Production of Massive Muon Pairs in π^--Nucleus Collisions

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We present measurements of the differential cross section for the production of massive muon pairs in 225-GeV/c π^--nucleus collisions. We have used the data between the ψ and Υ resonances in the framework of the Drell-Yan quark-antiquark annihilation model to predict the behavior of the cross section in the high-mass ($m_{\mu\mu} > 11$ GeV/c^2) region. The data are consistent with this extrapolation provided that a QCD leading-logarithmic evolution is included in the structure functions.

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Lepton-pair production in hadronic collisions has provided important information about the structure of hadrons. In the continuum mass region, experimental results are in qualitatively good agreement with the Drell-Yan model of quark-antiquark annihilation.[1] The data do, however, show deviations from this "naive" model. The measured magnitude of the dimuon cross section is larger than predicted (the K factor), as is the mean transverse momentum of the lepton pair. These effects have prompted the revision of the original model to include QCD corrections, which introduce scaling violations as a function of $m_{\mu\mu}^2$.[2]

To test these predictions, data on muon-pair production are needed over a wide kinematic range. We report here results from an experiment which was designed to be especially sensitive in the high-mass region, where "anomalous" scale-breaking results have recently been reported.[3]

The experiment was carried out in the high-intensity P-West area at Fermilab. A 225-GeV/c π^- beam was incident on a 2-interaction-length tungsten target, with the noninteracting beam and most of the hadronic debris from the target passing through a 20-mrad tapered vacuum pipe to a dump downstream of the apparatus. The typical beam intensity was 5×10^8 pions/pulse. Muons produced in the target were momentum analyzed in a magnetized toroidal iron spectrometer. The beam and detector have been described in detail elsewhere.[4–6] Reference 6 also contains a full description of the data analysis.

The detector was divided azimuthally into eight identical octants, each instrumented with seven planes of scintillation counters for triggering, and fifteen drift-chamber planes for track reconstruction. A two-level trigger required a target-associated muon signature in two distinct octants. In the first level, the selection was made by matrix circuitry which operated on pairs of counter planes in the front half of the detector. The second level accepted a track if the struck counters through the full depth of the detector matched a muon-trajectory pattern. The set of acceptable patterns was selected by Monte Carlo study to accept preferentially high–transverse-momentum target-produced muons and reject beam-halo muons.

Drift-chamber hits associated with struck counters were used to identify and reconstruct tracks in each octant. Potential tracks were fitted with two hypotheses. The constrained fit required a track to pass through the target center, while the unconstrained fit removed that requirement so that beam-halo muons could be identified. A track was accepted if it had a constrained fit $\chi^2/DF < 3$ (DF means degrees of freedom), $p\,\Delta\theta < 1.5$ GeV/c, and $\Delta p/p < 0.3$, where $\Delta\theta$ (Δp) is the difference between the angles (momenta) determined by the constrained and unconstrained fits. The latter two criteria were found to be very useful in the selection of good target-associated tracks and rejection of halo muons.

The remaining background, from the accidental coincidence of uncorrelated target-produced muons, was measured by use of the spectra of target muons from the sample of events containing a target muon and a halo muon. We verified that this method reproduced the shape and normalization of our same-sign dimuon data. This background is peaked at low masses, going from $\sim 17\%$ of the signal in the 4.5- to 5.5-GeV/c^2 mass interval to less than 1% for all masses greater than 7 GeV/c^2. We measured the background from non-target-associated muon pairs with target-out runs and found it to be less than 1% of the data.

The efficiencies of the counters and the trigger were measured with special runs. A few counters were found to be slightly inefficient, and the Monte Carlo program was correspondingly modified. The remaining uncertainties in the trigger efficiency were included in the estimate of the systematic errors. There was evidence of inefficiency in the drift-chamber wires closest to the beam in the front of the spectrometer. Tracks going through these regions were eliminated from the final data sample, so that the result would be insensitive to the precise determination of the efficiency. The above cut predominantly affected the low-mass region.

The acceptance of the apparatus and the effect of resolution smearing were calculated with a Monte Carlo simulation program. Monte Carlo events were generated with a dimuon-mass ($m_{\mu\mu}$) and Feynman-x (x_F) dependence given by the Drell-Yan formula:

$$\frac{d^2\sigma}{dm_{\mu\mu}\,dx_F}=\frac{8\pi\alpha^2}{9m_{\mu\mu}^3(x_1+x_2)}[V^\pi(x_1)G(x_2)+S^\pi(x_1)H(x_2)], \tag{1}$$

where α is the fine structure constant, $x_F=2p_\parallel^*/\sqrt{s}$, and x_1 (x_2) represents the fraction of the beam (target) momentum carried by the annihilating quark. The variables x_1 and x_2 are related to $m_{\mu\mu}$ and x_F by $x_1x_2=m_{\mu\mu}^2/s$ and $x_F=x_1-x_2$. G and H are linear combinations of the nucleon structure functions, for which we have used the Eichten-Hinchliffe-Lane-Quigg (EHLQ) parametrization.[7] $V^\pi(x_1)$ and $S^\pi(x_1)$ are the valence and sea structure functions of the pion and for a first iteration were taken from Badier *et al.*[8] The dimuon decay was parametrized by a $1+\cos^2\theta$ polar-angle distribution in the Collins-Soper[9] frame, and a flat distribution in azimuthal angle. The $p_\perp$ spectrum was assumed to be independent of the other variables as given by Ref. 8. The acceptance of the apparatus was found to be insensitive to the details of the model used. For the final extraction of the results, our parametrization for $V^\pi(x)$ and the $p_\perp$ distribution were used.

The Monte Carlo simulation included beam momentum spread, Fermi motion,[10] absorption in the target, multiple scattering and energy loss in the iron toroids, and the known inefficiencies of the apparatus. The generated events were reconstructed with the same programs used for the data.

We have extracted the pion valence structure function [$V^\pi(x)$] from the continuum data below the Υ in order to study its extrapolation to high mass. The ψ and Υ resonances were eliminated with the requirement $4.5 < m_{\mu\mu} < 8.5$ GeV/c^2. To minimize the contribution from the pion sea, x_1 was required to be > 0.25. Figure 1 shows the $m_{\mu\mu}$-x_F scatter plot of our data with the binning used for the fit. This sample contains 3327 events, with an estimated background of 87 ± 10 events.

The structure function was extracted by simultaneous fitting of the $m_{\mu\mu}$ and x_F dependence of the cross section given by Eq. (1) with use of the grid shown in Fig. 1. We used the following parametrization for the structure functions:

$$V^\pi(x)=x^{\alpha^\pi}(1-x)^{\beta^\pi}/B(\alpha^\pi,\beta^\pi+1),$$

$$S^\pi(x)=A(1-x)^{8.5},$$

where B is Euler's beta function, α^π was set equal to 0.5, and the normalization constant, A, was determined by the momentum sum rule with the fraction of pion momentum carried by the gluons equal to 0.47.[8] We used the EHLQ[7] parametrization for the nucleon structure function for the results presented here, but fits were performed with different formulas to test the sensitivity of our results.

QCD calculations predict that the structure functions should show logarithmic scaling violations. These are described in the leading-logarithm approximation by the equations of Altarelli and Parisi.[11] They were included in the pion valence structure function by the method of Buras and Gaemers,[12] with the $m_{\mu\mu}^2$ dependence of α^π,β^π of the form $\alpha^\pi=\alpha_0^\pi+\alpha_1^\pi\bar{s}$, $\beta^\pi=\beta_0^\pi+\beta_1^\pi\bar{s}$, where

$$\bar{s}=\ln\left\{\frac{\ln(m^2/\Lambda^2)}{\ln(m_0^2/\Lambda^2)}\right\},$$

Λ is set equal to 0.2 GeV/c^2, and m_0^2 is set equal to 44 (GeV/c^2)^2, the mean squared mass of the data in the region of the fit. The parameters α_1^π and β_1^π were obtained by solving the Altarelli-Parisi equations. Fits

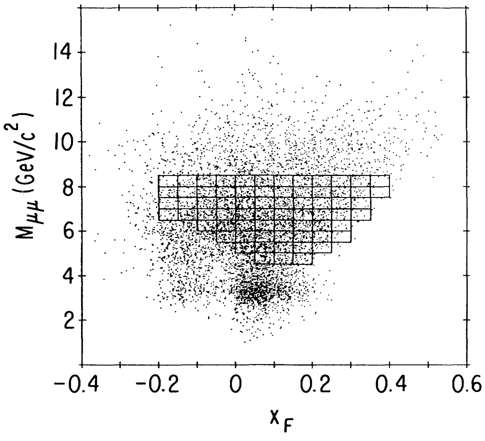

FIG. 1. Scatter plot of events in mass vs x_F. The binning used in the structure-function analysis is superimposed.

TABLE I. Pion structure-function results.

Evolving pion?	Evolving nucleon?	χ^2/DF	K	α_0^π	α_1^π	β_0^π	β_1^π
No	Yes	73.1/67	2.70 ± 0.08	0.5	0	1.21 ± 0.13	0
Yes	Yes	73.6/67	2.70 ± 0.08	0.5	−0.10	1.20 ± 0.12	0.73
No	No	72.1/67	2.72 ± 0.08	0.5	0	1.27 ± 0.13	0

were performed with and without QCD m^2 evolution in the pion valence and nucleon structure functions. An overall normalization constant for the cross section, K, was also included in each fit. The results are shown in Table I, where the errors indicated are statistical only.

We have examined possible sources of systematic error due to experimental uncertainties which affect the acceptance calculation. We assigned an error of 0.4 to K and 0.18 to β^π, this resulting from the uncertainties in the mean beam momentum, the magnetic field and the mean energy loss of muons in the toroids, the detector geometry, and the trigger efficiency. In addition, we considered the effect on the result of different parametrizations of the model. We estimated uncertainties in the K factor of 0.4 due to the nucleon structure functions, 0.2 due to the pion sea, and 0.5 due to normalization of the pion structure function. We estimated uncertainties in β^π of 0.02 due to the nucleon structure function and 0.14 due to the pion sea. The $V^\pi(x)$ we obtained is consistent with recent results obtained at CERN.[3,8]

The data are not sensitive to QCD scaling violations in the mass region between the ψ and the Υ. We have therefore extended the test by comparing the data above the Υ with the extrapolated prediction of the Drell-Yan model. We have used both our structure function and a world average given by $\alpha^\pi = 0.41$ and $\beta^\pi = 0.99$ at $m_{\mu\mu}^2 = 25$ $(\mathrm{GeV}/c^2)^2$. The two forms give virtually identical results. Figure 2 shows $d\sigma/dm_{\mu\mu}$ from the data along with the predictions of the model, with and without QCD leading-logarithm scaling violations. Our data favor the former, with the "naive" Drell-Yan model overestimating the cross section at high masses. The χ^2/DF for $m_{\mu\mu} > 11$ GeV/c^2 is 39/10 for the "naive" model and 6.3/10 for the model which includes scaling violations. The prediction for $d\sigma/dx_\mathrm{F}$ is compared with the data for $m_{\mu\mu} > 11$ GeV/c^2 in Fig. 3. We do not see evidence for an anomalous scaling violation in $d\sigma/dx_\mathrm{F}$ as reported by Betev *et al.*[3]

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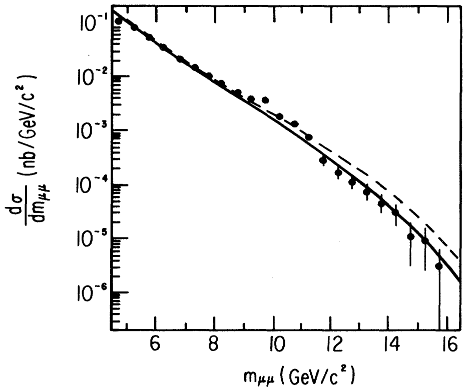

FIG. 2. The $d\sigma/dm_{\mu\mu}$ distribution. The solid curve is the prediction of the Drell-Yan model, incorporating QCD leading-logarithmic scaling violations in the structure functions and using our pion structure function. The dashed curve is the prediction of the "naive" Drell-Yan model.

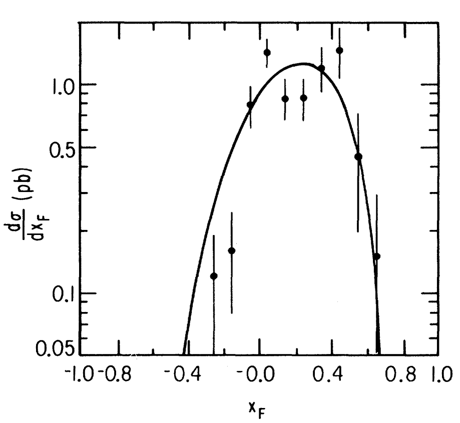

FIG. 3. The $d\sigma/dx_\mathrm{F}$ distribution for $m_{\mu\mu} > 11$ GeV/c^2. It is compared with the prediction of the Drell-Yan model including QCD leading-logarithmic scaling violations.

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