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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 an 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 800 GeV 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 protons 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 the fast quark propagating through cold nuclei and help to pin down nuclear parton distribution functions.

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1 Introduction

In proton–proton collisions, we learn about the interactions between the quarks and gluons that make up the colliding nucleon [1]. Parton distribution functions in the nucleon have been obtained by relative high energy reaction data [2]. These analyses help us calculate the 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 [3]. In proton–nucleus collisions, we hope to gain information about the modification of the parton distribution functions in the 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 ultra-relativistic 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 the 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 the J/ψ 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 [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 momen-

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tum 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 phenomenon is that the projectile suffers multiple collisions and repeated energy losses in the nuclear matter. In other words, each quark or gluon in the projectile can lose 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 a 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 the 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 the nucleus, a variety of approaches to this question existing in the literature [8] are available. Recently, there have been two groups doing a global analysis of nuclear parton distribution functions. Eskola, Kolhinen, Ruuskanen and Salgado (EKRS) produced the EKS98 package of nuclear parton distributions [9]. Hirai, Kumano, Miyama and Nagai derived several sets of nuclear parton distribution functions from extensive experimental data [10, 11]. In 1999, Eskola, Kolhinen, Ruuskanen and Salgado (EKRS) [9] suggested a set of nuclear parton distributions, which were studied within the framework of the DGLAP evolution. The measurements of F_2^A/F_2^{D} in deep inelastic lA collisions and Drell–Yan dilepton cross sections measured in pA collisions were used as constraints. The kinematical ranges are $10^{-6} \le x \le 1$ and $2.25\,\mathrm{GeV}^2 \le Q^2 \le 10^4\,\mathrm{GeV}^2$ 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 [12]. In 2001, Hirai, Kumano and Miyama (HKM01) [10] proposed two types of nuclear parton distributions which were obtained by a quadratic and cubic type analysis and determined by a χ^2 global analysis of the existing experimental data on nuclear structure functions without including the proton–nucleus Drell–Yan process. The kinematical ranges covered $10^{-9} \le x \le 1$ and $1\,\mathrm{GeV}^2 \le Q^2 \le 10^5\,\mathrm{GeV}^2$ for nuclei from deuteron to heavy ones. As a result, they obtained a reasonable fit to the measured experimental data of F_2. In 2004, Hirai, Kumano and Nagai (HKN04) [11] re-analyzed the experimental data of the nuclear structure function ratios $F_2^A/F_2^{A'}$ and the Drell–Yan cross section ratios for obtaining other parton distribution functions in nuclei. In HKN04, Drell–Yan data [12, 13] were included for determining the sea quark modification in the range $0.02 < x_2 < 0.2$. In addition, HERMES data [14] are used. In this work, we will use these parameterizations and investigate the nuclear dependence of the Drell–Yan process.

Fermilab Experiment866 (E866) [13] performed the precise measurement of the ratios of the Drell–Yan cross section per nucleon for an 800 GeV proton beam incident 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 [12]. The extended kinematic coverage of E866 significantly increases its sensitivity to energy losses and shadowing. This is the first experiment on the energy loss of a 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 [15–17] of the cross section of Drell–Yan. After the E866 experimental data were reported, several groups have given a theoretical analysis of the data [18–20]. In the previous report [20], by means of EKRS and HKM01 nuclear parton distribution functions, we investigated the Drell–Yan production cross section ratios from the E866 data in the framework of the Glauber model. We found that the theoretical results with energy losses 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 dependences 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 distributions. Using the values of the quark energy loss from a fit to the E866 experimental data, the prospects are given for the lower energy proton beams off deuterons and tungsten. Comparing with future experiments can give valuable insight in the energy loss of a fast quark propagating through cold nuclei and help to pin down nuclear parton distributions functions.

2 Nuclear Drell–Yan reaction

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

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}M} = \frac{8\pi\alpha^2}{9M} e_f^2 \delta\left(\hat{s} - M^2\right) , \tag{1}$$

where $\sqrt{\hat{s}} = (x_1 x_2 s)^{1/2}$ is the center of mass system (CM system) energy of a $q\bar{q}$ collision, x_1 (respectively x_2) is the momentum fraction carried by the projectile (respectively target) parton, $\sqrt{s}$ 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:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}M} \tag{2}$$
$$= K\frac{8\pi\alpha^2}{9M}\frac{1}{x_1 s}\sum_f e_f^2\left[q_f^p\left(x_1\right)\bar{q}_f^A\left(x_2\right) + \bar{q}_f^p\left(x_1\right)q_f^A\left(x_2\right)\right] ,$$

where K is the high-order QCD correction, α 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 antiquark 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,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1} = K\frac{8\pi\alpha^2}{9x_1 s} \times \sum_f e_f^2 \int \frac{\mathrm{d}M}{M}\left[q_f^p(x_1)\bar{q}_f^A(x_2) + \bar{q}_f^p(x_1)q_f^A(x_2)\right] , \tag{3}$$

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

Now let us take into account 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 the uncertainty principle, $\Delta x_1 \propto A^{1/3}$, which can be rewritten as

$$\Delta x_1 = \alpha\frac{\langle L\rangle_A}{E_p} , \tag{4}$$

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

$$\Delta x_1 = \beta\frac{\langle L\rangle_A^2}{E_p} . \tag{5}$$

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 losses, the production cross section in the pA Drell–Yan process can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1} = K\frac{8\pi\alpha^2}{9x_1 s} \times \sum_f e_f^2 \int \frac{\mathrm{d}M}{M}\left[q_f^p(x_1')\,\bar{q}_f^A(x_2) + \bar{q}_f^p(x_1')\,q_f^A(x_2)\right] . \tag{6}$$

3 Constraint on quark energy loss from E866

In order to pin down quark energy losses by comparing with the experimental data from the E866 collaboration [13], we introduce the nuclear Drell–Yan ratios as follows:

$$R_{A_1/A_2}(x_1) = \frac{\mathrm{d}\sigma^{p-A_1}}{\mathrm{d}x_1}\bigg/\frac{\mathrm{d}\sigma^{p-A_2}}{\mathrm{d}x_1} . \tag{7}$$

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

$$\chi^2 = \sum_j \frac{\left(R^{\mathrm{data}}_{A_1/A_2,j} - R^{\mathrm{theo}}_{A_1/A_2,j}\right)^2}{\left(R^{\mathrm{err}}_{A_1/A_2,j}\right)^2} , \tag{8}$$

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

Taking advantage of the EKRS [9] nuclear parton distribution functions with (4), the obtained χ^2 value is $\chi^2 = 51.4$ for the 56 total data points when $\alpha = 0.0$ (without energy-loss effects). The χ^2 per degree of freedom is given by $\chi^2/\mathrm{d.o.f.} = 0.918$. It is apparent that theoretical results without energy-loss effects agree very well with the E866 experimental data. We consider also combining an HKM01 cubic type of nuclear parton distribution [10] with the linear quark energy-loss parameterizations, i.e. (4). With $\alpha = 0.0$ (without energy-loss effects), the obtained χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} = 2.526$. With $\alpha = 1.99$ (with energy-loss effects), the obtained χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} = 1.008$. The results given by an HKM01 quadratic type are nearly the same as these above. As an example, the calculated results with the energy-loss expression are shown in Figs. 1 and 2 , which are the Drell–Yan cross section ratios for Fe to Be and W to Be as functions of x_1 for various intervals of M, respectively. The solid curves are the ratios with only the nuclear effect on the parton distribution as in the DIS scattering process, and the dotted curves correspond to an energy-loss effect with nuclear effect on the structure function. From comparison with the experimental data, it is found that our theoretical results with energy-loss effect are in good agreement with Fermilab E866. If employing the HKN04 nuclear parton distribution function [11], with $\alpha = 0.0$ (without energy-loss effects), the obtained χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} = 2.526$. With $\alpha = 1.92$ (with energy-loss effects), the obtained χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} = 1.045$. It is obvious that the results with HKM01 are closest to those with HKN04. We notice that HKM01 do not use the nuclear Drell–Yan data, and HKN04 include the E772 and E866 Drell–Yan experimental data. We give the results from a fit to E866, $R_{\mathrm{W/Be}}$ and $R_{\mathrm{Fe/Be}}$, in Table 1. It can be seen from this table that they are similar by means of HKM01 and HKN04. Although HKN04 includes the E772 and E866 Drell–Yan cross section ratios versus x_2, HKN04 does not give a good fit to the W/Be Drell–Yan ratios at small x_2 [11], which may be the reason for the two similar results.

Table 1. The detailed results from a fit to E866 with HKM01 and HKN04

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

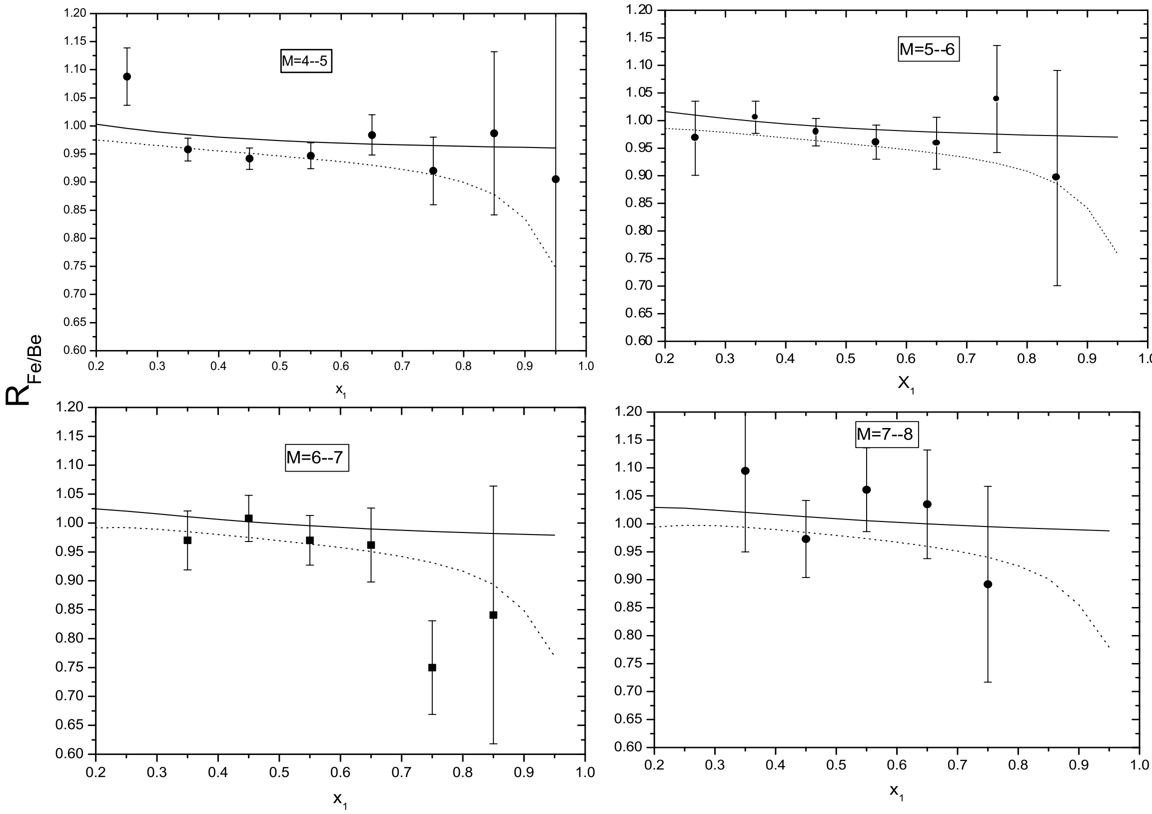

Fig. 1. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on Fe to Be for various intervals M. Solid curves correspond to the nuclear effect on the structure function. Dotted curves show the combination of shadowing and energy-loss effect with HKM01 cubic type of nuclear parton distributions. The experimental data are taken from the E866 [13]

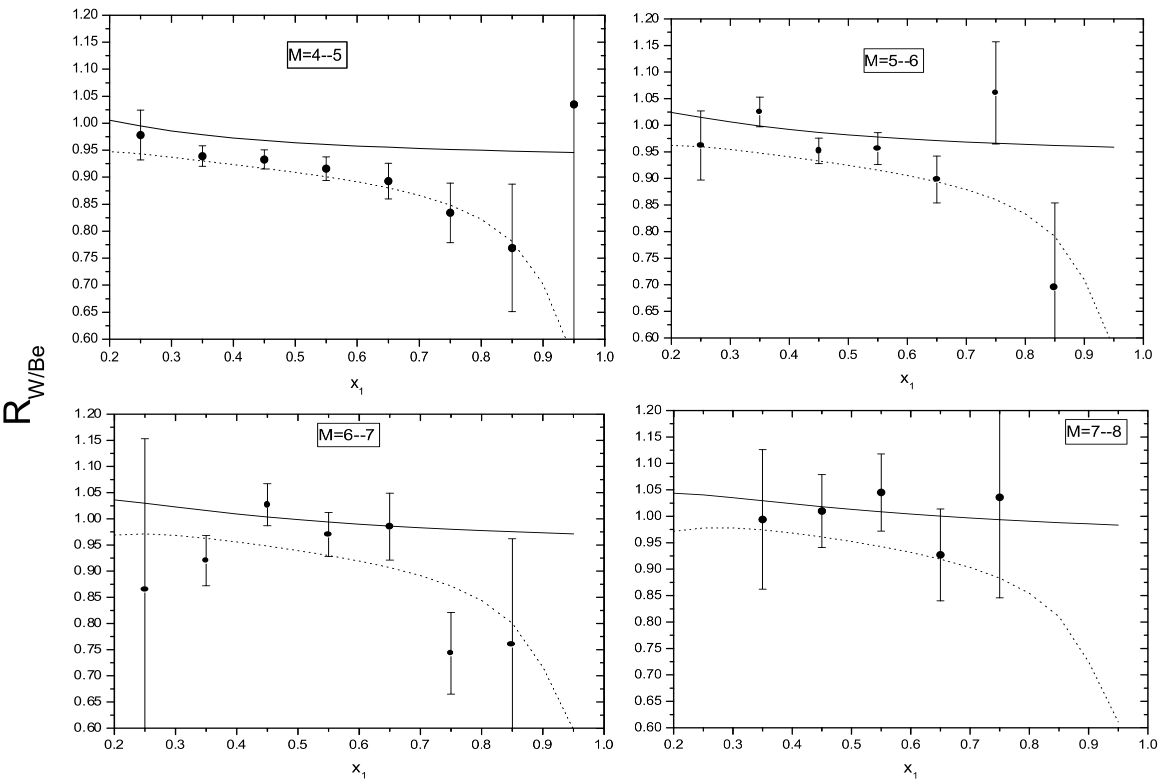

Fig. 2. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to Be for various intervals M. The comments are the same as Fig. 1

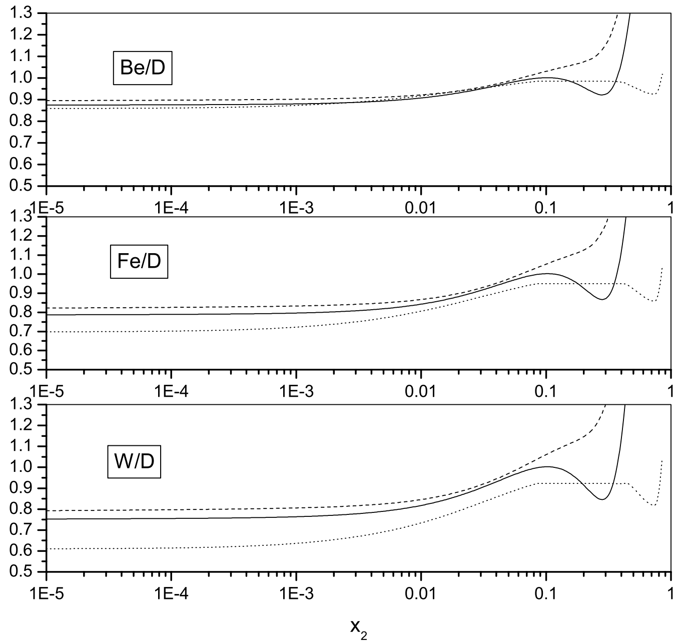

Fig. 3. The nuclear modifications of sea quark distributions in EKRS (dotted line), HKM01 (dashed line) and HKN04 (solid line) at $Q^2 = 5.0\,\mathrm{GeV}^2$ for Be/D, Fe/D and W/D

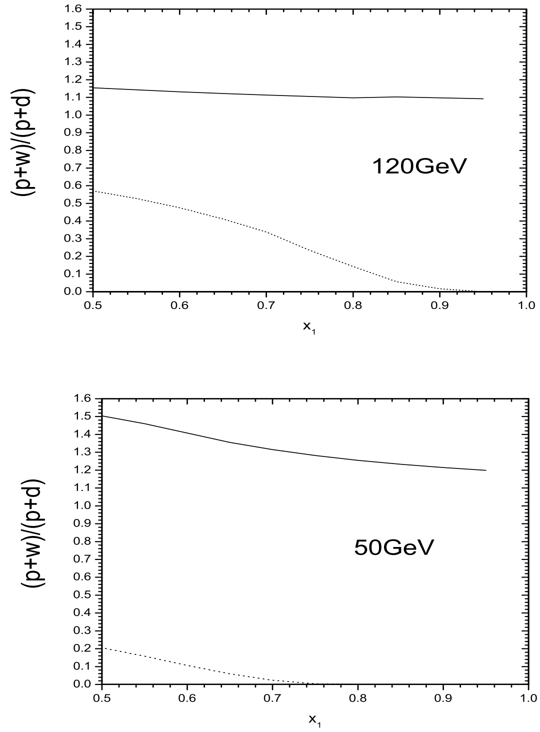

Fig. 4. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to D at 120 GeV and 50 GeV incident proton beams with a linear energy loss $\alpha = 1.99\,\mathrm{GeV/fm}$. Solid curves correspond to the nuclear effect on the structure function. Dotted curves show the combination of shadowing and energy-loss effect with HKM01 cubic type of nuclear parton distributions

In Fig. 3, we show the nuclear modifications of sea quark distributions in EKRS (dotted line), HKM01 (dashed line) and HKN04 (solid line) at $Q^2 = 5.0\,\mathrm{GeV}^2$ 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 the 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 $4.0 < M < 8.4\,\mathrm{GeV}$. Therefore, the results from HKM01 ($\alpha = 1.99$) are similar to those of HKN04 ($\alpha = 1.92$). The sea quark modifications in EKRS are the lowest ones, so that we obtain the theoretical results without quark energy losses in good agreement with the E866 experimental data. It is noticeable that HKN04 employ the E772 and E866 Drell–Yan data, and EKRS include the E772 experimental data.

4 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, 120 GeV proton beam) [23] and the Japan Proton Accelerator Research Complex (J-PARC, 50 GeV proton beam) [24], where the shadowing effect disappears and the energy-loss effect of fast quarks could provide the dominant nuclear dependence, will be operational. The precise measurements of the nuclear dependence of the 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 the quark energy loss would affect the $(p+\mathrm{W})/(p+\mathrm{D})$ Drell–Yan cross sections per nucleon at 50 GeV and 120 GeV proton beam. The kinematic ranges cover $M > 4.2\,\mathrm{GeV}$ in order to avoid contamination from charmonium decays. In this calculation, the energy loss per unit length is $\alpha = 1.99\,\mathrm{GeV/fm}$ from a good fit to E866 with the 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 $(p+\mathrm{W})/(p+\mathrm{D})$ 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 $\beta = 0.29\,\mathrm{GeV/fm}^2$ and to a linear energy loss of $\alpha = 1.99\,\mathrm{GeV/fm}$ from a fit to E866 at 120 GeV and 50 GeV proton beams, respectively. As seen in Fig. 5, we can easily distinguish between the L and L^2 dependences 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 antiquark distributions in the $x > 0.2$ region. Nuclear valence quark distributions in the medium- and large-x region can be relatively well determined. It is well to consider that the precise nuclear parton distributions must be known in order to calculate the cross sections of high energy nuclear reactions accurately and find a signature of the quark–gluon plasma in high energy heavy-ion reactions. We suggest using precise neutrino scattering experimental data, which can provide a

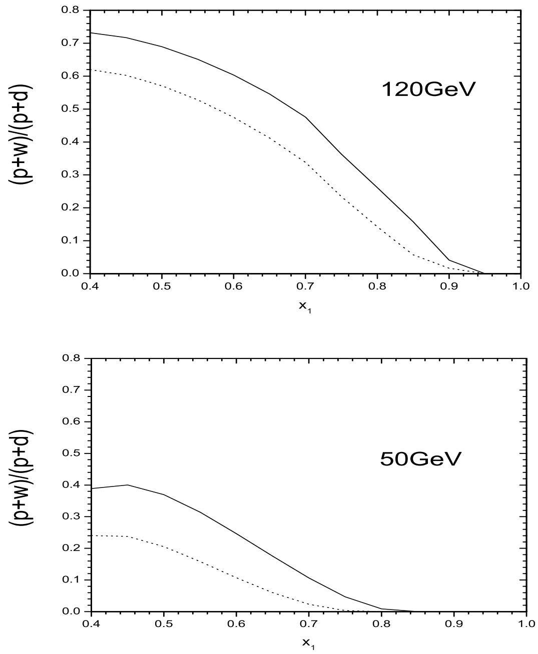

Fig. 5. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to D at 120 GeV and 50 GeV incident proton beams with a linear energy loss of $\alpha = 1.99\,\mathrm{GeV/fm}$ and a quadratic energy loss of $\beta = 0.29\,\mathrm{GeV/fm^2}$. Solid curves correspond to a quadratic energy loss. Dotted curves show the linear energy-loss effect with HKM01 cubic type of nuclear parton distributions

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 clarified [25,26]. The nuclear antiquark distributions can be fixed by means of the $F_2(x,Q^2)$ 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 the E866 data in nuclei by taking into account 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 [20]. We find that the quark energy loss is close to the nuclear parton distribution functions. We desire to perform precise measurements of the experimental study of the relatively low energy nuclear Drell–Yan process. These new experimental data can shed light on the enengy loss of a fast quark propagating in cold nuclei and help to pin down nuclear parton distribution functions which have a direct impact on the interpretation of many hard scattering processes in nuclei.

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