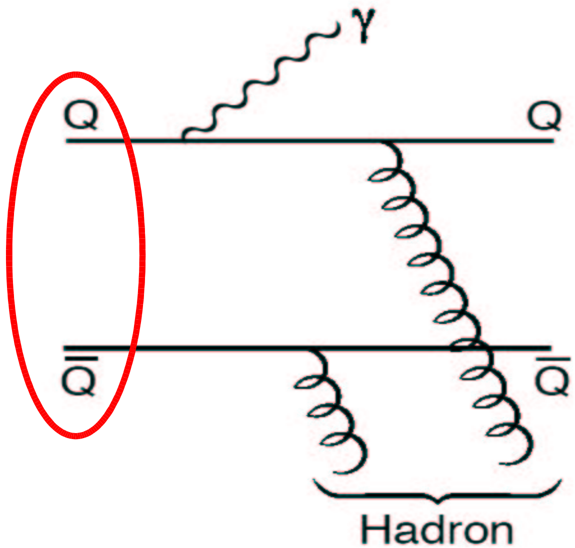
Backup slides

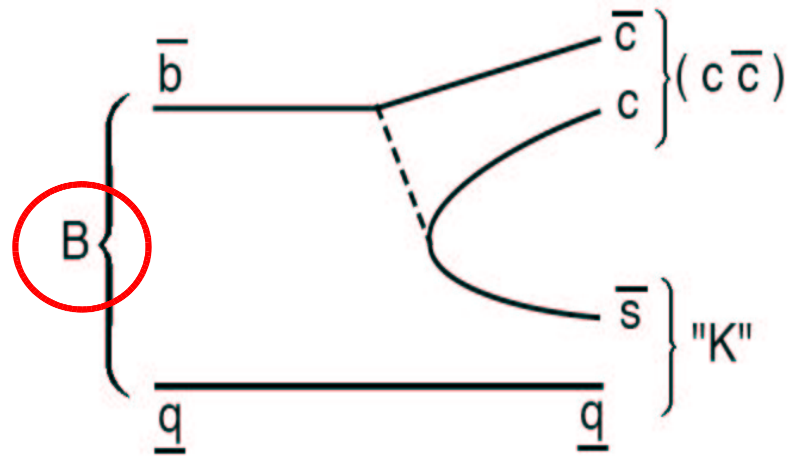
News on the $Q\bar{Q}$ Spin-Singlets

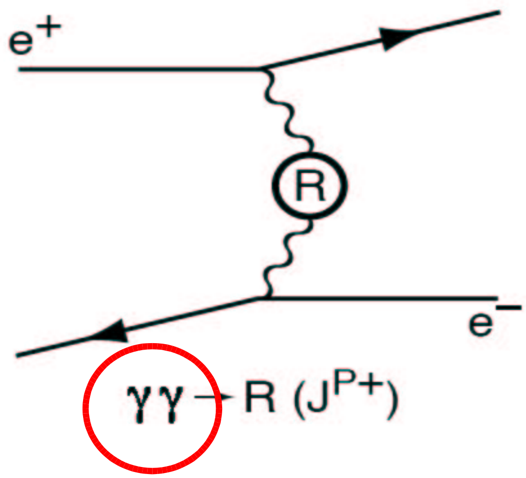


$J^{PC} = 0^{-+}$ (η's) and 1^{+-} (h's)

Production of $Q\bar{Q}$ Spin-Singlets:







… as well as hadro-production which is the most egalitarian!

$Q\bar{Q}$ Spin-Singlets:

- $b\bar{b}$ (η_b's and h_b): limits from CLEO in '03 … no news
- h_c ($^1P_1$, 1^{+-}): not yet (maybe that is news?)
- η_c ($^1S_0$, 0^{-+}): Ground state of charmonium
  - Still only ~30% of decays known … some updates
  - New publ'd mass determinations … no big shifts
  - Seen by CLEO in $\psi' \to \gamma\eta_c$ ($>8\sigma$) [LP03:hep-ph/0311243]
- See QWG Yellow Report for up-to-date information