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Energy loss effect in high energy nuclear Drell–Yan process

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Abstract. The energy loss effect in nuclear matter, which is a nuclear effect apart from the nuclear effect on the parton distribution as in deep-inelastic scattering process, can be measured best by the nuclear dependence of the high energy nuclear Drell–Yan process. By means of the nuclear parton distribution studied only with lepton deep-inelastic scattering experimental data, the measured Drell–Yan production cross sections for 800 GeV proton incident on a variety of nuclear targets are analyzed within the Glauber framework which takes into account the energy loss of the beam proton. It is shown that the theoretical results with considering the energy loss effect are in good agreement with the FNAL E866 data.

1 Introduction

The propagating of a high energy particle through a nuclear medium is of interest in many areas of physics. High energy proton–nucleus scattering has been studied for many decades by both the nuclear and particle physics communities [1]. By means of the nuclei, we can study the space-time development of the strong interaction during its early stages, which is inaccessible by interactions between individual hadrons. The Drell–Yan reaction [2] on nuclear targets provides, in particular, the possibility of probing the propagation of a projectile through nuclear matter, with the produced lepton pair carrying away the desired information on the projectile 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 [3].

Drell–Yan scattering is closely related to deep-inelastic scattering (DIS) of leptons, but unlike DIS, it is directly sensitive to the antiquark contributions in the 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 [4]. 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 [5]. The energy loss effect is another nuclear effect; it stands apart from the nuclear effect on the parton distribution as in DIS scattering process. Shadowing and the initial-state energy loss effect are processes that occur in both the Drell–Yan reaction and J/ψ formation. Characterizing the energy loss effect in nuclear matter should further the understanding of 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.

In 1999, the Fermilab Experiment866 Collaboration (E866) [6] reported 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 [7]. The extended kinematic coverage of E866 significantly increases its sensitivity to energy loss and shadowing.

Recently, M.B. Johnson, B.Z. Kopeliovich and I.K. Potashnikova [8] and F. Arleo [9] gave a theoretical analysis of the E866 Drell–Yan experimental data by means of different methods, respectively. Johnson et al. examined the effect of initial-state energy loss on the Drell–Yan cross section ratios versus the incident proton's momentum fraction by employing a new formulation of the Drell–Yan process in the rest frame of the nucleus. Arleo carried out a leading-order analysis of the E866 Drell–Yan data in nuclei according to multiple scattering of a high energy parton traversing a large nucleus ("cold" QCD matter) studied by Baier et al. (BDMPS) [10], in which the multiple soft gluon emission from the incoming parton leads to parton energy loss.

Since the EMC effect was discovered, various phenomenological models have been proposed to investigate the nuclear effect [11–14]. R.P. Bickerstaff, M.C. Birse, and G.A. Miller [15] found that, although most of the theoretical models provide good explanations for the EMC effect, they do not give a good description of the nuclear Drell–Yan process. Most of them overestimate the Drell–Yan differential cross section ratios. In a previous paper [16], we suggested an additional nuclear effect due to the energy loss in nuclear Drell–Yan processes by means of the Glauber model [17], which has been extensively employed in nucleus–nucleus reactions with a good fit to the related experiment [18]. It was found that the nuclear Drell–Yan ratio is suppressed significantly as a consequence of the continuous energy loss of the projection proton to the target nucleon in their successive binary nucleon–nucleon collisions. This suppression balances the overestimate of the Drell–Yan ratio only by consideration of the nuclear effect from the parton distribution.

Recently, there were two trials to obtain nuclear parton distributions from the existing world experimental data. In 1999, Eskola et al. (EKS) [19] suggested a set of nuclear parton distributions which are 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 $10^{-6} \leq x \leq 1$ and $2.25\,\mathrm{GeV}^2 \leq Q^2 \leq 10^4\,\mathrm{GeV}^2$ 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. In 2001, Hirai et al. (HKM) [20] proposed two types of nuclear parton distributions which were obtained by quadratic- and cubic-type analyses, and determined by a χ^2 global analysis of the existing experimental data on the nuclear structure functions without including the proton–nucleus Drell–Yan process. The kinematical ranges covered $10^{-9} \leq x \leq 1$ and $1\,\mathrm{GeV}^2 \leq Q^2 \leq 10^5\,\mathrm{GeV}^2$ for nuclei from deuteron to heavy ones. As a result, they obtained a reasonable fit to the measured experimental data of F_2. In this report, by means of the EKS and HKM nuclear parton distribution functions, the Drell–Yan production cross section ratios for 800 GeV protons incident on a variety of nuclear targets are analyzed by using the Glauber model, taking into account the energy loss of the projective proton going through the nuclei.

2 Method

According to the Glauber model [17], the projectile proton scattering inelastically on a nucleus (A) makes many collisions with nucleons bound in the nuclei. The probability of having n collisions at an impact parameter $\vec{b}$ can be expressed as

$$P(\vec{b},n) = \frac{A!}{n!(A-n)!}[T(\vec{b})\sigma_{\mathrm{in}}]^n[1-T(\vec{b})\sigma_{\mathrm{in}}]^{A-n}, \quad (1)$$

where σ_{in} ($\sim 30\,\mathrm{mb}$) is the non-diffractive cross section for an inelastic nucleon–nucleon collision, and $T(\vec{b})$ is the thickness function of the impact parameter $\vec{b}$. For collisions of nucleons which are not polarized, the collisions do not depend on the orientation of $\vec{b}$, and $T(\vec{b})$ depends only on the magnitude $|\vec{b}| = b$. So, we could consider only this case of $T(\vec{b}) = T(b)$. In a nucleon–nucleus collision without impact parameter selection, the number of nucleon–nucleon collisions n (for $n = 1$ to A) has a probability distribution

$$P(n) = \frac{\int \mathrm{d}\vec{b}P(n,\vec{b})}{\sum\limits_{n=1}^{A}\int \mathrm{d}\vec{b}P(n,\vec{b})}. \quad (2)$$

In the following calculation, the thickness function can be conveniently written as [18]

$$T(\vec{b}) = \begin{cases} \frac{1}{2\pi\beta_A^2}\exp(-\vec{b}^2/2\beta_A^2), & A \leq 32, \\ \frac{3}{2\pi R_A^3}\sqrt{R_A^2-\vec{b}^2}\,\theta(R_A-|\vec{b}|), & A > 32. \end{cases} \quad (3)$$

Here $R_A = r_0 A^{1/3}$ is the radius of a colliding nucleus with $r_0 = 1.2\,\mathrm{fm}$, θ is the step function, and $\beta_A = 0.606A^{1/3}$.

In the multiple-collision Glauber model, the basic process is the nucleon–nucleon collision for the proton-nucleus Drell–Yan process. The leading-order contribution to the Drell–Yan process 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

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}M} = \frac{8\pi\alpha^2}{9M}e_f^2\delta(\hat{s}-M^2), \quad (4)$$

where $\hat{s} = x_1x_2s$ is the center of mass system (c.m. 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 hadron:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}M} = K\frac{8\pi\alpha^2}{9M}\frac{1}{x_1s}\sum_f e_f^2[q_f^p(x_1)\bar{q}_f^A(x_2)+\bar{q}_f^p(x_1)q_f^A(x_2)], \quad (5)$$

where K is the high-order QCD correction, α is the fine-structure constant, 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 addition, one has the kinematic relations

$$x_1x_2 = \frac{M^2}{s}, \quad x_{\mathrm{F}} = x_1 - x_2, \quad (6)$$

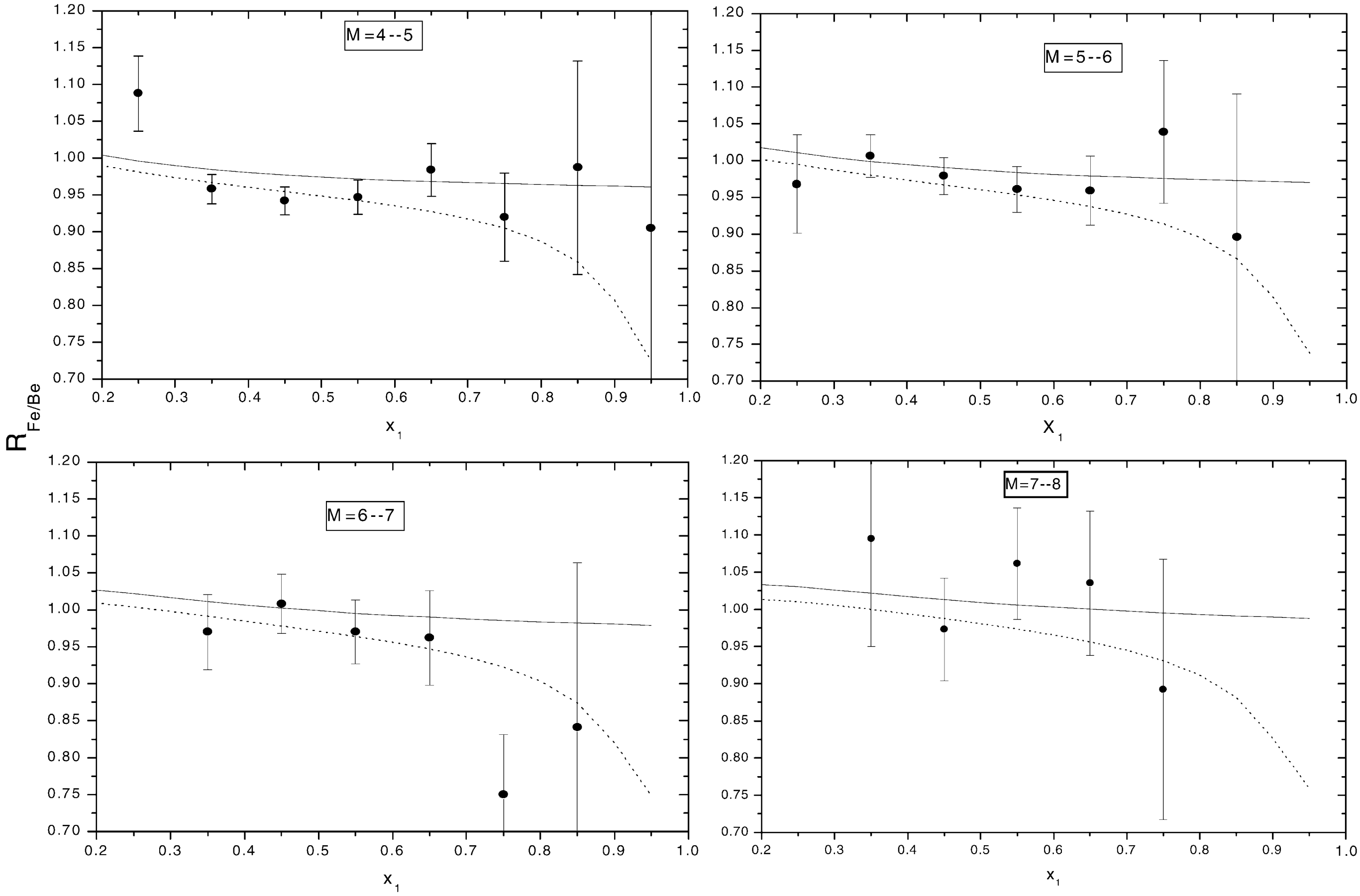

Fig. 1. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on Fe to Be for various M intervals. Solid curves correspond to the nuclear effect on the structure function. Dotted curves show the combination of shadowing and the energy loss effect ($\Delta\sqrt{s} = 0.18\,\mathrm{GeV}$) with HKM cubic type of nuclear parton distributions. The experimental data are taken from E866 [6]

with the Feynman scaling variable

$$x_{\mathrm{F}} = \frac{2p_{\mathrm{L}}}{\sqrt{s}}, \tag{7}$$

where p_{L} is the longitudinal momentum of the virtual photon,

Now let us take into account the energy loss of the projectile proton moving through the nuclei. In proton–nucleus Drell–Yan collisions, the incident proton passes through the nucleus before producing the high Q^2 dimuon pair. On the one hand, the projectile proton may interact with a spectator nucleon bound in nuclei, in which soft (non-perturbative) minimum bias collisions may occur before making the final lepton pair. As a result, the projectile proton imparts energy to the struck nucleon and therefore must lose energy. On the other hand, the projectile proton, which travels through the nucleus, while there occur multiple collisions, may emit a soft gluon between two bias collisions in the nucleus, and must consequently experience energy loss. Thus the energy loss from the two above aspects in multiple collisions can induce a decrease of the c.m. system energy of the nucleon–nucleon collision producing a dimuon and affect the measured Drell–Yan cross section. After the projectile proton has n collisions with nucleons in nuclei, suppose for convenient calculation that the c.m. system energy of the nucleon–nucleon collision producing a dimuon can be expressed as

$$\sqrt{s'} = \sqrt{s} - (n-1)\Delta\sqrt{s}, \tag{8}$$

where $\Delta\sqrt{s}$ is the c.m. system energy loss per collision in the initial state. Therefore, the cross section for the Drell–Yan process can be rewritten as

$$\begin{aligned}&\frac{\mathrm{d}^2\sigma^{(n)}}{\mathrm{d}x_1\mathrm{d}M} \\ &= K\frac{8\pi\alpha^2}{9M}\frac{1}{x_1 s'}\sum_f e_f^2[q_f^p(x_1')\bar{q}_f^A(x_2') + \bar{q}_f^p(x_1')q_f^A(x_2')].\end{aligned} \tag{9}$$

Here the rescaled quantities are defined by

$$x'_{1,2} = r_s x_{1,2}, \tag{10}$$

with the c.m. system energy ratio

$$r_s = \frac{\sqrt{s}}{\sqrt{s'}}, \tag{11}$$

because of

$$x'_{\mathrm{F}} = \frac{2p_l}{\sqrt{s'}} = r_s x_{\mathrm{F}}. \tag{12}$$

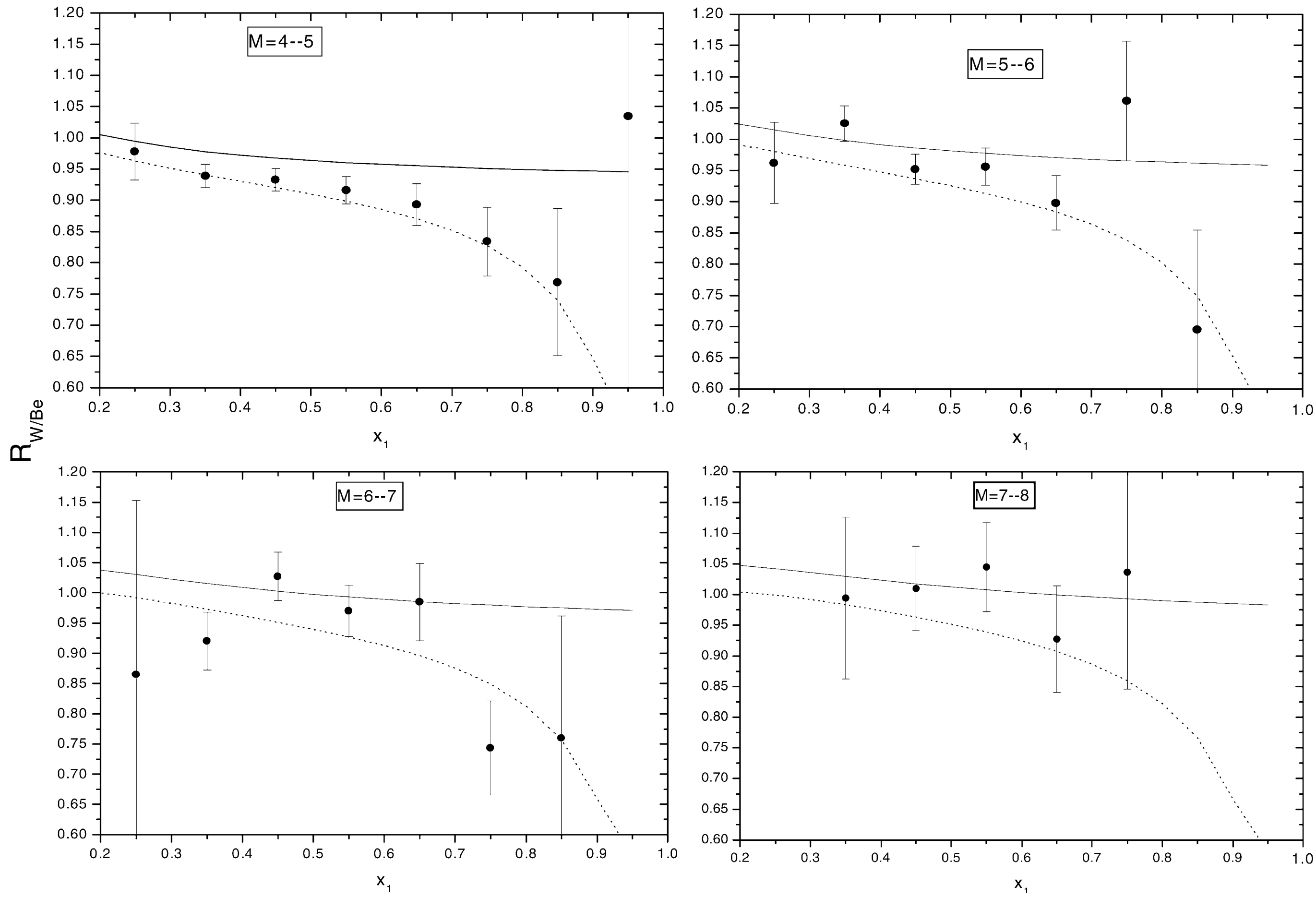

Fig. 2. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ on W to Be for various M intervals. The comments are the same as in Fig. 1

It is obvious that r_s is always greater than one. Combining the above ingredients, the measured Drell–Yan cross section in proton–nucleus collision experiments can be expressed as

$$\left\langle \frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1 M} \right\rangle = \sum_{n=1}^{A} P(n) \frac{\mathrm{d}^2\sigma^{(n)}}{\mathrm{d}x_1 dM}. \quad (13)$$

3 Results and discussion

In order to compare with the experimental data from the E866 Collaboration [6], we introduce the nuclear Drell–Yan ratios:

$$R_{A_1/A_2}(x_1) = \frac{\int \mathrm{d}M \langle \frac{\mathrm{d}^2\sigma^{p-A_1}}{\mathrm{d}x_1 \mathrm{d}M} \rangle}{\int \mathrm{d}M \langle \frac{\mathrm{d}^2\sigma^{p-A_2}}{\mathrm{d}x_1 \mathrm{d}M} \rangle}. \quad (14)$$

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} and found to be

$$\chi^2 = \sum_j \frac{(R^{\mathrm{data}}_{A_1/A_2,j} - R^{\mathrm{theo}}_{A_1/A_2,j})^2}{(R^{\mathrm{err}}_{A_1/A_2,j})^2}, \quad (15)$$

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}.

If the EKS [19] nuclear parton distribution functions are used together with the CTEQ (the Coordinated Theoretical Experimental Project on QCD) [21] parton distribution functions in a proton, the obtained χ^2 value is $\chi^2 = 51.4$ without energy loss effects for the total of 56 data points. The χ^2 per degree of freedom is given by $\chi^2/\mathrm{d.o.f.} = 0.918$. It is shown that the theoretical results agree very well with the E866 experimental data, which results from the EKS parametrization of nuclear parton distributions studied with including the Drell–Yan process.

In addition, we consider also using HKM [20] nuclear parton distribution functions together with MRST [22] parton distribution functions in a proton. The calculated results with HKM cubic type of nuclear parton distribution 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: $\Delta\sqrt{s} = 0.18\,\mathrm{GeV}$ with nuclear effect on the structure function. The obtained χ^2 values are $\chi^2 = 56.39$ with energy loss effect (i), $\chi^2 = 143.74$ (ii) without energy loss effect, respectively, for the total of 56 data points. The χ^2 per degree of freedom are $\chi^2/\mathrm{d.o.f.} = 1.007$ (i), 2.567 (ii), respectively. Employing the HKM quadratic type of nuclear parton distribution, the χ^2 values are $\chi^2 = 56.81$ with energy loss effect, and $\chi^2 = 143.88$ without energy loss effect, respectively. The χ^2 per degree of freedom are $\chi^2/\mathrm{d.o.f.} = 1.015$, 2.569, respectively. This implies that the observed energy loss of the incident proton is $\Delta\sqrt{s} = 0.18\,\mathrm{GeV}$ at 1σ, which is almost equal to our previous result, $\Delta\sqrt{s} = 0.2\,\mathrm{GeV}$ [16]. 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 data.

In summary, we have made a leading-order analysis of the E866 data in nuclei within the framework of the Glauber model by taking into account the energy loss effect of the beam proton. In continuous multiple collisions, the energy loss effect in the initial state causes the suppression of the proton-induced nuclear Drell–Yan cross section. It is found that the theoretical results with energy loss are in good agreement with the Fermilab E866 experiment by means of the parametrization of the nuclear parton distributions studied without nuclear Drell–Yan process. This is a nuclear effect apart from the nuclear effect on the parton distribution as in DIS scattering process. The nuclear effect on the structure functions and initial-state energy loss can occur in both Drell–Yan production and J/ψ formation. Hence, these researches should also further the understanding of J/ψ production. Considering the existence of an energy loss effect in Drell–Yan lepton pairs production, we think that the determination of nuclear parton distribution functions should not include Drell–Yan experimental data. Although there are abundant data on electron and muon deep-inelastic scattering, valence quark distributions in the small x region and the antiquark distributions are with difficulty determined. At this stage, only valence quark distributions in the medium 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 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 precise neutrino scattering experiments, 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 valence quark distribution functions can well be determined. Combining the lepton inelastic scattering data with the neutrino scattering experiments, valence quark and antiquark distribution functions will be obtained in the future, which makes us better understand the energy loss effect in high energy nuclear Drell–Yan collisions.

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