Fermilab FERMILAB-Pub-00/220-E E791 October 2000

Observation of color-transparency in diffractive dissociation of pions

E. M. Aitala,[9] S. Amato,[1] J. C. Anjos,[1] J. A. Appel,[5] D. Ashery,[14] S. Banerjee,[5] I. Bediaga,[1] G. Blaylock,[8] S. B. Bracker,[15] P. R. Burchat,[13] R. A. Burnstein,[6] T. Carter,[5] H. S. Carvalho,[1] N. K. Copty,[12] L. M. Cremaldi,[9] C. Darling,[18] K. Denisenko,[5] S. Devmal,[3] A. Fernandez,[11] G. F. Fox,[12] P. Gagnon,[2] S. Gerzon,[14] C. Gobel,[1] K. Gounder,[9] A. M. Halling,[5] G. Herrera,[4] G. Hurvits,[14] C. James,[5] P. A. Kasper,[6] S. Kwan,[5] D. C. Langs,[12] J. Leslie,[2] J. Lichtenstadt,[14] B. Lundberg,[5] S. MayTal-Beck,[14] B. Meadows,[3] J. R. T. de Mello Neto,[1] D. Mihalcea,[7] R. H. Milburn,[16] J. M. de Miranda,[1] A. Napier,[16] A. Nguyen,[7] A. B. d'Oliveira,[3,11] K. O'Shaughnessy,[2] K. C. Peng,[6] L. P. Perera,[3] M. V. Purohit,[12] B. Quinn,[9] S. Radeztsky,[17] A. Rafatian,[9] N. W. Reay,[7] J. J. Reidy,[9] A. C. dos Reis,[1] H. A. Rubin,[6] D. A. Sanders,[9] A. K. S. Santha,[3] A. F. S. Santoro,[1] A. J. Schwartz,[3] M. Sheaff,[17] R. A. Sidwell,[7] A. J. Slaughter,[18] M. D. Sokoloff,[3] J. Solano,[1] N. R. Stanton,[7] R. J. Stefanski,[5] K. Stenson,[17] D. J. Summers,[9] S. Takach,[18] K. Thorne,[5] A. K. Tripathi,[7] S. Watanabe,[17] R. Weiss-Babai,[14] J. Wiener,[10] N. Witchey,[7] E. Wolin,[18] S. M. Yang,[7] D. Yi,[9] S. Yoshida,[7] R. Zaliznyak,[13] and C. Zhang[7]

(Fermilab E791 Collaboration)

[1] *Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[2] *University of California, Santa Cruz, California 95064*
[3] *University of Cincinnati, Cincinnati, Ohio 45221*
[4] *CINVESTAV, Mexico*
[5] *Fermilab, Batavia, Illinois 60510*
[6] *Illinois Institute of Technology, Chicago, Illinois 60616*
[7] *Kansas State University, Manhattan, Kansas 66506*
[8] *University of Massachusetts, Amherst, Massachusetts 01003*
[9] *University of Mississippi-Oxford, University, Mississippi 38677*
[10] *Princeton University, Princeton, New Jersey 08544*
[11] *Universidad Autonoma de Puebla, Mexico*
[12] *University of South Carolina, Columbia, South Carolina 29208*
[13] *Stanford University, Stanford, California 94305*
[14] *Tel Aviv University, Tel Aviv, Israel*
[15] *Box 1290, Enderby, BC, VOE 1V0, Canada*
[16] *Tufts University, Medford, Massachusetts 02155*
[17] *University of Wisconsin, Madison, Wisconsin 53706*
[18] *Yale University, New Haven, Connecticut 06511*

(October 17, 2000)

We have studied the diffractive dissociation into di-jets of 500 GeV/c pions scattering coherently from carbon and platinum targets. Extrapolating to asymptotically high energies (where $t_{\rm min} \rightarrow 0$), we find that when the per-nucleus cross-section for this process is parameterized as $\sigma = \sigma_0 A^\alpha$, α has values near 1.6, the exact result depending on jet transverse momentum. These values are in agreement with those predicted by theoretical calculations of color-transparency.

Color transparency (CT) is the name given to the prediction that the color fields of QCD cancel for physically small singlet systems of quarks and gluons [1]. This color neutrality (or color screening) should lead to the suppression of initial and final state interactions of small-sized systems formed in hard processes [2], often referred to as point-like configurations (PLC's). Observing color transparency requires that a PLC is formed and that the energies are high enough so that expansion of the PLC does not occur while traversing the target [3–5] (the "frozen" approximation). To demonstrate that the interactions of a PLC with the nucleons in a nucleus are suppressed compared to those of ordinary hadrons requires identifying observables which depend explicitly on the cross-sections of the PLC's. Measurements of color transparency are important for clarifying the dynamics of bound states in QCD [6,7].

Perturbative QCD predicts that a PLC is formed in many two-body hadronic processes at very large momentum transfer [2,8]. Experimental studies of such processes have failed to produce convincing evidence of color transparency [9–11]. However, the momentum transfer may not have been high enough and/or the frozen approximation not valid under these experimental conditions. Evidence for color transparency (small hadronic cross-sections) has been observed in other types of processes: in the A-dependence of J/ψ photoproduction [12], in the Q^2-dependence of the t-slope of diffractive ρ^0 production in muon scattering [13] (where Q^2 is the invariant mass of the virtual photon and t denotes the negative square of the momentum transfer from the virtual photon to the target proton), in the yield of non-diffractive ρ^0 production in deep inelastic muon scattering [14], and in the energy and flavor dependences of vector meson production in ep scattering at HERA [15]. In this paper, we report a direct observation of color transparency in the A-dependence of diffractive di-jet production by pions.

The pion wave function can be expanded in terms of Fock states:

$$\Psi = \alpha|q\bar{q}\rangle + \beta|q\bar{q}g\rangle + \gamma|q\bar{q}gg\rangle + \cdots . \tag{1}$$

The first (valence) component is dominant at large Q^2. The other terms are suppressed by powers of $1/Q^2$ for each additional parton, according to counting rules [16,17]. When the relative velocities of all participating particles are nearly light-like, time dilation lengthens the lifetimes of these states and "freezes" the partonic content of the pion "seen" by the other particles. Bertsch *et al.* [18] proposed that when high momentum pions hit a nuclear target, the physically small $|q\bar{q}\rangle$ components will be filtered by the nucleus and materialize as diffractive di-jets. In a more recent calculation, based on a generalization of the QCD factorization theorem, Frankurt *et al.* [19] proposed that these small $|q\bar{q}\rangle$ components can scatter coherently from nuclei producing high mass di-jets. When the transverse momentum of the individual jets with respect to the beam direction (k_t) is large, the mass of the di-jet must also be large. Frankurt *et al.* show that for $k_t > 1.5\,\mathrm{GeV}/c$ the interaction with the nucleus is completely coherent and $\sigma(|q\bar{q}\rangle\mathcal{N} \rightarrow$di-jets $\mathcal{N})$ is small. This leads to an A^2 dependence of the forward amplitude squared for asymptotically high energies (where $t_{\mathrm{min}} \rightarrow 0$).

As a good approximation, the integrated *per-nucleus* cross-section for producing these high mass di-jets grows as $A^{4/3}$. The forward amplitude squared provides a factor of A^2 [19] and the integral of the elastic-scattering form factor, $\approx \int exp(-\beta R_0^2 t)\, dt$, contributes a factor $A^{-2/3}$ (on the assumption that $R_0 \approx A^{1/3}$ and β, which depends on nuclear density, is the same for all targets). This should be compared with $\sigma \propto A^{2/3}$ typical of normal pion-nucleus interactions (for which the shadowing cross-section is approximately the full π-$\mathcal{N}$ inelastic cross-section). Using more realistic nuclear form factors and accounting for higher twist effects will change the A-dependence modestly, and electromagnetic contributions should produce negligible effects [20].

In this Letter we report measurements of the A-dependence of the diffractive dissociation into di-jets of 500 GeV/c pions scattering coherently from carbon and platinum targets using data from Fermilab experiment E791. We recorded 2×10^{10} π^--nucleus interactions during the 1991/92 fixed-target run at Fermilab using an open geometry spectrometer [21] in the Tagged Photon Laboratory. The segmented target consisted of one platinum foil and four diamond foils separated by gaps of 1.34 to 1.39 cm. Each foil was approximately 0.4% of an interaction length thick (0.5 mm for platinum and 1.6 mm for carbon). Six planes of silicon microstrip detectors (SMD) and eight proportional wire chambers (PWC) were used to track the beam particles. The downstream detector consisted of 17 planes of SMDs for vertex detection, 35 drift chamber planes, two PWCs, two magnets for momentum analysis, two multi-cell threshold Čerenkov counters (not used in this analysis), electromagnetic and hadronic calorimeters for electron identification and for online triggering, and two planes of muon scintillators. An interaction trigger required a beam particle and an interaction in the target. A very loose transverse energy trigger, based on the energy deposited in the calorimeters, and a fast data acquisition system allowed us to collect data at a rate of 30 Mbytes/s with 50μs/event dead time and to write data to tape at a rate of 10 Mbytes/s.

Data reconstruction and additional event selection were done using offline parallel processing systems. The data for this analysis are selected with the primary requirement that at least 90% of the beam momentum is carried by charged particles. This reduces the effects of unobserved neutral particles. In addition, this analysis uses events produced relatively early in the experiment, before the performance of the drift chambers degraded in the region through which the pion beam passed. The offline selection for this analysis was implemented after most of the data had already been filtered for other analyses, and we use data taken only when all five targets were in place. In all, about 10% of the experiment's integrated data set is used in this analysis.

The JADE jet-finding algorithm [22] is used to identify two-jet events. The algorithm's cut-off parameter (m_{cut}) was optimized for this analysis using Monte Carlo simulations which are described below. For each two-jet event we calculate the transverse momentum of each jet with respect to the beam axis (k_t), the transverse momentum of the di-jet system with respect to the beam axis (q_t), and the di-jet invariant mass, M_J. The di-jet invariant mass is related to the quarks' longitudinal momentum fractions in the pion infinite momentum frame (x) by simple kinematics: $M_J^2 = k_t^2/[x(1-x)]$. To assure clean selection of high-mass di-jet events, a minimum k_t of 1.2 GeV/c is required. The selection of clean di-jet

events was verified by testing their relative azimuthal angle which for pure di-jets should be near 180°. This angle is required to lie within 20° of this value. The size of a $|q\bar{q}\rangle$ system which produces di-jets with $k_t > 1.5$ GeV/c can be estimated as $1/Q \leq 0.1$ fm where $Q^2 \sim M_J^2 \geq 4k_t^2 \sim 10$ GeV$^2/c^2$. The distance that the $|q\bar{q}\rangle$ system travels before it expands appreciably, the coherence length, is given by $\ell_c \sim (2p_{\rm lab})/(M_J^2 - m_\pi^2)$ [3] which is ~ 10 fm for $M_J \sim 5$ GeV/c^2. Therefore, we expect that the di-jet signal events selected in this analysis evolve from point-like configurations which will exhibit color transparency.

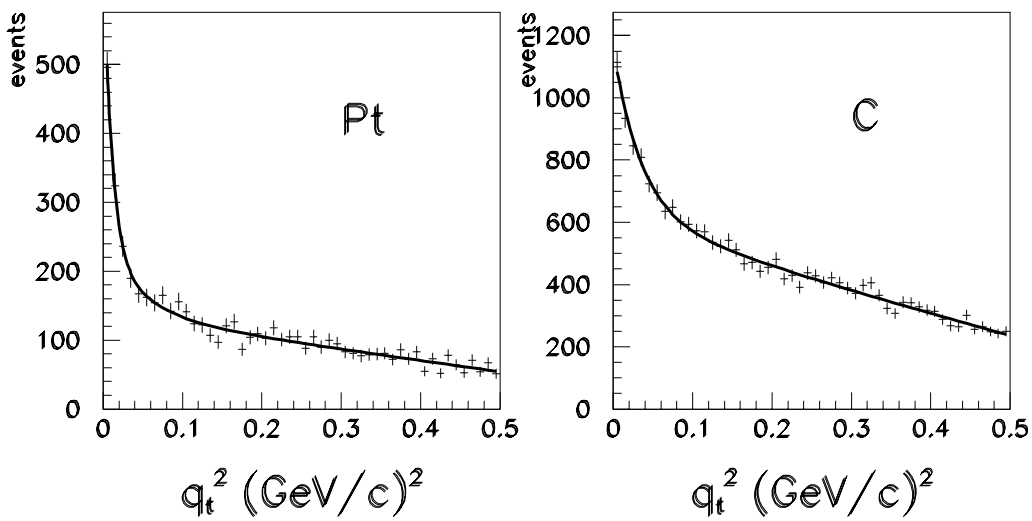

FIG. 1. q_t^2 distributions of di-jets with $k_t \geq 1.25$ GeV/c from interactions of 500 GeV/c π^- with platinum and carbon targets.

The q_t^2 distributions of the selected di-jet events are shown in Fig. 1. The peaks at small q_t^2 arising from coherent scattering from nuclei are smeared due to missing neutrals and detector resolution, but the integrated coherent signals can be extracted with reasonable accuracy. Before detector acceptance and smearing, coherent peaks should be produced with $dN/dq_t^2 \propto \exp(-bq_t^2)$ with b inversely proportional to the nucleus's radius (2.44 fm for carbon and 5.27 fm for platinum [23]). Because theory predicts that the A-dependence varies with k_t [19], the analysis is carried out in three k_t regions: 1.25 GeV/c $\leq$ k$_{\rm t}$ $\leq$ 1.5 GeV/c, 1.5 GeV/c $<$ k$_{\rm t}$ $\leq$ 2.0 GeV/c, and 2.0 GeV/c $<$ k$_{\rm t}$ $\leq$ 2.5 GeV/c. Altogether, we find about 5000 coherent di-jet events in the carbon data set and about 2800 in the platinum data set.

To determine the relative number of coherent events produced in each target, we fit the data of Fig. 1 as sums of q_t^2 distributions of di-jet events produced coherently from nuclear targets, of di-jet events produced coherently from individual nucleons but incoherently with respect to the nuclear targets, and of background. The shapes of the di-jet distributions are calculated using Monte Carlo simulations. We use the LUND PYTHIA-JETSET package [24] to generate di-jet events with masses of 4, 5, and 6 GeV/c^2. This covers the range of

k_t observed in the data. The quark momentum distribution inside the pions is generated using an asymptotic wave function [25,26] which is consistent with the data presented in our companion paper [27]. Coherent nuclear events are generated with q_t^2 slopes appropriate to carbon and platinum. Coherent nucleon events are generated with q_t^2 slopes appropriate to the nucleon radius (0.8 fm), truncated at $q_t^2 = 0.015$ (GeV/c)^2 to account for the nucleon binding energy. The generated events are passed through a detector simulation and digitized to mimic real events. They are reconstructed and analyzed using the same programs used to reconstruct and analyze the real data.

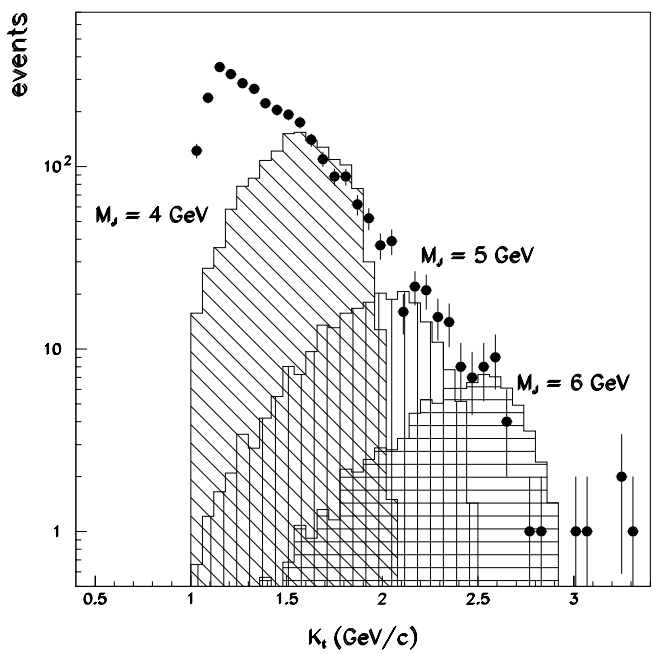

FIG. 2. k_t distributions of simulated di-jets with 4 (slanted lines), 5 (vertical lines), and 6 GeV/c^2 (horizontal lines) masses normalized and superimposed on the distribution from data taken with a platinum target.

To determine the relative efficiencies for observing di-jet events produced through coherent diffractive scattering from carbon and platinum nuclei, we use Monte Carlo samples generated with di-jet masses of 4, 5, and 6 GeV/c^2. The proportions are adjusted to reproduce the k_t spectrum of the data, as observed in Fig. 2. For each k_t range, and for each target, we fit the q_t^2 distribution using the signal shapes from the Monte Carlo simulations and assuming the background contribution is linear in q_t^2. Fig. 3 shows the results of the fit for 1.5 GeV/c $\leq$ k$_t$ $\leq$ 2.0 GeV/c. The dashed line shows the coherent nuclear distribution, the dotted line the coherent nucleon/incoherent nuclear distribution, and the dash-dotted line the residual background. This background represents the components of the data which are not simulated well, such as badly identified jets. The background's contribution in the

region of the coherent distribution is small. These fits provide normalization factors between the number of simulated events of each kind and the data.

We derive the relative numbers of produced di-jet events for each target in each k_t bin by integrating over the diffractive terms in the fits and accounting for the relative efficiencies as described above. The signals from the carbon and platinum targets in any one k_t range have slightly different mass distributions, and we correct the relative yields to account for this. Using the measured target thicknesses, we determine the ratio of cross-sections for coherent production of diffractive di-jets from the carbon and platinum targets (which received essentially the same beam flux). Theoretical calculations of color transparency at asymptotically high energies predict $\sigma = \sigma_0 A^\alpha$ with $\alpha = 4/3$ assuming very simple nuclear wave functions. At the energy of this experiment, $|t_{\rm min}| > 0$ reduces the cross-sections for coherent scattering on carbon (platinum) targets to 0.98 (0.93), 0.97 (0.87), and 0.94 (0.76) times their asymptotic high-energy values for $M_J = 4.2$, 5.0, and 6.0 GeV/c^2 (masses relevant for our k_t^2 bins). We extrapolate our calculations of α to asymptotically high energies dividing the yields by these factors. The results for each k_t bin are listed in Table I. Using more realistic wave functions, the predicted value of the asymptotic value of α is 1.45 for carbon and platinum targets. Frankfurt et al. [19] predict some dependence of α on k_t as well. These values, labelled α(CT), are also listed in Table I.

We have considered the sources of systematic uncertainty which are listed in Table II. The degree to which the simulations represented correctly the effect of not including the neutral component of the jets is checked by raising the minimum total momentum of charged particles from 450 GeV/c to 470 GeV/c. The difference in the final results of α with and without this requirement is taken to be the corresponding systematic uncertainty ("effect of neutrals"). The uncertainty due to using discrete masses in the Monte Carlo simulation is estimated using the difference between results assuming that all the events in a given k_t range have one mass or another ("discrete masses"). A third uncertainty is assigned to the change in yields due to mass-distribution differences in carbon and platinum. We also observe some sensitivity to the fitting range used; the associated differences are taken as a fourth systematic uncertainty. The total systematic uncertainty is taken by adding these contributions in quadrature, retaining the signs when not symmetric.

In summary, we have measured the relative cross-sections for diffractive dissociation into di-jets of 500 GeV/c pions scattering from carbon and platinum targets. Extrapolating to asymptotically high energies (where $t_{\rm min} \to 0$), we find that when the cross-section is parameterized as $\sigma = \sigma_0 A^\alpha$, $\alpha \sim 1.6$. This is consistent with expectations based on calculations of color-transparency models and is clearly inconsistent with the $\sigma \propto A^{2/3}$ dependence observed for inclusive π-nucleus scattering. We have measured α in three ranges of k_t; because the uncertainties are large, the results are consistent with no variation, but also with the predicted variation. The clear diffractive structure of the signals and variation of the coherent cross-section with A indicate that we have observed the coherent scattering of $|q\bar{q}\rangle$ point-like configurations predicted by color-transparency.

We thank Drs. S.J. Brodsky, L. Frankfurt, G.A. Miller, and M. Strikman for many

fruitful discussions. We gratefully acknowledge the staffs of Fermilab and of all the participating institutions. This research was supported by the Brazilian Conselho Nacional de Desenvolvimento Científico e Technológio, the Mexican Consejo Nacional de Ciencia y Tecnologica, the Israeli Academy of Sciences and Humanities, the United States Department of Energy, the U.S.-Israel Binational Science Foundation, and the United States National Science Foundation. Fermilab is operated by the Universities Research Association, Inc., under contract with the United States Department of Energy.

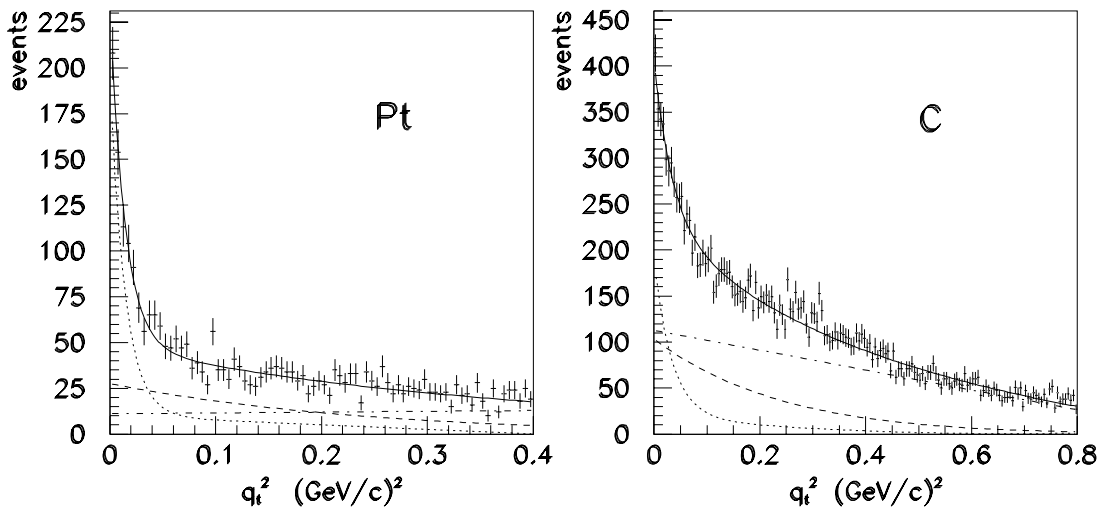

FIG. 3. q_t^2 distributions of di-jets with $1.5 \leq k_t \leq 2.0$ GeV/c for the platinum and carbon targets. The lines are fits of the MC simulations to the data: coherent nuclear dissociation (dotted line), coherent nucleon/incoherent nuclear dissociation (dashed line), background (dashed-dotted line) and total fit (solid line).

TABLE I. The exponent in $\sigma \propto A^{\alpha}$, experimental results for coherent dissociation and the Color-Transparency (CT) predictions.

k_t bin GeV/c	α	$\Delta\alpha_{stat}$	$\Delta\alpha_{sys}$	$\Delta\alpha$	α (CT)
1.25 − 1.5	1.64	±0.05	+0.04 −0.11	+0.06 −0.12	1.25
1.5 − 2.0	1.52	±0.09	±0.08	±0.12	1.45
2.0 − 2.5	1.55	±0.11	±0.12	±0.16	1.60

TABLE II. The systematic errors

k_t bin GeV/c	effect of neutrals	discreet masses	different efficiency for C and Pt	fit range sensitivity	total
1.25 − 1.5	−0.09	+0.03 −0.06	±0.02	±0.02	+0.04 −0.11
1.5 − 2.0	±0.03	±0.03	±0.06	±0.04	±0.08
2.0 − 2.5	±0.06	±0.05	±0.06	±0.07	±0.12

[1] F. E. Low, Phys. Rev. **D12**, 163 (1975); S. Nussinov, Phys. Rev. Lett **34**, 1286 (1975).
[2] A.H. Mueller in Proceedings of Seventeenth Rencontre de Moriond, Les Arcs, 1982 ed. J Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1982) Vol. I, p13; S.J. Brodsky in Proceedings of the Thirteenth Int'l Symposium on Multiparticle Dynamics, ed. W. Kittel, W. Metzger and A. Stergiou (World Scientific, Singapore 1982,) p963.
[3] G.R. Farrar, H. Liu, L.L. Frankfurt & M.I. Strikman, Phys. Rev. Lett. **61**, 686 (1988).
[4] B.K. Jennings and G.A. Miller, Phys. Lett. **B236**, 209 (1990); B.K. Jennings and G.A. Miller, Phys. Rev. **D44**, 692 (1991); Phys. Rev. Lett. **69**, 3619 (1992); Phys. Lett. **B274**, 442 (1992).
[5] S.J. Brodsky and A.H. Mueller, Phys. Lett. **B206**, 685 (1988).
[6] L. Frankfurt, G.A. Miller, and M. Strikman, Comments Nucl. Part. Phys. **21**, 1 (1992); Nucl. Phys. **A555**, 752 (1993).
[7] L. Frankurt and M. Strikman, Phys. Rep. **160**, 235, (1988).
[8] H.-N. Li and G. Sterman, Nucl. Phys. **B381**, 129 (1992); J. Botts and G. Sterman, Nucl. Phys. **B325**, (1989) 62.
[9] I. Mardor *et al.*, Phys. Rev. Lett. **81**, 5085 (1998).
[10] N.C.R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994); T.G. O'Neill *et al.*, Phys. Lett **B351**, 87 (1995).
[11] D. Abbott *et al.*, Phys. Rev. Lett. **80**, 5072 (1998).
[12] M.D. Sokoloff *et al.*, Phys. Rev. Lett. **57**, 3003 (1986).
[13] M.R. Adams *et al.*, Z. Phys. **C74**, 237 (1997).
[14] M.R. Adams *et al.*, Phys. Rev. Lett. **74**, 1525 (1995).
[15] H. Abramowicz and A. Caldwell, Rev. Mod. Phys. **71**, 1275 (1999).
[16] S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).
[17] G. Sterman and P. Stoler, Ann. Rev. Nuc. Part. Sci. **43** (1997) 193, and references therein.
[18] G. Bertsch, S.J. Brodsky, A.S. Goldhaber, J. Gunion, Phys. Rev. Lett. **47**, 297 (1981).
[19] L.L. Frankfurt, G.A. Miller, and M. Strikman, Phys. Lett. **B304**, 1 (1993).
[20] L.L. Frankfurt, G.A. Miller, and M. Strikman, Found. of Phys. **30**, 533 (2000); L.L. Frankfurt, G.A. Miller and M. Strikman, preprint NT@UW-99-25.
[21] E791 Collaboration, E.M. Aitala *et al.*, Eur. Phys. J.direct **C4**, (1999) 1, and references therein.
[22] JADE collaboration, W. Bartel et al., Z. Phys. **C33**, 23 (1986).
[23] C.W. de Jager, H. de Vries, and C. de Vries, Atom. Data and Nucl. Data Tabl. **14**, 479 (1974); the radius for Pt is derived from that reported for Au scaled by $A^{1/3}$.
[24] H.-U. Bengtsson and T. Sjöstrand Comp., Phys. Comm. **82**, 74 (1994); T. Sjöstrand, PYTHIA 5.7 and JETSET 7.4 Physics and Manual, CERN-TH.7112/93, 1995.
[25] S.J. Brodsky and G.P. Lepage, Phys. Rev. **D22**, 2157 (1980); S.J. Brodsky, G.P. Lepage, Phys. Scripta **23**, 945 (1981); S.J. Brodsky, Springer Tracts Mod. Phys. **100**, 81 (1982).
[26] A.V. Efremov, A.V. Radyushkin, Theor. Math. Phys. **42**, 97 (1980).
[27] E791 Collaboration, E.M. Aitala *et al.*, Fermilab PUB-00/221-E and submitted for publication.