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Inclusive Lepton Production in e^+e^- Annihilation at 29 GeV*

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Abstract

We use data taken by the Mark II detector at the PEP storage ring to study inclusive lepton production in e^+e^- annihilation at 29 GeV. From fits to the inclusive lepton momentum and transverse momentum spectra we measure the semileptonic branching ratios for charm and bottom hadrons. We also determine with good precision the mean value of the bottom fragmentation function using both electron and muon samples.

Semileptonic decays of charm and bottom hadrons are the primary sources of leptons in hadronic events from high energy e^+e^- annihilation. The momentum and transverse momentum distributions of these leptons depend on the parent quark masses and fragmentation functions; the rates of production depend on the weak decay semileptonic branching ratios. We separate the charm and bottom contributions to the prompt lepton signal by using the harder transverse momentum spectra of leptons from B decay. After making this separation, we use the lepton momentum spectra to study the fragmentation properties of charm and bottom hadrons. We have previously reported an analysis of inclusive electrons for a data sample with an integrated luminosity of 35 pb^{-1}.[1] In this Letter, we present new results for both inclusive muon and electron production from our full PEP data sample of 204 pb^{-1}.[2] The increased amount of data represents a significant statistical improvement over previous results and allows us to perform extensive crosschecks on our analysis procedure.

The data were taken with the Mark II detector at the PEP e^+e^- storage ring at the Stanford Linear Accelerator Center. The Mark II detector has been described previously,[3] as have the elements necessary for electron identification.[1] We describe here the components essential for the identification of muons. The momenta of charged particles are measured in two cylindrical drift chambers immersed in an axial magnetic field of 2.3 kG. The rms momentum resolution is given by $(\delta p/p)^2 \approx (0.025)^2 + (0.011 p_\perp)^2$, where $p_\perp$, the momentum perpendicular to the beam direction, is in units of GeV/c. The muon detectors consist of layers of hadron absorber and proportional chambers mounted on four sides of the central detector. Each wall has four alternating layers of iron and chambers; the innermost layer measures the polar angle of the track while the outer three layers measure the azimuthal angle. The proportional chamber wires are separated by 2.5 cm. Including the electromagnetic calorimeter there are 7.3 nuclear interaction lengths preceding the fourth muon layer. The solid angle coverage of the outer layer of the muon system is 45% of 4π.

Muons with momenta greater than 1.8 GeV/c are expected to penetrate to the outermost muon layer leaving proportional chamber hits in all four layers. Hadrons, however, are expected to be absorbed in the iron due to inelastic nuclear collisions. In the muon-hadron separation algorithm, drift chamber tracks are extrapolated into the muon system. At each of the four muon layers a mean standard deviation due to Coulomb scattering, extrapolation error and the proportional chamber intrinsic resolution is calculated based on the total amount of material traversed. A muon candidate is required to leave a hit within two standard deviations of the track extrapolation in all four layers. The muon identification efficiency has been measured using $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events and varies from 78% at $p = 2$ GeV/c to 91% at high momenta.[4]

The background to the lepton sample has two components, decay and misidentification of hadrons. What we call *decay* muons arise from charged pion and kaon decays and *decay* electrons come from Dalitz π^0 decays and photon conversions in the drift chamber. *Misidentified* muons consist of hadronic primary or secondary punchthrough in the muon system and *misidentified* electrons arise from hadronic interaction or photon overlap in the calorimeter. We describe here our estimation of these backgrounds to the muon signal; the backgrounds to the electron signal are discussed in detail in Ref. 1 (typical electron misidentification probabilities are 0.5% but are as high as 1.6% for 2 GeV/c tracks in the core of a jet). The muon decay background is estimated using a detailed Monte Carlo simulation of the decays of pions and kaons in the drift chamber. The per track probability for such a background decay varies from 0.4% at 2 GeV/c to 0.25% at 8 GeV/c with a systematic uncertainty of 20%. The muon misidentification background has been estimated in three ways: 1) using a source of pions from $\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$ events, 2) performing a fit to the distribution of muon chamber hits among the four layers for tracks in hadronic events failing the muon identification criteria,[5] and 3) using a detailed Monte Carlo simulation[6] of hadronic interactions in the material preceding and included in the muon system. From these studies we estimate the per track misidentification probability to vary from 0.28% at 2 GeV/c to 0.45% at 8 GeV/c with a systematic uncertainty of 40%.

The hadronic event sample was selected by requiring events to have at least six charged tracks. We required the total scalar momenta of the charged tracks to be greater than 7.25 GeV. The event vertex was required to lie within 4 cm of the beam position in the direction perpendicular to the beams and within 10 cm in the direction along the beams. In each event the thrust direction was calculated from charged tracks (including any lepton candidates). To ensure that the event was well contained in the detector, we required that the absolute value of the cosine of the angle between the thrust direction and the beam direction was less than 0.7. After these cuts there were 64,459 events.

We searched in these hadronic events for lepton candidates with momenta greater than 2 GeV/c. Background electrons from Dalitz π^0 decays and photon conversions were removed by a pair finding algorithm.[7] We also required each lepton candidate to have at least two associated hits in the inner drift chamber to suppress conversions occurring between the inner and main drift chambers.

There is a background to the inclusive electron signal from the two-photon process $e^+e^- \rightarrow e^+e^- + Hadrons$ where one of the electrons scatters into the central detector. Momentum conservation in the plane perpendicular to the beams requires that the hadronic shower recoils against the scattered electron; as a result, the two-photon events often have the topology of an isolated energetic electron opposite a low energy hadron jet. We imposed several cuts taking advantage of this topology to suppress the two-photon background.[8] These cuts removed approximately 5% of the electron sample. We measured the sensitivity of these cuts by using a Monte Carlo simulation that incorporates complete lowest calculations for the $e^+e^- \rightarrow q\bar{q}$ process,[9] followed by fragmentation of the quarks into hadrons using the LUND 6.3 shower code.[10] From this study, we found good agreement between the number of events removed by the two-photon cuts and the number predicted by the simulation. We estimate the background from two-photon processes to contribute less than 2% contamination in the electron sample. The background in the lepton signals from τ pair production is negligible.

After all cuts, we were left with a sample of 2621 electron and 1230 muon candidates. We determined the transverse momentum of each lepton measured relative to the thrust axis. The lepton candidates were separated into bins of momentum (p) and transverse momentum (p_t), of width 0.5 GeV/c and 0.25 GeV/c, respectively.

We performed binned maximum likelihood fits to the observed lepton p, p_t distributions. The sources of these observed leptons are 1) background from misidentified hadrons, 2) background from decay of hadrons, 3) primary bottom quark decay, 4) primary charm quark decay and 5) decay of charm quarks in $b\bar{b}$ events (secondary b decay). To estimate the contribution from charm and bottom decay we used a Monte Carlo program to produce bottom and charm quarks and string fragmentation.[10] We used the Peterson parameterization[11] of the fragmentation function $f(z) = 1/[z(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2]$, where $z \equiv (E + p_{\|})_{\rm hadron}/(E+p)_{\rm quark}$ and ϵ is a free parameter. The variables in the fits were the average semileptonic branching ratios for B and C hadron decay and $< z_b >$, the mean of the fragmentation function for b quark hadronization. We also allowed the background levels to vary by including multiplicative scale factors for the amount of misidentification and decay background. The values of the scale factors obtained from the fit provided a check of our background estimates. We generated $b\bar{b}$ events at different values of $< z_b >$; in the fit we interpolated between them to obtain the value which best fit the data. The value of $< z_c >$ was chosen to be 0.68 in agreement with exclusive D^* measurements[12] and the results of other inclusive lepton analyses.[13]

The results obtained from the fit are shown in Table 1. The first error for each result is statistical and the second is systematic. The lepton momentum and transverse momentum spectra are shown in Fig. 1. The systematic errors arise from a number of sources of which the uncertainty in the background estimate is dominant.

To account for background uncertainties, the fits were repeated allowing the background level to vary within the systematic errors assigned during its estimation. We also allowed the shape of the background contribution to vary (to account, for example, for a different K/π ratio from that assumed). The value of $< z_c >$ was allowed to vary within the range of 0.68 ± 0.06, accounting for the finite precision of the exclusive D^* measurements and the possible inclusion of charmed hadrons other than the D^*. Although we did not include a term to account for leptons from $b \to \tau \to l$ decays, we allowed this branching ratio to be as large as 5% for the estimate of the systematic errors. We accounted for uncertainties in the lepton identification efficiency, the fiducial acceptance and the number of non-hadronic events in the data. The systematic error resulting from uncertainty in the rest frame momentum and p_t distributions of leptons from heavy quark decays was found to be negligible. In the fits we assumed that b quarks decay 100% of the time to c quarks. The systematic effect of the possible inclusion of 5% fraction of $b \to u$ transitions had a negligible effect on the lepton momentum spectra.

The summed χ^2 for the fits are 51.7 and 85.8 for the muon and electron distributions, respectively, for 58 degrees of freedom. The electron fit has a small number of bins with large χ^2 values. These bins do not cluster at specific values of p, p_t indicating that the large χ^2 for the electron fit is likely due to statistical fluctuations. The values for the background scale factors obtained from the fit agree very well with our estimates of the decay and misidentification backgrounds. We have verified the analysis procedure by fitting a sample of 100,000 hadronic Monte Carlo events. The values obtained from the fit agree well with those used in the generation.

World average values for the branching ratios and fragmentation $< z_b >$ are given in Table 1. These values are calculated using previously published measurements from PEP/PETRA experiments;[12,13] earlier results from the Mark II Collaboration are not included.[14] The measurements presented in this analysis are in good agreement with the earlier results and have comparable precision to the world average values. The measurements also indicate that B fragmentation is peaked towards high values of $< z_b >$, confirming previous results.

In conclusion, we have reported precise measurements of the momentum and transverse momentum distributions for prompt muons and electrons in hadronic events in e^+e^- annihilation at 29 GeV. From a fit to these distributions we determine the semimuonic branching ratios to be BR($B \rightarrow \mu$)=($11.8 \pm 1.2 \pm 1.0$)% and BR($C \rightarrow \mu$)=($7.8 \pm 0.9 \pm 1.2$)% and the semielectronic branching ratios to be BR($B \rightarrow e$)=($11.2 \pm 0.9 \pm 1.1$)% and BR($C \rightarrow e$)=($9.6 \pm 0.7 \pm 1.5$)%. The mean value of the fragmentation function for the b quark is found to be $< z_b > (\mu) = 0.82 \pm 0.04 \pm 0.05$ and $< z_b > (e) = 0.85 \pm 0.03 \pm 0.05$.[15]

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5. The parameters of the fit are the punchthrough probabilities to the first three layers. The punchthrough to the fourth layer is obtained by extrapolation.
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14. The world averages were computed by weighting individual results by their statistical and systematic errors combined in quadrature. Fragmentation $< x >$ values were scaled into the corresponding $< z >$ values as discussed in Ref. 12. The systematic error for an average value was taken to be the smallest systematic error of the individual measurements. This conservative approach was adopted because the measurements largely have common systematic errors.

15. The value of the parameter ϵ_b in the Peterson formula was determined to be $0.0069\,^{+0.0067}_{-0.0038}\,^{+0.0089}_{-0.0045}$ using muons, and $0.0038\,^{+0.0031}_{-0.0019}\,^{+0.0059}_{-0.0027}$ using electrons. These values were obtained from $< z_b >$.

Quantity		This Analysis	World Average
BR($C \to l$) (%)	μ:	$7.8 \pm 0.9 \pm 1.2$	$7.9 \pm 0.7 \pm 1.1$
	e:	$9.6 \pm 0.7 \pm 1.5$	$10.5 \pm 0.6 \pm 0.8$
BR($B \to l$) (%)	μ:	$11.8 \pm 1.2 \pm 1.0$	$12.6 \pm 0.9 \pm 0.8$
	e:	$11.2 \pm 0.9 \pm 1.1$	$12.5 \pm 1.0 \pm 1.0$
$< z_b >$	μ:	$0.82 \pm 0.04 \pm 0.05$	$0.84 \pm 0.03 \pm 0.03$
	e:	$0.85 \pm 0.03 \pm 0.05$	$0.79 \pm 0.03 \pm 0.03$

Table 1. Inclusive lepton results. The first column shows the results of this analysis. In the second column, the world average values are given. The measured quantities are described in the text.

Figure 1. Lepton momentum and transverse momentum spectra for the muon and electron samples. The histograms represent the contributions from background, charm decay and bottom decay (including secondary b decay). Plots a) and d) show the lepton momentum spectra for $p_t < 1.0$ GeV/c while b) and e) are for $p_t > 1.0$ GeV/c. Plots c) and f) are the lepton transverse momentum spectra. The highest momentum bins in a), b), d) and e) contain all tracks with momenta greater than 6 GeV/c; the highest p_t bins in c) and f) contain all tracks with p_t greater than 1.5 GeV/c. The data points are shown with statistical errors only.

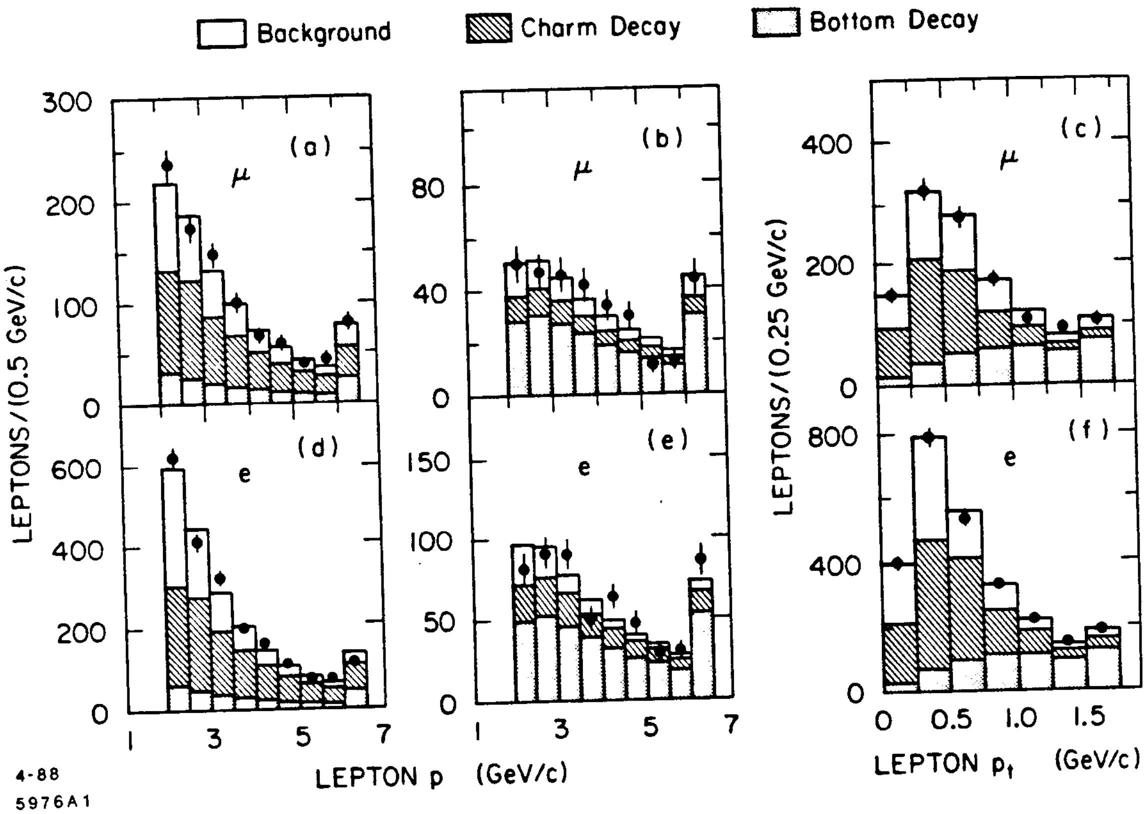
Background
Charm Decay
Bottom Decay
LEPTONS/(0.5 GeV/c)
LEPTONS/(0.25 GeV/c)
(a)
(b)
(c)
(d)
(e)
(f)
μ
e
LEPTON p (GeV/c)
LEPTON p_t (GeV/c)
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Fig. 1