DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 83-029
April 1983

EXPERIMENTAL STUDY OF INCLUSIVE MUON SPECTRA AT PETRA

by

MARK-J Collaboration

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

DESY 83-029
April 1983

ISSN 0418-9833

EXPERIMENTAL STUDY OF INCLUSIVE MUON SPECTRA AT PETRA

MARK-J COLLABORATION

B. Adeva, D.P. Barber, U. Becker, J. Berdugo, G. Berghoff, A. Böhm, J.G. Branson, J.D. Burger, M. Capell, M. Cerrada, C.C. Chang, H.S. Chen, M. Chen, M.L. Chen, M.Y. Chen, Y.S. Chu, R. Clare, E. Deffur, M. Demarteau, P. Duinker, Z.Y. Feng, H.S. Fesefeldt, D. Fong, M. Fukushima, D. Harting, T. Hebbeker, G. Herten, M.C. Ho, M.M. Ilyas, D.Z. Jiang, W. Krenz, P. Kuijer, Q.Z. Li, D. Luckey, E.J. Luit, C. Mana, M.A. Marquina, G.G.G. Massaro, R. Mount, H. Newman, M. Pohl, F.P. Poschmann, R.R. Rau, J.P. Revol, S. Rodriguez, M. Rohde, J.A. Rubio, H. Rykaczewski, J. Salicio, I. Schulz, K. Sinram, M. Steuer, G.M. Swider, H.W. Tang, D. Teuchert, Samuel C.C. Ting, K.L. Tung, M.Q. Wang, M. White, H.G. Wu, S.X. Wu, B. Wyslouch, B. Zhou, R.Y. Zhu, and Y.C. Zhu.

III. Physikalisches Institut, Technische Hochschule, D-5100 Aachen, Federal Republic of Germany.*

Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, Federal Republic of Germany.

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge/Massachusetts, USA 02139.

Junta de Energia Nuclear, Madrid, Spain.

Nationaal Instituut voor Kernfysica en Hoge-Energiefysica (NIKHEF), 1009-DB Amsterdam, The Netherlands.

Institute of High Energy Physics, Chinese Academy of Science, Beijing, People's Republic of China.

California Institute of Technology, Pasadena, California, USA 91125.

* Supported by the Deutsches Bundesministerium für Forschung und Technologie.

ABSTRACT

We report the results of a high statistics study of inclusive muon spectra at PETRA. We obtain new mass limits on the production of heavy quarks, heavy leptons, and charged Higgs particles. We show that the fragmentation properties of b quarks and c quarks are different with the mean fragmentation variables $\langle z_b \rangle = 0.75 \pm 0.03 \pm 0.06$, $\langle z_c \rangle = 0.46 \pm 0.02 \pm 0.05$ and the average semi-leptonic branching ratios for the B and C hadrons BR(B) = 10.5±1.5±1.3%, BR(C) = 11.5±1.0±1.7%.

In the last twenty years experimental studies of leptons from synchrotrons and colliders have yielded important information in our understanding of particle physics. The discovery of the $J(c\bar{c})$ (1), the $\Upsilon(b\bar{b})$ (2) and the heavy lepton τ (3) are good examples. It follows naturally that we can use the study of leptons at higher energies to search for new quark states(4), new heavy leptons $(L^{\pm})$ (5), charged Higgs $(H^{\pm})$ (6). To search for X (L,H) particles from

$$e^+e^- \to (X^+ \to \mu + \nu\text{'s}) + (X^- \to \text{jet}) \to \mu + \text{jet} \qquad (1)$$

we look for events with an isolated μ opposite to a hadron jet.

In the framework of Quantum Chromodynamics (QCD), the precision measurement of inclusive muon spectra provides us with information on fragmentation(7) processes. The inclusive μ spectrum from the reaction

$$e^+e^- \to \text{jet}_1(\mu) + \text{jet}_2 \qquad (2)$$

can be visualized via the following sequence:

(i) Heavy quark pairs $Q\bar{Q}$ (Q = b, c quarks) are produced via QED $e^+e^- \to Q\bar{Q}$.

(ii) The fragmentation of $Q \to M + q$ produces hadron M which carries the signature of Q and q = u, d, s quarks which fragment into more hadrons.

(iii) The semi-leptonic decay of $M \to \mu + x$. The hadron M can be identified by its μ decay because the μ has a distinctive large transverse momentum (with respect to jet axis):

$P_T \simeq \frac{m_Q}{4}$, with m_Q the mass of the Q quark.

A measurement of the inclusive μ spectra determines the production of M and its semi-leptonic decay branching ratio. A comparison of the production of Q and M determines the fragmentation of $Q \to M$. Let E_M, E_Q be the energy of M and Q and P_M, P_Q be their momenta along the Q direction. The quantity $z = (E_M + P_M)/(E_Q + P_Q)$ is a measure of the energy which the heavy quark retains after fragmentation and the average value of $\langle z_Q \rangle$ is a direct measurement of the fragmentation properties of Q quarks.

The fragmentation probability of $Q \to M + q$ can be obtained from the Uncertainty Principle to be proportional to $(E_Q - E_M - E_q)^{-2}$. Taking into account phase space(9), we have the explicit function

$$f_Q(z) = \frac{1}{z}\left(1 - \frac{1}{z} - \frac{h_Q^2}{1-z}\right)^{-2} ; \; h_Q \text{ is the fragmentation parameter} \qquad (3)$$

Let B, C be the hadron states with b, c quark signatures respectively and BR(B), BR(C) be their average semi-leptonic decay branching ratios. High statistics inclusive μ spectra measure BR(B), BR(C), h_c, h_b, $\langle z_c \rangle$, $\langle z_b \rangle$ directly. The quantity $\langle z_Q \rangle$ can also be measured without an assumption of a functional form by dividing the available z-region into many intervals and fitting the data bin by bin.

It follows from equation (2) and $P_T \simeq \frac{m_Q}{4}$ that the thrust and P_T distributions are sensitive signatures for new heavy quarks and enable us to set new mass limits on charge 1/3, 2/3 quarks.

The MARK-J detector is a 4π calorimeter which measures the directions and energies of e, μ, γ, and jets(10). It was designed for μ detection with $\simeq$ 30 cm decay path for hadrons and $\simeq$ 1 m of magnetized iron with $\int B dL \geq 17$ kG-m as a hadron filter. We collected a total of 76 pb^{-1} integrated luminosity in the region $33 \leq \sqrt{s} \leq 38.54$ GeV. From a total of 25000 hadron events we select events with a reconstructed muon track in the outer drift chambers. The data can be divided into two groups:

(1) There are 806 events with an isolated muon opposite to a hadron jet corresponding to production of τ pairs. Using the analysis method reported before(5,6), the major increase in statistics enables us to extend the mass limit of a new sequential lepton to be $m_L > 18$ GeV and the mass limit of charged Higgs to $m_H > 14$ GeV if the branching ratio $H^{\pm} \to \tau^{\pm} \nu > 0.25$.

(2) A muon in one of the hadron jets. To obtain mass limits on the production of new quarks and to study the fragmentation processes, we reduce the effect of hard gluon emission by collecting events with a broad jet oblateness cut of $O_b < 0.3$. By comparing the position of the reconstructed trajectory with the measured coordinate inside the hadron absorber we are able to reduce the background from punch-through and decay to 13% and 19%, respectively, leaving 850 muon candidates. All results of the following analysis are corrected for this background. The Monte Carlo calculation included radiative corrections, detector simulation and the assumption that B decays via $B \to C + x$ only. We have grouped the $B \to C \to \mu + x$ contribution into the $C \to \mu + x$ sample. The r.m.s. resolution $\Delta P_T/P_T$ is about 0.5 due to a momentum resolution $\Delta P/P \sim 0.25$ and the error in the reconstruction of the jet axis.

Fig. 1a shows the differential cross section in P_T^2 compared with the pion distribution(11). The muon P_T^2 distribution is distinctly different from the pion distribution, with a shoulder in the range $2 \lesssim P_T^2 \lesssim 5\ \mathrm{GeV}^2$ which is indicative of the decay of a particle of mass around 5 GeV. Fig. 1b shows the data compared with the Monte Carlo prediction for the total μ rate and its components $B \rightarrow \mu + x$ and $C \rightarrow \mu + x$. The shoulder is well explained by B decays, and the Monte Carlo prediction agrees with the data. A P_T cut is used to divide the data into B-enriched and C-enriched samples. The B-enriched sample ($P_T > 1.2$ GeV) has a composition, according to Monte Carlo, of 64% B decays, while the expected composition of the C-enriched sample ($P_T < 1.2$ GeV) is 85% C decays.

Fig. 2 shows the thrust distribution for the B- and C-enriched samples and all hadron events. The B-enriched sample exhibits a broader distribution than does the sample of hadrons. No significant difference exists between the C-enriched sample and the hadron sample. Similar to Fig. 1 the thrust distributions of the B-enriched and C-enriched samples can be explained by QCD with known quarks. The P_T and thrust distributions enable us to obtain the limits on the production[4] of new charge 1/3 quarks(B'), to m > 16 GeV (Fig.2) and a charge 2/3 quark to m > 19 GeV.

Figs. 3a and 3b show the $x = 2P/\sqrt{s}$ distributions for B-enriched and C-enriched samples respectively together with the Monte Carlo predictions. The x distribution depends mainly on the fragmentation properties of the quarks. The fact that the average x of the B sample is significantly higher than that of the C sample implies that the $\langle z_b \rangle$ is much larger than $\langle z_c \rangle$.

As seen from Figs. 1 and 2 the P_T and thrust distributions separate B and C samples independently. Fig. 3 shows that the x (or P) distribution is a measure of $\langle z_b \rangle$ and $\langle z_c \rangle$. To obtain the values of BR(B), BR(C) and h_Q we divide the data into an 8 x 8 x 8 three-dimensional grid in the variables of P and P_T of the muon and the thrust. From a maximum likelihood fit we

find[12][13][14][15]

$$\mathrm{BR(C)} = 11.5 \pm 1.0 \pm 1.7\%$$
$$\mathrm{BR(B)} = 10.5 \pm 1.5 \pm 1.3\%$$
$$|h_c| = 0.8 \pm 0.1 \pm 0.2$$
$$|h_b| = 0.15 \pm 0.03 \pm 0.05$$

This yields $\langle z_c \rangle = 0.46 \pm 0.02 \pm 0.05$ and $\langle z_b \rangle = 0.75 \pm 0.03 \pm 0.06$. The ratio $|h_c| / |h_b|$ is $5.3 \pm 1.3 \pm 2.2$ and may be compared with the ratio of the quark masses m_b/m_c, which is approximately 3. The first errors are statistical (68% C.L. for each variable). The second errors are systematic, including uncertainty (± 20%) in the background subtraction, the simulation of detector resolution and acceptance, the variation of mean transverse momenta of the primary particles B and C from 200 to 500 MeV and the uncertainties in the decay $B \rightarrow \mu + \nu\ (C + x)$ where the mass of the (C + x) system varies from 1.9 to 2.4 GeV.

The direct measurement of $\langle z_Q \rangle$ was done by dividing the available z region into 10 equal bins and fitting bin by bin. This yields $\langle z_b \rangle = 0.74 \pm 0.1$, $\langle z_c \rangle = 0.46 \pm 0.05$ independent of any specific form of f(z).

In conclusion, we have set new limits on the production of new leptons, charged Higgs particles, and charge 1/3 and 2/3 quarks. We have also measured the semi-muonic branching ratios for charm and beauty particles. Our determination of f(z) and $\langle z_b \rangle / \langle z_c \rangle \simeq 1.6$ show that b and c quarks have different fragmentation properties, with the b quark retaining 75% of its energy in fragmentation.

We thank Professors V. Soergel and P. Söding for their support.

FIGURE CAPTIONS

Fig. 1 (a) The P_T^2 distributions of muons normalized to the total hadronic cross section σ_T. The open circles are the cross section with P > 2 GeV; the solid points are the cross section extrapolated to all P. They differ only on the first two points with $P_T^2 < 2(\text{GeV})^2$. The inclusive π spectrum is also indicated as a dashed curve, scaled by 10^{-2}.

(b) Comparison of the data of reaction 2 with Monte Carlo, including individual $B \to \mu$, $C \to \mu$ contributions.

Fig. 2 The normalized thrust distribution of the B-, C-enriched samples and hadronic events. The dashed curve is the Monte Carlo prediction for the B-enriched sample with an additional charge 1/3 quark (B') of mass 16 GeV.

Fig. 3 (a) The x distribution for the B-enriched sample.

(b) The C-enriched sample. The Monte Carlo curves are also shown.

REFERENCES

(1) J.J. Aubert et al., Phys. Rev. Lett. 33, 1404 (1974);
J.E. Augustin et al., Phys. Rev. Lett. 33, 1406 (1974);
J.M. Feller et al., Phys. Rev. Lett. 40, 274 (1978);
R.H. Schindler et al., Phys. Rev. D24, 78 (1981).

(2) S.W. Herb et al., Phys. Rev. Lett. 39, 252 (1977);
W.R. Innes, Phys. Rev. Lett. 39, 1240 (1977);
C. Bebek et al., Phys. Rev. Lett. 46, 84 (1981);
K. Chadwick et al., Phys. Rev. Lett. 46, 88 (1981);
L.J. Spencer et al., Phys. Rev. Lett. 47, 771 (1981);
Ch. Berger et al., Phys. Lett. 76B, 243 (1978);
C.W. Darden et al., Phys. Lett. 76B, 246 (1978).

(3) M.L. Perl et al., Phys. Lett. 63B, 466 (1976).

(4) M. Chen, Proc. of 1981 Banff Summer School, Aug. 1981;
J. Bürger, Proc. of the Symposium on Lepton and Photon Interactions, Bonn, p. 115 (1981);
P. Duinker, Rev. of Modern Physics 54, 325 (1982).

(5) B. Adeva et al., Phys. Rev. Lett. 48, 967 (1982);
D.P. Barber et al., Phys. Rev. Lett. 45, 1904 (1980);
R. Brandelik et al., Phys. Lett. 99B, 163 (1981);
Ch. Berger et al., Phys. Lett. 99B, 489 (1981);
W. Bartel et al., Phys. Lett. 123B, 349 (1983).

(6) A. Ali et al., Nucl. Phys. B191, 93 (1981);
B. Adeva et al., Phys. Lett. 115B, 345 (1982);
W. Bartel et al., Phys. Lett. 114B, 211 (1982);
H.J. Behrend et al., Phys. Lett. 114B, 287 (1982);
M. Althoff et al., Phys. Lett. 122B, 95 (1983).

(7) C.R.D. Field and R.P. Feynman, Nucl. Phys. B136, 1-76 (1978).

(8) M. Suzuki, Phys. Lett. 71B, 139 (1977);
A. Ali, DESY-Report 81/16 (1981) and Proc. of the 5th International Summer College on Physics and Contemporary Needs (Plenum Publishing, 1982).

(9) C. Peterson et al., Phys. Rev. D27, 105 (1983).

(10) D.P. Barber et al., Phys. Report 63, 337 (1980).

(11) R. Brandelik et al., Phys. Lett. 113B, 98 (1982);
G. Wolf, DESY-Report 82-077 (1982).

(12) The world average branching ratio is $19^{+4}_{-3}\%$ for $D^{\pm} \to e + x$ and < 6% for D^o.
M. Roos et al., Phys. Lett. 111B (April 1982).

(13) Our BR(B) can be compared eith the value 12.4±1.7±3.1% measured on the resonance T''.
K. Chadwick et al., Phys. Rev. D27, 475 (1983).

(14) For earlier measurements on h_c, see:
M. Althoff et al., DESY-Report 83-010 (1983);
K. Kleinknecht and B. Renk, UNIDO 82/274 (to be published in Zeitschr. f. Physik C);
J.M. Yelton et al., Phys. Rev. Lett. 49, 430 (1982).

For preliminary results on h_b, see:
G.H. Trilling, 21st Int. Conf. on High Energy Physics, PC-3-58, Paris (1982).

(15) It should be noted that the probability distribution is approximately gaussian in the h's, not in the more commonly quoted parameter h^2.

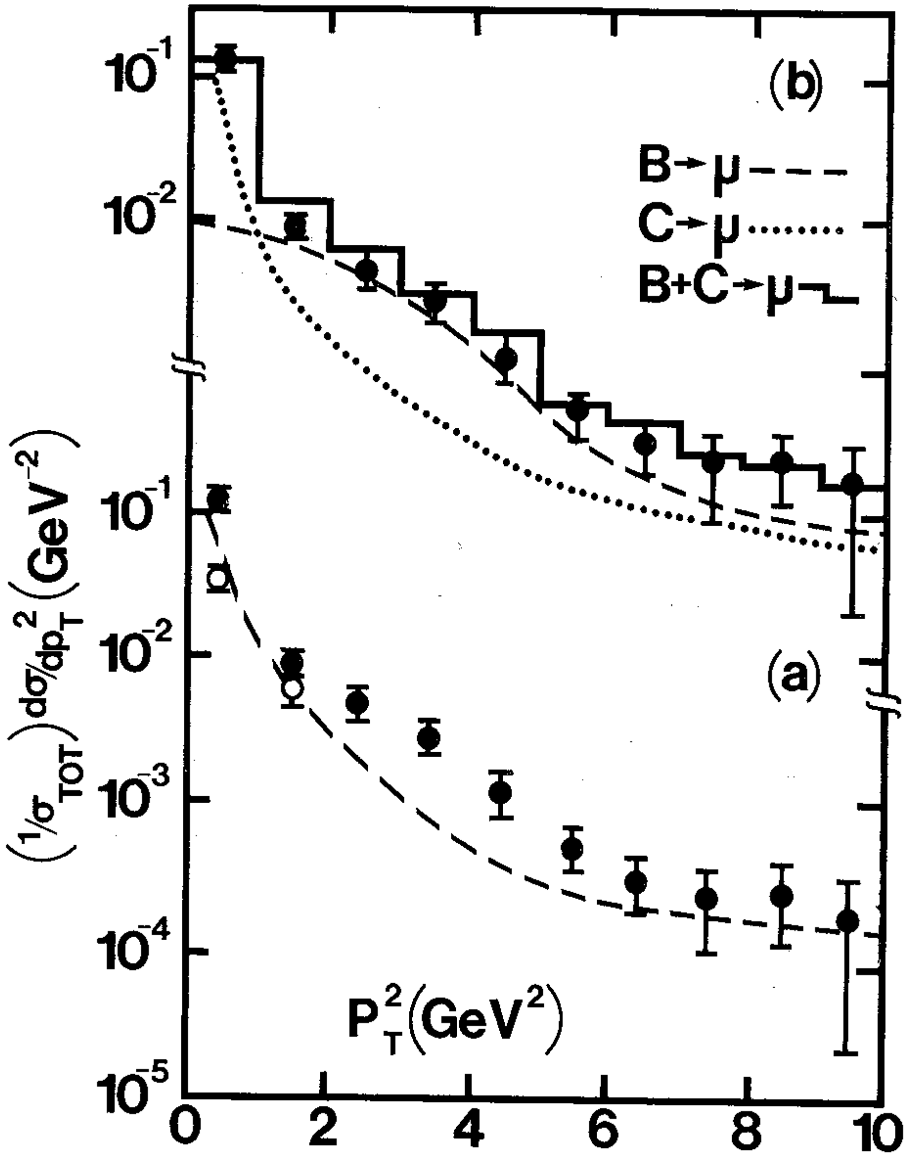
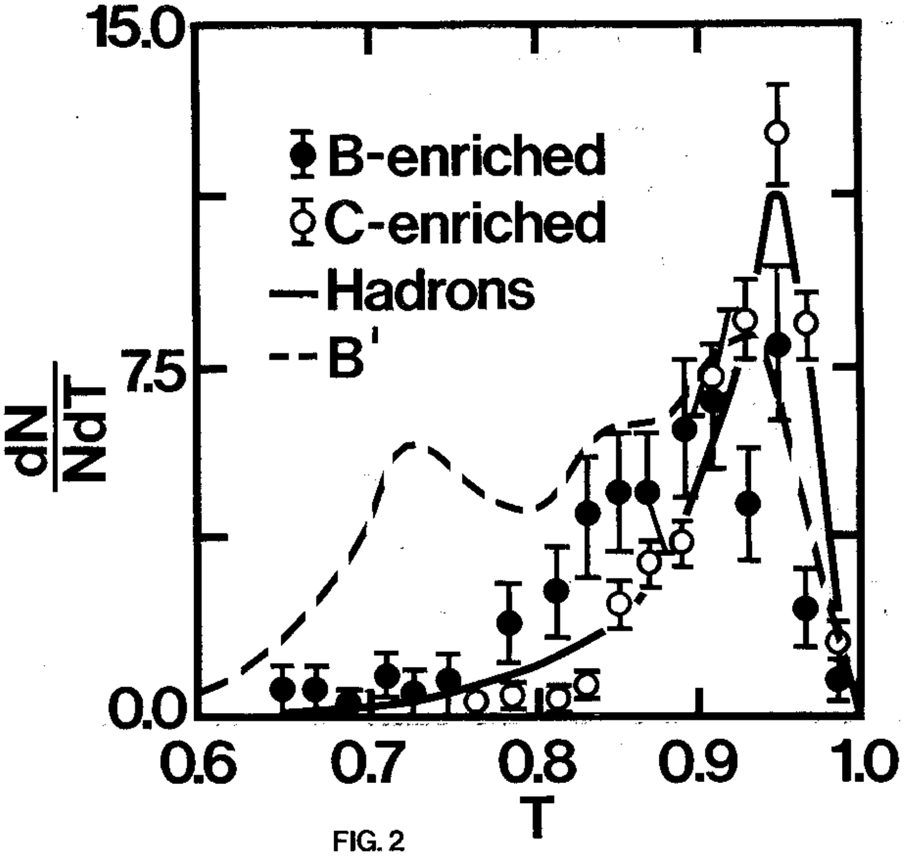
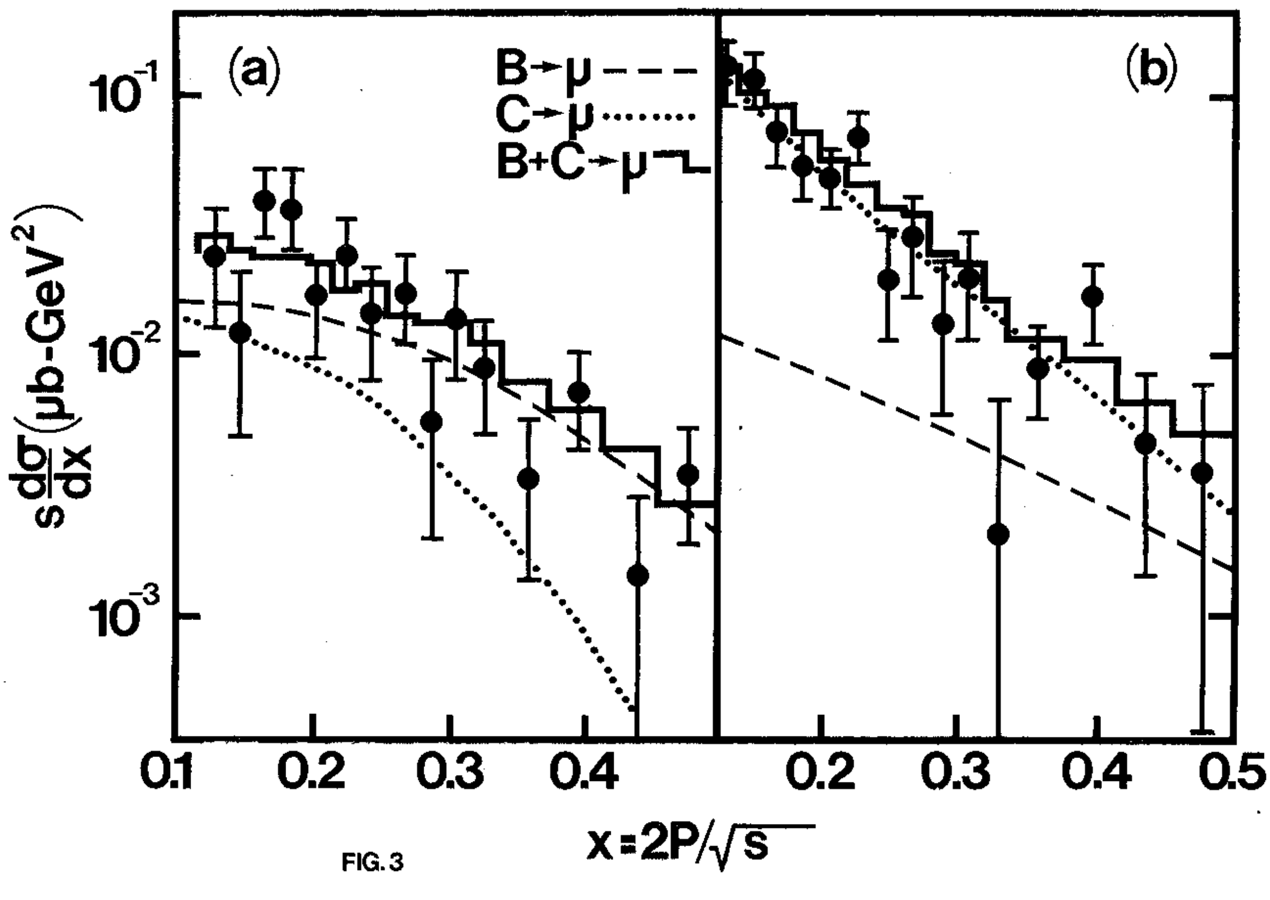


FIG.1



15.0
B-enriched
C-enriched
Hadrons
B'
7.5
dN/NdT
0.0
0.6
0.7
0.8
0.9
1.0
T

FIG. 2



(a)
(b)
B→μ
C→μ
B+C→μ
10^{-1}
10^{-2}
10^{-3}
$s\frac{d\sigma}{dx}(\mu b\text{-}GeV^2)$
0.1
0.2
0.3
0.4
0.5
$x = 2P/\sqrt{s}$

FIG. 3