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**PION AND KAON MULTIPLICITIES IN HEAVY QUARK JETS  
FROM  $e^+e^-$  ANNIHILATION AT 29 GeV**

TPC/Two-Gamma Collaboration

H. AIHARA <sup>a</sup>, M. ALSTON-GARNJOST <sup>b</sup>, R.E. AVERY <sup>b</sup>, J.A. BAKKEN <sup>c</sup>, A. BARBARO-GALTIERI <sup>b</sup>, A.R. BARKER <sup>d</sup>, A.V. BARNES <sup>b</sup>, B.A. BARNETT <sup>c</sup>, D.A. BAUER <sup>d</sup>, H.-U. BENGTSOON <sup>e</sup>, D.L. BINTINGER <sup>f</sup>, B.J. BLUMENFELD <sup>c</sup>, G.J. BOBBINK <sup>g</sup>, T.S. BOLOGNESE <sup>b</sup>, A.D. BROSS <sup>b</sup>, C.D. BUCHANAN <sup>e</sup>, A. BUIJS <sup>h</sup>, D.O. CALDWELL <sup>d</sup>, C.-Y. CHIEN <sup>c</sup>, A.R. CLARK <sup>b</sup>, G.D. COWAN <sup>b</sup>, D.A. CRANE <sup>c</sup>, O.I. DAHL <sup>b</sup>, K.A. DERBY <sup>b</sup>, J.J. EASTMAN <sup>b</sup>, T.K. EDBERG <sup>b</sup>, P.H. EBERHARD <sup>b</sup>, A.M. EISNER <sup>i</sup>, R. ENOMOTO <sup>a</sup>, F.C. ERNÉ <sup>h</sup>, T. FUJII <sup>a</sup>, J.W. GARY <sup>b</sup>, W. GORN <sup>j</sup>, J.M. HAUPTMAN <sup>k</sup>, W. HOFMANN <sup>b</sup>, J.E. HUTH <sup>b</sup>, J. HYLEN <sup>c</sup>, T. KAMAE <sup>a</sup>, H.S. KAYE <sup>b</sup>, K.H. KEES <sup>f</sup>, R.W. KENNEY <sup>b</sup>, L.T. KERTH <sup>b</sup>, Winston KO <sup>l</sup>, R.I. KODA <sup>e</sup>, R.R. KOFLER <sup>m</sup>, K.K. KWONG <sup>d</sup>, R.L. LANDER <sup>l</sup>, W.G.J. LANGEVELD <sup>j</sup>, J.G. LAYTER <sup>j</sup>, F.L. LINDE <sup>h</sup>, C.S. LINSEY <sup>j</sup>, S.C. LOKEN <sup>b</sup>, A. LU <sup>d</sup>, X.-Q. LU <sup>c</sup>, G.R. LYNCH <sup>b</sup>, L. MADANSKY <sup>c</sup>, R.J. MADARAS <sup>b</sup>, K. MAESHIMA <sup>l</sup>, B.D. MAGNUSON <sup>i</sup>, J.N. MARX <sup>b</sup>, G.E. MASEK <sup>f</sup>, L.G. MATHIS <sup>b</sup>, J.A.J. MATTHEWS <sup>c</sup>, S.J. MAXFIELD <sup>m</sup>, S.O. MELNIKOFF <sup>j</sup>, E.S. MILLER <sup>f</sup>, W. MOSES <sup>b</sup>, R.R. McNEIL <sup>l</sup>, P. NEMETHY <sup>n</sup>, D.R. NYGREN <sup>b</sup>, P.J. ODDONE <sup>b</sup>, H.P. PAAR <sup>h</sup>, D.A. PARK <sup>c</sup>, S.K. PARK <sup>k</sup>, D.E. PELLET <sup>l</sup>, A. PEVSNER <sup>c</sup>, M. PRIPSTEIN <sup>b</sup>, M.T. RONAN <sup>b</sup>, R.R. ROSS <sup>b</sup>, F.R. ROUSE <sup>b</sup>, K.A. SCHWITKIS <sup>d</sup>, J.C. SENS <sup>h</sup>, G. SHAPIRO <sup>b</sup>, M.D. SHAPIRO <sup>b</sup>, B.C. SHEN <sup>j</sup>, W.E. SLATER <sup>c</sup>, J.R. SMITH <sup>l</sup>, J.S. STEINMAN <sup>e</sup>, M.L. STEVENSON <sup>b</sup>, D.H. STORK <sup>e</sup>, M.G. STRAUSS <sup>e</sup>, M.K. SULLIVAN <sup>i</sup>, T. TAKAHASHI <sup>a</sup>, J.R. THOMPSON <sup>f</sup>, N. TOGE <sup>a</sup>, S. TOUTOUNCHI <sup>m</sup>, R. VAN TYEN <sup>b</sup>, B. VAN UITERT <sup>h</sup>, G.J. VANDALEN <sup>j</sup>, R.F. VAN DAALEN WETTERS <sup>c</sup>, W. VERNON <sup>f</sup>, W. WAGNER <sup>l</sup>, E.M. WANG <sup>b</sup>, Y.X. WANG <sup>d</sup>, M.R. WAYNE <sup>e</sup>, W.A. WENZEL <sup>b</sup>, J.T. WHITE <sup>f</sup>, M.C.S. WILLIAMS <sup>l</sup>, Z.R. WOLF <sup>b</sup>, H. YAMAMOTO <sup>b</sup>, S.J. YELLIN <sup>d</sup>, C. ZEITLIN <sup>l</sup> and W.-M. ZHANG <sup>c</sup>

<sup>a</sup> University of Tokyo, Tokyo, Japan

<sup>b</sup> Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

<sup>c</sup> Johns Hopkins University, Baltimore, MD 21218, USA

<sup>d</sup> University of California, Santa Barbara, CA 93106, USA

<sup>e</sup> University of California, Los Angeles, CA 90024, USA

<sup>f</sup> University of California, San Diego, CA 92093, USA

<sup>g</sup> Carnegie-Mellon University, Pittsburg, PA 15213, USA

<sup>h</sup> National Institute for Nuclear and High Energy Physics, Amsterdam, The Netherland

<sup>i</sup> University of California Institute for Research at Particle Accelerators, Stanford, CA 94305, USA

<sup>j</sup> University of California, Riverside, CA 92521, USA

<sup>k</sup> Ames Laboratory, Iowa State University, Ames, IA 50011, USA

<sup>l</sup> University of California, Davis, CA 95616, USA

<sup>m</sup> University of Massachusetts, Amherst, MA 01003, USA

<sup>n</sup> New York University, New York, NY 10003, USA

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The multiplicities per event of  $\pi^\pm$  and  $K^\pm$  are measured separately for  $e^+e^-$  annihilation into  $c\bar{c}$ ,  $b\bar{b}$ , and light quark pairs at  $E_{\text{cm}} = 29$  GeV. The  $K^\pm$  multiplicity is higher for heavy quark events than for light quark events. The  $\pi^\pm$  multiplicity and the  $\pi^\pm$  scaled differential cross section at low  $x = E_{\text{hadron}}/E_{\text{beam}}$  are found to be higher for  $b\bar{b}$  events than for other events.

Annihilation of  $e^+e^-$  into quark pairs is characterized by jet formation. Extensive studies of quark jets and comparisons with QCD predictions have been made in recent years for events comprising a mixture of light and heavy quarks. Recent studies have obtained charged particle multiplicities and momentum distributions for charm quark jets and, separately, for bottom quark jets [1]. In this paper, using the time projection chamber (TPC) particle identification capability, we report for the first time separate charged pion and kaon multiplicities and pion scaled cross sections for charm quark jets, bottom quark jets and light quark jets.

The analysis is based on data corresponding to an integrated luminosity of  $77 \text{ pb}^{-1}$  collected with the TPC facility at SLAC. The TPC has been described in detail elsewhere [2]. This analysis uses data from the time projection chamber itself, the muon system, and the hexagonal calorimeter (HEX). The TPC tracking in the 4 kG magnetic field provides a momentum resolution of  $(dp/p)^2 = (0.06)^2 + (0.035p)^2$ , where  $p$  is the momentum in GeV/c. The TPC also samples ionization energy loss up to 183 times along a track, resulting in  $dE/dx$  resolution of typically 3.7%. The simultaneous measurement of momentum and  $dE/dx$  provides particle identification which, although insufficient to give good separation of  $\mu^\pm$  and  $\pi^\pm$ , allows separation of  $e^\pm$ ,  $(\mu^\pm/\pi^\pm)$ ,  $K^\pm$ , and  $p, \bar{p}$  over most of the momentum range. The muon chambers system [3] consists of layers of drift chambers placed at several depths in the iron hadron filter which surrounds the TPC. For this analysis we use only the central muon chambers, which cover an angular region with respect to the beam of  $55^\circ < \theta < 125^\circ$ . The HEX is a 10 r.l.-thick lead gas-sampling calorimeter operated in the Geiger mode [4]<sup>11</sup>. It has an energy resolution of  $17\%/ [E (\text{GeV})]^{1/4}$ , and an effective fiducial area similar to the muon system.

The selection of a sample of 24 761 multihadron events is described in detail in ref. [5]. The selection basically requires events to have at least five charged

tracks, with the sum of their energies greater than 7.25 GeV. We add the requirement that the thrust axis of the event be more than  $45^\circ$  away from the beam axis. Heavy quark enriched event samples are obtained by selecting events which have identified leptons. The identification of muons is also described in ref. [5]. Briefly, muon candidates are found by looking for charged tracks with  $p > 2$  GeV/c that penetrated 1 meter of iron, which have  $dE/dx$  in the TPC consistent with that expected for a muon, and which are consistent with coming from the primary vertex. However, the tight cut on muon chamber hit residuals in our previous paper is relaxed for this study to obtain a larger sample of 758 muon candidates. The 382 electron candidates are selected as described in ref. [6], that is by taking tracks with  $p > 1.5$  GeV/c and requiring that the  $dE/dx$  measurement from the TPC and the shower energy and lateral shape from the hexagonal calorimeter be consistent with expectations for electrons.

Because of the larger mass of b quarks, leptons from their decays tend to have larger transverse momentum ( $p_t$ ) with respect to the event thrust axis than leptons from c quark decays. The events with leptons are divided into a b-enriched sample with lepton  $p_t > 1$  GeV/c and a c-enriched sample with lepton  $p_t < 1$  GeV/c. The requirement of a high momentum lepton creates biases in the particle multiplicities of events in the heavy quark samples. For two-jet events, however, long range jet-jet correlations are weak so that the fragmentation of the jets proceeds almost independently. Thus we divide each event in the data sample into two hemispheres with respect to the thrust axis, and define the group of particles in the hemisphere containing the lepton to be a "tag" jet and the group of particles in the opposite hemisphere to be a "heavy" jet. We then take the multiplicities of the average heavy quark events to be twice the multiplicities of the "heavy" jets.

To find pion, kaon and proton multiplicities we select tracks which are associated with the primary vertex, have well measured momentum, have at least 80  $dE/dx$  samples, are not kinematically identified as part of a possible photon conversion pair, and are

<sup>11</sup> The resolution quoted here is the result of more recent studies. This energy dependence is valid up to 6 GeV.

not identified as muons by the muon system. We then fit the  $dE/dx$  spectrum in appropriate momentum slices to find the number of electrons, pions, kaons, and protons. This procedure is discussed in detail in ref. [7]. We exclude from the fitting the “ $dE/dx$  cross over” regions where the  $dE/dx$  for different particle types is the same:  $1.0 \text{ GeV}/c < p < 1.35 \text{ GeV}/c$  for pions and kaons,  $1.65 \text{ GeV}/c < p < 2.01 \text{ GeV}/c$  for pions and protons, and  $2.23 \text{ GeV}/c < p < 3.67 \text{ GeV}/c$  for kaons and protons. Residual electrons in the electron–pion and electron–kaon cross-over regions are estimated from the sidebands and subtracted.

The background to the prompt muons consists of misidentified hadrons and of muons from kaon and pion decays. We use a Monte Carlo simulation of the detector to produce a track misidentification probability as a function of angle, momentum and track type which can be used to find the probability that a given hadron in the actual data would give a fake prompt muon signal [5]. The background to the prompt electrons consists mainly of electrons from photon conversion and Dalitz decays. A background probability is calculated from Monte Carlo simulations of these processes [6]. Due to these backgrounds in the lepton samples, some of the jets tagged as “heavy” are really generated by light quarks. To find the resulting number of background pions, kaons and protons in the “heavy” jet samples, we take each of the events in the general  $q\bar{q}$  sample, calculate the probability of producing a fake prompt lepton in one hemisphere by convoluting the misidentification probabilities over the tracks, and count the hadrons in the opposite jet weighted by that misidentification probability. We do the identical  $dE/dx$  fitting on these background tracks as on the actual “heavy” jet tracks, and subtract the resulting number of pions, kaons, protons and hadrons in each momentum bin from the “heavy” jet data samples.

Acceptances for event and track selection are calculated using the Lund Monte Carlo generator [8]<sup>12</sup> and a full detector simulation. The resulting heavy quark and background components of the b-enriched and c-enriched samples [5,6] are shown in table 1.

<sup>12</sup> We use version 5.3 of the Monte Carlo, with decay multiplicities for mesons containing bottom and charm adjusted to measured values from refs. [9,10], and with  $\text{BR}(b \rightarrow \mu X) = \text{BR}(b \rightarrow e X) = 10.7\%$  and  $\text{BR}(c \rightarrow \mu X) = \text{BR}(c \rightarrow e X) = 7.86\%$ .

The Monte Carlo is also used to correct for the effects of initial state radiation and the relative effects on the samples of hard gluon radiation. (For example, the requirement of  $p_t > 1 \text{ GeV}/c$  enriches the three-jet events in the c-event component of the b-enriched sample. These three-jet events tend to have more tracks in the low momentum region and fewer tracks in the high momentum region as compared to the average c events.) The systematic error on the acceptance is estimated to range from 4% (for high momentum pions) to 10% (for low momentum kaons and protons).

Using the background subtracted b-enriched and c-enriched samples, we determine the number of  $\pi^\pm$  as a function of  $x = E_\pi/E_{\text{beam}}$  in b jets [ $N_b^\pi(x)$ ] and in c jets [ $N_c^\pi(x)$ ] by solving the equations

$$n_\pi^>(x) = n_{\text{jet}}^> [F_b^> N_b^\pi(x) A_b^\pi(x) + F_c^> N_c^\pi(x) A_c^\pi(x) R(x)],$$

$$n_\pi^<(x) = n_{\text{jet}}^< [F_b^< N_b^\pi(x) A_b^\pi(x) + F_c^< N_c^\pi(x) A_c^\pi(x)].$$

Here  $n_\pi^>(x)$  is the number of observed  $\pi^\pm$  in an  $x$  bin in the  $p_t > 1 \text{ GeV}/c$  “heavy” jet sample,  $n_{\text{jet}}^>$  is the number of observed jets in the  $p_t > 1 \text{ GeV}/c$  sample,  $F_b^>$  is the fraction of b jet events in the  $p_t > 1 \text{ GeV}/c$  sample,  $A_b^\pi(x)$  is the acceptance for  $\pi^\pm$  in b jets,  $R(x)$  is the correction factor for the extra three-jet contributions by c jets in the  $p_t > 1 \text{ GeV}/c$  sample, and so on.  $F$ ,  $A$ , and  $R$  are obtained by Monte Carlo. The numbers found for “heavy” jets are doubled to give  $N_{b\bar{b}}^\pi$  and  $N_{c\bar{c}}^\pi$ , the number of  $\pi^\pm$  in heavy  $q\bar{q}$  events. Figs. 1a and 1b show the resulting scaled cross sections  $1/(\beta N_{ev}) (dN_{b\bar{b}}^\pi/dx)$  and  $1/(\beta N_{ev}) (dN_{c\bar{c}}^\pi/dx)$ . Decay products of particles with lifetimes less than  $5 \times 10^{-10} \text{ s}$  are included in the cross sections. The cross section for  $\pi^\pm$  from light quark (u, d, s) jets (fig. 1c) is calculated using the “heavy” jet results and assuming that average jets are 1/11 b jets, 4/11 c jets and 6/11 light quark jets. We see that the pion cross section at low  $x$  is larger for  $b\bar{b}$  events than for average events. However, there is no statistically significant difference between the pion cross section for  $c\bar{c}$  events and for the average events. The figures also show the predictions from the Lund Monte Carlo, which are in good agreement with our data.

Table 1

The components of the prompt lepton events samples due to: b decay to lepton, c decay to lepton, the cascade decay b to c to lepton, and background.

Tag	b quark	c quark	b→c	Background	Events
$e(p_t < 1)$	$12 \pm 2\%$	$57 \pm 8\%$	$7 \pm 1\%$	$24 \pm 6\%$	279
$e(p_t > 1)$	$65 \pm 6\%$	$20 \pm 3\%$	$4 \pm 1\%$	$11 \pm 3\%$	83
$\mu(p_t < 1)$	$15 \pm 3\%$	$49 \pm 5\%$	$5 \pm 1\%$	$31 \pm 3\%$	565
$\mu(p_t > 1)$	$61 \pm 6\%$	$17 \pm 4\%$	$3 \pm 1\%$	$19 \pm 2\%$	193

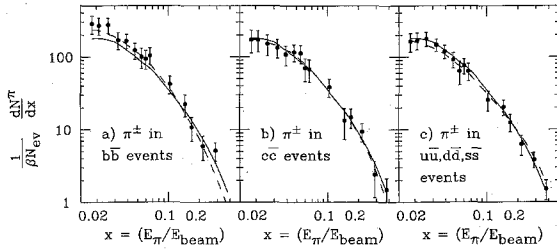


Fig. 1. The  $\pi^\pm$  scaled differential cross section per event for (a)  $e^+e^- \rightarrow b\bar{b}$  events, (b)  $e^+e^- \rightarrow c\bar{c}$  events, and (c)  $e^+e^- \rightarrow u\bar{u}/d\bar{d}/s\bar{s}$  events. The solid line shows the measured cross section for average events for comparison. The dashed lines give the predictions from the Monte Carlo [8] (see footnote 2) for (a)  $b\bar{b}$ , (b)  $c\bar{c}$ , and (c)  $u\bar{u}/d\bar{d}/s\bar{s}$ .

Cross sections summed over charged hadron species are derived in a similar fashion, and are displayed in fig. 2. They also show an excess of hadrons at low  $x$  for  $b\bar{b}$  events, and are also in good agreement with the Lund Monte Carlo.

The mean number of pions  $N^\pi$  and total hadrons  $N^h$  per event are found by summing up the scaled differential cross sections in the  $x$  regions where they

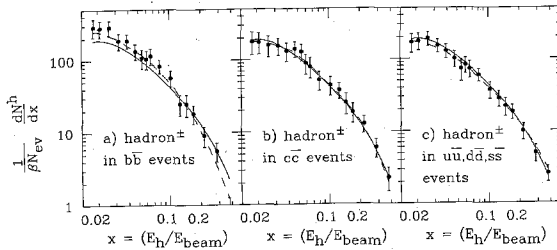


Fig. 2. The charged hadron scaled differential cross section per event for (a)  $e^+e^- \rightarrow b\bar{b}$  events, events, (b)  $e^+e^- \rightarrow c\bar{c}$  events, and (c)  $e^+e^- \rightarrow u\bar{u}/d\bar{d}/s\bar{s}$  events. The solid line shows the measured cross section for average events for comparison. The dashed lines give the predictions from the Monte Carlo [8] (see footnote 2) for (a)  $b\bar{b}$ , (b)  $c\bar{c}$ , and (c)  $u\bar{u}/d\bar{d}/s\bar{s}$ .

are measured, and using a functional form (the sum of two exponentials) fitted to the measured regions to fill in the gaps. The contributions from unmeasured  $x$  regions are on the order of 25%. The resulting multiplicities of charged pions and total charged hadrons are given in table 2, along with comparison numbers from the Lund Monte Carlo. A second method of finding the total multiplicity (fitting the distribution of the number of charged hadrons per "heavy" jet with an efficiency matrix times a functional form for the number of generated tracks) was also used and gave very similar results.

To derive kaon multiplicities, we do  $dE/dx$  fitting and quark tag unfolding in only five momentum bins because of low statistics for the kaons. We are not able to constrain a multi-parameter functional form as we did when summing up the multiplicity for pions, and thus use a Monte Carlo momentum spectrum and only fit the normalization. The systematic errors on this spectrum are estimated by changing the parameters of the fragmentation functions in the Lund Monte Carlo. The resulting kaon multiplicities are given in table 2. The errors for  $N_{b\bar{b}}^K$  and  $N_{c\bar{c}}^K$  are highly correlated, as can be seen in the contour plot in fig. 3. This figure shows that heavy quark events contain more kaons than average events, although we are unable to determine what fraction of this excess is due to  $b\bar{b}$  events as opposed to  $c\bar{c}$  events.

To find  $p, \bar{p}$  multiplicities, we count the number of  $\bar{p}$  in the range of 0.50–1.35 GeV/c, where  $dE/dx$  for  $\bar{p}$  is very well separated from  $dE/dx$  for other particles. Only the anti-protons are used because of the large proton background from secondary interactions. We use the Lund Monte Carlo to extrapolate the total proton multiplicity from the measured range. After background subtraction and sample unfolding, we obtain the results listed in table 2. Within the very

Table 2

The measured multiplicities of  $\pi^\pm$ ,  $K^\pm$ ,  $p(\bar{p})$  and total charged hadrons in different  $e^+e^- \rightarrow q\bar{q}$  events, with combined statistical and systematic error estimations. Also shown are the Monte Carlo predictions.

	$N^\pi$	$N_{MC}^\pi$	$N^K$	$N_{MC}^K$	$N^p$	$N_{MC}^p$	$N^h$	$N_{MC}^h$
$b\bar{b}$	$13.8 \pm 1.0$	12.2	$1.7 \pm 0.6$	2.1	$0.7 \pm 0.6$	0.3	$15.9 \pm 1.0$	14.6
$c\bar{c}$	$10.8 \pm 0.9$	10.6	$2.0 \pm 0.5$	1.7	$0.6 \pm 0.5$	0.6	$13.2 \pm 0.9$	12.9
$u\bar{u}/d\bar{d}/s\bar{s}$	$10.1 \pm 0.9$	10.0	$0.9 \pm 0.4$	1.2	$0.6 \pm 0.4$	0.7	$12.0 \pm 0.9$	11.9
average	$10.7 \pm 0.5$	10.4	$1.4 \pm 0.1$	1.4	$0.6 \pm 0.1$	0.6	$12.8 \pm 0.6$	12.4

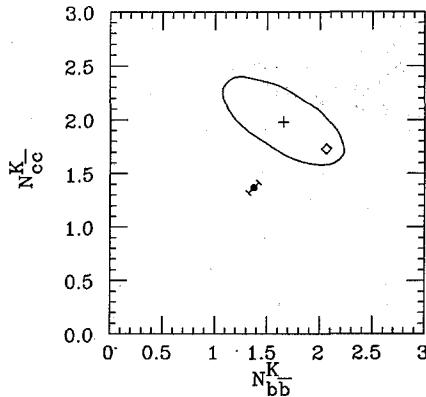


Fig. 3. The one standard deviation contour of the fit for the multiplicities of  $K^\pm$  in  $b\bar{b}$  and  $c\bar{c}$  events. In the plot “+” is the result for the fit for  $N_{bb}^K$  and  $N_{cc}^K$ . The “•” is the measured  $K^\pm$  multiplicity in average  $q\bar{q}$  events, plotted for comparison. The “◊” shows the Monte Carlo prediction [8] (see footnote 2).

large errors, we are unable to find any difference in proton multiplicities for the various event flavors.

Defining the decay products of the heavy hadrons which contain the primary b or c quarks as the “leading” part of the event, we can learn something about the properties of the remaining “nonleading” part of the heavy quark event by comparing the nonleading multiplicity with total multiplicity measured for  $e^+e^- \rightarrow q\bar{q}$  at an  $E_{cm}$  equal to the nonleading energy.

We calculate the multiplicities of all charged tracks (adding leptons from heavy quark decays to the hadron multiplicities found above) to be  $16.7 \pm 1.0$  and  $13.5 \pm 0.9$  for  $b\bar{b}$  and  $c\bar{c}$  events respectively. The multiplicity of the leading part of  $b\bar{b}$  events is taken directly from the CLEO [9] measurement of  $11.0 \pm 0.3$  for the multiplicity of  $B\bar{B}$  events. To obtain the leading multiplicity in  $c\bar{c}$  events, we first assume the leading hadrons to be  $D^*$  and  $D$  in the ratio 3 : 1. We take  $BR(D^{*+} \rightarrow D^0\pi^+) = 0.5$ , and include that  $\pi^+$

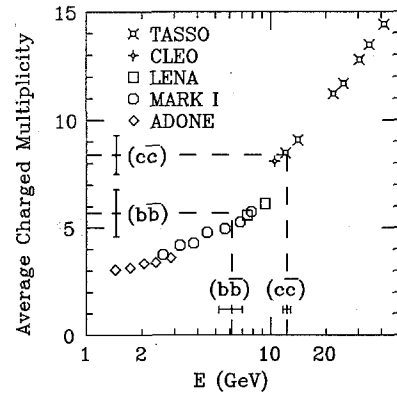


Fig. 4. The horizontal dashed lines show the nonleading multiplicities for bottom and charm events found in this experiment. The vertical dashed lines show the nonleading energies for bottom and charm events at this experiment’s  $E_{cm}$ , found using fragmentation measurements [11]. The intersection of these lines is compared with a compilation of data for average multiplicity versus CM energy in  $e^+e^-$  annihilation [12].

in the leading multiplicity. Then using the Mark II [10] measurements of  $2.47 \pm 0.14$  and  $2.16 \pm 0.16$  for the multiplicities of  $D^0$  and  $D^+$ , we obtain a total leading multiplicity of  $5.1 \pm 0.3$  per  $c\bar{c}$  event. Multiplicity differences due to other charm and bottom states are not included. Using our data for the total multiplicities, the nonleading multiplicities in heavy quark events are then  $N_{bb}^{nl} = 5.7 \pm 1.1$  and  $N_{cc}^{nl} = 8.4 \pm 0.9$ .

Relating the average nonleading energy  $\langle E_{q\bar{q}}^{nl} \rangle$  to the mean energy fraction of the heavy hadrons  $\langle X_q \rangle$  by  $\langle E_{q\bar{q}}^{nl} \rangle = E_{cm}(1 - \langle X_q \rangle)$  and using world average values [11] of  $\langle X_b \rangle = 0.79 \pm 0.03$  and  $\langle X_c \rangle = 0.58 \pm 0.02$  gives  $\langle E_{bb}^{nl} \rangle = 6.1 \pm 0.9$  GeV and  $\langle E_{cc}^{nl} \rangle = 12.2 \pm 0.6$  GeV. Fig. 4 shows representative multiplicity data for  $e^+e^-$  annihilation over a large range of center-of-mass energies [12]. In the figure, we compare our nonleading multiplicity with the

$e^+e^-$  multiplicity at an  $E_{\text{cm}}$  equal to this nonleading energy. The agreement is good, and we conclude that the hadronization of the nonleading part is proceeding in a manner independent of the leading flavor.

In summary, we measure inclusive spectra of charged pions and of charged hadrons in  $b\bar{b}$  events, in  $c\bar{c}$  events and in light quark ( $u\bar{u}$ ,  $d\bar{d}$ , or  $s\bar{s}$ ) events. The pion and hadron cross sections at low  $x$ , and hence the average multiplicities of pions and hadrons, are higher for  $b\bar{b}$  events than for average hadronic events. However, we find no statistically significant difference between pion or hadron rates in  $c\bar{c}$  events as compared to average events. The charged kaon multiplicity is found to be higher in heavy quark events than in light quark events. These results are consistent with data from other experiments, where available, and with predictions of the Lund Monte Carlo. Nonleading multiplicities determined for heavy quark events agree with the total multiplicities measured in annihilation events at a correspondingly reduced CM energy.

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