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# QCD IN THE LIMIT $x_F \to 1$ AS STUDIED IN THE REACTION $\pi^- N \to \mu^+\mu^- X$

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## ABSTRACT

In Fermilab experiment E 615 we[1] have measured the production of high-mass muon pairs with 80- and 252-GeV pion beams. The relatively large momentum of quarks in pions allows us the study the QCD subprocess $q\bar{q} \to \mu^+\mu^-$ in the kinematic limit $x_\pi^q \to 1$. The data are consistent with many of the features of a higher-twist analysis, particulary the departure of the muon-pair angular distribution from the standard form $1 + \cos^2\theta_t$. Analysis of $J/\psi$ and $\psi'$ production in the same data sample gives further evidence for interesting effects as $x_F \to 1$, which we attribute to the process $q\bar{q} \to c\bar{c}$.

## INTRODUCTION

In a previous experiment[2] we were the first to measure the valence-quark distribution in the pion, via a Drell-Yan-model[3] analysis of the reaction $\pi N \to \mu^+\mu^- X$. The valence-quark distribution is approximately

$$q_\pi^v(x_\pi) \sim 1 - x_\pi$$

for large $x_\pi$, the fraction of the pion's momentum carried by the quark. This is in contrast to the well-known result that in the proton

$$q_p^v(x_p) \sim (1 - x_p)^3$$

at large $x_p$. Thus with the pion the kinematic limit $x_\pi \to 1$ is rather accessible at presently available energies. In this limit the pion is nearly a single quark.

Theoretical impetus to pursue the limit $x_\pi \to 1$ came from a (so-called 'higher-twist') calculation by Berger and Brodsky[4] who consider that the fast quark in the pion receives its momentum via gluon exchange with other initial-state valence quarks. This leads to QCD corrections to the basic Drell-Yan subreaction $q\bar{q} \to \gamma^* \to \mu^+\mu^-$ which manifest 2 qualitative features:

- a change in the angular distribution of the $\mu^+$ in the muon-pair rest frame from $1 + \cos^2\theta$ to $\sin^2\theta$ as $x_\pi \to 1$;

- a component of the structure function $F_\pi(x_\pi)$ which is constant as $x_\pi \to 1$, with magnitude scaled by $k_T^2/M_{\mu\mu}^2$.

After suggestive evidence for the first feature was found in our previous experiment[5] we designed E 615 to study this physics in greater detail.

The apparatus is sketched in fig. 1 and described in detail elsewhere.[6] Data were collected with both 80- and 252-GeV $\pi^-$ beams on a tungsten target. Results from the 80-GeV sample have been reported previously,[7] while here we give the first major results from the 252-GeV run.

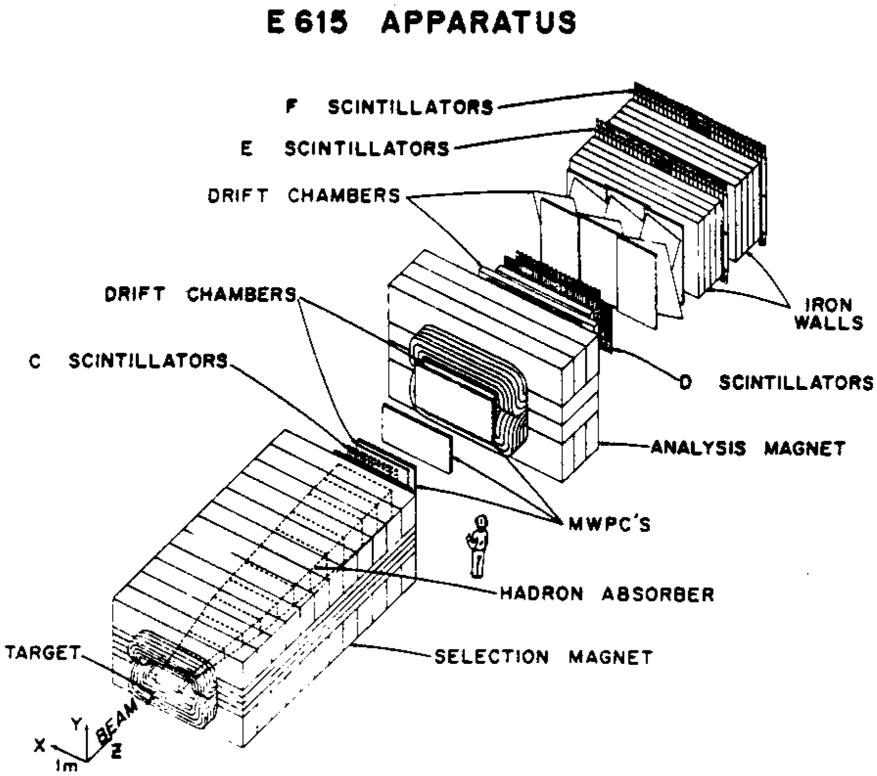


Figure 1. A view of the E 615 apparatus.

## CONTINUUM ANALYSIS

First we present the pion and nucleon structure functions, for which the observed continuum muon-pair production cross section is analyzed according to

$$\frac{d\sigma}{dx_\pi dx_N} = \frac{1}{3}\sum_q \sigma_{q\bar{q}}\left[\bar{q}_\pi(x_\pi)q_N(x_N) + q_\pi(x_\pi)\bar{q}_N(x_N)\right],$$

where the annihilation cross sections for massless quarks are

$$\frac{d\sigma_{q\bar{q}}}{d\Omega} = \frac{\alpha^2 Q_q^2}{4M_{\mu\mu}^2}(1+\cos^2\theta), \qquad \text{and} \qquad \sigma_{q\bar{q}} = \frac{4\pi\alpha^2 Q_q^2}{3M_{\mu\mu}^2},$$

and the functions $q(x)$ are the quark distributions introduced above. First-order QCD corrections in the next-to-leading-log approximation[8] modify the model calculations primarily in 2 ways:

$$\sigma_{\mu\mu} \to K\sigma_{\mu\mu} \quad \text{where } K \sim 2.5;$$

and

$$q(x) \to q(x, M_{\mu\mu}) \quad \text{with logarithmic dependence on } M.$$

In the continuum analysis the kinematic variables are related by

$$x_\pi x_N = \tau = \frac{M^2_{\mu\mu}}{s}, \qquad x_\pi - x_N = x_F = \frac{2p^*_L}{\sqrt{s}},$$

while $\sqrt{s} = 21.8$ for the 252-GeV data sample.

As our data are restricted to $x_\pi > 0.2$ the pair production is dominated by the valence quarks of the pion and we write

$$F_\pi = x_\pi \bar{u}^v(x_\pi) = x_\pi d^v(x_\pi).$$

The cross section then factorizes into

$$d\sigma_{\mu\mu} \sim F_\pi(x_\pi) G_N(x_N),$$

where

$$G_N = \frac{x_N}{9}\left[4\frac{Z}{A}u^v_p(x_N) + 4\left(1 - \frac{Z}{A}\right)d^v_p(x_N) + 5u^s_p(x_N)\right],$$

with $A$ and $Z$ labelling the atomic weight and atomic number of tungsten. Based on 36,000 pairs with mass above 4.05 GeV/c$^2$ we find the structure functions $F_\pi$ and $G_N$ shown in figs. 2 and 3.[9]

Our data for the nucleon structure function $G_N$, shown as solid cirlces in fig. 2, agree with the trend observed in the CERN NA3 experiment on muon-pair production,[10] as well as that inferred from deep-inelastic neutrino scattering.[11,12] Our result for the bin $0.04 < x_N < 0.06$ lies significantly above the trend of the higher $x_N$ data. The pairs in this bin have mass very close to the cut at 4.05 GeV/c$^2$. A study is presently underway to relax this cut, which requires separation of pairs from decay of the $J/\psi$ and $\psi'$ resonances from those due to the Drell-Yan mechanism.

Our results for the pion structure function (solid circles in fig. 3) confirm and extend the trend seen in other experiments.[2,10,13] As our acceptance is largest at high $x_\pi$, in contrast to the other experiments, we can address the question of the behavior of $F_\pi$ as $x_\pi \to 1$. For this we fit the data to the form

$$F_\pi \sim x^\alpha_\pi (1 - x_\pi)^\beta + \frac{2\gamma}{9M^2},$$

suggested by the Berger-Brodsky model.[4] The fitted parameters are given in the table:

| $E_\pi$ | $K$ | $\alpha$ | $\beta$ | $\gamma$ (GeV/c)$^2$ | $\chi^2$/d.o.f. |
|---|---|---|---|---|---|
| 80 GeV | – | 0.40 (fixed) | $1.37 \pm 0.07$ | $0.50 \pm 0.14$ | 132/126 |
| 252 GeV | $2.9 \pm 0.14$ | $0.37 \pm 0.02$ | $1.22 \pm 0.03$ | $0.60 \pm 0.24$ | 365/329 |
| 252 GeV$^\dagger$ | $2.8 \pm 0.10$ | $0.36 \pm 0.02$ | $1.15 \pm 0.03$ | $0.44 \pm 0.16$ | 348/331 |

$^\dagger$ includes QCD evolution

The parameters for our 80-GeV sample are from ref. 6 in which $x_\pi > 0.4$ and it was not possible to measure the $K$ factor. The parameters $\alpha$, $\beta$, and $\gamma$ in the third line of the table are actually functions of $M$. For this we follow the prescription of QCD

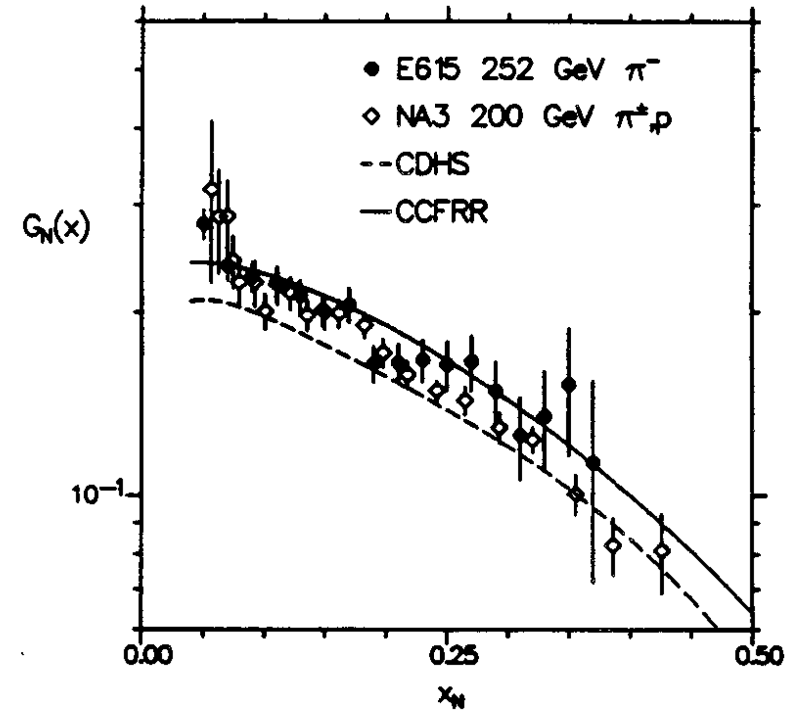


Figure 2. Measurements of the nucleon structure function, $G_N(x_N)$: • = this experiment; ◇ = NA3;[10] dashed curve = CDHS;[11] solid curve = CCFRR.[12]

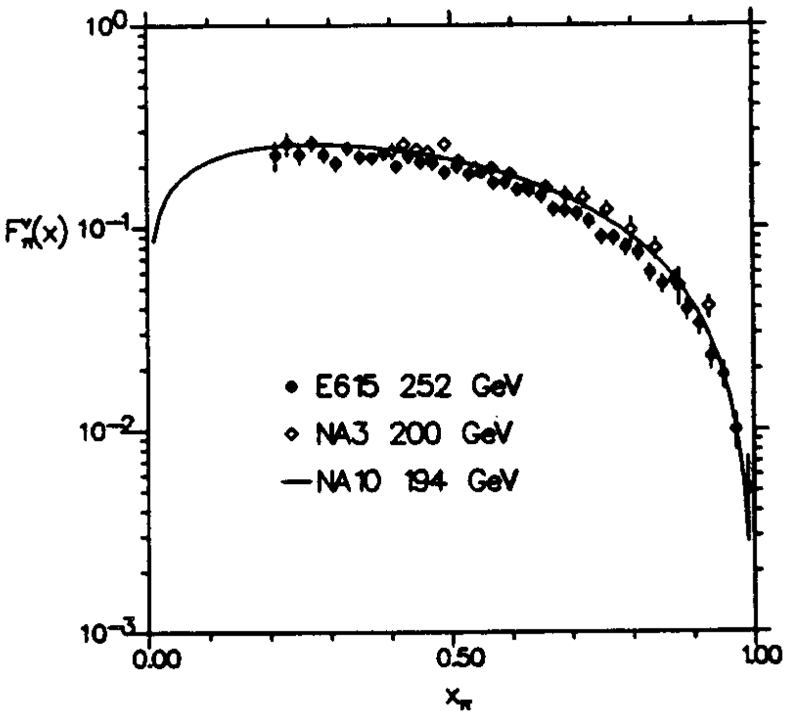


Figure 3. Measurements of the pion structure function, $F_\pi(x_\pi)$: • = this experiment; ◇ = NA3;[10] solid curve = NA10.[13]

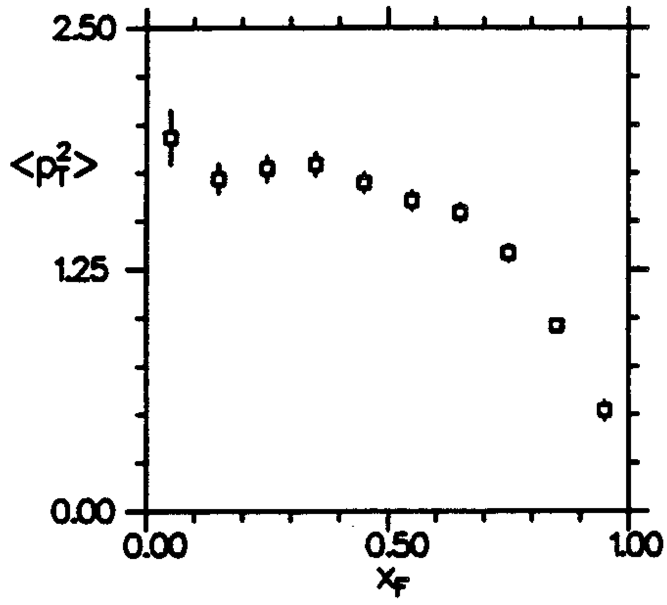


Figure 4. $\langle p_T^2 \rangle$ of the muon pairs as a function of $x_F$.

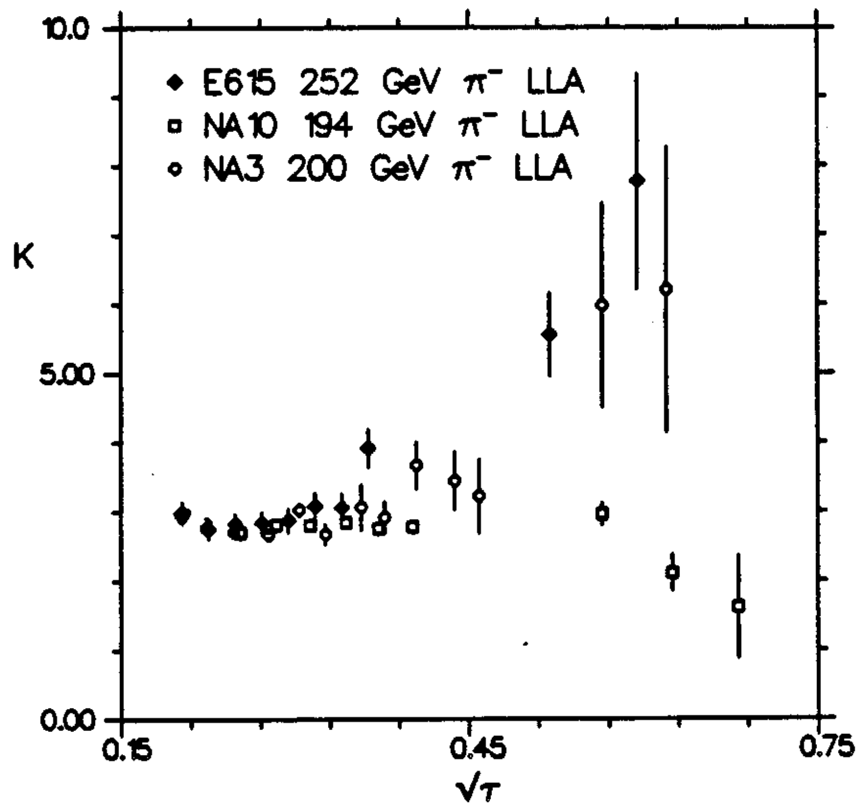


Figure 5. The $K$ factor defined in the text as a function of $\sqrt{\tau} = M/\sqrt{s}$: $\diamond$ = this experiment; $\square$ = NA10;[13] $\circ$ = NA3[10].

evolution given by Buras and Gaemers;[14] the stated values are evaluated at $M = 4.5$ GeV/c$^2$.

Our evidence for a constant component of $F_\pi$ as $x_\pi \rightarrow 1$, as measured by $\gamma$, is of 2.5 to 3 standard deviations in significance. The suggestion of Berger and Brodsky is that

$$F_\pi \sim (1 - x_\pi)^2 + \frac{2}{9}\frac{\langle k_T^2 \rangle}{M^2},$$

where $\langle k_T^2 \rangle$ is the square of the intrinsic transverse momentum of the quarks. Our values of $\beta \sim 1.2$ are not in close agreement with the model, while our nonzero values for $\gamma$ lend support to it.

The square of the transverse momentum of the muon pairs is shown in fig. 4 as a function of $x_F$. It takes a clear drop towards the value 0.5 (GeV/c)$^2$ as $x_F \rightarrow 1$. A possible interpretation of this is that gluon emission, which leads to larger transverse momentum at moderate $x_F$, is no longer prominent at large $x_F$ where the intrinsic transverse momentum dominates. If so, we find good consistency with the value of $\gamma \sim 0.5$ (GeV/c)$^2$ determined in the structure function analysis and interpreted in the Berger-Brodsky model.

In the structure function analysis we only consider pairs with $4.05 < M < 8.55$ GeV/c$^2$ to avoid contamination from resonances. Above the $\Upsilon$ family, we have 156 events with $M_{\mu\mu} > 11$ GeV/c$^2$. In fig. 5 we compare these high-mass events with the trend of other experiments,[10,13] plotting the $K$ factor as a function of $\sqrt{\tau} \equiv M/\sqrt{s}$. For this we define the $K$ factor as $d\sigma(\text{observed})/d\sqrt{\tau}$ divided by $d\sigma(\text{Drell-Yan})/d\sqrt{\tau}$, including QCD evolution in the structure functions but not in the normalization of the Drell-Yan calculation. Our results indicate a rise in the $K$ factor with $\sqrt{\tau}$, in contrast to the report of the CERN NA10 experiment.[13] The issue is complicated by the fact that the highest mass events come from the high-energy tail of the beam spectrum, or from nucleons with Fermi motion towards the beam particle. In particular, all Drell-Yan experiments attempt to correct the results for Fermi motion in slightly varying ways before comparing with calculations (while in the deep-inelastic-scattering experiments no such attempt is made).

Figure 6 shows the results of a fit to the angular distribution of the $\mu^+$ in the muon-pair rest frame, using the $t$-channel coordinate system in which the incident pion lies along the $z$-axis. The most general allowed form of the angular distribution is[15]

$$\frac{d\sigma}{d\Omega} \sim 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi.$$

In the naïve Drell-Yan model with massless quarks and no transverse momentum we would have $\lambda = 1$ and $\mu = \nu = 0$. Standard QCD corrections lead to the prediction that $\mu$ is small while $\nu$ can be nonzero, but $1 - \lambda = 2\nu$.[16] The Berger-Brodsky model notes that near $x_\pi = 1$ the quark in the pion must be off-shell, leading to the prediction

$$\frac{d\sigma}{d\Omega} \sim (1 - x_\pi)^2(1 + \cos^2\theta) + \frac{4}{9}\frac{\langle k_T^2 \rangle}{M^2}\sin^2\theta + \frac{2}{3}\sqrt{\frac{\langle k_T^2 \rangle}{M^2}}(1 - x_\pi)\sin 2\theta\cos\phi.$$

The solid curves in fig. 6 are only to guide the eye, while the dashed curves are for the Berger-Brodsky model. At moderate $x_\pi$ the sum rule $1 - \lambda = 2\nu$ does not seem

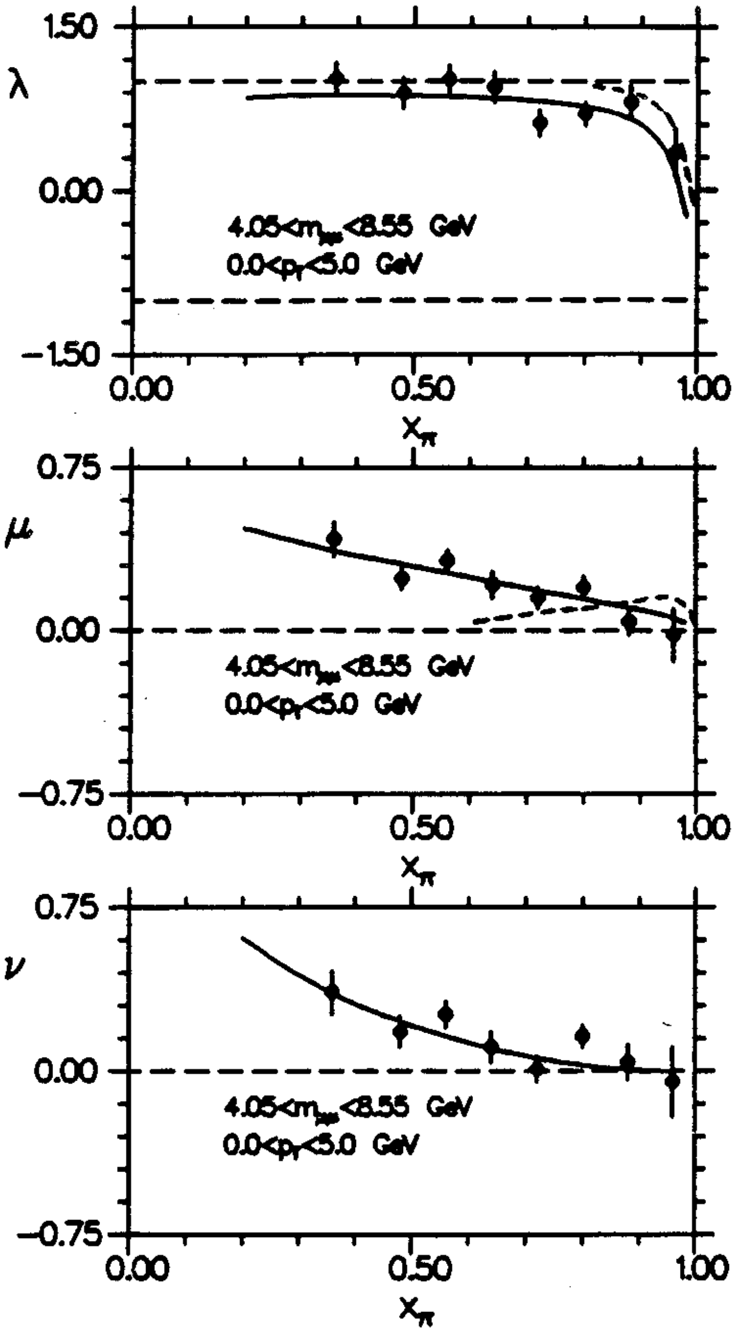


Figure 6. Fitted values of the parameters $\lambda$, $\mu$, and $\nu$ pertaining to the angular distribution of the $\mu^+$ about the direction of the incident pion in the muon-pair rest frame. The solid curves are only to guide the eye, while the dashed curves are from the Berger-Brodsky model.[4]

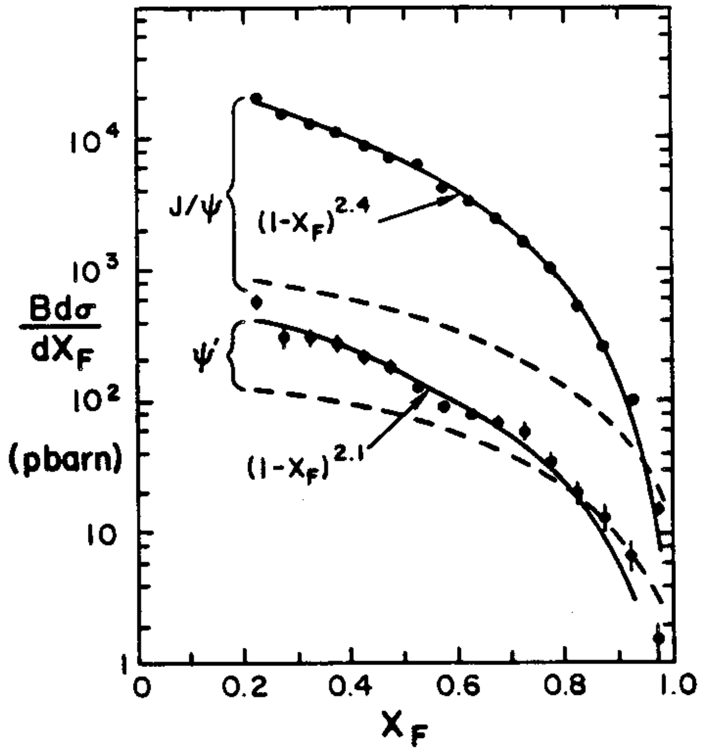


Figure 7. The cross section times branching ratio per nucleon for production of the $J/\psi$ and $\psi'$ resonances as a function of $x_F$. The solid curves are fits to the data, while the dashed curves are from the $q\bar{q} \rightarrow c\bar{c}$ annihilation model.

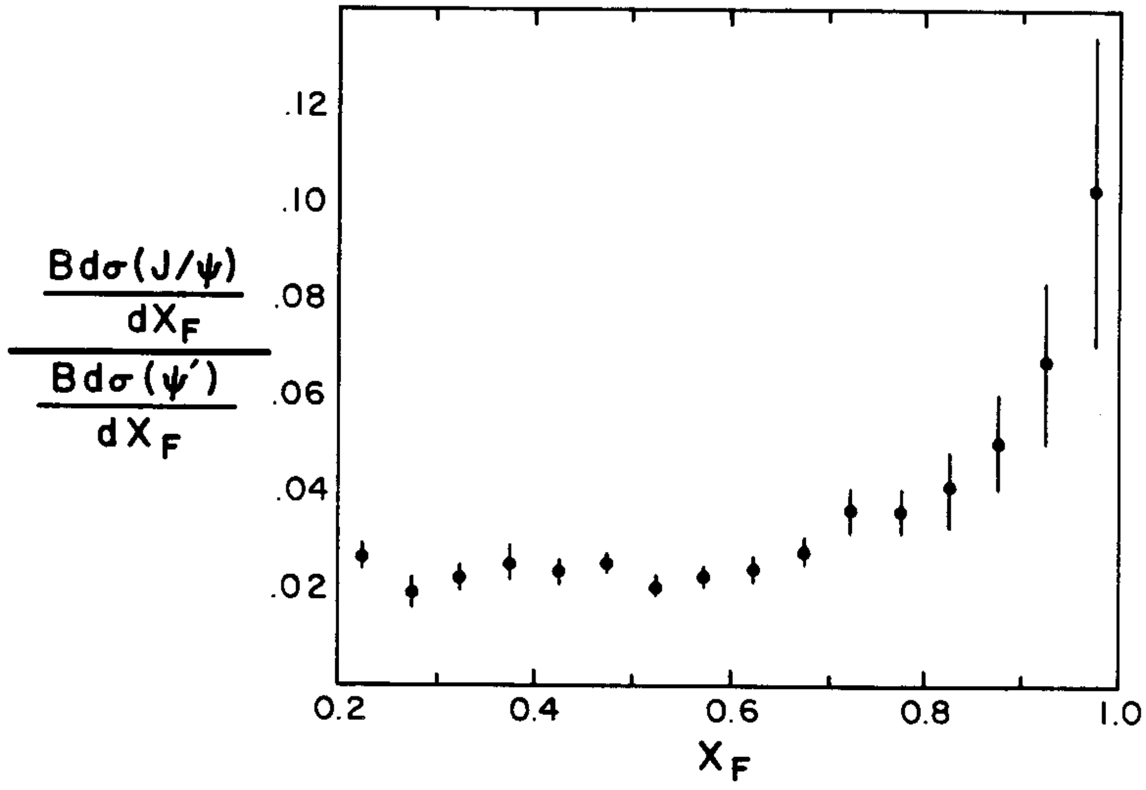


Figure 8. The ratio of the cross section (times branching ratio) for $\psi'$ to that for $J/\psi$ production. In the $q\bar{q}$ annihilation model this ratio has the value 0.15.

well satisfied, while at high $x_\pi$ the data are in reasonable agreement with the Berger-Brodsky model. Both $\mu$ and $\nu$ are observed to increase with transverse momentum, and are consistent with a linear dependence on this variable. Where our data overlap with those of the NA10 experiment[17] good agreement is found.

Our data on continuum muon-pair production thus broadly supports the view that a high-$x_\pi$ quark has gotten its momentum from a gluon which was emitted by another initial-state quark. This is a non-asymptotic QCD effect in that the gluon is not free, yet a well-defined calculation is possible. This contrasts with the typical application of QCD: calculations are possible only at asymptotic energies where no data exist, while the phenomena accessible at present energies cannot usually be calculated in the theory.

## RESONANCE ANALYSIS

QCD effects in the reaction $\pi N \to \mu^+\mu^- X$ occur in the initial state and so are not specifically tied to the Drell-Yan mechanism. It is provocative to examine our data on resonance production at large $x$ for additional evidence of the Berger-Brodsky effect. A first result has already been reported[18] in which we found that the decay angular distribution for $J/\psi \to \mu^+\mu^-$, while typically flat, approaches $\sin^2\theta$ as $x_F \to 1$. If the $J/\psi$ particles are produced via a $q\bar{q}$ annihilation of intial-state quarks this would indeed appear to be consistent with the view of Berger and Brodsky. However it is usually considered that the majority of $J/\psi$'s are produced by $gg$ interactions. Here we give new results that suggest the $q\bar{q}$ annihilation mechanism may dominate at large $x_F$.†

Figure 7 shows our measurement of the cross section times branching ratio for the $J/\psi$ and $\psi'$ particles as a function of $x_F$. The dashed curves show the calculated cross sections supposing the reaction $q\bar{q} \to c\bar{c}$ can be described by a Breit-Wigner resonance. The calculated rate includes a $K$ factor of 2.8 as observed to hold for our continuum data. This model falls below the data at moderate $x_F$, but agrees well at very large $x_F$. Figure 8 shows the ratio of $\psi'$ to $J/\psi$ production as a function of $x_F$. The $q\bar{q}$ annihilation model predicts a value of 0.15 for this ratio, which is approached by our data at large $x_F$. Thus resonance production by gluon fusion appears to die out with $x_F$, allowing $q\bar{q}$ annihilation to appear and to manifest QCD effects like those seen in continuum production at large $x_F$.

Our data provide several illustrations that the accessibilty of the limit $x_F \to 1$ in $\pi N$ interactions yields striking evidence for non-asymptotic, but calculable QCD effects at Fermilab energies.

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† For the resonance analysis we define $x_F = p^*_L/p^*_{L,\mathrm{max}}$, which has a maximum value of 1. This contrasts with the definition used in the continuum analysis for which the maximum is $1-\tau$.

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