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Prompt muon production in e^+e^- annihilations at 29 GeV

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We have studied the production of prompt muons in hadronic events from e^+e^- annihilation at a center-of-mass energy of 29 GeV with the PEP4-TPC (Time Projection Chamber) detector. The muon p and p_t distributions are well described by a combination of bottom- and charm-quark decays, with fitted semimuonic branching fractions of $(15.2\pm1.9\pm1.2)\%$ and $(6.9\pm1.1\pm1.1)\%$, respectively. The muon spectra imply hard fragmentation functions for both b and c quarks, with $\langle z(b \text{ quark})\rangle=0.80\pm0.05\pm0.05$ and $\langle z(c \text{ quark})\rangle=0.60\pm0.06\pm0.04$. We derive neutral-current axial-vector couplings of $a(b \text{ quark})=-0.9\pm1.1\pm0.3$ and $a(c \text{ quark})=1.5\pm1.5\pm0.5$ from the forward-backward asymmetries.

Semileptonic decays of heavy quarks are the main source of prompt leptons in multihadron events from e^+e^- annihilation. A consequence of the large mass difference between bottom (b) and charm (c) quarks is that leptons from their decays populate different regions of transverse momentum (p_t), measured with respect to the quark-antiquark jet axis. Leptons from bottom decays dominate at high p_t, whereas leptons from charm decays dominate at low p_t. In this paper we use the muon p_t to make a statistical separation of $b\bar{b}$ and $c\bar{c}$ events. We measure three properties of heavy-quark production with this technique. First, the muon production rate yields the semimuonic branching fractions of hadrons containing b and c quarks. Second, the momentum spectrum of the muons provides a measurement of the average energy carried by the heavy quarks. Finally, the direction of the flavor-tagged jet axis with respect to the beam determines the quark forward-backward asymmetry and thus the heavy-quark neutral-current axial-vector couplings.

Our measurement of prompt muons in multihadron annihilation events makes use of two components of the PEP4-TPC detector,[1] the Time Projection Chamber (TPC) and the muon-detection system. The TPC measures both the momentum and the ionization energy loss (dE/dx) for each track. The momentum resolution in the 4-kG magnetic field is given by

$$(dp/p)^2=(0.06)^2+(0.035p)^2 ,$$

where p is the momentum in GeV/c. The ionization energy loss is sampled up to 183 times along a track, providing dE/dx resolution of typically 3.7%. The muon chamber system[1,2] consists of layers of extruded triangular drift tubes 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 $55° < \theta < 125°$. These chambers are arranged in four layers, three with wires parallel to and one with wires orthogonal to the beam direction. This central muon detector has a minimum depth of 95 cm of iron, and covers 57% of 4π steradians.

The data, accumulated at a center-of-mass energy of 29 GeV, correspond to an integrated luminosity of 77 pb^{-1}. Multihadron events are selected by requiring that at least five charged tracks pass the following fiducial criteria: the track's angle from the beam axis must be greater than 30°, its momentum must be greater than 120 MeV/c, and it must extrapolate back to within 6 cm (10 cm) of the nominal interaction point in the direction perpendicular (parallel) to the beam axis. Two-photon and beam-gas events are eliminated by requiring that the total charged energy be greater than 7.25 GeV, and that the sum of the charged-particle momenta along the beam direction be less than 40% of the total charged momentum. $\tau\bar{\tau}$ events are rejected with a mass cut on three-prong jets and the requirement that the thrust for the event be less than 0.99. To minimize uncertainties in the acceptance and jet-axis reconstruction, only events with the thrust axis more than 45° from the beam axis are used. The data sample contains 24 396 events satisfying these requirements.

Muon candidates are initially selected by requiring that particles detected in the TPC penetrate the iron with a hit in each of the four muon-chamber layers. Fiducial cuts are applied by requiring that each track have an angle greater than 55° with respect to the beam axis and a momentum greater than 2 GeV/c (below which momentum muons range out in the iron) and less than 8 GeV/c (above which momentum hadron punch-through dominates). This initial muon sample contains 1094 candidates. Of these candidates, $(43\pm6)\%$ are shown by Monte Carlo simulation to be muons from kaon or pion decay, or hadrons punching through the iron. With these fiducial cuts the efficiency for detecting muons is measured with cosmic rays to be greater than 98%.

To reduce the background in the muon sample we apply two additional cuts:

(1) We require that the sum of the squares of the normalized residuals for the two outermost muon-chamber layers be less than 3.5. The normalized residual is defined as the distance of the muon-chamber hit from the extrapolated track, divided by the expected uncertainty due to multiple Coulomb scattering, extrapolation error, and muon chamber resolution. This cut retains between 85% and 95% of the prompt muons depending on the momentum.

(2) We require that the muon candidate have 40 or more ionization samples and that the dE/dx measurement be consistent with the expected dE/dx for a muon within two standard deviations. This cut retains between 78% and 86% of prompt muons depending on the transverse momentum p_t. This dependence results from the requirement of 40 good ionization samples, a requirement less likely to be met by low p_t tracks which tend to overlap with other tracks in the core of the jet.

The final muon sample contains 644 candidates.

The prompt-muon efficiencies and the backgrounds from $\pi \to \mu$ and $K \to \mu$ decays and hadrons punching through the muon-absorber iron are determined using detailed Monte Carlo[3] simulations of the PEP4-TPC detector. Individual Monte Carlo runs determine the probability for positive and negative pions, kaons, protons, and muons to satisfy the muon-chamber requirements as a function of momentum and angle. The number of background "muons" is then predicted either by convoluting the single-particle misidentification probabilities over the hadrons as measured in the actual data sample or by using these probabilities in an e^+e^- annihilation Monte Carlo that is tuned to reproduce both the measured hadron distribution and the dE/dx performance of the TPC. These two methods give consistent results. The momentum distribution for the final muon candidates and the background distribution predicted by the Monte Carlo are shown in Fig. 1 for two p_t intervals. The total background values are 18% for the p_t interval above 1.0 GeV/c and 30% for the interval below 1.0 GeV/c. The background consists of 53% pion decay, 22% pion punch-through, 17% kaon decay, and 8% kaon punch-through.

We check the Monte Carlo simulation in several ways. First, we use three-prong τ decays to provide a nearly pure source of pions. In a sample of 660 $\tau\bar{\tau}$ events which decay to 1 + 3 prongs,[4] eight muon candidates are found in the three-prong decays. This agrees with the Monte Carlo prediction of 7.7 tracks from pion decay and punch-through. Second, in the multihadron sample itself, we use dE/dx to check how well the hadron backgrounds are understood. Figure 2 shows the distribution of dE/dx for TPC tracks in the muon chamber acceptance region divided by the dE/dx expected for pions of the same momentum. Figure 2(a) contains those tracks which do not have associated hits in the muon chambers; Figure 2(b) contains the muon candidates. In comparison to Fig. 2(a), the main peak in Fig. 2(b) is shifted towards higher dE/dx, as expected for muons.[5] A fit to the number of

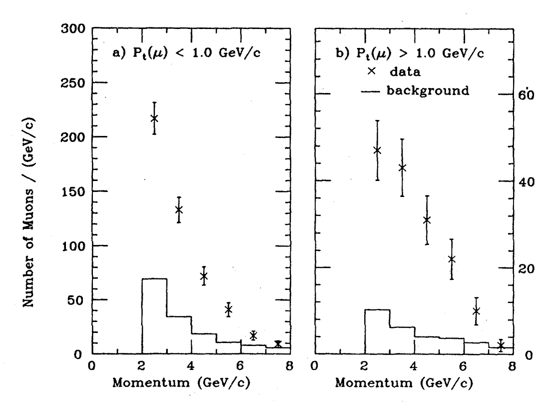

FIG. 1. Muon momentum spectra ($2 < p < 8$ GeV/c): (a) for $p_t < 1.0$ GeV/c and (b) for $1.0 < p_t < 2.0$ GeV/c where p_t is the transverse momentum of the muon relative to the event thrust axis. The solid line is the estimated background from hadron decay and punch-through.

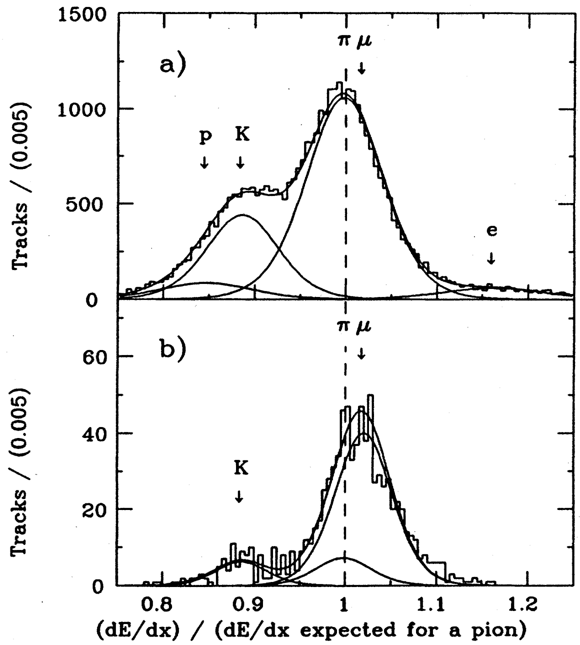

FIG. 2. The measured dE/dx divided by the dE/dx expected for a pion for tracks with 2.0 GeV/c $<p<$ 8.0 GeV/c, $55^\circ<\theta<125^\circ$, and at least 40 good dE/dx samples on the track: (a) for tracks that do not have associated hits in the muon chambers, and (b) for tracks that do. The solid curves show the fitted amounts of protons, kaons, pions, muons, and electrons in these data.

particles of each species in Fig. 2(b) yields 650 ± 60 muons, 116 ± 56 pions, 95 ± 14 kaons, and 9 ± 8 protons. The corresponding predictions from the background Monte Carlo are 170 pions, 106 kaons, and 7 protons. The good agreement between these results, in particular for the cleanly separated kaons, demonstrates the reliability of our detector simulation and punch-through calculations. Third, sample sizes obtained from the data and Monte Carlo always agree to better than 10% as the selection cuts are varied.

In order to translate the measured prompt-muon p and p_t distributions into the heavy-quark semimuonic branching fractions and fragmentation functions, we employ the Lund model[6] to generate e^+e^- annihilation events. In this model b quarks always decay to c quarks.[7] We include the effects of initial-state photon radiation[8] and a full simulation of the detector acceptance. With this Monte Carlo, we determine the probabilities for the heavy-quark semileptonic decays to produce a muon with a given p and p_t as a function of the quark type and of the fractional initial energy,

$$z=E(\text{hadron})/E(\text{beam}) ,$$

of the first hadron containing the heavy quark. We determine separate probabilities for $b\to\mu$, $b\to c\to\mu$, and $c\to\mu$ decays as a function of p, p_t, and z.

We fit the prompt-muon data using the following four parameters: the branching fraction of $b\to\mu$, the branching fraction of $c\to\mu$, and the parameters ϵ_b and ϵ_c of the Peterson-Schlatter-Schmitt-Zerwas heavy-quark fragmentation functions:[9]

$$D(z)\propto\frac{1}{z\left[1-\dfrac{1}{z}-\dfrac{\epsilon_q}{1-z}\right]^2} .$$

We parametrize $D(z)$ because our data is not sufficient to determine its detailed shape. Using the numbers of $b\bar{b}$ and $c\bar{c}$ events expected from the integrated luminosity, a background determined by the Monte Carlo, and the probability maps described in the preceding paragraph, we perform a two-dimensional maximum-likelihood fit in p and p_t. The resulting fit is shown in Fig. 3. The b and c semileptonic branching fractions into muons are found to be

$$B(b\to\mu)=(15.2\pm1.9\pm1.2)\%$$

and

$$B(c\to\mu)=(6.9\pm1.1\pm1.1)\% .$$

The first error is statistical and includes the effect of correlations among these variables; the second is systematic, with contributions from uncertainties in the background subtraction and event modeling. The corresponding fragmentation parameters are $\epsilon_b=0.011^{+0.015+0.011}_{-0.007-0.007}$ and $\epsilon_c=0.14^{+0.14+0.08}_{-0.07-0.05}$. These values of ϵ correspond to an average z for the leading hadron of $\langle z_b\rangle=0.80\pm0.05\pm0.05$ and $\langle z_c\rangle=0.60\pm0.06\pm0.04$. Thus the first hadron containing a heavy b or c quark retains most of the quark energy, as suggested by simple kinematical considerations.[10] The Monte Carlo indicates that in the absence of initial-state radiation the average z would increase to $\langle z_b\rangle=0.84$ and $\langle z_c\rangle=0.64$.

Figure 4 shows the acceptance for a muon as a function of the z of its heavy-hadron parent, as well as the shapes of the fragmentation parametrizations fitted above. Because of the limited sensitivity for charm fragmentation at low z, we also fit the data while fixing ϵ_c at 0.25 ± 0.05,

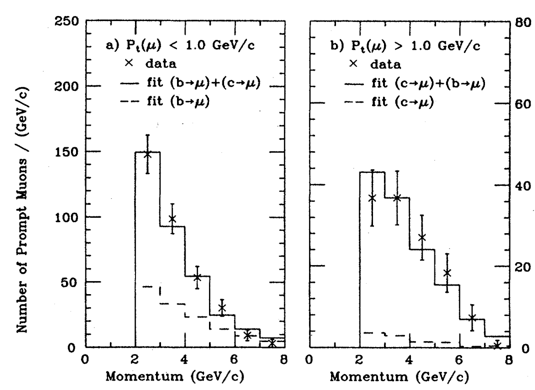

FIG. 3. Background-subtracted prompt muon spectra ($2<p<8$ GeV/c): (a) for $p_t<1.0$ GeV/c and (b) for $1.0<p_t<2.0$ GeV/c. The solid line is the result of the fit to the data and includes the heavy-quark-decay contributions $b\to\mu$, $b\to c\to\mu$, and $c\to\mu$. The dashed line shows the contribution from the "minority" source: for $p_t<1.0$ GeV/c this is the sum of $b\to\mu$ and $b\to c\to\mu$ decays, for $p_t>1.0$ GeV/c this is the contribution of $c\to\mu$ decays.

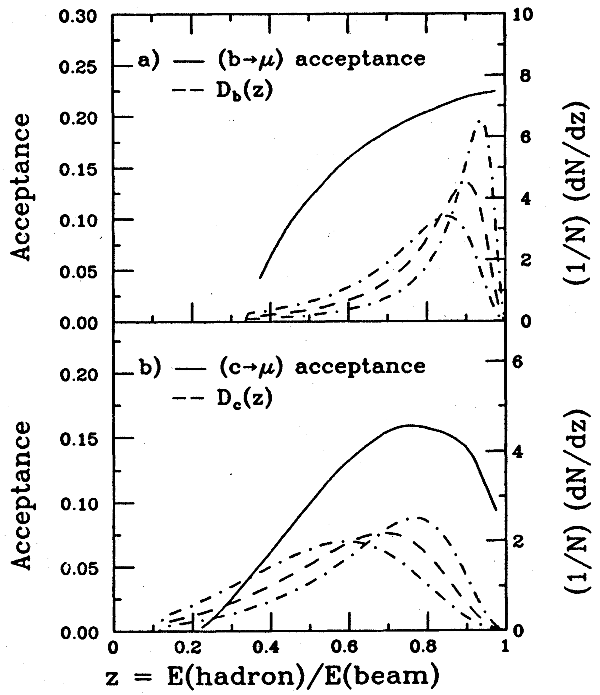

FIG. 4. The acceptance for muons from heavy-hadron decays as a function of $z = E(\text{hadron})/E(\text{beam})$ for (a) hadrons containing b quarks and (b) hadrons containing c quarks. The dashed curves are the shapes of the (a) b-hadron and (b) c-hadron fragmentation functions derived from fitting our data with the Peterson-Schlatter-Schmitt-Zerwas (PSSZ) form. The fitting error is indicated by plotting the PSSZ form for ϵ one standard deviation away from the fitted ϵ.

in accordance with D^* measurements from other experiments.[11] The resulting $B(c \to \mu)$ is $(7.7 \pm 0.8)\%$. The effect on the bottom results is small.

These semimuonic branching fractions for bottom and charm can be compared to the semielectronic values

$$B(b \to e) = (11.0 \pm 1.8 \pm 1.0)\%$$

and

$$B(c \to e) = (9.1 \pm 0.9 \pm 1.3)\%$$

measured by this experiment.[12] The average z_b measured with the prompt electrons[12] is

$$\langle z_b \rangle = 0.74 \pm 0.05 \pm 0.03 \;;$$

combining the muon and electron results gives

$$\langle z_b \rangle = 0.77 \pm 0.04 \pm 0.03 \;.$$

These results are consistent with the prompt-lepton data from other experiments.[13]

In the electroweak model of Weinberg and Salam, the interference between weak and electromagnetic amplitudes produces an asymmetry in the quark production angle with respect to the beam direction in $e^+e^- \to q\bar{q}$ annihilation events. The angular distribution[14] for the quark contains a term linear in $\cos(\theta)$,

$$\frac{d\sigma}{d\cos(\theta)} \propto 1 + C(q)\cos(\theta) + \cos^2(\theta) \;,$$

where θ is the angle between the initial-e^- direction and the scattered-quark direction. Assuming the quark charges of the standard model and taking the axial-vector coupling constants (in the notation of Ref. 15) to be $a(e) = -1$, $a(b) = -1$, and $a(c) = +1$, the asymmetry parameters for bottom and charm are predicted to be $C(b) = -0.48$ and $C(c) = -0.24$ at a center-of-mass energy of 29 GeV.

We use muons as a tag of heavy-quark flavor and charge in order to measure these asymmetry parameters. We divide the data into a $b\bar{b}$-enriched sample, $p_t > 1.0$ GeV/c, and a $c\bar{c}$-enriched sample, $p_t < 1.0$ GeV/c. Figure 5 shows the background-subtracted angular distribution of the jet-thrust axis with respect to the initial-e^- direction for each of these samples. The "forward" direction of the thrust axis is taken as the hemisphere containing the positive muon. Thus, θ_{jet} corresponds to θ_{quark} for $c \to \mu$ and $b \to c \to \mu$ decays, but corresponds to $\pi - \theta_{\text{quark}}$ for $b \to \mu$ decays.

To determine the b- and c-quark asymmetry parameters, we fit the data in the interval $-0.7 < \cos(\theta_{\text{thrust}}) < 0.7$ assuming the quadratic form of the quark angular distribution given above. The fit uses acceptance maps generated by the Monte Carlo simulation. The maps give the probability that a bottom or charm quark in a given interval of $\cos(\theta_{\text{quark}})$ produces a jet with a thrust axis in each interval of $\cos(\theta_{\text{thrust}})$ and an accepted muon in each p_t interval. The reconstructed thrust axis is typically at a slightly greater angle to the beam axis than the original quark direction because of the lack of acceptance for charged particles near the beam axis. This small systematic shift is corrected by the Monte Carlo map. We perform a maximum-likelihood fit simultaneously to the b-quark-enriched and c-quark-enriched angular distributions. The fit varies the values of $C(b)$, $C(c)$, and an overall normalization constant. The resulting fit is shown in Fig. 5. The angular-asymmetry parameters are

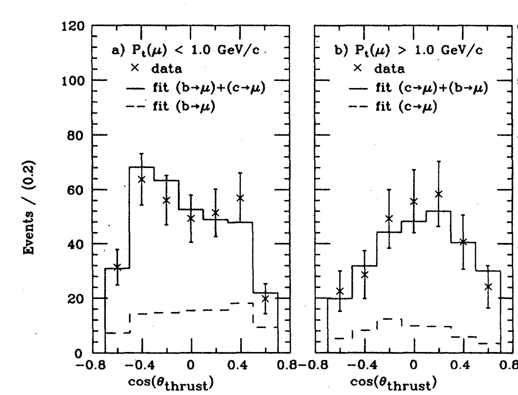

FIG. 5. Angular distribution of the event jet axis (see text) for events (a) in the c-enriched ($p_t < 1.0$ GeV/c) and (b) in the b-enriched ($p_t > 1.0$ GeV/c) samples. The distribution of background events, expected from hadrons that satisfy the muon identification criteria, has been subtracted. The solid curve is the result of the fit to the data of angular distributions for $e^+e^- \to c\bar{c}$ and for $e^+e^- \to b\bar{b}$ annihilation reactions. The dashed curve shows the contribution from the "minority" source: for $p_t < 1.0$ GeV/c this is $e^+e^- \to b\bar{b}$ and for $p_t > 1.0$ GeV/c this is $e^+e^- \to c\bar{c}$.

$C(b)=-0.41\pm0.52\pm0.14$ and $C(c)=-0.37\pm0.36\pm0.12$. These values correspond to the axial-vector coupling constants $a(b)=-0.9\pm1.1\pm0.3$ and $a(c)=1.5\pm1.5\pm0.5$. The systematic errors include contributions from uncertainties in the background, the b and c semileptonic branching fractions and fragmentation functions, and the effects of initial-state (photon) and final-state (gluon) radiation. Combining these measurements with those from the prompt-electron data from this same experiment,[12] we find

$$a(b)=-1.1\pm0.9\pm0.3$$

and

$$a(c)=1.9\pm1.0\pm0.4 .$$

These measurements agree with results from other SLAC PEP and DESY PETRA experiments,[15,16] and suggest that the sign of the coupling constant is as expected.

In summary, we use the prompt-muon data measured in the PEP4-TPC detector to determine several parameters of heavy-quark production and semileptonic decay. The average b- and c-quark semileptonic branching fractions into muons are $B(b\to\mu)=(15.2\pm1.9\pm1.2)\%$ and $B(c\to\mu)=(6.9\pm1.1\pm1.1)\%$. The b- and c-quark fragmentation functions are found to be "hard" with an average z of $\langle z_b\rangle=0.80\pm0.05\pm0.05$ and $\langle z_c\rangle=0.60\pm0.06\pm0.04$. Using the muon data with $p_t>1.0$ GeV/c to obtain an enriched sample of $b\bar{b}$ events and data with $p_t<1.0$ GeV/c to obtain a $c\bar{c}$ sample, we measure the b- and c-quark axial-vector coupling constants to be $a(b)=-0.9\pm1.1\pm0.3$ and $a(c)=1.5\pm1.5\pm0.5$.

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