Nuclear parton distribution functions and energy loss effect in the Drell-Yan reaction off nuclei

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Abstract

The energy loss effect in nuclear matter is another nuclear effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering process. The quark energy loss can be measured best by the nuclear dependence of the high energy nuclear Drell-Yan process. By means of two typical kinds of quark energy loss parametrization and the different sets of nuclear parton distribution functions, we present a analysis of the E866 experiments on the nuclear dependence of Drell-Yan lepton pair production resulting from the bombardment of Be, Fe and W targets by 800GeV protons at Fermilab. It is found that the quark energy loss in cold nuclei is strongly dependent on the used nuclear parton distribution functions. The further prospects of using relatively low energy proton incident on nuclear targets are presented by combining the quark energy loss rate determined from a fit to the E866 nuclear-dependent ratios versus \( x_1 \), with the nuclear parton distribution functions given from LA deep inelastic scattering (DIS) data. The experimental study of the relatively low energy nuclear Drell-Yan process can give valuable insight in the energy loss of fast quark propagating a cold nuclei and help to pin down nuclear parton distributions functions.

Keywords: Drell-Yan, energy loss, nuclear parton distribution functions

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I Introduction

In proton-proton collisions, we learn about the interactions between the quarks and gluons that make up the colliding nucleon\cite{1}. Parton distribution functions in nucleon have been obtained by the relative high-energy reaction data \cite{2}. These analysis help us calculate precise cross sections for finding new physics phenomena. In nucleus-nucleus collisions, we may find a signal for the existence of the deconfining phase of QCD, the quark-gluon plasma \cite{3}. In proton-nucleus collisions, we hope to gain information about the modification of the parton distribution functions in nucleon when it is immersed in the nuclei, and to learn the space-time development of the strong interaction during its early stages. Understanding the initial stages of ultrarelativistic heavy ion collisions is of utmost importance in order to understand the outcome of the high energy heavy ion experiments, such as the BNL relativistic heavy ion collider(RHIC) and CERN large hadron collider (LHC). Understanding the modifications of the parton distribution functions and the parton energy loss in nuclei should be the first important step towards pinning down the initial conditions of a heavy-ion collision and 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.

The production of lepton pairs in proton-nucleus collisions, the Drell-Yan process\cite{4}, is one of most powerful tools to probe the structure of nuclei, and the propagating of partons through cold nuclei. Its parton model interpretation is straightforward — the process is induced by the annihilation of a quark-antiquark pair into a virtual photon which subsequently decays into a lepton pair. The Drell-Yan process in proton-nucleus collisions therefore is closely related to the quark distribution functions in nuclei. Unlike DIS, it is directly sensitive to 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 nucleon number \( A \) due to shadowing\(^5\). 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 DIS and Drell-Yan reactions has a common origin \(^6\).

In high energy inelastic hadron-nucleus scattering, the projectile rarely retains a major fraction of its momentum after traversing the nucleus. Rather, its momentum is shared by several produced particles, which form a hadron jet in the forward direction. The classical description of this phenomena is that the projectile suffers multiple collisions and repeated energy loss in the nuclear matter. In other words, each quark or gluon in the projectile can loss a finite fraction of its energy in the nuclear target due to QCD bremsstrahlung\(^7\). The Drell-Yan reaction\(^4\) on nuclear targets provides, in particular, the possibility of probing the propagation of quark through nuclear matter, with the produced lepton pair carrying away the desired information on the projectile quark after it has travelled in the nucleus. Only initial-state interactions are important in Drell-Yan process since the dimuon in the final state does not interact strongly with the partons in the nuclei. This makes Drell-Yan scattering an ideal tool to study energy loss. Therefore, shadowing and initial state partonic energy loss are processes that occur in the proton-induced Drell-Yan reaction on nuclei.

In order to describe the modification of the initial state parton distributions in nucleus, a variety of approach to this question exist in the literature\(^8\). Recently, there are two groups doing global analysis of nuclear parton distribution functions. Eskola, Kolhinen, Ruuskanen and Salgado(EKRS) produces EKS98 package of nu-
clear parton distributions\textsuperscript{[9]}. Hirai, Kumano, Miyama and Nagai derived several sets of nuclear parton distribution functions from extensive experimental data\textsuperscript{[10,11]}. In 1999, Eskola, Kolhinen, Ruuskanen and Salgado (EKRS)\textsuperscript{[9]} suggested a set of nuclear parton distributions, which are studied within a framework of the DGLAP evolution. The measurements of $F_2^A/F_2^P$ in deep inelastic $tA$ collisions, and Drell-Yan dilepton cross sections measured in $pA$ collisions were used as constraints. The kinematic ranges are $10^{-6} \leq x \leq 1$ and $2.25 GeV^2 \leq Q^2 \leq 10^4 GeV^2$ for nuclei from deuteron to heavy ones. With the nuclear parton distributions, the calculated results agreed very well with the relative EMC and Fermilab E772 experimental data\textsuperscript{[12]}. In 2001, Hirai, Kumano and Miyama (HKM01)\textsuperscript{[10]} proposed two types of nuclear parton distributions which were obtained by quadratic and cubic type analysis, and determined by a $\chi^2$ global analysis of existing experimental data on nuclear structure functions without including the proton-nucleus Drell-Yan process. The kinematical ranges covered $10^{-9} \leq x \leq 1$ and $1 GeV^2 \leq Q^2 \leq 10^5 GeV^2$ for nuclei from deuteron to heavy ones. As a result, they obtained reasonable fit to the measured experimental data of $F_2$. In 2004, Hirai, Kumano and Nagai (HKN04)\textsuperscript{[11]} re-analyze experimental data of nuclear structure function ratios $F_2^A/F_2^A'$ and Drell-Yan cross section ratios for obtaining their another parton distribution functions in nuclei. In HKN04, Drell-Yan data \textsuperscript{[12,13]} are included for determining the sea quark modification in the range $0.02 < x_2 < 0.2$. In addition, HERMES data\textsuperscript{[14]} are used. In this work, we will use these parameterizations and investigate the nuclear dependence of the Drell-Yan process.

Fermilab Experiment866 (E866) \textsuperscript{[13]} performed the precise measurement of the ratios of the Drell-Yan cross section per nucleon for an 800GeV proton beam incident on Be, Fe and W target 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\cite{12}. The extended kinematic coverage of E866 significantly increases its sensitivity to energy loss and shadowing. This is the first experiment on the energy loss of quark passing through a cold nucleus.

For many years it has been suggested that fast quark energy loss might give rise to a nuclear dependence\cite{15,16,17} of the cross section of Drell-Yan. After the E866 experimental data was reported, several groups have given their theoretical analysis of the data\cite{18,19,20}. In previous report\cite{20}, by means of EKRS and HKM01 nuclear parton distribution functions, we investigated the Drell-Yan production cross section ratios from E866 data in the framework of Glauber model. We found that the theoretical results with energy loss are in good agreement with the Fermilab E866 experiment by means of HKM01 nuclear parton distributions. However, the calculated results without energy loss can give good fits by using EKRS nuclear parton distribution functions. In this report, the nuclear dependence of the pA Drell-Yan production cross sections are studied by combining two typical kinds of quark energy loss parametrization with the EKRS, HKM01 and HKN04 nuclear parton distribution. Using the values of quark energy loss from a fit to E866 experimental data, the prospects are given for the lower energy proton beams off deuteron and tungsten. Comparing with future experiments can give valuable insight in the energy loss of fast quark propagating a cold nuclei and help to pin down nuclear parton distributions functions.

II Nuclear Drell-Yan reaction

In the Drell-Yan process\cite{4}, the leading-order contribution is quark-antiquark annihilation into a lepton pair. The annihilation cross section can be obtained from the $e^+e^- \rightarrow \mu^+\mu^-$ cross section by including the color factor $\frac{1}{3}$ with the charge $e_f^2$
for the quark of flavor $f$.

$$
\frac{d\hat{\sigma}}{dM} = \frac{8\pi\alpha^2}{9M} e_f^2 \delta(\hat{s} - M^2),
$$

(1)

where $\sqrt{\hat{s}} = (x_1x_2s)^{1/2}$, is the center of mass system (c.m.system) energy of $q\bar{q}$ collision, $x_1$(resp.$x_2$) is the momentum fraction carried by the projectile (resp.target) parton, $\sqrt{\hat{s}}$ is the center of mass energy of the hadronic collision, and $M$ is the invariant mass of the produced dimuon. The hadronic Drell-Yan differential cross section is then obtained from the convolution of the above partonic cross section with the quark distributions in the beam and in the target:

$$
\frac{d^2\sigma}{dx_1dM} = K \frac{8\pi\alpha^2}{9M x_1 s} \sum_f e_f^2 [q_f^p(x_1)\bar{q}_f^A(x_2) + \bar{q}_f^p(x_1)q_f^A(x_2)],
$$

(2)

where $K$ is the high-order QCD correction, $\alpha$ is the fine-structure constant, the sum is carried out over the light flavor $f = u, d, s$, and $q_f^{p(A)}(x)$ and $\bar{q}_f^{p(A)}(x)$ are the quark and anti-quark distributions in the proton (nucleon in the nucleus $A$).

In order to obtain the $x_1$ dependence of Drell-Yan production, we shall deal in the following with the single differential cross section,

$$
\frac{d\sigma}{dx_1} = K \frac{8\pi\alpha^2}{9x_1 s} \sum_f e_f^2 \int \frac{dM}{M} [q_f^p(x_1)\bar{q}_f^A(x_2) + \bar{q}_f^p(x_1)q_f^A(x_2)],
$$

(3)

where the integration over the dimuon mass is performed in the range given from E866 experiment.

Now let us take into account of the energy loss of the fast quarks moving through the cold nuclei. In this work, we will introduce two typical kinds of quark energy loss expressions. One is given by Brodsky and Hoyer[7] from uncertainty principle, $\Delta x_1 \propto A^{1/3}$, which can be rewritten as

$$
\Delta x_1 = \alpha \frac{<L>_A}{E_p},
$$

(4)
where $\alpha$ indicate the incident quark an energy loss per unit length in nuclear matter, 
$< L >_A$ is the average path length of the incident quark in the nucleus $A$, $E_p$ is the energy of the incident proton. The average path length is employed using the conventional value, $< L >_A = 3/4(1.2A^{1/3})\text{fm}^{[22]}$. In addition to the linear quark energy loss rate, another is deduced by Baier et.al.$^{[21]}$as $\Delta x_1 \propto A^{2/3}$, which can be rewritten as

$$\Delta x_1 = \beta \frac{< L >_A^2}{E_p}.$$  \hspace{1cm} (5)

Obviously, the partonic energy loss is quadratic with the path length.

After considering the quark energy loss in nuclei, the incident quark momentum fraction can be shifted from $x_1' = x_1 + \Delta x_1$ to $x_1$ at the point of fusion. Combining the shadowing with initial state energy loss, the production cross section in pA Drell-Yan process can be written as

$$\frac{d\sigma}{dx_1} = \frac{8\pi\alpha^2}{9x_1s} \sum_f e_f^2 \int \frac{dM}{M} [q_f^p(x_1')\bar{q}_f^A(x_2) + \bar{q}_f^p(x_1')q_f^A(x_2)].$$  \hspace{1cm} (6)

### III Constraint on quark energy loss from E866

In order to pin down quark energy loss by comparing with the experimental data from E866 collaboration$^{[13]}$, we introduce the nuclear Drell-Yan ratios as:

$$R_{A_1/A_2}(x_1) = \frac{d\sigma^{p-A_1}}{dx_1} / \frac{d\sigma^{p-A_2}}{dx_1}.$$  \hspace{1cm} (7)

The integral range on M is determined according to the E866 experimental kinematic region. In our theoretical analysis, $\chi^2$ is calculated with the Drell-Yan differential cross section ratios $R_{A_1/A_2}$ as

$$\chi^2 = \sum_j \frac{(R_{A_1/A_2,j}^{\text{data}} - R_{A_1/A_2,j}^{\text{theo}})^2}{(R_{A_1/A_2,j}^{\text{err}})^2},$$  \hspace{1cm} (8)

where the experimental error is given by systematic errors as $R_{A_1/A_2,j}^{\text{err}}$, and $R_{A_1/A_2,j}^{\text{data}}$ ( $R_{A_1/A_2,j}^{\text{theo}}$) indicates the experimental data (theoretical values) for the ratio $R_{A_1/A_2}$. 


Taking advantage of the EKRS\cite{9} nuclear parton distribution functions with Eq.(4), the obtained $\chi^2$ value is $\chi^2 = 51.4$ for the 56 total data points when $\alpha = 0.0$(without energy loss effects). The $\chi^2$ per degrees of freedom is given by $\chi^2/d.o.f. = 0.918$. It is apparent that theoretical results without energy loss effects agree very well with the E866 experimental data. We consider also combining HKM01 cubic type of nuclear parton distribution\cite{10} with the linear quark energy loss parameterizations, i.e. Eq.(4). With $\alpha = 0.0$(without energy loss effects), the obtained $\chi^2$ per degrees of freedom is $\chi^2/d.o.f. = 2.526$. With $\alpha = 1.99$(with energy loss effects), the obtained $\chi^2$ per degrees of freedom are $\chi^2/d.o.f. = 1.008$. The results given by HKM01 quadratic type are nearly the same as these above. As an example, the calculated results with energy loss expression are shown in Fig.1 and Fig.2. which is the Drell-Yan cross section ratios for Fe to Be and W to Be as functions of $x_1$ for various interval of $M$, respectively. The solid curves are the ratios with only the nuclear effect on the parton distribution as in DIS scattering process, and the dotted curves correspond to an energy loss effect with nuclear effect on structure function. From comparison with the experimental data, it is found that our theoretical results with energy loss effect are in good agreement with the Fermilab E866. If employing the HKN04 nuclear parton distribution function \cite{11}, With $\alpha = 0.0$(without energy loss effects), the obtained $\chi^2$ per degrees of freedom is $\chi^2/d.o.f. = 2.526$. With $\alpha = 1.92$(with energy loss effects), the obtained $\chi^2$ per degrees of freedom are $\chi^2/d.o.f. = 1.045$. It is obvious that the results with HKM01 are most near to those with HKN04. We notice that HKM01 don’t use the nuclear Drell-Yan data, and HKN04 include E772 and E866 Drell-Yan experimental data. We give the results from a fit to E866 $R_{W/Be}$ and $R_{Fe/Be}$ in Table 1. It can be seen from the Table that they are similar by means of HKM01 and HKN04. Although
Table 1: The results in detail from a fit to E866 with HKM01 and HKN04

|                      | $\alpha = 1.99$ (HKM01) | $\alpha = 1.92$ (HKN04) |
|----------------------|--------------------------|--------------------------|
| $\chi^2$/d.o.f.(Fe/Be) | 0.873                    | 0.898                    |
| $\chi^2$/d.o.f.(W/Be)  | 1.143                    | 1.193                    |

HKN04 include the E772 and E866 Drell-Yan cross section ratios versus $x_2$, HKN04 don’t give a good fit to W/Be Drell-Yan ratios at small $x_2^{[11]}$, which may be the reason for two similar results.

In Fig.3, we show the nuclear modifications of sea quark distributions in EKRS(dotted line), HKM01(dashed line) and HKN04(solid line) at $Q^2 = 5.0 GeV^2$ for Be/D(up), Fe/D(middle) and W/D(down). It is found that the trend is the same for EKRS, HKM01 and HKN04 in the region $x_2 < 0.12$. The differences occur in the region $x_2 > 0.12$ among EKRS, HKM01 and HKN04. For E866 Drell-Yan measurement, the kinematic ranges cover $0.01 < x_2 < 0.12$ and $0.21 < x_1 < 0.95$ with dimuon mass in the range $4.0 < M < 8.4 GeV$. Therefore, the results from HKM01($\alpha = 1.99$) are similar to those of HKN04($\alpha = 1.92$). The sea quark modifications in EKRS is the lowest one, so that we obtain the theoretical results without quark energy loss in good agreement with the E866 experimental data. It is noticeable that HKN04 employ E772 and E866 Drell-Yan data, and EKRS include E772 experimental data.

**IV Prospects and summary**

It is demonstrated that the effects of quark energy loss are largest at lower incident proton energies at larger $x_1^{[22]}$. In the future, the Fermilab Main Injector (FMI, 120GeV proton beam)$^{[23]}$ and the Japan Proton Accelerator Research Complex (J-PARC, 50GeV proton beam)$^{[24]}$, where shadowing effect disappears and energy loss effect of fast quarks could provide the dominant nuclear depen-
dence, will be operated. The precise measurements of the nuclear dependent of Drell-Yan production can shed light on the quark energy loss. The HKM01 cubic type of nuclear parton distribution functions are employed in the following discussion. Figure 4 shows how quark energy loss would affect the \((p + W)/(p + D)\) per nucleon Drell-Yan cross sections at 50GeV and 120GeV proton beam. The kinematic ranges cover \(M > 4.2\text{GeV}\) in order to avoid contamination from charmonium decays. In this calculation, the energy loss per unit length \(\alpha = 1.99\text{GeV/fm}\) from a good fit to E866 with HKM01 nuclear parton distribution functions.

In addition, nuclear dependent Drell-Yan data can also further determine whether this energy loss is linear or quadratic with the path length. The \((p + W)/(p + D)\) per nucleon Drell-Yan cross section ratios are given in Fig.5 where the solid and dotted lines correspond to a quadratic energy loss of \(\beta = 0.29\text{GeV/fm}^2\) and to a linear energy loss of \(\alpha = 1.99\text{GeV/fm}\) from a fit to E866 at 120GeV and 50GeV proton beams, respectively. As seen in Fig.5, we can easily distinguish between \(L\) and \(L^2\) dependence of energy loss.

Although there are currently abundant data on electron and muon deep inelastic scattering off nuclei, it is difficult to determine nuclear valence quark distributions in the small \(x\) region and the nuclear anti-quark distributions in the \(x > 0.2\) region. Nuclear valence quark distributions in medium- and large-x region can be relatively well determined. It is well considered that the precise nuclear parton distributions must be known in order to calculate cross sections of high energy nuclear reactions accurately and find a signature of quark-gluon plasma in high energy heavy-ion reactions. We suggest using precise neutrino scattering experimental data, which can provide a good method for measuring the \(F_2(x, Q^2)\) and \(xF_3(x, Q^2)\) structure functions. Using the average of \(xF_3^\nu A(x, Q^2)\) and \(xF_3^{\bar{\nu} A}(x, Q^2)\),
the nuclear valence quark distribution functions can be well be clarified\textsuperscript{[25,26]}. The nuclear antiquark distribution can fixed by means of $F_2(x, Q^2)$ and Drell-Yan experimental data. From our results, the energy-loss effects are large in the large-$x_1$ region, especially in low-energy experiments (Fig.4). However, they are not large effects at moderate $x_1$, as shown in Figs.1 and 2, in the Fermilab experiments. In order to determine the nuclear antiquark distribution in the region, $x > 0.2$, we need another Drell-Yan experiment at lower incident proton energies. We suggest that, considering the existence of quark energy loss, the energy-loss effects should be taken into account for the extraction of precise nuclear parton distribution functions from the Drell-Yan experimental data.

In summary, we have made a leading-order analysis of E866 data in nuclei by taking into account of the energy loss effect of fast quarks. Our theoretical results with quark energy loss are in good agreement with the Fermilab E866 experiment by means of the HKM01 and HKN04 parametrizations of nuclear parton distributions, which is the same as that in our previous work\textsuperscript{[20]}. We find that the quark energy loss is close to nuclear parton distribution functions. We desire to operate precise measurements of the experimental study of the relatively low energy nuclear Drell-Yan process. These new experimental data can shed light on the energy loss of fast quark propagating in a cold nuclei and help to pin down nuclear parton distributions functions which have a direct impact on the interpretation of many hard scattering processes in nuclei.

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Figure 1: The nuclear Drell-Yan cross section ratios \( R_{A_1/A_2}(x_1) \) on Fe to Be for various intervals M. Solid curves correspond to nuclear effect on structure function. Dotted curves show the combination of shadowing and energy loss effect with HKM01 cubic type of nuclear parton distributions. The experimental data are taken from the E866[13].
Figure 2: The nuclear Drell-Yan cross section ratios $R_{A_1/A_2} (x_1)$ on W to Be for various intervals M. The comments are the same as Fig.1
Figure 3: The nuclear modifications of sea quark distributions in EKRS (dotted line), HKM01 (dashed line) and HKN04 (solid line) at $Q^2 = 5.0 GeV^2$ for Be/D, Fe/D and W/D.
Figure 4: The nuclear Drell-Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to D at 120GeV and 50GeV incident proton beams with a linear energy loss $\alpha = 1.99 GeV/fm$. Solid curves correspond to nuclear effect on structure function. Dotted curves show the combination of shadowing and energy loss effect with HKM01 cubic type of nuclear parton distributions.
Figure 5: The nuclear Drell-Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to D at 120GeV and 50GeV incident proton beams with a linear energy loss of $\alpha = 1.99\,\text{GeV/fm}$ and a quadratic energy loss of $\beta = 0.29\,\text{GeV/fm}^2$. Solid curves correspond to a quadratic energy loss. Dotted curves show the linear energy loss effect with HKM01 cubic type of nuclear parton distributions.