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Inclusive Muon Production at c.m. Energies 12 to 31.6 GeV

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In this Letter, a measurement of inclusive muon production ($p_\mu > 2$ GeV/c) in e^+e^- annihilation into hadrons at center-of-mass energies from $\sqrt{s} = 12$ to 31.6 GeV is reported. The results agree with the expected semileptonic decays from charmed and bottom mesons.

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Many features of e^+e^- annihilation into hadrons are successfully described by assuming the production of u, d, s, c, and b quarks which then fragment into hadrons.[1] One of the central points in elementary particle physics today is the success of gauge theories in incorporating these quarks into a common framework with the more directly observable leptons. Just as the weak decays of the lighter quarks have guided the formulation of gauge theories, it is of great interest to explore the weak decays of the heavier quarks in order to test these theories and perhaps guide their further development.[2-4]

The data presented here come from the PLUTO detector operating at PETRA in Hamburg. The magnetic detector PLUTO[5] consists of an inner detector, two forward spectrometers, and a muon identifier. The inner detector measures charged and neutral particles with about 90% of 4π-sr acceptance. The muon identifier consists of ~1.0 m of iron covered by four planes of drift chambers, two overlapping chambers for each coordinate. The drift-chamber system consists of a total of 1510 cells, 16.0 cm by 1.6 cm, with lengths from 1.0 to 2.9 m. The two-coordinate coverage is 80% of 4π sr. The half-cell overlap for the drift chambers of each coordinate allows us to resolve left-right ambiguity and to measure the angle with which tracks traverse the chambers to ± 6°. Cosmic rays were used to check the position of the drift chambers and to monitor the chamber efficiencies during data taking.

Muons are identified by matching hits in the muon chambers with the extrapolation of tracks seen in the inner detector. The distance between the hit position and extrapolated track position was required to be less than 1.78 times the rms deviation expected from multiple Coulomb scattering and track measurement error. The acceptance of this cut was determined with cosmic-ray muon tracks of different momenta and was shown to accept on average $(94.3 \pm 1.1)\%$ of all muon tracks exciting the detector. The thickness of the muon filter is not completely uniform over the entire detector, leading to a smearing of the minimum muon penetration momentum. The half-acceptance momentum is about 1.4 GeV/c and the 95% acceptance point is reached at 2.0 GeV/c. For most of the present analysis we consider only muons with momenta greater than 2.0 GeV/c where the uncertainties introduced by these acceptance corrections are negligible.

Hadronic events were selected from data taken at c.m. energies between 12 and 31.6 GeV.[6] The chief criteria for hadronic event selection demand more than two charged tracks with a common vertex at the interaction point, and a total visible energy greater than one-third of the c.m. energy.[1a,7] About 10% of the sample still consisted of non-muon-producing events such as beam-gas interactions and 2γ hadronic events.[8] Their estimated number was subtracted from the number of hadronic candidate events.

A few nonhadronic muon-producing events such as $e^+e^- \to \tau\tau$ where at least one of the τ's decays hadronically, and $e^+e^- \to \mu\mu\gamma$ where the γ showers in the detector, were still present in the sample. They were rejected in a scan of the muon-candidate events which yielded two $\mu\mu\gamma$ events and six probable τ events. The total sample then consisted of 1349 hadronic candidate events, 1205 of which were estimated to be real hadronic annihilation events. These events were examined to find muon candidates.

The main sources of background to the muon signal in hadronic events are the decay punchthrough of pions and kaons. Using a test beam and a simulation of the actual muon-detector geometry, we have measured the punchthrough of pions at momenta of 3, 6, and 10 GeV/c. We have also used the measurements of Harris *et al.*[9] and calculations of Gabriel and Bishop.[10] We conclude that the probability for a pion to simulate a muon in the PLUTO detector is 1.1%, 2.5%, and 4.8% for pion momenta of, respectively, 2, 6, and 10 GeV/c.

We integrate these punchthrough probabilities over the momentum spectrum of all tracks observed in hadronic events. Considering the actual event topologies, we include the contribution of tracks which punch through into the muon-acceptance zones of neighboring tracks. The resulting background per event is dependent on the c.m. energy, increasing from $(0.31^{+0.11}_{-0.04})\%$ per event at 12 GeV to $(2.3^{+1.0}_{-0.3})\%$ at 30 GeV. The error in the calculation takes into account uncertainties in the K/π ratio, and the larger but unmeasured kaon punchthrough probabilities.

The results are summarized in Table I. The number of candidates and real hadronic events at each energy are given in columns 2 and 3, respectively. The number of muon candidates observed with momentum greater than 2 GeV/c and the remaining muon signal after background subtraction are given in columns 4 and 5. As can be seen, approximately half the observed candidates must be attributed to background. Column 6 displays the number of background-subtracted muons with momentum greater than 2 GeV/c per hadronic event. This number has been obtained by dividing the muon signal by the number of hadron events and by correcting for the efficiency of muon recognition $[(94.3 \pm 1.1)\%]$, track reconstruction $[(82 \pm 4)\%]$, and the geometric acceptance for muons in accepted hadronic events $[(81 \pm 2)\%]$. Column 9 gives the invariant cross section for inclusive

TABLE I. Inclusive muon production (with $p_\mu > 2$ GeV/c).

					muons per hadronic event			$s \cdot \sigma_\mu$ (> 2 GeV/c)		
$\sqrt{s}$ (GeV)	candidate hadronic events	hadronic events	muon candidates	muon signal	value (%)	+error (%)	-error (%)	value (nb · GeV^2)	+error (nb · GeV^2)	-error (nb · GeV^2)
12.0	227	199	3	2.3	1.8	+2.4	-1.3	6.2	+8.0	-4.6
22.0	32	28	1	0.6	3.3	+13.1	-4.8	11.2	+44.6	-16.3
27.6	168	157	10	6.7	6.8	+4.4	-3.4	23.2	+15.3	-12.2
30.0	223	209	11	5.8	4.4	+3.4	-3.0	15.0	+11.9	-10.4
30.7	699	612	32	15.2	3.9	+1.9	-2.3	13.4	+6.7	-8.2
Σ>27	1090	978	53	27.7	4.4	+1.5	-2.1	14.9	+5.6	-7.4

muon production in e^+e^- annihilation to hadrons which was obtained from the number of muons per hadronic event with use of the value of $R = 3.9 \pm 0.5$ measured by PLUTO for this energy range.[1a,7] We present these results graphically in Fig. 1. The full error bars shown on each datum point include the effects of systematic uncertainties, primarily in the hadronic punch-through estimate. The (Poisson) statistical error is indicated by the horizontal bars.

We compare these results to expectations from the production and the semileptonic decay of mesons containing heavy quarks c, b, and possibly t, according to a Field-Feynman two-jet production model[11] modified to include heavy quarks, as described by Ali.[12] Assuming a heavy-quark semileptonic branching ratio to muons of 10%,[13] we have computed inclusive muon production with $p_\mu > 2$ GeV/c for the following three cases: (i) the four-quark model, *udsc*, (ii) the five-quark model, *udscb*, and (iii) the six-quark model, *udscbt*. As a modification of the five-quark model we consider in case (iv) that b mesons decay only semileptonically with equal branching ratios to electrons, muons, and τ leptons.[14]

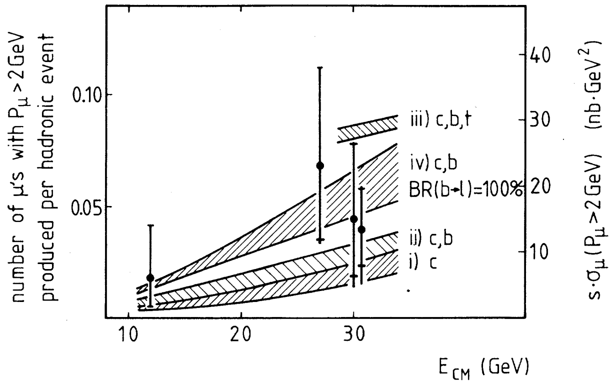

FIG. 1. The inclusive production of muons with momentum greater than 2 GeV/c per hadronic event, corrected for full acceptance. The full error bars include systematic uncertainties. Statistical (Poisson) errors alone are indicated by the horizontal bars. The shaded bands show the predictions of heavy-quark-decay models as discussed in the text.

We have studied the sensitivity of these predictions to various assumptions such as the heavy-quark masses, the quark fragmentation functions, the chirality of the quark weak decay couplings, and the emission of gluons. The only significant variation arises from different assumptions concerning quark fragmentation. We therefore present the predicted muon signals as the shaded bands in Fig. 1. The top edge of each band corresponds to the assumption of a constant fragmentation function, while the bottom edge corresponds to the standard Feynman-Field fragmentation[15] for light quarks:

$$f(z) = 0.23 + 2.31(1-z)^2.$$

As can be seen from Fig. 1, our measurements are consistent with models (i), (ii), and (iv) for the full range of fragmentation functions considered here. Limited information is gained concerning the muonic decays of the b quarks, since our results are compatible with all branching ratios from zero to 33%. The larger muon signal expected if the top threshold had been crossed is, however, not supported by our data.

If model (ii) with constant heavy-quark fragmentation is taken to describe expected muon production, then our results establish upper limits on any additional muon production in hadronic events. With use of the combined statistics of all our measurements at 27 GeV and above, the upper limit for the rate per hadronic event of such additional production of muons with momenta greater

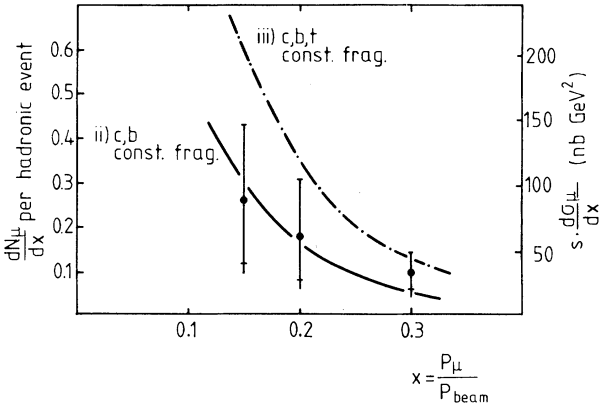

FIG. 2. The momentum spectrum of muons produced in hadronic events at c.m. energies from 27 to 31.6 GeV, expressed as a function of the scaled momentum. The smooth lines show predictions of the models (ii) and (iii) as discussed in the text.

than 2 GeV/c is 4.0% or, expressed in terms of a cross section, $s\sigma_\mu(p_\mu > 2\ \text{GeV}/c)$ is less than 14.5 nb GeV^2 at the 95% confidence level.

Figure 2 shows the momentum spectrum of the muons observed at c.m. energies above 27 GeV. Also shown are the predictions of models (ii) and (iii) for comparison. As can be seen, our measurements are consistent with the shape of either predicted spectrum although in absolute magnitude they naturally reflect the same conclusions as can be drawn from the integral results.

We have also searched for events having two or more muons. We have initially restricted our analysis to dimuons separated by at least 90°, but allow the momentum of the less-energetic muon in the event to be as low as the effective 1.4-GeV/c limit imposed by energy loss in the steel absorber. We observe three such dimuon events, of which one has the like-charge signature expected from a bottom cascade decay. Using model (ii), we compute the expected events from background $(0.59^{+0.27}_{-0.09})$, charm (0.22), and bottom (0.22). In view of the dominant contribution expected from background and the limited statistics, we do not feel that the discrepancy between these expectations and our observations is significant.

In conclusion, we have measured the inclusive muon production in hadronic events in the energy range $\sqrt{s} = 12-31.6$ GeV. The results are consistent with the expected semileptonic decays from only charmed and bottom mesons.

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Is the $x \to 1$ Behavior of the Deep-Inelastic Structure Functions in the Bjorken Limit Sensitive to the Confinement Mechanism?

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This Letter incorporates confinement to the covariant parton model and investigates its consequences on the qualitative behavior of the deep-inelastic structure functions in the Bjorken limit. It is proved that this incorporation does not change the known behavior of the baryonic structure functions, but it leads, for mesons, to a nonvanishing value of $\nu W_2(\omega^{-1})$ and $W_1(\omega^{-1})$ in the $\omega^{-1} \to 1$ limit and to a violation of the Callan-Gross relation.

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The deep-inelastic structure functions, νW_2 and W_1, associated to deep-inelastic electroproduction processes are directly related to the absorptive part of the virtual Compton amplitude $\gamma^* h \to \gamma^* h$. In the covariant parton model[1] and in the Bjorken limit, it can be seen that this amplitude is dominated by the hand-bag diagrams (Fig. 1), where the internal lines are associated with quarks.

In this model, if one applies the usual ideas of analyticity to the quark-hadron amplitude, the Bjorken scaling for $\nu W_2(\omega^{-1})$ and $W_1(\omega^{-1})$ is obtained[2] $[\omega = 2\nu/(-q^2)]$.

Azcoiti, Alonso, and Cruz[3] have proved that if, in the context of the covariant parton model, one takes into account the differences which the quark model establishes between baryons and mesons, one can obtain, in turn, essential differences between baryonic and mesonic structure functions. In particular, they proved that if the sum of the free masses of the valence quarks in a meson is less than the meson mass, $m_q + m_{\bar{q}} < M_m$, one can obtain a nonvanishing value of the mesonic structure functions in the $\omega^{-1} \to 1$ limit, as well as a violation of the Callan-Gross relation for mesons.

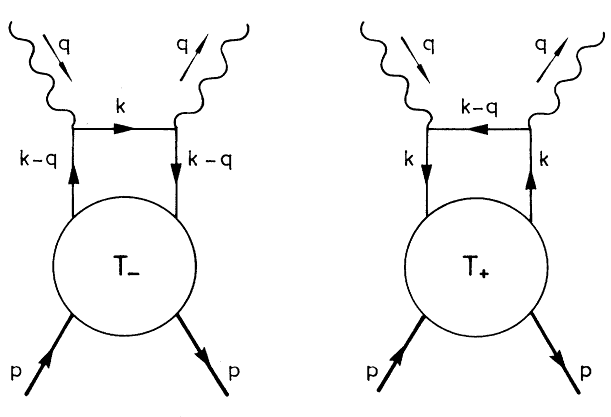

FIG. 1. Hand-bag–diagram contributions to the virtual Compton amplitude.