Fermi National Accelerator Laboratory

FERMILAB-Pub-82/99-EXP
7550.537
(Submitted to Phys. Lett.)

COMPARISON OF ENERGY DEPENDENCE OF TRANSVERSE MOMENTUM OF DIMUONS PRODUCED IN pN AND π^-N INTERACTIONS WITH QCD PREDICTIONS

B. Cox and P. K. Malhotra

December 1982

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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COMPARISON OF ENERGY DEPENDENCE OF TRANSVERSE MOMENTUM OF DIMUONS PRODUCED IN pN AND π^-N INTERACTIONS WITH QCD PREDICTIONS

B. Cox and P.K. Malhotra*
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL. 60510

Abstract

We have analyzed the dependence of the average transverse momentum squared, $\langle p_T^2 \rangle$, of dimuons produced in pN and π^-N interactions, on s, the square of the center of mass energy. The presently available data indicate a linear increase of $\langle p_T^2 \rangle$ with s in both reactions with the rate of increase being approximately twice as large in the π^-N reaction. The value of $\langle p_T^2 \rangle$ at s=0 which is interpreted as the intrinsic $\langle k_T^2 \rangle$ of the π^- and p constituents is the same within errors for both reactions. First order QCD consistently predicts a lower $\langle p_T^2 \rangle$ at all s than observed in the data.

*On leave from the Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005, India.

A well known prediction of perturbative quantum chromodynamics (QCD) is that the average transverse momentum squared, $\langle p_T^2 \rangle$, of dimuons produced in hadronic collisions is given to order α_s by the relationship[1-3]

$$\langle p_T^2 \rangle = \langle k_T^2 \rangle + \alpha_s(Q^2) \cdot f(\tau, x_F, \ell n\, Q^2) \cdot s \qquad (1)$$

where α_s is the running coupling constant, M is the mass of the dimuon, s is the center of mass energy squared, $\tau = M^2/s$, and $\langle k_T^2 \rangle$ is the sum of the intrinsic transverse momentum squared of the constituents that take part in the interaction. Equation (1) implies that $\langle p_T^2 \rangle$ should grow linearly with s at a given τ and x_F. A linear relationship has been reported[4-6]. The aim of this paper is to extract quantitative information from presently existing data on the s variation of $\langle p_T^2 \rangle$ in π^-N and pN reactions and to compare the observed data with the predictions of first-order QCD.

The perturbative expression for the differential cross section to first order in α_s for dimuon production can be written as[7]:

$$\frac{d\sigma_p}{dM\, dy\, dp_T^2} = \frac{d\sigma_A}{dM\, dy\, dp_T^2} + \frac{d\sigma_C}{dM\, dy\, dp_T^2}$$

$$= \frac{16\alpha^2}{27}\,\frac{s}{M}\int_{x_1^{min}}^{1} dx_1\, \frac{x_1 x_2 \alpha_s}{x_1 s + u - M^2}\, \frac{(\hat{t}-M^2)^2 + (\hat{u}-M^2)^2}{s^2 \hat{t}\hat{u}} \cdot \sum_i e_i^2 \left[q_i^{h_1}(x_1,Q^2)\, \bar{q}_i^{h_2}(x_2,Q^2) + (1 \leftrightarrow 2) \right]$$

$$+ \frac{2\alpha^2}{9}\,\frac{s}{M}\int_{x_1^{min}}^{1} dx_1\, \frac{x_1 x_2 \alpha_s}{x_1 s + u - M^2}\, \frac{\hat{s}^2 + \hat{u}^2 + 2M^2\,\hat{t}}{-\hat{s}^3 \hat{u}} \cdot \sum_i e_i^2 \left[q_i^{h_1}(x_1,Q^2)\, G_i^{h_2}(x_2,Q^2) + (1 \leftrightarrow 2) \right] \qquad (2)$$

Here σ_A and σ_C represent the contributions of the order α_S quark-antiquark annihilation and Compton scattering diagrams shown in Figs. 1b and 1c, respectively. The q_i's and G_i's in Eq. (2) are the quark and gluon distribution functions, and the various kinematic variables are given by:

$$x_1^{min} = -u/(s+t-M^2), \quad x_2 = [-x_1 t-(1-x_1)m^2]/(x_1 s+u-m^2)$$

$$t = M^2-\sqrt{s}\, M_T\, e^{-y}, \quad u = M^2-\sqrt{s}\, M_T\, e^{y},$$

$$\hat{s} = x_1 x_2 s, \quad \hat{t} = x_1 t+(1-x_1)M^2, \quad \hat{u} = x_2 u + (1-x_2)M^2,$$

$M_T^2 = p_T^2 + M^2$ and $\alpha_s = 12\pi/[25\, \ell n(Q^2/\Lambda^2)]$, with $Q^2 = M^2$ in expression (2).

Equation (2) is useful only for large p_T since it has a singularity at $p_T = 0$. Furthermore, it ignores the intrinsic transverse momentum, k_T, of the constituents. Altarelli, Parisi and Petronzio[1] have given the following prescription which uses this intrinsic k_T to regularize the $p_T = 0$ divergence:

$$\frac{d\sigma}{dM\, dy\, dp_T^2} = \int d^2q_T \frac{d\sigma_P}{dM\, dy\, dp_T^2} [f(\vec{p}_T - \vec{q}_T) - f(p_T)] + \pi f(p_T) \frac{d\sigma_{DY}}{dM\, dy} \tag{3}$$

Here $\vec{q}_T = \vec{p}_T - \vec{k}_T$, σ_{DY} is the Drell-Yan cross section (see Fig. 1a) and f is the soft k_T distribution. We have assumed the k_T distribution to have a Gaussian form with the normalization

$$\int f(p_T)\, d^2p_T = \frac{1}{\pi<k_T^2>} \int d^2p_T \exp[-p_T^2/<k_T^2>] = 1 \tag{4}$$

The structure functions used in this calculation of $<p_T^2>$ are given by

$$
\begin{aligned}
x\,u_p &= u_o\, x^{0.52-0.16\bar{s}}\,(1-x)^{2.79+0.77\,\bar{s}} \\
x\,d_p &= d_o\, x^{0.52-0.16\bar{s}}\,(1-x)^{3.79+0.77\bar{s}} \\
x\,S_p &= (0.26+0.18\bar{s})\,(1-x)^{7.8+0.78\bar{s}} \\
x\,G_p &= 3.06(1-x)^{5.0} \\
x\,V_\pi &= V_o\, x^{0.4}\,(1-X)^{0.9} \\
x\,S_\pi &= 0.24\,(1-x)^{6.9} \\
x\,G_\pi &= 2.0\,(1-x)^{3.0}
\end{aligned}
\qquad (5)
$$

with $\bar{s} = \ell n[(Q^2/0.25)/\ell n(20/0.25)]$. The valence quark distributions are normalized to obtain the proper number of valence quarks for π's and protons. We have assumed that the strange quark-antiquark pairs are suppressed by a factor of 2 compared to $u\bar{u}$ or $d\bar{d}$ pairs. The quark distribution functions for the proton correspond to the CDHS results[8] while the quark distribution functions for the pion correspond to the NA3 results[6,9]. The Q^2 dependence is quite small over the range of interest. We have used a Q^2 independent gluon distribution for the proton corresponding to counting rules; the conclusions arrived at here are not affected if the power index is varied in the range 5.0 $\pm$ 1.0.

When we use the structure functions (5) in Eq. (3) and integrate over p_T, we obtain the Q^2 dependent Drell-Yan cross section which is known to be lower than the experimental cross sections for dimuon production by π's, p, or antiprotons by factors in the range 1.6 to 2.6 (a compilation of K factors $\equiv (d\sigma/dMdy)_{data}/(d\sigma/dMdy)_{DY}$ for various reactions is given in Refs. 10,11). At

the level of the accuracy of the data these K factors have been determined to be independent of τ and y. Theoretical justifications of constant K factors have been provided by several authors[12] who have carried out a full $O(\alpha_S)$ calculation and have confirmed the observed independence on K on τ and y for $\tau < 0.5$. In these calculations the largest part of correction to the cross section for $\tau \leq 0.3$, (i.e., for the range of the current experiments) is found to arise from the vertex correction diagram (Fig. 1d). This diagram, however, contributes no p_T other than the k_T of the constituents to the dimuons. In addition, more complete calculations to order α_S^2 which have been done by Ellis et al.,[13] indicate that the K is only a slowly varying function of p_T. Therefore, we have used empirical K factors assumed to be independent of τ, x_F, and p_T in fitting the dimuon p_T distributions at various energies.

Using Eq.(3), the structure functions given by (5), and the empirical K factors, we have been able to fit published dimuon transverse momentum distributions for proton interactions at 400 GeV/c and 2050 GeV/c, for π^- interactions from 125 GeV/c to 280 GeV/c and for $\bar{p}$ interactions at 125 GeV/c. While the agreement of the calculations with the proton data is quite good at a given s, a $\langle k_T^2 \rangle$ varying from 0.9 $(GeV/c)^2$ at $\sqrt{s}$ = 23.4 GeV to 1.5 $(GeV/c)^2$ at $\sqrt{s}$ = 62 GeV, is required. similarly $\langle k_T^2 \rangle$ must vary from 0.9 $(GeV/c)^2$ at $\sqrt{s}$ = 15.3 GeV to 1.2 $(GeV/c)^2$ at $\sqrt{s}$ = 22.8 GeV for the π^- reaction. Thus we find that QCD to order α_S with a constant $\langle k_T^2 \rangle$ is unable to describe the existing p_T data at different energies.

To make explicit the failure of first order QCD with constant $\langle k_T^2 \rangle$ to explain the transverse momentum distributions of dimuon at different energies, we have compared the observed second moments of the p_T distributions of the data to the $\langle p_T^2 \rangle$ predicted by (3). Figure 2 shows the existing

measurements[5,6,14,15] of $\langle p_T^2 \rangle$ for $\sqrt{\tau} = 0.28$ and $x_F > 0$ at different values of s for the π^-N reaction. Figure 3 shows $\langle p_T^2 \rangle$ for the pN data[5,16,17] for $\sqrt{\tau} = 0.22$. The pN data points from the CFS experiment[15] are for $\langle y \rangle$ ranging from 0.03 for 400 GeV/c to 0.40 for 200 GeV/c. To take into account the expected dependence of $\langle p_T^2 \rangle$ on y we have used the QCD formalism described above to correct the CFS data to correspond to $y \geq 0$. Linear fits of the form $\langle p_T^2 \rangle = A+Bs$ are shown for both sets of data. The details of the fits are given below in Table I.

TABLE 1

Fits of $\langle p_T^2 \rangle = A+B(\tau)s$ to existing dimuon data

Fit	Reaction	$\sqrt{\tau}$	Intercept (A)	slope (B)	χ^2/NDF
$\langle p_T^2 \rangle$	π^-N	0.28	0.59 ± 0.05	$(2.8 \pm 0.2)10^{-3}$	1.2
	pN	0.22	0.52 ± 0.11	$(1.4 \pm 0.2)10^{-3}$	0.3

As shown in the figures and in Table I, the s=0 intercept is the same within errors for the pN and π^-N data but the slope of the rise of $\langle p_T^2 \rangle$ with s is approximately twice as large for the π^-N data as for the pN data.

Since within errors the intercepts $\langle p_T^2 \rangle_{s=0}$ are the same and since we interpret $\langle p_T^2 \rangle_{s=0}$ to be equal to $\langle k_T^2 \rangle$ from Eq. (1), we have set $\langle k_T^2 \rangle = 0.59$ $(GeV/c)^2$ in the QCD calculations. The results of the calculation of $\langle p_T^2 \rangle$ with this choice of $\langle k_T^2 \rangle$ are shown in Figs. 2 and 3 for two different values of Λ(0.3 and 0.5 GeV/c). The predictions of QCD fall well below the data in

the case of both the pN and the π^-N reactions. However, the calculations do show a steeper slope for π^-N than for pN in qualitative agreement with the data.

In conclusion we have examined the behavior of $\langle p_T^2 \rangle$ as a function of s for the high mass di-muons produced in pN and π^-N interactions. We find that the data are consistent within errors with the same $\langle p_T^2 \rangle$ intercept at s=0 for p and π^-, but that the rise of $\langle p_T^2 \rangle$ with s is approximately twice as fast for the π^-N reaction as for the pN reaction. We have interpreted the s=0 intercept as the sum of the $\langle k_T^2 \rangle$ of the constituents of the proton and pion participating in the interaction and have used the observed intercept, $\langle k_T^2 \rangle$ = 0.59 GeV^2/c^2, in the first-order QCD prescription of Altarelli et al., to calculate the expected behavior of $\langle p_T^2 \rangle$ with s. We find that this $O(\alpha_s)$ formalism of QCD to (with the assumption of a p_T independent K factor and $Q^2 = M^2$) is unable to account for the observed energy dependence of $\langle p_T^2 \rangle$ with the disagreement worsening at larger s.

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Figure Captions

Fig. 1. (a) Drell-Yan Process.

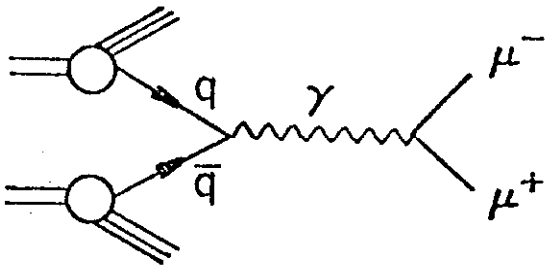
(b) $O(\alpha_s)$ QCD quark-antiquark annihilation process.

(c) $O(\alpha_s)$ QCD Compton scatter process.

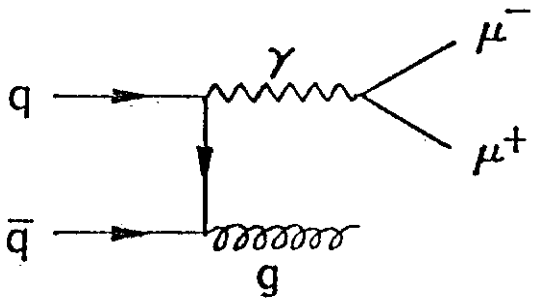
(d) Vertex correction to the Drell-Yan process with virtual gluon exchange.

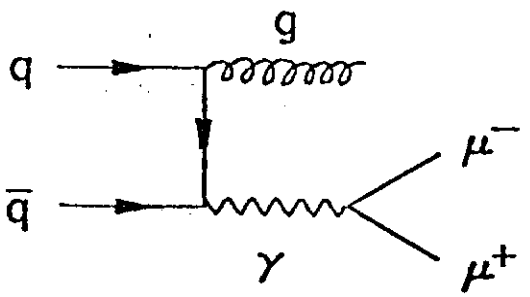
Fig. 2. $\langle p_T^2 \rangle$ versus s for dimuons produced in π^- nucleon interactions. The solid curve is a linear fit to the data. The dotted and dashed curves are the predictions of first order QCD using the Altarelli et al., prescription for different values of Λ.

Fig. 3. $\langle p_T^2 \rangle$ versus s for dimuons produced in p-Nucleon interactions. The solid curve is the linear fit to the data. The dotted and dashed curves are the predictions of first order QCD using the Altarelli et al., prescription for different values of Λ.

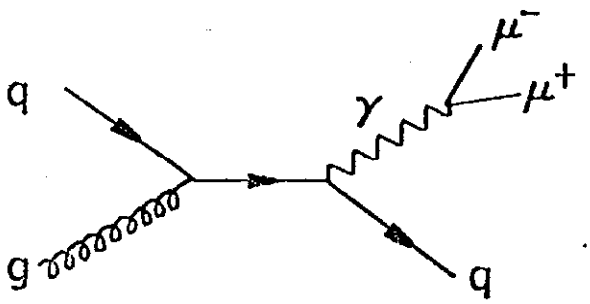


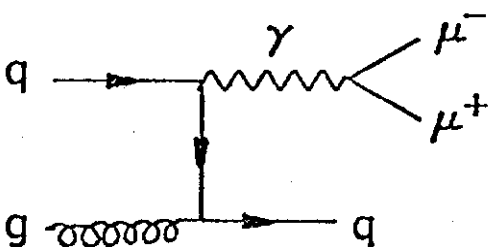
(a)



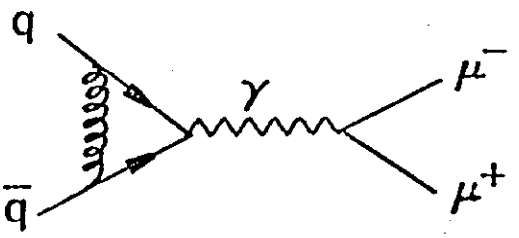


(b)





(c)



(d)

Fig. 1

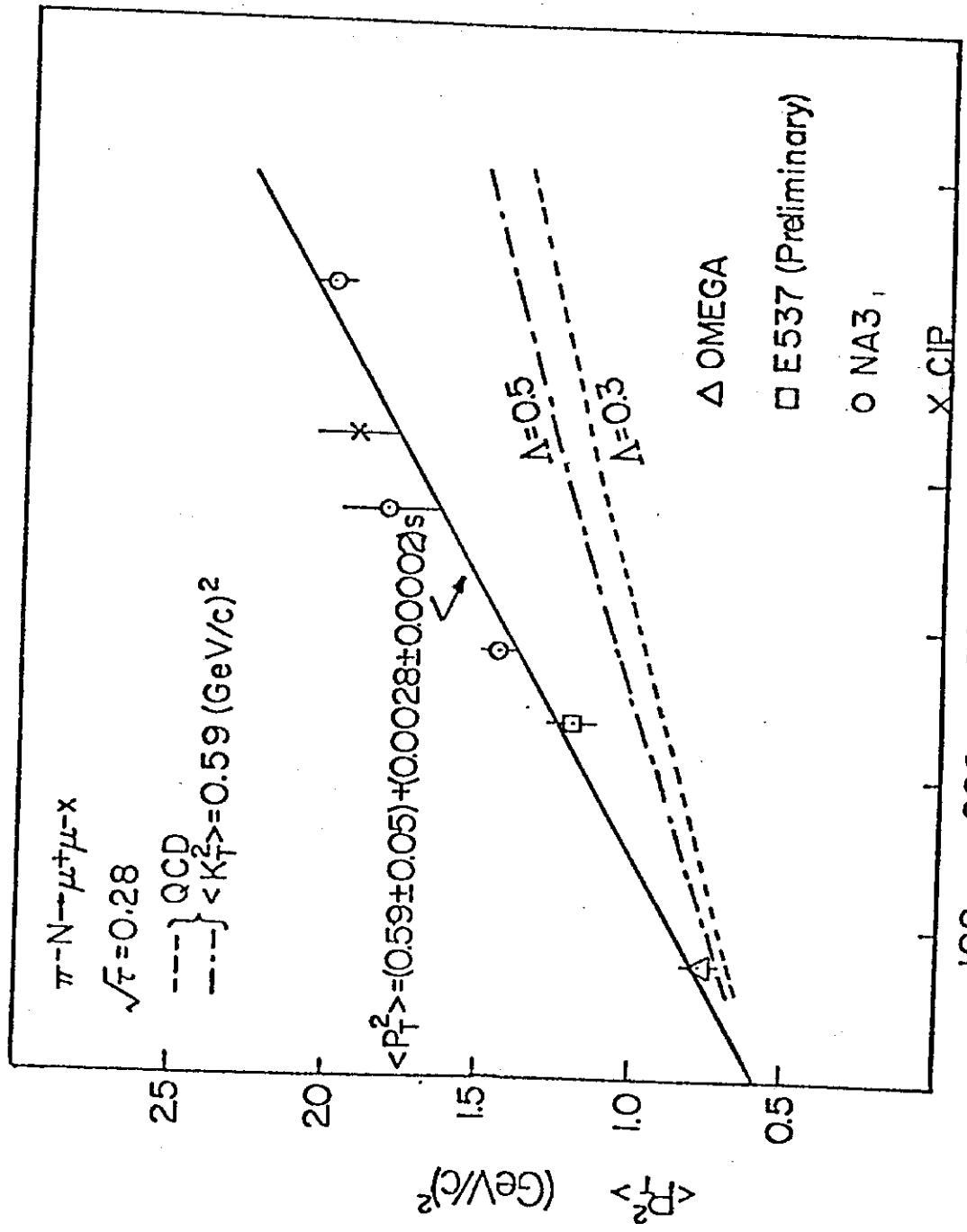

π⁻N→μ⁺μ⁻X
√τ=0.28
---} QCD
-·-} <K_T^2>=0.59 (GeV/c)^2
<P_T^2>=(0.59±0.05)+(0.0028±0.0002)√s
Λ=0.5
Λ=0.3
Δ OMEGA
□ E537 (Preliminary)
○ NA3
X CIP
<P_T^2> (GeV/c)^2
S (GeV^2)
0.5
1.0
1.5
2.0
2.5
100
200
300
400
500
600

Fig. 2

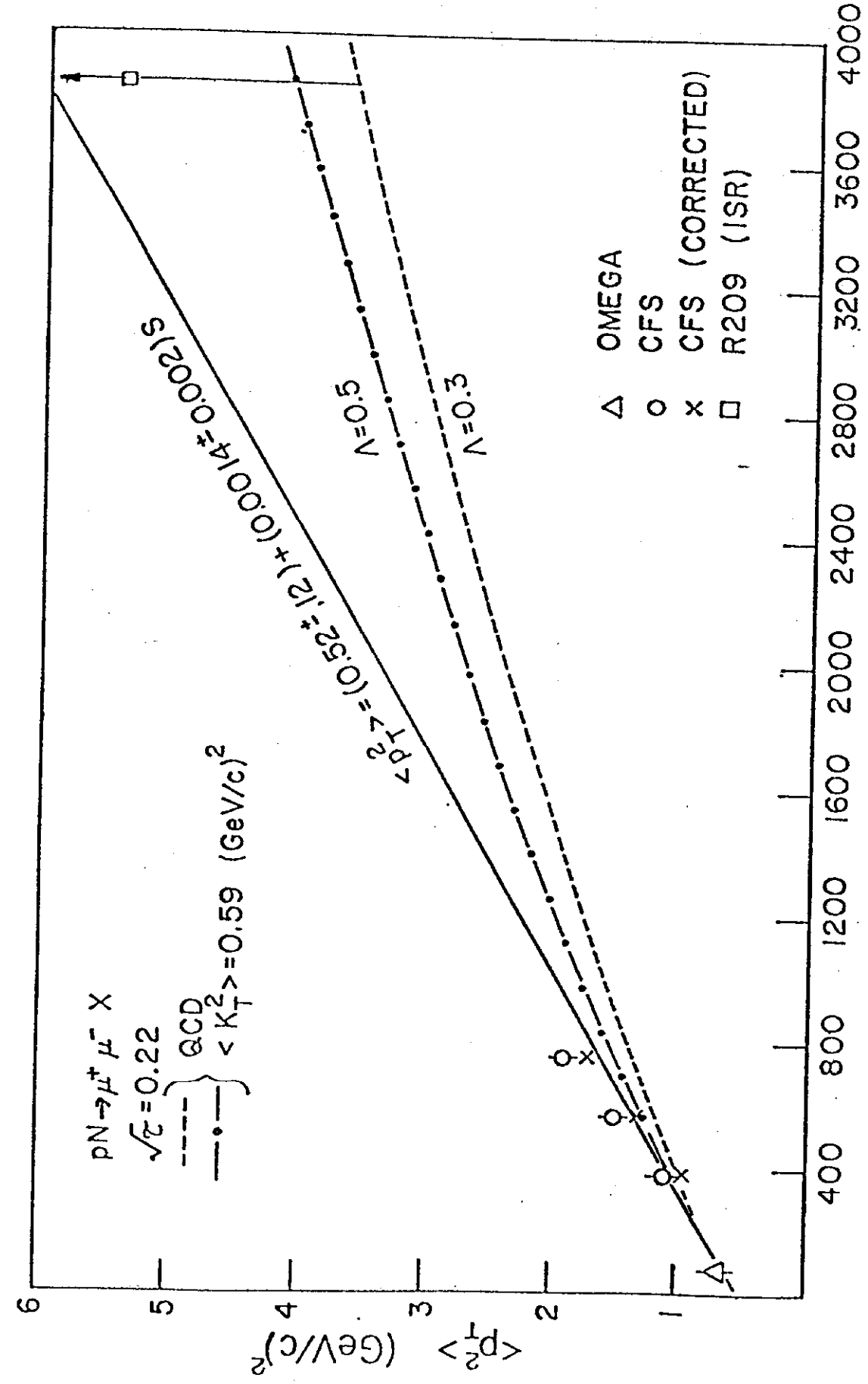

pN→μ⁺μ⁻X
√s=0.22
QCD
< K_T^2 >=0.59 (GeV/c)^2
<p_T^2> = (0.52±0.12)+(0.001±0.002)S
Λ=0.5
Λ=0.3
OMEGA
CFS
CFS (CORRECTED)
R209 (ISR)
<p_T^2> (GeV/c)^2
S GeV^2
1
2
3
4
5
6
400
800
1200
1600
2000
2400
2800
3200
3600
4000

Fig. 3