Testing for QCD Energy Loss at High x_F

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Gavin has had a long interest in parton interactions in nuclei. In addition to their obvious relevance to heavy ion physics, studies of high energy hadron–nucleus and lepton–nucleus collisions provide unique, fundamental spacetime information on QCD [1]. Hard scattering processes such as ψ formation or Drell–Yan dilepton production fleetingly produce high energy quarks and gluons. These partons undergo additional interactions while traversing the nuclear target, gaining transverse momentum [2, 3] and losing energy [4] as they go. Energy loss can lead to a subtle but observable modification of the momentum dependence of the ψ or the DIS jet relative to expectations drawn from standard QCD perturbation theory [5].

To extract quantitative information on these parton interactions from data, it is vital to know the production rates for hard processes in the absence of nuclear effects. In [5], we provide calculations for the Drell–Yan process at next–to–leading order in perturbative QCD for energy and kinematic regimes relevant to nuclear experiments. In [6], we use these results as backgrounds against which signals of thermal dilepton production can be identified. These studies were performed as part of an ongoing Hard Probe Collaboration for RHIC and LHC, a working group patterned after similar groups in the high energy community to provide systematic signal and background computations for RHIC and LHC.

A.H. Mueller, R. Baier, Y. Dokshitser, S. Peigne, and M. Schiff (BDPMS) have calculated the energy loss of high energy partons in nuclear targets [8]. An exciting phenomenological consequence of this calculation is the suggestion that perhaps the total energy loss of a fast quark scales with $A^{2/3}$. This behavior can be understood by estimating the energy loss ΔE of a parton of high energy E as it traverses a nucleus of length $L \propto A^{1/3}$. Emission of a single bremsstrahlung gluon of four-momentum $(\omega, \vec{k}_t, k_z)$ results in an energy loss $\Delta E \sim \omega$. Both the gluon and the parton can undergo further interactions in the nucleus, but only after the gluon travels a transverse distance $r_t \sim 1/k_t$ so that it can be 'resolved' from the parton. In the standard argument [9], one assumes that neither the parton nor the gluon undergo elastic scattering, so that their separation grows as $r_t \sim v_t t$, where $v_t = k_t/\omega$. It then takes a time $t \sim r_t/v_t \sim \omega r_t/k_t \sim \omega/k_t^2$ for the gluon to be resolved. The parton travels a distance Δz in that time. Before that time, any further interactions occur with the gluon-parton system, collectively of energy E. Only after the parton travels a formation length $\Delta z \sim \omega/k_t^2$ can the parton begin it to lose additional energy. Therefore, the parton's energy loss per unit length is limited to a value $dE/dz \sim k_t^2$.

BDPMS observe, however, that before the parton-gluon system is resolved, both the parton and the gluon may suffer *elastic* interactions, which have no formation length [8]. These interactions increase the average $\langle k_t^2 \rangle \propto \Delta z$. Therefore, the energy loss per unit length $dE/dz \sim \langle k_t^2 \rangle$ can grow as $A^{2/3}$. The detailed BDPMS result in a large nucleus is

$$dE/dz = 3\alpha_s \langle k_t^2 \rangle / 8 \tag{1}$$

corresponding to a total energy loss of $\Delta E \approx 15$ GeV for a parton crossing 10 fm of nuclear matter. In contrast, the old estimate $dE/dz \sim 0.3 - 1$ GeV/fm [9] gives $\Delta E \approx 3 - 10$ GeV.

In Ref. [7], we ask whether experimental measures of energy loss reflect a BDPMS $A^{2/3}$ quantum energy loss. To be sure, the leap from the idealized infinite-matter BDPMS calculation to hard-scattering processes in nuclear interactions is not without risk. Nevertheless, there is good experimental evidence that the average transverse momentum in the Drell Yan and other hard processes grows as $A^{1/3}$ [3, 10, 11]. Observe that Huang, Sarcevic and Wang have proposed that photon-hadron jets constitute probe of BDPMS energy loss. Our works are intended to be complementary. They point out that the BDPMS loss leads to strong jet quenching, and ask for future experiments of direct relevance to the jet quenching probe of dense matter. We ask if current pA data are consistent with a BDMPS-type loss.

S. Gavin and J. Milana [4] pointed out that at hard processes near their kinematic extremes are sensitive to parton energy loss. To produce a Drell Yan lepton pair at x_F near the kinematic limit $x_F = 1$, the projectile and target partons must carry momentum fractions $x_p \sim 1$ and $x_t \sim 0$. In a proton-nucleus collision, the projectile parton can lose energy in the nuclear target prior to the hard Drell-Yan process. To produce a lepton pair of x_F, the projectile parton would have to have an $x_p = x_F + x_t + \Delta x > x_F + x_t$. The Drell Yan cross section is proportional to the product of the parton distribution functions f, implying:

$$\frac{\sigma_{pA}}{\sigma_{pp}} \sim \frac{f_p(x_p + \Delta x)}{f_p(x_p)} \sim [1 - \Delta x/(1 - x_F)]^n \tag{2}$$

where the projectile parton distribution is dominated by the quark distribution and varies as $f_p \sim (1-x)^n$ for $n \sim 3$. Even a tiny energy loss corresponding to $\Delta x = \Delta E/E$ can produce a strong effect as x_F, $x_p \to 1$.

To make the leap from BDPMS to initial-state scattering in proton-nucleus collisions, one must assume that the interactions that occur initial state scattering can lead to energy loss and that BDPMS gives a rough account of these interactions. These assumptions are far from obvious. To properly apply apply these expressions to data, one must also account for shadowing of the target distribution as evident in DIS data.

Energy-loss effects can be stronger in open charm and charmonium production, since interactions can occur in both the final and the initial state. Moreover, interactions of a gluon or a color-octet $c\bar{c}$ are likely stronger than those of color-triplet quarks. For incident partons of sufficient incident energy, the cross section with n initial and m final state scatterings is:

$$\left(\frac{d\sigma}{dx_F}\right)_{pA\to\psi} = \sum_{n,m} \int d^2b dz \rho(b,z)\ P_n^i(b,z) P_m^f(b,z) \left(\frac{d\sigma}{dx_F}\right)(x_1 + n\Delta x_i, x_2 + m\Delta x_f) \tag{3}$$

where ρ is the nuclear density, $d\sigma/dx_F$ is the relevant QCD cross section at the shifted x_p and x_F. The initial and final state Glauber probabilities, P_n^i and P_m^f, depend on cross sections for initial and final state Bremsstrahlung. To simulate the BDPMS effect we make the ansatz that the initial and final state energy losses per collision are themselves proportional to the number of collisions, $\Delta x_i \propto n$ and $\Delta x_f \propto m$.

To incorporate the effect of shadowing on the target distribution, one can modify that distribution in calculating $d\sigma/dx_F$. To illustrate the extent to which shadowing can affect the pA cross section, we take the rough ansatz that the target sea antiquark distribution have the same nuclear dependences as measured in F_{2A}. Note that it is by no means clear that shadowing and energy loss are independent, as we assume. Some authors view shadowing as yet another manifestation of multiple scattering. We can only hope that phenomenological studies like ours will help to clarify this issue.

We have found that the large BDPMS energy losses are not inconsistent with the available, Drell Yan, charmonium and bottomonium production [7]. In figs. 1 and 2, We show the possible impact of BDPMS energy loss on the x_F in Drell Yan and Υ production in 800 GeV proton–nucleus collisions relative to proton–proton at FNAL.

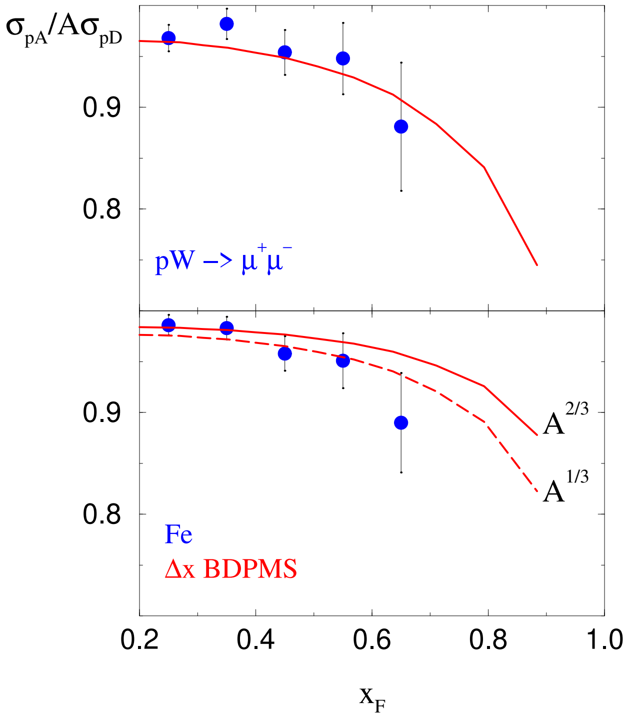

Figure 1: Comparison of Drell Yan in p+W and p+Fe collisions shows the target mass dependence of energy loss.

Inspired by the BDPMS work on energy loss Gavin and Sarcevic plan to address the following interesting questions:

1. Energy loss is relevant to estimating the perturbative contribution to energy deposition and baryon stopping in heavy ion collisions at RHIC and LHC. In particular, the nonlinearities evident in the quantum-mechanical BDPMS result can have striking consequences in A+A collisions. The predicted behavior may be strikingly different from classical cascade codes.
2. The BDPMS form applies to light partons. What about the heavy charm and bottom quarks? In the regime where interference between successive scattering is unimportant, the QCD Bethe-Heitler dE/dz is valid. This result varies as m^{-2}, which suggests that charm energy loss might be much smaller than BDPMS approach would suggest.

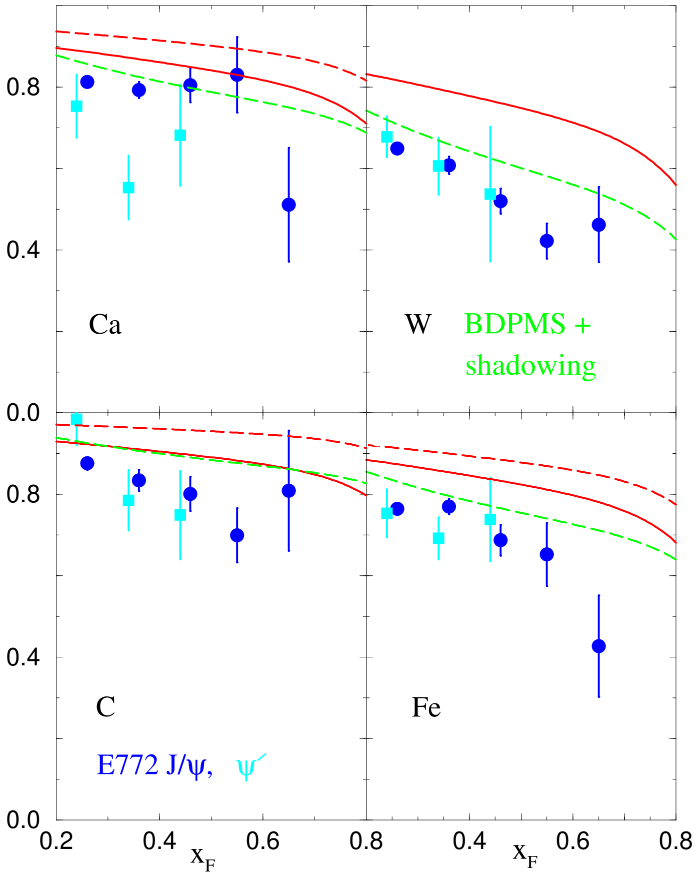

Figure 2: Comparison of charmonium production in four nuclear targets. Calculations include BDPMS-like energy loss and a simple parametrization of shadowing.

3. Energy loss for charm quarks can have an observable impact on dilepton spectra at RHIC, as pointed out in ref. [12]. However, the BDPMS energy loss (or a variant corrected for the charm mass) is likely different from $dE/dz = 1$ GeV assumed in that work. It is worthwhile reexamining [6] in light of our energy loss results.

4. The Glauber probabilities that enter our calculation depend on parton- nucleon cross sections which were taken as an input parameters. It will be interesting to see whether the parton nucleon cross sections in [13] agree with data in the relevant x regime.

More generally, we hope to understand the interplay between the energy loss described by BDPMS and the parton scatterings [13] in high-energy nuclear collisions.

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