# Nuclear dependence of Drell-Yan and $J/\psi$ production in FNAL E866

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Fermilab E866 has measured the target-mass dependence of Drell-Yan and $J/\psi$ dimuon production induced by an 800 GeV proton beam on targets of Be, Fe and W. Clear evidence of nuclear shadowing is observed in the Drell-Yan cross section ratios per nucleon at small $x_2$. The $x_1$ dependence of the cross section ratios provides a determination of the energy loss of ultra-relativistic quarks as they pass through cold nuclei. Preliminary results for $J/\psi$ yields show maximum cross section ratios that are slightly less than 1 at an $x_F$ value near 0.1. The yield on heavy targets is much more strongly suppressed relative to light targets at larger values of $x_F$.

The Drell-Yan process can be used to study the interactions of fast partons penetrating through cold nuclei. Only initial state interactions are important in Drell-Yan production 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, a subject of considerable theoretical interest[1–4], by comparing the observed yields from a range of nuclear targets. 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 (Bjorken $x$) $x < 0.08$ 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 $x_2$ and should be particularly apparent at $x < 0.06$ where DIS on nuclei, like Drell-Yan, is dominated by scattering off sea quarks.

Strong suppression of the yields for $J/\psi$'s produced in heavy nuclei relative to light nuclei has been observed in proton (E772)[7], pion (NA3)[8] and heavy-ion (NA50) induced collisions[9]. The kinematic dependencies of this suppression are strong, especially with Feynman-$x$ ($x_F$) and transverse momentum ($p_T$), and broad coverage in these kinematic

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variables is essential to be able to unravel the sources of the suppression. Also important in understanding these mechanisms is to contrast suppression of vector meson production with similar studies of the Drell-Yan process and open charm production.

Here we report measurements made during Fermilab E866 of Drell-Yan and $J/\psi$ production for proton-nucleus collisions on Be, Fe, and W targets over broad ranges in the kinematic variables. Over 130,000 Drell-Yan muon pairs were observed with dimuon mass in the range 4.0 GeV $< M <$ 8.4 GeV, target-parton momentum fraction $0.01 < x_2 < 0.125$, $x_F$ in the range $0.2 < x_F < 0.94$ and $p_T$ values up to 4 GeV/$c$. Over three million $J/\psi$'s with $x_F$ between -0.15 and 0.95 and $p_T$ up to 4 GeV/c were also observed.

The experiment was carried out using a 3-dipole magnet pair spectrometer employed in previous experiments (E605[10], E772[7], and E789[11]). Modifications for E866 included the addition of new drift chambers and hodoscopes with larger acceptance at the first tracking chamber and a new trigger system[12]. An 800 GeV/c extracted proton beam bombarded solid targets of Be, Fe, and W. The non-interacting beam was absorbed in a copper dump located inside the second magnet. Following the dump was a 13.4 interaction length absorber wall which filled the entire aperture of the magnet, eliminated hadrons, and assured that only muons were tracked through a series of detector stations composed of drift chambers and hodoscopes.

Two magnetic field settings were used for $J/\psi$ production to span the full range in $x_F$, small-$x_F$ (SXF) and large-$x_F$ (LXF). Drell-Yan data were obtained with the LXF settings. Random muon pairs, the dominant background source, were determined from a detailed construction of random pairs using single-muon events. Detailed Monte Carlo simulation of the resonance peaks and of the Drell-Yan continuum were used to generate line shapes to fit the mass spectra to extract the resonance yields.

Ratios of Drell-Yan cross sections 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 reduction in the cross section per nucleon on the heavy targets, characteristic of shadowing, is clearly apparent at small $x_2$. A similar reduction is apparent at large $x_F$ and $x_1$, but these events are in general the same ones 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[13]– a code that parametrizes the effects of shadowing at small $x$ based on fits to DIS and hence includes no energy loss effects – together with the MRST parton distribution functions[14].

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. However, 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 2 shows cross section ratios versus $x_1$ 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.

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 $\Delta x_1 = -\kappa_1 \, x_1 \, A^{1/3}$ (GM). From a

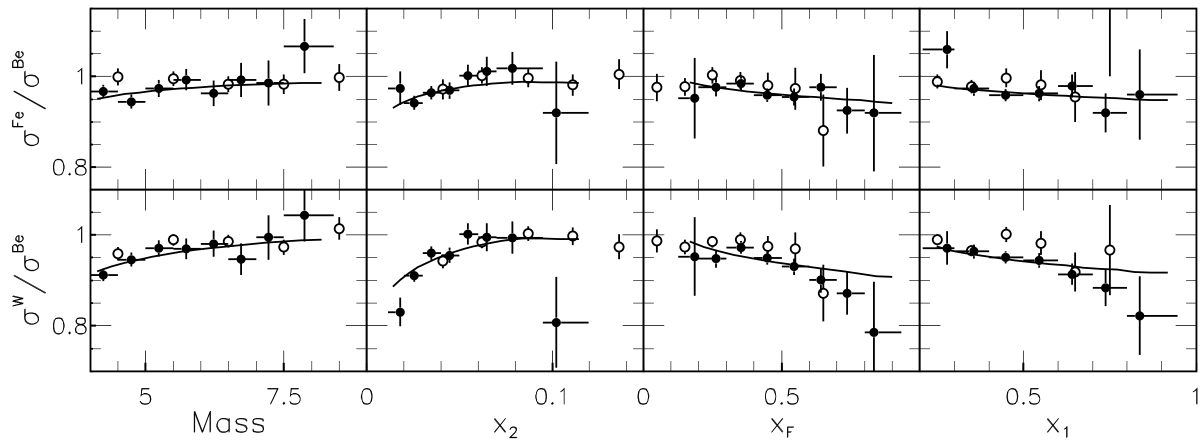


Figure 1. Ratios of the measured cross section per nucleon for Drell-Yan events from E866 are shown as solid circles and data from E772 as open circles. The solid curves are shadowing predictions as discussed in the text.

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. Brodsky and Hoyer[2] used an analogy to the photon bremsstrahlung process to obtain a form for gluon radiation leading to an initial parton energy loss $\Delta x_1 \approx -\frac{\kappa_2}{s} A^{1/3}$ (BH). They also noted that elastic scattering should make a similar contribution to the energy loss and concluded that energetic partons should lose $< 0.5$ 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 $\Delta x_1 \approx -\frac{\kappa_3}{s} A^{2/3}$ (B). We have obtained 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. 2. The solid curves are the best fit using the energy loss form (GM), and the dashed curves show the $1\sigma$ upper limits. The dotted curves show the $1\sigma$ upper limits using the energy loss forms (BH) and (B), which produce essentially identical results. When assuming the form (GM), we find $\kappa_1 = 0.0004 \pm 0.0009$ which implies that the observed fractional energy loss of the incident quarks is $< 0.14\%$/fm. For the energy loss forms (BH) and (B), 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.

Results for $J/\psi$ production are shown in Fig. 3 as $\alpha$ versus $x_F$, where $\alpha$ is obtained by fitting the cross section dependence on nuclear mass, $A$, to the form $\sigma_A = \sigma_N \times A^\alpha$. The results have been corrected for a strong $x_F$ dependence to the $p_T$ acceptance. The suppression observed in Fig. 3 can arise from several sources. Gluon shadowing and energy loss can occur prior to resonance production. Final state energy loss may change the $x_F$,

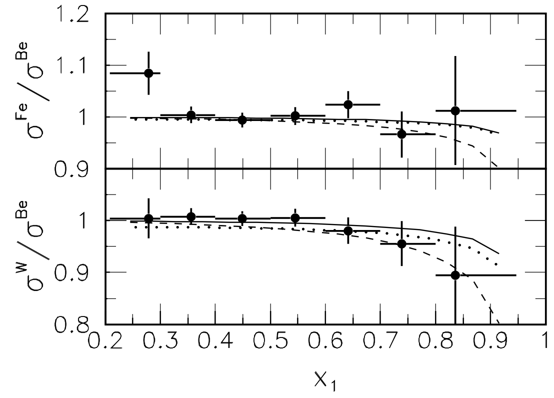


Figure 2. Cross section ratios corrected for shadowing. The energy loss predictions (curves) are described in the text

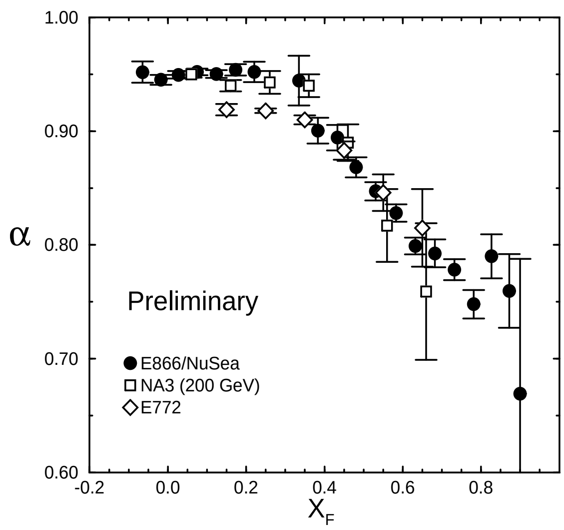


Figure 3. $\alpha$ versus $x_F$ for $J/\psi$ production from E866 compared to E772 and NA3.

and interactions with the medium and comovers may play a role in reducing the resonance yields after they have formed. Even the resonance production mechanism is still not well understood. These questions will need to be resolved in order to make $J/\psi$ production a useful probe in future relativistic heavy ion interactions.

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