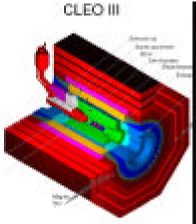

New and Recent Results from Upsilon Spectroscopy at CLEO

Todd K. Pedlar

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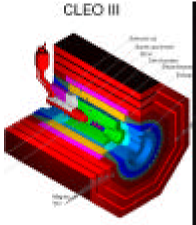
For the CLEO Collaboration

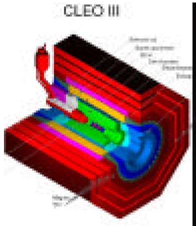
Aspen Winter Conference
February 5, 2004



New and Recent Results from Upsilon Spectroscopy at CLEO

Subtitle:

Aspen Winter Conferenc
February 5, 2004



The obligatory outline

- CLEO Detector and Status
- Upsilon Spectroscopy: What's Interesting?
- CLEO Results
  - Observation of "new" states (triplet D)
  - Observation of "new" decays (hadronic decay of $\chi_b(2P)$)
  - More precise measurements of "old" decays ($\Upsilon(1S) \to J/\psi X$)

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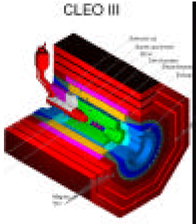
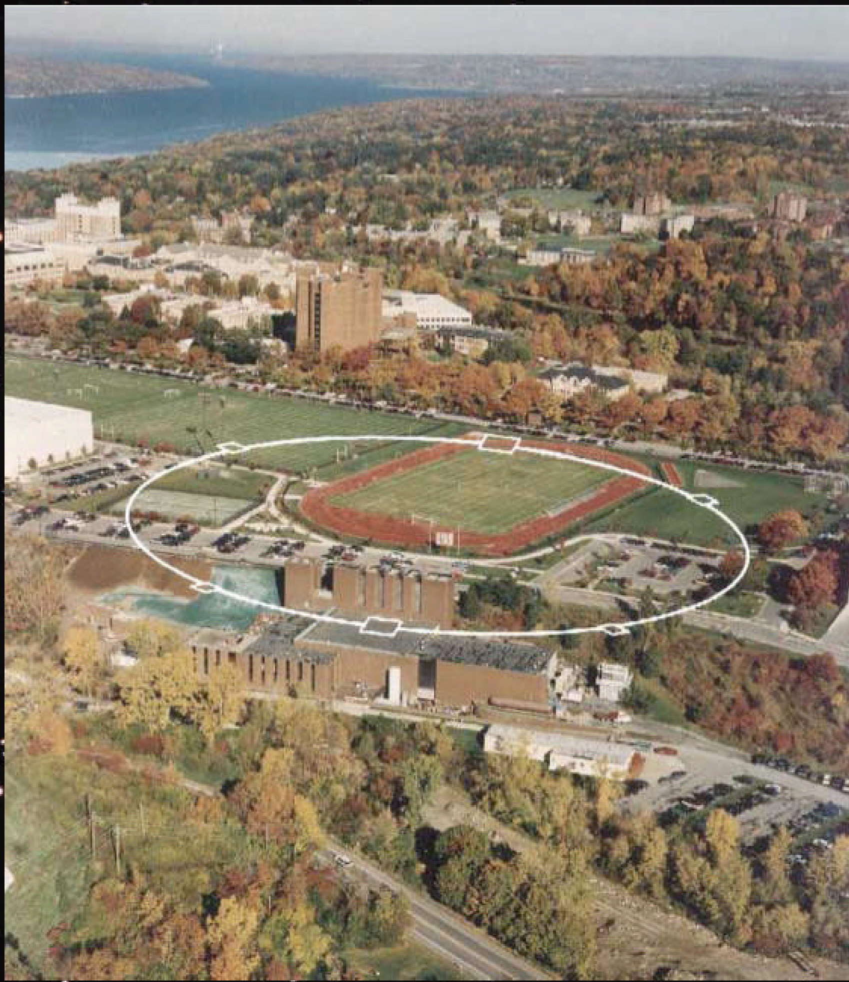
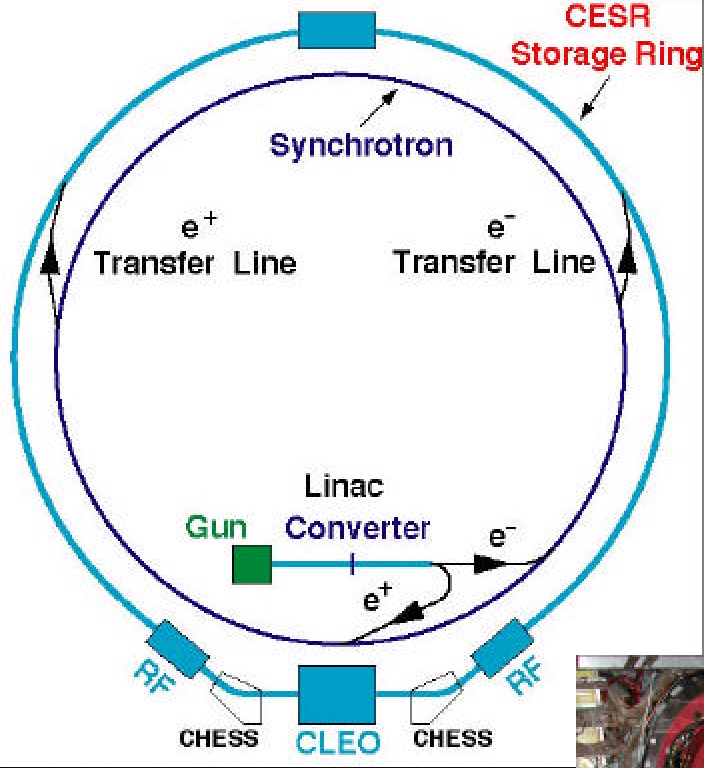
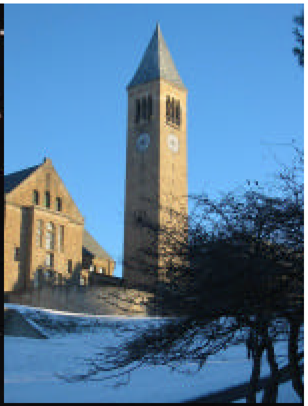


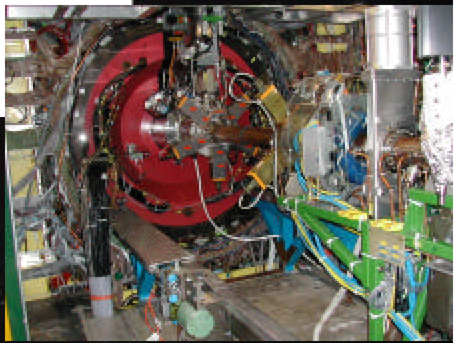
The CLEO Experiment

CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS









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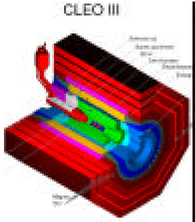
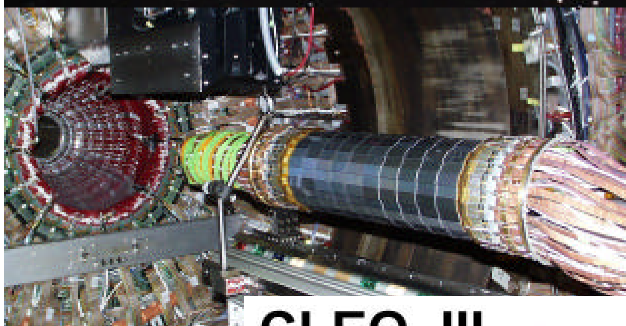
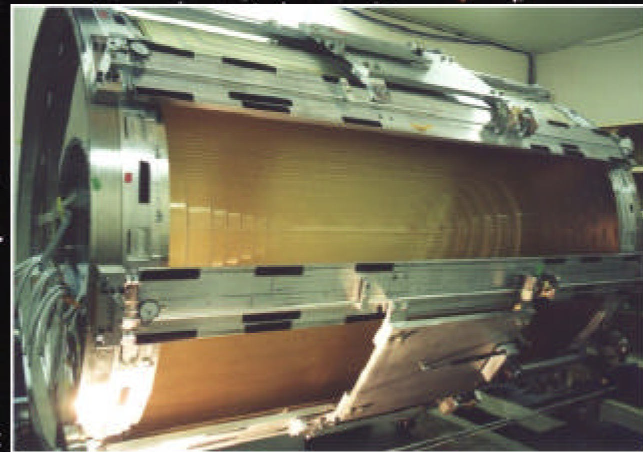
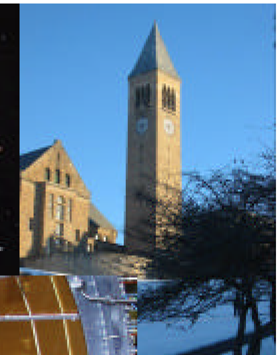
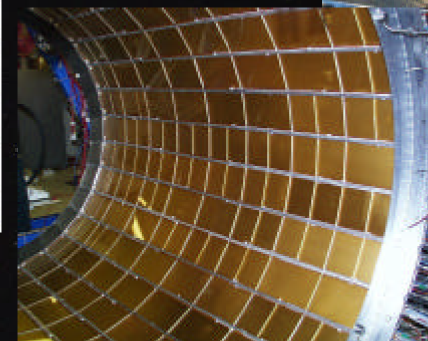


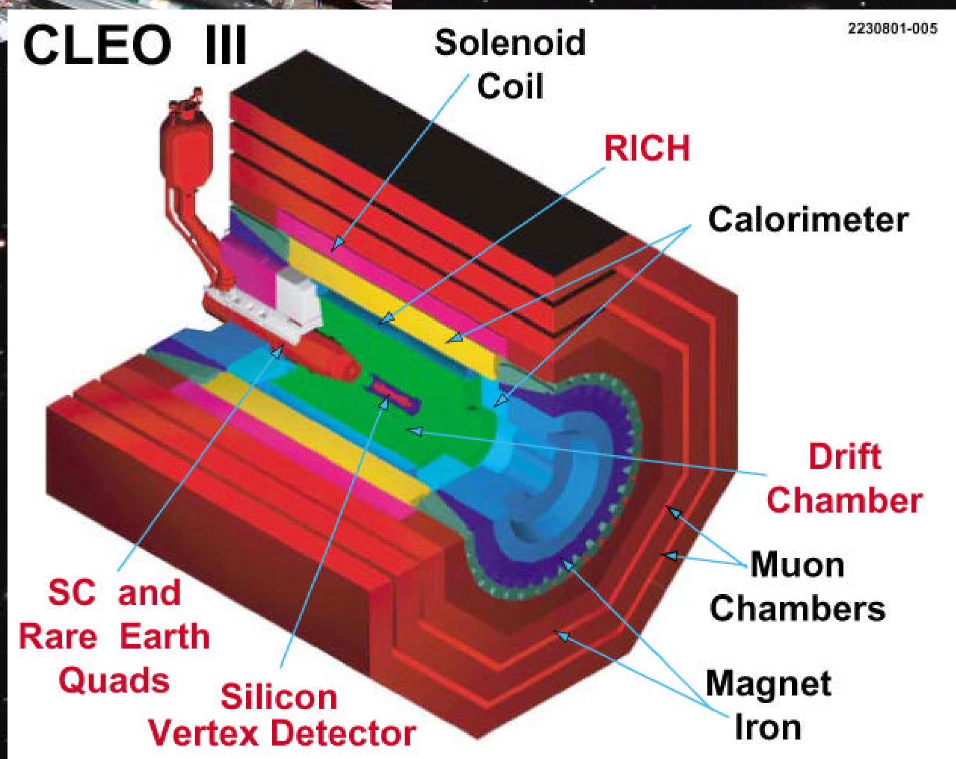
The CLEO detector

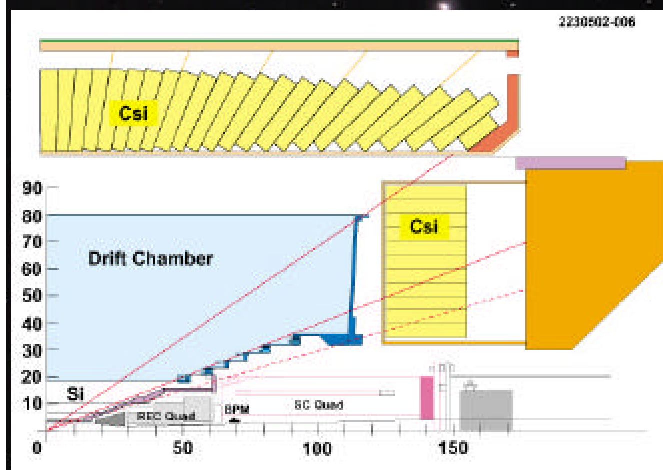


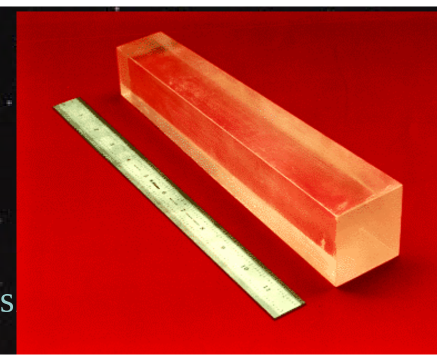












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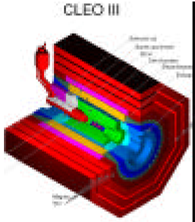
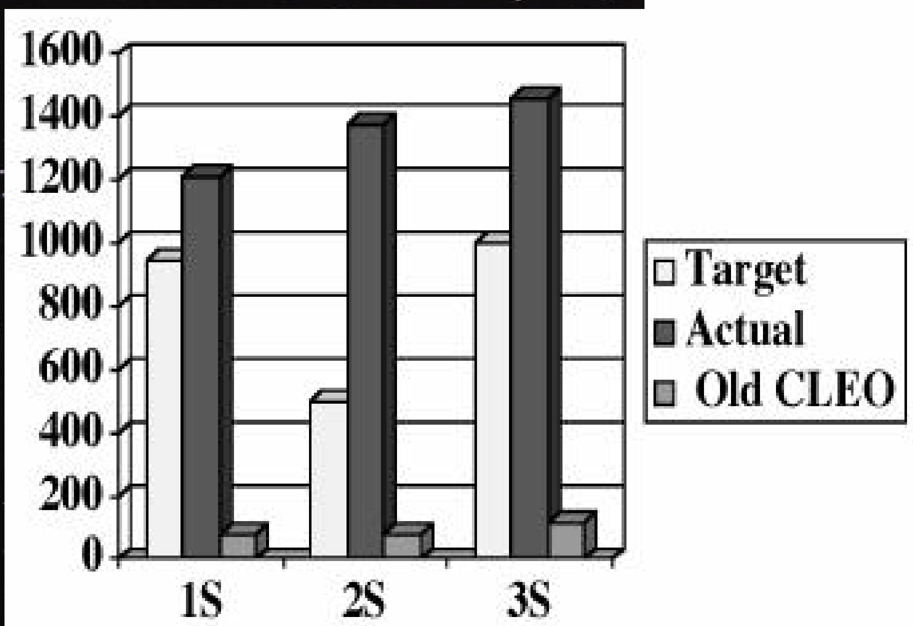


CLEO Recent History and Current Operations Status

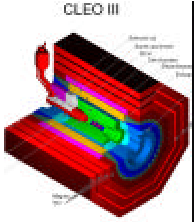
Luminosity Accumulated "on resonance" (pb^{-1})

	Υ(1S)	Υ(2S)	Υ(3S)
Target	950	500	1000
Actual	1210	1380	1460
Old	79	74	110
Processed	100%	100%	100%



For those who like to be completely up-to-date: As of 26 January 2004 CLEO-c has:

63.1 pb^{-1} on ψ(3770)
3.2 pb^{-1} on ψ(3686)
11.3 pb^{-1} continuum (3670 MeV).



Upsilon Spectroscopy: What's Interesting?

Everything!

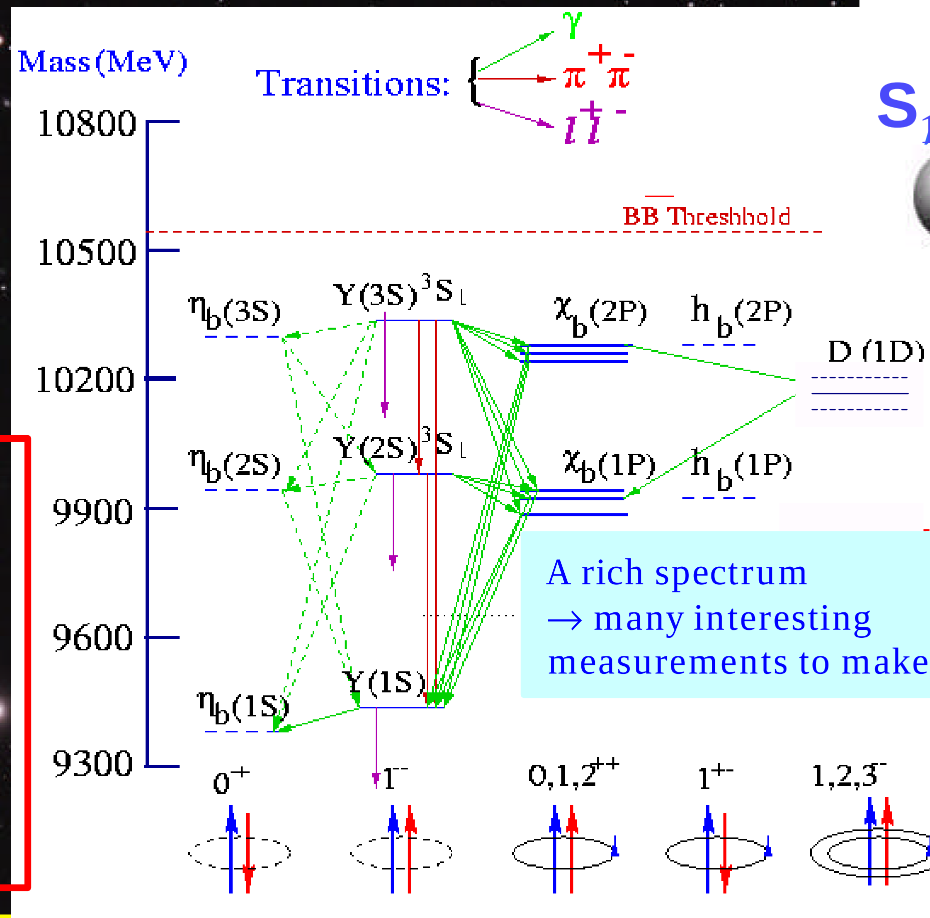
Okay... well, not quite everything.

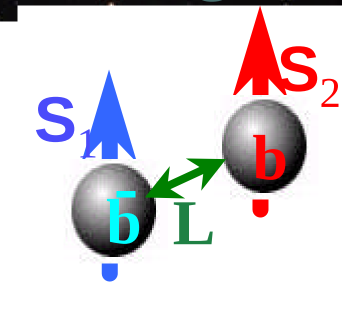
BUT JUST ABOUT!

Quarkonia are the simplest strongly-interacting system

(well, we shall not argue about gluonia!)

freer from relativistic effects





A rich spectrum
→ many interesting measurements to make

States shown are specified by the quantum numbers, J^{PC}:

$$\vec{S} = \vec{S}_1 + \vec{S}_2 \qquad \vec{J} = \vec{L} + \vec{S} \qquad P = (-1)^{L+1} \qquad C = (-1)^{L+S}$$

or by spectroscopic notation: $^{2S+1}L_J$

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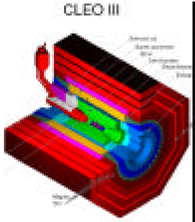
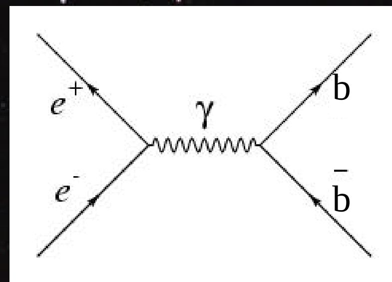
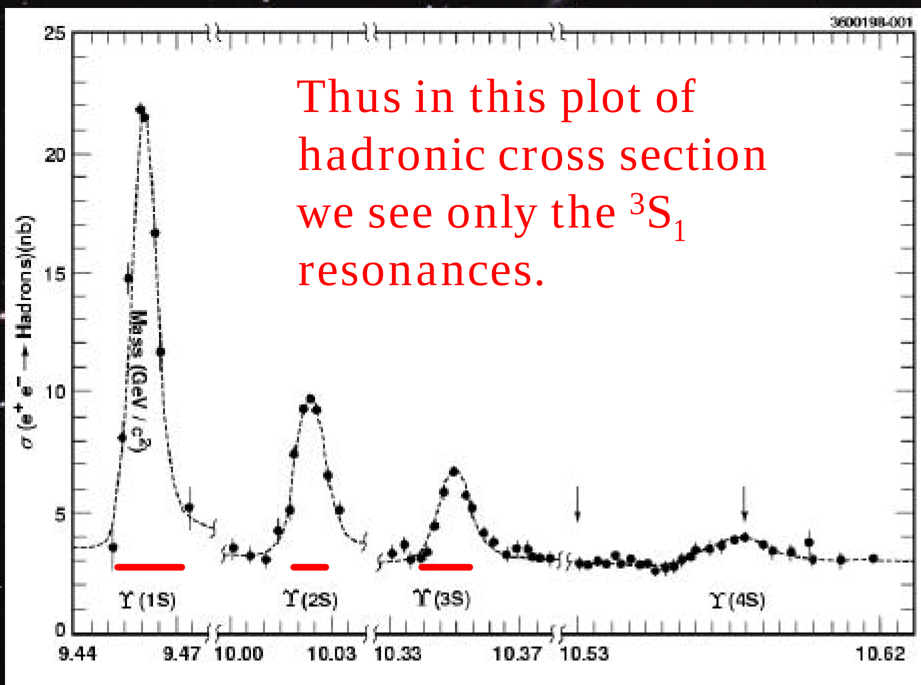


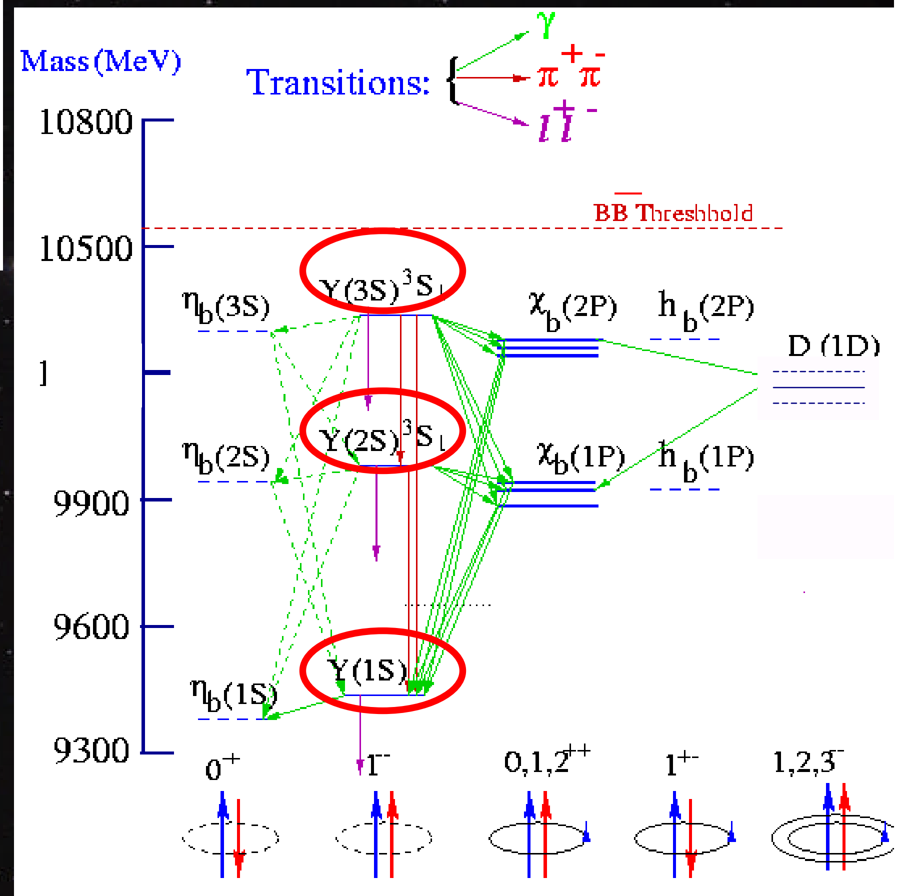
Upsilon spectroscopy: Practical limits of e+e- annihilation

In e+e- annihilation we directly produce only the ${}^3S_1$ states





Thus in this plot of hadronic cross section we see only the ${}^3S_1$ resonances.



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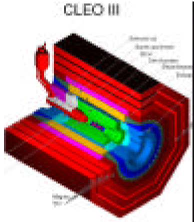
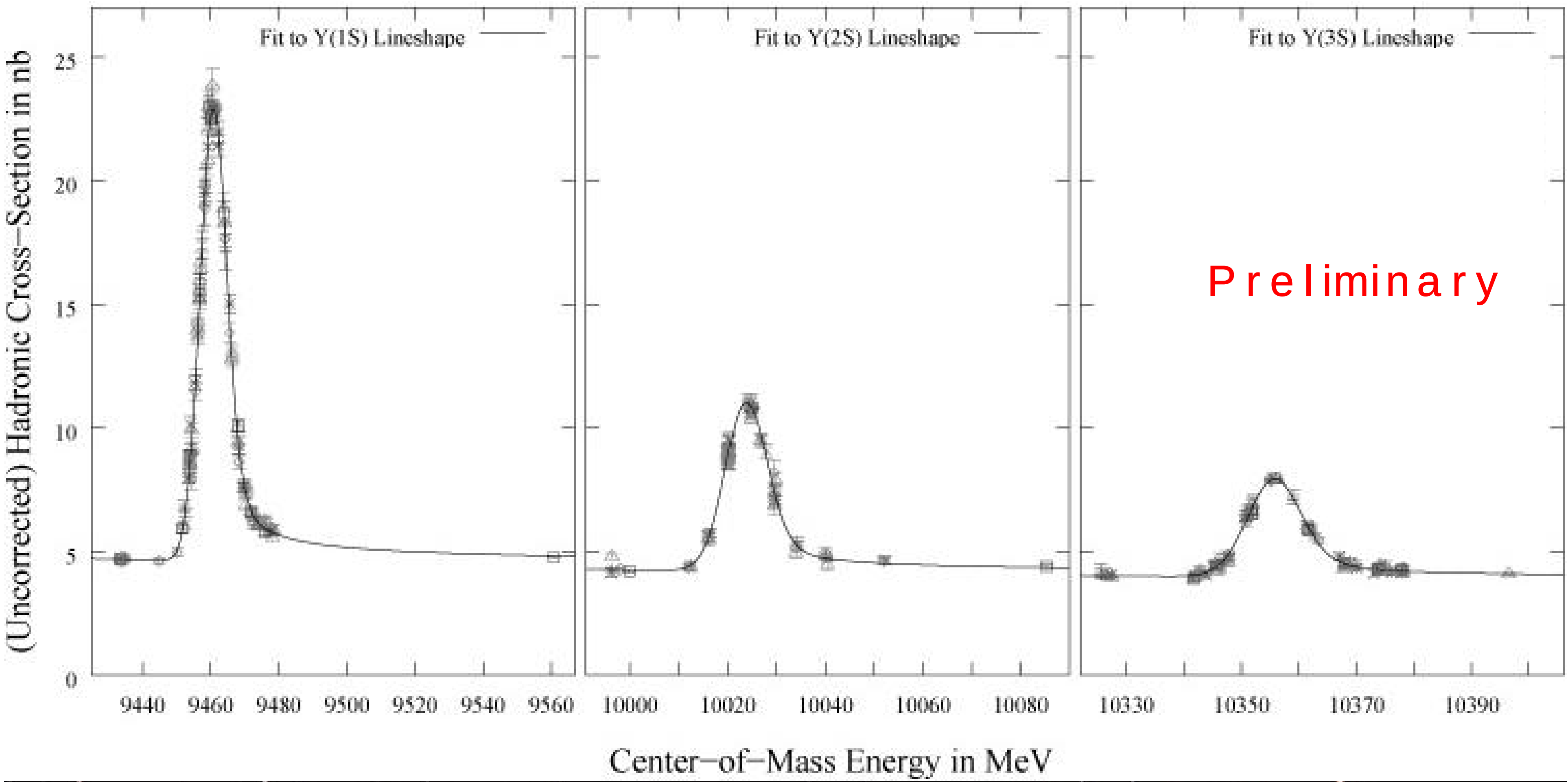


Hadronic Cross Section for Y(1S), Y(2S), and Y(3S) From CLEO III Resonance running (dedicated scans)



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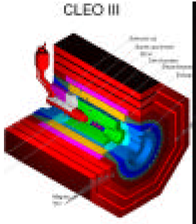
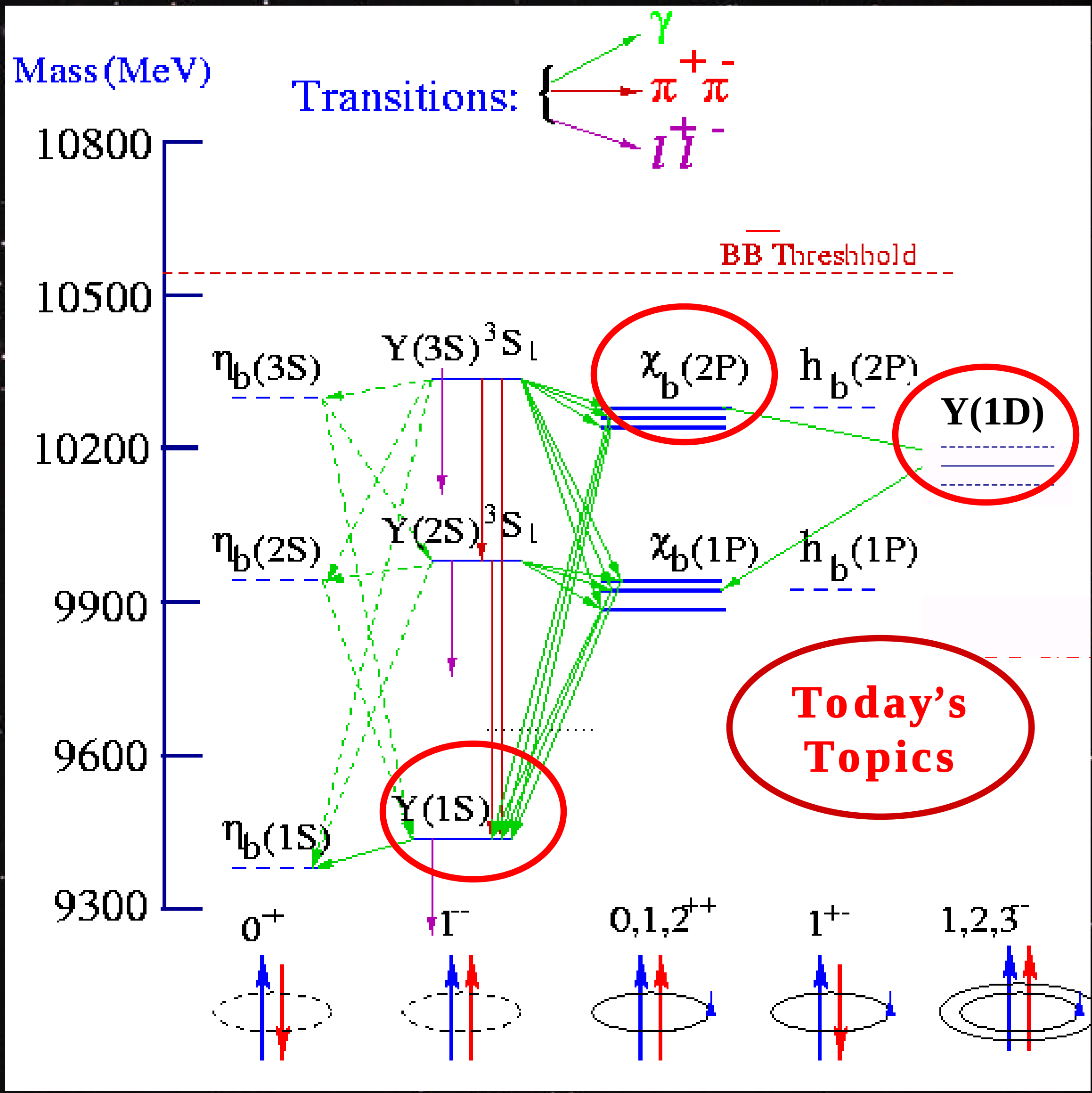


Upsilon spectroscopy

- Vector states: direct production
- Others: only as daughters of vectors
- Underscores the need for statistics such as CLEO III *now has* on the resonances



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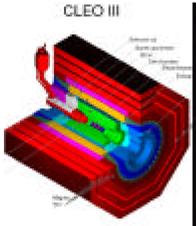

The 1D levels of bottomonium: Observing new states : $\Upsilon(1^3D_2)$

- The known states of bottomonium, up until 2002, were only 9 (below BB threshold). The discovery of which I speak is the first new state in 20 years
- CLEO's resonance data set includes 5.8 x 10^6 $\Upsilon(3S)$ decays
- In studies of radiative decay cascades among the bottomonium states, we have found evidence of transition through a heretofore unobserved intermediate state
- This state we conclude to be one of the triplet D states predicted to lie near 10.16 GeV (Godfrey & Rosner, PRD64 097501 (2001))
  - Preliminary results presented at ICHEP'02 and Moriond '03
  - These updated (but still preliminary) results (more data and better background suppression) shown at Lepton-Photon 2003

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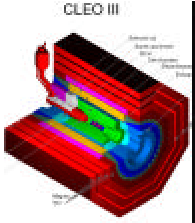
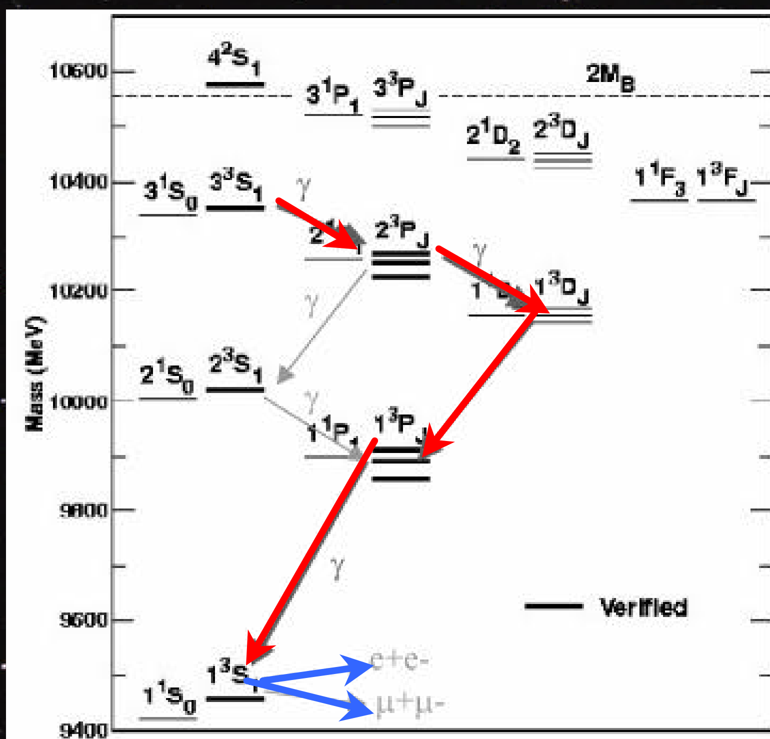


The 1D levels of bottomonium:
Observing new states : $\Upsilon(1^3D_2)$

♦ The signal is sought via a four-photon chain:

$\Upsilon(3S) \rightarrow \gamma\chi(2P) \rightarrow \gamma\gamma\Upsilon(1D) \rightarrow \gamma\gamma\gamma\,\chi(1P) \rightarrow \gamma\gamma\gamma\gamma\;\; \Upsilon(1S)$

$\hookrightarrow\; e^+e^-, \mu^+\mu^-$



Godfrey & Rosner predicted The overall BR for this chain (integrated over all allowed combinations of 2P, 1D, 1P participants) should be roughly 4 x 10^{-5}

PRD64 097501 (2001)

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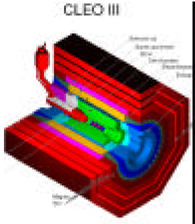
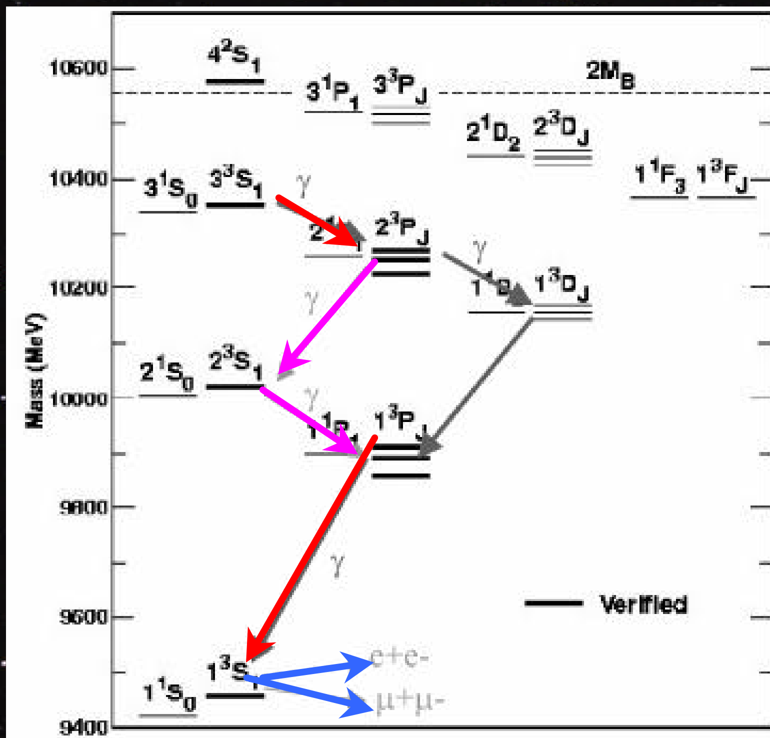


The 1D levels of bottomonium:
Observing new states : $\Upsilon(1^3D_2)$

- A significant background is also a four-photon chain:

$$\Upsilon(3S) \rightarrow \gamma\chi(2P) \rightarrow \gamma\gamma\,\Upsilon(2S) \rightarrow \gamma\gamma\gamma\,\chi(1P) \rightarrow \gamma\gamma\gamma\gamma\;\Upsilon(1S)$$
$$\hookrightarrow e^+e^-, \mu^+\mu^-$$

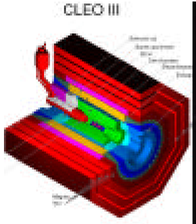


The overall BR for this background channel is (PDG2002) roughly 7 x 10^{-5}

The difficulty here is that two photons match in energy quite closely the expected signal photon energies

(99 MeV vs 131 MeV, and 261 MeV vs. 229 MeV)

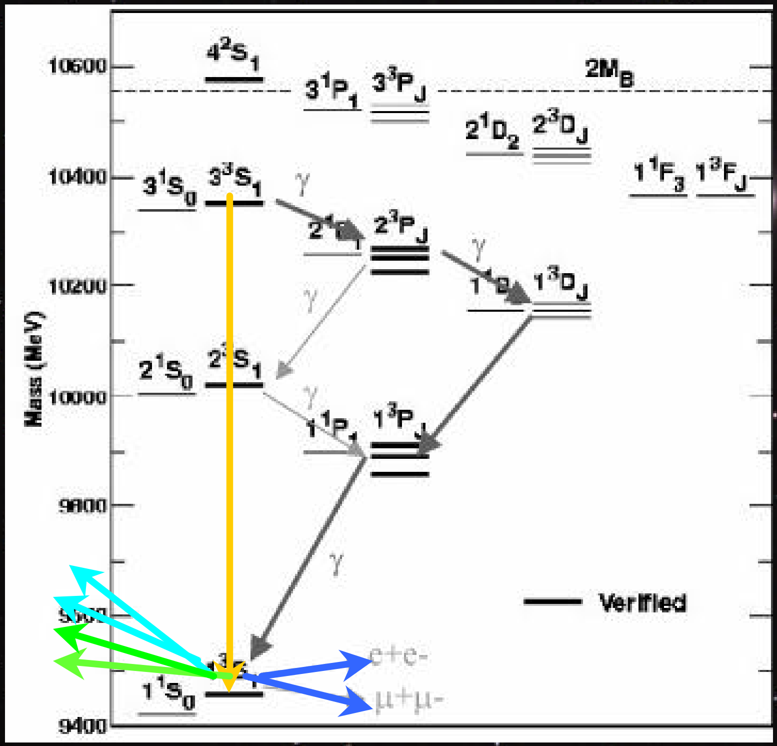
A χ^2 variable is constructed for the photon energies assuming the background chain, and antiselecting (choosing large χ^2) used to discriminate



The 1D levels of bottomonium:
Observing new states : $\Upsilon(1^3D_2)$

- The dominant background is also a four-photon chain of sorts:

$\Upsilon(3S) \rightarrow \Upsilon(1S)\ \pi^o\pi^0 \rightarrow \gamma\gamma\ \gamma\gamma\ \Upsilon(1S)$ ⟶ $e^+e^-, \mu^+\mu^-$



The overall BR for this background channel is roughly 5.6 x 10^{-4}

Can be carefully removed by antiselecting events ML fit to a $\pi^o\,\pi^o$ hypothesis

As a product of this background analysis, a new measurement was obtained:

B(U**(3S)** ® U**(1S)** pop0**) =** **(2.33** ± 0.09 ± 0.16)%

Preliminary

cf. (2.03 ±0.28 ±0.19)% (CLEOII)
(2.3 ±0.4 ±0.3)% (CUSB)

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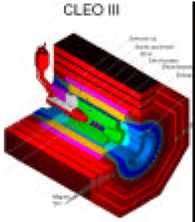
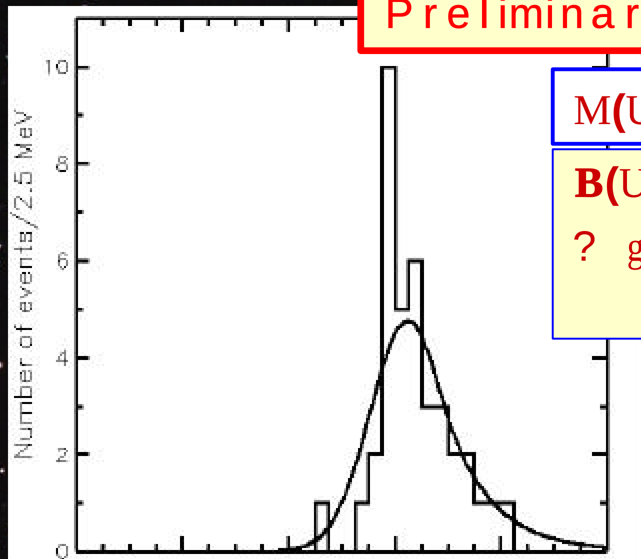


The 1D levels of bottomonium : Observing new states: $Y(1^3D_2)$

Preliminary



Mass recoiling against
Two lowest energy photons (MeV)

Fit yield :

34.5 ± 6.5 events

$M(U(1^3D_2))$ = **10161.1±0.6±1.6 MeV**

B(U(3S) ? ggU**(1D)**
? gggg U**(1S)** ? gggg$\ell^+\ell^-$**)**
=(2.6±0.5±0.5) 10^{-5}

Recall Godfrey & Rosner prediction for all 2P,1D,1P spin combinations: 4 x 10^{-5}

If limited to only 1^3D_2, they predict 2.56 x 10^{-5}

This 1D state is unique among possible D states we can observe in that it lies below open flavor threshold (charmonium 1D mixes with S states and is above open charm threshold)

mass measurement good test for LQCD and potential models

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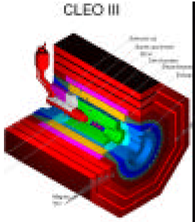
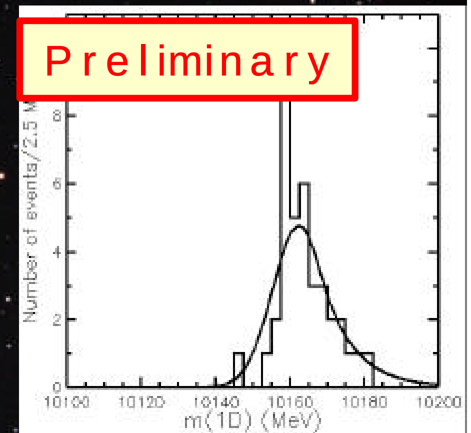
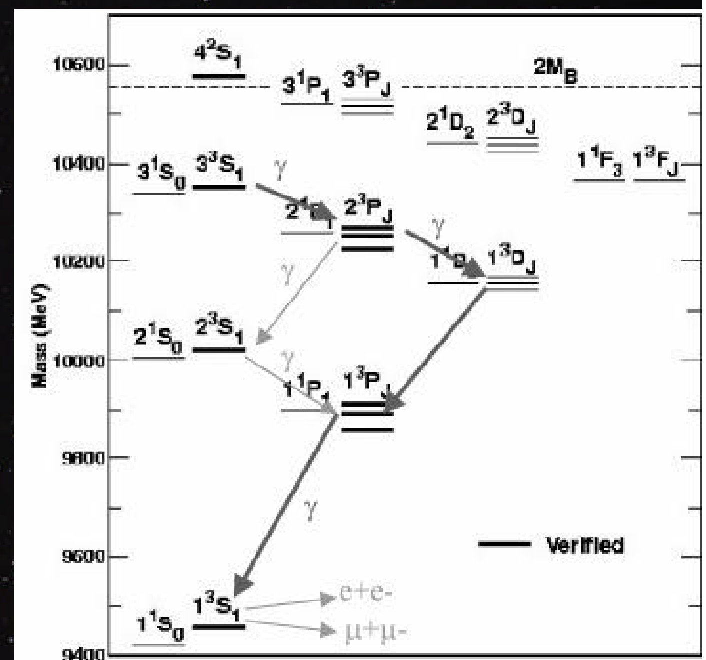


The 1D levels of bottomonium :
Observing new states: $\Upsilon(1^3D_2)$

- ML fit is tried for all possible 2P and 1P intermediate states in the chain
  - ML fit prefers production through J=1 $\chi_b(2P)$ and J=1 $\chi_b(1P)$ states for nearly all events.
  - Production through J=2, J=2 is preferred in only a handful of events.
  - Other spin combinations negligible
  - Thus assignment of $^3D_3$ is strongly disfavored (2,2 is the only way $^3D_3$ can be produced)
  - In 1-1 combination, $^3D_2$ is favored 6:1 over $^3D_1$
- Thus CLEO favors $^3D_2$ assignment





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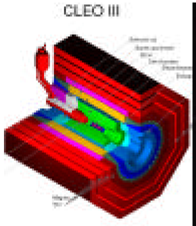


The 1D levels of bottomonium :
Observing new states: $\Upsilon(1^3D_2)$

The observation of $M(\Upsilon(1^3D_J))$= 10161.1±0.6±1.6 MeV can be used to predict masses of the charmonium counterpart

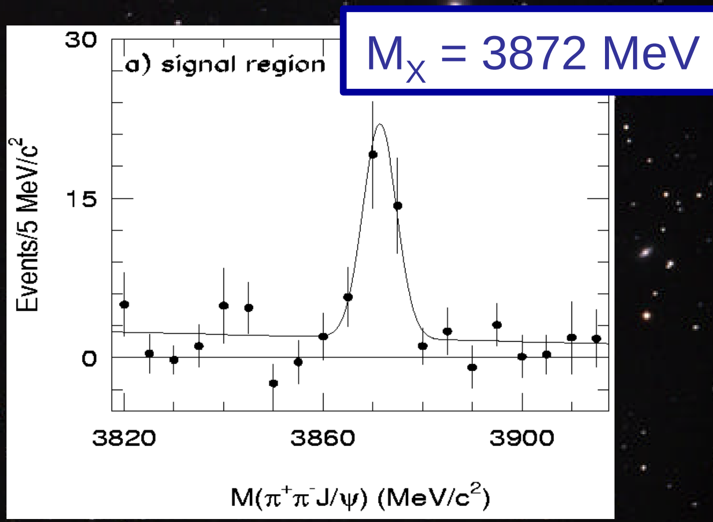
Scaling to cc using M(2S)-M(1S): M(y(1^3D_2))~3831 MeV
Scaling to cc using M(1P)-M(1S): M(y(1^3D_2))~3780 MeV

Compare to

The y(3770), m = 3770 MeV, thought to be D-S mixture (or pure D)

Or

the state observed by BELLE via B ® KX, X ® J/ypp) (thought by some to be a DD* molecule or other exotic)



3872 seems at least NOT to be 3D2 (as Kay mentioned)

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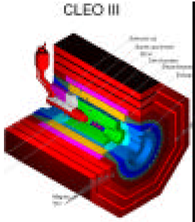
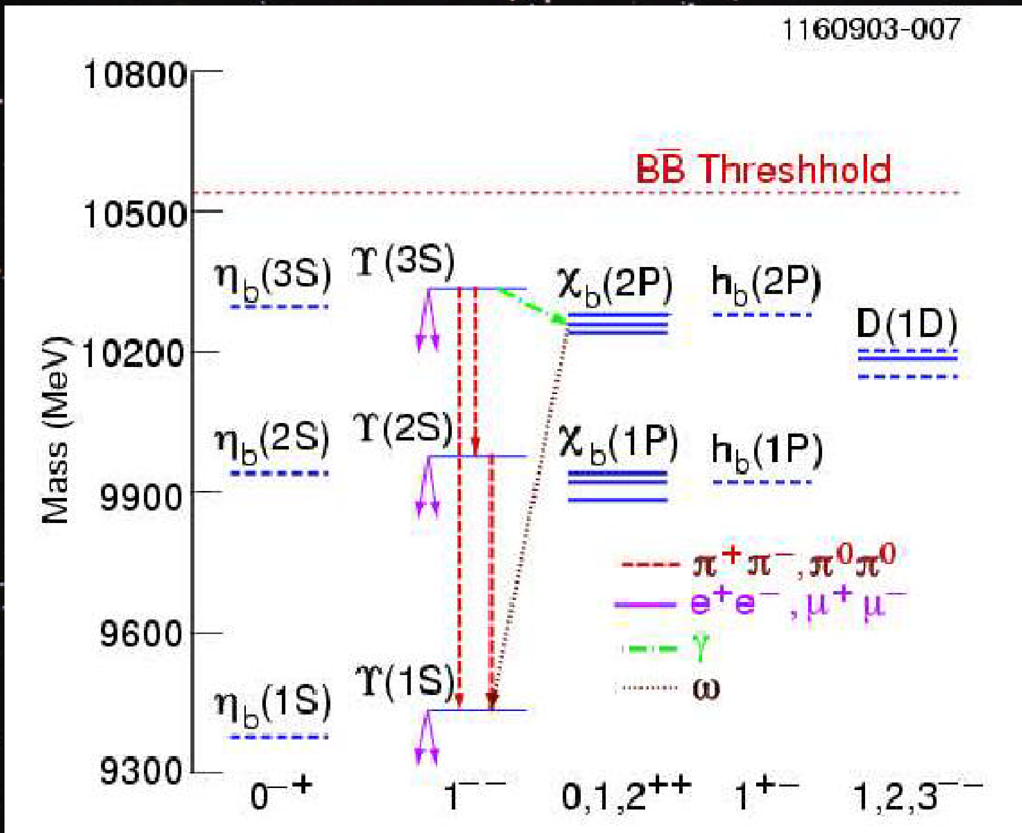
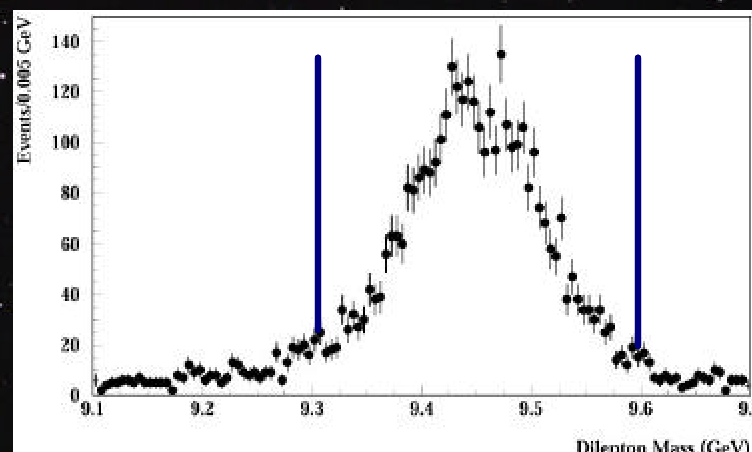


Hadronic Decay of the $\chi_b(2P)$ states: Observing new transitions

- ♦ 5.8 x 10^6 Υ(3S) decays



- ♦ Final state will be $l^+l^-\gamma\pi^+\pi^-\pi^0$
- ♦ Begin with requiring a pair of tracks with large invariant mass (> 9 GeV)
- ♦ In addition, 3 neutral clusters, 2 additional tracks
- ♦ Dilepton mass shown below:



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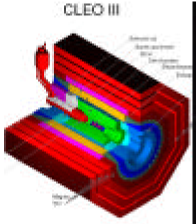
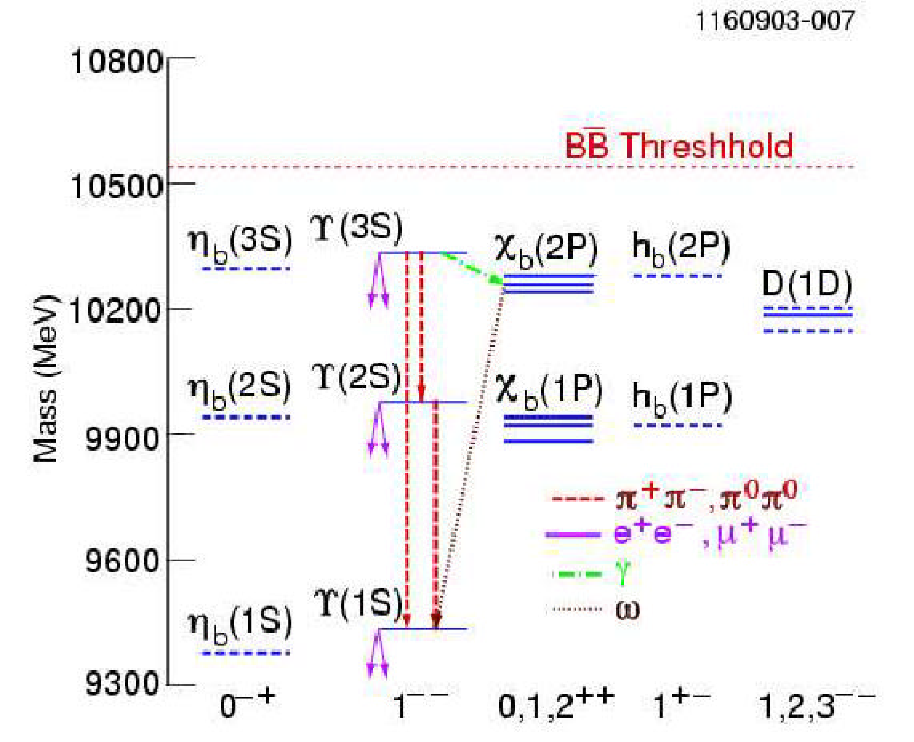
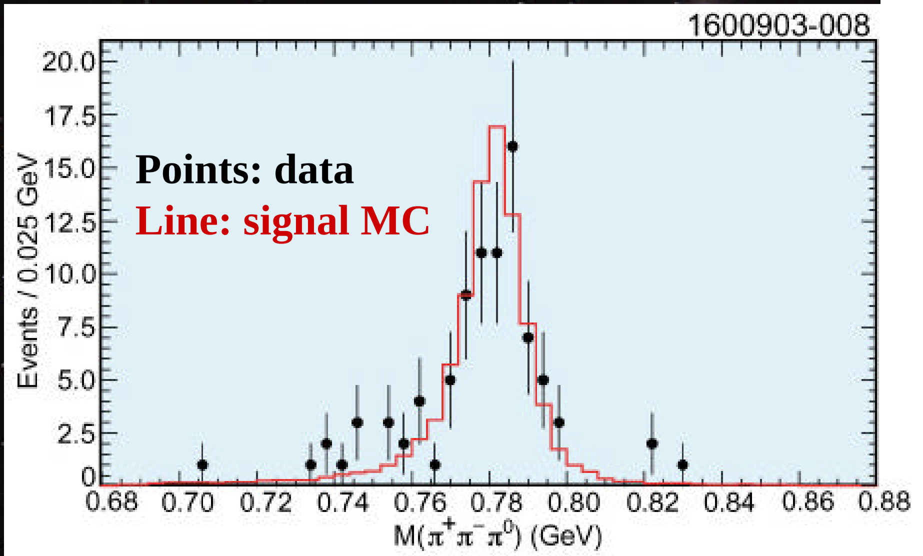


Hadronic Decay of the $\chi_b(2P)$ states: Observing new transitions

- In events having a good Υ(1S) candidate, construct pion trios (π^+,π^-,π^0) from the additional tracks & clusters satisfying basic kinematic criteria





Next, perform kinematic fit for the omega candidate, and select events w/good χ^2/dof (< 2)

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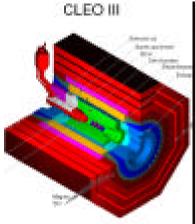
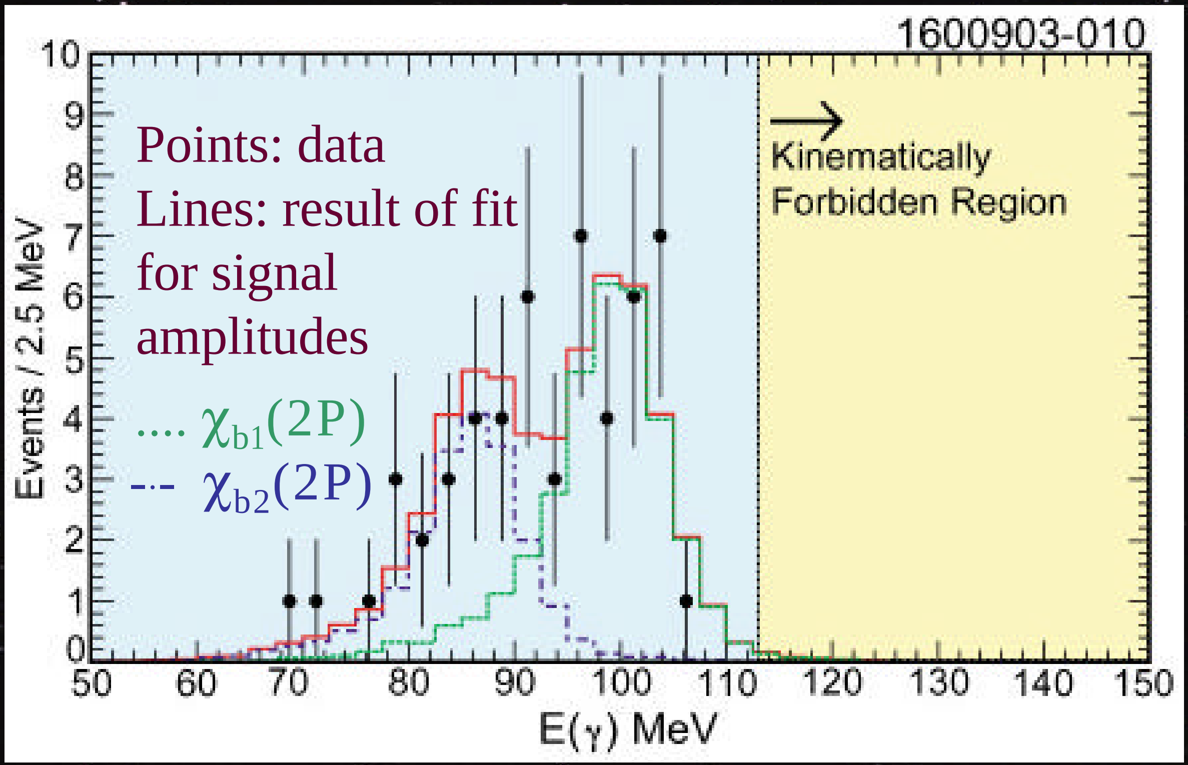


Hadronic Decay of the $\chi_b(2P)$ states: Observing new transitions

- Examine spectrum of accompanying photons in the event (expect 100 MeV, 87 MeV for transitions $\Upsilon(3S)\rightarrow\gamma\chi_2(2P)$ and $\gamma\chi_1(2P)$, respectively)



Simultaneous likelihood fit yields significances of 10.2 and 5.1 sigma, for $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$, respectively

A very clean spectrum (MC indicates background of only a fraction of an event in signal region)

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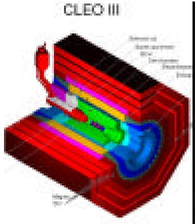

Hadronic Decay of the $\chi_b(2P)$ states:
Observing new transitions

Hep-ex/0311043 and Submitted to PRL

Event yields from fit yield the following branching ratios:

$$B(\chi_{b1}(2P) \to \omega \Upsilon(1S)) = 1.63\,^{+0.35}_{-0.31}\,^{+0.16}_{-0.15}\,\%$$

$$B(\chi_{b2}(2P) \to \omega \Upsilon(1S)) = 1.10\,^{+0.32}_{-0.28}\,^{+0.11}_{-0.10}\,\%$$

First observation of a hadronic transition for states other than those among the triplet S states (first new transition in bottomonium in ~20 years)

Should give theorists something to chew on for a while as we work on other heretofore unobserved hadronic transitions:

Dipion transitions $\chi_b(2P) \to \chi_b(1P)\ \pi\pi$

Dipion transitions $\Upsilon(1D) \to \Upsilon(1S)\ \pi\pi$

Search for h_b via $\Upsilon(3S) \to \pi^0 h_b$

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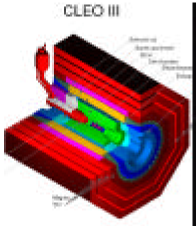

Direct Production of J/ψ in Υ decay:
Improving old measurements

- This is new work based on the CLEO III Υ(1S) data set
  very preliminary

- Recall that 10 years ago (or so) CDF observed anomalously high rates of prompt J/ψ(1S) and ψ'(2S) production in proton antiproton collisions
  - Color octet model (Braaten/Fleming, et al.) was invoked to explain
  - Issues with polarization data arose
  - Also issues with HERA J/ψ photoproduction, for which color octet model predicted factor 10 too much

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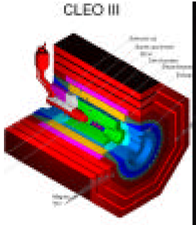

Direct Production of J/ψ in Υ decay: Improving old measurements

Given recent BaBar and BELLE results, the plot thickens:

$\sigma(e^+e^- \to J/\psi + X) = 2.52 \pm 0.21 \pm 0.21$ pb (BaBar) **PRL 87, 162002**

$\sigma(e^+e^- \to J/\psi + X) = 1.47 \pm 0.10 \pm 0.13$ pb (BELLE) (3σ lower) **PRL 88, 052001**

Angular distributions for $p < 3.5$ GeV disagree

Results from BELLE on J/ψ produced with another cc pair: **PRL 89, 142001**

$$\sigma(e^+e^- \to J/\psi\, c\bar{c})/\sigma(e^+e^- \to J/\psi\, X) = 0.59^{+0.15}_{-0.13} \pm 0.12$$

~10 times larger than expected

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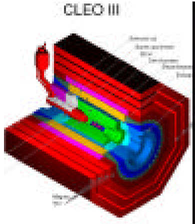

Direct Production of J/ψ in Υ decay : Improving old measurements

- Cheung, Keung and Yuan (PRD 54, 929, (1996)) suggest searching in Υ decay for octet production of J/ψ
- Rationale is two-fold:
  - Υ(1S) decays are glue rich: substantial expectation of color octet production
  - Kinematics of the daughter J/ψ may tell us something unique as well (color octet expects peaking at high values of $x = p/p_{max}$

$$P_{max} = \frac{1}{2\sqrt{s}}(s - M^2_{J/\psi})$$

$$\sqrt{s} = 2E_b$$

- J/ψ production mechanisms:
  - Υ(1S) → ggg, Υ(1S) → γ*→ qqbar
  - Continuum production : $e^+e^- \rightarrow J/\psi + X$
  - Radiative return directly to J/ψ: $e^+e^- \rightarrow e^+e^-\gamma \rightarrow J/\psi + X$
- In the CLEO analysis, we
  - remove radiative return contribution by selective cuts
  - use continuum data taken just below Υ(4S) to subtract the continuum and γ* contributions

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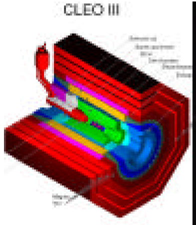


Direct Production of J/ψ in Υ decay : Improving old measurements

- CLEO III has accumulated 21.2×10^6 Υ(1S) decays
- J/ψ is observed in both e^+e^- and $\mu^+\mu^-$

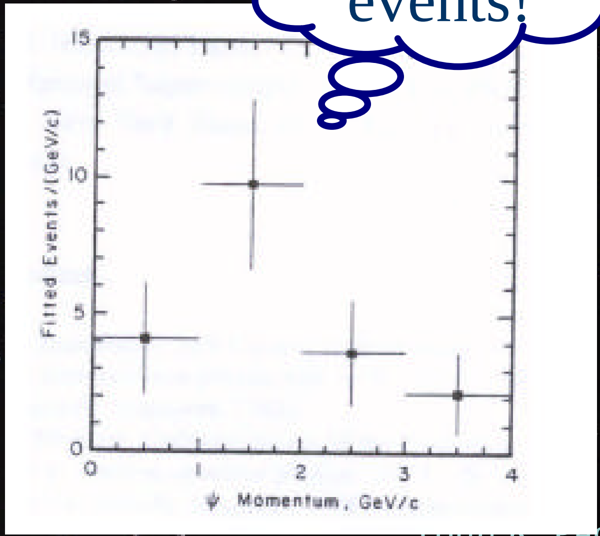
35 times the size of the Data set used for the previous analysis

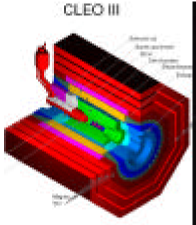
- We have measured the branching ratio $B(\Upsilon(1S) \rightarrow J/\psi + X)$ and the momentum distribution for J/ψ
- The former observation by CLEO (1989) gave a branching ratio of

$$B(\Upsilon(1S) \rightarrow J/\psi + X) = (1.1 \pm 0.4 \pm 0.2) \times 10^{-3}$$

Physics Letters B224, 445 (1989)

All of 20 events!





Direct Production of J/ψ in Υ decay : Improving old measurements

Selection main points:

Removal of jetty continuum by
requiring ≥ 3 trk, $R_2 < 0.6$

Attack radiative return by requiring
if 3-4 tracks, can have no γ candidate > 3.75 GeV
also, $p_{evt} < 3.75$ GeV (or if 3-4 tracks, < 2 GeV)

The data set for this analysis consists of

Signal: 1.2 fb^{-1} on Υ(1S) resonance

For Systematic Checks: 0.2 fb^{-1} below Υ(1S) resonance
5.0 fb^{-1} on Υ(4S) resonance
2.3 fb^{-1} below Υ(4S) resonance

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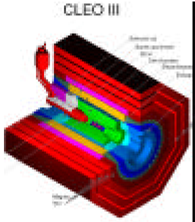
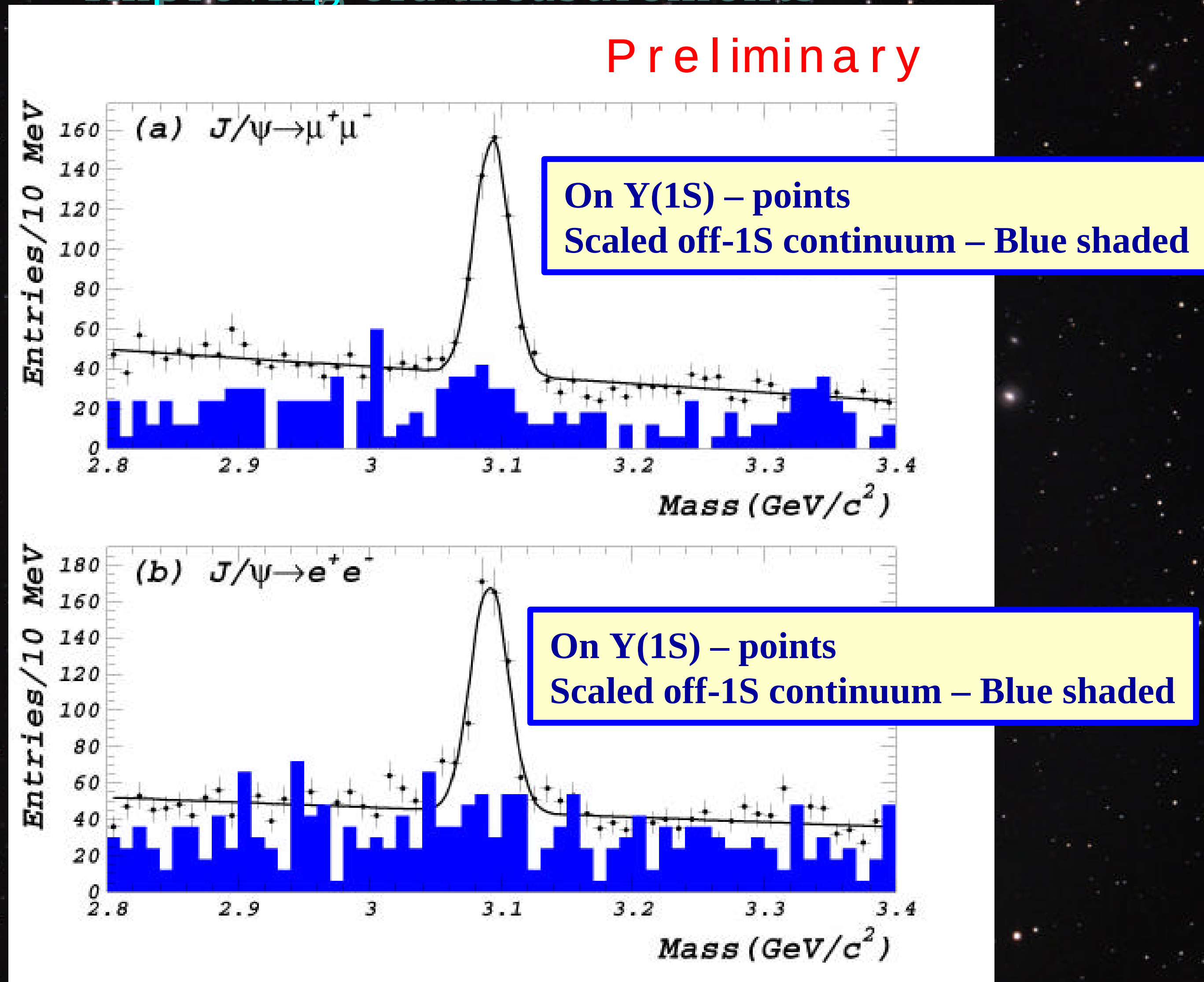


Direct Production of J/ψ in Υ decay : Improving old measurements

- Dilepton Invariant Mass Spectra

  On Υ(1S) Resonance



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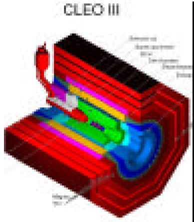
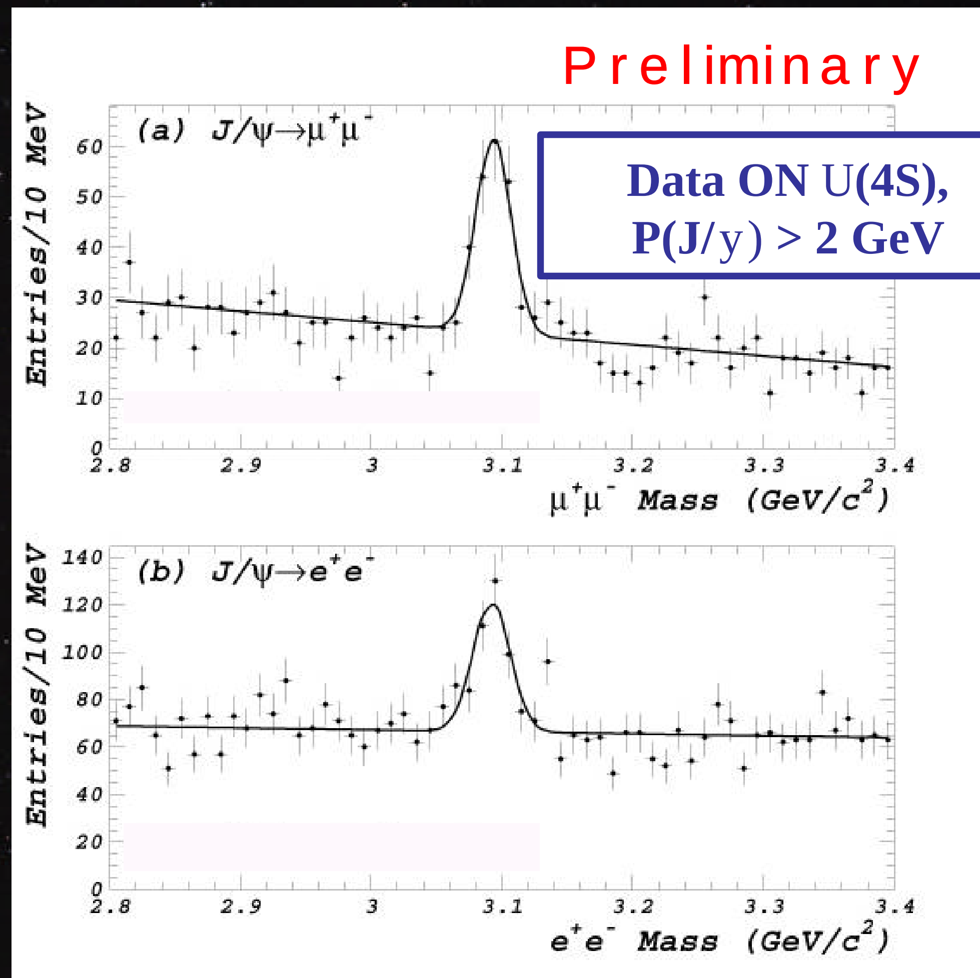


Direct Production of J/ψ in Υ decay : Improving old measurements

Dilepton Invariant Mass Spectrum On Υ(4S) Resonance

require p > 2 GeV to remove all contributions from $B \rightarrow J/\psi X$

Thus at right are due to continuum production at 10.58 GeV



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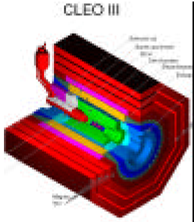
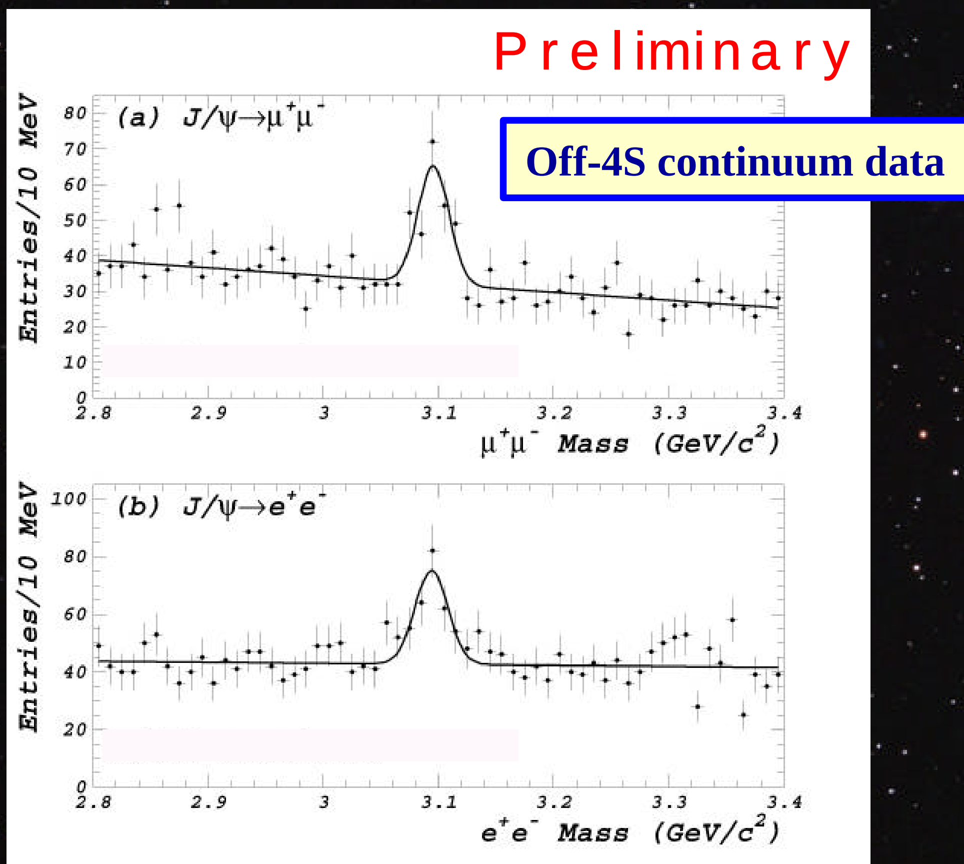


Direct Production of J/ψ in Υ decay : Improving old measurements

Dilepton Invariant Mass Spectrum

Continuum at sqrt(s) < M(Υ(4S))



From this and the previous slide

CLEO III Preliminary

Continuum Cross Sections

$\sigma(e^+e^- \to J/\psi + X)$

$\mu^+\mu^-$: 2.0 ± 0.2 pb

e^+e^-: 1.7 ± 0.2 pb

cf:

2.52 ± 0.21 ± 0.21 pb (BaBar)

1.47 ± 0.10 ± 0.13 pb (BELLE)

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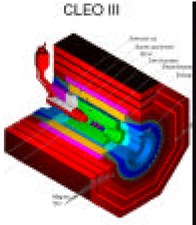
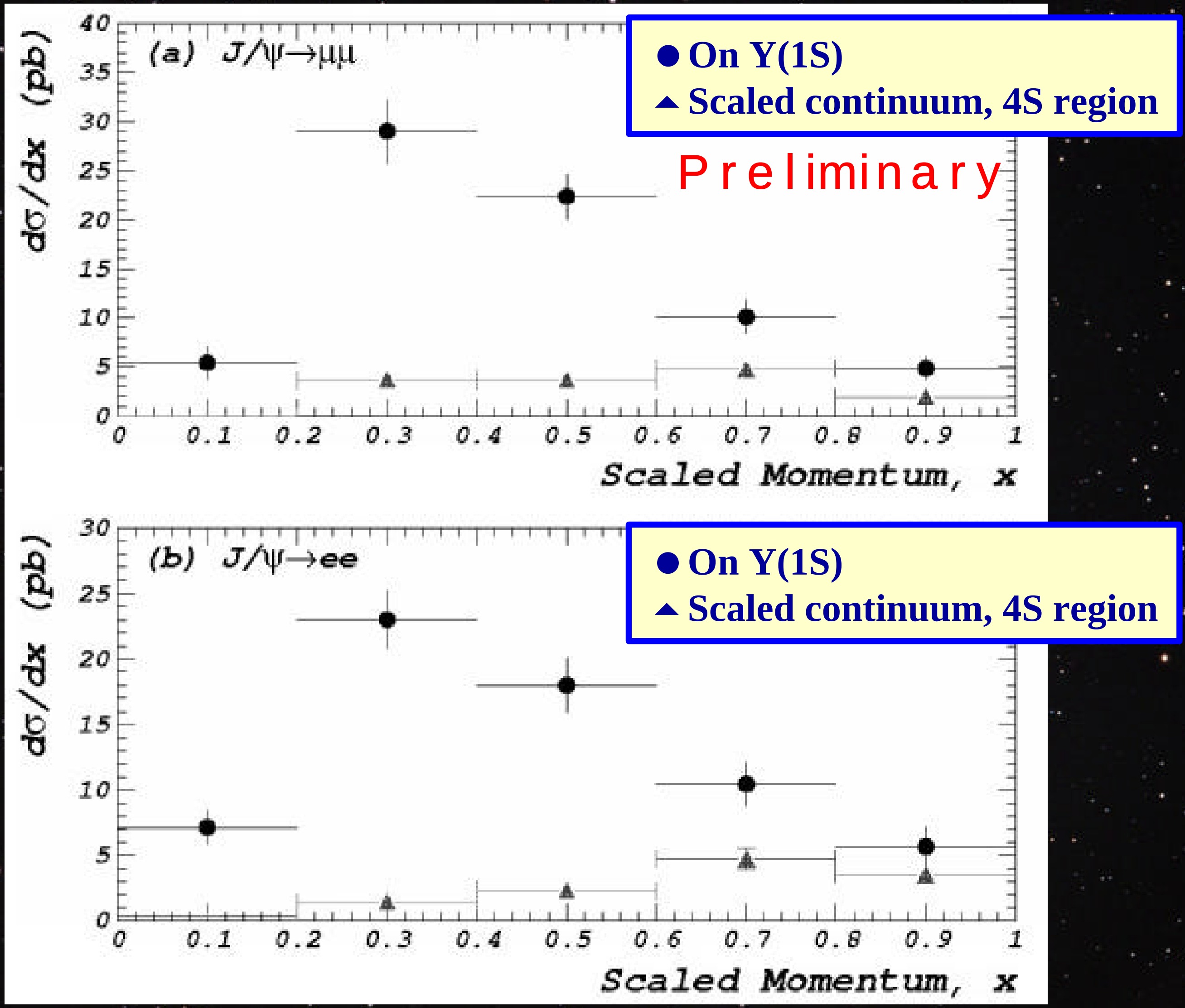


Direct Production of J/ψ in Υ decay : Improving old measurements

J/ψ Momentum Spectra



Note:
High x portion mostly accounted for by continuum production

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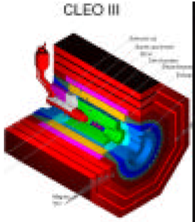
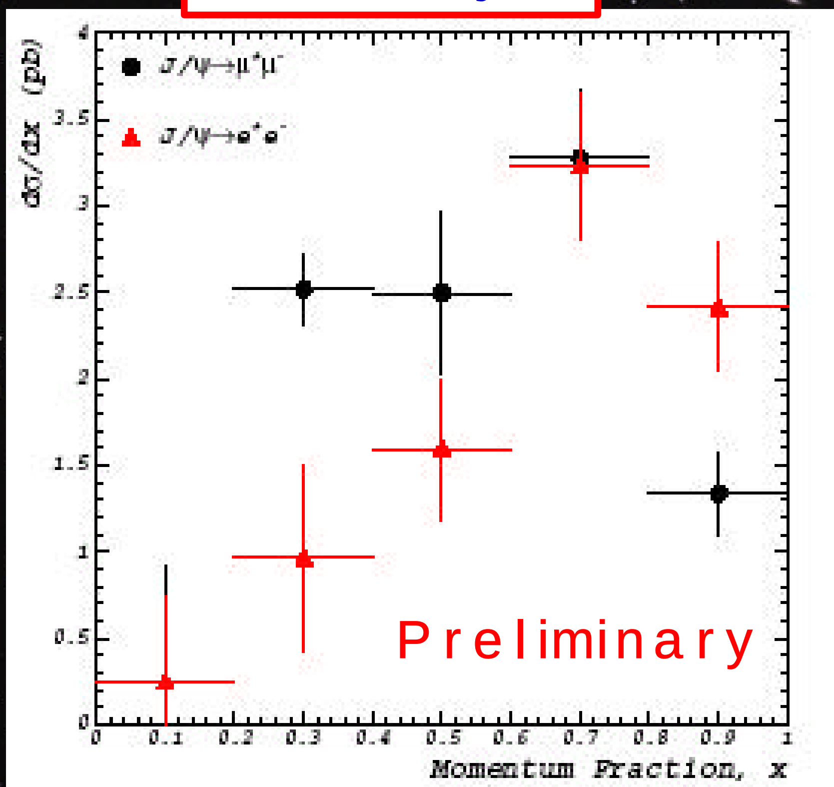
Momentum Distributions for J/y in continuum



This Analysis



BaBar

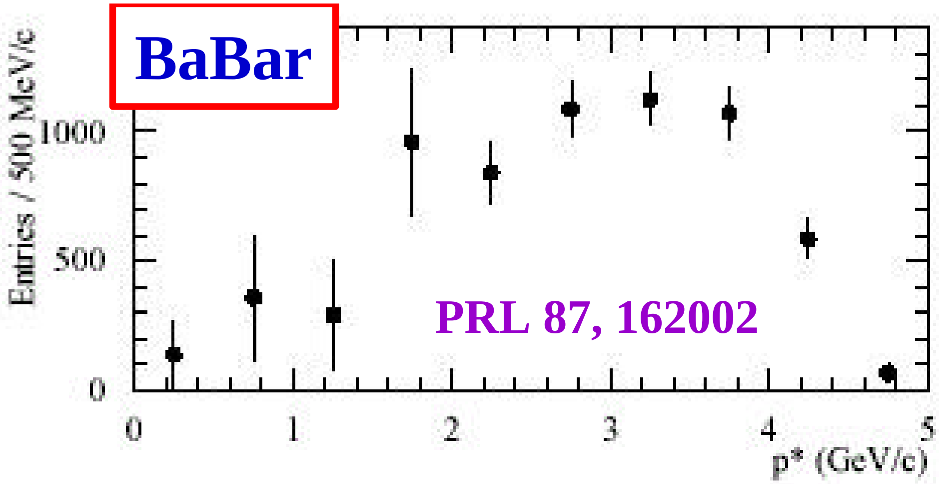
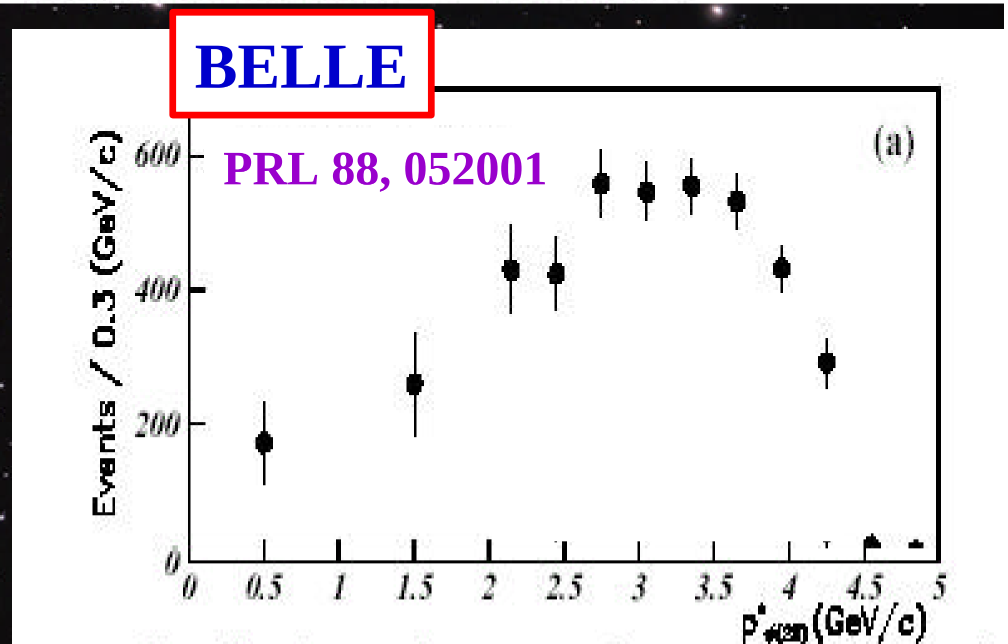


FIG. 3: Center of mass momentum distribution of J/ψ mesons produced in continuum e^+e^- annihilation.

BELLE



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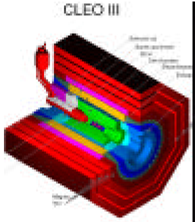
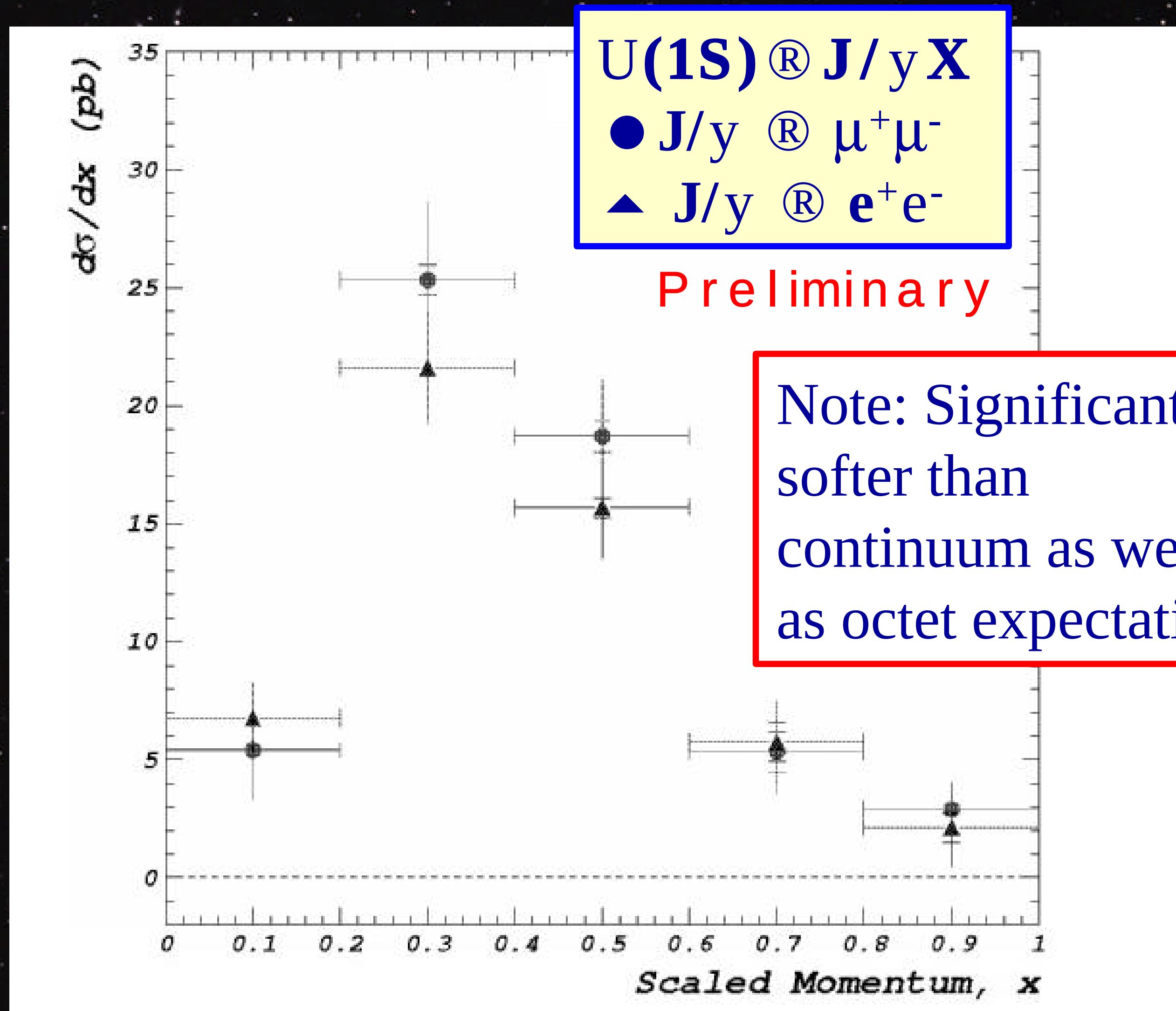


Direct Production of J/ψ in Y decay :

Improving old measurements

Continuum-
Subtracted
J/ψ Momentum
Spectra



Note: Significantly softer than continuum as well as octet expectation

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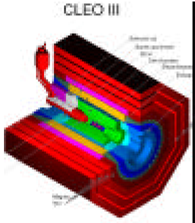

Direct Production of J/ψ in Υ decay : Improving old measurements

Branching Fraction Measurement

$$"B(\Upsilon(1S)\rightarrow J/y + X)" = \frac{N(y)_{1S} - N(y)_{cont} - N(y)_{g^*}}{e \times B(J/y \rightarrow ll) \times N(\Upsilon(1S))} = \frac{\Gamma(\Upsilon(1S)\rightarrow J/yX)}{\Gamma_{tot} - \Gamma(\Upsilon(1S)\rightarrow g^* \rightarrow q\bar{q})}$$

$\mu^+\mu^-$: (6.4 ± 0.5) x 10^{-4}

e^+e^-: (5.7 ± 0.4) x 10^{-4}

Preliminary

Color octet predicts 6.2 x 10^{-4}
Color singlet (Υ(1S) → J/ψcc+X) predicts 5.4 x 10^{-4}

Above does not contain the contribution from γ*.
If we add that back, we find the full BR for inclusive J/ψ

$$B(\Upsilon(1S)\rightarrow J/y + X) = \begin{matrix} mm: & (6.9\pm 0.5)\times 10^{-4} \\ ee: & (6.1\pm 0.5)\times 10^{-4} \end{matrix}$$

Preliminary

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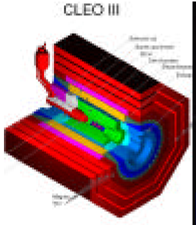

Results: J/ψ in Υ decay

Preliminary

B(U(1S) ® J/y +X) = (6.4 ±0.4 ± 0.6) x 10^{-4}

Conclusions:

- Rate is in rough agreement with both with the color octet model, as well as color singlet calculation of $e^+e^- \rightarrow J/\psi cc + X$
- Momentum spectrum disagrees sharply with the color octet predictions, and disagrees as well with color singlet calculations.
- As is usually the case… the production mechanism isn't necessarily a simple matter of either/or

Coming soon to a theatre near you:

$\Upsilon(1S) \rightarrow \psi'(2S) + X$ and $\chi_c(1P) + X$

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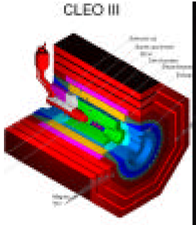
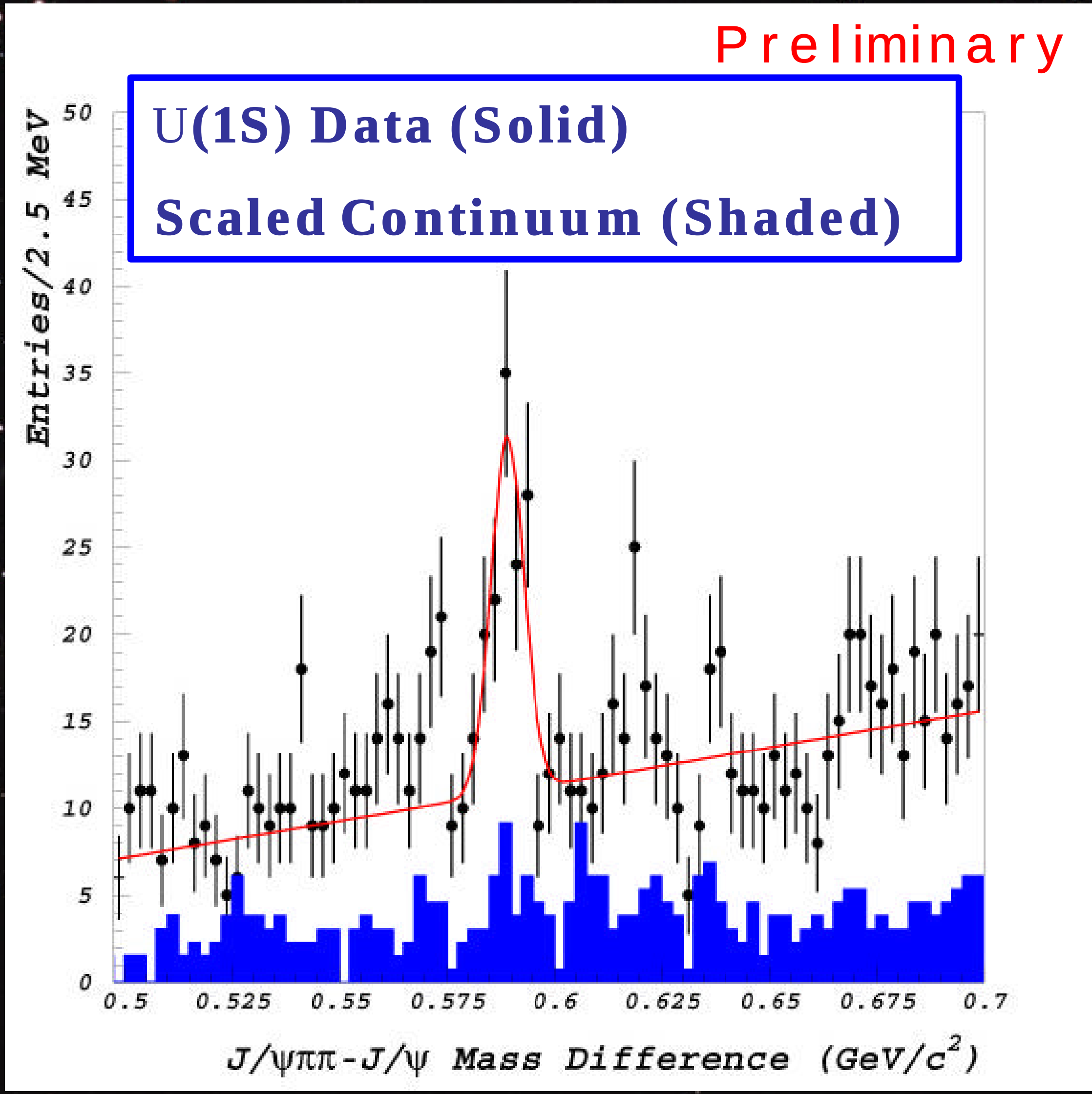


Results: Forthcoming in Υ decay

- For itching eyes....



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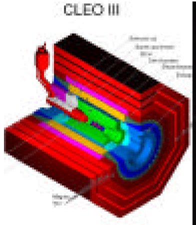

Other results on the horizon

- Given the time constraints of this conference, I've only had time for a smattering of recent results. I've unfortunately had to neglect the following topics
  - Leptonic width measurements
  - Searches for η_b and h_b
  - Detailed study of dipion transitions (invariant mass spectrum and angular distributions: checking S vs. D wave contributions)
- CLEO has enormous data sets on the resonances that we're only beginning to sift through.
- And, related, though not strictly in the subject matter of this talk, look for many new results in charmonium spectroscopy from CLEO-c over the coming year

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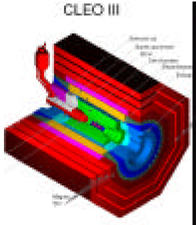

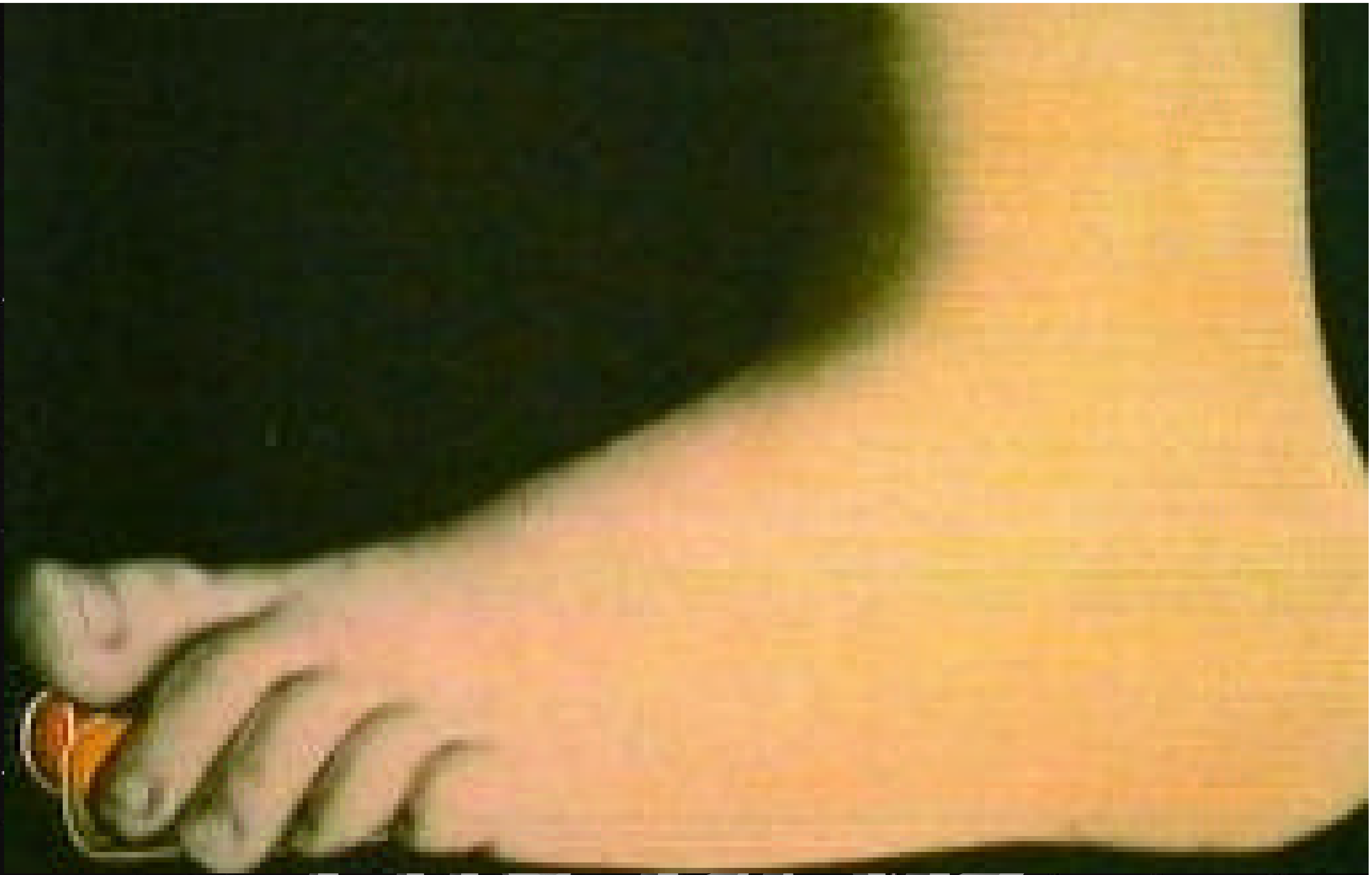

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