Continuum Dimuon Production in $\bar{p}$-W Collisions at 125 GeV/c

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(Received 11 March 1985)

The cross section for the reaction $\bar{p}N \rightarrow \mu^+\mu^- X$ with muon pairs in the mass range $4 < M < 9$ GeV/c^2 and $x_F > 0$ was measured to be $\sigma = 0.104 \pm 0.005 \pm 0.008$ nb/nucleon. The distributions $d\sigma/dx_F$ and $M^3\, d\sigma/dM$ were compared to the QCD-improved Drell-Yan model and to calculations including first-order QCD corrections, with use of deep-inelastic structure functions. Excellent agreement with the data was obtained if the calculations were multiplied by factors of 2.45 and 1.41, respectively.

PACS numbers: 13.85.Qk

Many predictions of the Drell-Yan model[1] for high-mass dimuon production by hadrons have been confirmed by measurements with proton and pion beams.[2] The integrated polar-angle decay distribution of the muon pairs is consistent with $1+\cos^2\theta$. Scaling in $\tau = M^2/s$ has been verified in proton-produced data over the energy range ($\sqrt{s} = 19.4$–62 GeV) spanned by Fermilab and the CERN intersecting storage rings. The measured dependence of the cross section on the atomic number of the target is very close to $A^{1.0}$. These features along with the observation that the ratio of π^+ to π^- dimuon production tends toward $\frac{1}{4}$ give confidence that high-mass muon-pair production is an electromagnetic process of the type hypothesized by Drell and Yan. However, comparisons of the measured absolute cross sections to the model are more difficult since the predictions for the proton-induced reaction are affected by uncertainties in the nucleon-sea structure functions and the pion structure function cannot be measured independently at large Q^2. In contrast, data with incident antiprotons can be directly compared to the absolute predictions of the Drell-Yan model since the valence-quark structure function of the nucleon (and hence the valence-antiquark structure functions of the antiproton) have been independently determined in deep-inelastic lepton scattering (DIS) experiments.[3]

The present experiment was performed at Fermi National Accelerator Laboratory with a tertiary beam[4] of 1.5×10^7 particles/sec and consisting of 18% $\bar{p}$ and 82% π^- resulting from $\bar{\Lambda}^0$, Λ^0, and K_S^0 decays. Particle type was determined by two Cherenkov counters resulting in less than 0.5% pion contamination of the antiproton data. Counter hodoscopes and proportional chambers were used to determine the trajectory and momentum of each incident beam particle. Only one experiment[5] has previously reported significant $\bar{p}$ data, but because the antiproton content of the beam was only a few percent of the total flux of 5×10^7 particles/sec, a 25% subtraction for π^- contamination in the $\bar{p}$ data sample was required.

The experimental spectrometer[6] is shown in Fig. 1. It included a tungsten target, a copper hadron absorber (10.3 absorption lengths), twenty proportional- and drift-chamber planes, a large-aperture analysis magnet, an X-Y charged-particle scintillation-counter hodoscope, and a 13.2-absorption-length steel and concrete muon detector with three imbedded muon trigger planes of sixty counters each. Two-thirds of our data were accumulated with a 1.5-absorption-length

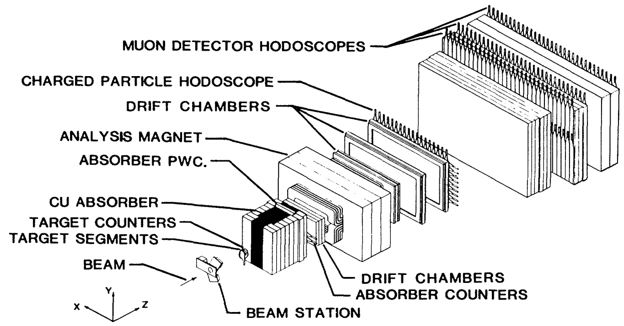

FIG. 1. General layout of the large-acceptance spectrometer.

tungsten target. The remainder of the data were taken with 0.4- and 0.5-absorption-length tungsten targets to allow estimation and corrections for reinteraction effects. The fast dimuon trigger required at least two threefold coincidences among aligned counters in each of the three muon hodoscope planes, at least two hits in the X-Y charged-particle hodoscope, and a $\bar{p}$ signal from the beam tagging system. Events which produced a fast trigger were sent to an ECL-CAMAC trigger processor.[7] This processor used hits from the drift chambers downstream of the analysis magnet to calculate the momenta of muon candidates and the masses of all possible muon pairs. Events with candidates of invariant mass greater than 2.0 GeV/c^2 were recorded on magnetic tape.

The data presented here consist of 380 $\bar{p}$-produced muon pairs with masses between 4 and 9 GeV/c^2. Corrections have been applied to our data to take into account trigger-processor inefficiency (1%), scintillation-counter inefficiency and gaps between adjacent counters (10%), reinteraction in the target (3.5%), vertex-cut inefficiency (1%), accidental coincidences (1.5%), reconstruction inefficiency (10%), and ψ' contamination (2.4%). Our overall systematic normalization error of 8% includes the uncertainties in all of these corrections as well as the uncertainty in the acceptance calculation. In calculating the spectrometer acceptance we have assumed the $1+\cos^2\theta$ distribution which is expected from the Drell-Yan model and which is consistent with our data, where θ is the angle between the positive muon and the beam in the muon-pair rest frame. To extract a cross section per nucleon from our tungsten data, we have assumed a linear A dependence, since high-statistics proton and pion experiments[2] currently measure $A^{1.00\pm0.02}$. With

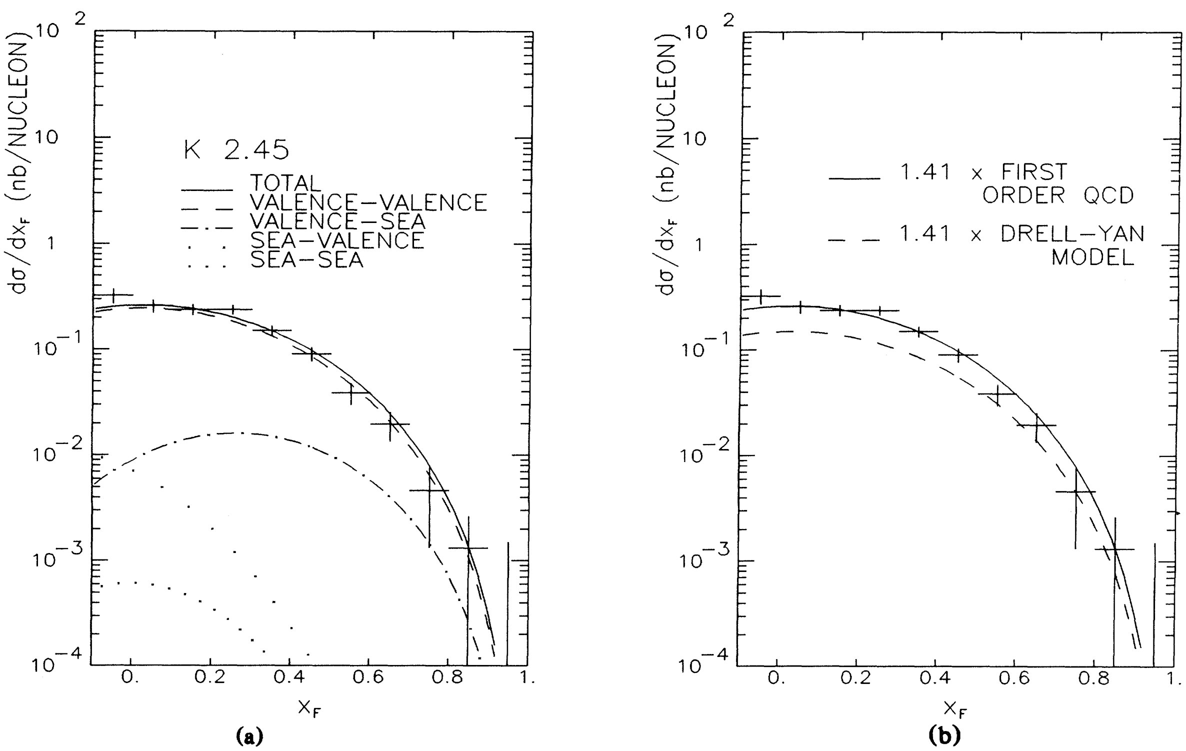

FIG. 2. $d\sigma/dx_F$ vs x_F for dimuons produced by 125-GeV/c antiprotons, compared to (a) the prediction of the Drell-Yan formula (1), calculated with use of the structure functions of Ref. 9, together with the component contributions, and (b) the first-order QCD prediction calculated with use of the same structure functions. The errors shown are statistical only.

these assumptions we find the total cross section for $4 < M < 9$ GeV/c^2 and $x_F > 0$ to be $\sigma = 0.104 \pm 0.005 \pm 0.008$ nb/nucleon. The first error is statistical only and the second is the estimated systematic uncertainty in our measurement. An additional error of 11% is contributed by the experimental uncertainty in the A dependence.

In the QCD-improved parton model, the cross section for hadronic muon-pair production, integrated over the transverse momentum of the pair, is given by[8]

$$\frac{d^2\sigma}{dM\,dx_F} = \frac{8\pi\alpha^2}{9M^3}\frac{(1-\tau)}{[x_F^2(1-\tau)^2+4\tau]^{1/2}}\sum_{q=u,d,s} e_q^2[\bar{q}_B(x_1,Q^2)q_T(x_2,Q^2)+q_B(x_1,Q^2)\bar{q}_T(x_2,Q^2)], \quad (1)$$

where M is the invariant mass of the muon pair, $\tau = M^2/s$, $x_F = 2p_L/[\sqrt{s}(1-\tau)]$ is the ratio of the longitudinal momentum of the pair to the maximum allowable momentum in the center-of-mass frame, e_q is the quark charge, x_1 (x_2) is the momentum fraction of the beam (target) particle carried by the interacting quark, and the $q(x_i,Q^2)$'s are the quark structure functions of the interacting hadrons. The structure functions have been measured at spacelike values of Q^2 and are continued to timelike Q^2 by making the identification $Q^2 = M^2$.

Figure 2(a) shows our data compared to the prediction of (1) for $d\sigma/dx_F$ integration over M and use of the structure-function parametrizations obtained by Duke and Owens[9] from a QCD fit to neutrino, muon, and electron DIS data. Component terms are also shown, indicating that the valence-valence interaction accounts for 87% of the predicted cross section. The curves have been multiplied by $K = 2.45$ in order to reproduce the measured total cross section for $x_F > 0$. The statistical error on our determination of K is ± 0.12 and the systematic uncertainty of our experiment is ± 0.20. Additional uncertainties of up to 11% and 20% can be attributed to the A dependence and the normalization differences among the DIS experiments.[3,9] In the kinematic regime ($4 < M < 9$ GeV/c^2) comparable K factors[10] extracted for the π^- reaction are in the range 2.2 to 2.5 and for the p reaction are in the range 1.6 to 2.2.

Figure 2(b) shows our data compared to the cross section calculated when next-to-leading-logarithm [of $O(\alpha_S)$] QCD corrections as evaluated by Kubar *et al.*[10] are included. These corrections consist of the annihilation-vertex (virtual gluon) diagram, the quark annihilation diagram, and the gluon Compton diagram. We have used the same structure functions as above and a value of the QCD scale parameter, $\Lambda = 0.2$ GeV/c, consistent with these parametrizations. In this case the prediction must be multiplied by a factor of 1.41 to reproduce the integrated cross section for $x_F > 0$. The statistical and systematic errors in this factor are ± 0.07 and ± 0.11, respectively. The first-order calculation is also sensitive to the choice for Λ. Using $\Lambda = 0.4$ GeV/c, a value also consistent with the DIS data,[9] increases the first-order QCD prediction by 13%. The calculation of Stirling[11] which includes effects higher than first order predicts cross sections that are closer to our measurements than the first-order calculations[2] mentioned above.

Figure 3 shows the scaling cross section $M^3\,d\sigma/dM$ with $x_F > 0$ as a function of $\sqrt{\tau}$ for our antiproton data and the 150-GeV/c antiproton data of the experiment of Badier *et al.*[5] The two measurements agree within errors and are consistent with the shape predicted by either formula (1) or the first-order QCD calculation.

In conclusion, we have measured the cross section for the reaction $\bar{p}N \to \mu^+\mu^- X$ with muon pairs in the

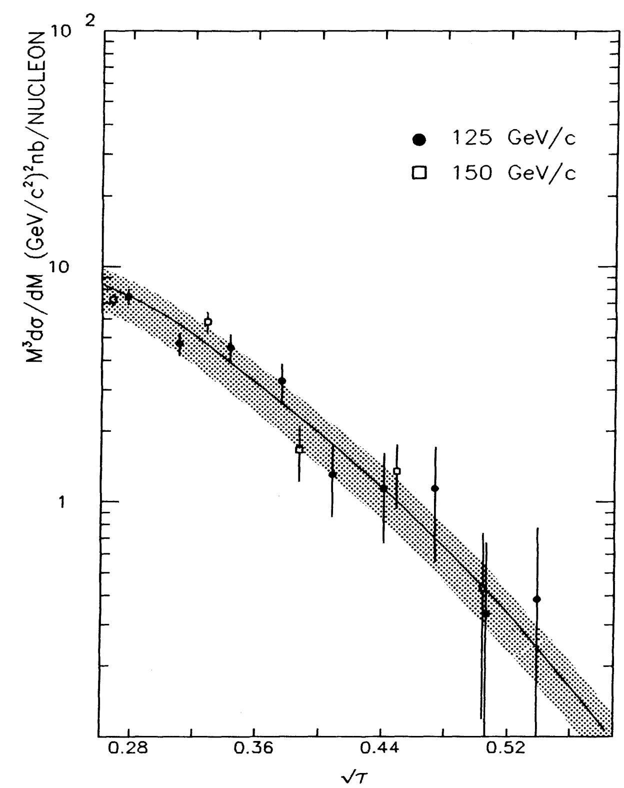

FIG. 3. $M^3\,d\sigma/dM$ vs $\sqrt{\tau}$ for dimuons produced by antiprotons in this experiment (125 GeV/c) and the data of Ref. 5 at 150 GeV/c. The solid curve is the prediction of (1) integrated over x_F. The shaded region represents the quadrature sum of systematic errors in the prediction due to uncertainty in the A dependence (11%) and the uncertainty in the normalizations of the deep-inelastic data (20%) used to determine the structure functions.

range $4 < M < 9$ GeV/c^2 and $x_F > 0$ and compared the result to the Drell-Yan model and a calculation including first-order QCD corrections, using the deep-inelastic structure function parametrizations of Duke and Owens.[9] We find excellent agreement between the measured differential cross sections $d\sigma/dx_F$ and $M^3\, d\sigma/dM$ and these calculations, provided that we multiply the predictions by 2.45 and 1.41, respectively.

This work was performed at Fermi National Accelerator Laboratory and supported by the U. S. Department of Energy, the International Programs and High Energy Physics Divisions of the National Science Foundation, the Natural Sciences and Engineering Research Council of Canada, the Quebec Department of Education, and the Hellenic Science and Technology Agency.

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