Energy Loss of Fast Quarks in Nuclei

M. B. Johnson,[1] B. Z. Kopeliovich,[2] I. K. Potashnikova,[2] P. L. McGaughey,[1] J. M. Moss,[1] J. C. Peng,[1] G. T. Garvey,[1] M. J. Leitch,[1] M. R. Adams,[3] D. M. Alde,[1] H. W. Baer,[1,6,*] M. L. Barlett,[4] C. N. Brown,[5] W. E. Cooper,[5] T. A. Carey,[1] G. Danner,[1,6] G. W. Hoffmann,[4] Y. B. Hsiung,[5] D. M. Kaplan,[7,†] A. Klein,[1,‡] C. Lee,[1] J. W. Lillberg,[1] R. L. McCarthy,[1] C. S. Mishra,[1,§] and M. J. Wang[6,¶]

(FNAL E772 Collaboration)

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2]*Max-Plank-Institut für Kernphysik, 69029 Heidelberg, Germany*
[3]*University of Illinois, Chicago, Illinois 60510*
[4]*University of Texas, Austin, Texas 78712*
[5]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[6]*Case Western Reserve University, Cleveland, Ohio 44106*
[7]*Northern Illinois University, DeKalb, Illinois 60115*
[8]*State University of New York at Stony Brook, Stony Brook, New York 11794*

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We report an analysis of the nuclear dependence of the yield of Drell-Yan dimuons from the 800 GeV/c proton bombardment of ^{2}H, C, Ca, Fe, and W targets. Employing a new formulation of the Drell-Yan process in the rest frame of the nucleus, this analysis examines the effect of initial-state energy loss and shadowing on the nuclear-dependence ratios versus the incident proton's momentum fraction and dimuon effective mass. The resulting energy loss per unit path length is $-dE/dz = 2.32 \pm 0.52 \pm 0.5$ GeV/fm. This is the first observation of a nonzero energy loss of partons traveling in a nuclear environment.

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For many years it has been suggested that quark energy loss might give rise to a nuclear dependence [1–4] of the cross section of Drell-Yan (DY) [5] production. When a proton enters a nucleus the first (soft) inelastic collision liberates a quark, which then loses energy via hadronization (due to confinement) and interaction in the nuclear medium. A lepton pair created from a subsequent interaction then has reduced energy compared with the DY process on a free nucleon. The goal of the present analysis is to search for this effect in the nuclear dependence of the DY process.

Fermilab E772 made a precise measurement of the nuclear dependence of the DY process using 800 GeV/c protons. The experimental details of E772 have been described previously [6–8]. Briefly we indicate those germane to the present discussion. Muon pairs were recorded from targets of ^{2}H, C, Ca, Fe, and W, in the mass range $M \geq 4$ GeV/c^2. Excluding the Υ resonance region, $9 \leq M \leq 11$ GeV/c^2, we reconstruct 2.5×10^5 DY dimuons. The spectrometer acceptance for this subset of the data had transverse momentum coverage out to 3.5 GeV/c. Since E772 was designed to make a precision comparison of the yields of dimuons from the heavy targets to that from ^{2}H, relative target-to-target normalization errors were kept to $\leq$2%.

The parton model description of high-energy processes is reference-frame dependent. Because energy loss is most commonly described in the rest frame of the nucleus, it is best to adopt this frame for the description of the DY process as well. In the target rest frame the DY process for proton-nucleon collisions is treated as bremsstrahlung [9]: An incident quark with momentum fraction x_q emits a virtual photon that carries a fraction $x_1^q = x_1/x_q$ of the quark momentum. The inclusive cross section for the production of lepton pairs with momentum fraction x_1 is given by

$$\frac{d\sigma_{\rm DY}^{pN}(M^2)}{dx_1} = \int_{x_1}^{1} dx_q\, F_q^p(x_q)\, \frac{d\sigma_{\rm DY}^{qN}(x_1^q, M^2)}{dx_1^q}\,, \qquad (1)$$

where $F_q^p(x_q)$ is the quark distribution function of the proton and $d\sigma_{\rm DY}^{qN}(x_1^q, M^2)/dx_1^q$ is the quark-nucleon differential cross section for lepton-pair production [9–11].

Nuclear effects modify this in two important ways. The first is the possibility of quark energy loss in the nuclear medium—the main subject of this manuscript. The second is shadowing, a phenomenon well known from nuclear dependence studies [12] of a closely related process, deeply inelastic lepton scattering (DIS). Energy loss and shadowing are shown pictorially in Fig. 1. Since the two processes produce apparently similar effects in proton-nucleus collisions, it is necessary to adopt a consistent analysis where both are considered on the same footing. The framework for accomplishing this is detailed in the following paragraphs, first for energy loss, then for shadowing.

Consider a proton entering a nucleus (Fig. 1). The first inelastic interaction, at point z_1, removes the coherence among the soft projectile partons, which then move apart losing energy as they would in the vacuum. A quark continues to propagate arriving at point z_2, where a DY

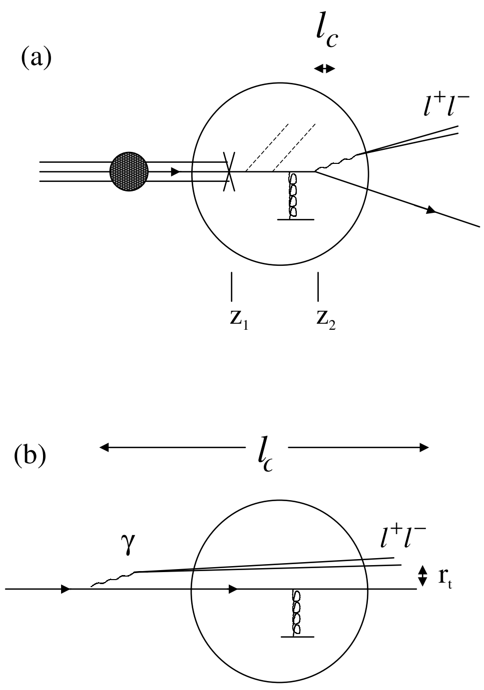

FIG. 1. Schematic representation, in the nuclear rest frame, of two processes producing a nuclear dependence of the DY cross section. (a) Energy loss. a proton entering a nucleus undergoes its first inelastic collision at point z_1, liberating a quark. The quark propagates, losing energy to hadronization (dashed lines), to point z_2, where it undergoes a hard (DY) interaction, producing a virtual photon that decays into a lepton pair. (b): Shadowing. a fast quark undergoes a virtual fluctuation into a photon and quark. The quark propagates into the nucleus, liberating the fluctuation. Since the coherence length is large, the entire nucleus participates as a single entity.

interaction takes place with diminished energy $\tilde{x}_q E_p = x_q E_p - \Delta E$, where ΔE is the energy loss to be measured and E_p is the energy of the proton beam. Correspondingly, one has $\tilde{x}_1^q = x_1/(x_q - \Delta E/E_p)$. Assuming that the rate of energy loss is constant, $\Delta E \propto L$, where $L = z_2 - z_1$. Because of energy loss, the ratio of p-A to p-N cross sections versus x_1 is

$$R_{A/N}^{\Delta E}(x_1, M^2) = \frac{\int_{x_1+\Delta E/E_p}^{1} dx_q\, F_q^p(x_q)\, \frac{d\sigma_{\rm DY}^{qN}(\tilde{x}_1^q, M^2)}{d\tilde{x}_1^q}}{\frac{d\sigma_{\rm DY}^{pN}(M^2)}{dx_1}}. \quad (2)$$

A distribution of energy losses occurs. We have calculated this distribution using Glauber theory. In the calculation, the relatively small probability for inelastic collisions of the incident proton leads to a significant reduction of $\langle L \rangle = \langle z_2 - z_1 \rangle$ with respect to the mean path length L_0. For example, for tungsten we find $\langle L \rangle = 2.4$ fm, whereas for a uniform sphere $L_0 = 3R_0 A^{1/3}/4 = 4.9$ fm.

Shadowing is the well-known reduction of the cross section per nucleon, observed experimentally in DIS [12] for x less than about 0.07. In proton-nucleus DY production a reduction in the cross section per nucleon at small x is seen at the highest available proton energy, 800 GeV/c [6,13,14]. It is, however, an open question whether this is shadowing, energy loss, or both. The framework for analyzing shadowing in the rest frame of the nucleus, given below, is crucial to resolving this puzzle [9,11,15,16].

In both DIS and DY shadowing occurs when the nuclear coherence length grows larger than the distance between nucleons, ≈2 fm. The coherence length is a measure of the lifetime of the fluctuation of a quark into a virtual photon and residual quark. For the DY process, the mean nuclear coherence length is given [11,17] by

$$l_c = \left\langle \frac{2E_q x_1^q (1 - x_1^q)}{(1 - x_1^q) M^2 + (x_1^q m_q)^2 + k_T^2} \right\rangle, \quad (3)$$

where $E_q = x_q E_p$ and m_q are the energy and mass of the projectile quark which radiates the virtual photon. The resulting lepton pair has an effective mass M, a transverse momentum k_T, and carries a fraction x_1^q of the initial momentum of the quark. The mean coherence length for the kinematic conditions of E772 has been evaluated in Ref. [17] by integrating over x_1^q and k_T. This is similar to a previous very successful treatment of shadowing in DIS [16]. The result is shown versus x_1 in Fig. 2 for various fixed values of x_2. The coherence length is nearly independent of M^2 at fixed x_2, but it vanishes at $x_1 \to 1$, violating factorization. We note that the values of l_c given by Eq. (3) are significantly smaller than the commonly cited $l_c \approx 1/2m_N x_2$ (see discussion in [16]).

In the weak shadowing approximation [18],

$$R_{A/N}^{\rm shad}(x_1, M^2) \approx 1 - \frac{1}{4}\, \sigma_{\rm eff} \langle T_A \rangle F_A^2(q_c). \quad (4)$$

This expression is accurate for the whole kinematic range of E772. Here, $\langle T_A \rangle$ is the mean value of the nuclear thickness function, $q_c = 1/l_c$, and

$$F_A^2(q_c) = \frac{1}{A\langle T_A \rangle} \int d^2b \left| \int_{-\infty}^{\infty} dz\, e^{iq_c z} \rho_A(b, z) \right|^2 \quad (5)$$

is the longitudinal nuclear form factor [19], where $\rho_A(b, z)$ is the nuclear density. The effective cross section is defined as [9] $\sigma_{\rm eff} = \langle \sigma^2(x_1^q r_T) \rangle / \langle \sigma(x_1^q r_T) \rangle$, where $\sigma(x_1^q r_T)$ is the

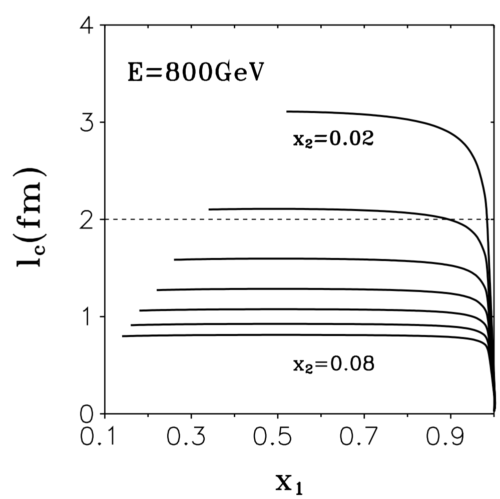

FIG. 2. The mean coherence length as a function of x_1 at fixed values of $x_2 = 0.02, 0.03, \ldots, 0.08$, evaluated for the kinematic conditions of E772.

$q\bar{q}$ dipole cross section [20], and r_T is the transverse separation between the virtual photon and the quark (Fig. 1); $\sigma_{\rm eff}$ is in the range 3.5–5.5 mb for E772 [17].

Energy loss and shadowing provide mechanisms for nuclear suppression in the DY process that are effective in different regimes. If l_c is short, no shadowing occurs [$F_A^2(q_c) \rightarrow 0$ in Eq. (4)], but energy loss can reduce the yield of DY pairs. In the opposite limit, $l_c \gg R_A$, shadowing achieves its full strength [$F_A^2(q_c) \rightarrow 1$]. Here, initial state interactions do not affect the DY cross section, except for transverse momentum broadening [1,21]. Our ansatz is that the transition between these limiting regimes is controlled by $F_A^2(q_c)$. The only expression which is linear in $F_A^2(q_c)$ and has the right limits at $q_c \rightarrow 0$ and $q_c \rightarrow \infty$ reads

$$R_{A/N}(x_1, M^2) = (R_{A/N}^{\Delta E}(x_1) - 1)[1 - F_A^2(q_c)] + R_{A/N}^{\rm shad}(x_1, M^2). \quad (6)$$

Given the above framework, the energy-loss analysis was accomplished as follows. The quark-nucleon cross section in Eqs. (1) and (2) was assumed to have the form

$$\frac{d\sigma_{\rm DY}^{qN}(M^2)}{dx_1^q} = K(M^2) \times (1 - x_1^q)^m, \quad (7)$$

where K and m were determined from a fit to the $p + {}^2$H data with Eq. (1). It was found that m did not change significantly with mass bin; thus one slope parameter was sufficient to characterize the full range of the $p + {}^2$H data. Because the mass-dependent normalization (K) of the $q - N$ cross section occurs in both the numerator and the denominator of Eq. (2), the energy loss term in Eq. (6) becomes independent of mass.

Thus, in this formulation, energy loss and shadowing have different kinematic dependence. Therefore it is essential to analyze nuclear-dependence ratios that are binned in dilepton mass. This allows l_c to be evaluated for each bin in mass and x_1. A two-parameter fit using Eq. (6) was applied to the heavy-target cross section ratios for C, Ca, Fe, and W; the parameters were $-dE/dz$ and an overall normalization factor, C. The systematic normalization error, $\pm 1\%$, was treated as an additional statistical error. The fit yields a substantial energy loss, $-dE/dz = 2.32 \pm 0.52 \pm 0.5$ GeV/fm (statistical and systematic), with $C = 1.010 \pm 0.006$, consistent with the E772 normalization uncertainty [6]. The systematic error associated with $-dE/dz$ arises from uncertainties in cut parameters, the range of applicability of Eq. (7), and the shadowing analysis (discussed below). Fits to W/^{2}H and to C/^{2}H in four mass intervals are shown by solid curves in Figs. 3 and 4.

Our analysis depends critically on having separated the effects for energy loss and shadowing. Dashed curves show the net shadowing contribution. Nuclear suppression of the DY cross section for tungsten is mainly due to energy loss. On the other hand, energy loss effects for carbon are small, the main contribution to nuclear suppression arising from shadowing. This difference between the A and M dependence of energy loss and shadowing permits the two effects to be disentangled.

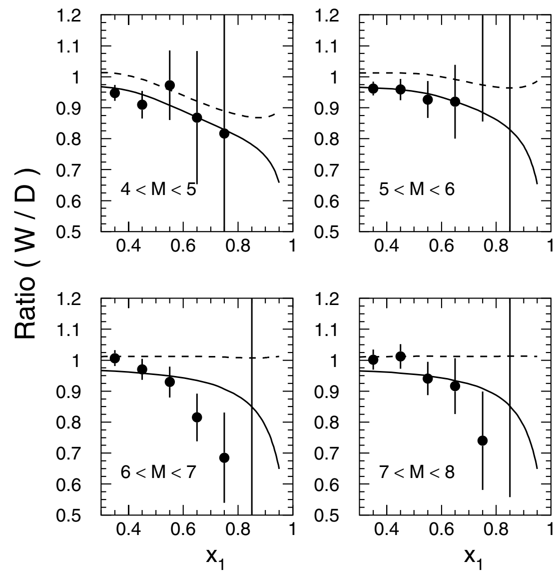

FIG. 3. Ratio of tungsten-to-deuterium Drell-Yan yields per nucleon versus x_1 for different intervals of M. Dashed curves correspond to net shadowing, solid curves show the full effect, including shadowing and energy loss.

We have checked the sensitivity of the results by the following tests: (i) eliminated shadowing in Eq. (6) by fixing $F_A^2 = 0$ ($-dE/dz = 2.24 \pm 0.53$); (ii) doubled the shadowing corrections, $1 - R_{A/D}^{\rm shad} \Rightarrow 2(1 - R_{A/D}^{\rm shad})$ ($-dE/dz = 2.64 \pm 0.53$); (iii) mixed energy loss and shadowing effects differently from Eq. (6), $R_{A/D} = R_{A/D}^{\Delta E} \times R_{A/D}^{\rm shad}$ [$-dE/dz = 2.35 \pm 0.53$ (this is the E866 procedure [13])]; (iv) selected for analysis only data with small $x_2 < x_2^{\rm max}$ (within error bars $-dE/dz$ is constant

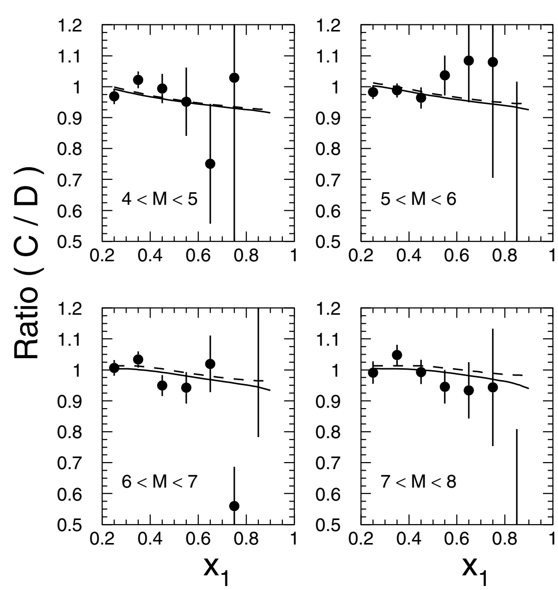

FIG. 4. Ratio of carbon to deuterium. Same labeling as Fig. 3.

for $0.3 \geq x_2^{\max} \geq 0.12$). Thus $-dE/dz$ is subject to only a small variation within the error bars. These modifications all lead to a significant growth of χ^2.

Recently the E866 Collaboration [13] analyzed DY nuclear-dependence data from targets of Be, Fe, and Cu. The E866 data set, 1.3×10^5 muon pairs in the range $4 \leq M \leq 8.5$ GeV/c^2, was more concentrated at low x_2 than the present one. E866 subtracted a phenomenological shadowing contribution, yielding new "shadowing-corrected" nuclear-dependence ratios. Shadowing was calculated by employing the results of the global phenomenological analysis of DIS and DY data by Eskola *et al.* (EKR) [22]. The EKR analysis itself included the DY data from E772, with the presumption that the low-x_2 nuclear dependence arose entirely from shadowing. This clearly introduced an inconsistency into the E866 search for energy loss. Considering the critical importance of separating shadowing and energy loss, which, at 800 GeV, can be achieved only via mass-binned nuclear-dependence ratios, it is not surprising that the E866 analysis missed the effect.

The value of dE/dz determined here is not very different from that found many years ago by Gavin and Milana [4] (GM) using the mass-averaged W-D ratio from E772. In our model, shadowing is a very small effect for the mass-averaged W data, so the GM analysis, which ignores shadowing, should not be too far off. The GM value, $dE/dz \approx 1.5$ GeV/fm, should be increased by a factor of ≈ 2 to account for the reduction of the effective nuclear path length, discussed earlier in connection with Eq. (2). Unlike the GM model, our analysis presumes a constant dE/dz, yielding an energy loss that is independent of laboratory beam energy (see Ref. [23]).

Much theoretical attention has been devoted in recent years to the elucidation of the QCD analog of the famous Landau-Pomeranchuk-Migdal [24] effect (see Ref. [25]). Gluon radiation induced when a quark penetrates nuclear matter leads to additional energy loss proportional to the square of the path length traversed. By using the measured transverse-momentum broadening [7] this can be estimated for tungsten as rising to a maximum value, $-(dE/dz)_{\rm rad} \approx 0.2$ GeV/fm. Thus for cold matter, radiative energy loss is not a large contribution to the total.

In light of the present finding that quark energy loss is significant, one should reexamine the role of energy loss in the nuclear dependence of J/ψ production (see Ref. [26]). It was demonstrated many years ago [3,27] that the x_F dependence of J/ψ suppression at energies 150–300 GeV could be well described by energy loss, with $-dE/dz \approx 3$–4 GeV/fm. The larger value for a projectile gluon is consistent with an enhancement due to the Casimir factor, 9/4.

In summary, we have made the first determination of quark energy loss using an analysis that takes into account nuclear shadowing. The result, $-dE/dz = 2.32 \pm 0.52 \pm 0.5$ GeV/fm, is in approximate accord with the theoretical expectation that energy loss should be at least the order of the string tension, $\kappa \approx 1$ GeV/fm. At 800 GeV, mass binning of the nuclear dependence ratios is crucial to the separation of energy loss and shadowing effects. It would be very desirable to have precise measurements of the nuclear dependence of DY production at lower beam energies (100–300 GeV), where shadowing disappears and energy loss would provide the dominant nuclear dependence.

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*Deceased.

†Present address: Illinois Institute of Technology, Chicago, Illinois 60616.

‡Present address: Old Dominion University, Norfolk, Virginia 23529.

§Present address: Fermi National Accelerator Laboratory, Batavia, Illinois 60510.

¶Present address: Institute of Physics, Academia Sinica, Taiwan 11529.

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