Measurement of Nuclear Transparencies from Exclusive ρ^0 Meson Production in Muon-Nucleus Scattering at 470 GeV

M. R. Adams,[6] S. Aïd,[9] P. L. Anthony,[8] D. A. Averill,[6] M. D. Baker,[10] B. R. Baller,[4] A. Banerjee,[14] A. A. Bhatti,[15] U. Bratzler,[15] H. M. Braun,[16] H. Breidung,[16] W. Busza,[10] T. J. Carroll,[11] H. L. Clark,[13] J. M. Conrad,[5] R. Davisson,[15] I. Derado,[11] S. K. Dhawan,[17] F. S. Dietrich,[8] W. Dougherty,[15] T. Dreyer,[1] V. Eckardt,[11] U. Ecker,[16] M. Erdmann,[1] F. Faller,[5] G. Y. Fang,[5] J. Figiel,[7] R. W. Finlay,[13] H. J. Gebauer,[11] D. F. Geesaman,[2] K. A. Griffioen,[14] R. S. Guo,[6] J. Haas,[1] C. Halliwell,[6] D. Hantke,[11] K. H. Hicks,[13] V. W. Hughes,[17] H. E. Jackson,[2] G. Jancso,[11] D. M. Jansen,[15] Z. Jin,[15] S. Kaufman,[2] R. D. Kennedy,[3] E. R. Kinney,[2] T. Kirk,[2] H. G. E. Kobrak,[3] A. V. Kotwal,[5] S. Kunori,[9] S. Lancaster,[5] J. J. Lord,[15] H. J. Lubatti,[15] D. McLeod,[6] P. Madden,[3] S. Magill,[6] A. Manz,[11] H. Melanson,[4] D. G. Michael,[5] H. E. Montgomery,[4] J. G. Morfin,[4] R. B. Nickerson,[5] S. O'Day,[9] K. Olkiewicz,[7] L. Osborne,[10] R. Otten,[16] V. Papavassiliou,[2] B. Pawlik,[7] F. M. Pipkin,[5,*] D. H. Potterveld,[2] E. J. Ramberg,[9] A. Röser,[16] J. J. Ryan,[10] C. W. Salgado,[4] A. Salvarani,[3] H. Schellman,[12] M. Schmitt,[5] N. Schmitz,[11] K. P. Schüler,[17] G. Siegert,[1] A. Skuja,[9] G. A. Snow,[9] S. Söldner-Rembold,[11] P. Spentzouris,[12] H. E. Stier,[1,*] P. Stopa,[7] R. A. Swanson,[3] H. Venkataramania,[17] M. Wilhelm,[1] Richard Wilson,[5] W. Wittek,[11] S. A. Wolbers,[4] A. Zghiche,[2] and T. Zhao[5]

(Fermilab E665 Collaboration)

[1]*Albert-Ludwigs-Universität Freiburg i. Br., Germany*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*University of California, San Diego, California 92093*
[4]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[5]*Harvard University, Cambridge, Massachusetts 02138*
[6]*University of Illinois, Chicago, Illinois 60680*
[7]*Institute for Nuclear Physics, Krakow, Poland*
[8]*Lawrence Livermore National Laboratory, Livermore, California 94551*
[9]*University of Maryland, College Park, Maryland 20742*
[10]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[11]*Max-Planck-Institut für Physik, Munich, Germany*
[12]*Northwestern University, Evanston, Illinois 60208*
[13]*Ohio University, Athens, Ohio 45701*
[14]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[15]*University of Washington, Seattle, Washington 98195*
[16]*University of Wuppertal, Wuppertal, Germany*
[17]*Yale University, New Haven, Connecticut 06511*

(Received 5 August 1994)

Nuclear transparencies measured in exclusive incoherent ρ^0 meson production from hydrogen, deuterium, carbon, calcium, and lead in muon-nucleus scattering are reported. The data were obtained with the E665 spectrometer using the Fermilab Tevatron muon beam with a mean beam energy of 470 GeV. Increases in the nuclear transparencies are observed as the virtuality of the photon increases, in qualitative agreement with the expectations of color transparency.

PACS numbers: 25.30.Mr, 13.60.Le, 24.85.+p

Exclusive production of vector mesons by virtual photons from complex nuclei was suggested as a way of testing the idea of a "shrinking photon" before the advent of quantum chromodynamics (QCD) [1], when high energy photon-hadron reactions were understood in terms of hadronic fluctuations of the photon. The "size" of the hadronic components of a virtual photon at high four-momentum transfer squared, $-Q^2$, was conjectured to be smaller than the size of a normal hadron, thereby accounting for the pointlike behavior and diminished absorption of virtual photons in nuclear interactions compared to real photons.

In QCD, the reaction amplitudes for exclusive interactions at large momentum transfer are expected to be dominated by components of the wave function with small transverse size, which give rise to diminished final state interactions in a nuclear medium [2]. In the asymptotic limit where both Q^2 and energy are very high, one expects the total cross section for an exclusive process that involves nucleons in a nucleus to be proportional to A, the total number of nucleons in the nucleus. The first results on color transparency from a $(p,2p)$ experiment [3] observed an increase in the transparency for $Q^2 \sim 5-9$ GeV^2, but then a decrease for $Q^2 \sim 9-11$ GeV^2.

0031-9007/95/74(9)/1525(5)$06.00

These results spurred extensive theoretical activity [4]. A more recent study performed using the reaction $(e, e'p)$ [5,6] from $Q^2 \sim 1$ to 7 GeV^2 saw "little evidence of effects associated with color transparency."

Exclusive electroproduction of vector mesons such as the ρ^0, in which the initial size of the vector meson is controlled by Q^2 [7], the virtuality of the photon, provides a new and different window into this physics [8–11]. Even at a modest value of $Q^2 = 2$ GeV^2 the transverse separation of the $q\bar{q}$ pair in the ρ^0, varying roughly as $2\hbar c/Q$, is about 0.3 fm, which is much smaller than the size of a normal hadron ($\approx$1 fm). Furthermore, in the kinematic region covered by the data reported here (the energy carried by the ρ^0 mesons, ν, is typically 120 GeV) the coherence length $2\hbar c\nu/(Q^2 + m_v^2)$ (the longitudinal distance involved in the production process) and the formation length $\hbar c\nu/m_v\delta m_v$ (the distance over which the ρ^0 meson grows to its normal size [10], where m_v is the mass of vector meson and δm_v is the typical mass splitting of the vector mesons) are of the order of 20 and 50 fm, respectively, at Q^2 of 2 GeV^2, much larger than the size of even the heaviest nucleus. Thus the resultant ρ^0 mesons should remain small until long after they have left the nucleus. In contrast, in the kinematics of the $(p, 2p)$ and $(e, e'p)$ reactions, the energies of the emerging hadrons are much smaller (6 GeV or less), leading to coherence and formation lengths of the order of 1 fm or less. Therefore, because of the favorable kinematics in this experiment, one may find the nucleus to be transparent to the ρ^0 mesons produced at Q^2 values comparable to that covered by the quasielastic scattering measurements.

In this Letter we report results on the transparency measurements from incoherent, exclusive ρ^0 meson production in muon scattering from nuclear targets. Here exclusive production refers to a process in which the ρ^0 meson is the only hadron present in the final state, in addition to the recoiling nucleon, and the ρ^0 carries all the energy of the virtual photon except that elastically transferred to the nucleon, typically less than 0.2 GeV (the recoil nucleon is not detected in this measurement, thus the definition of exclusiveness is subject to the uncertainties discussed at the end of the paper). The data were obtained at the Fermilab NM beam line with the E665 spectrometer [12]. The mean beam energy was 470 GeV. The momentum resolution of the beam and forward spectrometers was about 0.5% and 1% at 470 GeV/c, respectively. Hadron-electron separation was aided by a fine-grained electromagnetic calorimeter consisting of twenty planes of proportional tubes sandwiched between one-radiation-length lead sheets. Five targets were used for these measurements: liquid hydrogen and deuterium, each one meter long, and solid carbon, calcium, and lead. The solid targets, segmented longitudinally into five equal pieces and distributed with equal separation over the length of the liquid targets, were 0.35, 0.16, and 0.028 interaction length long, respectively. A remotely controlled target assembly cycled the targets every minute, thus greatly reducing the target-to-target systematic effects associated with long term variations in the running conditions.

The kinematic variables describing exclusive vector meson production are $Q^2 = -(k - k')^2$, $\nu = p \cdot q/M$, $x_{\mathrm{Bj}} = Q^2/2M\nu$, $t = (q - r)^2$, $t' = t - t_{\mathrm{min}}$, and $z = E_\rho/\nu$, where k, k', q, r, and p are the four-momenta of the incoming muon, the outgoing muon, the virtual photon, the vector meson, and the target nucleon, respectively, $-Q^2$ is the invariant mass squared of the virtual photon, ν is the energy loss of the muon in the laboratory system, t is the four-momentum transfer squared between the vector meson and the nucleon, z is the fraction of the energy lost by the muon that is carried by the vector meson, $|\, t_{\mathrm{min}} \,|$ is the minimum $|\, t \,|$ allowed by the kinematics (t_{min} corresponds to the limit of zero angle between $\mathbf{q}$ and $\mathbf{r}$ in the laboratory system for fixed values of ν, Q^2, and the mass of the vector meson), E_ρ is the energy of the ρ^0 meson, and M is the mass of the nucleon.

Events accepted by the present analysis were required to have exactly two oppositely charged hadrons in addition to the scattered muon. The energies of the hadrons were required to be greater than 10 GeV to ensure that the particles were in well-understood regions of acceptance of the forward spectrometer. The electromagnetic calorimeter information served to eliminate events in which electrons from photon conversion were mistakenly identified as hadrons. Events from ϕ meson production were rejected by removing all events with $m_{KK} \leq 1.05$ GeV/c^2, where m_{KK} was the invariant mass calculated assuming that the observed particles are kaons. Inelastic (events for which the ρ^0 meson was accompanied by other undetected particles) and combinatorial (events for which the invariant mass of a pair of uncorrelated oppositely charged hadrons was close to the ρ mass) contamination was suppressed by a cut on z: $-1.5 \leq (z - 1)/\delta z \leq 3$ where δz is the uncertainty in z as calculated from the measurement errors. To further reduce contributions from events in which additional particles were produced, but not reconstructed, the number of unused hits in the vertex drift chambers, which accepted all particles with an energy greater than 1 GeV, was limited to a value consistent with the normal level of spurious hits. Events originating from nontarget interactions were removed statistically assuming that they came from carbonlike material. The following additional cuts were imposed on the final data sample: $Q^2 \geq 0.1$ GeV^2, $\nu \geq 20$ GeV, $\delta\nu/\nu \leq 0.25$, $m_{\pi\pi} \leq 1.5$ GeV/c^2, $y_{\mathrm{Bj}} \leq 0.7$, and $0.1 \leq |\, t' \,| \leq 0.8$ GeV^2. Figure 1 shows the distribution, summed over all targets, of $(z - 1)/\delta z$ for all the events passing the selection criteria described above except the cut on $(z - 1)/\delta z$ itself.

The invariant mass $m_{\pi\pi}$, obtained assuming that the observed hadrons are pions, is shown in the inset to Fig. 1. The curve is a fit by a p-wave Breit-Wigner form multiplied by a mass skewing factor $(m_\rho/m_{\pi\pi})^n$ [13,14]. The

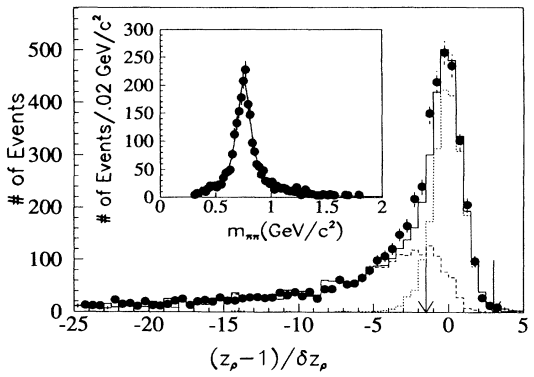

FIG. 1. The $(z-1)/\delta z$ distribution for incoherent $[|t'| \geq 0.1\ (\mathrm{GeV}/c)^2]$ ρ^0 candidates passing the cuts described in the text from the data (points) and the simulated sample (solid histogram). The Monte Carlo sample includes contributions from exclusive ρ^0 (dotted histogram) and inclusive background (dashed histogram) events only. The Monte Carlo events were generated by a specially written generator (exclusive sample) and a Lund-based generator (inclusive sample) with full detector simulation and processed through the same analysis procedure as that used for the data. The region accepted is indicated by arrows. Shown in the inset is the invariant-mass distribution for the ρ^0 candidates passing all the cuts.

results are $m_\rho = 0.780 \pm 0.004\ \mathrm{GeV}/c^2$, $\Gamma_\rho = 0.188 \pm 0.010\ \mathrm{GeV}/c^2$, and $n = 3.18 \pm 0.18$.

Exclusive production of vector mesons from a nuclear target can be coherent, corresponding to production from the nucleus as a whole, or incoherent, corresponding to production from individual nucleons in the nucleus. Since the rate of falloff of the t' distribution for a diffractive scattering process measures the physical size of the scatterer, one expects to see t' fall steeply initially (coherent production), followed by a region with a shallow slope (incoherent production). The observed t' distributions of the ρ^0 candidates for hydrogen and calcium are shown in Fig. 2. Two distinct processes are clearly identifiable. The line for hydrogen is a fit by $N_n e^{-b_n|t'|}$ using only the points between 0.08 and 0.50 GeV^2 ($b_n =$ 6.29 ± 0.37 GeV^{-2}). The lines for calcium are fits by $N_A e^{-b_A|t'|}$ using only points between 0.00 and 0.02 GeV^2 ($b_A = 100 \pm 6\ \mathrm{GeV}^{-2}$) and $N_n e^{-b_n|t'|}$ using only points between 0.08 and 0.50 GeV^2 ($b_n = 6.20 \pm 0.53\ \mathrm{GeV}^{-2}$).

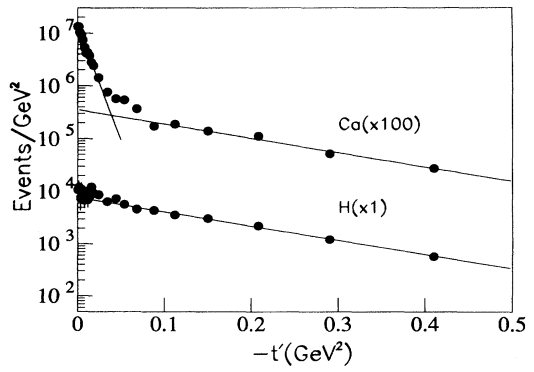

FIG. 2. The t' distributions (not corrected for the experimental resolution and acceptance) for hydrogen (lower curve) and calcium (upper curve).

In the present analysis, events with $|t'| > 0.1$ GeV^2 were selected for the incoherent sample (the same cut is applied for all targets). Contributions from coherent events were estimated by integrating the fitted coherent exponential functions from 0.1 GeV^2 to infinity. The level of coherent background (subtracted from the signal) was less than 1% for all but the deuterium target for which the contamination was about 8%.

The main source of background comes from events in which a ρ^0, or a pair of oppositely charged hadrons with $m_{\pi\pi}$ consistent with the ρ^0 mass, are produced through fragmentation with a sum of z values close to 1 and no other detected particles. A Lund-based Monte Carlo [15] program was used to generate a sample of deep-inelastic events. These events were subjected to the same analysis procedure as that used for the data. The surviving events were then normalized to the data by demanding that the number of total events integrated over $(z-1)/\delta z$ (from $-\infty$ to -3) from the Monte Carlo sample be equal to that of the data. The estimated background events were then subtracted from the data.

For each Q^2 region considered, the exclusive ρ^0 production cross section from a nucleus, σ_A, can be fit by a power law $\sigma_A = \sigma_0 A^\alpha$ in which σ_0 and α are parameters. σ_0 can be interpreted as the best estimate of the $A = 1$ cross section, and α characterizes the A dependence. The transparencies $T = \sigma_A/A\sigma_0$, for incoherent ρ^0 production off hydrogen, deuterium, carbon, calcium, and lead versus A for the three Q^2 regions are shown in Fig. 3(a). Also shown in Fig. 3(a) are the functions $T = A^{\alpha-1}$. In

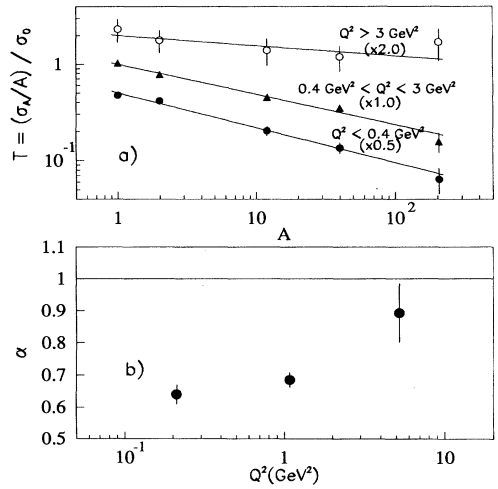

FIG. 3. (a) The transparency T, defined in the text, as a function of A for three Q^2 regions. Note that the points have been multiplied by 2, 1, and 0.5, respectively, for the three Q^2 points. (b) α as a function of Q^2. $\alpha = 1$ corresponds to complete transparency. The errors shown in these plots are statistical only.

Fig. 3(b) we show α as a function of Q^2. The α values are 0.640 ± 0.030, 0.685 ± 0.024, and 0.893 ± 0.092, corresponding to Q^2 values of 0.212, 1.08, and 5.24 GeV^2, respectively. The corresponding average x_{Bj} and ν values are $\langle x_{\mathrm{Bj}} \rangle = 0.0016$, 0.0069, 0.0330, and $\langle \nu \rangle = 144$, 115, 122 GeV, respectively. The probability of α being independent of Q^2 is 2.7%. In contrast, the α values characterizing the A dependence of nuclear shadowing measured from the total cross section in μA scattering [16] are significantly larger and vary between 0.92 and 0.98 over the comparable Q^2 and x_{Bj} regions. Preliminary results on α from total cross sections from E665 are consistent with [16] and will be addressed by a separate publication. The limit $\alpha = 1$ implies that all the nucleons in the nucleus participate in the production equally, i.e., the nucleus is completely transparent. At low Q^2, the value of α we measure is about 2/3, a value characteristic of soft nuclear interactions. The observed rise in T as a function of Q^2 agrees with the expectations for color transparency. On the other hand, if we assume that the intermediate $q\bar{q}$ state and the produced ρ^0 meson are of normal size, the Glauber [17] multiple scattering mechanism predicts a Q^2-independent transparency.

Since the procedure for background subtraction depends on the Monte Carlo input, uncertainties in the hadron z distributions could, in principle, affect the deduced transparencies. The effects of these uncertainties on α measurements were studied by varying the absolute levels of inclusive contributions. A 10% change in background contamination resulted in a change of less than 3% in α in the worst case, resulting in a change in the confidence level from 97.3% to 96.7%.

Because of the target cycling many systematic errors cancel to a large extent. Effects due to secondary interactions in the target were estimated by subdividing the targets into upstream and downstream halves and performing the analysis separately. Effects due to photon conversion events mimicking exclusive ρ^0 events were estimated by varying the kinematic cuts and comparing the resultant transparencies. Errors on normalization were estimated by comparing different procedures of counting incident muons in the experiment. The uncertainties on T from the above sources were all found to be less than 2%. Radiative corrections on T were found to be less than 1%.

The following two issues need to be explicitly addressed in a quantitative interpretation of these results. Transparencies presented here do not exclude final-state elastic interactions. Events in which the produced ρ^0 mesons undergo elastic interactions are included in the transparency analysis provided that the energy losses introduced from these interactions are small. The effect on the Q^2 dependence from this inclusion is expected to be small. The second issue is the fact that the recoiling nucleons are not detected in this measurement. This means that the measured transparencies as defined here represent an average over subprocesses corresponding to different recoil systems.

In summary, we have measured the nuclear transparencies in incoherent, exclusive ρ^0 production off deuterium, carbon, calcium, and lead. At 97% confidence level increases in the transparencies with Q^2 are observed, in general agreement with the predictions of color transparency.

We wish to thank all those personnel, both at Fermilab and at the participating institutions, who have contributed to this experiment. We also wish to thank S. J. Brodsky, L. L. Frankfurt, A. H. Mueller, N. N. Nikolaev, and M. Strikman for many informative and stimulating discussions. This work was supported by the National Science Foundation, the U.S. Department of Energy, Nuclear Physics and High Energy Physics Divisions, the A. P. Sloan Foundation, the Bundesministerium für Forschung und Technologie, and the Polish Committee for Scientific Research.

Note added.—Since this Letter was submitted, the New Muon Collaboration have published [18] their most recent results on the A dependence of exclusive vector meson production at Q^2 values of 4 and 10 GeV^2. They find similar transparencies and conclude that they are in agreement with the present results.

*Deceased.

[1] T. H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978); H. Cheng and T. T. Wu, Phys. Rev. **183**, 1324 (1969); J. D. Bjorken, J. B. Kogut, and D. E. Soper, Phys. Rev. D **3**, 1382 (1971); J. B. Kogut, Phys. Rev. D **5**, 1152 (1972); T. H. Bauer, Nucl. Phys. **B57**, 109 (1973). Previous measurements on high energy exclusive electroproduction of vector mesons: W. R. Francis *et al.*, Phys. Rev. Lett. **38**, 633 (1977); W. D. Shambroom *et al.*, Phys. Rev. D **26**, 1 (1982); J. J. Aubert *et al.*, Phys. Lett. **161B**, 203 (1985); J. Ashman *et al.*, Z. Phys. C **39**, 169 (1988); P. Amaudruz *et al.*, Z. Phys. C **54**, 239 (1992).

[2] A. H. Mueller, in *Proceedings of the XVII Recontre de Moriond, Moriond, Les Arcs, France,* edited by J. Tran Thanh Van (Editions Frontiers, Gif-sur-Yvette, 1982), p. 13; S. J. Brodsky, in *Proceedings of the XIII International Symposium on Multi-Particle Dynamics, Voldendam, The Netherlands,* edited by E. W. Kittel, W. Metsger, and A. Stergion (World Scientific, Singapore, 1982), p. 963.

[3] A. Carroll *et al.*, Phys. Rev. Lett. **61**, 1698 (1988).

[4] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **60**, 1924 (1988); J. Ralston and B. Pire, Phys. Rev. Lett. **61**, 1823 (1988); B. Z. Kopeliovich and B. G. Zakharov, Phys. Lett. B **264**, 434 (1991); B. Jennings and B. Kopeliovich, TRIUMF Report No. TRI-92-95 (1992); S. Frankel and W. Frati, Phys. Lett. B **291**, 368 (1992).

[5] N. C. R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994).

[6] T. G. O'Neill *et al.* (to be published).

[7] It is argued in [10] that only the size of longitudinally polarized ρ^0's decreases as Q^2. An opposing view is presented in [9], in which the authors argue that there is no significant difference in the transverse size between the longitudinally and the transversely ρ^0 mesons produced in the Q^2 regions covered by this measurement. Data on polarization measurement from E665 are being analyzed

and will be presented at a later date. Preliminary results indicate that there is little target dependence in the fraction of the ρ^0 mesons produced with longitudinal polarization to that produced with transverse polarization.

[8] S. J. Brodsky and A. H. Mueller, Phys. Lett. B **206**, 685 (1988).

[9] L. Frankfurt and M. Strikman, Phys. Rep. **160**, 235 (1988).

[10] B. Z. Kopeliovich *et al.,* Phys. Lett. B **309**, 179 (1993); **324**, 469 (1994).

[11] S. J. Brodsky *et al.,* Phys. Rev. D **50**, 3134 (1994).

[12] M. Adams *et al.,* Nucl. Instrum. Methods A, **291**, 533 (1990).

[13] M. Ross and L. Stodolsky, Phys. Rev. **149**, 1172 (1966).

[14] M. Schmitt, Ph.D. thesis, Harvard University, 1991 (unpublished).

[15] M. Bengtsson *et al.,* Nucl. Phys. **B301**, 554 (1988); T. Sjöstrand, Comput. Phys. Commun. **27**, 243 (1982); **39**, 347 (1986).

[16] J. Ashman *et al.,* Z. Phys. C **57**, 211 (1993). This paper combines measurements from EMC and NMC.

[17] R. L. Glauber, in *Lectures in Theoretical Physics,* edited by W. E. Brittin *et al.* (Interscience, New York, 1959).

[18] M. Arneodo *et al.,* Nucl. Phys. **B429**, 503 (1994).