Fermi National Accelerator Laboratory

FERMILAB-Conf-95/018

Some Highlights of the Recent Fermilab Fixed Target Program of Interest to the Nuclear Physics Community

Janet Conrad, Vassili Papavassiliou and Marek Zielinski

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

February 1995

Presented at the *DPN/NSAC Town Meeting on Nuclear Physics with Intermediate Energy and High Energy Hadron Probes*, Argonne National Laboratory, Argonne, Illinois, January 29-30, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

SOME HIGHLIGHTS OF THE RECENT FERMILAB FIXED TARGET PROGRAM OF INTEREST TO THE NUCLEAR PHYSICS COMMUNITY

Janet Conrad, Columbia University,
Vassili Papavassiliou, Illinois Institute of Technology,
Marek Zieliński, University of Rochester

ABSTRACT

Many of the high energy physics questions addressed by the Fermilab Fixed Target Experiments are also of interest to the members of the nuclear community. Some recent highlights of the program, including studies of A-dependence of cross sections, evidence for parton rescattering in nuclear media, studies of heavy quark production, evidence for color transparency, and insights into QCD from meson systems, are discussed.

1 Introduction

There is a large overlap between questions of interest to nuclear physicists and those of interest to high energy physicists. Fermilab has encouraged investigation of these questions by various fixed target experiments. Many results of interest to nuclear physicists have been published in the last five years and only a fraction can be covered in this review.[1] Interested readers are urged to contact Jeff Appel, head of the Fermilab Physics Section, for further information about the program.

As a sampling of the diverse results, this review focuses on studies of shadowing effects; evidence for quark rescattering in nuclear media; measurements of A-dependence in heavy quark production; evidence for color transparency; and insights into QCD from meson-systems. The experiments are described in detail in The Fermilab Workbook.[2]

2 A-Dependence of Cross Sections

The scattering cross-section for hadrons incident on nuclear material is qualitatively different for the "soft," or low-Q^2, kinematic region compared to the "hard," or high-Q^2 kinematic region. The exact mechanisms for the nuclear effects in the soft-scattering region are unknown, hence studies of the transition between the hard- and soft- interaction regions are of great interest for comparing models. Recent results from Fermilab have added significantly to the body of knowledge on these nuclear effects.

In a soft hadronic interaction, the incident hadron appears to scatter near the "surface" of the bound nucleus. Thus the "per nucleon" cross section for interacting with bound nucleons is expected to be smaller than for interactions with a free nucleon such as the proton. Because the radius of the nucleus goes as $A^{\frac{1}{3}}$, the cross section should be proportional to A^{α} where $\alpha = \frac{2}{3}$. The data is often expressed as the per nucleon cross section, which goes as $A^{\alpha-1} = A^{-\frac{1}{3}}$. This reduction in the per nucleon cross section of bound nuclei compared to free nucleons is called "shadowing."

This effect is expected in experiments which use electromagnetic probes as well as those which use hadronic probes. According to the vector meson dominance model (VDM), real or virtual photons can fluctuate into quark–antiquark pairs which form mesons with quantum numbers identical to the original probe. The

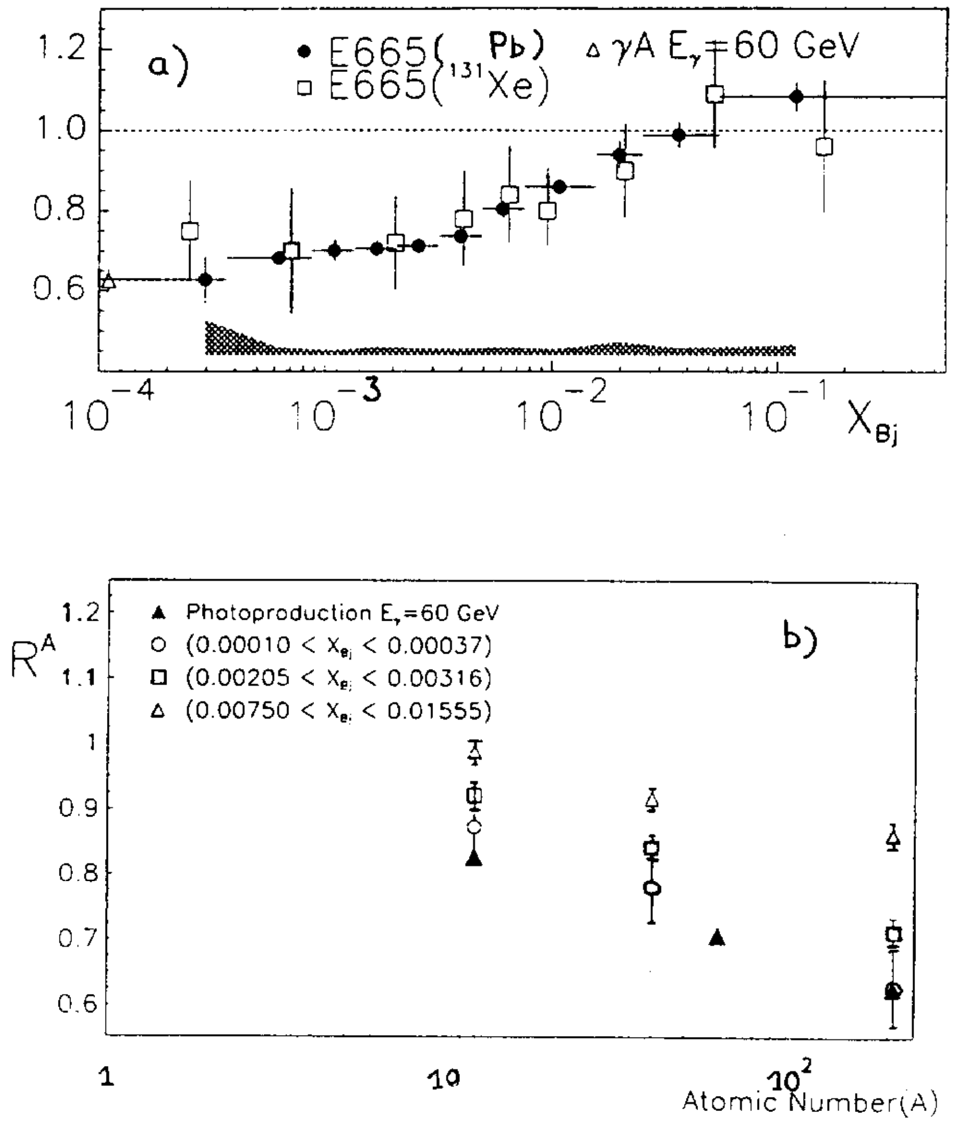

Figure 2: a) Ratio of cross section per nucleon for lead and xenon to deuterium as a function of x. b) Ratio of cross sections per nucleon for carbon, calcium and lead to deuterium as a function of atomic number for three low-x bins. The data approach the photoproduction results at very low-x.

mesons then interact hadronically, with the A dependence described above.

The lifetime of a quark–antiquark fluctuation is given by $\Delta t = \frac{1}{Mx}$, where M is the target nucleon mass and x is the Bjorken scaling variable. The Bjorken scaling variable in deep inelastic scattering is related to the virtuality (negative squared four-momentum transfer) of the exchanged photon, Q^2, and the energy of the virtual photon, ν, by the relation: $x = Q^2/2M\nu$. Hence the low-x (large Δt) region is also the low-Q^2 region for most fixed target experiments.

On the other hand, in the case of hard scattering, the partons are considered to be "quasi-free," and not be affected by bound-state effects. The cross-section should therefore scale as A^α, where $\alpha = 1$.

2.1 Hadroproduction of Pions and Direct Photons

Experiment E706 has recently reported a high-statistics study of cross sections for π^0 production in nuclear materials.[3] This experiment used a 515 GeV π^- beam on beryllium and copper targets to study the production of pions as a function of transverse momentum, p_T. In hadroproduction, Q^2 is taken to be proportional to p_T^2. Hence, lower-p_T jets are expected to show large nuclear effects, while high-p_T jets and direct photons, which result from hard-QCD interactions, should display a far weaker nuclear dependence of the cross section. In each p_T bin the data were fit to the form $\sigma_0 A^\alpha$, which is a common parameterization for such studies.

Figure 1a shows the new E706 results for α as a function of p_T. Also shown are studies of charged pion production performed at Fermilab in the early 1980's.[4] The data show clearly that α is < 1 and is strongly p_T dependent at low p_T, but slowly varying and > 1 at high p_T. This suggests that the transition between scattering from a bound quark system, which has large absorption effects, to hard parton scattering, in which the parton can scatter from the whole nuclear volume occurs near 2–3 GeV/c. In principle, the hard scattering cross section should lead to an $\alpha = 1$ dependence, but in practice quark rescattering preceeding or following the hard interaction can yield $\alpha > 1$.[5]

The preliminary E706 data (figure 1b) for direct photon production indicate that α is consistent with unity for $p_T > 3$ GeV/c. Because the photon will not reinteract strongly as it traverses the nuclear medium, rescattering effects should only occur preceeding the interaction and are expected to be small as a result. However, even accounting for the large errors, it is surprising that there appears

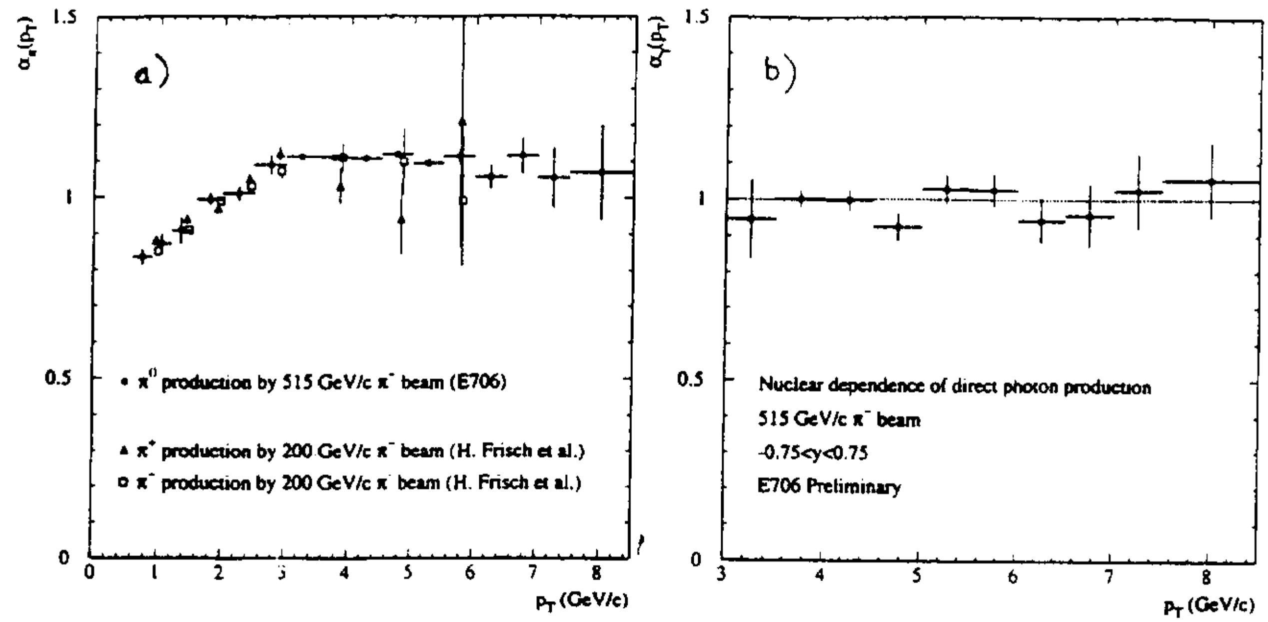

Figure 1: a) α for pion production as a function of p_T observed by E706 and previous experiments. b) Preliminary α for direct photon production from E706.

to be no evidence for any rescattering.

Rescattering effects are discussed further in section 3.

2.2 Shadowing in Muoproduction

Experiment E665 used 500 GeV muons incident on carbon, calcium, lead and xenon targets to study shadowing in deep inelastic scattering. The ratio of cross sections from the heavy targets were compared to the cross section from a deuterium target and were studied as a function of the Bjorken scaling variable, x, and the negative squared four-momentum transfer, Q^2.[6]

The range of this experiment was $0.0001 < x < 0.56$. At high x, very little shadowing was observed, as expected because the lifetime of the quark-antiquark state is small. Figure 2a shows the onset of shadowing in lead and xenon as $x \to 0$. At very low x, the data are consistent with the real photon measurements.[7] This is expected because the low x region is the region of low Q^2, where the virtual photon is "almost real." Figure 2b shows the ratio for carbon, calcium and lead as a function of atomic number for three x bins. Again, in this plot, the trend toward the photoproduction data at low x is clear. At lowest x, the A-dependence is described by $\alpha = 0.886 \pm 0.041(stat) \pm 0.022(norm)$.

New E665 measurements of the cross section of muon scattering from deu-

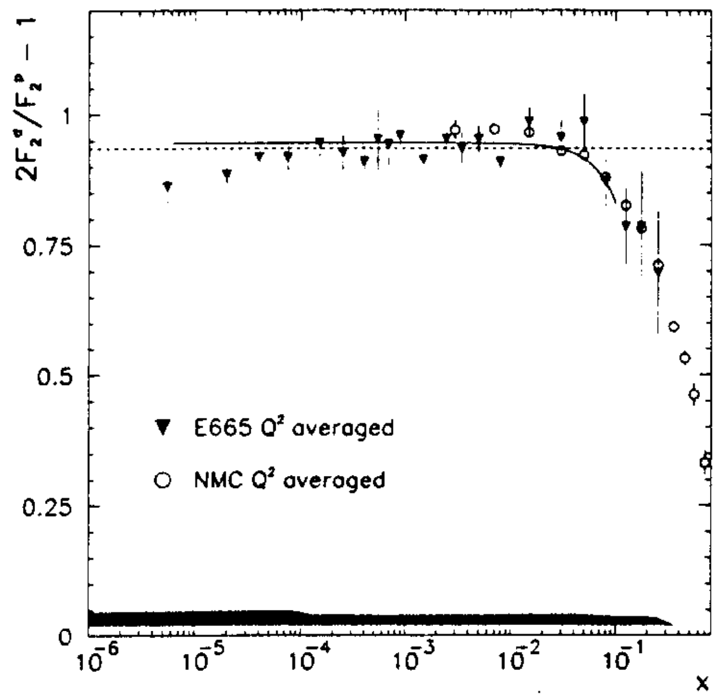

Figure 3: $2(\sigma^D/\sigma^H) - 1$ as a function of x. Model is by Badelek, *et al.* (see text).

terium compared to hydrogen allow investigation of shadowing in the deuteron.[8] Because the deuteron is a loosely bound nucleus, nuclear effects have been ignored in many analyses. However, in some cases, such as evaluation of the Gottfried Sum Rule,[9] even small nuclear effects can be important. Moreover, the deuteron, as a two-body system, should be an ideal case for calculating shadowing effects in different models. Comparing these effects to high-precision experimental data can provide valuable insight into the nature of shadowing.

The E665 result, $2(\sigma^D/\sigma^H) - 1 = 0.935 \pm 0.008(stat) \pm 0.034(sys)$ for $x < 10^{-2}$, is below unity and in agreement with predictions made by the model of Badelek, *et al.*[10] (see figure 3) and Melnitchouk, *et al.*,[11] which include nuclear shadowing effects. This may be interpreted as the first evidence for shadowing in the deuteron system.

2.3 Shadowing in Drell-Yan Production

Experiment E772 has used an 800-GeV proton beam incident on deuterium, carbon, calcium, iron, and tungsten targets to investigate A-dependent effects in Drell-Yan production.[12] In Drell-Yan production[13] a quark-antiquark pair annihilate producing two opposite-sign muons. Alternatively, the pair can annihilate and

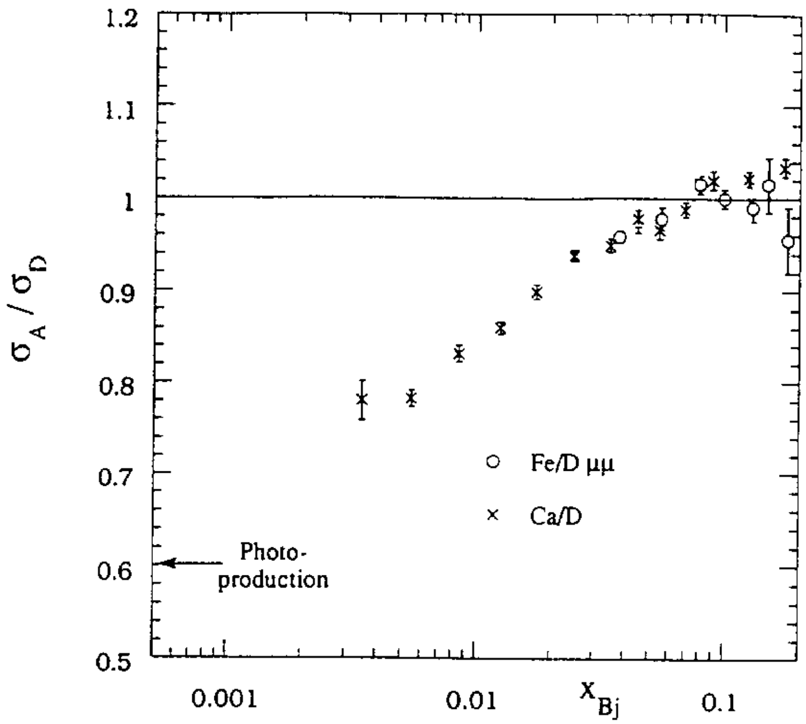

Figure 4: Ratio of the cross sections for Drell-Yan production on iron to deuterium (E772) compared to the ratio of cross sections from muon scattering on calcium to deuterium (E665).

become a charm-quark pair which can form a J/ψ or ψ' particle, which can then also decay into a dimuon pair. The two processes are distinguished by identifying the J/ψ and ψ' mass peaks.

The Drell-Yan data extends only down to $x_2 = 0.04$, where x_2 is the x of the target quark. The cutoff is due to the lower limit of 4 GeV imposed on the dimuon mass M, in order to stay above the ψ resonances. However, the data are at $Q^2 = M^2 = 16 - 80\ GeV^2$, which is much higher than the Q^2 values of the muon scattering data for similar x values.

Figure 4 shows the ratio of the Drell-Yan cross sections from iron and deuterium. There is evidence for the onset of shadowing and the data are in agreement with the muon-scattering cross-section ratio of calcium to deuterium from the NMC experiment at CERN.[14] This agreement is often claimed to point to a partonic origin of the shadowing effect, but a VDM-type mechanism may also be able to reproduce the observed ratios.

3 Quark Rescattering in Nuclear Matter

In hard QCD interactions, it is possible that the partons can participate in strong interactions either before or after the principal interaction takes place. Evidence for such an effect has been presented in section 2.1 above. In this section, we consider a particularly sensitive variable to study quark rescattering effects: the out-of-plane component of the dijet transverse momentum, $k_{T\phi}$.[15] Defining $\Delta\phi$ as the azimuthal angle between the high-p_T jets emerging from the hard interaction and p_T as the magnitude of the transverse momentum, $k_{T\phi} = \frac{1}{2}(p_{T\ jet\ 1} + p_{T\ jet\ 2})sin\Delta\phi$. An illustration of the definition of this variable is shown in figure 5a. This section presents new results on the variation of $\langle k_{T\phi}^2 \rangle$ with atomic number and with hard scattering process.

Experiment E683 used a 50–400 GeV wideband photon beam incident on deuterium, beryllium, carbon, aluminum, copper, tin and lead targets. Jets of particles with transverse momentum greater than 3 GeV were identified as candidates for hard scattering. Figure 5b shows the dependence of the average value of $k_{T\phi}^2$ on atomic number.[16] If the data are fit to the form $C_0 + C_1(A-1)^\alpha$, then $\alpha = 0.32 \pm 0.08$. These results are consistent with $\alpha = 0.33$, which is expected for phenomena that depend on the length of nuclear matter traversed. C_1 is related to the average Lorentz force encountered by the partons due to the nuclear medium.[5]

Experiment E706 used 530 GeV incident π^- and proton beams on hydrogen, beryllium, copper and silicon targets for its $k_{T\phi}$ studies.[3] The trigger was a direct photon or π^0, which were usually accompanied by opposite side recoil jets. The triggers were required to have $p_T > 5.5$ GeV. Figure 5c shows the preliminary E706 results for direct photon candidates (closed squares) and π^0 data (open circles) for incident pion beam. It is surprising that the results are in such good agreement, because the direct photon process has one less parton that can rescatter than is the case for π^0 production. (It should be noted that the direct photon data have not been corrected for π^0 background, which is comparable in size.)

These results can be compared to those of E683 for real photoproduction shown in figure 5b, which correspond to the inverse process of direct photon production. It should be noted that E706 data were produced using a higher energy beam than the E683 data and have a higher p_T cut on the triggers. The dependence on the atomic number is very similar, although the overall normalization of the E706

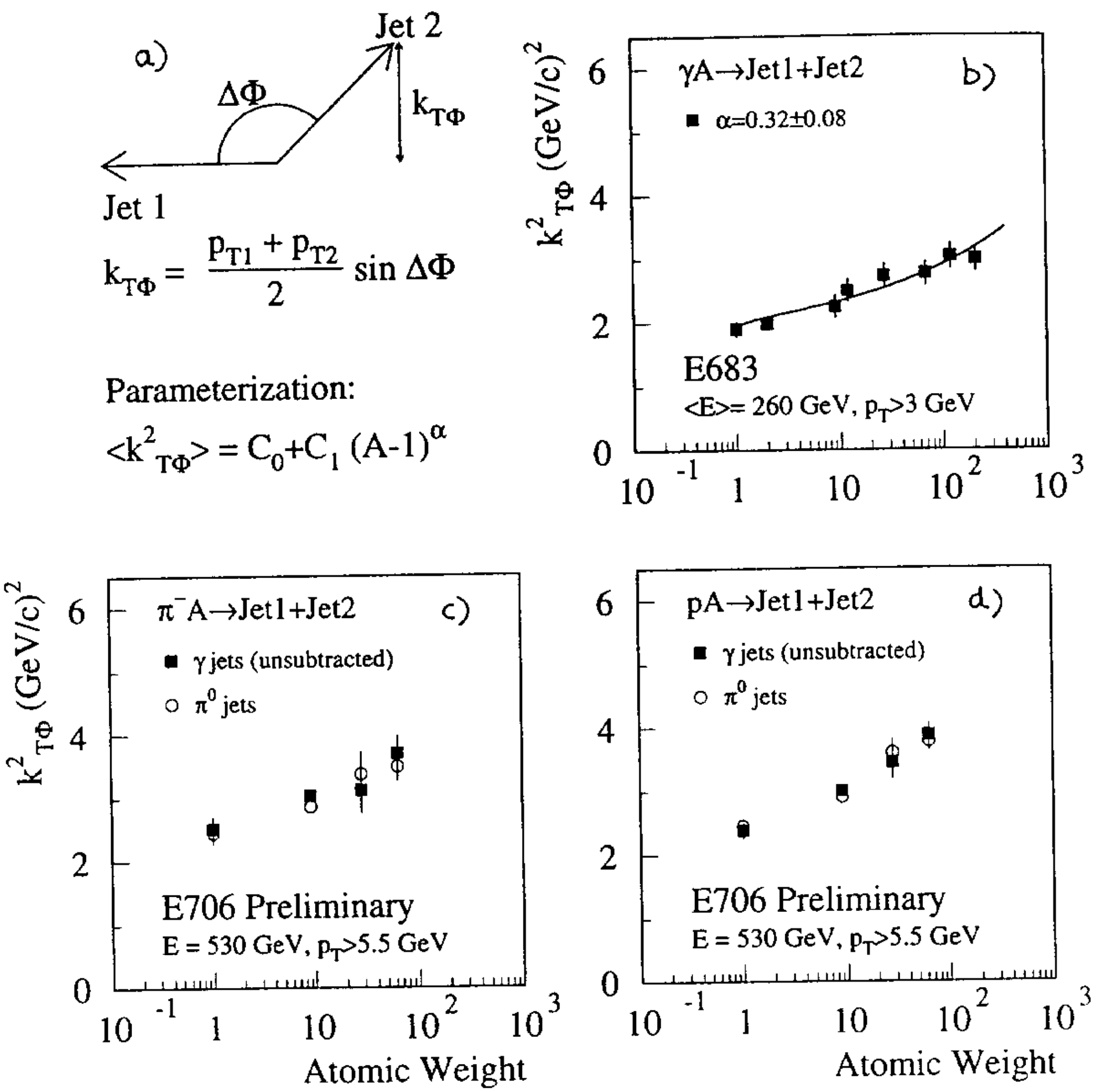

Figure 5: a) Diagram showing the definition of $k_{T\phi}$; b) Photoproduction results from E683; c) Preliminary results from E706 using a π^- beam for direct photon triggered jets (closed squares) and π^0 triggered jets (open circles); d) Preliminary results from E706 using a proton beam.

data is somewhat higher than the E683 data.

Figure 5d shows the preliminary E706 results for the proton beam data. This is in good agreement with the pion beam results, indicating that there is little dependence on incident hadron.

These $k_{T\phi}$ results provide qualitative evidence for quark rescattering in the nuclear medium. Higher statistics on heavier targets and at higher energies are needed to advance these studies.

4 A-dependence of Heavy Quark Production

In contrast to the relatively small nuclear effects in the Drell-Yan process, J/ψ production in proton-nucleus collisions was found, by experiments E672,[17] E772[18] and E789,[19] to exhibit strong A-dependence. Figure 6 shows this effect for the E772 data. In this figure, the ratio of production from high-A targets to production from hydrogen targets is shown as a function of A. The ratio for Drell-Yan production is in agreement with unity. However, the J/ψ data clearly shows a ratio which decreases with A.

A parameterization of the form A^α for the total cross section describes the J/ψ data in the positive x_F region with $\alpha \simeq 0.9$. This value is strongly x_F-dependent, decreasing further at large x_F, corresponding to small values of the fractional momentum x_2 of the target nucleon carried by the parton that participates in the interaction. Similar behavior is seen in ψ' production by E772,[18] also shown in figure 6. Charmonium production in this process is thought to proceed mostly via gluon-gluon fusion. It is tempting to try to explain the observed A-dependence as a manifestation of a decrease of the gluon sea in a nuclear environment in the relevant x-range. However, there are two problems with this interpretation. Comparison with experiments at lower energies shows that the ratio does not scale with x_2, as a partonic origin would require; instead it scales with x_F, suggesting possible higher twist effects, such as intrinsic charm.[20] The second difficulty, which also seems to argue against the intrinsic charm hypothesis, is that experiments E769,[21] and E789,[22] that have looked for open charm production in proton- or pion-nucleus interactions at somewhat more central x_F, find no evidence for A-dependence: α is consistent with unity for D-meson production. A different approach relates charmonium production from nuclei to propagation of colored states through nuclear matter.[23] Final state interactions can then reproduce the observed x_F-dependence

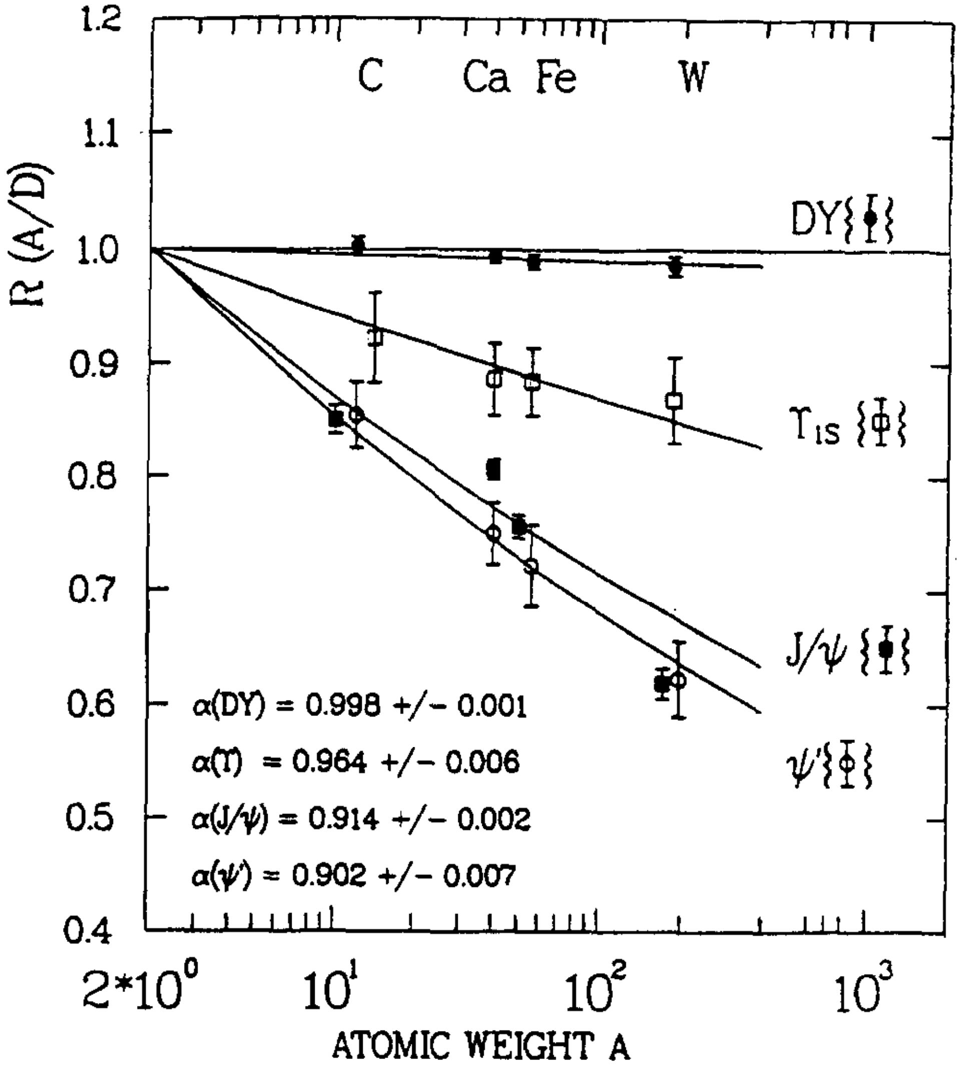

Figure 6: A-dependence of J/ψ and Υ production compared to Drell-Yan scattering from experiment E772. Ratios of production from high-A targets (per nucleon) to production from deuterium are shown as a function of A.

and also predict a corresponding suppression for open-charm production from nuclei at large x_F. The shift toward lower overall values of α for the ψ states is due to the additional interaction channel (total absorption) available to the charmonium as compared to the open-charm states. It is worth mentioning here that older experiments have seen some evidence for nuclear suppression of charm production; all these experiments had acceptance at higher x_F.[24] Finally, some suppression has been seen in hadroproduction of bottomonium states from nuclear targets by E772[25] (see figure 6). The suppression is smaller than for the ψ states; the kinematic range corresponds to smaller, including negative, x_F, or large values of x_2. The study of nuclear effects in J/ψ hadroproduction is also relevant for interpreting results from heavy-ion collisions, where a suppression of J/ψ production has been suggested as a signature for quark–gluon-plasma formation.[26] Clearly the topic of open- and hidden-charm production in hadron-nucleus interactions is very important for studies of perturbative and non-perturbative QCD effects.[27]

5 Color Transparency

The idea of Color Transparency (CT) is that a hadron will have a reduced probability of interaction in nuclear matter if it is found in a Fock-space configuration that has a small size compared to the physical hadron size. Such a small-size state can be produced in certain hard-scattering processes and the manifestation of CT would be an increase in the value of the nuclear transparency, defined as $T = \mathrm{d}\sigma_A / A\mathrm{d}\sigma_N$, where $\mathrm{d}\sigma_A(\mathrm{d}\sigma_N)$ is the total cross section for the process from a nuclear target (free nucleon). As the size becomes smaller, the expectation from CT is that $T \to 1$. This is because the color fields of the overlapping partons cancel each other, resulting in a state that appears colorless to the surrounding medium and thus is more likely to escape being absorbed as it propagates through the medium. This is the QCD analogue of the QED Chudakov effect observed in bubble chambers, where an outgoing electron and positron produced in a Bethe-Heitler process from a high-energy photon did not appear to leave any tracks in the medium until the charged particles were sufficiently spacially separated.[28]

For a CT signal to be observed, in addition to the hard process that selects a small-size state, the state must be sufficiently long-lived that it survives as it propagates through the nuclear medium. This is governed by the so-called formation length l_f. At large enough projectile energies, this length can be larger

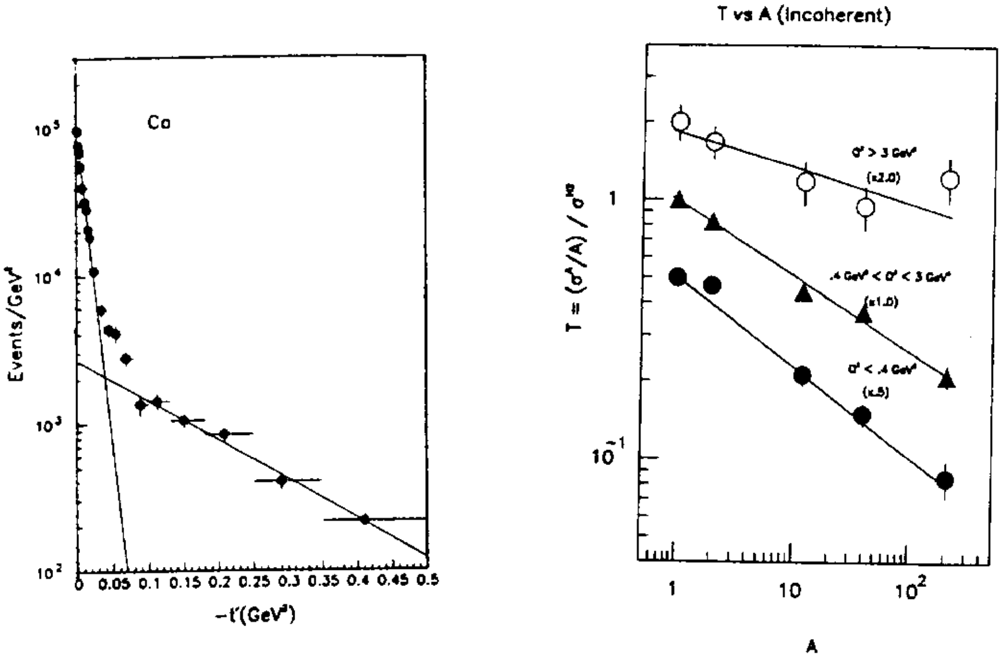

Figure 7: a) Momentum transfer squared for the calcium target, with contributions from coherent and incoherent scattering identified; b) Transparency of incoherently scattered ρ^0 mesons as a function of Q^2 and atomic number.

than the nuclear radius due to Lorentz dilation and CT should appear.

Until recently, the evidence for color transparency was relatively weak. A signal was reported from the E834 experiment at Brookhaven[29] that measured the cross-section ratio for quasi-elastic and elastic proton-proton scattering. This process is expected to be dominated, at high energies, by the lowest-multiplicity (three-quark) states of the proton, which should have a smaller size than the physical proton size. The transparency was found to first increase with beam energy and then decrease. Similarly, SLAC NE18 measured the corresponding ratio for (quasi-)elastic electron-proton scattering. In this process, the size is assumed to be given by the inverse of the Q^2 value of the virtual photon. The experiment reported no significant change of the transparency for Q^2 in the range 1–7 GeV^2. In both cases it is possible that higher beam energy might allow a more definitive test of the idea of CT.

Recently, results have become available from a muon deep inelastic scattering experiment, E665, and a photoproduction experiment, E691, at Fermilab, that provide support for the idea of CT. Also, the NMC muon scattering experiment at CERN has presented new data on J/ψ production that can be explained in the framework of CT.

Experiment E665 measured the nuclear transparency for incoherent exclusive ρ^0 production in deep inelastic muon scattering.[31] Measurements were made as a function of Q^2 on deuterium, carbon, calcium and lead targets. The ρ^0 mesons were identified by appropriate cuts on the $\pi\pi$ mass peak. A sample of incoherent scatters was obtained by fitting the distribution of $-t'$, the momentum transfer squared between the meson, seen in figure 7a. Coherent scattering dominates at low $-t'$, and the slope of distribution will depend on the charge radius of the nucleus, R_{chg} (calcium is shown in figure 7a). Incoherent scattering, with a $-t$ that is independent of A, can be isolated by cutting at $-t' > 0.1\ GeV^{-2}$. From CT, one expects the nuclear attenuation for the $q\bar{q}$ pair propagating through the nucleus, before it evolves into a full-size vector meson, to be determined by the pair transverse size, inversely proportional to $\sqrt{(Q^2 + m_V^2)}$, where m_V is the meson mass. The results, shown in figure 7b, have the predicted behavior of increasing transparency with Q^2.

Similarly, the nuclear transparency for real photoproduction ($Q^2 = 0$) of J/ψ is predicted to be identical to the transparency in electroproduction of the ρ^0 at $Q^2 \approx m_{J/\psi}^2 - m_\rho^2$, as the attenuation scales approximately with $(Q^2 + m_V^2)$.[32] The NMC result[33] for the ratio of the transparencies for J/ψ production, extrapolated to $Q^2 = 0$, from Sn and C targets is $T_{\mathrm{Sn}}/T_{\mathrm{C}} = 0.7 \pm 0.1$, consistent with the E665 result on ρ^0 production at $Q^2 = 7$ GeV^2 from Pb and C, $T_{\mathrm{Pb}}/T_{\mathrm{C}} = 0.6 \pm 0.25$.

Color Transparency can also predict the transparency for coherent vector-meson production, where a similar scaling law is expected to apply for the magnitude of the final-state interactions. Table 1 compares the predictions, in the limit of vanishing final-state interactions, for the ratio of transparencies for two nuclear targets, to the real-photoproduction data for J/ψ of E691[34] at Fermilab, and of NMC, again extrapolated to the real photoproduction limit.[33] The data lie $\sim 30\%$ below the prediction in all three cases, presumably due to final-state interactions. This deviation is of the same magnitude as the one seen for the highest-Q^2 bin of the E665 coherent-ρ^0 production, again consistent with the scaling law for final-state interactions expected from CT.

Other Fermilab experiments, including Experiment E791, which uses pions incident on heavy targets, are in the process of studying color transparency. New results on this effect are expected shortly.

Ratio	Prediction	J/ψ Measurement (Expt.)
T_{Sn}/T_C	2.76	2.15 ± 0.10 (NMC)
T_{Fe}/T_{Be}	2.82	2.28 ± 0.32 (E691)
T_{Pb}/T_{Be}	4.79	3.47 ± 0.50 (E691)

Table 1: Comparison of the prediction for the transparency, in the absence of final-state interactions, for real coherent photoproduction of ρ^0 and J/ψ to the measurements of the E691 and NMC experiments

6 Insight into QCD from Meson Studies

In this section we highlight two lesser known studies of QCD which focus on mesons. In the first case, new results on the Kaon form factor are presented. Although the Kaon form factor cannot be predicted from first principles, various QCD-inspired models can be tested. In the second case, new results of charmonium studies are presented. Charmonium is an ideal system for testing the form of the QCD potential because it is heavy enough to be calculable while light enough to obtain feasible event rates. Both cases can provide valuable insights into QCD from an unusual vantage-point.

6.1 Form Factors in the Kaon System

Although the primary goal of the Fermilab kaon program is CP violation studies, experiment E799 also has engaged in extensive studies of rare kaon decay branching ratios. Among these are radiative decays, which are interesting because they are sensitive to the non-perturbative (long-distance) aspects of the strong interactions. Understanding the long distance contributions is interesting as a tool for comparing non-perturbative models as well as an input into rare decay measurements used for extracting standard model parameters.

The differential decay rate for $K_L \to \ell^+\ell^-\gamma$ with respect to the $\ell^+\ell^-$ invariant mass squared can be calculated from QED, if one introduces a form factor for the $K\gamma\gamma^*$ vertex. The form factor has been parameterized with only one free parameter, α_K, by the model of Bergstrom, *et al.*,[35] as a combination of the vector meson dominance and vector-vector transition models. In the vector dominance model of Quigg, *et al.*,,[36] $\alpha_K = 0$. E799 has measured[37] $\Gamma(K_L \rightarrow \mu + \mu^- \gamma)/(K_L \rightarrow \gamma\gamma) = (5.66 \pm 0.59) \times 10^{-4}$, which is equivalent to $\alpha_K = -0.028^{+0.115}_{-0.111}$. This is the first measurement of α_k in the muon mode. It is in agreement with the Quigg model and appears to indicate that vector-meson-dominance contributions are small. The result is also within 2σ of world average,[38] which are from electron-mode results: $\alpha_K = -0.28 \pm 0.08$.

E799 is in the process of studying double Dalitz decays of the form $K_L \rightarrow \ell^+\ell^-\ell^+\ell^-$. The preliminary result on $K_L \rightarrow e^+e^-e^+e^-$, with 27 events, represents the largest sample in this mode reconstructed to date. The measured branching ratio,[39] $(3.96 \pm 0.78(stat) \pm 0.32(sys)) \times 10^{-8}$, is in good agreement with the measurements from AGS-845,[40] $(3.04 \pm 1.24 \pm 0.26) \times 10^{-8}$, and NA31, $(4 \pm 3) \times 10^{-8}$.[41] The branching ratio for $K_L \rightarrow \mu^+\mu^-e^+e^-$, which is predicted[42] to be 0.8×10^{-9}, is under study. In the future, when large data samples become available, these decays can be used for further form factor studies.

6.2 The QCD Potential from Charmonium

The properties of charmonium are particularly interesting because charmonium can be regarded as the "positronium" of QCD, allowing investigation of the form of the potential between quark and antiquark. In the last series of runs, E760 took $p\overline{p}$ data using an apparatus located in the antiproton accumulator ring. This experiment made the first observation of the long-sought $^1P_1$ charmonium state.[43] The η_c and η_c' are presently under study. As shown in table 2, the new FNAL results provide precise measurements for the masses and widths of the χ and ψ states.[44]

As an example of the sensitivity of this data, consider the separation between the center of gravity of the ^3P-states and the ^1P state. This separation is due to the hyperfine interaction alone and is expected to be small for states with L $\neq$ 0. Both the sign and the magnitude of this difference have been the subject of much theoretical work. Recent calculations[46] predict a difference, $M(c.o.g.) - M(^1P_1)$, of $-0.7 \pm 0.2 MeV/c^2$ which is impressively close to the measured separation of $-0.9 \pm 0.3 MeV/c^2$ As can be seen, both experiment and theory have a remarkable ability to make precision tests of QCD.

E835 will take data in the next fixed target run to continue these charmonium

Resonance	Mass (MeV)	Width (keV)
J/ψ (E760)	3096.88 $\pm 0.01 \pm 0.06$	99 $\pm 12 \pm 6$
J/ψ (Old Value)	3096.93 ± 0.09	86 ± 6
χ_1 (E760)	3510.53 $\pm 0.04 \pm 0.12$	880 $\pm 110 \pm 80$
χ_1 (Old Value)	3510.6 ± 0.5	< 1300
χ_2 (E760)	3556.15 $\pm 0.07 \pm 0.12$	1980 $\pm 170 \pm 70$
χ_2 (Old Value)	3556.3 ± 0.4	2600 $^{+1200}_{-900}$
$\chi_2 - \chi_1$ (E760)	45.62 $\pm 0.08 \pm 0.12$	
ψ' (E760)	3686.0 (input)	312 $\pm 36 \pm 12$
ψ' (Old Value)	3686.0 ± 0.1	243 ± 43
$^1P_1$ (E760)	3526.2 ± 0.3	< 1100
χ c.o.g (E760)	3525.3 ± 0.1	

Table 2: Summary of the results on Charmonium resonance parameters from E760 compared to previous results.

studies.[45] This experiment plans to measure the mass and total width of the η_c' and its decay to $\gamma\gamma$, to improve the measurements of the η_c parameters and to continue studies of the $^1P_1$ state. It also will focus on a search for another set of missing charmonium mesons: the $^{3,1}D_2$ states.

7 Conclusions

In the past, Fermilab has supported a diverse program of fixed target physics. Within this program, many questions of interest to both the nuclear and high energy communities have been addressed. This tradition will continue in the future as new facilities such as the Main Injector and extraction from the new Linac come on line.

Thanks

Many people contributed to this review, particularly Guang Fang, Debbie Harris, Donna Naples, Stephen Pordes and Panagiotis Spentzouris. The Fermilab Program is supported by the U.S. Department of Energy. The National Science Foundation contributes funding for many of the experiments.

References

[1] The fixed target program published forty-four papers during this period in *Physical Review D, Physical Review Letters, Physics Letters B,* and *Zeitshcrift für Physik* alone. A list, compiled by Peter Garbincius, of all FNAL publications during the last fiscal year which appeared in these four journals is available from Peter Garbincius (garbincius@fnalv.fnal.gov), MS 122, PO Box 500, Batavia, Il 60510.

[2] The Fermilab Workbook is available through Fermilab Program Planning, PO Box 500, Batavia, Il 60510.

[3] Alverson *et al.*, Phys. Rev. D48 (1993) 5.

[4] Frisch, *et al.*, Phys. Rev. D27 (1983) 1001.

[5] Luo, *et al.*, Phys. Lett. B279 (1992) 377.

[6] Adams, *et al.*, Phys. Lett. 287 (1992) 375. Carroll, "Observation of Nuclear Shadowing at low x in Carbon, Calcium, and Lead," Thesis, University of Illinois, Urbana (1994).

[7] Caldwell, *et al.*, Phys. Rev. Lett. 42 (1979) 553.

[8] Spentzouris, *et al.*, Fermilab-Conf-94-220-E (1994), to be published in the proceedings of the Intersections of Particle and Nuclear Physics, St. Petersburg, FL, 31 May - 6 June, (1994). Paper to be submitted to Phys. Rev. Lett.

[9] Amaudruz, *et al.*, Phys. Rev. Lett. 66 (1991) 2712.

[10] Badelek, *et al.* , Phys. Rev. D50 (1994) 4.

[11] Meltnitchouk, *et al.* , Phys. Rev. D47 (1993) 3783.

[12] Alde, *et al.* , Phys. Rev. Lett. 64 (1990) 2479.

[13] Drell, *et al.*, Phys. Rev. D1 (1970) 2402.

[14] Amaudruz, *et al.*, Z. Phys. C51 (1991) 387.

[15] Corcoran, *et al.*, Phys. Rev. Lett. 70 (1993) 143; T. Fields, Nucl. Phys. A544 (1992) 565c; Corcoran, *et al.* Phys. Lett. B259 (1991) 209.

[16] Naples, *et al.*, Phys. Rev. Lett. 72 (1994) 2341.

[17] Kartik, *et al.* , Phys. Rev. D41 (1990) 1.

[18] Alde, *et al.* , Phys. Rev. Lett., 66 (1991) 133.

[19] Kowitt, *et al.* , Phys. Rev. Lett. 72 (1994) 1318.

[20] Using lower E experiments to suggest Higher Twist as cause.

[21] Alves, *et al.* , Phys. Rev. Lett. 70 (1993) 722.

[22] Leitch, *et al.* , Phys. Rev. Lett. 72 (1994) 2542.

[23] Kopeliovich, *et al.* , Sov. J. Nucl. Phys. 42 (1985) 504. See also Benesh, Qiu and Vary, Phys. Rev. C50 (1994) 1015, and Ralston and Jain, preprint KANSAS 94-5-22 for competing models.

[24] Cobbaert, *et al.* , Phys. Lett B207 (1987) 456; Duffy, *et al.* , Phys. Rev. Lett. 55 (1985) 1816.

[25] Alde, *et al.* , Phys. Rev. Lett. 66 (1991) 2285.

[26] Matsui, *et al.* , Phys. Lett. B178 (1978) 416.

[27] Albrow, *et al.* , FERMILAB-FN-622 (1994).

[28] Perkins, Phil. Mag. 46 (1955) 1146.

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

[30] Makins, *et al.*, Phys. Rev. Lett. 72 (1994) 1986.

[31] Adams, *et al.*, FERMILAB-PUB-94-233-E (1994); submitted to Phys. Rev. Lett.

[32] Nemchik, *et al.*, KFA-IKP(Th)-1994-20; submitted to the proceedings of The Workshop on CEBAF at Higher Energies, CEBAFR, 14-16 April 1994.

[33] Mariotti, Proceedings of the Joint International Lepton-Photon Symposium and Europhysics Conference on High-Energy Physics, Geneva, 25 July - 1 August (1991).

[34] Sokoloff, *et al.*,Phys. Rev. Lett. 57 (1986) 3003.

[35] Bergstrom, *et al.*, Phys. Lett. 131B (1983) 229.

[36] Quigg, *et al.*, UCRL-18487 (1968).

[37] Spencer, *et al.*, submitted to Phys. Rev. Lett., Jan. 1995.

[38] Particle Data Group, Montanet, *et al.*, Phys. Rev. D50 (1994) 1173.

[39] Gu, *et al.*,Phys. Rev. Lett. (1994) 3000.

[40] Vagins, *et al.*, YAUG-A-93/1 (1993).

[41] Barr, *et al.*, Phys. Lett. 98 (1991) 1355.

[42] Miyazaki, *et al.*, Phys. Rev. D8 (1973) 2051.

[43] Armstrong, *et al.*, Phys. Rev. Lett., 69 (1992) 2337.

[44] Hasen, *et al.*, Nucl. Phys. A558 (1993) 53. Pordes, *et al.*, Fermilab-Conf-93-383 (1993), submitted to the proceedings of The Advanced Studies Conference on Heavy Flavours, Pavia, 3-7 September (1993).

[45] Armstrong, *et al.*, Fermilab-Proposal-P-835 (1993).

[46] Halzen, *et al.* Phys. Lett. B, 283 (1992) 379.