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The Contribution of Muon Pairs to the Yield of Single Prompt Muons*

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Abstract

Using data from our recent experiment on inclusive μ-pair production by 150 GeV/c protons on beryllium, we have calculated the contribution of muon pairs to the yield of single prompt muons. We find, both at 90° in the CM system and in the forward direction, that the resulting single muon cross sections are in reasonable agreement with existing measurements where only one muon is detected.

A number of hadron scattering experiments have observed the production of single muons from some source other than π and K decay.[1] The effect has been measured for many kinematic regions, incident hadron energies, and target materials. All the experiments, however, have had very limited detection efficiency for observing a second muon. The source of the prompt muons remains unknown. Speculations have included the leptonic or semileptonic decay of some unknown particle (possibly a charmed particle), or al-

ternatively, the production of photons and hence μ-pairs through parton annihilation[2] or an internal bremsstrahlung mechanism.[3] Several authors have estimated the contribution of μ-pairs from vector meson decay.[4] The data used for these estimates is taken from experiments performed under widely differing conditions of incident hadron energy, target materials, and systematic uncertainties. The general conclusion has been that vector mesons could account for at most 30% of the observed signal.

We recently reported results from an experiment on inclusive μ-pair production in proton-beryllium interactions at 150 GeV/c.[5] The μ-pair mass spectrum is studied with broad acceptance in Feynman-x (x_F) and P_T for all masses above the kinematic minimum of 211 MeV. The experiment is sensitive to μ-pair production from vector-meson decay or any other source. It is now possible to calculate the contribution of μ-pairs from all sources, to the single prompt muon cross section, using the results of one self-contained experiment.

In the following analysis, cross sections will be given per beryllium nucleus, which is the quantity directly measured. No attempt is made to extrapolate to proton-nucleon cross sections since the A dependence of the Lorentz invariant cross section depends on both particle mass and transverse momentum.[6] Since good measurements of π production from beryllium are available, the prompt μ/π ratio can be deduced with no assumptions of A dependence. The production of single prompt muons has been observed from a variety of nuclear targets including beryllium.[7]

Our μ-pair studies are in the range $x_F > 0.15$ and $0 \leq P_T \lesssim 2$ GeV/c. To compare these results with existing single-muon measurements at $x_F = 0$ the

data must be parameterized to obtain a reasonable extrapolation to $x_F = 0$. As already discussed[5] we find that an extrapolation of a fit to $d\sigma/dx_F \propto (1-x_F)^c$ gives an integrated cross section which is within 10% of the value obtained by assuming that $Ed\sigma/dx_F = d\sigma/dy$ is flat for $x_F < 0.15$. An extrapolation of a fit of $Ed\sigma/dx_F$ to $(1-x_F)^c$ gives substantially larger cross sections at low mass since no rapidity plateau is imposed. Accordingly, we parameterize the data in terms of $d\sigma/dx_F$ for the present calculation. The results of fitting the data to the form $d\sigma/dx_F = A(1-x_F)^c$ and $d\sigma/dP_T/P_T \propto \exp(-bP_T)$ are given in Table I. The quality of the fits is very similar to that shown in Ref. 5 for the Lorentz invariant form of the x_F dependence.

The contribution of μ-pairs to the single-μ cross section was calculated independently for each of the sources listed in Table I. For the continuum components, $d\sigma/dM_{\mu\mu}$ was parameterized as $\exp(-5M_{\mu\mu})$ within each of the intervals, as indicated by the data. The masses of all resonances were fixed at their nominal values except the ρ which was assumed to have a Gaussian distribution of 150 MeV FWHM. We assume that $\sigma_\rho = \sigma_\omega$. The separation of the ρ-ω signal into two components was done only to allow for the width of the ρ.

The calculation proceeded by standard Monte Carlo techniques. Mu-pair events were generated in x_F and P_T, appropriate to the cross sections given in Table I. The μ-pair state was allowed to decay isotropically in its own rest frame and events were binned on the basis of the x_F and P_T of one of the decay muons. Events were assigned a weight so that each bin accumulated the Lorentz invariant production cross section for single muons of a given charge.

To check the calculation, a second independent computation was made using analytic techniques and numerical integration. The two calculations agreed in

all respects. The sensitivity of the result to the assumption of an isotropic decay of the μ-pair was tested using a $1+\cos^2\theta^*$ decay distribution. The single-μ cross section as a function of P_T, at $x_F = 0$, changed by less than 10% for all P_T less than 2.5 GeV/c. An analysis of the decay angular distribution of our ρ-ω data shows that any polarization is small.[5]

To understand the sensitivity of the single-μ cross section to the P_T spectrum of the μ-pairs, the parentage of single muons at fixed x and P_T was studied. For muons of P_T significantly larger than half the mass of the parent, the P_T of the parent is, on average, only slightly larger than that of the μ. For example, single μ's of P_T = 1.0 GeV and $x_F = 0$, produced by ω decay, arose from parent ω-mesons with a mean P_T of 1.2 GeV. Thus, for transverse momenta less than 2 GeV/c, the single-μ cross section is relatively insensitive to the P_T spectrum of the parents beyond the region of measurement.

Figure 1(a) shows the resulting single-μ Lorentz-invariant cross section as a function of transverse momentum at $x_F = 0$. The curve for the π^- cross section ($\times 10^{-4}$) represents measurements from a beryllium target at 300 GeV, scaled down by about 30% using the energy dependence as a function of P_T measured in the same experiment.[6] The contribution of the vector mesons to the single muon cross section is shown, in addition to the signal from all pair sources. The continuum contributes approximately 50% of the signal at a P_T of 1.5 GeV/c and 30% at 2 GeV/c. The contribution of $J \to \mu^+\mu^-$ to these two regions is 20% and 34% respectively.

Figure 1(b) shows the μ^-/π^- ratio and the comparison with existing single-μ measurements.[7,8,9] Since the data show no difference between μ^+/π^+ and μ^-/π^-, measurements of both ratios are included. The experiments of Ref. 7 were performed at 300 GeV, Ref. 8 at a mean energy of 150 GeV, and Rev. 9 at 70 GeV. We see that the yield of single-μ's from μ-pairs is a good representation of the experimental data. The error in our μ/π ratio is dominated by normalization uncertainties at low P_T and is increased by the uncertainty in the μ-pair transverse momentum spectrum as the P_T increases. Also shown in Fig. 1(b) is the μ/π signal arising from the vector mesons alone.

Prompt electron measurements are not included in Fig. 1(b) since the contribution of continuum e^+e^--pairs may be substantially different than μ-pairs.

Figure 2(a) shows the single-μ yield in the forward direction, integrated over P_T less than 600 MeV, as is required for comparison with the single muon measurements. We see that the total single-μ signal falls more quickly with x_F than pion production or the single-μ cross section from vector mesons. This follows from the steep x_F-dependence of the low mass μ-pair continuum.

The pion cross section from beryllium given in Fig. 2(a) is from a CERN-PS experiment,[10] assuming Feynman scaling. We have compared these results with a less complete set of measurements at 200 and 300 GeV[11] and find agreement to within 20%. Figure 2(b) shows the μ^-/π^- ratio as a function of x_F and the comparison with experiments in the forward direction.[12, 13]

The size of the continuum signal relative to the vector mesons is significantly larger in this low P_T region. The total μ^-/π^- signal predicted from pairs has the same x_F dependence as the single μ measurements although it lies below them by about a standard deviation. Our result tends to support the conclusions of Adair et al.,[12] that the single muons in the forward direction arise predominantly from a μ-pair source other than vector meson decay. We find however that the μ-pair mass spectrum is not dominated by any unusual source near 900 MeV as suggested in Ref. 12.

Figure 3 shows the expected pair-produced single-muon signal in other kinematic regions. The errors to be associated with these curves can be estimated from the error bands of Figs. 1(b) and 2(b).

In conclusion, the present measurements of prompt single muons are in reasonable agreement with the yield expected from μ-pairs. In the forward direction the μ-pair continuum plays a significant role in producing the single muons.

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TABLE CAPTION

Table I Parameterization of inclusive μ-pair production cross section. The x_F dependence is fit to the form $d\sigma/dx_F = A(1-x_F)^c$. The P_T dependence is fit to $d\sigma/dP_T/P_T \propto \exp(-bP_T)$.

FIGURE CAPTIONS

Figure 1(a) The Lorentz invariant cross section for single muons at $x_F = 0$ arising from μ-pairs produced in 150 GeV p + Be interactions. Also shown in the π^- cross section from beryllium.

Figure 1(b) The calculated μ^-/π^- ratio and comparison with existing data at $x_F = 0$. The symbols ● and □ refer to the two experiments of Ref. 7, ▲ Ref. 8, ■ Ref. 9. The solid line and error bounds show the predicted μ/π ratio from all pair sources. The broken line is the predicted ratio for vector mesons alone.

Figure 2(a) Cross section for single-muon production as a function of x_F, integrated over all P_T less than 600 MeV. The dashed line shows the predicted cross section for vector mesons alone.

Figure 2(b) The calculated μ/π^- ratio and comparison with existing data in the forward direction. The symbol ● is the data of Ref. 12, ■ of Ref. 13.

Figure 3 Lorentz invariant cross section for the production of single muons of a given sign from pairs, as a function of x_F and P_T.

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TABLE I

Source	A nb	b $(GeV/c)^{-1}$	c
ρ	$4.28 \pm .85 \times 10^3$	$3.79 \pm .09$	$4.32 \pm .13$
ω	$7.6 \pm 1.5 \times 10^3$	$3.79 \pm .09$	$4.32 \pm .13$
ϕ	$2.2 \pm .4 \times 10^3$	$3.93 \pm .27$	$5.57 \pm .38$
J	140 ± 42	$2.08 \pm .26$	$3.76 \pm .48$
Continuum (Mass Range)			
< 0.45	$6.2 \pm 1.2 \times 10^4$	$4.63 \pm .15$	$8.25 \pm .23$
0.45 - 0.65	$2.0 \pm 0.4 \times 10^4$	$4.58 \pm .14$	$6.45 \pm .22$
0.65 - 0.93	$4.4 \pm .9 \times 10^3$	$3.79 \pm .09$	$4.32 \pm .13$
0.93 - 1.13	$1.4 \pm .3 \times 10^3$	$3.93 \pm .27$	$5.57 \pm .38$
1.13 - 2.0	$6.4 \pm 1.3 \times 10^2$	$3.41 \pm .85$	$5.10 \pm .90$

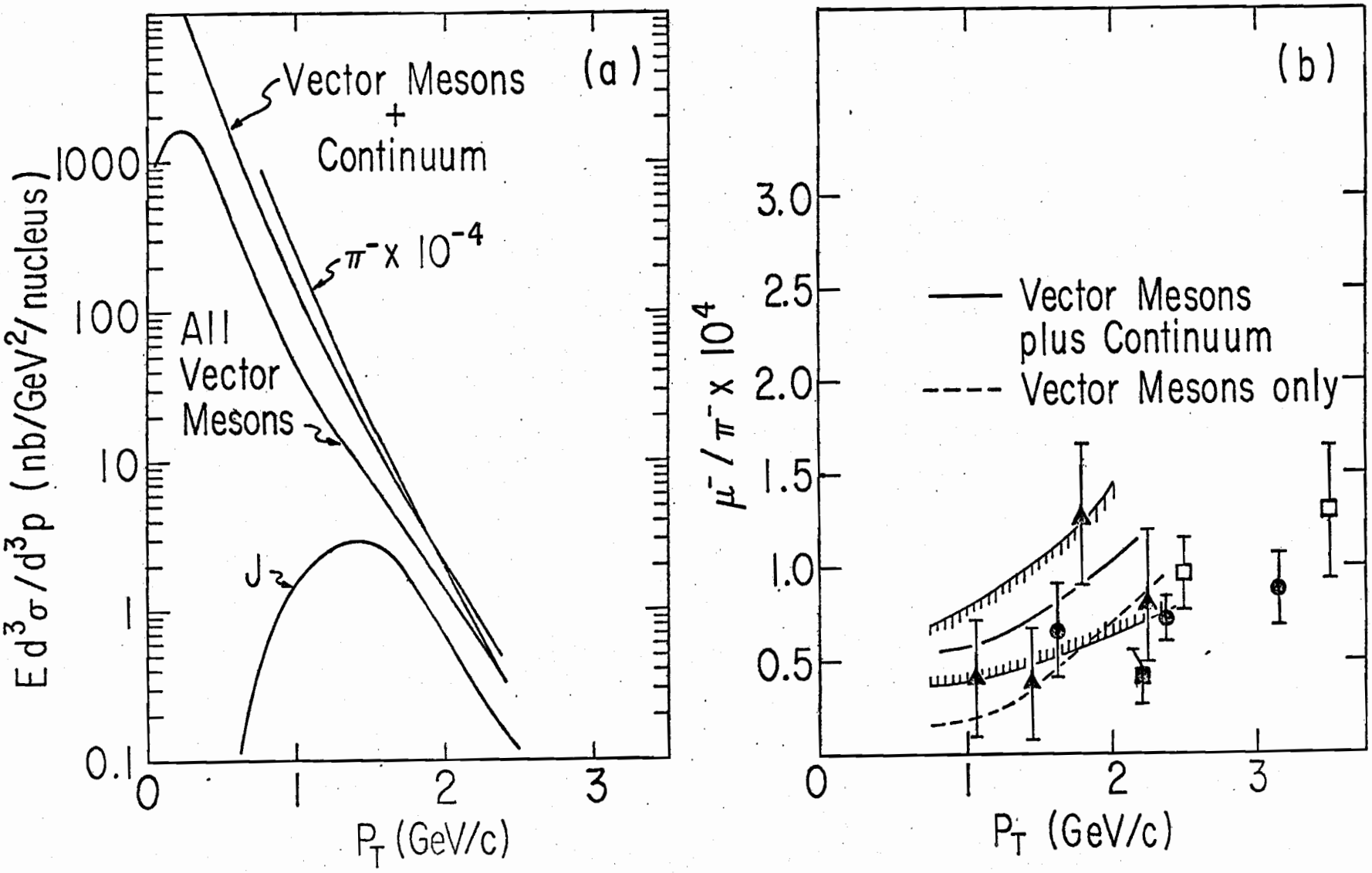
(a)
Vector Mesons
+
Continuum
$\pi^- \times 10^{-4}$
All
Vector
Mesons
J
$E\,d^3\sigma/d^3p$ (nb/GeV^2/nucleus)
1000
100
10
1
0.1
0
1
2
3
P_T (GeV/c)
(b)
Vector Mesons
plus Continuum
Vector Mesons only
$\mu^-/\pi^- \times 10^4$
3.0
2.5
2.0
1.5
1.0
0.5
0
1
2
3
P_T (GeV/c)

Fig. 1

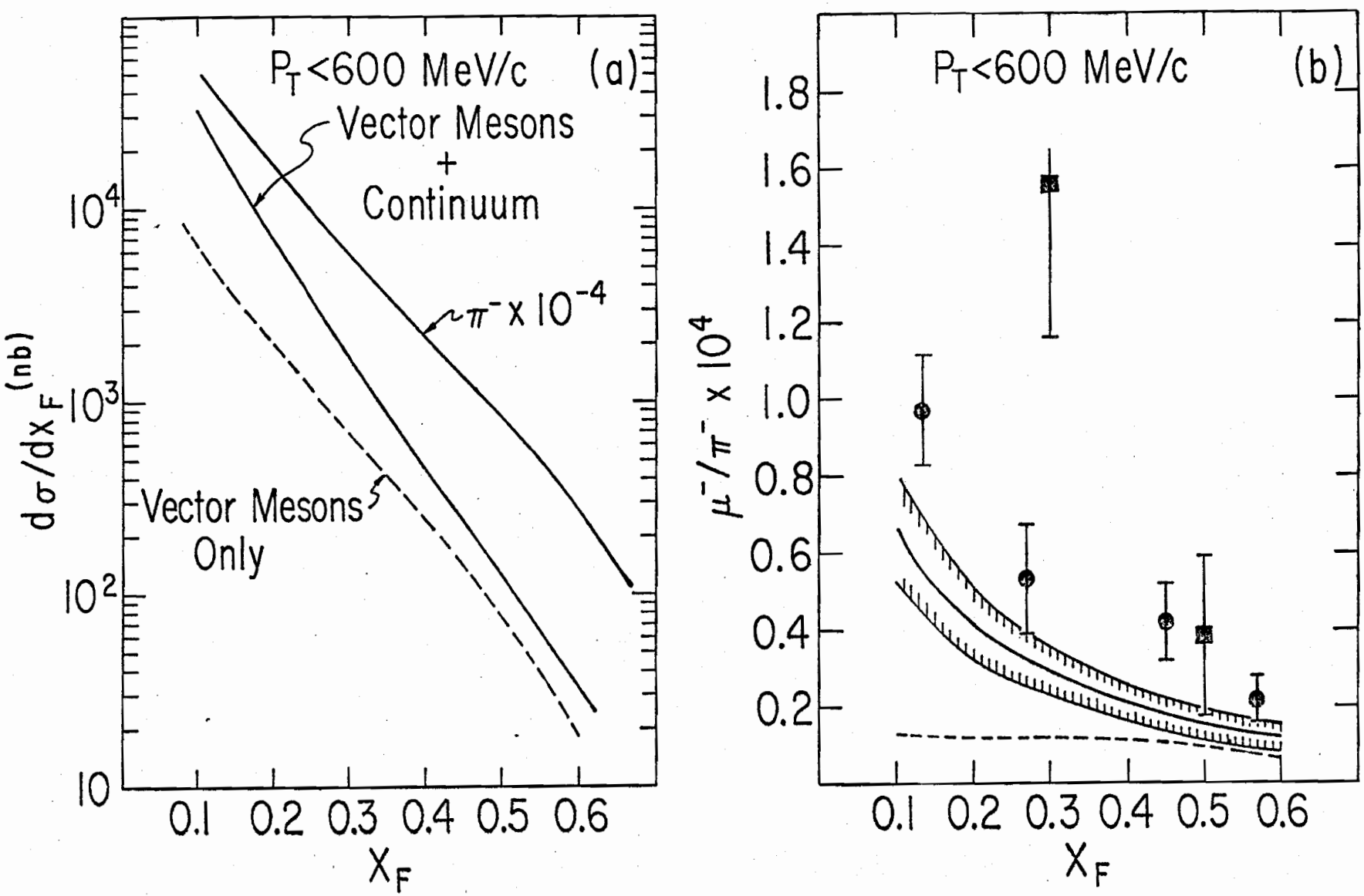
P_T<600 MeV/c
(a)
Vector Mesons
+
Continuum
$\pi^- \times 10^{-4}$
Vector Mesons
Only
$d\sigma/dx_F$ (nb)
10^4
10^3
10^2
10
0.1 0.2 0.3 0.4 0.5 0.6
X_F
P_T<600 MeV/c
(b)
$\mu^-/\pi^- \times 10^4$
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.1 0.2 0.3 0.4 0.5 0.6
X_F

Fig. 2

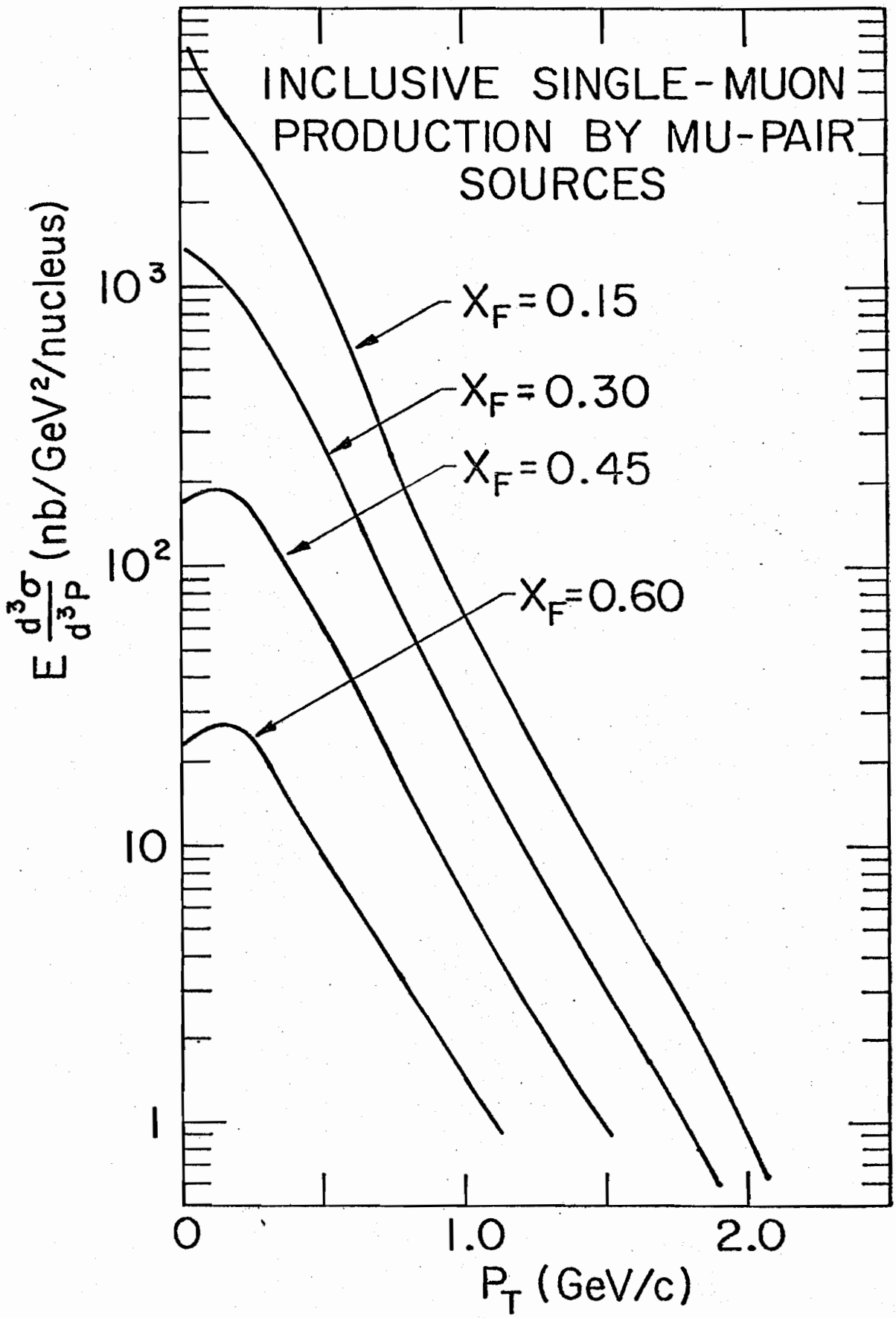
INCLUSIVE SINGLE-MUON PRODUCTION BY MU-PAIR SOURCES
$X_F = 0.15$
$X_F = 0.30$
$X_F = 0.45$
$X_F = 0.60$
$E \frac{d^3\sigma}{d^3p}$ (nb/GeV²/nucleus)
10^3
10^2
10
1
0
1.0
2.0
P_T (GeV/c)

Fig. 3