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Fragmentation of Heavy Quarks Produced in e^+e^- Annihilation*

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ABSTRACT

Identification of muons in hadronic events from e^+e^- annihilation observed in the MAC detector at PEP provides flavor tagging of heavy primary quarks. A sample enriched in events from $b\bar{b}$ production is obtained and the b quark fragmentation function is inferred from the momentum spectrum of the muons. The b quark is found to fragment predominantly with high values of z, with $<z_b> = 0.8 \pm 0.1$, and to have an overall semimuonic branching fraction of $(15.5\,^{+5.4}_{-2.9})\%$.

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Detection of muons in hadronic events produced in electron-positron annihilation is a signature of weak decays of heavy quarks, and provides a means of tagging events originating from heavy quarks. The spectrum of the muon momentum transverse to the jet direction is determined by the mass of the decaying particle, and can be used to separate events with b parent quarks from those originating from c quarks. With this method, fragmentation of the b quark can be studied by analyzing the momentum spectrum of the muons from b decay. Based on the inclusive muon spectrum measured by the MAC detector at PEP, with center of mass energies at or near 29 GeV, we obtain a new, high-statistics determination of the b fragmentation function.

The MAC detector has been described in detail elsewhere.[1] Briefly, the detector is centered around a cylindrical drift chamber for tracking charged particles.[2] The chamber consists of ten layers of drift cells, of which six are skewed by plus or minus three degrees from the beam axis to provide position measurement in all three dimensions. The drift chamber is surrounded by a solenoid coil providing a magnetic field of 5.7 kG, and, in a hexagonal geometry, by a shower chamber followed by a hadron calorimeter. Layers of lead interspersed with proportional wire chambers constitute the shower chamber, amounting to 16 radiation lengths of material. The hadron calorimeter alternates layers of steel with proportional wire chambers, with normally incident particles traversing 90 cm of steel. The hadron calorimeter and the shower chamber are each segmented into 192 azimuthal sectors and three radial layers from which independent readouts are obtained. Charge division is used to determine the axial position of showers in both detectors. Two endcap calorimeters, alternating steel and proportional chambers, provide calorimetry at angles greater than 10 degrees from the beam. The solid angle subtended by calorimeters is therefore about 98% of 4π. Both the hadron calorimeter and the endcaps are surrounded by toroid coils, which provide a field of 17 kG.

The entire calorimetric detector is surrounded by drift chambers whose purpose is muon tracking. These chambers determine the radial and axial components of the location and direction of particles penetrating the hadron calorimeters. For the present analysis, chambers covering all of the central hadron calorimeter and much of the endcaps are used, subtending a total solid angle of 77% of 4π. Five of the sextants have four layers of cylindrical drift cells, each with 88 cells per sextant, while the remaining sextant has three layers of drift planes.

The parent sample for this analysis consists of 25000 multihadron events, each having more than 4 charged prongs and energy deposited in all calorimeters greater than the beam energy.[3] The sample corresponds to integrated luminosities of 52 pb^{-1} at 29 GeV center-of-mass energy and 2 pb^{-1} at 28 GeV. Within these events, tracks reconstructed in the drift chambers surrounding the calorimeter constitute muon candidates. A momentum assignment is made for each of these tracks by extrapolating it back through the toroidal magnetic field of the calorimeter to the primary event vertex, taking into account the ionization loss of the particle in the calorimeter. In order to obtain the azimuthal component of the momentum vector, it is required that the track be matched to a segment reconstructed from the energy deposited in the central or endcap calorimeter. The momentum resolution is about 30%, due mostly to multiple scattering.

It is required that the momentum assigned to the muon candidate be greater than 2 GeV/c. This cut discriminates against backgrounds both from the decay in flight of pions and kaons to muons, which is more copious for particles with low momenta, and from leakage of particles from hadronic cascades in the calorimeters ("punch-through"). The latter particles often emerge at wide angles with respect to the incident hadron direction, leading to a soft apparent momentum spectrum. Further discrimination against punch-through is achieved by rejecting candidate tracks (1) whose path length through the iron in the calorimeters is less than about 80 cm (one-third of candidates removed by this cut); (2) with evidence in the outer drift chamber of more than one particle having emerged from the calorimeter in the same vicinity (17% of candidates removed); or (3) with ionization in the outermost calorimeter layer in more than two adjacent segments (5% of candidates removed). A few non-hadronic events are removed from the remaining sample by scanning. The final sample contains 476 events.

To estimate the remaining background and to study heavy flavor decay, we have constructed a Monte Carlo model to simulate the production and decay of hadrons[4] and to trace in detail their interactions and the response of the detector.[5] With this model, we find the level of background remaining in the sample from π and K decays to be $(23 \pm 1)\%$. The calculation also provides the spectra for both decay and punch-through backgrounds used in the analysis described below.

Because the magnitude of the punch-through background is sensitive to the modelling of the tails of distributions, we determine this level empirically. The hadronic decays of tau leptons provide a source of purely hadronic jets. From a sample of 1600 tau pair events, we find roughly 3 muon candidates in hadronic jets attributable to punch-through, after the decay contribution has been subtracted. Differences between the energy spectra of tau and multihadron jets are accounted for by taking the ratio of the energy deposited in the outermost calorimeter layer in the two samples. From these studies, we find the punch-through fraction in the inclusive muon sample to be $(9 \pm 7)\%$.

The fragmentation function of a quark is defined as the probability distribution of the fragmentation variable z, which is the fraction of a quark's $E + p_{||}$ ($p_{||}$ denotes the component of momentum along the original quark axis) carried off by the meson containing that quark. According to the model of Field and Feynman,[6] one of a pair of quarks from the sea is the other constituent of that meson, and the remaining $E+p_{||}$ is taken by the other member of the pair, which fragments by drawing further pairs of quarks from the sea. The fragmentation functions for the heavy quarks have not been determined to any great precision, while those for the light quarks are well-understood, and peak at low values of z. Theoretical arguments[7] favor a function that is peaked at higher values of z for greater quark mass.

Since it is the meson containing the heavy quark that decays, producing a muon, the momentum spectrum of the mesons will determine that of the muons. But for each quark flavor, the distribution of the component of the muon's momentum perpendicular to the thrust axis ($p_{\perp}$) is roughly independent of the fragmentation function, except for normalization. Shown in Fig. 1 is the $p_{\perp}$ spectrum of the observed muons, along with Monte Carlo predictions for muons from b and c quarks, and the overall (decay plus punch-through) background prediction. The b and c quark predictions are normalized according to the best fit obtained as described below. It should be noted that the background is concentrated at low values of $p_{\perp}$, and is well separated from the $b\bar{b}$ predicted spectrum.

As we have noted, the muon's total momentum is sensitive to the fragmentation function, while cuts on $p_\perp$ are useful in obtaining samples enriched in $c\bar{c}$ or $b\bar{b}$ events. Accordingly, events were binned by p and $p_\perp$ into a 20 element array with $p_\perp$ lower limits at 0, 0.5, 1, and 1.5 GeV/c, and p lower limits at 2, 3, 4, 5, and 6 GeV/c. In order to use these data to constrain the fragmentation functions, the functions for the c and b quarks were approximated by coarse (6-interval) histograms with adjustable heights for each z interval. Monte Carlo events were generated using these "functions," and the heights of the z intervals and the overall c and b quark branching ratios to muons were adjusted to obtain best fits to the data. Fits were constrained so that the histogram for each quark was appropriately normalized, the heights were non-negative, and each resulting histogram approximation of a fragmentation function had a single peak. For the c quark, the 6 regions of z are equal divisions of the range $0 < z_c < 1$. For the b quark, the regions of z equally divide the range $0.4 < z_b < 1$; all functions compatible with the data have small values for $0 < z_b < 0.4$.

Fig. 2 shows the momentum spectrum for muons with $p_\perp > 1.5$ GeV/c, the region containing the highest fraction of $b\bar{b}$ events. The dashed lines illustrate the effect of fixing the b fragmentation function at particular values of z (i.e., only one interval of z has non-zero weight), and allowing the c fragmentation function and the semileptonic branching fractions of both quarks to vary to obtain best fit to the p by $p_\perp$ array. It can be seen that low values of $<z_b>$ are ruled out. The solid curve is the predicted spectrum for the best fit, allowing all parameters to vary.

The shaded region in Fig. 3 is the one standard deviation envelope of all b quark fragmentation functions with predicted spectra that yield acceptable fits; in other words, it contains the set of all histograms of the b fragmentation function that are properly normalized, have a single peak, and are consistent with the data. It is found that $<z_b> = 0.8 \pm 0.1$. A variety of functions produce chi-squares that are very close to the best-fit value; all of these have most of their contribution in the interval $0.8 < z_b < 0.9$. The semimuonic branching ratio for the b quark, averaged over the neutral and charged B mesons that decay, is found to be $(15.5^{+5.4}_{-2.9})\%$.

A broad range of c fragmentation functions is permitted by the data, with the one-sigma envelope allowing $0.17 < \langle z_c \rangle < 0.67$. The semimuonic branching fraction is found to be $(7.6^{+9.7}_{-2.7})\%$; the large uncertainty is due to the dependence of the branching fraction on the exact fragmentation function.

A specific functional form for fragmentation, suggested by Peterson *et al.*,[8] has

$$D_q(z) \quad \propto \quad \left(z(1 - \frac{1}{z} - \frac{\epsilon_q}{1-z})^2 \right)^{-1}$$

For this functional form, we find that $\epsilon_b = 0.008^{+0.037}_{-0.008}$, but with a somewhat worse chi-square than for a more sharply peaked function. The function with $\epsilon_b = 0.008$ is shown in Fig. 3.

In conclusion, the fragmentation function of the b quark is determined to be peaked at $z_b \approx 0.8$, in agreement with a result from Mark II using inclusive electrons.[9] The c quark fragmentation function peaks with $z_c < 0.67$, a result consistent with direct measurements of the momenta of D* mesons.[10] The measured overall semimuonic branching fraction for the b quark of $(15.5^{+5.4}_{-2.9})\%$ is consistent with the best measurement.[11] The results of this analysis, therefore, fully confirm the postulated hard fragmentation behavior of heavy quarks.

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FIGURE CAPTIONS

1. $p_\perp$ spectrum of muons with $b\bar{b}$ (dashed curve), $c\bar{c}$ (dot-dashed), background from decay and punch-through (dotted), and total (solid curve) predictions.
2. Total momentum of muons with $p_\perp > 1.5$ GeV/c. Dashed curves are the best fits obtained with the b fragmentation fixed to a narrow range of z. The solid curve is the best overall fit.
3. The shaded region is the envelope of acceptable b quark fragmentation functions. The curve represents the Peterson *et al.* function (see Ref. 5) for $\epsilon_b = 0.008$.

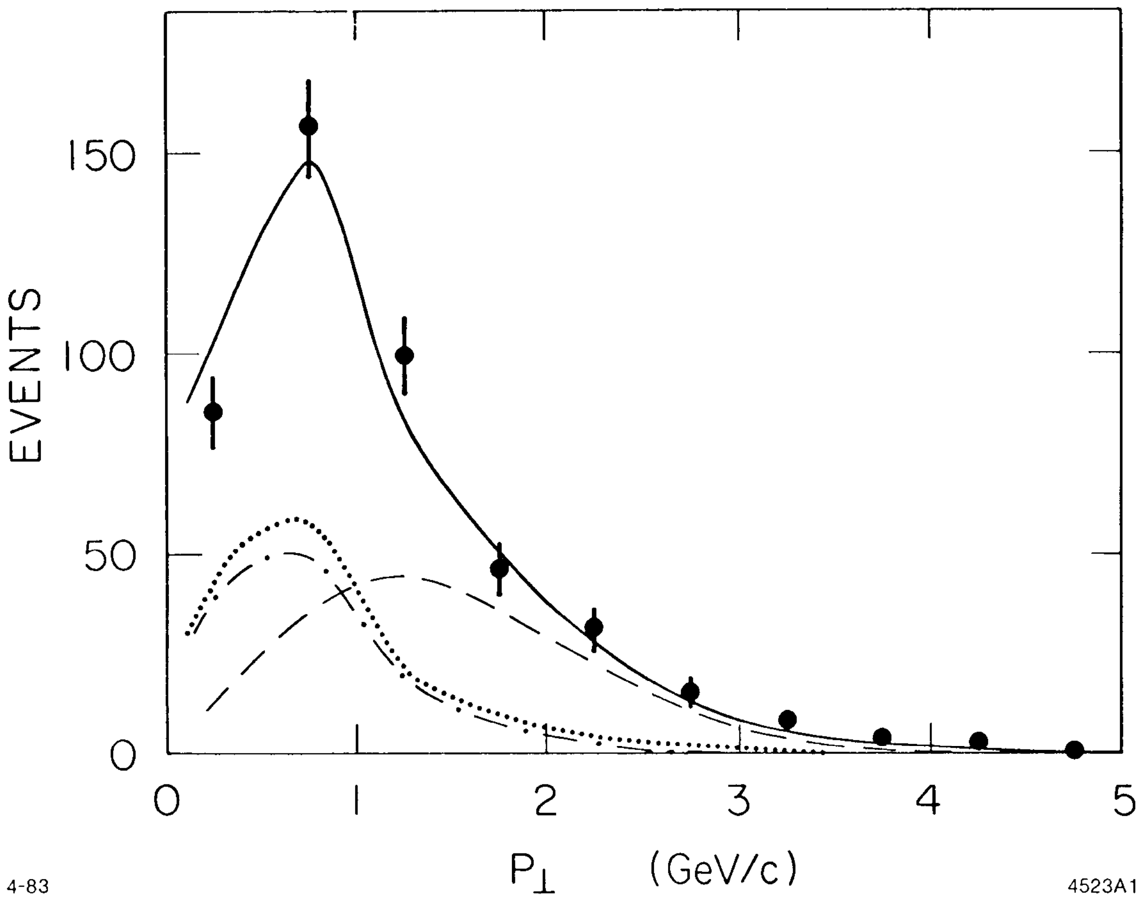

Fig. 1

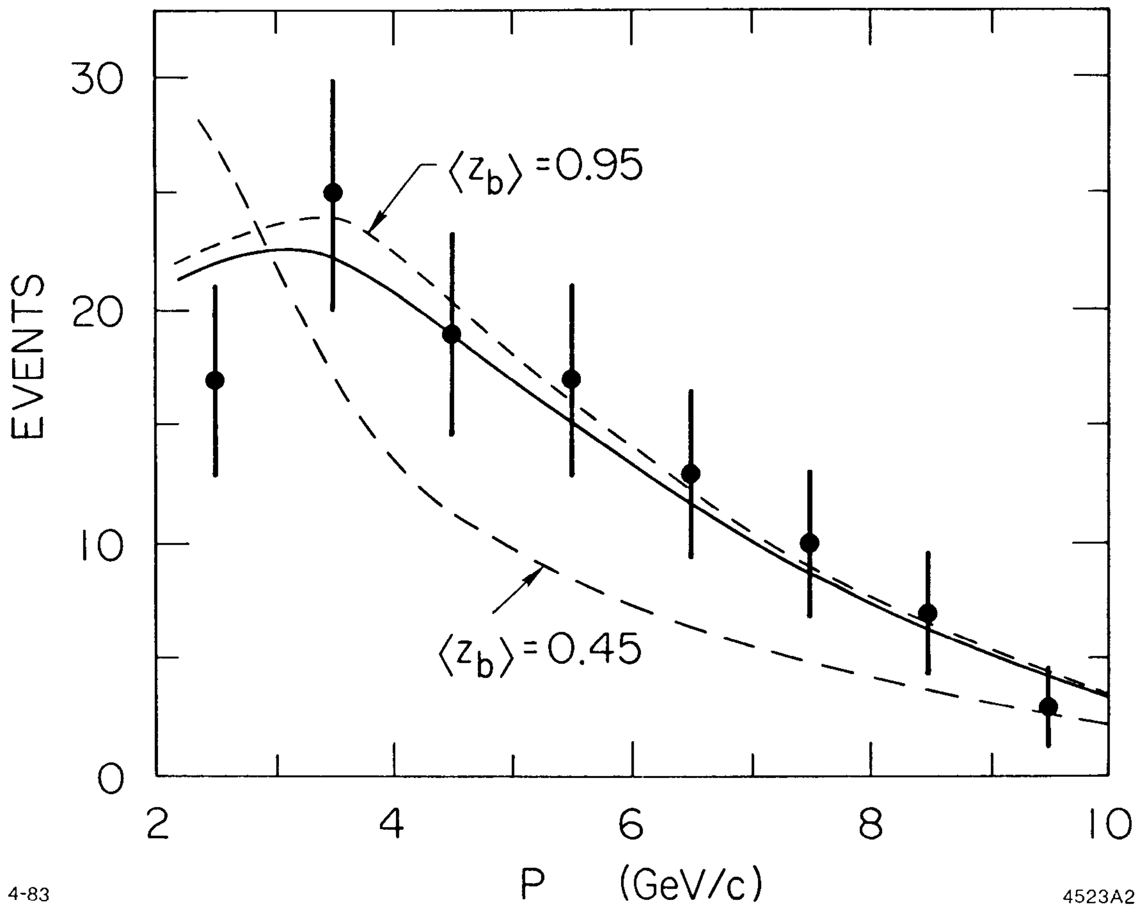

Fig. 2

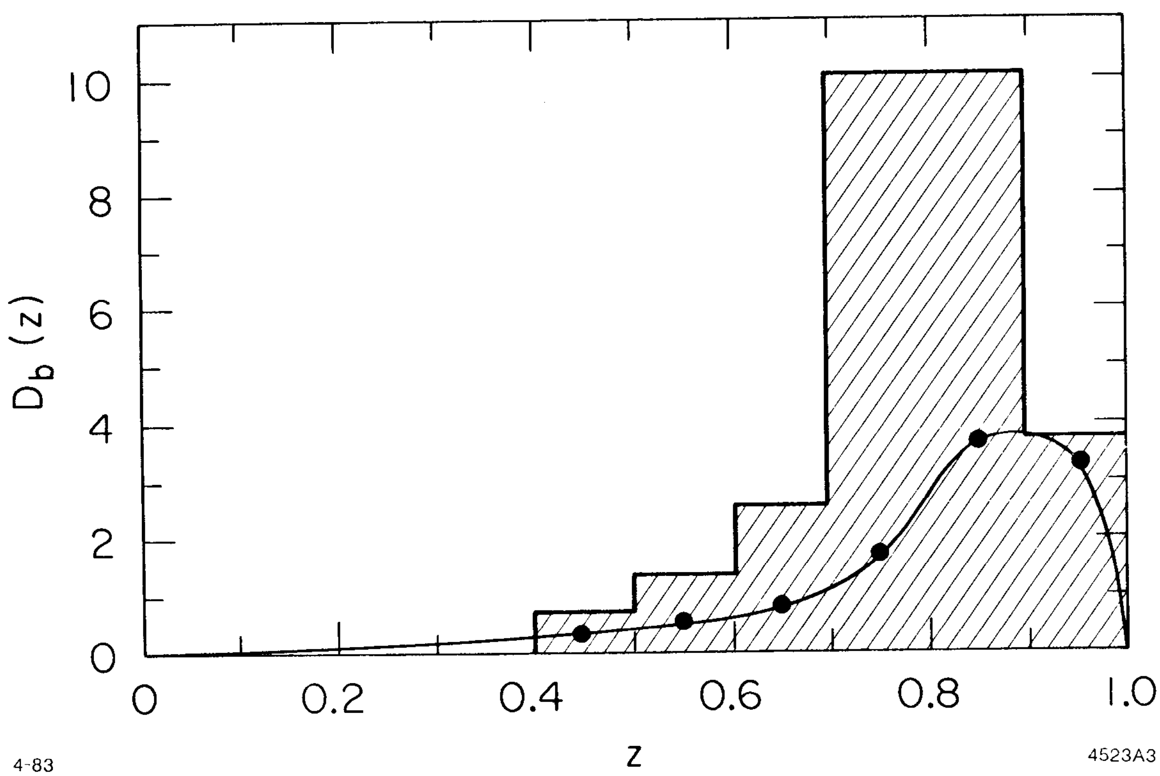

Fig. 3