Energy Loss at Large x_F in Nuclear Collisions

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Measurements of the Drell-Yan process and of charmonium and bottomonium production at CERN and Fermilab show a depletion at high Feynman x in large relative to small nuclear targets. We can attribute this depletion to energy loss of initial and final states, provided that the loss is $(dE/dz)_{\text{Drell-Yan}} = \frac{4}{9}(dE/dz)_{\text{charm}} \sim 1.5$ GeV/fm at the highest x_F measured. This small loss is magnified in the differential cross section due to the strong behavior $\sim(1-x)^n$ of the projectile's structure functions at large x.

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Fermilab experiment E772 has measured the A dependence of the Drell-Yan process [1] and J/ψ production [2] in proton-nucleus collisions at the center-of-mass energy $\sqrt{s}=40$ GeV. Data for the ratio $A^{-1}(d\sigma_{pA}/dx_F)/(d\sigma_{pp}/dx_F)$ in Fig. 1 exhibit a strong depletion for J/ψ and Drell-Yan pairs carrying a significant fraction x_F of the projectile momentum. While NA3 at CERN had reported [3] a similar behavior for J/ψ at $\sqrt{s}=20$ GeV, E772's is the first demonstration of such a nuclear x_F dependence in the Drell-Yan process. We propose that energy loss due to multiple parton scattering can consistently explain the high-x_F depletion in the Drell-Yan process and J/ψ production. Depletion arises because of a sensitive dependence of the projectile's structure functions at large x to small energy losses of the initial- and final-state partons.

The fractional loss for the projectile quark needed to explain the Drell-Yan depletion at the highest $x_F \approx 0.64$ is quite small, $(\Delta x_F)_q \approx 0.0125$ in tungsten. For the E772 beam energy $E_{\text{beam}}=800$ GeV, this loss corresponds to an energy degradation per unit distance $dE/dz \sim \Delta x_F E_{\text{beam}}/R \sim 1.5$ GeV/fm ($R \approx 6.5$ fm for tungsten). We will extrapolate this Drell-Yan energy loss to describe the J/ψ depletion at high x_F. Our analysis implies an estimate, perhaps an upper bound, on dE/dz because other nuclear effects can also contribute to the depletion, such as sea-quark structure function modification in the target [1,4,5] in the Drell-Yan process and intrinsic charm in the projectile [6] in J/ψ production. However, evidence for multiple scattering [7] is seen in the $p_\perp$ data of the Drell-Yan process and Υ production data [8]. The possibility that partons lose energy while traversing a nucleus is discussed elsewhere in the literature [9], most recently in the context of jet quenching [10]. Gyulassy, Plümer, and co-workers [10,11] extract a similar $dE/dz \sim 1$–2 GeV/fm for quarks from an analysis of deep inelastic lepton-nucleus scattering data from SLAC and Fermilab E665 [12].

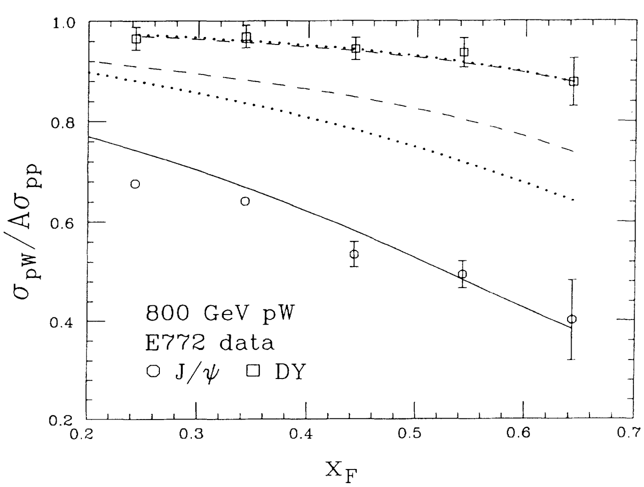

FIG. 1. The depletion from tungsten. The dotted and dashed curves are the expected depletion in J/ψ production arising solely from initial-state scattering using two different sets of structure functions. Also included are the results for the Drell-Yan data (squares). The solid curve compares our calculation for charmonium including final-state energy loss to J/ψ data (circles).

A larger fractional loss $(\Delta x_F)_g \approx \frac{9}{4}(\Delta x_F)_q$ is expected for J/ψ production, where the incident partons are gluons. In fact, the measured high-x_F depletion is substantially stronger in J/ψ production than in the Drell-Yan process, owing in part to this enhanced loss and, as discussed below, to a greater structure function sensitivity for gluons. However, an additional energy loss can arise because the $c\bar{c}$ pair can interact in the final state. At low $p_\perp$, the J/ψ forms predominantly through gluon fusion $g+g \to c\bar{c}+g$, where at least one soft or collinear gluon must be radiated to render the charm pair a color singlet. The proper time needed for this gluon emission ~ 0.1–1 fm is Lorentz dilated at high energy, so that pairs with $x_F > 0.3$ at E772 energy require >8–80 fm to form in the target rest frame. Such a pair will traverse the nucleus as a color octet and lose energy as if it were a gluon. A small fraction $\sim 30\%$ of J/ψ are produced via a color singlet state through χ formation [13,14]. We expect this fraction to suffer roughly half the energy loss of the octet majority. Note that final-state interactions that dissociate the pair must resolve the two quarks and are inhibited by time dilation at large x_F. Most applications of color transparency to J/ψ formation [15] do not address these effects involving color.

The parton energy loss that we describe here, although present in a wide range of nuclear phenomena, is quite small on the scale of high-energy collisions. The high-x_F Drell-Yan process and J/ψ production are nevertheless sensitive to this loss due to their structure function dependence. The Drell-Yan cross section for a pair with mass Q is

$$Q^2\frac{d\sigma}{dx_F dQ^2}=\frac{x_1x_2}{x_1+x_2}\sum_q \sigma^{q\bar{q}}\{q(x_1)\bar{q}(x_2)+q(x_2)\bar{q}(x_1)\}\,, \tag{1}$$

where q and $\bar{q}$ are the quark and antiquark structure functions, $x_F=x_1-x_2$, $x_1x_2=Q^2/s$, and $x_{1,2}$ are the momentum fractions carried by the projectile and target partons. A similar expression for J/ψ production that depends on the gluon structure function g is given below [Eq. (4)]. At high x_F, this rate is acutely sensitive to the projectile structure functions near $x_1=1$:

$$xq(x)\sim(1-x)^3,\;\; x\bar{q}(x)\sim(1-x)^7,\;\; xg(x)\sim(1-x)^5\,. \tag{2}$$

If a fraction of the incoming or outgoing energy is lost due to initial- or final-state interactions, then the measured $x_F\sim x_1$ is smaller than the initial x_1. Consequently, hA collisions sample the parton distribution at a larger x_1 where the structure functions are smaller than those in hN interactions at the same x_F. Observe that J/ψ production through gluon fusion is more sensitive to this effect than the Drell-Yan process.

We expect open charm and J/ψ production to display essentially the same high-x_F depletion. In addition, we expect high-x_F direct photon production [16] to be sensitive to energy loss through the parton density dependence in Compton scattering and annihilation processes, although such effects have not been resolved in the present data. Analogously, deep-inelastic scattering data can reflect the energy loss of the quark or antiquark jet of energy ν in the A dependence of the leading hadrons at high $z=E_{\rm hadron}/\nu$, due to the $\mathcal{D}\sim(1-z)^n$ falloff of the fragmentation functions near $z=1$. However, we estimate the effect on $\mathcal{D}_A/\mathcal{D}_p$ to be within 5% for the kinematics probed by most current experiments. Indications [12] of energy loss at the lowest ν and highest $z\gtrsim0.4$ are discussed in Refs. [10,11].

To explore the effect of energy loss in the Drell-Yan production, we determine the cross section Eq. (1) at $x_F=x_1-x_2-\Delta x$, where Δx is the average loss of the projectile parton in a nuclear collision. This approximation is reasonable provided these losses are small. We extract the average loss for the quark, Δx_q, needed to describe the Drell-Yan data in tungsten at $x_F=0.64$, and fix the A and parton-variable dependence to confront the other data. Motivated by the QCD analysis of Sterman and co-workers [16–18], we take

$$\Delta x_i=\kappa x_i C_i(Q_0/Q)^n A^{1/3}\,, \tag{3}$$

where $C_g=3$ for gluons, $C_q=4/3$ for quarks, and the Drell-Yan data imply $\kappa\approx0.003$ at $Q\approx Q_0\equiv4$ GeV. Energy loss in QCD is a higher twist effect. Although the higher twist analysis of the Drell-Yan process in Ref. [17] does not address energy loss *per se*, we infer the qualitative form of (3) by analogy to the discussion of the transverse spin asymmetry in direct photon production in Ref. [16]. There, the leading twist-3 contribution increases with increasing x_F due to a dependence on the x derivative of a higher twist parton distribution. We expect a similar dependence in the Drell-Yan process, and simulate the corresponding increase by the schematic linear x dependence in (3). Generally, Δx must vanish as $x\rightarrow0$, since a projectile parton near $x_i=0$ carries none of the projectile's energy and has nothing to lose. Furthermore, one expects the leading contribution to the unpolarized Drell-Yan cross section to be twist 4, so that $\Delta x\propto Q^{-2}$ for large Q, i.e., $n=2$. However, corrections to the cross section from (3) will be large for J/ψ production, perhaps signifying a breakdown of the Q^{-1} expansion. We also consider the possibility that Δx is independent of Q, corresponding to $n=0$.

One can interpret (3) as follows: Suppose that the projectile hadron h suffers $n_{hN}\propto A^{1/3}$ soft, inelastic hadron-nucleon subcollisions on its way to a hard interaction involving the parton i from h. The average loss $\Delta x_i=E_h^{-1}\Delta E_i$ is roughly $\Delta x_i\approx n_{hN}\langle P(ij|hN)\delta x_{ij}\rangle$, where $P(ij|hN)$ is the probability that i can strike a target parton j in a hN subcollision, δx_{ij} is the loss from the ij interaction, and $\langle\cdots\rangle$ represents an average over the parton distribution in N. Partons lose energy through soft gluon interactions, and the linear form (3) is reminiscent of the QED Bethe-Heitler result for relativistic electrons (see, however, the penultimate paragraph). The probability $P(ij|hN)\sim\sigma_{ij}/\sigma_{hN}$ is determined by the parton cross section σ_{ij} and depends on poorly known parton distributions at soft scales. One can argue that the transverse wavelength $\sim Q^{-1}$ of the projectile parton determines σ_{ij}, so that $P(ij|hN)\sim Q^{-2}$. On the other hand, it is plausible that σ_{ij} is determined by soft physics, e.g., Fermi motion, and is independent of Q. These alternatives correspond to $n=2$ and 0 in (3), respectively. Observe that for $n=2$, the parton mean free path $\lambda\sim\sigma_{ij}^{-1}\sim Q^2$ is typically much larger than the nuclear size, so that the Bethe-Heitler linear x dependence of (3) should strictly apply [10].

Our calculations for the Drell-Yan process in tungsten are presented as the upper curves in Fig. 1. The dotted and dashed curves show the expected depletion using the two structure function sets discussed below. The corresponding curves in Fig. 2 contain our results for iron. In each case we obtain excellent agreement with the data. The E772 data strictly include muon pairs of masses $4\le M_{\mu\mu}\le9$ and $M_{\mu\mu}\gtrsim11$ GeV. In computing (1), we assume that the rate is dominated by the lowest $Q \sim 4$ GeV.

We now turn to charmonium production. To obtain concrete estimates, we use the phenomenologically successful color evaporation model [19] in which charmonium production is determined from the $c\bar{c}$ rate below the open charm $D\bar{D}$ threshold. Gluon fusion $gg \to c\bar{c}$ and quark annihilation $q\bar{q} \to c\bar{c}$ are included. The rates for specific J/ψ and ψ' states are given by A-independent empirical factors $2 < f < 7$. One writes

$$\frac{d\sigma}{dx_F} = f \int_{4m_c^2}^{4m^2} \frac{dQ^2}{Q^2} \frac{x_1 x_2}{x_1 + x_2} \left\{ \sum_q \sigma^{q\bar{q} \to c\bar{c}} [q(x_1)\bar{q}(x_2) + q(x_2)\bar{q}(x_1)] + \sigma^{gg \to c\bar{c}} g(x_1) g(x_2) \right\} \quad (4)$$

for the charm quark and D meson masses $m_c \sim 1.5$ GeV and $m \sim 1.85$ GeV. We expect the same A dependence for all charmonium states. As in the Drell-Yan process, (3) and (4) imply that the energy loss effect essentially scales with x_F at high energies. Unlike the case for the Drell-Yan process, (4) depends on the gluon structure function at large x_1 and small x_2 where there is little experimental information. To estimate the associated uncertainty, we use a scaling form [20] and a Q-dependent parametrization [21] of $g(x)$ at leading order.

The calculated depletion due to initial- and final-state scattering is compared to E772 data for $pA \to J/\psi + X$ at $\sqrt{s} = 40$ GeV in Figs. 1 and 2. The dotted and dashed curves illustrate the effect of initial-state scattering alone for the loss (3) with $n=0$ for the two different structure function sets. The solid curves show the additional effects of a final-state loss $\approx \Delta x_g$ for the octet $c\bar{c}$ using the first structure function set [20]. Calculations for $n=2$ in Eq. (3) are in similar accord with data for (i) initial- and final-state scattering using the second set [21], and (ii) initial-state scattering alone using the first set. Observe that the energy loss for an octet with $n=2$ at $Q = m_{J/\psi}$ extracted from the Drell-Yan triplet value at $Q=4$ GeV is large, $(dE/dz)_{n=2} \approx 6$ GeV/fm, compared to the $n=0$ octet value $(dE/dz)_{n=0} \approx 3$ GeV/fm. We feel that the $n=0$ value is more appropriate at the lower Q, since the leading twist $n=2$ approximation is suspect when corrections to the cross section are too large. As expected, the measured nuclear effects in ψ' and J/ψ production [2] are the same within experimental errors [cf. Eq. (4)]. More importantly, we find similar agreement for pA and $\pi A \to J/\psi$ data at $\sqrt{s} = 20$ GeV using the pion's $g(x)$ from Ref. [3]. Although structure function uncertainties obscure detailed information about $\Delta x(Q)$, the overall agreement with charmonium data is quite good.

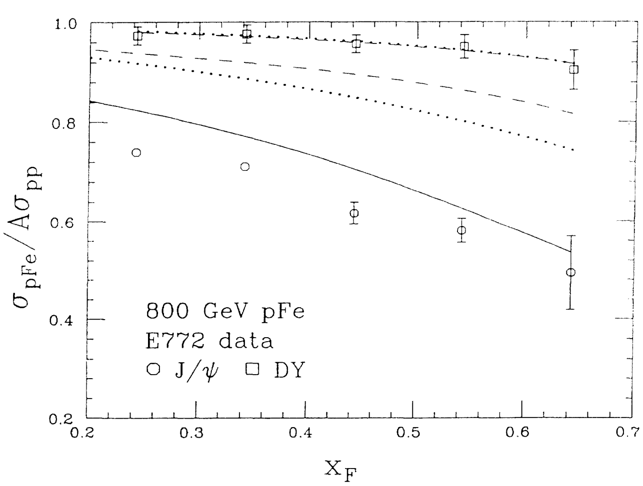

FIG. 2. The depletion from iron.

We expect bottomonium production [22] at Fermilab to display less depletion than charmonium since it is produced predominantly through quark fusion. Using the $n=0$ Δx_g for both initial- and final-state scattering together with the second structure function set, we obtain the dashed curve in Fig. 3. Taking $n=2$ in Eq. (3) as the Q^2 expansion suggests [17], we obtain the solid curve. We emphasize that these calculations apply equally for Υ_{1S}, Υ_{2S}, and Υ_{3S} production. These data suggest that this effect is of a higher twist nature. In contrast to J/ψ production, applications of a Q^{-2} expansion to the Drell-Yan process and Υ production is better founded, since the corrections are relatively small. In particular, experimental studies of the A dependence of $d\sigma/dx_F dQ^2$ for the Drell-Yan process can provide important information on the Q^2 behavior of energy loss.

One may ask why the parton energy loss in hadron-nucleus collisions is so small—$dE/dz \approx 1.5$ GeV/fm for a $x_F E_{\rm beam} \approx 500$ GeV quark. Recently, Gyulassy *et al.* [10] have studied the radiative losses of a fast parton in a homogeneous quark-gluon plasma including the Landau-

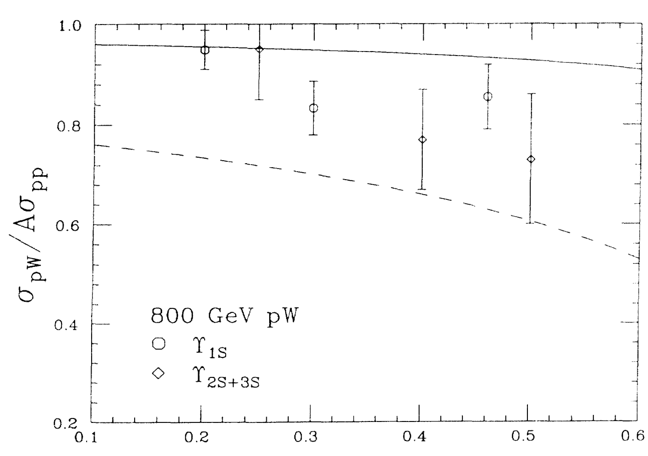

FIG. 3. The depletion for bottomonium production (Υ_{1S}, Υ_{2S+3S}) from tungsten. The solid curve incorporates a Q^{-2} dependence of the energy loss expected from a higher twist analysis. The dashed curve does not.

Migdal-Pomeranchuk (LMP) effect. In QED, the interference between successive bremsstrahlung and pair production events inhibits the radiative loss of an ultrarelativistic electron of energy E in matter, so that rough estimates yield $(dE/dz)_{\rm LMP} \propto \sqrt{E}$ in contrast to the linear Bethe-Heitler behavior [23]. Recent QCD estimates [10] indicate that an analogous LMP interference can limit the losses of quarks and gluons to $\sim 1-2$ and 2-4 GeV/fm, respectively, for the parton energies probed in the present data [1-3,12]. These values are in agreement with our estimates. Moreover, we find that the Δx_i obtained from Ref. [10], which increases logarithmically with increasing x_i, is comparable to (3) in its agreement with the data at all but the lowest x_F. Nevertheless, to assess the quantitative role of the LMP effect in the present hA context, one must understand the emission of gluons from *distinct* hN subcollisions in a finite nucleus together with a hard interaction.

To summarize, we have explored the role of energy loss in the Drell-Yan process and in charmonium and bottomonium hadroproduction in nuclear targets at high x_F. Our analysis only provides an estimate for the energy loss because intrinsic charm [6] and nuclear structure function effects [1,4,5] may also contribute to the high-x_F depletion at some level. Furthermore, our assumption that the $c\bar{c}$ loses additional energy as a color octet depends on poorly understood details of the production process, although our results support such final-state energy loss. As we have mentioned, Q^2-resolved Drell-Yan and high-x_F direct photon production can help to resolve the various nuclear effects that may contribute. Recently, Drees and Kim have proposed that experimental studies of associated $J/\psi+\gamma$ production can help to isolate the direct formation of color singlet $c\bar{c}$ in collider experiments [24]. We expect that final-state energy loss would not affect the depletion of such states at high x_F, so that associated data from nuclear targets would clarify the role of initial-state interactions. With the information in hand, however, many features of our simple model are in good accord with data. The magnitude of dE/dz extracted from the Drell-Yan process is consistent with analyses of deep-inelastic scattering data [10,11]. The similarity of the J/ψ data at 200 and 800 GeV from NA3 [3] and E772 [1], respectively, is consistent with the $x_F \sim x_1$ scaling of the energy loss of the projectile parton. The reduced high-x_F nuclear depletion of $b\bar{b}$ relative to $c\bar{c}$ is consistent with the proposed higher-twist nature of the energy loss mechanism [17,18]. Data on ψ, ψ', and Υ, $1S$, $2S$, and $3S$ states support our expectation that resonances of similar masses suffer roughly the same energy loss.

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[1] D. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).
[2] D. Alde *et al.*, Phys. Rev. Lett. **66**, 133 (1991).
[3] J. Badier *et al.*, Z. Phys. C **20**, 101 (1983).
[4] L. L. Frankfurt, M. I. Strikman, and S. Liuti, Phys. Rev. Lett. **65**, 1725 (1990).
[5] K. E. Lassila, U. P. Sukhatme, A. Harindranath, and J. P. Vary, Phys. Rev. C **44**, 1188 (1991).
[6] S. J. Brodsky and P. Hoyer, Phys. Rev. Lett. **63**, 1566 (1989); R. Vogt, S. J. Brodsky, and P. Hoyer, Nucl. Phys. **B360**, 67 (1991).
[7] S. Gavin, Helsinki University Report No. HU-TFT-91-33, 1991 (to be published); S. Gavin and M. Gyulassy, Phys. Lett. B **214**, 241 (1988).
[8] N.B. these data are dominated by small x_F where the production is insensitive to energy loss; see the Drell-Yan curves in Figs. 1 and 2.
[9] B. Z. Kopeliovich and F. Niedermayer, Dubna Report No. JINR-E2-84-834, 1984 (unpublished); P. McGaughey, in Proceedings of the Fourth Conference on the Intersections between Particle and Nuclear Physics, Tucson, Arizona, 24-29 May 1991 (to be published); E. Quack, in Proceedings of the Conference on Hadronic Physics, Rio de Janeiro, Brazil, January 1991, edited by T. Kodama *et al.* (to be published).
[10] M. Gyulassy, M. Plümer, M. H. Thoma, and X. N. Wang, LBL Report No. LBL-31002 (to be published).
[11] M. Gyulassy and M. Plümer, Nucl. Phys. **B346**, 1 (1990).
[12] L. S. Osborne *et al.*, Phys. Rev. Lett. **40**, 1624 (1978); H. Melanson, E665 (private communication).
[13] C. E. Carlson and R. Suaya, Phys. Rev. D **23**, 1521 (1981).
[14] Y. Lemoigne *et al.*, Phys. Lett. **113B**, 509 (1982).
[15] S. J. Brodsky and A. Mueller, Phys. Lett. B **206**, 685 (1988).
[16] J. Qiu and G. Sterman, Phys. Rev. Lett. **67**, 2264 (1991).
[17] J. Qiu and G. Sterman, Nucl. Phys. **B353**, 105 (1991).
[18] K. Kastella, J. Milana, and G. Sterman, Phys. Rev. D **39**, 2586 (1989).
[19] M. Gluck, J. F. Owens, and E. Reya, Phys. Rev. D **17**, 2324 (1978). We also note that the model is consistent with the χ data of Ref. [14]. See J. Milana, Phys. Rev. D **42**, 1468 (1990).
[20] G. Altarelli, R. K. Ellis, and G. Martinelli, Nucl. Phys. **B157**, 461 (1979).
[21] R. Baier, J. Engels, and B. Peterson, Z. Phys. C **6**, 309 (1980).
[22] D. Alde *et al.*, Phys. Rev. Lett. **66**, 2285 (1991).
[23] T. Stanev *et al.*, Phys. Rev. D **25**, 1291 (1982), and references therein.
[24] M. Drees and C. S. Kim, DESY Report No. 91-085, 1991 (to be published).