

CHARGED MULTIPLICITY OF HADRONIC EVENTS CONTAINING HEAVY QUARK JETS*

P. C. Rowson, G. H. Trilling, G. S. Abrams, D. Amidei^a, A. R. Baden,
T. Barklow, A. M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat,
D. L. Burke, F. Butler, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney,
M. S. Gold, G. Goldhaber, L. J. Golding, J. Haggerty, G. Hanson, K. Hayes,
D. Herrup, R. J. Hollebeek, W. R. Innes, J. A. Jaros, I. Juricic, J. A. Kadyk,
D. Karlen, A. J. Lankford, R. R. Larsen, B. W. LeClaire, M. E. Levi^b, N. S. Lockyer^c,
V. Lüth, C. Matteuzzi^b, M. E. Nelson^d, R. A. Ong, M. L. Perl, B. Richter,
K. Riles, M. C. Ross, T. Schaad, H. Schellman, D. Schlatter^b, W. B. Schmidke,
P. D. Sheldon, C. de la Vaissiere^e, D. R. Wood, J. M. Yelton, and C. Zaiser

*Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720*

*Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305*

*Department of Physics
Harvard University, Cambridge, Massachusetts 02138*

ABSTRACT

The charged particle multiplicities of hadronic events deriving from produced bottom or charm quarks have been measured in the Mark II detector at PEP in e^+e^- annihilation at 29 GeV. For events containing one semi-leptonic and one hadronic heavy hadron weak decay, we find multiplicities of $15.2 \pm 0.5 \pm 0.7$ for bottom and $13.0 \pm 0.5 \pm 0.8$ for charm. The corresponding multiplicities of charged particles accompanying the pair of heavy hadrons are $5.2 \pm 0.5 \pm 0.9$ for bottom, and $8.1 \pm 0.5 \pm 0.9$ for charm.

Submitted to *Physical Review Letters*

* This work was supported in part by the Department of Energy, contracts DE-AC03-76SF00515 and DE-AC03-76SF00098.

^aPresent address: U. of Chicago, Chicago, IL 60637

^bPresent address: CERN, CH-1211 Geneva 23, Switzerland

^cPresent address: U. of Pennsylvania, Philadelphia, PA 19104

^dPresent address: California Institute of Technology, Pasadena, CA 91125

^ePresent address: LPNHE, Univ. Pierre Marie Curie, Paris, France F-75230

The properties of hadronic events produced in e^+e^- annihilation have generally been studied as averages over all flavors weighted by the relative flavor populations. There is little reason to assume much difference between hadronic jets from up, down and strange quarks, but for charm and especially bottom, the weak decay products and quark fragmentation properties play an important role. We present in this Letter measurements of the charged particle multiplicities in events containing bottom jets, and for events with charm jets. Prompt leptons produced in heavy flavor decays tag bottom or charm production, and kinematic cuts on the leptons statistically separate the two heavy flavors. From the known decay multiplicities of the heavy flavor hadrons, which we shall denote as *leading* multiplicities, we can deduce the *non-leading* multiplicities of charged particles produced in association with the two heavy hadrons. Knowledge of these non-leading multiplicities provides a way of studying heavy quark fragmentation.

This analysis is based on an integrated luminosity of 205 pb^{-1} collected with the Mark II detector at PEP at a center of mass energy of 29 GeV. The Mark II detector has previously been described in detail^{1, 2}; here we summarize the features relevant to our measurement. Charged particle tracking is accomplished by means of two cylindrical drift chambers concentric with the beam line and immersed in a 2.35 kG solenoidal magnetic field. The inner chamber consists of seven high resolution axial sense wire layers, while the outer chamber has sixteen layers including both axial and stereo orientations. The momentum resolution is $\delta p/p \approx \sqrt{(0.025)^2 + (0.01p)^2}$, where the units of p are GeV/c. Eight lead-liquid-argon calorimeter modules, located outside the magnet coil, cover 64% of 4π and are used for electron identification and photon detection. Finally, 4 layers of proportional tubes, sandwiched between steel plates and covering 45% of 4π , are used for muon identification.

We select candidate hadronic events by requiring that the total observed energy

(charged plus neutral) exceed $0.25E_{cm}$, and that the charged multiplicity be at least five. The sample is enriched with well reconstructed events by the requirement that the event thrust axis (determined from charged and neutral tracks) point away from the edges of the detector's active region ($|\cos\theta_{thrust}| \leq 0.5$). We consider in these events only those charged tracks which extrapolate to the origin within 4 cm in the plane perpendicular to the beams (xy) and 8 cm in z , and which have measured momenta between 100 MeV/c and 16 GeV/c. In addition, a cut is made on the polar angle of each track ($|\cos\theta| \leq 0.7$) to insure that it lies within the high efficiency volume of the drift chamber. An electron pairfinding algorithm is used to remove γ conversion and Dalitz pair electrons.

Samples with enhanced heavy flavor content are obtained by the selection of events containing a single lepton. The lepton sample is divided into bottom- and charm-enriched subgroups on the basis of the lepton's momentum transverse to the event thrust direction³. The high p_T lepton sample is bottom-enriched, whereas the low p_T sample is more often due to charm decay. We require lepton momentum $p \geq 2$ GeV/c, and take $p_T \geq 1$ GeV/c for the bottom-enriched sample and $p_T < 1$ GeV/c for the charm-enriched sample. Both electron and muon selection criteria are described elsewhere^{3, 4}. For the above kinematic regions, hadron misidentification probabilities for electrons are typically 0.5 – 1.0%, and for muons are 0.5% (punchthrough) and 0.4% (decays in flight). From a detailed analysis of the p and p_T distributions of prompt leptons⁵ we determine that for the b region, $64 \pm 8\%$ of the lepton candidates arise from bottom, $16 \pm 8\%$ from charm, and $20 \pm 8\%$ are background, while for the c region, $19 \pm 8\%$ are from bottom, $35 \pm 8\%$ from charm, and $46 \pm 8\%$ are background. Background here refers to either hadrons misidentified as leptons or leptons which do not arise from charm or bottom decays. The numbers for the b-region include the contributions of leptons

from charmed particles originating in b decay. The observed multiplicity distributions for b,c,and untagged datasets, after subtraction of γ conversions and Dalitz decays, are truncated below a multiplicity of five, and then corrected for acceptance with the following unfold technique.

Monte Carlo simulation is used to generate the unfold efficiency matrix defined by:

$$\epsilon_{pq} = \frac{\text{number of times } q \text{ tracks observed when } p \text{ tracks produced}}{\text{number of times } p \text{ tracks are produced}}$$

The produced track count is the total number of charged Monte Carlo tracks exclusive of those arising from pair conversions or Dalitz decays. Thus the two charged tracks from K_s and Λ decay are included.

We then make a maximum likelihood fit of the observed distribution to the following parameterization of the parent distribution,

$$P_{\mu,a}(p) = N(\mu, a) \frac{e^{-\mu/a} (\mu/a)^{p/a}}{\Gamma(p/a + 1)}, p \text{ even.} \quad (1)$$

where both ' μ ' and ' a ', are taken as free parameters. This distribution (1) is a generalization of the Poisson distribution with mean value approximately equal to μ and RMS width approximately equal to $\sqrt{\mu a}$. The overall normalization factor $N(\mu, a)$ is absorbed by our normalization method. Using the unfold matrix and the fitting function (1), we obtain, as a function of the two parameters, the expected number of events in each multiplicity bin, with the sum over all bins constrained to be equal to the total number of observed events. A Poisson likelihood function is then maximized to obtain the best estimates of ' μ ' and ' a '.

The effect of background in both the b and c regions has been simulated by the application to real hadron data of lepton misidentification probability tables, binned by p and p_T ⁵. The muon misidentification tables include the effects of hadron punch through and non-prompt muons due to pion and kaon decays, while the electron

tables take account of the effect of showering hadrons and the overlap of showers and charged tracks. This procedure is designed to model correctly the correlation between higher multiplicity and the probability that a given event contains a fake lepton.

We obtain the unfolded mean multiplicities for the overall hadronic sample, and for the b and c regions and their respective backgrounds. Figure 1 shows the observed multiplicity distributions for both the b and c regions, and the expected distributions deduced from our fits. We use the results for the tagged regions and their backgrounds to solve for the pure $b\bar{b}$ and $c\bar{c}$ event mean charged multiplicities from the equations,

$$\begin{aligned} n_b &= f_b^b m_{b\bar{b}} + f_c^b m_{c\bar{c}} + f_{b\text{kgnd}}^b n_{b\text{kgnd}}^b \\ n_c &= f_b^c m_{b\bar{b}} + f_c^c m_{c\bar{c}} + f_{b\text{kgnd}}^c n_{b\text{kgnd}}^c \end{aligned} \quad (2)$$

where the "n's" are the four fit results, the " f_x^X 's" are the 'x' enrichment factors in the 'X-region' and the "m's" are the unknown pure flavor mean multiplicities.

Final corrections, determined from Monte Carlo analysis, are applied to the fit results to take account of effects that tend to bias our multiplicity measurement. Firstly, initial state radiation reduces the effective center of mass energy (E_{cm}) and hence the observed multiplicity. From a parametrization of existing measurements of multiplicity vs. E_{cm} we obtain a correction of $+0.25 \pm 0.10$ particles. Secondly, the lepton momentum lower limit of 2 GeV /c biases the data in favor of smaller multiplicities. The corrections, for this effect, to be *added* to the final pure heavy flavor fit results are 0.3 ± 0.1 ($b\bar{b}$) and 0.9 ± 0.3 ($c\bar{c}$), where the errors include statistical and systematic Monte Carlo uncertainties. We have checked that the corrected results are insensitive to modest variations of the lepton momentum cut. Finally, the requirement in the b region that the lepton transverse momentum be at least 1 GeV /c tends to enrich the charm component of this region with high

multiplicity three-jet events, a bias not present in the c region. We determine the corresponding corrections to be -0.4 ± 0.3 ($b\bar{b}$) and $+0.2 \pm 0.2$ ($c\bar{c}$).

The dominant sources of systematic error are the efficiency uncertainties in the event selection and track quality cuts, and the errors on the flavor composition percentages listed above. Other contributing factors include the details of the fitting procedure, the background simulation and the radiative and kinematic corrections discussed above. Combined in quadrature, the systematic errors to be applied to the pure bottom ($b\bar{b}$) and charm ($c\bar{c}$) fit results are ± 0.7 and ± 0.8 respectively. The systematic error for the overall hadronic fit, where no tag lepton is required, is ± 0.6 .

The results for the overall hadronic sample, corrected for initial state radiation, are $12.9 \pm 0.1 \pm 0.6$ for the mean multiplicity, and 1.4 ± 0.1 for the width parameter ' α '. Both of these results are in good agreement with existing measurements ^{6,7}. The pure heavy flavor events in our selected sample consist almost entirely of combinations of one semi-leptonic decay and one hadronic decay of the produced heavy meson pair. From our known lepton identification efficiencies, we correct for the small contamination of double lepton events in which one lepton has been missed. The corresponding pure heavy flavor results are given in the first line of Table I. We use results from the CLEO collaboration for both hadronic and semi-leptonic B-meson decay charged multiplicities ⁸, as well as known D-meson decay multiplicities ¹ to subtract out the average leading charged multiplicities in our $b\bar{b}$ and $c\bar{c}$ events ⁹ and obtain the non-leading multiplicities shown in the last line of Table I. We also give the 'unbiased' results, where the relative numbers of semi-leptonic and hadronic heavy meson decays are determined by the respective branching ratios, in the second line of Table I. By combining our overall hadronic multiplicity result with these unbiased multiplicities for bottom and charm, we can extract the

light quark (u,d,s) event multiplicity, also given in Table I. The results given in Table I are compatible with charm jet and bottom jet multiplicity measurements at comparable energies ^{10, 11}.

Table I. Mean Charged Multiplicities

	b \bar{b}	c \bar{c}	light quarks	all hadrons
1 S.L. and 1 Hadronic	$15.2 \pm 0.5 \pm 0.7$	$13.0 \pm 0.5 \pm 0.8$	—	—
Nominal mixture	$16.1 \pm 0.5 \pm 1.0$	$13.2 \pm 0.5 \pm 0.9$	$12.2 \pm 0.4 \pm 1.3$	$12.9 \pm 0.1 \pm 0.6$
Non-leading	$5.2 \pm 0.5 \pm 0.9$	$8.1 \pm 0.5 \pm 0.9$	—	—

We can relate the non-leading multiplicities in Table I to the b and c quark fragmentation functions. The lower non-leading multiplicity for b \bar{b} relative to c \bar{c} provides independent evidence that b fragmentation is harder than c fragmentation. We can approximately translate these non-leading multiplicities to energies via existing multiplicity data for e⁺e⁻ annihilation over a large range of center of mass energies shown in Figure 2 ¹². Using this information we find from the non-leading multiplicities that bottom and charm hadrons fragment with mean energy fractions of $0.79_{-0.05}^{+0.10}$ and $0.60_{-0.11}^{+0.09}$ respectively. These values are in good agreement with measurements based on leptonic inclusive spectra ^{3, 13, 14, 15}, and D^{*} fragmentation ^{10, 16, 17, 18}.

REFERENCES

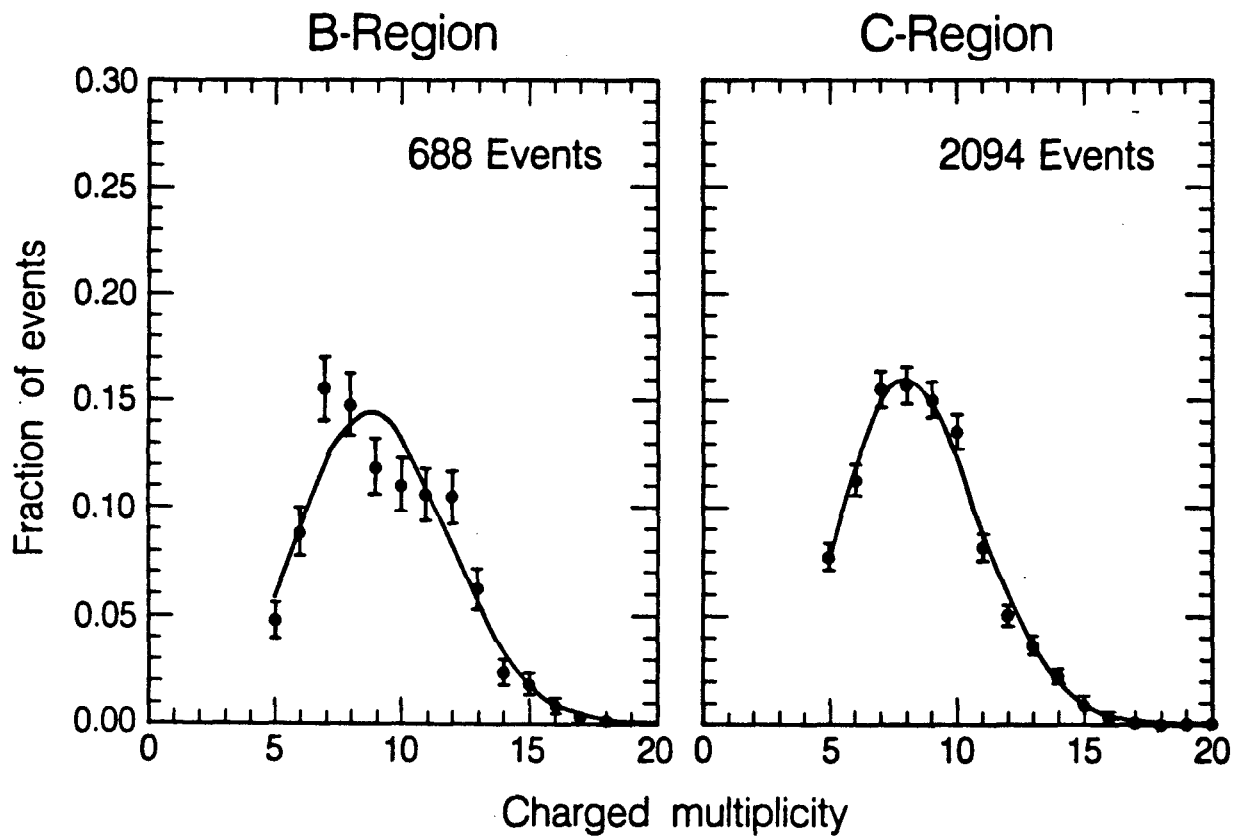
1. R. H. Schindler et al., Phys. Rev. D 24, 78 (1981).
2. J. Jaros in Proceedings of the International Conference on Instrumentation for Colliding Beam Physics, SLAC-Report 250, edited by W. Ash, Stanford CA, 29 (1982).
3. M. E. Nelson et al., Phys. Rev. Lett. 50, 1542 (1983).
4. N. S. Lockyer et al., Phys. Rev. Lett. 51, 1316 (1983).
5. M. E. Nelson, thesis, University of California, Berkeley, LBL-16724 (1983).
6. M. Althoff et al., Z. Phys. C22, 307, (1984).
7. D. Bender et al., ANL-HEP-PR-84-08, (1984), submitted to Phys. Rev. D.
8. R. Giles et al., Phys. Rev. D. 30, 2279 (1984).
9. Our estimates of leading multiplicities are based on measured D and B meson decay multiplicities, where we have included the contribution of the pion in the decay $D^{*\pm} \rightarrow D^0 + \pi^\pm$ as part of the leading charm multiplicity. This procedure neglects possible small multiplicity differences due to heavy baryons or other charm and bottom states.
10. M. Althoff et al., Phys. Lett. 135B, 243 (1981) give a multiplicity measurement for charm jets opposite to a D^* tag at 34.5 GeV.
11. M. Sakuda et al., CALT-68-1164 (1984), submitted to Phys. Lett., give a multiplicity measurement for bottom jets opposite to a lepton tag at 29 GeV.

12. The procedure used here depends on the assumption that the relation between energy and multiplicity is unaffected by the flavor population of the events. The available multiplicity data are based on u,d,s,c,and b whereas our measured non-leading multiplicities arise from u,d,and s fragmentation. As shown in this paper, this assumption is not exactly fulfilled, but the deviations are small enough to have no significant impact on the quoted energy fractions.
13. E. Fernandez et al., Phys. Rev. Lett. 50, 2054 (1983).
14. B. Adeva et al., Phys. Rev. Lett. 51, 443 (1983).
15. M. Althoff et al., Z. Phys. C22, 219, (1984).
16. J. Yelton et al., Phys. Rev. Lett. 49, 430 (1982).
17. P. Avery et al., Phys. Rev. Lett. 51, 1139 (1983).
18. M. Derrick et al., Phys. Lett. 146B, 261 (1984).

FIGURE CAPTIONS

Figure 1: The observed multiplicity distribution for both the b and c regions, with the expected distributions deduced from the fit results (solid line).

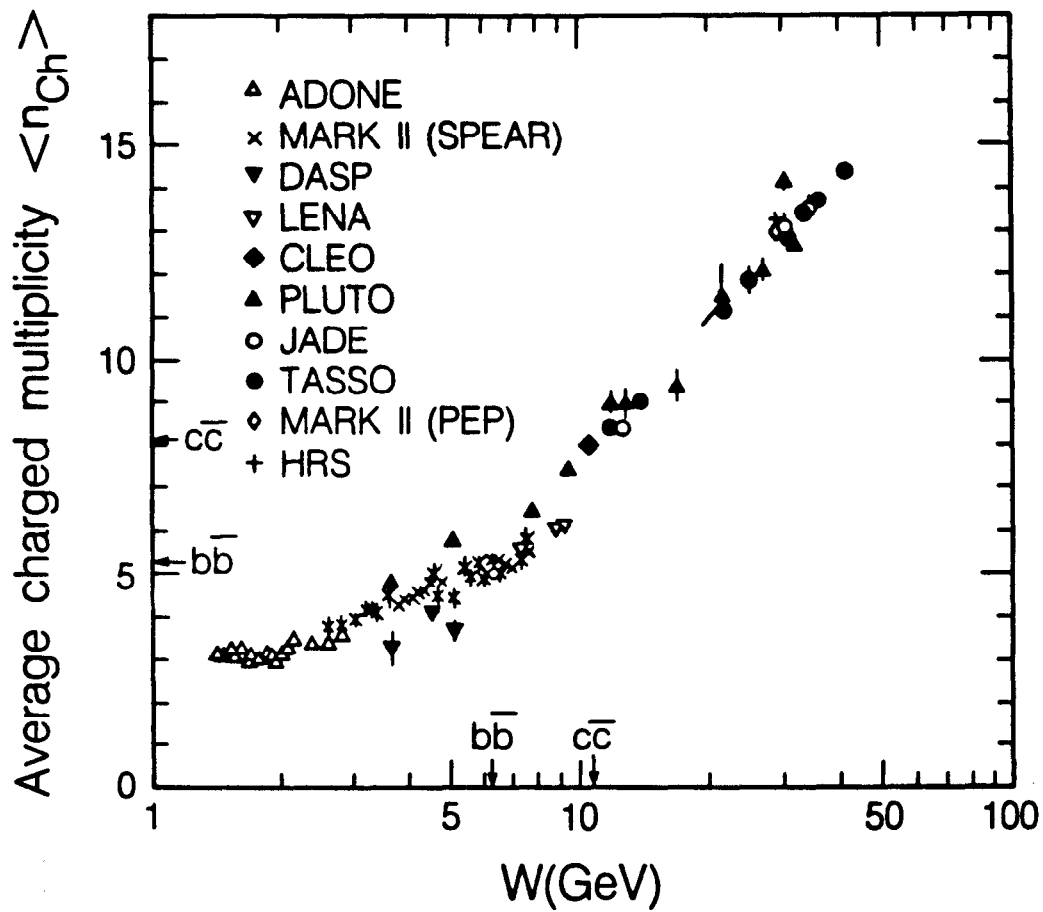
Figure 2: The energy dependence of charged multiplicity in e^+e^- annihilation ⁶, ⁷, where the errors are statistical. The arrows indicate the non-leading charged multiplicities for $b\bar{b}$ and $c\bar{c}$ events, and the corresponding energies.



XBL 851-9702

Fig. 1

$e^+e^- \rightarrow \text{hadrons}$



XBL 851-9701

Fig. 2