RECENT RESULTS FROM CESR

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Abstract

Recent experiments on the production and decay of the upsilon states, carried out by the CLEO and CUSB groups at the Cornell Electron Storage Ring (CESR), are described. B-meson decays are shown to agree with the standard six quark model of weak interactions and to disagree with various exotic models, including a general class with no t-quark. Decays of the narrow upsilon states are compared to QCD predictions. A new determination of the QCD scaling parameter yields $\Lambda_{\overline{MS}} = 100^{+34}_{-25}$ MeV.

I. Introduction

Early results[1] from CESR obtained by the CLEO[2] and CUSB[3] groups showed four resonant states at energies close to 10 GeV. These are the first four ^3S states of the b quark and $\bar{b}$ antiquark. The first three states are narrow, bound states of the $b\bar{b}$ system. The fourth is a broad resonance indicating the opening of the strong decay into B and $\bar{B}$ mesons. The present values of the cross sections for $e^+e^- \to$ hadrons measured by the CLEO group is shown in Fig. 1, where these four states are clearly seen. No other resonances have been observed and in a later section I will report limits on the cross sections for other resonances.

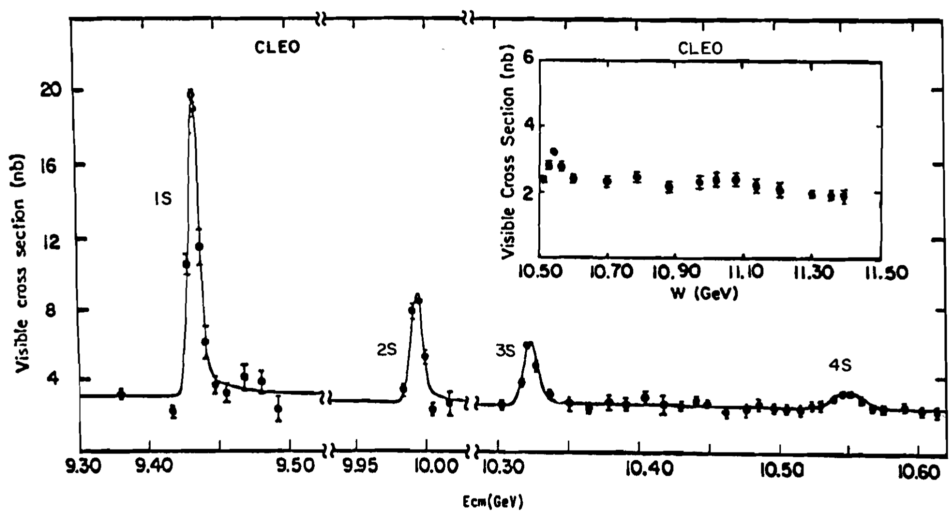


Fig. 1: Total cross sections for $e^+e^- \to$ hadrons (CLEO). The data contains about 60,000 hadron events and an integrated luminosity of 16000 nb^{-1}

The narrow resonances provide a very useful system for the study of heavy quark dynamics. Their masses and leptonic widths have been shown to agree with calculations based on QCD inspired potentials.(4) Comparison of the J/ψ and upsilon states have shown the potentials to be flavor independent.(4) There is much to be learned about QCD from the decay of these states and that will form part of this report.

The Υ(4S) state is a resonance in which free B and $\bar{B}$ mesons are produced nearly at rest. The decay of B-mesons provides important information on the structure of the electroweak theory. Does the B-decay as expected from the standard six-quark model? How is the b-quark coupled to the other quarks? The properties of B-decay and the answers they provide to such questions will comprise the major part of this report.

The particular topics which I intend to discuss are listed below:

1. <u>B-Meson Decay and Comparison with Various Models</u>

   Inclusive properties of B-meson decay
   Semileptonic branching ratios
   Dileptons: Limits on flavor changing neutral currents
   K^0 and $K^\pm$ yields from B-decay
   Limits on B* production
   Search for exotic decays

2. <u>Decay of Narrow Resonances – Comparison with QCD</u>

   $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$
   $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$
   $\Upsilon(1S) \to \mu^+\mu^-$ – Determination of $\Lambda_{\overline{MS}}$
   $\Upsilon(2S) \to \mu^+\mu^-$
   $\Upsilon(1S) \to ggg$

3. <u>Baryon ($p,\bar{p}$ and $\Lambda,\bar{\Lambda}$) production</u>

4. <u>Total Cross Sections</u>

Other recent results from CESR are reported by D. Schamberger in his survey of the spectroscopy of heavy quark systems.(5)

II. The Detectors

The CLEO and CUSB detectors have been described elsewhere(6) and I will review only very briefly their main characteristics. Their principle components are shown in Figs. 2 and 3. CLEO is a magnetic detector with various tracking

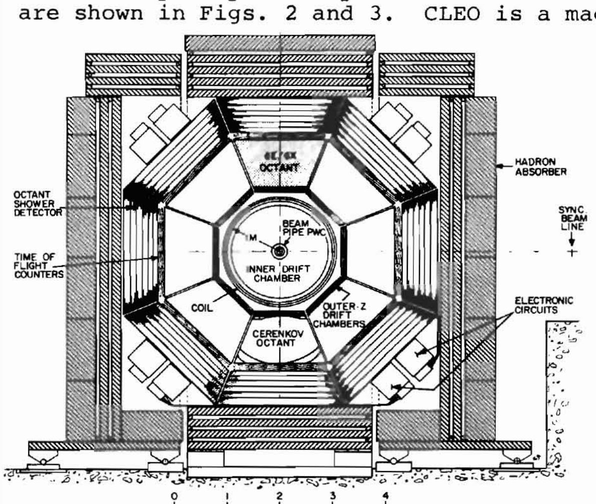


Fig. 2: The CLEO detector

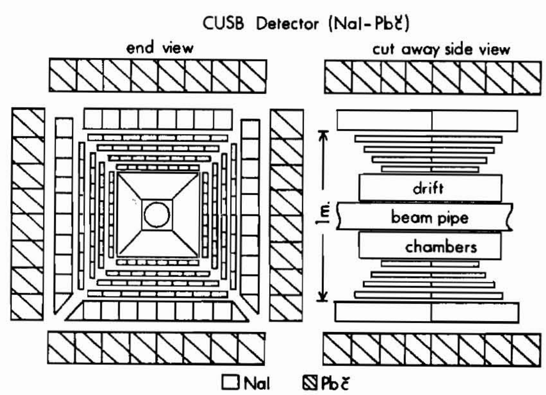


Fig. 3: The CUSB detector

devices inside an aluminum solenoid. Outside the solenoid are tracking and particle identifying detectors. CUSB is a non-magnetic detector. It consists of tracking chambers and NaI and lead glass counters for precision electromagnetic calorimetry. Some of the characteristics and capabilities of the detectors will become clear as the results are discussed.

III. B-Meson Decay

In the standard model[7] of weak decays, six quarks are assigned to the three left-handed doublets

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

The b-quark has charge -1/3e and decays by $b \to W^- u$ or $b \to W^- c$. The ratio of these couplings depends on the mixing of the b-quark with the other quarks and is an important parameter of the theory.

A simple and useful picture of B-decay is provided by the spectator model, in which the b-quark decays as shown in Fig. 4.

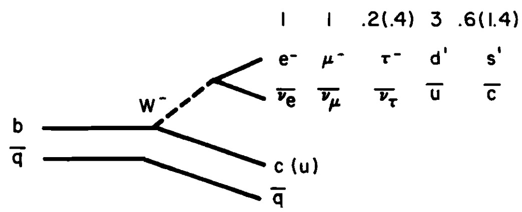


Fig. 4: b-quark decay in the spectator model. The numbers are phase space X color factors for $b \to c$. The numbers in parenthesis are for $b \to u$.

In this picture the light quark, $\bar{q}$, plays no active role. The numbers shown are proportional to the relative probabilities for decay into the channels shown for $b \to c(u)$, assuming these probabilities are governed by phase space and color factors only.

Several important results follow from this picture. The branching ratio for semileptonic decays, $B \to \ell \nu x$, should be about 17%. The model also suggests that on average there will be about one more K-meson per B-decay when $b \to c$, than when $b \to u$. Thus, K-meson yields from B-decay provide information of the relative probability of these decays. Non-spectator processes will alter these conclusions somewhat. Leveille[8] has studied several of these contributions and finds they are important for some processes. We shall refer to his work when we compare the measurements with the standard six quark model.

I now turn to the measurements on B-decay that have been submitted to the conference. All results on B-decay refer to yields from the $\Upsilon(4S)$ after subtracting the continuum contributions.

a) Inclusive Properties of B-Decay

The CLEO group has measured some of the general features of B-decay; shape distributions, multiplicities and momentum spectra. Each of these clearly signals the onset of a new threshold.

Various shape distributions for $B\bar{B}$ decay and for continuum events are shown in Figure 5. Continuum, refers to the energy region between the $\Upsilon(3S)$ and $\Upsilon(4S)$ where one expects distributions characteristic of two high energy jets. The B-decay distributions are strikingly more spherical than the continuum. They agree well with what one would expect from the decay of two low momentum particles of 5 GeV mass.

Let me digress briefly for some remarks on $B\bar{B}$ production at energies above the $\Upsilon(4S)$.

$B\bar{B}$ cross sections at energies above the $\Upsilon(4S)$ can be estimated by comparing the shape distributions at these energies with the $B\bar{B}$ and continuum distributions.

CLEO finds 6.5±2±2% $B\bar{B}$ events, corresponding to $\Delta R = 0.26\pm.12$. Direct measurements of ΔR by CLEO yield $\Delta R = 0.20\pm.08$. CUSB finds $\Delta R = 0.29\pm.06$. From lepton yields, CLEO finds $\Delta R = 0.42\pm0.16$. This increase is consistent with what one expects for a charge 1/3 quark.

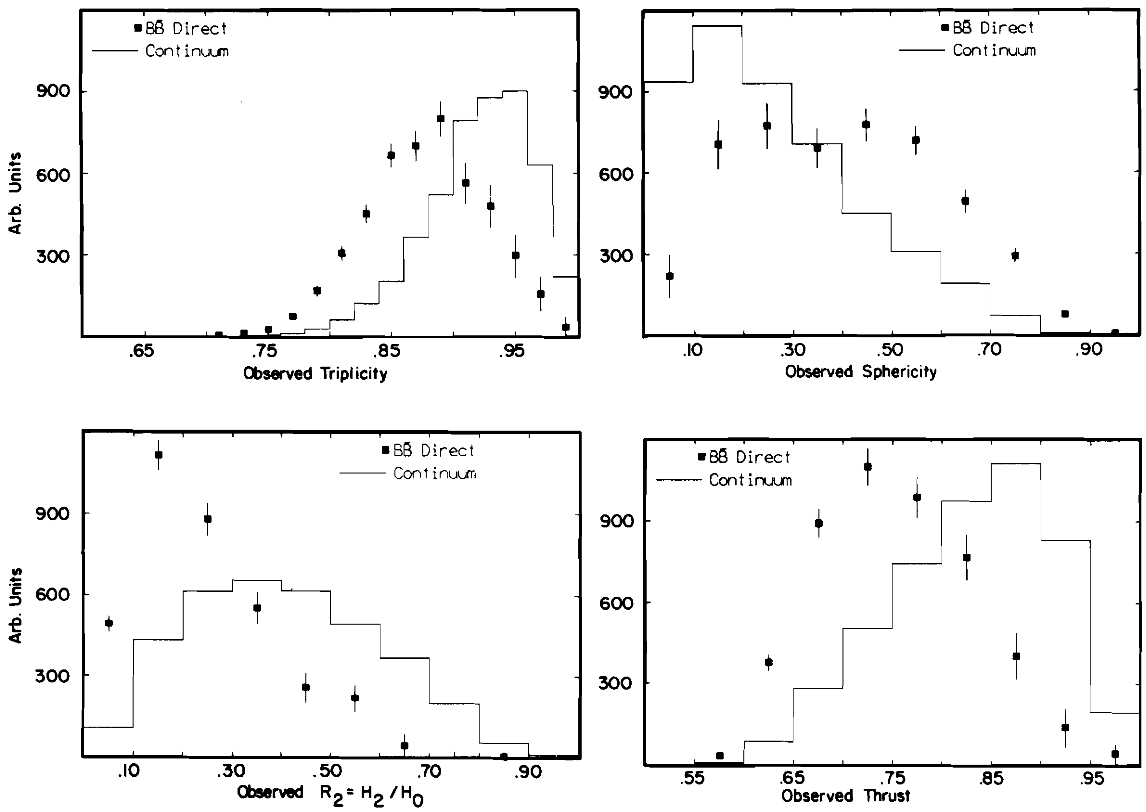


Fig. 5: Various shape distribution for $B\bar{B}$ decay and for continuum events.

Charged multiplicity distributions for continuum events and $B\bar{B}$ decay are shown in Fig. 6.

True multiplicities are determined using a Monte Carlo similar to that developed at LUND[9]. The average charged multiplicities per event, determined from the Monte Carlo simulations are:

$$\langle N_{ch} \rangle = 11.6\pm0.4 \qquad B\bar{B}\ \text{decay}$$

$$\langle N_{ch} \rangle = 8.3\pm0.4 \qquad \text{Continuum}$$

Multiplicity distributions for events in which one of the B-mesons has decayed semileptonically are shown in Fig. 7. From the data of Figs. 6 and 7, we can determine separately the average multiplicities for semileptonic

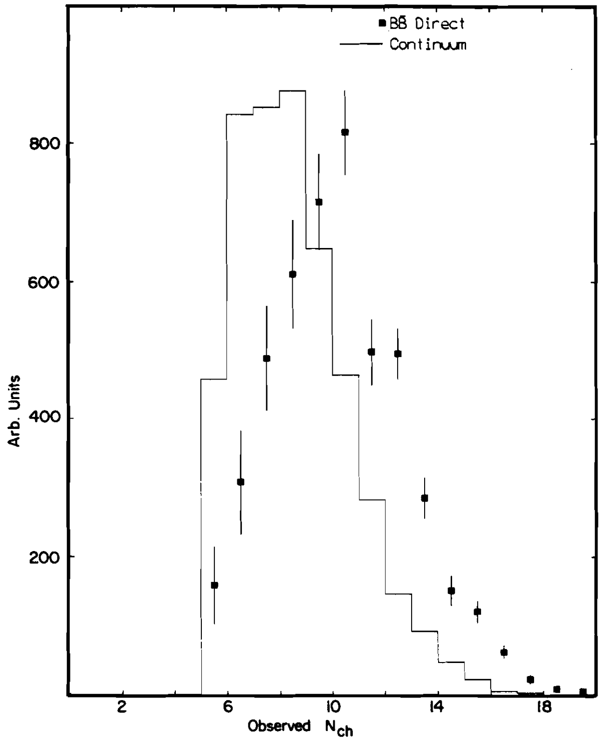


Fig. 6: Charged multiplicities for $B\bar{B}$ decays and for continuum events.

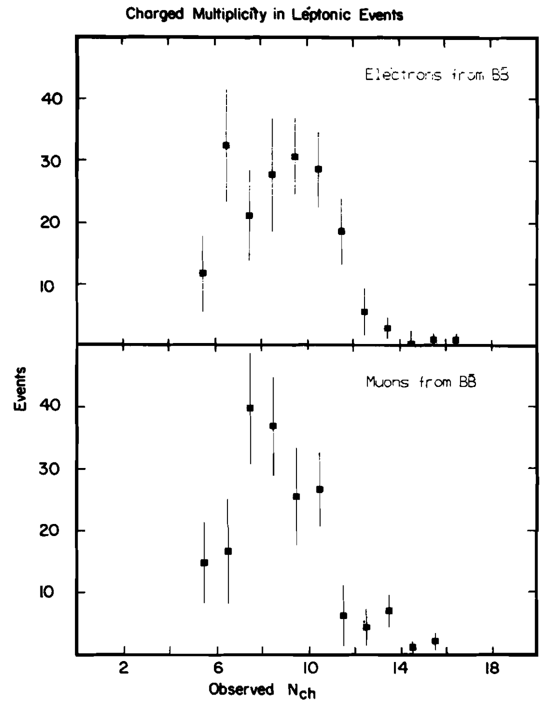


Fig. 7: Charged multiplicity distribution in $B\bar{B}$ decays when one B decays semi-leptonically.

and for nonleptonic decays of the B-mesons with the results

$$\langle N_{ch} \rangle = 3.50 \pm 0.35 \qquad \text{semileptonic decay}$$

$$\langle N_{ch} \rangle = 6.31 \pm 0.35 \qquad \text{hadronic decay}$$

If we subtract the lepton's charge, the average number of charged hadrons in semileptonic decay is 2.5±0.3. SPEAR data show[10] that an equal mixture of D and D* decays into an average of 2.5±0.1 charged hadrons. The above multiplicities suggest the following picture of B-decay:

$$B \rightarrow \ell\nu(D \text{ or } D^*) \qquad \text{in semileptonic decays}$$
$$B \rightarrow D + 4\pi^{\pm} + 2\pi^{0} \qquad \text{in hadronic decays}$$

Inclusive momentum distributions of charged particles from B-decay are shown in Figure 8. The continuum data agrees with what one expects, from scaling laws, for the decay of a particle of mass 10 GeV. The steeper slope of the $B\bar{B}$ distribution (ignore the "bump" at X = 0.3 due to leptons from semileptonic decay) agrees with the scaling result for decay of a 5 GeV particle. A nice demonstration that "$B\bar{B}$" events are, in fact, coming from decay of 5 GeV objects.

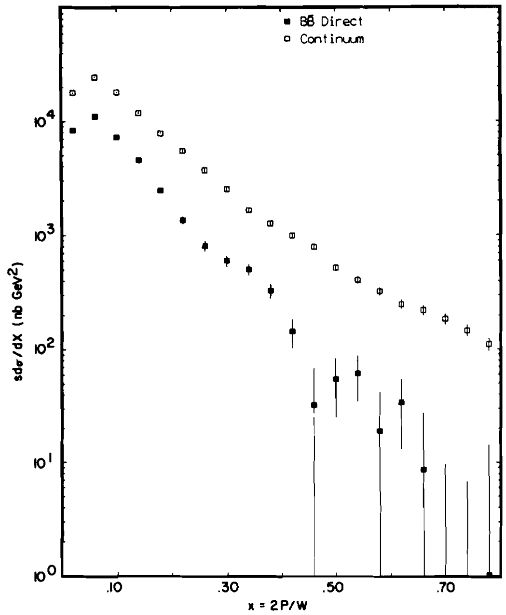


Fig. 8: Fractional momentum distribution for continuum and $B\bar{B}$ data. The bump at X = 0.3 in the $B\bar{B}$ data is due to leptons from semi-leptonic decays.

b) Semileptonic decays of the B-meson

There are new measurements of the semileptonic branching ratio $B \to e\nu x$ from both CLEO and CUSB. Criteria for identifying electrons in both detectors have been discussed in previous papers[11] and though some refinements have been added the techniques remain basically the same.[12]

Figures 9 and 10 show the visible inclusive cross section for production of electrons with momenta greater than 1 GeV.[13] One sees a large increase at the Υ(4S), attributed to the semileptonic decay of B-mesons.

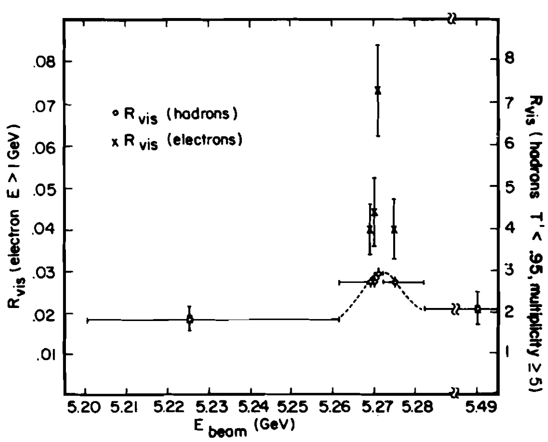


Fig. 9: R for electrons and hadrons (CUSB).

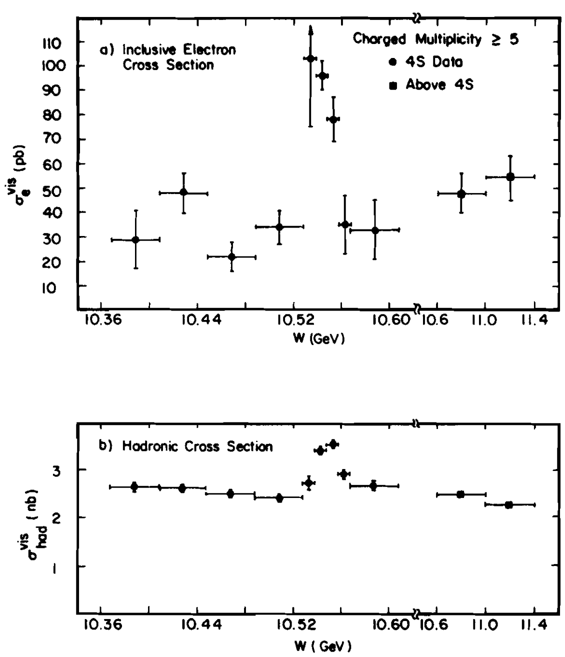


Fig. 10: Visible cross section for electrons and hadrons (CLEO).

The spectra of the electrons from the $\Upsilon(4S)$, after subtracting the continuum background, are shown in Fig. 11. The curves result from Monte Carlo calculations of the electron spectrum for various assumptions about the mass of the hadrons in the decay. The CLEO data are well fit by the assumption that $B \to e\nu DX$, where $M_{DX} = 2.2$ GeV. The CUSB data prefer $M_{DX} = 1.8$ GeV. They would both probably tolerate $M_{DX} = 2$ GeV.

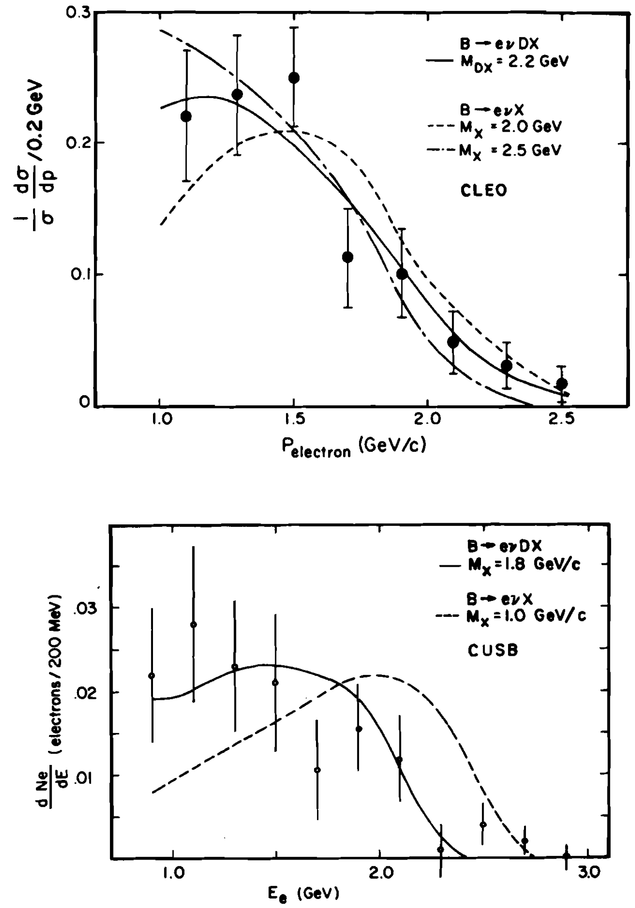


Fig. 11: Momentum distribution of electrons from B-decay. The curves are Monte Carlo calculations for various assumptions about the mass of the hadrons in the decay.

CLEO has also measured the semileptonic branching fraction for decay into muons, $B \to \mu\nu x$. The inclusive muon cross section is shown in Fig. 12. One sees a large increase in the cross section at the $\Upsilon(4S)$, similar to that for electrons.

The continuum subtracted momentum spectrum of the muons is seen in Fig. 13. The spectrum is different than the electron spectrum because some of the muons with momenta less than 1.8 GeV are absorbed in the iron. The curve shown is calculated for $B \to \mu\nu x$ with $M_x = 2.0$ GeV. The data will accommodate any value of M_x between 1.5 GeV and 2.0 GeV.

To determine the semileptonic branching ratios, we must include a correction for the unobserved low momentum electrons, $p < 1$ GeV. This correction depends on the mass of the hadrons. The fraction of observable electrons ($p > 1$ GeV) is 0.72 for $M_x = 2.0$ GeV and 0.62 for $M_x = 2.5$ GeV. The systematic errors quoted in the results shown in Table I include the uncertainty in this

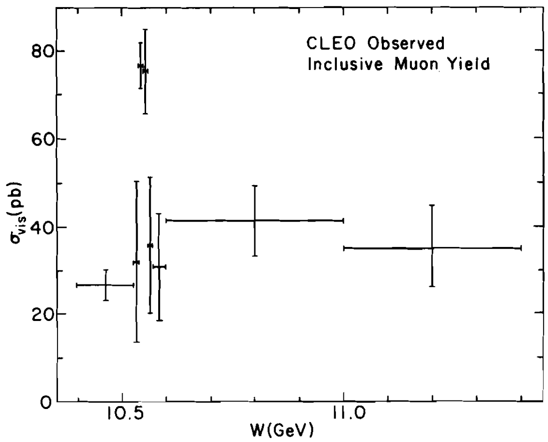


Fig. 12: Inclusive muon cross sections vs. energy (CLEO).

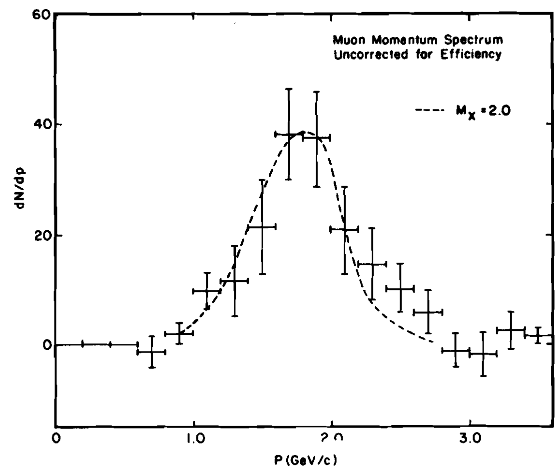


Fig. 13: Observed muon spectrum from B-decay not corrected for efficiency vs. momentum (CLEO)

correction. Electrons from D-decay, about 8% of the total, have been subtracted.

TABLE I <u>Branching Ratios for Semileptonic Decay of the B-meson</u>

	$BR[B \to e\nu x]$	$BR[B \to \mu\nu x]$
CLEO	13.6±2.1±1.7%	10.0±1.3±2.1%
CUSB	13.6±2.5±3.0%	

These branching ratios are somewhat smaller than predicted by the spectator model. They can be brought into agreement either by enhancing the hadron decays relative to the leptons or by non-spectator contributions.(8)

These results apply to some unknown mixture of charged and neutral B-mesons. A major task for the future is to determine the branching ratios of each separately.

The electron and muon spectra are consistent with all $b \to c$ decays, but a small $b \to u$ component cannot be excluded. A quantitative determination of the $b \to c/b \to u$ ratio can only be made from these data in a model dependent way. Unequivocal evidence for $b \to u$ can be obtained by observing leptons with momenta greater than allowed by the decay $B \to D\ell\nu$, an effort now underway.

c) <u>Dilepton Events – Limit on Flavor Changing Neutral Current Decays</u>

A number of events with two leptons (P>1 GeV) have been observed in CLEO. Such events are expected from the semileptonic decay of both the B and $\bar{B}$. A more exciting possibility is that they arise from the decay $B \to \ell^+\ell^- x$. Several authors(14) have discussed models without t-quarks in which such decays are allowed. Kane and Peskin(15) have shown that if the b-quark is assigned to a singlet and if it decays through the $W^\pm$ and Z^o, neutral current decays must satisfy

$$r = \frac{\Gamma(B \to \ell^+\ell^- x)}{\Gamma(B \to \ell\nu x)} > 0.12$$

independently of the number of quarks with which the b can mix. The CLEO results are shown in Table II.

TABLE II Dilepton Events from B-decay

	ee	eμ	μμ	Total
observed	5	5	0	10
"expected"	3.04	6.08	3.04	12.16

The "expected" numbers assume that dilepton events arise only from the semileptonic decay of both the B and $\bar{B}$.

These results lead to the limit on neutral current decays,

$$Br(B \to \ell^+\ell^- x) \leq 0.74\% \ (90 \text{ CL.})$$

Combining this with the measured semileptonic branching ratios we find r < 0.08, ruling out these topless models at better than the 90% confidence level.

Two events in which a pair of high energy electrons whose mass is consistent with J/ψ have been observed. One of these events is shown in Fig. 14. Assuming these two events arise from B → Ψx, we deduce a branching ratio of about 4% for inclusive decays of the B-meson to J/ψ.

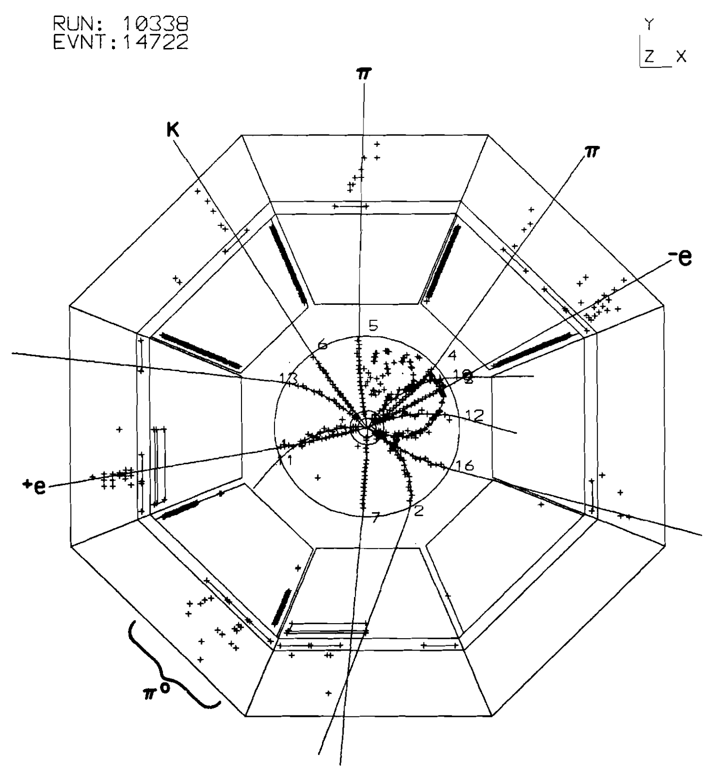


Fig. 14: Possible decay B → ψx. The mass of the e+e- is 3.15±0.15 GeV. The particles labeled K or π are identified by time-of-flight, DE/DX measurements, or both.

d) Kaon Yields from B-decay

As discussed previously in this report, kaon yields from B-decay provide information on the b-quark couplings, particularly on the question of how often $b \to c$ or $b \to u$. New measurements of neutral and charged kaon cross sections by CLEO and CUSB shed some light on this question. I describe the K^o results first.

Neutral kaons are identified by their decay, $K^o_s \to \pi^+\pi^-$. In CLEO, K^o candidates require two drift chamber tracks of opposite sign with a net momentum P>0.3 GeV/c, and a secondary vertex at least 7 mm from the beam line. A typical mass distribution for such pairs of tracks is plotted in Fig. 15, showing a prominent peak at the kaon mass. The efficiency for detecting $K^o_s \to \pi^+\pi^-$, determined from Monte Carlo studies, varies from about 15% for P = 0.3 GeV to 23% for P>0.8 GeV. The data presented here contain about 2600 K^o's.

CUSB also requires a pair of particles which form a secondary vertex. Having no magnetic field, the mass of the pair is not reconstructed. Various geometric and kinematic cuts are applied to enhance the signal. The average efficiency for detecting $K^o_s \to \pi^+\pi^-$ is 7.5%. Backgrounds are about 25% and are determined from events which form vertices on the wrong side of the beam line. Contamination from Λ^o is calculated to be less than 5%.

Fig. 16 shows the continuum inclusive K^o spectrum measured by CLEO. The results fall on the usual scaling curves. Fig. 17 shows the K^o cross sections measured by CUSB. The K^o cross sections follow the

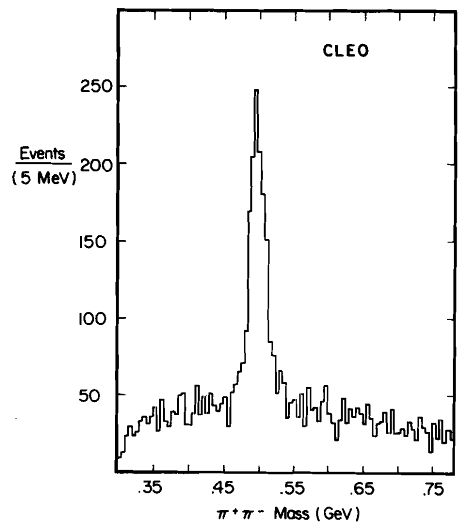


Fig. 15: $\pi^+\pi^-$ mass (GeV). The full data contains about 2600 K^o's

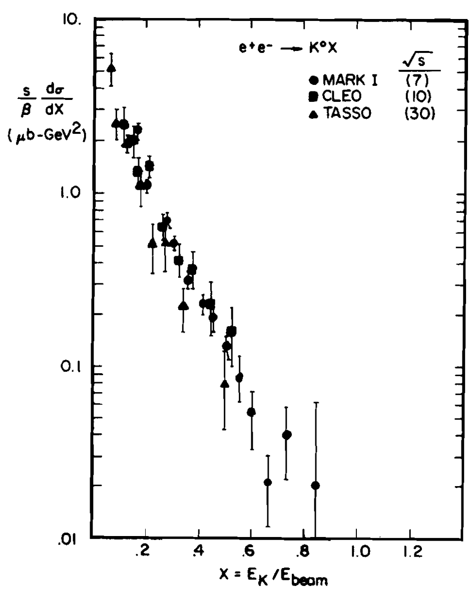


Fig. 16: Inclusive K^o fractional energy distribution for various experiments. Continuum data.

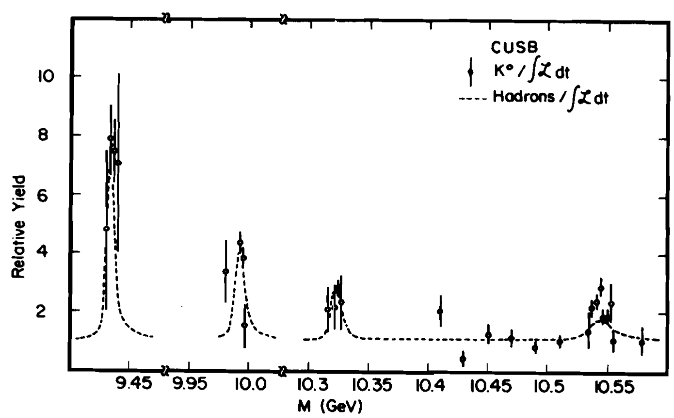


Fig. 17: K^o cross sections as a function of center of mass energy. The dotted curve is the hadron cross section. There are 1050 K^o's in this data.

total cross section except at the $\Upsilon(4S)$ where the K^o cross sections rise more steeply than the total cross sections.

Figure 18 shows the K^o and $K^{\pm}$ cross sections measured by CLEO in the

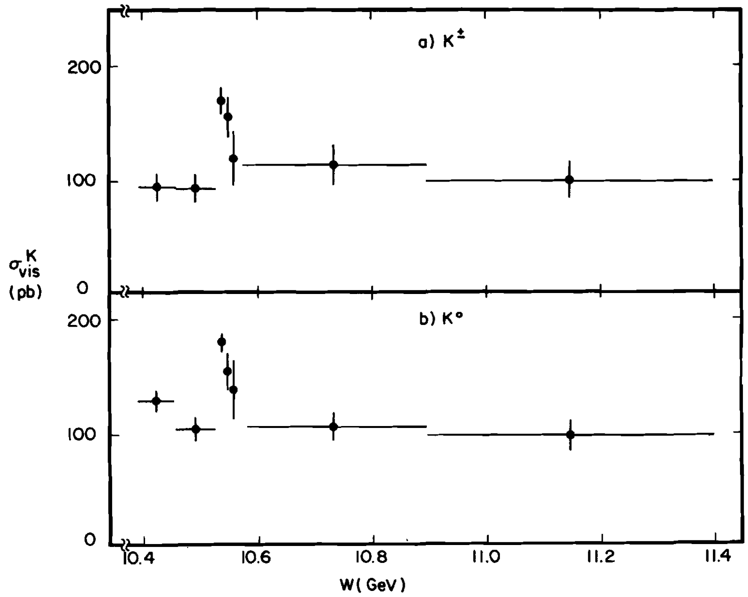


Fig. 18: $K^{\pm}$ and K^o cross sections as a function of energy (CLEO)

neighborhood of the $\Upsilon(4S)$. The kaon cross sections increase about a factor of two at the $\Upsilon(4S)$. Since $\sigma(e^+e^- \to B\bar{B})$ is about equal to $\sigma(e^+e^- \to D\bar{D}x)$ at the $\Upsilon(4S)$, and since most kaons in the continuum come from D-decay, the factor of two increase in kaon cross section suggests that B-mesons almost always decay to D-mesons.

These considerations can be made more quantitative. In Table III we show the measured K's/event and the Monte Carlo calculations for $b \to c$ and $b \to u$. The

TABLE III <u>Comparison of Kaon Yields with Monte-Carlo</u>

Data	# of Kaons/event		
	K^o CLEO	$K^{\pm}$ CLEO	K^o CUSB
Continuum	0.73±0.05	1.12±0.16	0.82±0.08
$B\bar{B}$ Decay	1.43±0.25	2.02±0.25	1.52±0.20
$R = \frac{B\bar{B}\text{ Decay}}{\text{Continuum}}$	1.96±0.34	1.80±0.32	1.85±0.30
Monte Carlo: $\frac{1}{2}(K^{\pm} + K^o)$			
Continuum	0.90		
$B\bar{B}$ $b \to c$	1.60	R = 1.78	
$B\bar{B}$ $b \to u$	0.90	R = 1.00	

charged kaon cross sections are about a factor of 1.5 greater than the neutral kaons. This seems likely to be an error in the detector efficiency for one of the two measurements. In order to desensitize our conclusions to normalization errors, we compare calculated and measured results for R, the ratio of K's/event at the $\Upsilon(4S)$ and in the continuum. The value of R is the same for neutral and charged K's.

The data are in good agreement with the Monte Carlo calculations for $b \to c$. The calculated value of R is not sensitive to the model. Including the non-spectator terms of Leveille,(8) or changing the $s\bar{s}$ component of the fragmentation within reasonable limits, has little effect on the calculated value of R.

Thus far, we have observed that qualitatively the data agree with Monte Carlo results for $b \to c$. To make this somewhat more quantitative, we write

$$R_{meas} = fR(b \to c)_{mc} + (1-f)R(b \to u)_{mc}$$

where f = fraction of $b \to c$ decays and the subscripts refer to measured and Monte Carlo calculated results. Using values of R_{meas} and R_{mc} from Table III, we find

$$f = 1.12 \pm 0.25$$

The kaon yields are consistent with $b \to c$.

e) K-lepton and K,K events from B-decay

Events with both a kaon and a lepton as well as events with two kaons have been studied by the CLEO group. The cross sections for the K-lepton events are shown in Fig. 19. The number of K-lepton and K,K events observed in B-decay are

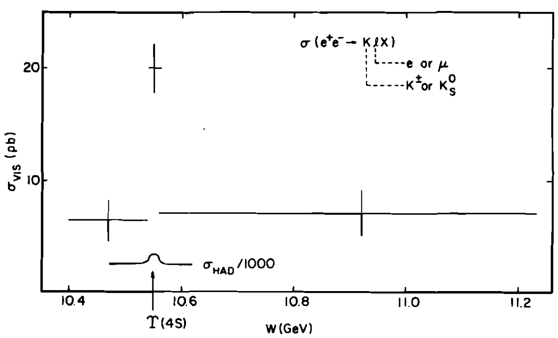


Fig. 19: Visible cross sections for K-lepton events (CLEO).

given in Table IV together with Monte Carlo calculations for the number of such events expected when $b \to c$ and when $b \to u$. This data, also, is consistent with

TABLE IV Comparison of K-lepton and KK yields with Monte Carlo

	K-lepton events	(K,K) events
$B\bar{B}$ data	36.1±11.0	55±16
$B\bar{B}$ Monte Carlo ($b \to c$)	39.4	36.6
$B\bar{B}$ Monte Carlo ($b \to u$)	13.0	22.8

all $b \to c$. From the K-lepton yields, together with the kaons per B-decay (Table III), we can deduce the average number of kaons per B-decay for both semileptonic and nonleptonic decays. We find an average of 2.0±0.3 kaons per nonleptonic B-decay and 0.8±0.7 kaons per semileptonic B-decay. The number of kaons per semi-leptonic decay is expected to be about 1.0 for $b \to c$ and close to zero in $b \to u$.

The error in this measurement is too large to be useful as yet.

In summary, there are no surprises, as yet in B-decay. All the data agree with the predictions of the standard model. The semileptonic branching ratio is easily accounted for. The expectation that $b \to c$ dominates has been amply demonstrated. We cannot, however, demonstrate a non-zero probability for $b \to u$. Observation of $b \to u$ would rule out models(16) in which the b and c quarks form a right handed doublet, or any model in which the b-quark doesn't couple to the u-quark.

f) Search for B* production

In our discussion thus far, we have not distinguished between B and B*. If $M_{B^*} < M_B + M_\pi$, as expected, the B* should decay almost 100% of the time by $B^* \to \gamma B$. The CUSB group has looked for the monoenergetic photons from this decay. The observed photon spectrum, after subtracting the continuum contribution, is shown in Fig. 20. The shaded area shows what would be expected for one B*/event, assuming the photon energy is 50 MeV. From this data, they set a limit of

$$\frac{\Upsilon(4S) \to B^*B}{\Upsilon(4S) \to \text{all}} < 0.20$$

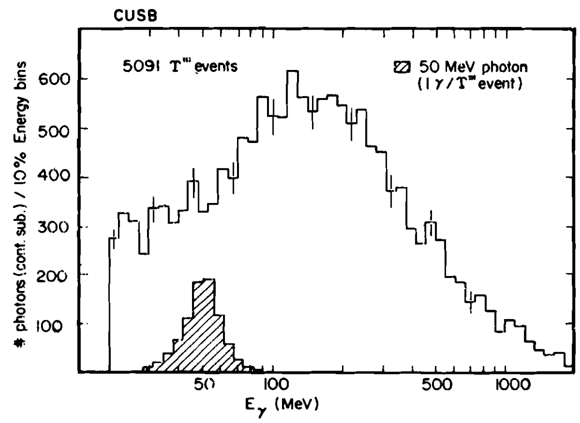


Fig. 20: Photon spectrum at the $\Upsilon(4S)$ (CUSB). shaded area is expected number of 50 MeV photons for one B*/event.

g) Search for Exotic Decays of the B-meson

Various models have been proposed in which the b-quark does not decay via $W^\pm$ or Z^0, but through emission of an exotic boson. These models lead to two classes of decays:

Class I	Class II
$b \to q\ell_i\ell_j$	$b \to \bar{q}\bar{q}\ell$
$b \to q\ell\ell$	$b \to \bar{q}\bar{q}\bar{\ell}$
$b \to q\bar{\ell}\bar{\ell}$	

where q is a u,d,s, or c quark and ℓ is a charged lepton or neutrino. Class I includes the model of Derwin(17) and Class II that of Georgi and Glashow.(18)

The CLEO group has looked for such exotic decays by measuring the energy carried by charged particles assuming all the charged particles are pions. The exotic decays will show a loss of charged energy either because of the energy carried off by neutrinos as in Class I, or because the mass of copiously produced baryons, analyzed as pions, is missing, as in Class II.

Measured charged energy fractions have been compared with Monte Carlo calculations in which events are generated with the maximum charged energy allowed by the model. The measured charged energy fractions and the Monte Carlo calculations for Class I and II decays are shown in Table V.

TABLE V Charged Energy Fractions

	Data		Monte Carlo
Continuum	0.625±0.003	Exotic I	<0.47
Υ(4S)	0.618±0.003	Exotic II	<0.54
$B\bar{B}$	0.601±0.01±0.02		

It is clear that these exotic decays cannot account for all of the decays of the B-meson.

The CLEO group has also looked for the b-quark to decay into a light charged Higgs particle via

$$b \to q h^- \quad \lfloor\!\to \tau\nu \text{ or } \bar{c}s$$

in which h^- is a real charged Higgs boson with mass $m_\tau < m_h < m_b$. We assume the b-quark decays most of the time as shown, as would be expected for a Higgs of this mass. We find that this model is excluded for any division between the two channels, $\tau\nu$ or $\bar{c}s$, either because the lepton yield is inconsistent with the data or because there is too much missing energy. The charged energy fraction, P_c versus the measured semileptonic branching fraction, f_μ is plotted in Figure 21.

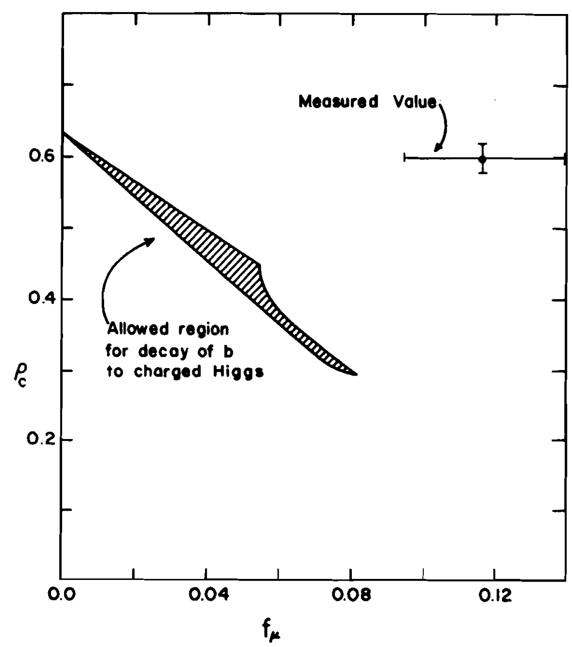


Fig. 21: Charged energy fraction "ρ_c" versus semileptonic branching fraction for e's or μ's. The point is the measured value (CLEO). The shaded region is that allowed for the Higgs' Decay model.

The shaded region, allowed by the model, is far from the measured point and is clearly ruled out by the data.

This concludes my discussion of B-meson decay. I turn now to the decays of the narrow resonances.

V. Upsilon Decays

a) Hadronic Transitions

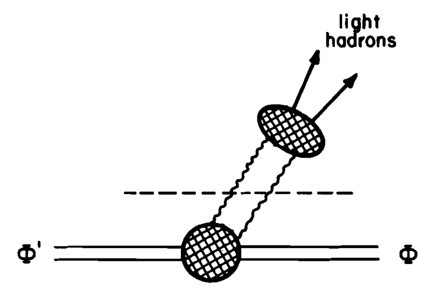
Hadronic transitions between the bound states of the heavy quarks provide important information about their dynamics. There is a very rich spectroscopy in these transitions whose study we have only begun. However, a beginning has been made which already tests important ideas in QCD. I want to describe some of these results.

We have measured branching ratios for the decays

$$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$$
$$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \qquad (1)$$

In QCD these processes take place by the emission of soft gluons which subsequently convert into hadrons. This process is depicted in Fig. 22.

Fig. 22: Hadronic transitions in QCD. Quarks emit gluons which subsequently convert to hadrons.



Perturbative QCD is not expected to be reliable for soft gluon emission; a different approach must be used.

Following a suggestion of Gottfried(19), Yan(20) and subsequently, Kuang and Yan(21) have developed a formalism for calculating such processes. They make a multipole expansion of the gluon field, in the same spirit as the multipole expansion for electromagnetic transitions. The small parameter in the expansion is the size of the heavy quark state compared to the wavelength of the gluons. As we shall see, the measurements agree well with the calculations based on this expansion.

The CLEO group has determined the branching ratio of $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ by measuring the missing mass recoiling against all oppositely charged pairs of particles, assumed to be pions. The missing mass distribution is shown in Fig. 23. One sees a prominent peak at the mass of the upsilon corresponding to the desired decay. The branching ratio deduced from these measurements is

$$BR[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)] = 19.1 \pm 3.1\%.$$

The calculations of Kuang and Yan for various assumptions about the $b\bar{b}$ potential is shown in Table VI. The agreement between measurement and theory is excellent.

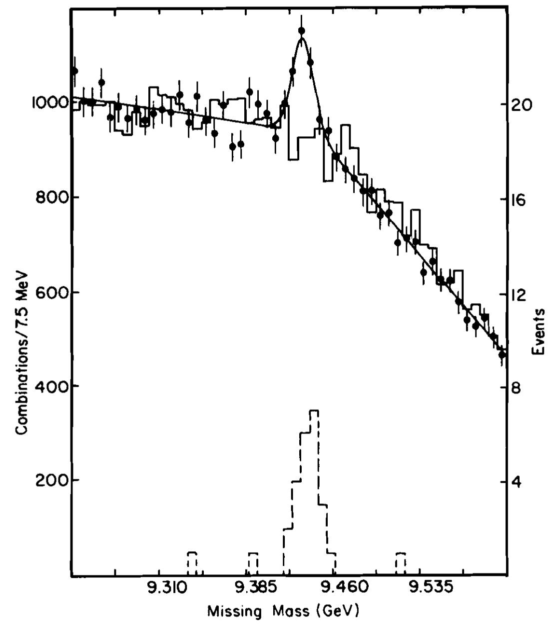


Fig. 23: Mass spectrum recoiling against the pions in $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$. The lower histogram is the mass of the leptons in $\Upsilon(2S) \to \pi^+\pi^- e^+e^-$ (CLEO).

Table VI also shows the comparison with theory for $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$. This branching ratio has been measured by both CLEO and CUSB with the results shown in Table VI. I'll describe these measurements in a moment.

TABLE VI 2π decays of $\Upsilon(2S)$ and $\Upsilon(3S)$

		$BR[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]$	$BR[\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)]$
Measurements:		19.1±3.1%	4.8±1.7%*
Theory:	Model A**	18.0	1.3
	B	19.4	2.0
	C	16.7	3.4

*Average value of CLEO and CUSB measurements

**A,B, and C refer to different $b\bar{b}$ potentials. (See Reference 21).

The agreement between theory and experiment for these decays indicates that the multipole expansion provides a reliable formalism for calculating soft gluon emission. Yan and Kuang have calculated many hadronic decay rates and further tests should be forthcoming in the next year.

b) $B_{\mu\mu}$: Leptonic Decay of the $\Upsilon(1S)$

Among the $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ decays, we observe a number of events in which the $\Upsilon(1S)$ decays leptonically to either e^+e^- or $\mu^+\mu^-$. The missing mass distribution measured by CLEO for these events is shown in the dashed histogram of Fig. 23. The missing mass distribution observed in CUSB is shown in Fig. 24. The branching ratios for the cascade decays determined from these

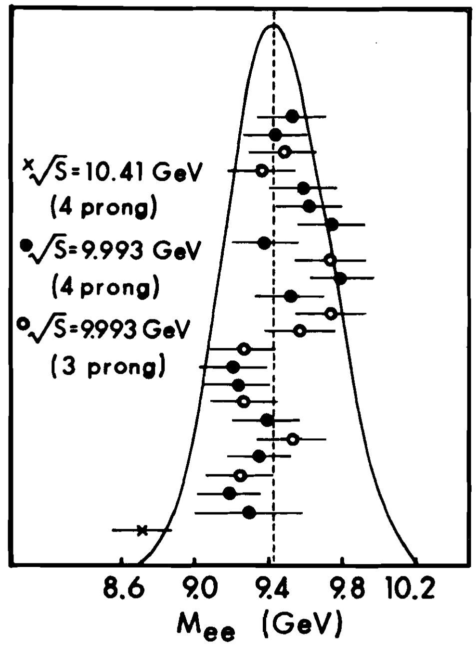


Fig. 24: Invariant mass of the lepton pair in $e^+e^-\pi^+\pi^-$ events.

measurements are:

$$BR[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S) \to \pi^+\pi^-e^+e^-(\mu^+\mu^-)]$$

$$= 0.68\pm0.14\%\ \text{CLEO}$$
$$0.63\pm0.13\%\ \text{CUSB}$$

From this branching ratio and the CLEO result for $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, we obtain the leptonic branching ratios of the $\Upsilon(1S)$, $B_{\mu\mu}$. The results are

$$B_{\mu\mu} = 3.6\pm0.9\%\ \text{CLEO}$$
$$3.2\pm0.8\%\ \text{CUSB}$$

$B_{\mu\mu}$ has also been measured by various groups at DORIS(22). The world average value is $B_{\mu\mu} = 3.3\pm0.5\%$

c) Determination of $\Lambda_{\overline{MS}}$

One of the most important problems of QCD is to determine the running coupling constant $\alpha_s(M)$, or equivalently, the scaling parameter $\Lambda_{\overline{MS}}$. The measurement of $B_{\mu\mu}$ reported in the previous section has been used for a new determination of this parameter.

The ratio of the gluonic and leptonic widths of the $\Upsilon(1S)$, in leading order QCD, is given by

$$\frac{\Gamma_{3g}}{\Gamma_{\mu\mu}} = \frac{1 - \left(3 + R + \frac{\Gamma_\gamma + \text{glue}}{\Gamma_{\mu\mu}}\right) B_{\mu\mu}}{B_{\mu\mu}} = \frac{10(\pi^2 - 9)\alpha_s^{\,3}(M)}{81\pi e_b^{\,2} e_m^{\,2}} \qquad (2)$$

R is the ratio of $e^+e^- \to$ hadrons to $e^+e^- \to \mu^+\mu^-$; $3 + R$ is the correction for the electromagnetic width into quark and lepton pairs.

$\frac{\Gamma_\gamma + \text{glue}}{\Gamma_{\mu\mu}}$ is the correction for the partial width into a photon plus gluons, and e_b is equal to -1/3, the charge of the b-quark.

The new result is that of Lepage and Mackenzie(23) who have calculated the first order QCD correction to this ratio. They find.

$$\frac{\Gamma_{3g}}{\Gamma_{\mu\mu}} = \frac{10(\pi^2 - 9)}{81\pi e_b^{\,2}} \; \frac{\alpha_s^{\,3}(M)_{\overline{MS}}}{\alpha_{em}^{\,2}} \left[1 - \frac{3\beta_o}{2} \ln\,(.48 \pm .01)\; \frac{M_\Upsilon}{M} \; \frac{\alpha_s(M)_{\overline{MS}}}{\pi}\right]$$

$\beta_o = 11 - 2/3\ N_f = \frac{25}{3}$; N_f = number of quark flavors. The first order correction is written in this way to show explicitly that for $M = 0.48\ M_\Upsilon$, the correction vanishes and equation (2) becomes "exact" to this order.

Using the average value of $B_{\mu\mu} = (3.3 \pm 0.5)\%$, Lepage and Mackenzie obtain $\alpha_s(.48\ M_\Upsilon) = 0.152^{+0.012}_{-0.010}$ and $\Lambda_{\overline{MS}} = 100^{+34}_{-25}$ MeV.

This value of $\Lambda_{\overline{MS}}$ is in reasonable agreement with that determined from recent measurements of deep inelastic scattering experiments which were reported to the conference.(24)

d) $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$

In a study of the decay of the $\Upsilon(3S)$, CLEO and CUSB have observed the cascade decay $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \to \pi^+\pi^-e^+e^-(\mu^+\mu^-)$. From these measurements and the value of $B_{\mu\mu}$, one obtains:

$$BR[\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)] = 3.7 \pm 1.9\% \quad \text{CLEO, 5 events}$$
$$= 9.4 \pm 4.7\% \quad \text{CUSB, 4 events}$$

As already noted (Table VI), the average value of $(4.8 \pm 1.9)\%$ is in reasonable agreement with the calculation of Kuang and Yan. This agreement is quite impressive since the width is suppressed by a factor of about forty because of a delicate cancellation in the overlap integral of the $\Upsilon(3S)$ and $\Upsilon(1S)$ wave functions.

e) Leptonic decay of the $\Upsilon(2S)$: $B'_{\mu\mu}$

A measurement of the $\mu^+\mu^-$ yield from decay of the $\Upsilon(2S)$ has been made by the CLEO group. Electromagnetic muon pairs were subtracted using yields from energies close to the $\Upsilon(2S)$. The result:

$$B'_{\mu\mu} \equiv BR(\Upsilon(2S) \to \mu^+\mu^-) = 1.6 \pm 1.0\%.$$

With this information, we can determine the width $\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))$. Gottfried[19] has remarked that the ratio of this width to $\Gamma(\psi' \to \pi^+\pi^-\psi)$ would be very different for the vector and scalar gluons. He estimated that

$$R = \frac{\Gamma(\Upsilon' \to \pi^+\pi^-\Upsilon)}{\Gamma(\psi' \to \pi^+\pi^-\psi)} \begin{array}{l} = 0.1 \text{ for vector gluons} \\ = 1.0 \text{ for scalar gluons} \end{array}$$

The difference arises because the amplitude for the decay is proportional to r, the size of the system, for vector gluons and is independent of r for scalar gluons. We proceed, then, to determine this ratio. From $B'_{\mu\mu}$, $\Gamma_{ee}(\Upsilon(2S)) = 0.52 \pm 0.07$[1], and the branching fraction $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ reported earlier in this paper we calculate

$$\Gamma_{tot}(\Upsilon(2S)) = 33^{+19}_{-13} \text{ KeV}$$

and

$$\Gamma(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)) = 9.3^{+5.6}_{-3.6} \text{ KeV}$$

using the accepted[25] value of

$$\Gamma(\psi' \to \pi^+\pi^-\psi) = 109 \text{ KeV}$$

we find

$$R = 0.085 \pm 0.058$$

Yet another time, the gluon is shown to be a vector particle.

f) Angular Distributions in the 3-gluon decay of $\Upsilon(1S)$

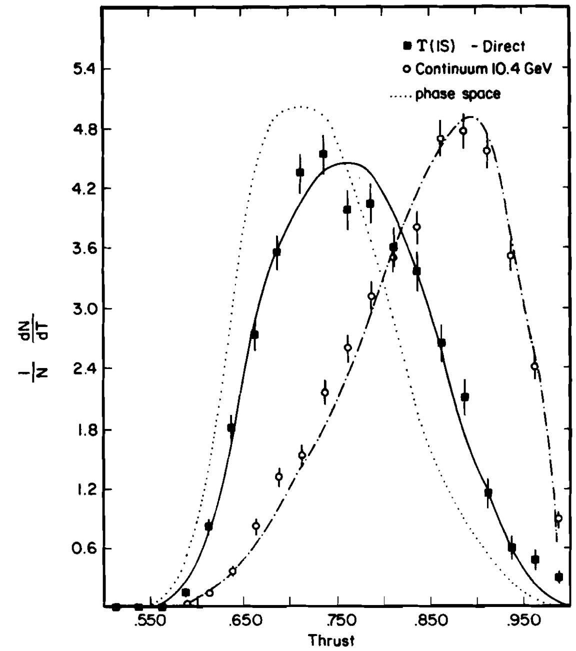
Measurements at DORIS [26,27] established that the event shape distributions of $\Upsilon(1S)$ decay-thrust, sphericity, triplicity, etc. – differed radically from that expected from two quark jets or from decay governed by phase space. The distributions are in reasonable agreement with calculations based on three gluon decay. Measurements at CESR confirm these results. Fig. 25 shows the thrust distribution measured by CLEO. The continuum distribution agrees very well with the Monte Carlo calculations shown in the dashed-dot curve. The $\Upsilon(1S)$ distribution is best fit by a mixture of 75% 3 gluon and 25% phase space. The phase space is probably required to account for more spherical events with four or more gluons. The dotted curve is the Monte Carlo calculation for pure phase space.

The gluon decay distributions depend on the spin of the gluon. The polar angle distribution of the thrust axis is given by QCD[28] as

$$1 + \alpha_T \cos^2\theta \qquad \begin{array}{ll} \alpha_T = 0.39 & \text{Vector gluons} \\ \alpha_T = -1 & \text{Scalar gluons} \end{array}$$

Similarly QCD predicts that the normal to the gluon plane should be distributed as

$$1 + \alpha_N \cos^2\beta \qquad \begin{array}{ll} \alpha_N = -0.33 & \text{Vector gluons} \\ \alpha_N = +1 & 0^+ \text{ gluons} \\ \quad\ = -1 & 0^- \text{ gluons} \end{array}$$



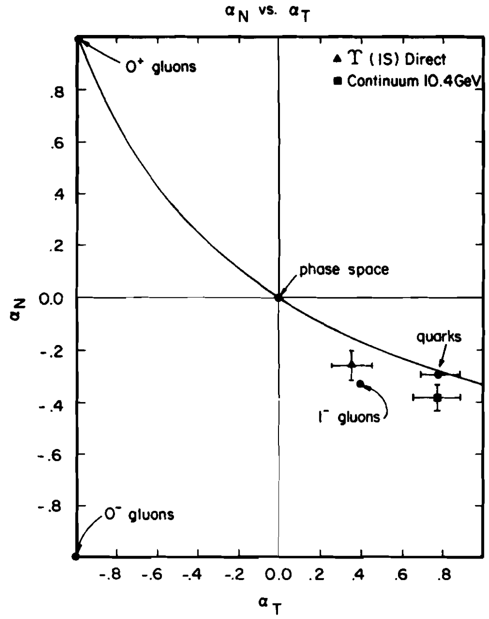


Fig. 25: Thrust distributions for continuum and ϒ(1S) decay. The dash-dot curve is the distribution calculated for quark jets. The solid curve for 75% 3 gluon and 25% phase space. (CLEO)

Fig. 26: Predictions for α_T and α_N for $J^P = 1^-,\ 0^-,\ 0^+$ gluons and for quark jets. Measurements are from CLEO.

The DORIS measurements (26,27) gave $\alpha_T = .33\pm.16$ conclusively ruling against scalar gluons. CLEO results are

$$\alpha_T = 0.35\pm0.11$$

$$\alpha_N = 0.26\pm0.03$$

The results for α_T confirm the DORIS results. The measurement of α_N is new. These results are shown graphically in Figure 26, where the CLEO measurements and QCD predictions are compared for both gluons and quarks.(29) One sees the scalar gluon prediction in violent disagreement with the data. Dramatic evidence for the vector nature of the gluon.

VI Baryon Production

The narrow upsilon resonances decay primarily into three gluons, the continuum into quark-antiquark jets, and the ϒ(4S) into B mesons.

The upsilon states and nearby continuum provide a fine tool for studying how gluons and quarks turn into hadrons. In a previous section I reported K-meson yields for these decays. Here I report on baryon production.

Protons and antiprotons are identified in CLEO by time-of-flight. Λ and $\bar{\Lambda}$ are identified by essentially the same procedure used to identify K_S^0. The mass of oppositely charged pairs of particles is calculated assuming the pair to be a proton and a pion. The mass distribution for these events observed in Υ(1S) and Υ(2S) decay are shown in Fig. 27. A clear Λ peak is evident.

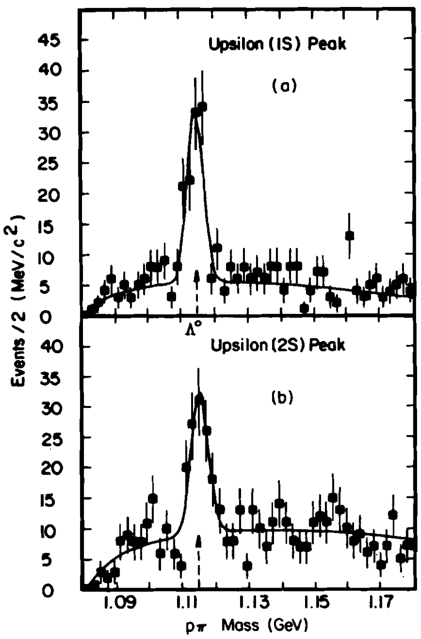


Fig. 27: Λ^o production, (a) at the Υ(1S) and, (b) at the Υ(2S). The event distribution is plotted vs. the $p\pi$ mass in GeV. (CLEO).

We have identified some six hundred $p+\bar{p}$ and 400 $\Lambda+\bar{\Lambda}$. The results for baryon production at different energies are shown in Table VII. The yields are quoted for $2\bar{p}$ rather than $p+\bar{p}$ because much of the Υ(1S) data had a large beam gas background due to a bad vacuum in CESR. The $2\bar{p}$ results are based on about $275\bar{p}$. The errors shown in the table are statistical. There is a 20% systematic error which does not effect the ratio of the various yields.

TABLE VII Baryons/Event

	Continuum	Υ(1S)	Υ(2S)	Υ(3S)	Υ(4S)
$\frac{2\bar{p}}{\text{event}}$	.22±0.04	.32±.07	.41±.08	.38±.10	.29±.19
$\frac{\Lambda+\bar{\Lambda}}{\text{event}}$	.14±.03	.23±.05	.31±.03	.17±.06	-.07±.10

The results do not bear out some preliminary indications from DASP[30] data of a large increase in baryon yield at the Υ(1S) compared to the continuum. The ratio of the yields is 1.5±0.5. Whether this modest increase is trying to tell us something about a difference between gluons and quarks is not obvious.

Notice that there are, if anything, fewer baryons from the B decay than from the continuum. This is further evidence against exotic models in which the B meson decays exclusively into baryons.[18]

VII: Total Cross Sections

The value of $R = \frac{\sigma_{e^+e^- \to \text{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$ is one of the most reliable predictions of QCD and thus an important result to determine as accurately as possible. In Fig. 28 we see measurements of R in the energy range 5 GeV < $\sqrt{s}$ < 10.6 GeV.

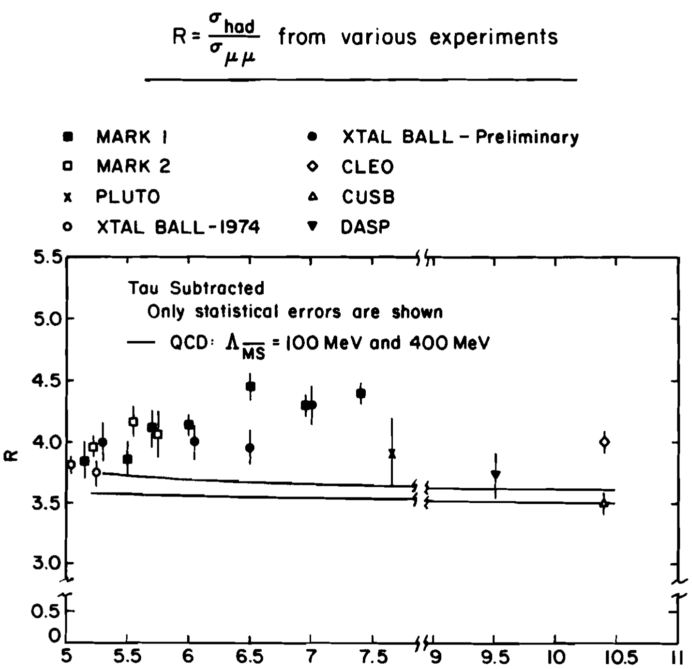


Fig. 28: $R = \frac{\sigma_{\text{hadrons}}}{\sigma_{\mu\mu}}$ from various experiments. References to most of the measurements are given in Barnett (Ref. 31). Only statistical errors are shown.

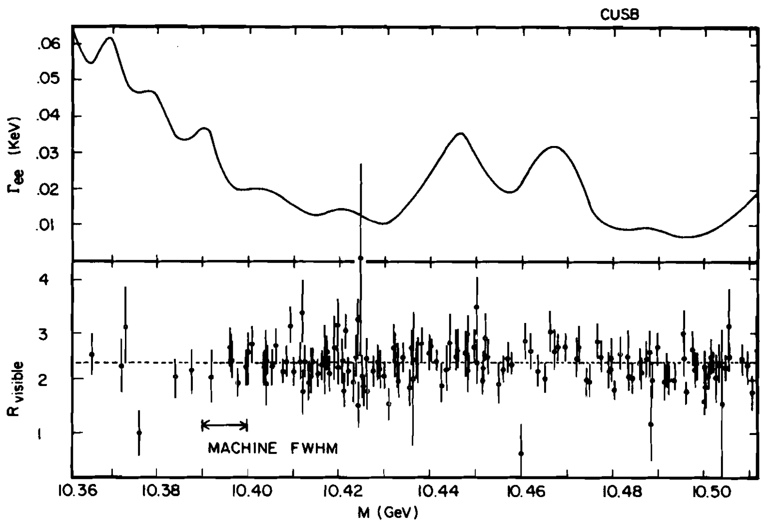
Also shown are the QCD predictions for several values of $\Lambda_{\overline{MS}}$.

Barnett[31] has suggested that the apparent discrepancy between the measurements and the QCD predictions may be due to production of new particles. In view of the systematic errors of about 10% quoted by most authors, an interpretation in terms of new physics is not compelling. However, it appears that if the "disagreement" with QCD is due to systematic errors, most of the experiments are making the same error. A source for an error common to most of the experiments is suggested in the paper of Tsai[32] submitted to the conference. He points out that the second order radiative corrections are not negligible – he estimates them at about 4% – and have not been made in most of the results of Figure 28. A correction of 4% would go some distance toward resolving the difference between measurement and theory. An accurate determination of R remains however, an urgent problem in e^+e^- physics.

An important feature of the total cross section measurements in the upsilon region is the lack of evidence for any of the vibrational states of Buchmüller and Tye.[33] According to them, the first such b-quark state should be found between the $\Upsilon(3S)$ and $\Upsilon(4S)$. CUSB measurements in this energy interval are shown in Figure 29.

The curve shows the upper limit on Γ_{ee} at various energies. CLEO quotes an upper limit of Γ_{ee} < 0.08 KeV (90% CL) in this same interval.

Fig. 29: (bottom) R visible in CUSB detector in the scan bins for the region between the ϒ" and ϒ"'. (top) 90% confidence level upper limit on Γ_{ee} for a narrow resonance as a function of mass.



However, I'd like to sound a note of caution. There is almost no data just above the ϒ(3S) in the energy interval 10.34 GeV – 10.40 GeV. This is one of two energy intervals where Buchmüller and Tye predict the occurrence of the lowest vibrational state. We are planning a more detailed look at this energy range in the near future.

This is the last of the measurements I will discuss. My discussion of most of this work has been very brief. More detailed information can be gotten from the papers submitted to the conference by CLEO and CUSB. These are listed in reference 34.

SUMMARY

I would like to summarize the main findings scattered through the body of this report.

We find that B-meson decay is well described by Kobayashi-Maskawa. Diverse measurements have shown that the B-meson decays primarily by $b \to c$, but a contribution of $b \to u$ of 25% or less cannot be ruled out.

We have tested a variety of exotic models including a broad class with no top quark and find them in conflict with the data. We can exclude a large branching fraction of B-meson decay into a charged Higgs particle whose mass lies between the τ mass and the B-meson mass.

We have evidence from hadronic decays of the ϒ(2S) and ϒ(3S) that soft gluon processes are well described by the multipole expansion formalism. A new determination of $\Lambda_{\overline{MS}}$ yields a value of about 100 MeV, considerably lower than the values popular a year ago. Finally, we have convincing, if somewhat belated, evidence for the vector nature of the gluon.

ACKNOWLEDGEMENTS

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Discussion

G. Barbiellini, CERN: Are the two events with mass of the e^+e^--pair in the J/ψ region coming from the 4S-state?

A. Silverman: One is from the 4S-state, the other is at higher energy.

H. Newman, DESY: Does your semi-leptonic branching ratio for $B \to \mu\nu X$ refer to the "primary" muons associated with B decay only? How are your results dependent on the ratio $\sigma(b \to \mu X)/\sigma(b \to cX)$?

A. Silverman: The contribution of about 5 % from D-meson decay has been subtracted. The results depend weakly on the mass of the recoiling particles because we measure the spectrum of lepton momenta above 1 GeV and make a correction below 1 GeV. This correction depends on the mass of the recoiling particles ($\sim$25 % from $m \sim 2$ GeV). However, we do not assume either $b \to \mu X$ or $b \to cX$ but use the momentum distribution to determine the recoiling mass and make a correction based on the observed mass.

G. Wolf, DESY: Is there a difference in the momentum spectrum of baryons coming from the $\Upsilon(1S)$ and from the continuum?

A. Silverman: I do not have that information with me.