Dimuon Production in 800-GeV Proton-Nucleus Collisions

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A measurement of continuum dimuon production in proton-copper collisions at 800-GeV incident energy is presented. The dimuons observed in this experiment cover the mass range from 6.5 to 18 GeV near $y=0$ in the proton-nucleon center-of-momentum frame. Scaling forms of the cross section for the continuum are compared with the results of other experiments in the context of the parton model and quantum chromodynamics. The present limitations of such scaling comparisons are discussed.

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The study of lepton pairs produced in hadronic collisions,

$$h_A+h_B \rightarrow l^+l^-+X,$$

is sensitive to the structure of hadrons in a way complementary to inelastic lepton-nucleon scattering, $l+N \rightarrow l'+X$. After the first such experiment showed a steeply falling dimuon mass spectrum,[1] Drell and Yan[2] suggested that the underlying process might be production of a lepton pair by the electromagnetic annihilation of a parton-antiparton pair. Much experimental and theoretical work has confirmed many of the details of this description.[3] The advent of high-energy dimuon-yield measurements, combined with the derivation of order-α_s perturbative QCD corrections[4] to the lowest-order Drell-Yan mechanism, imposes significant constraints on hadron structure functions.

The E605 spectrometer[5] at Fermilab was used to perform a precise measurement of the 6–18-GeV mass spectrum of dimuons produced in 800-GeV proton-copper collisions. A 1.2-m-thick lead absorber, blocking the exit aperture of the 15-m spectrometer magnet, absorbed low-energy backgrounds. This allowed incident intensities of 2×10^{11} protons per second. The combination of a small target and a proportional-drift-tube chamber immediately following the absorber yielded an excellent mass resolution (σ_m/m) of 0.3% at 10 GeV.

The incident beam intensity was measured with a secondary-emission monitor (SEM) located approximately 100 m upstream of the target. This monitor was calibrated by measuring ^{24}Na activation in a copper foil temporarily placed in the beam. The data reported here correspond to 1.3×10^{17} incident protons and a total luminosity of 1.4×10^{42} cm^{-2} per nucleon, recorded using two different (but overlapping) mass settings of the spectrometer magnets.

The acceptance of the spectrometer was evaluated using a Monte Carlo simulation of the apparatus and the functional form for the cross section indicated in Table I. This functional form was iterated until agreement was reached with the observed distributions versus dimuon mass m and transverse momentum p_t. The assumed form versus dimuon x_F (taken from Rutherfoord[3]) has negligible effect on our results since we present cross sections differential in dimuon x_F or c.m. rapidity y, and the distribution versus Collins-Soper[6] angle θ_{CS} has been established by previous experiments.[3] The simulation included radiative corrections,[7] multiple-scattering and energy-loss effects in the lead absorber, and an accurate geometrical survey of the apparatus.

Results are presented as functions of the dimuon kinematic variables m or $\sqrt{\tau}=m/\sqrt{s}$ and x_F or y. An integration over the limited p_t of the dimuon was performed. Integrations over the angular variables were

TABLE I. Distributions used for the simulation of dimuon events of mass m and momentum (p_t,ϕ,p_l) in the proton-nucleon c.m. (center of momentum) frame. The Collins-Soper (Ref. 6) convention is used to specify the μ^+ angles (θ_{CS},ϕ_{CS}) in the dimuon rest frame, and $\tau=m^2/s$, $x_F=(1-\tau)x_F'=2p_l/\sqrt{s}$, and $p_t^{max}=(\sqrt{s}/2)[(1-\tau)^2-x_F^2]^{1/2}$.

Variable	Range	Continuum dimuons
m (GeV)	(6,18.5)	$e^{-0.77m}$
x_F'	$(-1,1)$	$(1-x_F')^4(1+x_F')^5$
p_t (GeV)	$(0,p_t^{max})$	$p_t/[1+(p_t/3)^2]^6$
ϕ	$(0,2\pi)$	Uniform
$\cos\theta_{CS}$	$(-1,1)$	$1+\cos^2\theta_{CS}$
ϕ_{CS}	$(0,\pi)$	Uniform

performed either because they are trivial or because the range measured is too narrow to distinguish among differing shapes. The errors quoted throughout are statistical only (unless otherwise stated), and an overall-normalization systematic error estimated to be 15% should be added.

Figure 1 shows the cross section $d^2\sigma/dm\,dx_F$ vs m evaluated at $x_F \simeq 0$ averaged over our two data sets. The data are presented in mass bins of varying size corresponding to the FWHM of the mass resolution as determined by the simulation. The spectra reveal no statistically significant resonance peaks other than the three lowest-lying Υ S states. In the continuum analysis presented below, the Υ's are removed by excluding the mass range $9.0 < m < 10.5$ GeV.

Given the differing beam energies involved, comparisons of our results with those of Ito *et al.*[8] (E288 Collaboration) and Badier *et al.*[9] (NA3 Collaboration) are best presented by considering scaling forms of the dimuon cross section. In each case we have taken care to bin our data in the same variables and bins as reported in the other experiments. NA3 reported an uncertainty of about 12% in their luminosity measurement and E288 stated a global systematic error of less than 25%. E288 used a different SEM calibration value for ^{24}Na production by protons on copper, 3.5 mb, in contrast to the value used in our analysis,[10] 3.9 mb. Since the ^{24}Na cross section is believed to be energy independent from 400 to 800 GeV, we have multiplied the E288 cross sections by the factor $3.9/3.5=1.11$ in the comparisons below.

The three experiments assume a linear dependence of the cross section on the atomic weight of the target. The E288 data were taken with platinum and copper targets. NA3 used a platinum target and we used a copper target. While E288 and NA3 corrected their data for nucleon motion in the target, we have not applied that correction to our data.[11] E288 parametrized this correction (averaged over their rapidity acceptance) as

$$\frac{(d^2\sigma/d\sqrt{\tau}\,dy)_{corr}}{(d^2\sigma/d\sqrt{\tau}\,dy)_{uncorr}}=0.901+0.827\sqrt{\tau}-2.54\tau\,,$$

which results in a 4% decrease of the corrected cross sec-

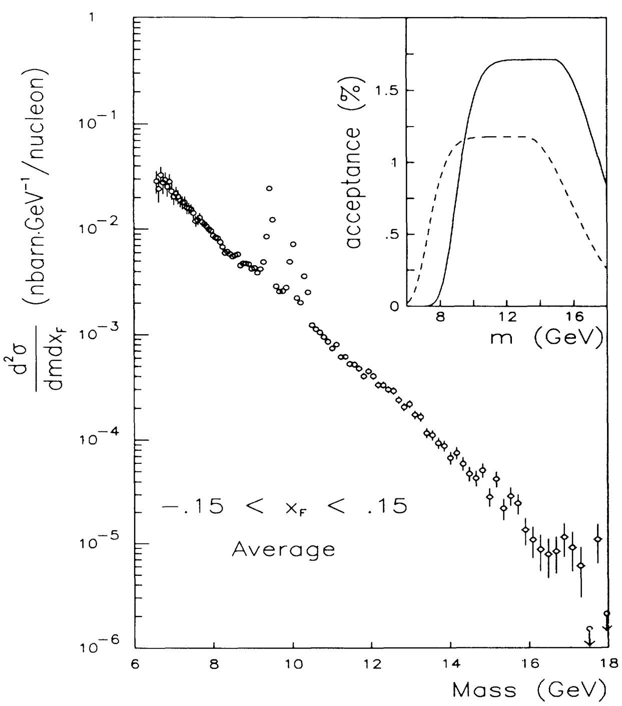

FIG. 1. Differential cross section averaged over our two data sets. Inset: The mass acceptance for each set.

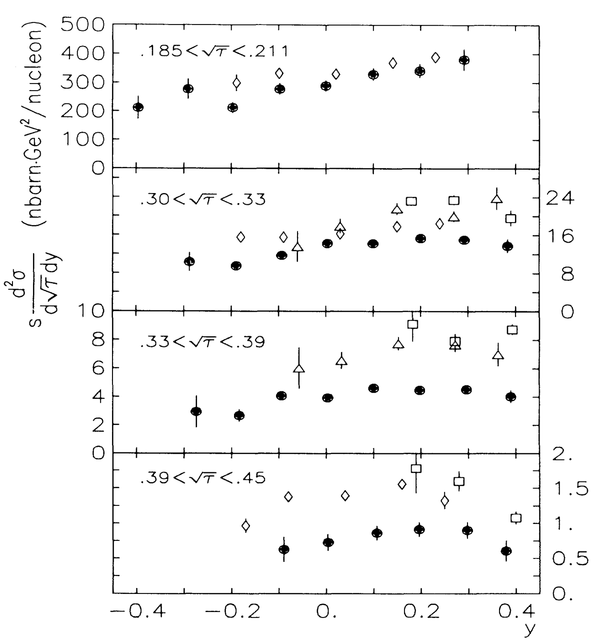

FIG. 2. Comparison of the scaled cross section vs rapidity at constant $\sqrt{\tau}$ with the corrected (see text) data of Ref. 8. Symbols are the same as those of Fig. 3.

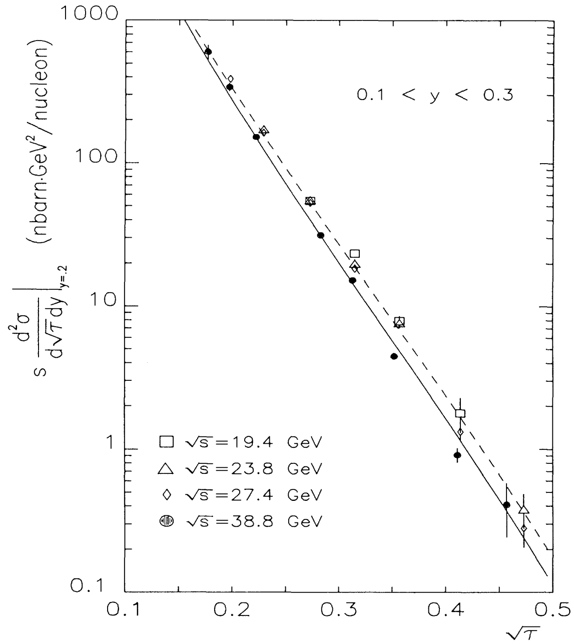

FIG. 3. Comparison of our data (●) at $y=0.2$ with the corrected E288 data. The dashed line corresponds to $\sqrt{s}=19.4$-GeV (solid line, $\sqrt{s}=38.8$ GeV) order-α_s QCD predictions of Martin, Roberts, and Stirling (Ref. 13).

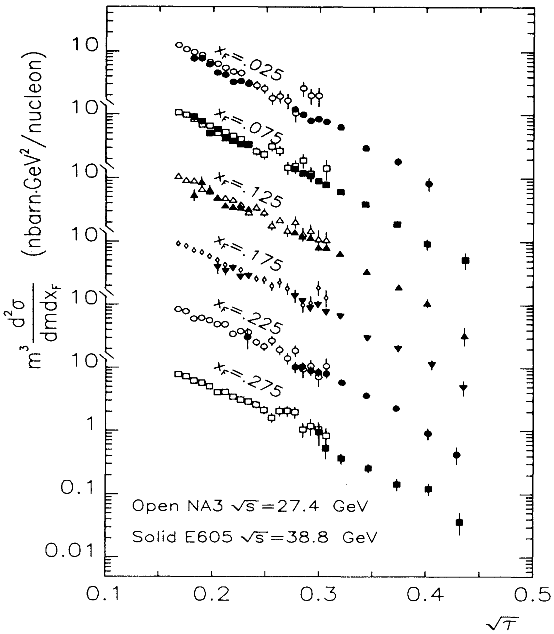

FIG. 4. Comparison of our averaged data and the data of Ref. 9 for the cross section vs $\sqrt{\tau}$ at constant x_F.

tion at $\sqrt{\tau}=0.2$, and a 17% decrease at $\sqrt{\tau}=0.4$. We have removed this correction from the E288 cross sections for the comparisons below.

Figure 2 compares a differential scaling form of the cross section, $s\,d^2\sigma/d\sqrt{\tau}\,dy$, versus rapidity for various $\sqrt{\tau}$ bins. The figure shows two interesting features: (1) The cross section has a positive slope at $y=0$ for fixed $\sqrt{\tau}$; and (2) our data fall off more rapidly than the E288 data as $\sqrt{\tau}$ increases.

In Fig. 2 the positive slopes at $y=0$ appear to be larger than predicted by the Drell-Yan model using a symmetric antiquark sea. (This effect exceeds that expected due to the presence of neutrons in the target.) Kaplan[12] and Ito *et al.*[8] showed that such an increase in the rapidity slope might derive from unequal $\bar{u}$ and $\bar{d}$ content in a proton.

The scaled cross section $s\,d^2\sigma/d\sqrt{\tau}\,dy$ at $y=0.2$ is presented in Fig. 3 versus $\sqrt{\tau}$. The average of our two data sets is plotted along with E288 results and predictions at two different values of $\sqrt{s}$, 19.4 and 38.8 GeV. The predictions are from the next-to-leading order (i.e., order α_s) QCD calculation of Martin, Roberts, and Stirling[13] based on structure functions derived from deep-inelastic lepton-scattering experiments. The lower yield predicted at 38.8 GeV compared to 19.4 GeV is a manifestation of QCD scale breaking in the order-α_s perturbative calculation.

Figure 4 presents a comparison of our results to those of the NA3 Collaboration in the alternative scaling form $m^3 d^2\sigma/dm\,dx_F$ vs $\sqrt{\tau}$ in six x_F bins. We have calculated the NA3 scaling form from their published results using the central values of their mass bins.

Figure 5 of Martin, Roberts, and Stirling[13] shows an apparent 30% disagreement between the E288 and NA3 data. We do not find this inconsistency. Our data in Figs. 2–4 lie only slightly below both E288 and NA3, qualitatively consistent with the scale breaking predicted by QCD.

The ensemble of the E288, NA3, and E605 data sets should provide a tight constraint on hadron-structure-function analysis since the predicted yield of Drell-Yan dimuons depends directly on the distribution of antiquarks in hadrons, a quantity not well determined in deep-inelastic-scattering experiments. The gluon structure of the nucleon is also probed by the order-α_s corrections. The data sets and theory are consistent within the normalization uncertainties reported, the possible dependence of the structure functions on the nuclear environment,[14] and the uncertainties in the perturbative calculations. These same systematic problems affect the deep-inelastic lepton-scattering data which contribute to the order-α_s comparison shown in Fig. 3. Despite these difficulties, the precision of the current ensemble of data warrants a coherent analysis of both deep-inelastic scattering and dimuon production.

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