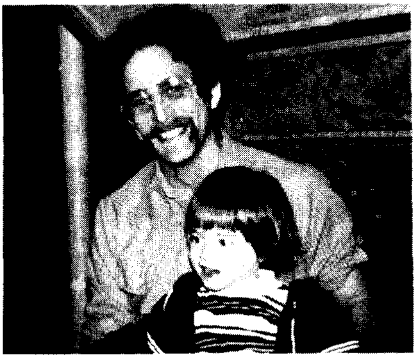
UPSILON SPECTROSCOPY FROM CESR

Richard Kass
Department of Physics
The Ohio State University
Columbus, Ohio 43210 U.S.A.



Abstract

Recent results on $b\bar{b}$ spectroscopy from the Cornell Electron Storage Ring (CESR) are reviewed. These results include measurements of both hadronic and radiative decays of the $\Upsilon(2S)$, measurement of both branching ratio and photon spectrum for the process $\Upsilon(1S)$ or $\Upsilon(2S)\to\gamma$+gluon+gluon and a search for the $\xi(2.2)$ in $\Upsilon(1S)$, $\Upsilon(2S)$, and B meson decay. Finally, evidence for a new $b\bar{b}$ bound state, the $\Upsilon(5S)$, is presented.

Introduction

In this report we present results from two experiments, CLEO and CUSB, on the spectroscopy of the Upsilon system. Both experiments reside at CESR and have been in operation for over four years. Detailed descriptions of both detectors can be found elsewhere[1,2]. We note only that CUSB is a compact detector emphasising precise photon calorimetry, while CLEO is a large general purpose magnetic spectrometer.

Figure 1 shows the Hadronic cross section as measured by the CLEO group in the energy region of the Upsilon system. As we increase the center of mass energy we see three narrow peaks [$\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$] and a fourth "wide" bump [$\Upsilon(4S)$]. The first three peaks correspond to bound states of a b and a $\bar{b}$ quark which are below energy threshold to decay into b-flavored mesons. The fourth peak is slightly above threshold for b meson production, hence its large natural width. Transitions between the narrow Upsilon states are predicted by many quarkonia models. An example of the level structure expected from these transitions is shown in Fig. 2.

Photon Transitions

As can be seen in Fig. 2 an excited $3\,^3S_1$ state can decay to a P state via photon emission. The photon emitted in this process is monoenergetic and hence measures the mass of the P state. In addition we expect the P state to be split into 3 levels corresponding to J=0,1,2 with J the total angular momentum of the state. A prerequisite for observing these states and their splitting is good photon energy resolution at ~100 MeV.

In Fig. 3a we show the inclusive photon spectrum from $\Upsilon(2S)$ decays as seen with the CUSB detector. There is a clear excess of events over the expected background for photons in the energy range near 120 MeV. After making a background subtraction the CUSB group finds evidence for three states (Fig. 3b) with the energies and branching fractions listed in Table 1. Details of the analysis as well as background calculations can be found in Ref. 3.

A second technique for locating the P states is to search for events corresponding to the decay chain $\Upsilon(2S)\to X_b\gamma$, $X_b\to\gamma\Upsilon(1S)$, $\Upsilon(1S)\to\ell^+\ell^-$ with ℓ an electron or muon. The CUSB group has performed such a search, the results of which are shown in Fig. 4. All event candidates with the topology $e^+e^-\to\gamma\gamma\ell^+\ell^-$ are entered in this plot. Since the radiative cascade from the Υ(2S) down to the Υ(1S) involves one monochromatic and one essentially monochromatic photon, the backgrounds to this process are greatly reduced compared to the inclusive photon search. The photon energies and branching fractions obtained from this analysis[4] are listed in Table 1. There is good agreement between these results and the ones obtained from the inclusive analysis of Υ(2S) decays.

Table 1

Experimental Results for $\Upsilon(2S)\to\chi_b\gamma$

	$^3P_2$	$^3P_1$	$^3P_0$	
CLEO	109±0.7±1	129.0±0.8±1	(158±7±1)	} Photon Energy (MeV)
CUSB (INCL)	108.2±0.3±2	129.1±0.4±3	149.4±0.7±5	
CUSB (EXCL)	106.8±3±2	127.8±2.0±3.0	---	
CLEO	10.2±1.8±2.1	8.0±1.7±1.6	(4.4±2.3±0.9)	} Branching Fraction (%)
CUSB	6.1±1.4	5.9±1.4	3.5±1.4	

The CLEO group has searched for the P states using its drift chamber as a pair spectrometer. For this search 10% of a radiation length of lead was inserted between the beam pipe proportional chamber and drift chamber. The beam pipe plus proportional chamber presented another 5% of a radiation length to the drift chamber. Photons that converted to e^+e^- pairs before the drift chamber were momentum analysised using a 3.5 KG magnetic field. The energy resolution for photons reconstructed with this technique is $\delta E/E=3.4\%$. Figure 5 shows an example of a photon which converts in the material between the beam pipe proportional chamber and drift chamber. The total efficiency for reconstructing such pairs is ~3%. Details of this analysis can be found in Ref. 5.

Figure 6 shows the energy spectrum of reconstructed photons from 220,000 hadronic events obtained at the Υ(2S). This corresponds to about 125,000 Υ(2S) decays. There is clear evidence for peaks near 109 and 129 MeV. A third peak can be accommodated at 158 MeV, but its statistical significance is less than two standard deviations. The energies and branching ratios obtained from this analysis are presented in Table 1. The energies and branching ratios obtained by CLEO are in good agreement with the CUSB results.

In Table 2 we compare the CLEO and CUSB results with the predictions of several theoretical models[6]. Spin independent potentials with parameters adjusted to give the correct Ψ splittings and Υ masses predict the center of gravity of the χ_b to ~30 MeV. The electric dipole rates are correctly given by many models. Relativistic corrections important for the $c\bar{c}$ system are not needed for the $b\bar{b}$ system.

Table 2

Comparison of experimental results with theoretical predictions

	$M(\chi_b)-M(\Upsilon)$	$\Delta M(2-1)$	$\Delta M(1-0)$	Γ_{E1}
CLEO	441±2 MeV	19.5±1.2 MeV	29±7 MeV	6.1±1.5 keV
CUSB	439±3	19.9±1.1	21.3±1.8	4.9±1.0
Eichten et al.	463	25	25	5.5
Buchmuller et al.	430	31	41	5.3
Klare	413	39	55	--
Gupta et al.	438	17	25	--
Muxhay, Rosner	446	11	26	6.6
McClary, Byers	463	22	49	5.0

Hadronic Transitions

Hadronic transitions between Υ states can be described in terms of gluon radiation from an excited $b\bar{b}$ state[7]. Models which use a multipole expansion of the gluon field to describe this radiation have been quite successful in predicting branching rates for various processes. In Table 3 we list some hadronic transitions which have been measured at CESR[8] along with the predictions of the multipole model. The agreement between theory and experiment is impressive. The factor of two between the rate for $\pi^+\pi^-$ and $\pi^o\pi^o$ decay shows that isospin is conserved in these decays.

Table 3

Hadronic transitions for the Upsilon system

Process	Experimental Rate (%)	Prediction
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$	19.1±1.7±0.6 CLEO 19.4±2.9 CUSB	18 - 21%
$\frac{\Upsilon(2S)\to\pi^0\pi^0\Upsilon(1S)}{\Upsilon(2S)\to\pi^+\pi^-\Upsilon(2S)}$	.54±.07 CUSB	.5
$\Upsilon(2S)\to\eta\Upsilon(S)$	<1% CLEO <0.2% CUSB	2~3% Phase space $<10^{-3}$ QCD multipole
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$	4.9±0.9±0.5 CLEO 4.6±1.5 CUSB	1.2 - 3.6%
$\Upsilon(3S)\to\pi^0\pi^0\Upsilon(2S)$ $\Upsilon(3S)\to\pi^0\pi^0\Upsilon(1S)$	observed CUSB	

The nonobservation of $\Upsilon(2S)\to\Upsilon(1S)\eta$ by both CLEO and CUSB is in agreement with the multipole model. Using data from the reaction $\Psi'\to\Psi\eta$ and phase space considerations we expect a branching ratio of about 3% for the Upsilon system. The gluon emission model predicts a further suppression of $(m_c/m_b)^4$ ~1/75 in agreement with the data.

Assuming PCAC and the multipole expansion model the dipion mass distribution can be calculated from the following matrix element:

$$M = Aq_{u1}q_{u2} + Bq_{01}q_{02} \quad . \tag{1}$$

In Eq.(1) q_1 and q_2 are the pion four momenta. A and B are free parameters. In Figs. 7a and 7b we show the dipion mass distribution from the reaction $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\to\Upsilon(1S)\pi^o\pi^o$ respectively. The shape of the distribution is in agreement with results from the reaction $\Psi'\to\Psi\pi^+\pi^-$. In Fig. 8 we show the dipion mass distribution for the reaction $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$. In constrast to the previous distributions this one does not peak at high values of the dipion mass, but is rather flat in this variable. Why the dipion mass distribution differs between the $\Upsilon(2S)$ and $\Upsilon(3S)$ is not understood. It is however allowed in the multipole model since the parameters A and B can be adjusted to fit the shape of most any dipion mass spectrum.

$\Upsilon \to \gamma$ gluon + gluon Process

The two gluon plus photon decay of the Upsilon state is predicted by QCD. The rate for this process as calculated to first order in QCD[9] is given in Eq. 2.

$$R = \frac{\Gamma(\Upsilon \to gg\gamma)}{\Gamma(\Upsilon \to ggg)} = \frac{36\alpha}{5\alpha_s} e_q^2 \left(1-2.2 \frac{\alpha_s}{\pi}\right)^{-1} . \tag{2}$$

For α_s=250 MeV Eq.(2) gives ~3% for the branching fraction relative to the 3 gluon decay of the Upsilon. Since the higher order corrections to Eq.(2) are thought to be small a measurement of this rate is in principle a highly accurate method for determining α_s and the QCD scale parameter $\Lambda_{\overline{MS}}$.

The photon energy spectrum for this process can be calculated using lowest order QCD[10]. Equation (3) gives the photon energy spectrum in terms of $Z=E_\gamma/E_{BEAM}$

$$\frac{dN}{dZ} \propto \frac{Z(1-Z)}{(2-Z)^2} + 2 \ln(1-Z) \left[\frac{(1-Z)}{Z^2} - \frac{(1-Z)^2}{(2-Z)^3}\right] + \frac{2-Z}{Z} . \tag{3}$$

As can be seen from Eq.(3) the photon energy spectrum (dN/dZ) rises linearly with photon energy. More than half the photons from this process should have energies greater than half the beam energy. Experimental backgrounds to this process include π^o production where the two photons merge into one photon in the detector, initial state radiation, and final state quark radiation. Fortunately for energetic photons the above backgrounds are manageable and can be calculated via Monte Carlo or estimated from data taken off the resonance.

Both CLEO and CUSB have measured the rate for $\Upsilon(1S) \to gg\gamma$. The CLEO result of 2.6±0.3±0.3% is in good agreement with CUSB result of 3.0±0.6%. In addition the CUSB group has also measured the rate for $\Upsilon(2S) \to gg\gamma$ to be 3.4±1.1%. All experimental results are consistent with the expectations of Eq.(2). In Fig. 9 the inclusive photon distribution after correcting for non-$gg\gamma$ backgrounds is shown. The dashed curve in this figure is the predicted photon spectrum from the $gg\gamma$ process [Eq.(3)] after including the resolution of the CLEO detector. There is good agreement between this naive formula and the data. Also plotted in Fig. 9 is the MARK II result for the low energy analog $\Psi\to gg\gamma$ (solid curve). Their data peak at an energy lower than expected from theory. This discrepancy might be due to some mass scale that is important in Ψ decay but not in Υ decay.

Of great interest is the determination of $\Lambda_{\overline{MS}}$, the QCD scale parameter. Using Eqs.(2) and (4) we can turn the experimental results for $gg\gamma$ decay into values for $\Lambda_{\overline{MS}}$.

$$\alpha_s = \frac{4\pi}{\beta_0 \ln \frac{M^2}{\Lambda^2} + \frac{\beta_1}{\beta_0} \ln \frac{M^2}{\Lambda^2}} \quad . \tag{4}$$

In Fig. 9 we plot the value of $\Lambda_{\overline{MS}}$ obtained from various measurements. All measurements are consistent with $\Lambda_{\overline{MS}}$~150 MeV. While the consistency of the results is impressive one must be aware that higher order corrections to Eq.(2) could cloud the picture.

Search for the $\xi(2.2)$

The MARK III group has recently discovered a new resonance in radiative Ψ decay.[11] Properties of the resonance include: decay to K^+K^- and K^oK^o final states, mass=2218±3±10 MeV, Γ<40 MeV(95% c.l.) and combined branching fraction $BR(\Psi\to\gamma\xi)\times BR(\xi\to K^+K^-)=(6\pm2\pm2)\times10^{-5}$. The fact that the width of this object is very narrow (consistent with experimental resolution) and its discovery was unanticipated have led to much speculation as to the nature of the beast. Foremost in many theorists' minds was could this object be the Higgs boson of the Standard Model of electroweak interactions. If not the Higgs of the Standard Model then perhaps the Higgs of some variant of the Standard Model.

In the Standard Model with a single Higgs the production rate in radiative vector meson decay has been calculated by Wilczek[12] to be:

$$BR(V \to \gamma H^o) = \frac{G_F M_V^2}{4\sqrt{2}\ \alpha\pi} \left(1 - \frac{M_{H^o}^2}{M_V^2}\right) BR(V \to \mu^+\mu^-) \qquad (5)$$

For the Ψ system Eq.(5) gives 3×10^{-5}, in contrast to the MARK III measurement of 6×10^{-5}. Thus the ξ is unlikely to be the "simple" Higgs. If we consider models more general than the Standard Model then it is possible to enhance the rate of $\Psi\to\gamma H^o$.

In the two doublet model of Ref. 13 the rate for $\Psi\to\gamma H^o$ can be enhanced by a factor x^2, where x is the ratio of the vacuum expectation value of two Higgs fields. In the two Higgs model where the same Higgs field couples to both charge 2/3 and -1/3 quarks the rate for $\Upsilon\to\gamma H^o$ is also enhanced by x^2. If one now takes the ratio of Υ to Ψ rates for this process then the (unknown) x^2 factor drops out. Equation (6) gives the ratio of the rates for Ψ and Υ decay into the Higgs.

$$\frac{BR(\Upsilon \to \gamma\xi)}{BR(\Psi \to \gamma\xi)} = \left(\frac{M_\Upsilon}{M_\Psi}\right)^2 \left(\frac{B_{\mu\mu}(\Upsilon)}{B_{\mu\mu}(\Psi)}\right)\left(1 - \frac{M_\xi^2}{M_\Upsilon^2}\right)/\left(1 - \frac{M_\xi^2}{M_\Psi^2}\right) \quad . \qquad (6)$$

Assuming that the MARK III has measured the rate for $\Psi\to\gamma H^o$ we can use Eq.(6) to predict the rates for the Upsilon system. We obtain:

$$BR(\Upsilon(1S) \to \gamma\xi) \times BR(\xi \to K^+K^-) = (4.3 \pm 1.8) \times 10^{-4}$$

and

$$BR(\Upsilon(2S) \to \gamma\xi) \times BR(\xi \to K^+K^-) = (2.6 \pm 1.1) \times 10^{-4} \quad .$$

If however the charged 2/3 and -1/3 quarks couple to different Higgs fields then the ratio of Υ decays to Ψ is suppressed by x^4. However in this model the process B(meson)$\to H^o X$ has a substantial rate. Kane and Haber[14] estimate that a plausible upper limit for $\xi\to K^+K^-$ is 1/6. Using the calculation of Willey[15] we obtain for a charged Higgs with mass less than M_W

$$BR(B \to \xi X) \times BR(\xi \to K^+K^-) \gtrsim 0.0034 \times (m_t/21\ \text{GeV})^4 \quad , \qquad (7)$$

with m_t the mass of the top quark.

The CLEO group has performed a search for the $\xi(2.2)$ using data taken at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(4S)$.[16] For the narrow resonances the event sample consisted of 70,000 $\Upsilon(1S)$ decays and 125,000 $\Upsilon(2S)$ decays. All events consistent with the topology $\Upsilon \to \gamma K^+K^-$ were subjected to a 4 constraint kinematic fit in order to improve the mass resolution of the K^+K^- pair. Events which had a $\chi^2 < 100$ and passed a visual scan by a physicist were retained for further analysis. A final check was made on the remaining sample to eliminate events with either an identified muon or electron. Events of this type are expected from the QED processes $e^+e^- \to e^+e^-\gamma$ or $e^+e^- \to \mu^+\mu^-\gamma$.

In Figs. 10a and 10b we show the invariant mass of the K^+K^- pair after the kinematic fit. For both cases there is no evidence for structure at 2.2 GeV. We find for the 90% confidence limit that

$$BR(\Upsilon(1S)) \times BR(\xi \to K^+K^-) < 2 \times 10^{-4}$$

$$BR(\Upsilon(2S)) \times BR(\xi \to K^+K^-) < 9 \times 10^{-5} \quad .$$

Thus the CLEO data eliminate the Higgs doublet model where the same Higgs field couples to the charged 2/3 and -1/3 quark.

The B meson sample consisted of 42,000 decays of the $\Upsilon(4S)$ into $B\bar{B}$ pairs. The ξ search was performed by calculating the invariant mass of all oppositely charged tracks with the assumption that the tracks are kaons. The mass spectrum obtained in this manner is shown in Fig. 11. There is no structure at 2.2 GeV, leading to a 90% confidence limit of

$$BR(B \to \xi X) \times BR(\xi \to K^+K^-) < 3 \times 10^{-3} \quad .$$

Thus under the assumptions stated above the CLEO result also eliminates models in which different Higgs fields couple to the charged 2/3 and -1/3 quark. If the $\xi(2.2)$ is a conventional object such as a meson or glueball, then its rate in Υ decay is expected to be suppressed by ~40 relative to Ψ decay $[(m_c/m_b \cdot e_b/e_c)^2]$. The CLEO result is consistent with this suppression.

Discovery of Υ(5S)

Recently CESR has been running at energies above the Υ(4S) to search for new members of the Upsilon family. In Table 4 we list some predictions for the location of the Υ(5S) and Υ(6S).[17] Figures 12a and 12b show the visible hadronic cross section from 30pb^{-1} of data in the regions of interest as measured by CLEO and CUSB. There is evidence for structure in the cross section at 10.87 GeV.

Table 4

Predictions for Υ(5S) and Υ(6S)

Theory	Υ(5S)	Υ(6S)
Eichten et al.	10.920 MeV	11.140 GeV
Martin	10.760	10.920
Büchmuller-Tye	10.860	------
Ono	10.806	10.999
Richardson	10.824	11.025
Bhanot-Rudaz	10.812	11.014
Krasemann-Ono	10.795	10.997

This structure is greatly enhanced by selecting events which have spherical topologies as expected from a resonance decaying into two B mesons. Figure 13a shows the CLEO data after a cut of R2<0.3 has been made. The CUSB data, subjected to a similar cut (Thrust<0.74) is shown in Fig. 13b. Both data sets are consistent with a new state of mass 10.875±0.005 GeV. In addition, the CLEO group has measured the inclusive lepton cross section (electrons and muons) using this data set (Fig. 14). The lepton cross section is consistent with the enhancement to be expected from the bump at 10.875 GeV.

The energy levels for the Upsilon system as calculated by several authors[17] is shown in Fig. 15. We tentatively identify the peak at 10.875 GeV as the Υ(5S). Finally we note that while several of the models give excellent predictions for the mass differences of the Υ's below B meson threshold, none of the models accurately predict both the 4S-3S and 5S-3S mass splitting.

Summary

We find good agreement between CLEO, CUSB, and theory on Upsilon transitions involving hadrons and photons. The two gluon plus photon decay of the $\Upsilon(1S)$ and $\Upsilon(2S)$ has been measured. The CLEO group has performed a search for the $\xi(2.2)$ in $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(4S)$ decay. The nonobservation of the $\xi(2.2)$ rules out a wide class of electroweak models with two Higgs doublets. Finally, new data on the hadronic cross section above the $\Upsilon(4S)$ provide evidence for the existence of a new resonance at 10.875 ± 0.005 GeV. We tentatively identify this state as the $\Upsilon(5S)$.

Acknowledgments

The author wishes to thank the members of both CLEO and CUSB for allowing him to present their data. This work was supported in part by the National Science Foundation, the U.S. Department of Energy, and The Ohio State University.

References and Footnotes

1] Andrews et al., Nucl. Inst. and Meth. 211, 47 (1983).
2] P. Franzini and J. Lee-Franzini, Phys. Reports 81, 240 (1983).
3] C. Klopfenstein et al., Phys. Rev. Lett. 51, 160 (1983).
4] F. Pauss et al., Phys. Lett. 130B, 439 (1983).
5] P. Haas et al., Phys. Rev. Lett. 52, 799 (1984).
6] See references listed in Ref. 5.
7] K. Gottfried, Phys. Rev. Lett. 40, 598 (1978); T.-M. Yan, Phys. Rev. D22, 1652 (1980); Y.-P. Kuang and T.-M. Yan, Phys. Rev. D24, 2874 (1981).
8] J. Green et al., Phys. Rev. Lett. 49, 617 (1982); G. Mageras et al., Phys. Lett. 118B, 453 (1982); P. M. Tuts, 1983 Photon Lepton Converence, Cornell University.
9] S. J. Brodsky et al., Phys. Rev. D28, 228 (1983).
10] A. Ore et al., Phys. Rev. 75, 1696 (1949); S. J. Brodsky et al., Phys. Lett. 73B, 203 (1978).
11] D. Hitlen, 1983 Photon Lepton Conference, Cornell University.
12] F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
13] L. J. Hall and M. B. Wise, Nucl. Phys. B187, 397 (1981).
14] H. E. Haber and G. L. Kane, SLAC-Pub-3209, Sept. 1983.
15] R. S. Willey and H. L. Yu, Phys. Rev. D26, 3086 (1982); R. S. Willey, University of Pittsburgh preprint PITT-17-83.
16] S. Behrends et al, Phys. Lett. 137B, 227 (1984).
17] K. Heikkila et al., Phys. Rev. D29, 110 (1984) and references therein. This article contains an excellent compilation of predictions for the energy levels of the $b\bar{b}$ systems.

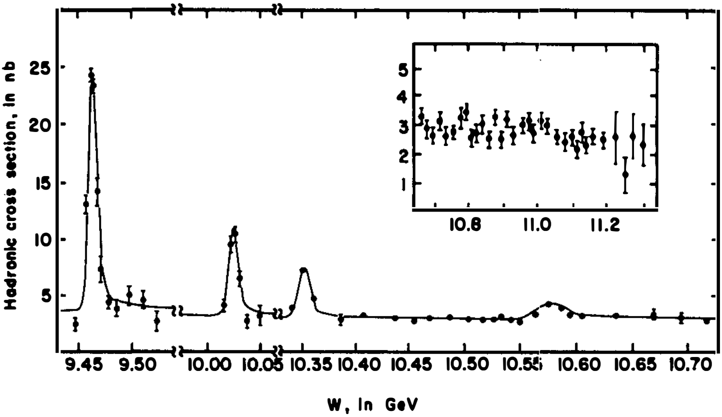


Fig. 1. The hadronic cross section in the Upsilon Region.

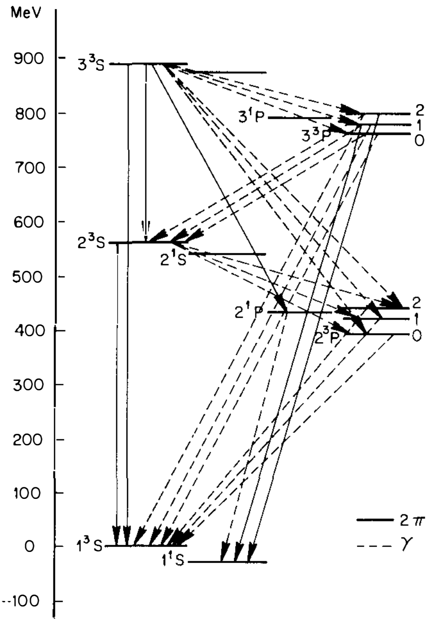


Fig. 2. Predictions for transitions between various Upsilon states.

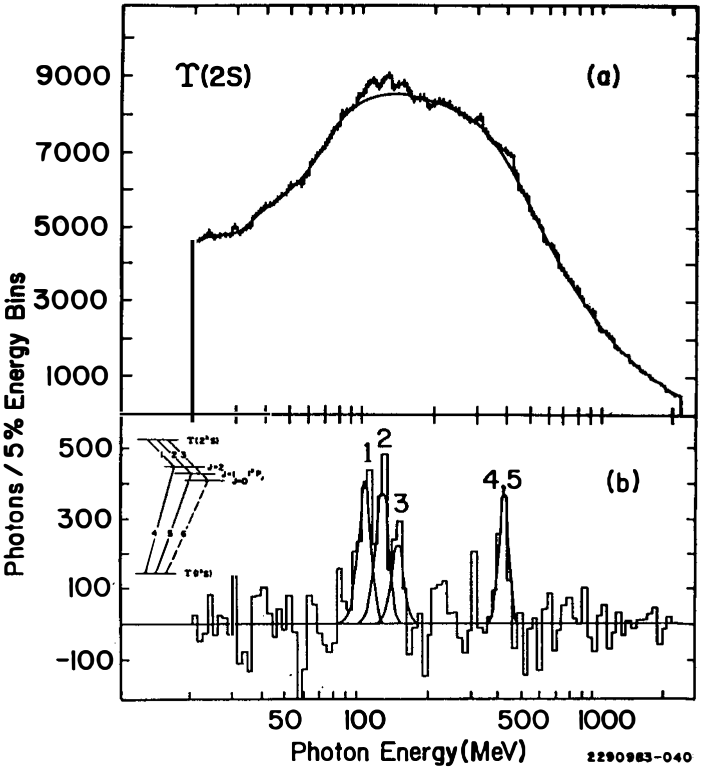


Fig. 3a, b. CUSB inclusive photon spectrum.

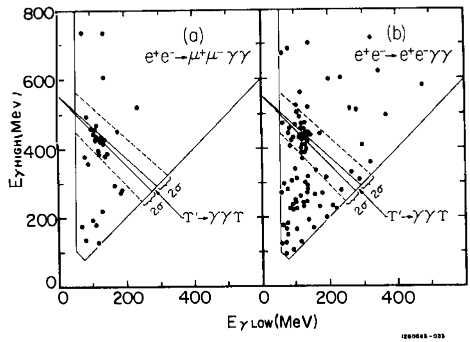


Fig. 4. CUSB exclusive photon results.

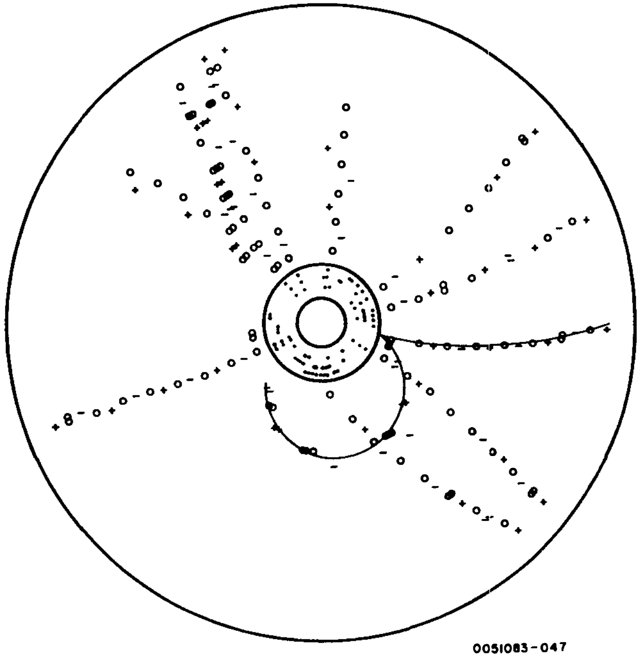


Fig. 5. Example of photon conversion in the CLEO drift chamber

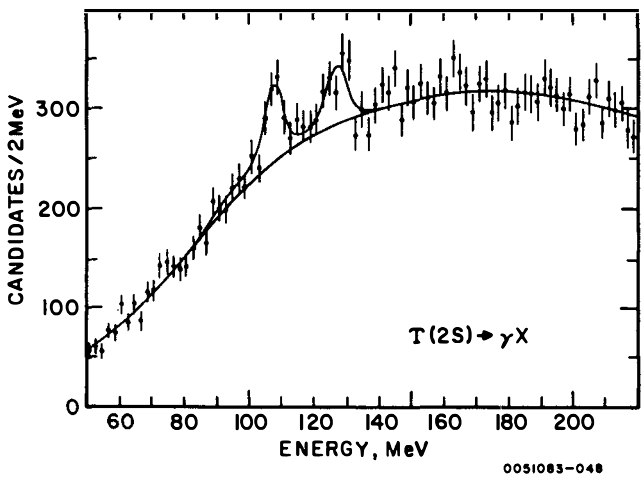
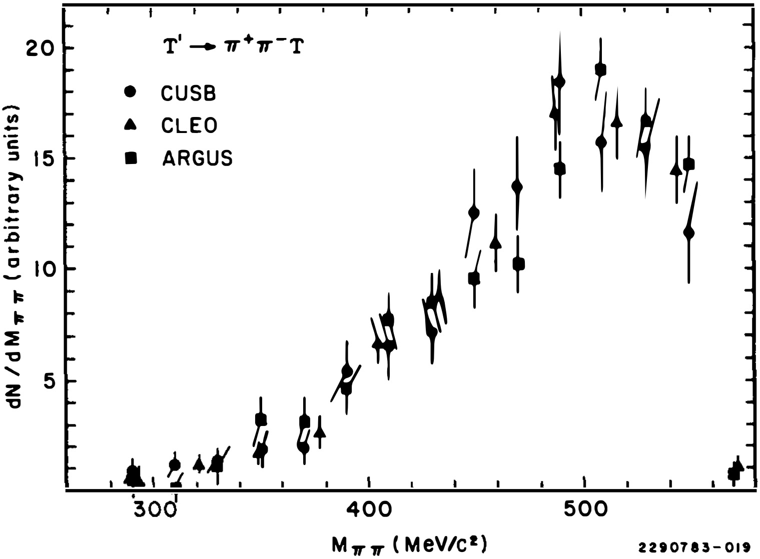


Fig. 6. CLEO inclusive photon spectrum



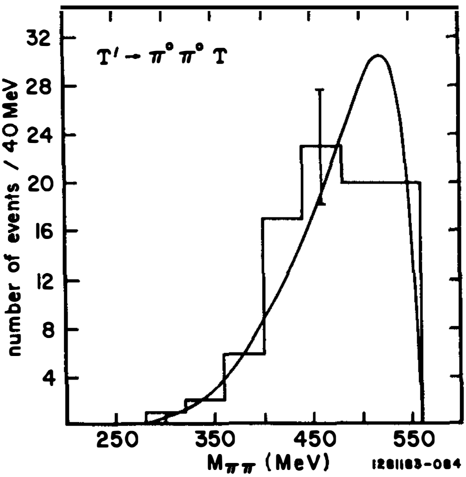


Fig. 7a, b. Dipion mass distribution from the reaction a) $\Upsilon(2S) \to \Upsilon(1S)\ \pi^+\pi^-$ and b) $\Upsilon(2S) \to \Upsilon(1S)\ \pi^o\pi^o$.

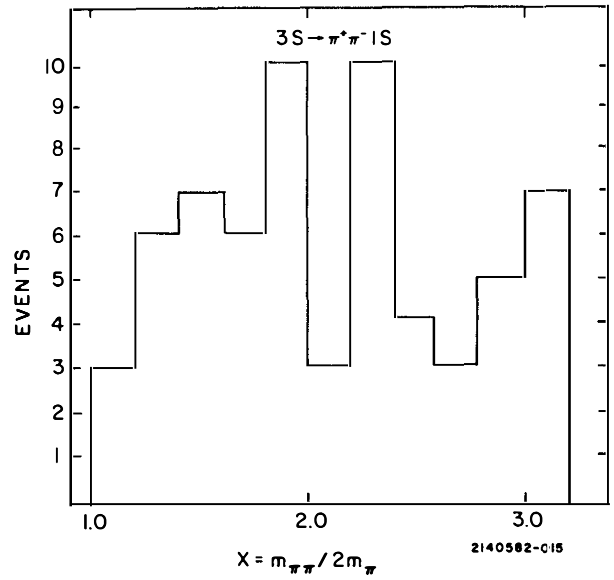


Fig. 8 The dipion mass distribution for $\Upsilon(3S) \to \Upsilon(1S)\ \pi^+\pi^-$

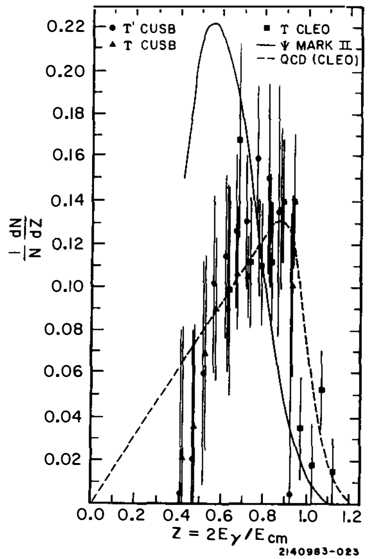


Fig. 9a. Photon spectrum from gluon + gluon + γ process.

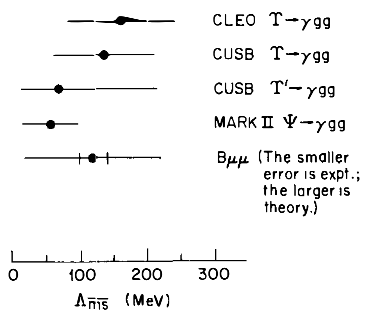


Fig. 9b. $\Lambda_{\overline{MS}}$'s from various processes.

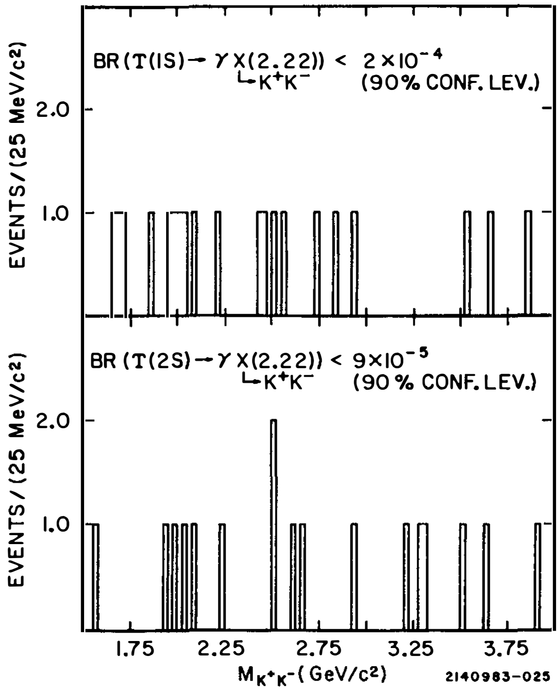


Fig. 10a, b. Invariant K^+K^- mass after 4 constraint fit.

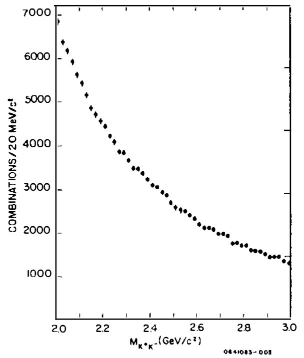


Fig. 11. Two body invariant mass assuming all particles are Kaons. Data was obtained at the Υ(4S).

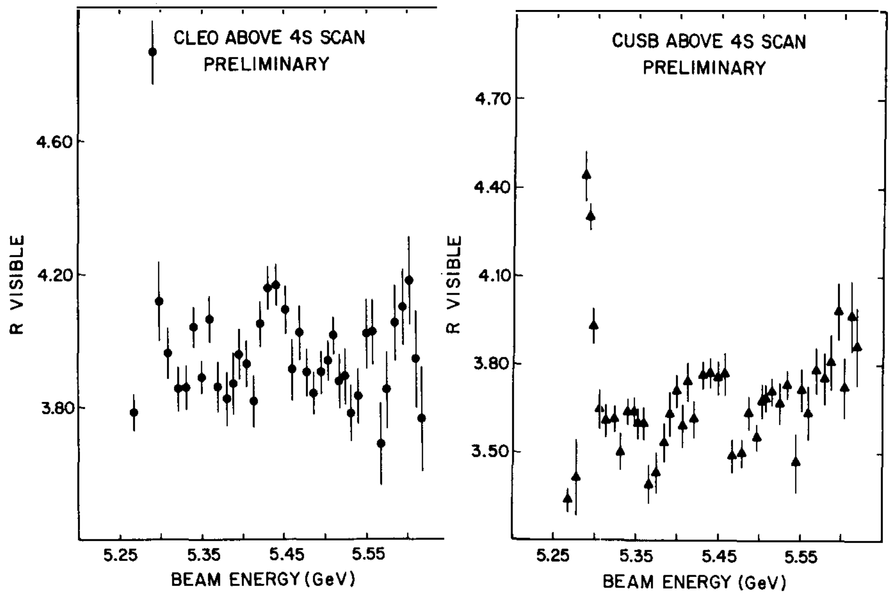


Fig. 12a, b. R visible above the Υ(4S) for CLEO (12a) and Cusb (12b).

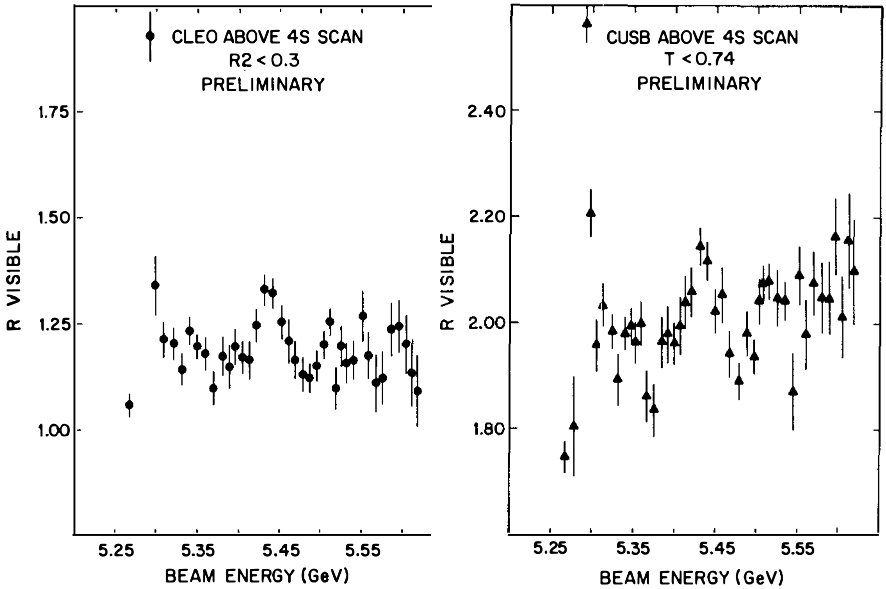


Fig. 13a, b. R visible above the Υ(4S) after enhancing $B\overline{B}$ events.

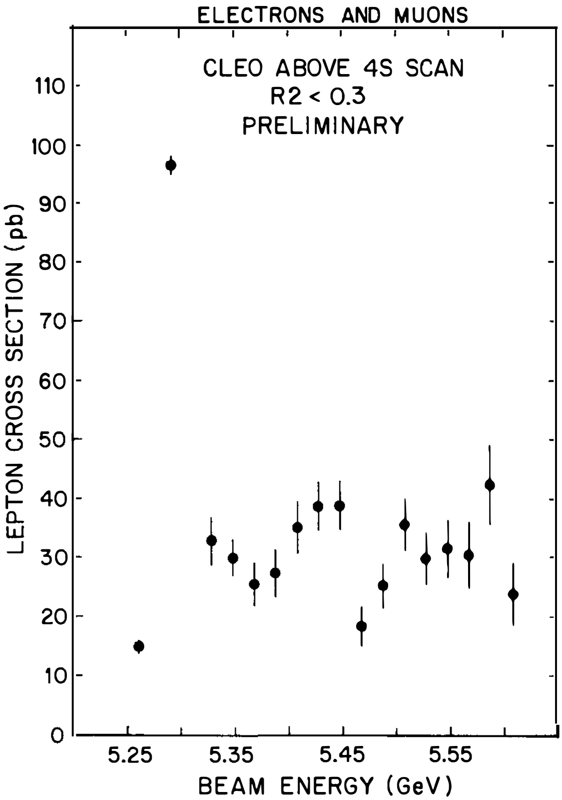


Fig. 14. The inclusive lepton cross section above the $\Upsilon(4S)$ as measured by CLEO.

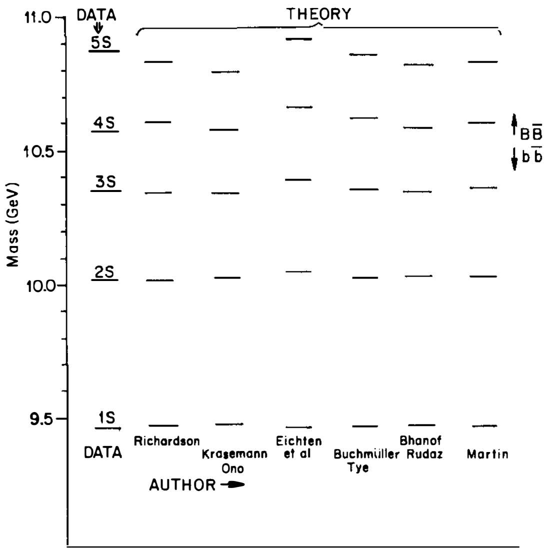


Fig. 15. Various estimates for the energy levels of the Upsilon system.