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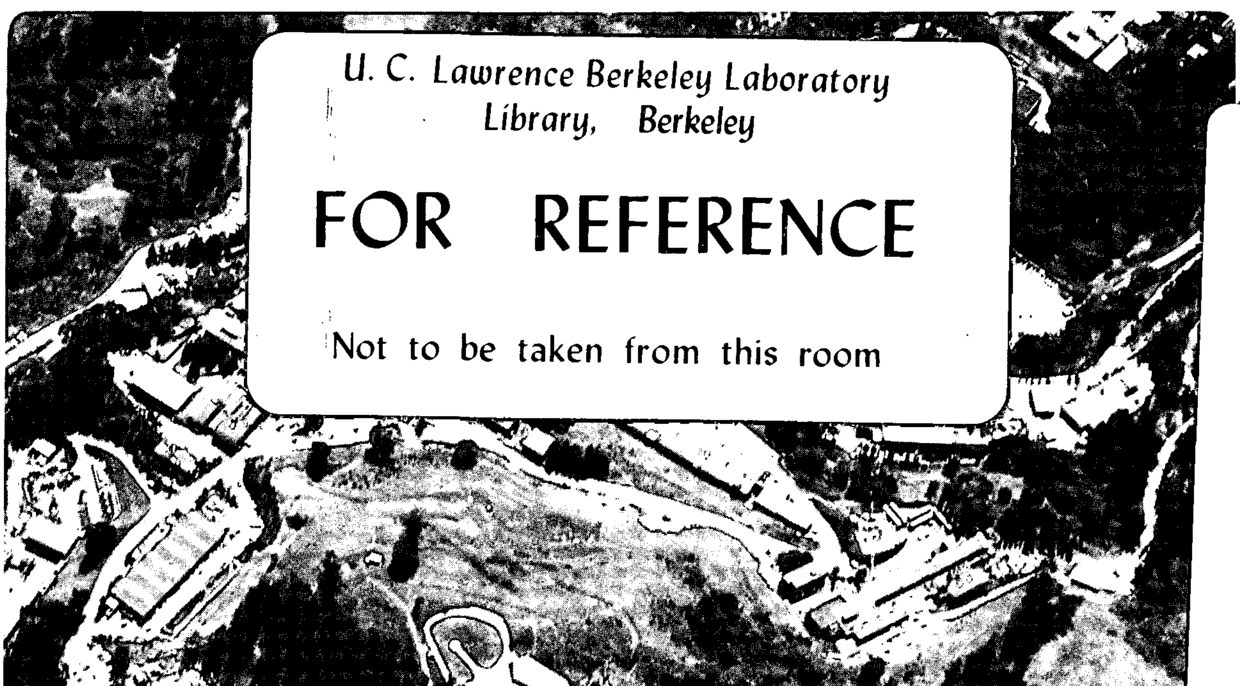

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Measurement of the Charged Multiplicity of Events Containing Bottom Hadrons at $E_{cm} = 91$ GeV*

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ABSTRACT

Using an impact parameter tag to select an enriched sample of $Z^0 \to b\bar{b}$ events, we have measured the difference between the average charged multiplicity of $b\bar{b}$ and all hadronic Z^0 decays to be $2.1 \pm 1.8(\text{stat}) \pm 0.6(\text{sys})$ tracks per event. The resulting total (non-leading) charged multiplicity for $Z^0 \to b\bar{b}$ events is $23.1(12.0) \pm 1.8 \pm 0.6$ tracks. A comparison of this non-leading multiplicity to hadronic multiplicity data in the range of 10 to 60 GeV supports the hypothesis of flavor independent hadronic fragmentation, and yields a measurement of the average energy fraction of bottom hadrons in Z^0 decays of $\langle x_E \rangle_b = 0.62 \pm 0.10 \pm 0.04$.

Within the framework of QCD, non-leading particle production in e^+e^- annihilation is governed by gluon fragmentation, triggered by the disruption of the vacuum by the color charge, and thus is expected to be independent of the flavor of the leading quarks. It has been suggested[1,2] that this hypothesis can be tested in heavy quark events by comparing the mean non-leading charged multiplicity - charged particles not resulting from the decay of the heavy hadrons - with the mean charged multiplicity of e^+e^- annihilation at the center-of-mass energy equal to the mean energy available to the non-leading system. If instead this property is assumed, then a measurement of the non-leading multiplicity can be used to constrain the mean energy fraction $\langle x_E \rangle = E_{hadron}/E_{beam}$ carried off by the heavy hadron after hadronization.[1]

The mean non-leading multiplicity ($\overline{n}_{nl}$) in e^+e^- annihilation to c and b quarks has been measured at E_{cm} between 29 and 42 GeV,[3] and provides support for the hypothesis of flavor independence. In this Letter, we present the first measurement of the mean non-leading multiplicity of $Z \rightarrow b\bar{b}$ events. The higher non-leading energy associated with heavy quark production at this energy is in a region for which the total multiplicity is well measured, and which is far from heavy quark production thresholds. This permits a more meaningful comparison with the lower energy total multiplicity data than was previously possible. In addition, the resulting measurement of $\langle x_E \rangle_b$ has systematic errors independent of those associated with the extraction of $\langle x_E \rangle_b$ from the lepton spectrum in $Z \rightarrow b\bar{b}$ events.[4]

The data reported here were taken with the Mark II detector[5] at the SLAC Linear Collider (SLC) during 1990. Charged particle tracking employed three detector systems: the central drift chamber (CDC), the drift chamber vertex detector (DCVD), and the silicon strip vertex detector (SSVD). The CDC[6] consisted of 72 axial and stereo layers from 19 to 152 cm from the beam axis. The DCVD[7,8] was located directly inside the CDC, with 38 axial layers between 5.1 and 16.6 cm. The SSVD[9] consisted of three axial layers located between 2.9 and 3.8 cm, just outside of the 2.5 cm radius beam pipe. The angular track separation resolution was 5 mrad or better for each of the three detectors. For this study, the multiplicity measurement relied primarily on information from the CDC, while the more accurate impact parameter measurement provided by the addition of the vertex detector information to the CDC tracks was used to select the b-enriched sample.

All impact parameters used in this analysis were for tracks projected into the plane perpendicular to the beam axis, and were measured with respect to a primary vertex (PV) which was fit event-by-event.[10] Including the uncertainty from the PV fit, the impact parameter uncertainty approaches 28 μm for high momentum tracks, and is 77 μm at $p_\perp\sqrt{\sin\theta} = 1$ GeV/c, where $p_\perp$ is the momentum transverse to the beam axis, and θ the angle relative to the beam axis.

The integrated luminosity was 10.1 ± 0.7 nb^{-1}, with $\langle E_{cm}\rangle = 90.9$ GeV. A sample of 196 hadronic Z^0 decays was selected by requiring that there be at least seven charged tracks in the fiducial tracking volume, that the sum of the energy of charged and neutral tracks exceed $0.5E_{cm}$, and that the thrust axis, calculated using charged tracks only, satisfy $|\cos\theta_{thrust}| < 0.7$.

For the multiplicity measurement, charged tracks were required to have at least 25 position measurements in the CDC, $|\cos\theta| < 0.8$, $p_\perp > 150$ MeV/c, and a point-of-closest-approach to the PV of < 15 mm both perpendicular to and along the direction of the beam axis. Tracks used for the impact parameter tag had to satisfy the additional requirements that there be at least 15 DCVD and 1 SSVD position measurements, that the impact parameter, b, satisfy $|\mathrm{b}| < 2$ mm, and that the impact parameter error from the track fit, including multiple Coulomb scattering, be less than 200 μm.

A b-enriched sample of 48 events was selected by an impact parameter tag requiring that the event contain two or more tracks which pass all the above cuts, and with $\mathrm{b}/\sigma_\mathrm{b} > 3.0$. The impact parameter is signed such that b is positive provided that the vector from the PV to the point where the track intersects the thrust axis makes an acute angle with respect to the track direction. The precise definition of σ_b, as well as a description of the simulation of the vertex detectors in the MC, is presented in ref. 10. Monte Carlo (MC) studies indicate that this tag is 72% efficient at selecting $Z \to b\bar{b}$ events, while providing an enriched sample of 65% purity. As a check, this yields $Br(Z \to b\bar{b})/Br(Z \to had) = 0.22 \pm 0.05(\text{stat.})$ in good agreement with the Standard Model and previous measurements.[10]

In determining the total charged $Z \to b\bar{b}$ multiplicity $\overline{n}_b$, we minimize systematic error, such as that due to tracking efficiency and scattering, by measuring $\delta\overline{n}_b = \overline{n}_b - \overline{n}_{had}$, and then adding back in the total hadronic charged multiplicity $\overline{n}_{had}$, which has been accurately determined by previous experiments. In terms of the $Z \to b\bar{b}$ branching fraction F_b and the *uncorrected* mean reconstructed multiplicities, $\overline{m}_h$ ($\overline{m}_t$), of the hadronic (tagged) samples

$$\delta\overline{n}_b = (1 - F_b) \cdot (\overline{n}_{dk} + \overline{n}_{nl} - \overline{n}_{udsc})$$

where $\overline{n}_{nl}$ and $\overline{n}_{udsc}$ satisfy

$$\overline{m}_h = C_{h,udsc} \cdot (1 - P_h) \cdot \overline{n}_{udsc} \; + \; C_{h,dk} \cdot P_h \cdot \overline{n}_{dk} \; + \; C_{h,nl} \cdot P_h \cdot \overline{n}_{nl}$$

$$\overline{m}_t = C_{t,udsc} \cdot (1 - P_t) \cdot \overline{n}_{udsc} \; + \; C_{t,dk} \cdot P_t \cdot \overline{n}_{dk} \; + \; C_{t,nl} \cdot P_t \cdot \overline{n}_{nl}.$$

We have separated the $Z \to b\bar{b}$ multiplicity into two components: one associated with the decay of the B hadrons ('dk'), and one associated with the remaining non-leading system ('nl'), since the former is well constrained by data from the $\Upsilon(4S)$. $\overline{n}_{dk} = 11.01 \pm 0.21$ is the sum of twice the B hadron decay multiplicity of 5.44 ± 0.14 tracks from the $\Upsilon(4S)$,[11,12] with a correction of 0.13 ± 0.06 tracks to account for B_s and B baryons.[13] The constants $C_{i,j}$ account for the effects of detector acceptance and inefficiencies, and the multiplicity bias introduced by the tag. The $C_{i,j}$ were evaluated with the MC detector simulation as the ratio of the number of reconstructed tracks to generated charged multiplicity tracks for the given sample (tagged, hadronic, $Z \to udsc$, etc.). We include in the generated multiplicity any charged track which is prompt, or is the decay product of a particle with a mean lifetime less than 3×10^{-10} s. The MC estimates the fraction of $Z \to b\bar{b}$ events in the hadronic and tagged samples to be $P_h = 0.227$ and $P_t = 0.653$, respectively.

Due to the loss of tracks with very low momentum and large $|cos\theta|$, the constants $C_{i,j}$ are somewhat dependent upon the model used to generate MC events; we have used the LUND 6.3 Parton Shower Model[14] with the coherent branching option, and parameter values tuned to hadronic Z^0 data.[15] To properly simulate B hadron decay, we have tuned the multiplicity and momentum spectrum of B decay products to the $\Upsilon(4S)$ data.[11][12][16] The resulting values for $C_{i,j}$ were 0.804, 0.848 and 0.749 for $C_{h,udsc}$, $C_{h,dk}$ and $C_{h,nl}$, and 0.878, 0.917 and 0.745 for $C_{t,udsc}$, $C_{t,dk}$ and $C_{t,nl}$, respectively.

The mean multiplicities of the two data samples were $\overline{m}_h = 16.71$ and $\overline{m}_t = 18.52$. Combining these with the $C_{i,j}$ via the above relations yields $\delta\overline{n}_b = 2.1 \pm 1.8$(stat.) tracks, where the error was determined from the scatter of measurements from 72 statistically independent MC 'experiments', each of which consisted of an event sample of identical size to that of the data. We have checked this result by using a tag that requires two or more tracks with $b/\sigma_b > 3.0$ in one hemisphere, and then measuring the multiplicity in the opposite hemisphere only, in order to reduce the bias of the tag. The resulting measurement of $\delta\overline{n}_b = 2.8 \pm 2.0$(stat.) is well within the 1.4 track one standard deviation difference given by making the same comparison with the 72 MC samples. As an additional check, the corrected total hadronic multiplicity $\overline{n}_{had} = 20.9 \pm 0.5$(stat.) is consistent with the world average of 20.94 ± 0.20.[17]

A list of systematic errors which contribute at least a 0.1 track uncertainty to the measurement of $\delta\overline{n}_b$ is presented in Table 1. Available hadronic data[15] provide a tight constraint on the modelling of $Z \rightarrow udsc$ decays, and the resulting uncertainty on the constants $C_{i,udsc}$ is small. Likewise, kinematic data from the $\Upsilon(4S)$[16] constrain the leading constants $C_{i,dk}$. In the case of the non-leading constants $C_{i,nl}$, however, no empirical constraint exists. In this case, the uncertainty has been estimated by varying the charged energy fraction of the non-leading system from 0.50 to 0.67, corresponding to pure I=$\frac{1}{2}$ (kaon-like) and pure I=1 (pion-like) production. Varying over wide ranges the parameters within LUND that control the hardness and angular spread of fragmentation products had little effect on the $C_{i,nl}$.

Adding the listed sources of systematic error in quadrature yields $\delta\overline{n}_b = 2.1 \pm 1.8 \pm 0.6$ tracks. Combining this with the world average of $\overline{n}_{had} = 20.94 \pm 0.20$ tracks, and the mean B hadron decay multiplicity of 11.01 ± 0.21 tracks, yields $\overline{n}_b = 23.1 \pm 1.8 \pm 0.6$ tracks, and $\overline{n}_{nl} = 12.0 \pm 1.8 \pm 0.6$ tracks. The effects of initial state radiation are small ($\delta E_{cm} \simeq 0.2$ GeV) and have not been corrected for.

Figure 1 shows the world sample of mean charged multiplicity data from e^+e^- annihilation, plotted vs. E_{cm}.[17][18] Also included are the mean non-leading multiplicities from the measurements at PEP and PETRA,[3] and from this measurement. The mean non-leading energies, $\langle E_{nl} \rangle$, are given by $(1 - \langle x_E \rangle) \cdot E_{cm}$, where $\langle x_E \rangle_c = 0.562$ at 29 GeV, and $\langle x_E \rangle_b = 0.751$ at 29 GeV, 0.740 at 35 GeV, 0.727 at 42.1 GeV[19] and 0.697 at 91 GeV.[4] In addition, an 'x_E-distribution' correction of -0.24, -0.10, -0.35, -0.45 and -1.50 GeV has been applied to the non-leading energies of the $c\overline{c}$ points at 29 GeV and $b\overline{b}$ points at 29, 35, 42.1 and 91 GeV, respectively. This accounts for the fact that the quantity we measure is $\langle \overline{n}(E_{nl}) \rangle$, rather than $\overline{n}(\langle E_{nl} \rangle) = \overline{n}([1 - \langle x_E \rangle] \cdot E_{cm})$.

The solid line in Figure 1 represents the results of a fit of the multiplicity data to the leading-logarithm approximation (LLA) inspired form[20] $\overline{n}_{had} = a + b \cdot \exp\left[c\sqrt{\ln E_{cm}}\right]$. In this fit, the contribution from $b\overline{b}$ and $c\overline{c}$ production has been removed, since no significant heavy quark production is expected for the non-leading system. At 29 GeV, the comparison of the $b\overline{b}$ and $c\overline{c}$ multiplicity measurements with the total hadronic charged multiplicity yields a heavy quark correction of -1.2 ± 0.5 tracks. The LUND MC has been used to extend this correction to other energies. The uncertainty in this correction is reflected by the dotted lines in Figure 1. Comparing the non-leading multiplicity points with the heavy quark corrected fit, it is seen that the addition of this measurement at higher energy serves to further support the flavor independence of non-leading particle production.

To extract $\langle x_E \rangle_b$, the total multiplicity data have been re-fit to the LLA form in the region between 12 and 60 GeV, and the fit modified to take into account both the heavy quark and x_E-distribution correction, yielding

$$\overline{n}_{had}^{corr} = 3.48 + 0.0511 \cdot \exp\left[2.737\sqrt{\ln E_{cm}}\right] - 141 \cdot E_{cm}^{-1.80} \quad (E_{cm} \text{ in GeV}).$$

Solving this for the non-leading energy corresponding to our value for $\overline{n}_{nl}$, and applying the relation $\langle x_E \rangle_b = 1 - \langle E_{nl} \rangle / E_{cm}$, yields $\langle x_E \rangle_b = 0.62 \pm 0.10 \pm 0.04$. The systematic error includes both the ± 0.6 track uncertainty in the non-leading multiplicity and the ± 0.5 track uncertainty in the heavy quark correction. This value is consistent with the measurement $\langle x_E \rangle_b = 0.697 \pm 0.013$ derived from the lepton spectrum in $Z \rightarrow b\bar{b}$ events.[4]

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13. For the corrections to the B hadron decay multiplicity, we have made use of a constraint of 0.18 ± 0.10 on the fraction of B_s production, derived from a comparison of $B^0 - \overline{B^0}$ mixing measurements at the Z^0 and $\Upsilon(4S)$, and from the unitarity of the KM-matrix, $|V_{td}|^2/|V_{ts}|^2 < 0.21$, which constrains

the relative mixing of B_d and B_s in the Standard Model. (See H. Schröder, DESY 91-139, Nov. 1991 and P. Roudeau, LAL 91-49.) The fraction of B baryon production was taken to be 0.1 ± 0.1 and the LUND MC was used to estimate the difference between the B_s, B baryon and $B_{u,d}$ multiplicities.

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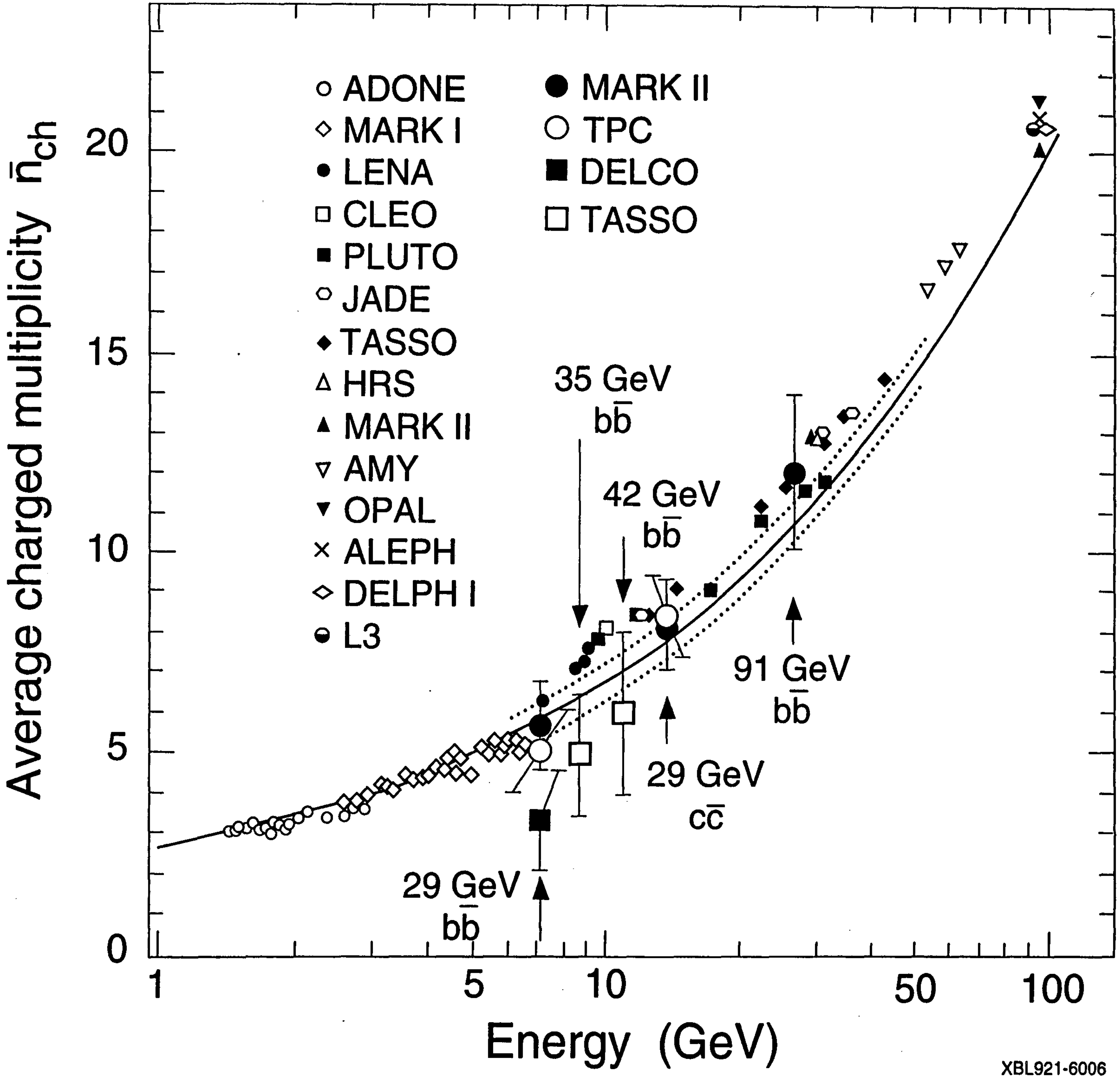
Source of systematic error on $\delta\bar{n}_b$	Contribution (tracks/event)
Hadronic decay modelling:	
udsc and B hadron decay	±0.1
$b\bar{b}$ non-leading	±0.4
Heavy quark parameters	±0.1
Materials and scattering	±0.1
$b\bar{b}$ tagging efficiency	±0.2
Monte Carlo statistics	±0.3

Table 1 Systematic errors on $\delta\bar{n}_b = \bar{n}_b - \bar{n}_{had}$.

Figure Caption

Figure 1: Energy dependence of total (without error bars) and non-leading multiplicity in e^+e^- annihilation. The non-leading multiplicities have been plotted at their corresponding mean non-leading energies. The fit, with its one standard deviation range, is to the total multiplicity data after removing the effects of heavy quark production.


ADONE
MARK I
LENA
CLEO
PLUTO
JADE
TASSO
HRS
MARK II
AMY
OPAL
ALEPH
DELPH I
L3
MARK II
TPC
DELCO
TASSO
Average charged multiplicity $\bar{n}_{ch}$
Energy (GeV)
35 GeV $b\bar{b}$
42 GeV $b\bar{b}$
91 GeV $b\bar{b}$
29 GeV $c\bar{c}$
29 GeV $b\bar{b}$
0
5
10
15
20
1
5
10
50
100
XBL921-6006