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Energy loss of fast quarks in nuclei

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We report an analysis of the nuclear dependence of the yield of Drell-Yan (DY) dimuons from the 800 GeV/c proton bombardment of ^2H, C, Ca, Fe, and W targets. A light-cone formulation of the DY process is employed in the rest frame of the nucleus. In this frame, for $x_2 \ll x_1$, DY production appears as bremsstrahlung of a virtual photon followed by decay into dileptons. We treat the two sources of nuclear suppression, energy loss and shadowing, in a consistent formulation. Shadowing, involving no free parameters, is calculated within the light-cone dipole formalism. Initial-state energy loss, the only unknown in the problem, is determined from a fit to the nuclear-dependence ratio versus x_1. With the assumption of constant energy loss per unit path length, we find $-dE/dz = 2.32 \pm 0.52 \pm 0.5$ GeV/fm. This is the first observation of a nonzero energy loss of partons traveling in nuclear environment.

Introduction Quarks should lose energy in traversing nuclear matter – but not very much. A commonly cited estimate is $-dE/dz \approx \kappa$, where $\kappa \approx 1$ GeV/fm is the QCD string tension. Before discussing quark energy loss it is instructive to consider the analogous problem in QED, the energy loss of relativistic electrons passing through solid targets. Fig. 1a is an accurate representation of a real experiment to measure dE/dz. In spite of its conceptual simplicity it was not until 1995 [1] that an accurate measurement of the energy loss in dense matter was made for a highly-relativistic electron beam. The experiment confirmed a prediction made forty years earlier, now termed the Landau-Pomeranchuk-Migdal (LPM) effect [2,3]. In QED the LPM effect is a suppression of bremsstrahlung caused by a quantum-mechanical interference between different scattering centers. In QCD there is an interesting analogue to the LPM effect [4] to which much theoretical attention has been devoted in recent years. We will return to this point later.

Since, unlike electrons and photons, neither quarks nor gluons travel long distances, the QCD *gedanken* energy-loss experiment needs an alternative realization. A feasible conceptual picture for measurement of quark energy loss is given in Fig. 1b. A quark from an incoming hadron at the left loses energy in a nucleus, then undergoes the Drell-Yan (DY) process [5] producing a lepton pair from the electromagnetic annihilation of the beam quark with a target antiquark, $q + \bar{q} \rightarrow \gamma^* \rightarrow l^+l^-$. Measurement of the four momenta of the leptons allows reconstruction of the momenta of the colliding quark and antiquark. But how much energy did the quark have in the first place? That question cannot be answered for a particular collision, but the average effect can be deduced by comparing DY production from a nucleus to that from a nucleon target where there is no energy loss.

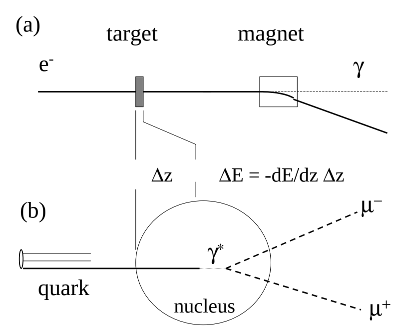

FIG. 1. Schematic measurements of (a) energy loss of a fast electron beam traversing a thin target, and (b) of a fast quark beam losing energy on the front side of a target nucleus. In (b) the energy of the initial quark is reconstructed from the four momenta of the lepton pair created in the final state.

I. SHADOWING AND ENERGY LOSS

The suppression of the cross section for deeply-inelastic lepton scattering (DIS) on heavy nuclear targets at small Bjorken-x is known as nuclear shadowing [6]. It is a well-characterized phenomenon, with onset for $x \leq 0.07$. In the infinite momentum frame, commonly employed in the description of DIS, shadowing can be visualized as the recombination of small-x partons whose longitudinal extent exceeds the internucleon spacing. Viewed in the target rest frame a different (but equivalent) picture of shadowing emerges. Here one focuses on the structure of the photon, and its virtual fluctuations into $q\bar{q}$ states which can interact with the target. Small x corresponds to fluctuations of the virtual photon whose coherence length exceeds the internucleon spacing: they are hence absorbed by more than one nucleon.

Shadowing should also affect hard hadronic processes.

The only experimental evidence to date is a suppression of the DY cross section on heavy targets observed in Fermilab experiments, E772 [7] and E866 [8]. But is this energy loss or shadowing or some combination of the two? Because the two effects can lead to an apparently similar nuclear suppression of the DY cross section, it is necessary to appeal to a consistently formulated description of both effects in order to analyze experimental data. This consistency was not required in previous analyses of DY data for quark energy loss [8,9].

II. DRELL-YAN PROCESS IN THE TARGET REST FRAME

For those used to the usual description of the DY process, where a quark and antiquark collide to produce a virtual photon at rest, the target rest frame (TRF) view [10–12] is downright strange. In the TRF an energetic quark from the incident hadron undergoes continual fluctuations into a virtual photon and a residual quark. The lepton pair results from the decay of the virtual photon when the residual quark interacts with the target. This picture, which is most useful for DY production at small x_2, makes no explicit reference to antiquarks in the target.

The TRF analysis begins with DY production from a nucleon target, ^2H in the case of E772. 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. One then integrates over all such processes that can yield lepton pairs of beam-quark momentum fraction x_1 and invariant mass M. The inclusive cross section is given by

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

where $F_q^p(x_q)$ is the quark distribution function of the proton and $d\sigma_{DY}^{qN}(M^2)/dx_1^q$ is the quark-nucleon differential cross section for lepton-pair production [10,11,13]. A fit to the p-^2H data yields the quark-nucleon cross section unmodified by energy loss or shadowing.

Moving to the description of the DY process on a nuclear target, we consider two limits. In the first, characterized by modest values of x_2, the virtual photon is able to resolve individual nucleons of the nucleus. In the second, at very small values of x_2, in a manner analogous to shadowing in DIS described earlier, the virtual photon is able to resolve only clusters of nucleons, and in the extreme, only the full size of the nucleus. The transition between the two is controlled by the coherence length of the virtual photon [13], a measure of its resolving power. For the DY process it is given by

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

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. [14] by integrating over x_1^q and k_T. Roughly speaking, energy loss is the dominant source of nuclear dependence when $l_c < 2$ fm, the average distance between nucleons in the nucleus. For $l_c > 2$ fm, shadowing predominates.

Two features of the TRF formulation of the DY process, pioneered by Kopeliovich and collaborators [10,12,15] are essential in the quantitative analysis of quark energy loss. First, shadowing may be calculated exactly (within the model assumptions) for both DIS and the DY process. The description for both is connected to the dipole cross section, $\sigma(\rho)$, for the absorption of a $q\bar{q}$ pair of transverse separation ρ. This phenomenology has been utilized extensively for high-energy photon reactions at HERA [16]. The second essential feature afforded by the TRF formulation is the determination of a more realistic path length for the projectile quark traversing the nuclear target. For example for tungsten the mean path length is $\langle L \rangle = 2.4$ fm, whereas for a uniform sphere $L_0 = 3R_0A^{1/3}/4 = 4.9$ fm. This leads to larger values of dE/dz derived from the data since there is a shorter path length in which to lose energy.

III. VACUUM ENERGY LOSS FROM DY NUCLEAR DEPENDENCE

With only one free parameter, the nuclear dependence ratios for C, Ca, Fe, and W were fitted to yield dE/dz. A crucial feature of the fit is that it is performed on the nuclear-dependence ratios binned in both x_1 and M, since energy loss and shadowing have contrasting kinematical features. The fit yields a substantial energy loss, $-dE/dz = 2.32 \pm 0.52 \pm 0.5$ GeV/fm (statistical and systematic errors). Fits to $W/^2H$ in four mass intervals are shown by solid curves in Fig. 2.

Our analysis, formulated in the TRF, differs significantly from previous energy-loss analyses [8,9] (see Ref. [14] for more detail). Among the most important differences is the treatment of shadowing. Fig. 3 shows pure shadowing in the DY process for C, Fe, and W targets as a function of the target momentum fraction x_2. The phenomenology of Ref. [18], based on QCD evolution applied to DIS and DY shadowing data, and employed in the analysis of E866 [8], shows stronger shadowing for W than for C at all values of x_2. However the present analysis shows a very rapid decrease in shadowing for W at larger values of x_2. At $M = 6.5$ GeV (corresponding to the lower-left frame in Fig. 2) the DY process is limited by kinematics to $x_2 \geq 0.028$. Here, shadowing is actually

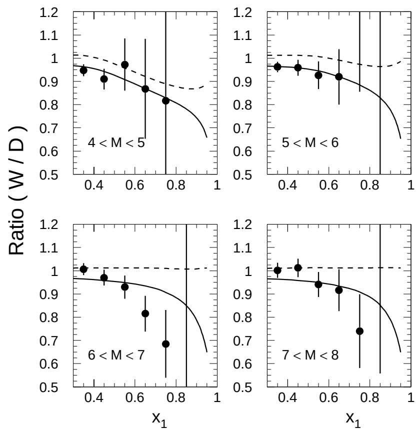

FIG. 2. Ratio of tungsten to deuterium Drell-Yan yields per nucleon versus x_1 for different intervals of M. Dashed curves show the effect of shadowing. The solid curves include both shadowing and energy loss. Note that shadowing predominates for small masses, while the opposite obtains in the larger-mass bins.

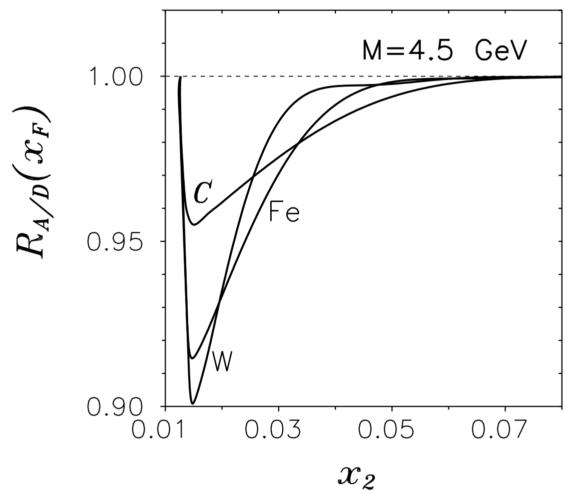

FIG. 3. Pure shadowing in the DY process in the present model as a function of x_2 at M = 4.5 GeV.

a larger effect for C than for W*. Thus, in our analysis, the observed decrease in $R(W/D)$ seen at higher masses in Fig. 2 (lower two frames) is predominantly energy loss. Unfortunately current shadowing data in DIS cannot distinguish between these two competing phenomenologies, where the most dramatic differences are seen for very heavy targets.

The energy loss determined here should be interpreted as the *vacuum energy loss*. It has little to do with the medium itself, but is brought about by the first interaction which triggers hadronization. Induced energy loss is dicussed below.

IV. INDUCED ENERGY LOSS

Much theoretical attention has been devoted in recent years to the QCD analogue of the famous LPM [2] effect [4]. It is now accepted that gluon radiation induced when a quark penetrates nuclear matter leads to additional energy loss proportional to the square of the path length traversed. This should lead to an observable broadening of the transverse momentum distribution given by,

$$-dE/dz = \frac{3}{4}\alpha_s p_t^2. \quad (3)$$

The measured p_t broadening [17] of DY muon pairs from Tungsten is $\Delta p_t^2 = 0.1$ GeV^2 implying a maximum value $-(dE/dz)_{rad} \approx 0.2$ GeV/fm. However, this value should be considered approximate since the derivation of Eq. 3 presumes the applicability of perturbative QCD, and the nuclear p_t broadening effect is clearly very small. Even so it is clear that induced energy loss in cold nuclear matter is not a large part of the total energy loss for 800 GeV/c protons.

The present analysis has relied on the contrasting kinematical behavior of energy loss and shadowing to separate the two effects at 800 GeV/c. It is clear in the present model that cold-matter energy loss, the effect of which scales as $\Delta E/E_p$ (E_p being the laboratory beam energy in the TRF), will make a much smaller contribution in p-A collisions at RHIC energies. There, shadowing will be the dominant nuclear effect. On the other hand at lower beam energies, such as the 120 GeV proton beam available at the Fermilab Main Injector (FMI), shadowing will be kinematically forbidden (for dilepton masses $\geq$ 4 GeV), with energy loss providing an even larger nuclear dependence to the DY process. Thus DY experiments at RHIC and the FMI are clearly very important in the ultimate clarification of these two important manifestations of QCD in bulk nuclear matter.

*To save space, we have not shown the corresponding calcuations at $M = 6.5$ GeV; see Ref. [14]

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