# Parton energy loss limits and shadowing in Drell-Yan dimuon production

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A precise measurement of the ratios of the Drell-Yan cross section per nucleon for an 800 GeV/$c$ proton beam incident on Be, Fe and W targets is reported. The behavior of the Drell-Yan ratios at small target parton momentum fraction is well described by an existing fit to the shadowing observed in deep-inelastic scattering. The cross section ratios as a function of the incident parton momentum fraction set tight limits on the energy loss of quarks passing through a cold nucleus.

24.85.+p; 13.85.Qk; 25.40.Ve; 25.75.q

The Drell-Yan process, where a beam quark (antiquark) fuses with a target antiquark (quark) producing a muon pair, can be used to study the interactions of fast partons penetrating through cold nuclei. Only initial state interactions are important in Drell-Yan since the dimuon in the final state does not interact strongly with the partons in the medium. This makes Drell-Yan scattering an ideal tool to study energy loss of fast quarks in nuclear matter by comparing the observed yields from a range of nuclear targets. The dynamics of fast parton energy loss in nuclear matter is the subject of considerable theoretical interest [1–4] and has significant implications for the physics of relativisitic heavy ion collisions.

Drell-Yan scattering is closely related to deep-inelastic scattering (DIS) of leptons, but unlike DIS it can be used specifically to probe antiquark contributions in target parton distributions. When DIS on nuclei occurs at $x < 0.08$, where $x$ is the parton momentum fraction, the cross section per nucleon decreases with increasing nuclear number $A$ due to shadowing [5,6]. Shadowing should also occur in Drell-Yan dimuon production at small $x_2$, the momentum fraction of the target parton, and theoretical calculations indicate that shadowing in the two reactions has a common origin [7,8]. This should be particularly apparent at $x < 0.06$ where DIS on nuclei, like Drell-Yan, is dominated by scattering off sea quarks.

Fermilab Experiment 866 (E866) measured the nuclear dependence of Drell-Yan dimuon production by 800 GeV/$c$ protons on Be, Fe and W targets at larger values of $x_1$, the momentum fraction of the beam parton, larger values of $x_F$ ($\approx x_1 - x_2$), and smaller values of $x_2$ than reached by the previous experiment, Fermilab E772 [9]. The extended kinematic coverage of E866 significantly increases its sensitivity to parton energy loss and shadowing. This Letter reports the results.

The experiment used the same 3-dipole magnet spectrometer that was described in [10]. An 800 GeV/$c$ extracted proton beam averaging $3 \times 10^{11}$ protons per 20 s spill bombarded one of three solid targets or an empty target frame. The Be, Fe and W targets were 9.4% – 19% of an interaction length thick. Their relative thicknesses were chosen carefully to match the background rates present in the spectrometer. The targets were located far upstream of the main dipole magnet to optimize the acceptance at low $x_2$ and large $x_F$. During a cycle, 2 beam spills were taken on each target and 1 spill was collected on an empty location. After passing through a target, the remaining beam was intercepted by a copper beam dump, which was followed by a thick absorber that removed hadrons produced in the target and the dump. This ensured that only muons traversed the spectrometer's detectors, which consisted of four tracking stations and a momentum analyzing magnet. The trigger required a pair of triple hodoscope coincidences having the topology of a muon pair from the target. Typically 1400 triggers per second were recorded with an average live time of 93%.

Over 130,000 muon pairs with dimuon mass in the

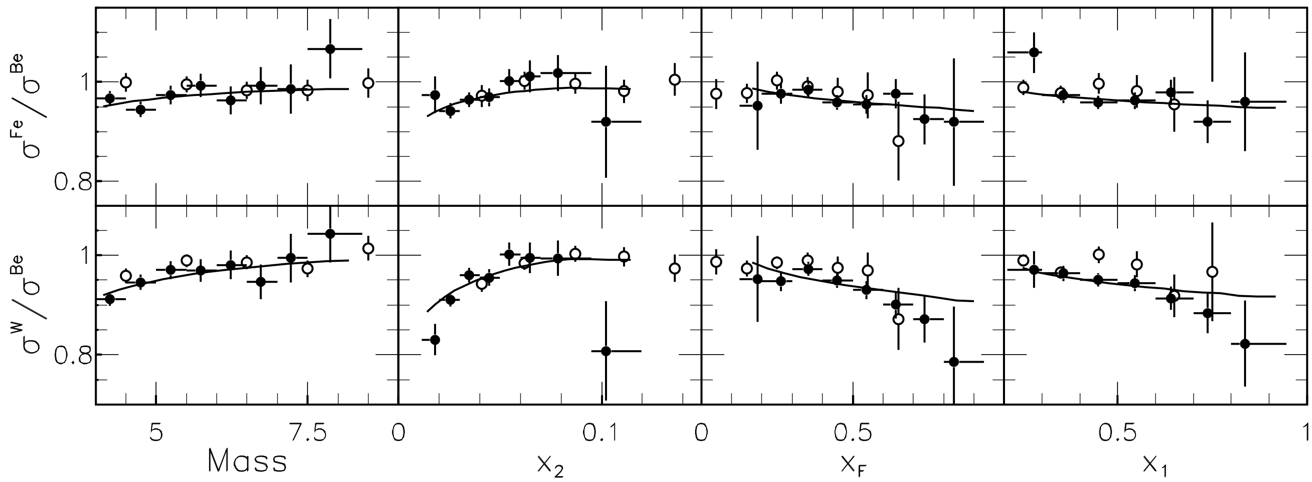


FIG. 1. Ratios of the measured cross section per nucleon for Drell-Yan events versus dimuon mass (in GeV/$c^2$), $x_2$, $x_F$ and $x_1$. The upper (lower) panels show ratios of Fe/Be (W/Be) from the present experiment as solid circles and Fe/C (W/C) from E772 as open circles. The errors are statistical only. The solid curves are the predicted cross section ratios, integrated over the hidden variables, from leading-order calculations using EKS98 [11] and MRST [12].

range $4.0 < M < 8.4$ GeV/$c^2$ survived the data cuts. Random pairs were subtracted from the data using simulated random dimuons constructed by mixing single muon tracks that were obtained simultaneously from prescaled single muon triggers. The normalization factor for the random correction was evaluated by comparing to the observed rate of same-charge muon pairs in the data. The random rate was 9% of the real events, and it occurred primarily at low dimuon mass and high $p_T$. A residual 3% background from the empty target was also subtracted. The solid targets intercepted the beam at nearly the same $z$ location, making differences in dimuon acceptance negligible. The overall systematic normalization uncertainty in the cross section ratios reported here is 1%.

The Drell-Yan events obtained by E866 extend over the ranges $0.01 < x_2 < 0.12$ and $0.21 < x_1 < 0.95$, with $\langle x_2 \rangle = 0.038$ and $\langle x_1 \rangle = 0.46$. They also cover the range $0.13 < x_F < 0.93$ and provide good $p_T$ coverage to 4 GeV/$c$. Ratios of the cross section per nucleon for Fe to Be and W to Be versus dimuon mass, $x_2$, $x_F$ and $x_1$ are shown in Fig. 1, along with similar results from E772 for Fe to C and W to C. The figure shows very good agreement between the experiments for the cross section ratios versus $x_2$. The agreement versus other variables is also quite good, given the much smaller $\langle x_2 \rangle$ and, hence, increased shadowing of the present data. Note that the $A$ dependence observed here and in E772 implies the change in the cross section ratios in Fig. 1 due to the choice of Be versus C is small compared to the effect of the difference in $\langle x_2 \rangle$. The reduction in the cross section per nucleon on the heavy targets, characteristic of shadowing, is clearly apparent at small $x_2$. A similar reduction, part of which could be related to incident parton energy loss, is apparent at large $x_F$ and $x_1$. However, it is important to recognize that the spectrometer acceptance coupled to the intrinsic Drell-Yan cross section leads to a strong anti-correlation between $x_2$ and $x_F$ for the observed events. Therefore, the events that show the cross section reduction at large $x_F$ and $x_1$ are in general the same events that appear in the shadowing region.

In order to identify the contributions from shadowing, Fig. 1 also shows the predicted cross section ratios, integrated over the hidden variables, from leading-order Drell-Yan calculations using the code EKS98 [11] together with the MRST parton distribution functions [12]. Essentially identical results are obtained using CTEQ5M or CTEQ5L parton distributions [13] instead. EKS98 describes the ratios $f_A(x, Q^2)/f_p(x, Q^2)$ of the various quark flavors in nucleus $A$, compared to those in the proton. It has been tuned to fit the shadowing observed in DIS [14] and E772 while conserving baryon number and momentum.

EKS98 provides an unbiased way to separate the effects of shadowing and energy loss in the present data because it uses a single shadowing function to describe the nuclear dependence of all sea quark distributions at its initial scale ${Q_0}^2 = 2.25$ GeV$^2$ and only DIS results are used to constrain that function for $x \lesssim 0.1$. The shape and magnitude of the ratios versus $x_2$ are well reproduced by the shadowing predictions. Most of the $A$ dependence observed in the ratios versus mass, $x_F$ and $x_1$ can also be explained by shadowing at small $x_2$. As a further test of the shadowing parametrization, the events in Fig. 1 have been separated into two sets at the median $x_2$ value. The cross section ratios differ by up to 6% when the events

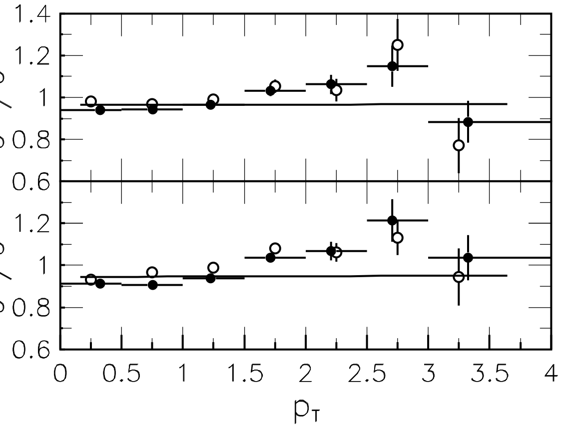


FIG. 2. Ratios of the measured Drell-Yan cross section per nucleon versus $p_T$. Ratios of Fe/Be and W/Be from the present experiment are shown as solid circles, and ratios of Fe/C and W/C from E772 are shown as open circles. The solid curves are shadowing predictions for the present experiment from leading-order calculations using EKS98 [11] and MRST [12].

at low and high $x_2$ – but at the same mass, $x_F$ or $x_1$ – are observed separately. EKS98 also describes these differences well. This is the first experimental demonstration that the shadowing observed in Drell-Yan and DIS is quantitatively similar.

Figure 2 shows the measured ratios of the Drell-Yan cross section per nucleon as a function of $p_T$. Unlike the longitudinal variables that have strongly correlated acceptances, the $p_T$ acceptance in E866 is nearly independent of the other kinematic variables, so the shadowing calculations predict essentially constant cross section ratios versus $p_T$, as shown by the smooth curves in the figure. The data demonstrate a clear $p_T$ dependence which must have an independent origin. The slight reduction in the cross section per nucleon observed for heavy nuclei at small $p_T$, coupled with the increase in the cross section per nucleon at large $p_T$, is characteristic of multiple scattering of the incident partons as they traverse the nucleus.

The $x_1$ dependence of the cross section ratios provides the best direct measure of the energy loss of the incident quarks in the nuclear medium. Table I gives the ratios of the measured cross section per nucleon as a function of $x_1$, and the mean values of $x_1$, $x_2$ and dimuon mass for each bin. However, as shown above, shadowing at small $x_2$ explains a substantial fraction of the apparent variation in the cross section ratios versus $x_1$. This must be removed before one can isolate a nuclear dependence due to energy loss. Figure 3 shows the same cross section ratios versus $x_1$ as given in Table I, but corrected for shadowing by weighting each event with the calculated ratio of the Drell-Yan cross sections per nucleon for deuterium and nucleus $A$ at the same $(x_1, x_2, Q^2)$, using EKS98 and MRST.

TABLE I. Ratios of the cross section per nucleon for Fe to Be and W to Be as functions of $x_1$, without correction for shadowing. Also given are mean values for $x_1$, $x_2$ and dimuon mass (in GeV/$c^2$) for each bin. Mean $x_F$ may be found from $\langle x_F\rangle = \langle x_1\rangle - \langle x_2\rangle$. The errors are statistical only.

| $x_1$ range | $\langle x_1\rangle$ | $\langle x_2\rangle$ | $\langle M\rangle$ | $\sigma^{\rm Fe}/\sigma^{\rm Be}$ | $\sigma^{\rm W}/\sigma^{\rm Be}$ |
|---|---|---|---|---|---|
| 0.21-0.3 | 0.279 | 0.055 | 4.76 | 1.059(41) | 0.971(37) |
| 0.3-0.4 | 0.356 | 0.046 | 4.92 | 0.973(16) | 0.964(15) |
| 0.4-0.5 | 0.448 | 0.039 | 5.07 | 0.959(14) | 0.951(13) |
| 0.5-0.6 | 0.545 | 0.034 | 5.17 | 0.962(17) | 0.944(16) |
| 0.6-0.7 | 0.642 | 0.030 | 5.24 | 0.979(25) | 0.914(23) |
| 0.7-0.8 | 0.738 | 0.026 | 5.27 | 0.920(42) | 0.884(40) |
| 0.8-0.95 | 0.836 | 0.023 | 5.28 | 0.960(99) | 0.822(86) |

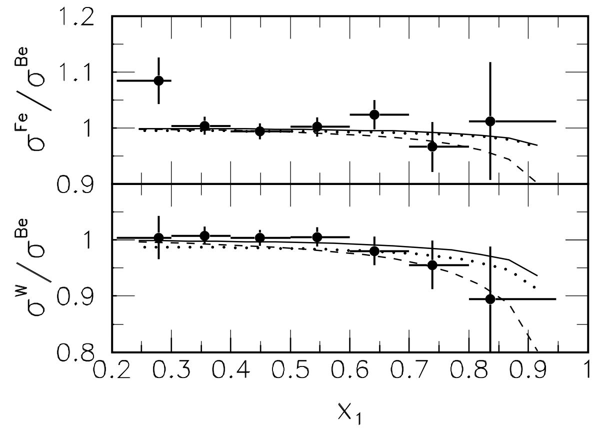


FIG. 3. Ratios of the cross section per nucleon versus $x_1$ for Fe/Be (upper panel) and W/Be (lower panel), corrected for shadowing. The solid curves are the best fit using the energy loss form (1), and the dashed curves show the $1\sigma$ upper limits. The dotted curves show the $1\sigma$ upper limits using the energy loss form (3). The $1\sigma$ upper limit curves using the energy loss form (2) are essentially identical to those using form (3).

Several groups have studied energy loss of partons in nuclei. Their results can be expressed in terms of the average change in the incident parton momentum fraction, $\Delta x_1$, as a function of target nucleus. Gavin and Milana [1] analyzed the E772 Drell-Yan data for energy loss based on the parametrization

$$\Delta x_1 = -\kappa_1\, x_1\, A^{1/3}, \tag{1}$$

where the factor $\kappa_1$ may have a $Q^2$ dependence. They based the form (1) on an analogy to the transverse spin asymmetry in direct photon production. From a comparison to the $x_F$ dependence seen by E772 and neglecting shadowing, they concluded that the fractional energy loss of quarks passing through nuclei is $\approx 0.4\%$/fm. Recently, other groups have assumed equivalent formulations with even more rapid energy loss [15,16]. Brodsky and Hoyer [2] argued that the energy loss found by Gavin and Milana was too large since the time scale for QCD bremsstrahlung was too short to allow for multiple contributions to the energy loss. Brodsky and Hoyer used an analogy to the photon bremsstrahlung process to obtain a form for gluon radiation leading to an initial parton energy loss [17]

$$\Delta x_1 \approx -\frac{\kappa_2}{s} A^{1/3}. \quad (2)$$

They found an upper limit for the gluon radiation from the uncertainty relation. They also noted that elastic scattering should make a similar contribution to the energy loss. Overall, they concluded that energetic partons should lose $\lesssim 0.5$ GeV/fm in nuclei. The formulation developed by Brodsky and Hoyer was extended by Baier *et al.* [3,4]. They found that the energy loss of sufficiently energetic partons depends on a characteristic length and the broadening of the squared transverse momentum of the parton. For finite nuclei, both factors vary as $A^{1/3}$, so Baier *et al.* predict

$$\Delta x_1 \approx -\frac{\kappa_3}{s} A^{2/3}. \quad (3)$$

Baier *et al.* predict that energy loss may be different in hot and cold nuclear matter and that there could a large coherent effect in relativistic heavy ion collisions. In contrast, tight limits have been placed on energy loss in S+S and Pb+Pb collisions [18], but the parton momenta relative to the hadronic medium were very much smaller in those cases than in the present experiment, making a direct comparison difficult.

Given these energy loss expressions, it is possible to obtain empirical values for the $\kappa$'s by performing simultaneous fits to the Fe/Be and W/Be Drell-Yan cross section ratios versus $x_1$ in Fig. 3. We assume that $\kappa_1$ is $Q^2$-independent [1,2] when using form (1) and that our incident quarks are sufficiently energetic when using form (3). Curves corresponding to the fits are included in Fig. 3. When assuming the form (1), we find $\kappa_1 = 0.0004 \pm 0.0009$. This implies that the observed fractional energy loss of the incident quarks is $< 0.14\%$/fm. For the energy loss forms (2) and (3), the best fits imply essentially zero energy loss. We find the $1\sigma$ upper limits to be $\kappa_2 < 0.75$ GeV$^2$ and $\kappa_3 < 0.10$ GeV$^2$. The $\kappa_2$ limit indicates that the incident quarks lose energy at a constant rate of $< 0.44$ GeV/fm. The $\kappa_3$ limit implies that the observed energy loss of the incident quarks within the model of Baier *et al.* is $\Delta E < 0.046$ GeV/fm$^2$ $\times\ L^2$, where $L$ is the quark propagation length through the nucleus. This is very close to the lower value given by Baier *et al.* for cold nuclear matter [19]. In all three cases, the quoted errors include both statistics and the overall normalization uncertainty, with the latter dominating.

One can also obtain an indirect estimate of the energy loss due to gluon radiation in the model of Baier *et al.* from the broadening of the $\langle {p_T}^2 \rangle$ as the incident quark passes through the nucleus, as shown in Fig. 2. However, such an analysis involves two significant difficulties. While the Drell-Yan cross section is very small for $p_T$ beyond 4 GeV/$c$, the change in $\langle {p_T}^2 \rangle$ from nucleus to nucleus, being the small difference of large numbers, is quite sensitive to the yield at very large $p_T$ where our acceptance is poor and the random background becomes significant. Meanwhile, the $p_T$ dependence of the ratio of the Drell-Yan cross sections per nucleon on hydrogen and deuterium shows possible evidence for a change in the reaction mechanism at $p_T \approx 3$ GeV/$c$ [20], complicating interpretation of the large $p_T$ ratio data in Fig. 2. Further analysis of the $p_T$ dependence of the Drell-Yan cross section will be presented in a future publication.

In summary, this Letter reports a measurement of the ratios of the Drell-Yan cross section per nucleon for Fe to Be and W to Be. Nuclear shadowing is found to be important in the small $x_2$ domain. For sufficiently small $x_2$, the shadowing observed in Drell-Yan has been demonstrated to be quantitatively similar to that in DIS. Subsequently, a correction for shadowing has been applied. The cross section ratios versus $x_1$ provide direct upper limits on the energy loss of the incoming parton as it traverses a cold nucleus that are tighter than previous constraints. Shadowing and initial state energy loss are processes that occur in both Drell-Yan production and $J/\psi$ formation. Hence, these results should also further the understanding of $J/\psi$ production, which is required if it is to be used as a signal for the quark-gluon plasma in relativistic heavy ion collisions.

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