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INCLUSIVE MUON PRODUCTION AT PETRA ENERGIES

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Abstract:

We report a measurement of inclusive muon production (p_μ > 2 GeV/c) in e^+e^- annihilation into hadrons at center of mass energies from $\sqrt{s}$ = 12 to 31.6 GeV. The results agree with the expected semi-leptonic decays from charm 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 the 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 the 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]

In the Kobayashi-Maskawa model[3] bottom is expected to decay dominantly to charm and charm to strangeness. Since there is an appreciable probability (~ 10 %) that each of these decays will be semi-muonic, copious production of muons in high energy e^+e^- annihilation, and in particular multi-muon production, might indicate that these cascade decays do in fact occur. According to the K-M model, the production of top quarks would be an even stronger muon source. Not only would top be expected to add yet another level to the bottom weak decay cascade, but it would be produced four times more frequently than bottom in e^+e^- annihilation. This general feature of a strong enhancement in the inclusive muon rate through heavy-quark production is also shared by other models.[4]

In light of these considerations we undertook to study the inclusive production of muons in high energy e^+e^- annihilation. The data presented here come from the PLUTO detector operating at the Positron-Electron-Tandem--Ring Accelerator PETRA at the Deutsches Elektronen-Synchrotron DESY in Hamburg. The magnetic detector PLUTO 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 acceptance. The inner detector and the forward spectrometer are described in more detail elsewhere.[5] The muon identifier consists of ~ 1.0 meter 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 m 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 degrees. Cosmic rays were used to check the position of the drift chambers and to monitor the chamber efficiencies during data taking. The results presented here were obtained in one year of operation at PETRA.

Muons are identified by matching clusters in the muon chambers with the extrapolation of tracks seen in the inner detector. Normally the passage of a muon produces a cluster of four hits in the overlapping drift-chamber layers. In order to eliminate a background of accidental hits due to externally incident soft photons, we required each cluster to consist of at least three hits. This requirement reduced our acceptance for real muons by only a few percent since the cell efficiency was essentially 100 % and the area lacking full four layer coverage was small. The distance between the hit position and extrapolated track position was measured in a plane perpendicular to the extrapolated track in units of ξ. ξ is the measured distance divided by the expected root-mean-square deviation due to multiple coulomb scattering and track measurement error. The muon sample is obtained by requiring $\xi < 1.78$, which for a strictly gaussian error distribution would accept 96 % of all muons. The actual acceptance of this cut was determined with cosmic ray muon tracks of different momenta and shown to accept on average (94.3 ±1.1) % of all muon tracks exiting 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.

Our method of muon detection required proper reconstruction of tracks in the inner detector. We have studied the loss of muon tracks due to improper track recognition by scanning hadronic events with valid muon-chamber clusters which were not associated to tracks. We estimate the overall loss of muons to this source as (11 ±3) %.

We have searched for muons in the hadronic events taken at $\sqrt{s}$ = 12, 22, 27, 30 and 30.7 GeV.[12] The 30.7 GeV data point is the result of an energy scan from $\sqrt{s}$ = 29.90 GeV to 31.46 GeV in 20 GeV steps with an average luminosity of 23 nb^{-1} per step. Also included is a run at $\sqrt{s}$ = 31.6 GeV. The total number of hadronic events observed at all energies is 1205. The criteria for hadronic event selection are given in refs. 1a and 10. After scanning the selected events to remove a background of Bhabha scatters where one or both of the electrons showered within the inner detector we obtained a sample of candidate hadronic events. About 10 % of the sample still consisted of background from i) two-gamma hadronic events, ii) $e^+e^- \rightarrow \mu\mu\gamma$, iii) $e^+e^- \rightarrow \tau\tau$ with multi-prong decays and iv) beam-gas events. The number of hadronic annihilation events in our sample was obtained by subtracting these estimated backgrounds. Since beam-gas and two-gamma events contribute a negligible number of muons, no correction to the observed muon signal on their account was necessary. τ and $\mu\mu\gamma$ events, on the other hand, would have contributed non-negligibly to the muon signal, and were removed in a scan of the muon-candidate events which rejected two $\mu\mu\gamma$ candidates and six probable τ events with a single muon in one hemisphere and a narrow jet of two or more tracks in the opposite hemisphere. This scan also could have rejected muons arising from the decay of new leptons heavier than the τ. In fact the rejected events are consistent with our estimate of the τ contribution.

The main sources of background to the muon signal in hadronic events are the decay and punchthrough of pions and kaons. In the background calculation we have used the inclusive momentum spectrum of all tracks observed in the hadronic events and assumed all such tracks to be either pions or kaons. The fraction of these tracks that are kaons we estimate in a momentum dependent way from the results of a Monte-Carlo program to be described later. 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.[6] and calculations of Gabriel and Bishop.[7] In calculating the fraction of punchthrough which falls within the region $\xi < 1.78$, we have included the contribution of tracks which punchthrough into the muon acceptance zones of neighbouring tracks. 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 1. 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 correcting for the efficiency of muon recognition (94.3 ±1.1) %, track reconstruction (89 ±3) % and the geometric acceptance for muons in accepted hadronic events (81 ±2) %. Column 7 gives the invariant cross section for inclusive muon production in e^+e^- annihilation to hadrons which was obtained from the number of muons per hadronic event using the value of R = 3.9 ±0.5 measured by PLUTO for this energy range.[1a,10]

We compare these results to expectations from the production and the semi-leptonic decay of mesons containing heavy quarks c, b and possibly t.

Monte-Carlo simulations have been used to test various hypotheses. These simulations are based on the Field-Feynman two-jet production model[8] modified to include heavy quarks, as described by Ali.[9] Assuming a heavy quark semi-leptonic branching ratio to muons of 10 % we have computed inclusive muon production with $p_\mu > 2$ GeV/c for the following 3 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 taus.[11]

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 for light quarks: $f(z) = 0.23 + 2.31\,(1 - z)^2$.[13]

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. The larger muon rate expected from the production of top mesons is ruled out by our measurements, which do not show the increase in the muon signal which would be expected to set in abruptly at the top threshold.

If model ii) with constant heavy quark fragmentation is taken to describe expected moun production, then our results establish upper limits on any additional muon production in hadronic events. Using 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 than 2 GeV/c is 4.0 % or, expressed in terms of a cross section, $s \cdot \sigma_\mu(p_\mu > 2$ GeV/c) is less than 14.5 nb GeV^2 at the 95 % confidence level.

Fig. 2 shows the momentum spectrum of the muons observed at center of mass 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.

Of particular importance to understanding the weak decays of the heavy quarks would be the observation of dimuon events. The charge identification of the muons and their association in either the same or opposite side jets provide a clear signature for the expected cascade decay of bottom through charm. The existence of $B_0\overline{B}_0$ mixing could also be detected, as well as a difference in the muon branching ratio between charged and neutral bottom mesons.

Since high multiplicity punchthrough processes present a difficult-to-analyse background for the identification of two muons appearing in the same jet, we have initially restricted our analysis to dimuons separated by at least 90^o. To increase our sensitivity to the softer spectrum of cascade decay muons, we 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 the energy range $\sqrt{s}$ = 12 to 31.6 GeV. The results are consistent with the expected semi-leptonic decays from charm and bottom mesons. The results do not agree with the production of a top quark.

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Figure Captions:

Fig. 1 The inclusive production of muons with momentum greater than 2 GeV/c per hadronic event, corrected for full geometric acceptance. The shaded bands show the predictions of heavy-quark-decay models as discussed in the text.

Fig. 2 The momentum spectrum of inclusive muons produced in hadronic events at center of mass energies from 27 GeV 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.

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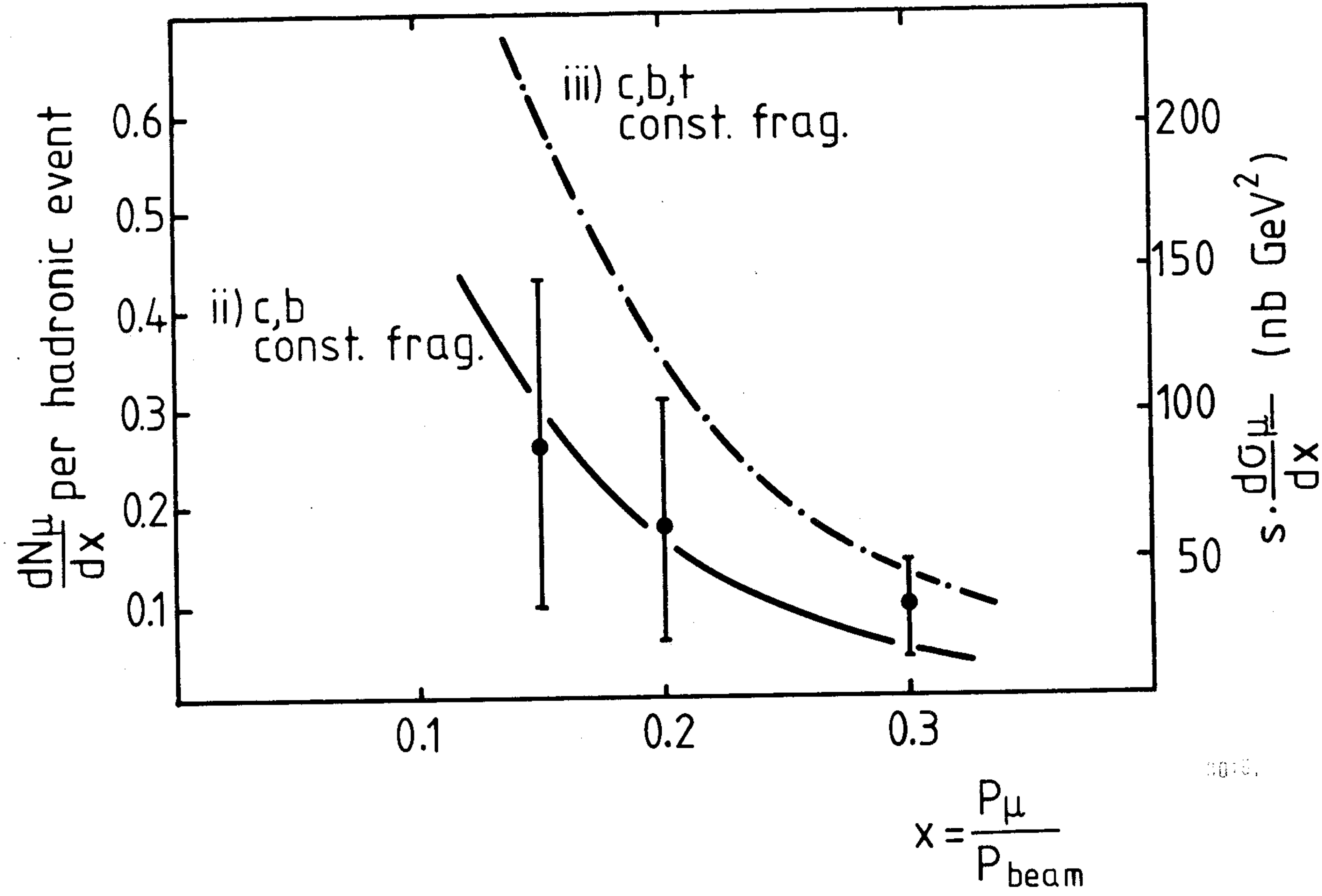
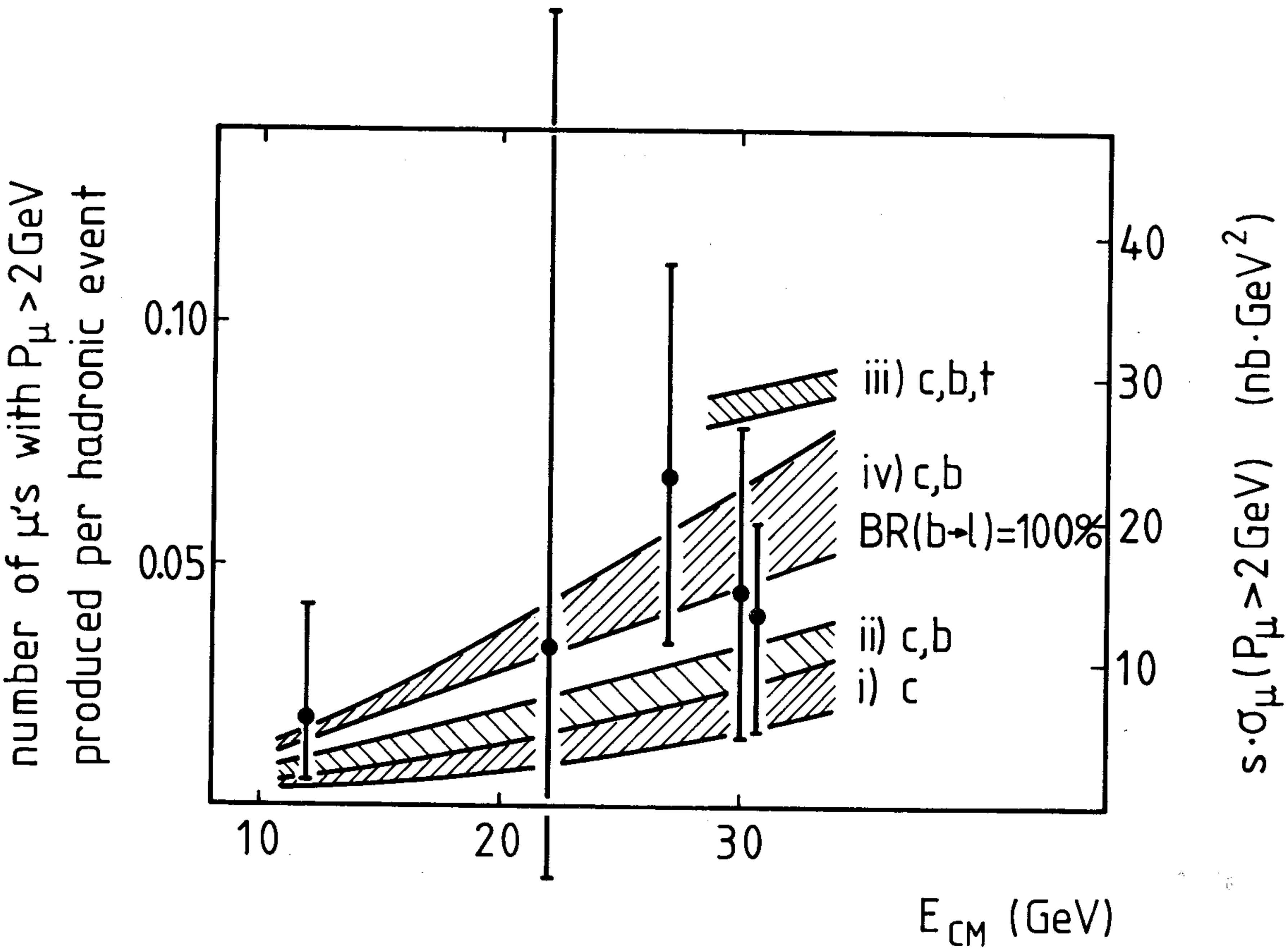
13 The function f(z) = 1 - z also falls very close to the lower edge of the bands.

Table 1 Inclusive muon production (with $p_\mu > 2$ GeV/c)

$\sqrt{s}$ (GeV)	candidate hadronic events	hadronic events	muon candi-dates	muon signal	muons per hadronic event (%)	$s \cdot \sigma_\mu$ (> 2 GeV) (nb · GeV²)
12.0	227	199	3	2.30	$1.83^{+2.35}_{-1.33}$	$6.2^{+8.0}_{-4.6}$
22.0	32	28	1	0.58	$3.30^{+13.1}_{-4.79}$	$11.2^{+44.6}_{-16.3}$
27.6	168	157	10	6.74	$6.82^{+4.39}_{-3.44}$	$23.2^{+15.3}_{-12.2}$
30.0	223	209	11	5.80	$4.41^{+3.44}_{-2.99}$	$15.0^{+11.9}_{-10.4}$
30.7	699	612	32	15.15	$3.94^{+1.88}_{-2.33}$	$13.4^{+6.7}_{-8.2}$
$\sum$>27	1090	978	53	27.70	$4.38^{+1.51}_{-2.08}$	$14.9^{+5.6}_{-7.4}$



0.6
0.5
0.4
0.3
0.2
0.1
dNμ/dx per hadronic event
iii) c,b,t
const. frag.
ii) c,b
const. frag.
200
150
100
50
s · dσμ/dx (nb GeV²)
0.1
0.2
0.3
x = Pμ/Pbeam


number of μ's with Pμ > 2GeV
produced per hadronic event
0.10
0.05
iii) c,b,t
iv) c,b
BR(b→l)=100%
ii) c,b
i) c
40
30
20
10
s·σμ(Pμ>2GeV) (nb·GeV2)
10
20
30
ECM (GeV)