Eur. Phys. J. C 50, 585–591 (2007)
DOI 10.1140/epjc/s10052-007-0229-3

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

The extraction of the nuclear sea-quark distribution and energy loss effect in a Drell–Yan experiment

C.-G. Duan[1,4,a], N. Liu[1,2], Z.-Y. Yan[3,4]

[1] Department of Physics, Hebei Normal University, Shijiazhuang 050016, P.R. China
[2] College of Mathematics and Physics, Shijiazhuang University of Economics, Shijiazhuang 050031, P.R. China
[3] Department of Applied Physics, North China Electric Power University, Baoding 071003, P.R. China
[4] CCAST (World Laboratory), P.O.Box 8730, Beijing 100080, P.R. China

Received: 6 October 2006 / Revised version: 16 January 2007 /
Published online: 20 February 2007 –

Abstract. A next-to-leading order and a leading order analysis are performed of the differential cross section ratios from the Drell–Yan process. It is found that the effect of next-to-leading order corrections on the differential cross section ratios as a function of the quark momentum fraction in the proton beam and the target nuclei for the current Fermilab and future lower proton energy beam can be considered negligible. The nuclear Drell–Yan reaction is an ideal tool to study the energy loss of fast quarks moving through cold nuclei. In a leading order analysis, the theoretical results with the quark energy loss are in good agreement with the Fermilab E866 experimental data on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton. It is shown that the quark energy loss effect has a significant impact on the Drell–Yan differential cross section ratios. Therefore, it is important to understand the energy loss effects for determining nuclear sea-quark distributions from future nuclear Drell–Yan experiments at the lower energy proton beams bombarding nuclei.

PACS. 12.38.-t; 13.85.Qk; 24.85.+p; 25.40.-h

1 Introduction

In 1983, the European Muon Collaboration (EMC) [1] reported that the ratios of the nuclear structure functions for iron and deuteron nuclei are not equal to unity but are a function of the Bjorken scaling variable x in charged lepton–nucleus deep inelastic scattering. It shows that the parton distributions are modified in the nuclear environment, because the structure function describes the quark momentum distributions in bound nucleons. From then on, the quark and gluon distributions in hadrons and nuclei have been one of the most active frontiers in nuclear physics and particle physics. The nuclear parton distribution directly affects the interpretation of the data collected from the nuclear reactions at high energies [2, 3]. The precise nuclear parton distribution function is very important in finding new physics phenomena and determining the electro-weak parameters, neutrino masses and mixing angles in neutrino physics.

In the early 1970s, Drell and Yan first studied the production of large-mass lepton pairs from hadron–hadron inelastic collisions, which is the so-called Drell–Yan process [4]. According to the parton model, the process is induced by the annihilation of a quark–antiquark pair into a virtual photon, which subsequently decays into a lepton pair. The nuclear Drell–Yan process of proton–nucleus collisions therefore is closely related to the quark distribution functions in nuclei. It is further natural to expect that the Drell–Yan reaction is a complementary tool for probing the structure of hadron and nuclei.

In 1990, Fermilab Experiment 772 (E772) [5] made a measurement of the nuclear dependence of the Drell–Yan process by using 800 GeV protons bombarding D, C, Ca, Fe, and W nuclei. Muon pairs were recorded in the range $4\,\mathrm{GeV} \leq M \leq 9\,\mathrm{GeV}$ and $M \geq 11\,\mathrm{GeV}$. The covered kinematical range was $0.1 < x < 0.3$, where x is the momentum fraction of the target parton. The aim was to investigate the modification of the quark structure in nuclei. Theoretical models, which can well describe the EMC effect in the charged lepton–nuclei deep inelastic scattering, were used to fit the observations of the Drell–Yan differential cross section ratios. It is found that some of the theoretical models overestimate the nuclear Drell–Yan ratios from Fermilab E772, such as the pion-excess model [6] and the quark-cluster model [7]. It indicated that there is another nuclear effect, apart from the nuclear effects on the parton distributions as in charged lepton–nucleus deep inelastic scattering.

In 1999, Fermilab Experiment 866 (E866) [8] performed a precise observation of the ratios of the Drell–Yan cross

[a] e-mail: duancg@mail.hebtu.edu.cn

section per nucleon for an 800 GeV proton beam incident on Be, Fe and W targets. The Drell–Yan events extend over the ranges $4\,\text{GeV} < M < 8.4\,\text{GeV}$, $0.01 < x_2 < 0.12$, $0.21 < x_1 < 0.95$ and $0.13 < x_F < 0.93$, where $x_{1(2)}$ and x_F are the momentum fraction of the beam parton (the target nuclear parton) and the Feynman scaling variable, respectively. The extended kinematic coverage of E866 significantly increased its sensitivity to the nuclear shadowing effect and the quark energy loss. This is the first experiment on the energy loss of a projectile particle moving through cold nuclei. The E866 group compared their experimental data with the results from leading order Drell–Yan calculations by using the EKRS (Eskola, Kolhinen, Ruuskanen and Salgado) nuclear parton distributions [9, 10] together with the MRST (Martin, Roberts, Stirling and Thorne) parton distribution functions [11]. It is shown that the energy loss effect can be considered negligible.

In previous works [12–14], we investigated the Drell–Yan differential cross section ratios as a function of the momentum fraction of the beam parton from the E866 data in the framework of the Glauber model by means of EKRS and HKM (Hirai, Kumano and Miyama) nuclear parton distribution functions [15]. We found that the theoretical results with the energy loss of the beam proton are in good agreement with the Fermilab E866 experiment by means of the HKM nuclear parton distributions. However, the calculated results without energy loss can give good fits by using the EKRS nuclear parton distribution functions. Furthermore, we introduced two typical kinds of quark energy loss parametrization, i.e. the models with linear and the quadratic quark energy loss in the average path length of the incident quark in the nucleus A. The nuclear dependence of the Drell–Yan production cross sections were calculated by combining the quark energy loss effect with the EKRS, HKM and HKN (Hirai, Kumano and Nagai) [16] nuclear parton distributions. The global fit of χ^2 to the Drell–Yan differential cross section ratios indicated that the theoretical results without energy loss effects agree very well with the E866 experimental data by taking advantage of the EKRS nuclear parton distribution functions. If employing the HKM nuclear parton distribution function, the results with energy loss effect are in good agreement with the Fermilab E866 data. In addition, the results with HKM are nearest to those with HKN. It is demonstrated that at current Fermilab incident proton energy we cannot distinguish between the linear and quadratic dependence of the quark energy loss. Further experiments are needed with nuclear Drell–Yan reactions with a lower energy incident proton. Using the values of the quark energy loss from a fit to the E866 experimental data, prospects are given for the lower energy proton beam bombarding deuteron and tungsten. It is shown that these future experiments can give valuable insight in the energy loss of a fast quark propagating through cold nuclei. In the analysis above, we performed leading order calculations of the Drell–Yan differential cross sections. As it is well known, QCD corrections can alter quite significantly the cross sections at a hadronic collider. Thus, these may have a serious bearing on the discovery potential of the Drell–Yan reactions, in which the leading order (LO) results may seriously underestimate the cross sections. This has led to the incorporation of the next-to-leading order (NLO) results. As for the nuclear parton distributions, the EKRS, HKM and HKN nuclear parton distributions have been obtained by Eskola et al. [9, 10] and Hirai et al. [15, 16] with a global analysis of the relative experimental data, respectively. It is noticeable that HKM use only charged lepton–nucleus deep inelastic scattering experimental data, and that HKN and EKRS employ the E772 and E866 nuclear Drell–Yan reaction data in order to pin down the nuclear antiquark distribution in the small-x region. In this report, we will explore the effect of the NLO correction on the Drell–Yan differential cross section ratios, and the influence of the quark energy loss on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton.

This paper is organized as follows. In Sect. 2, briefly the formalism for the differential cross section in the Drell–Yan process is presented. The effect of the NLO correction is given on the Drell–Yan differential cross section ratios in Sect. 3. The influence of the quark energy loss is given on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton in Sect. 4, and a summary is given in Sect. 5.

2 Brief formalism for differential cross section in Drell–Yan reaction

In the Drell–Yan process [4], the perturbative QCD 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:

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

where $\sqrt{\hat{s}} = (x_1 x_2 s)^{1/2}$, is the center of mass system (c.m. system) energy of the $q\bar{q}$ 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 nuclear 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 target,

$$\frac{\mathrm{d}^2\sigma^{\mathrm{DY}}}{\mathrm{d}x_1\,\mathrm{d}x_2} = \frac{4\pi\alpha^2}{9sx_1x_2} \sum_f e_f^2 \left[q_f^p(x_1, Q^2) \bar{q}_f^A(x_2, Q^2) + \bar{q}_f^p(x_1, Q^2) q_f^A(x_2, Q^2) \right], \tag{2}$$

where α is the fine-structure constant, the sum is carried out over the light flavor $f = u, d, s$, and $q_f^{p(A)}(x, Q^2)$ and $\bar{q}_f^{p(A)}(x, Q^2)$ are the quark and antiquark distributions in the proton (nucleon in the nucleus A).

In addition to the leading order Drell–Yan term, the contributions are needed from the $q\bar{q}$ annihilation processes ($q\bar{q} \to \gamma^* + g$) and gluon Compton scattering ($q + g \to \gamma^* + q$) [17] in the perturbative QCD next-to-leading order, which are denoted as Ann and Comp, respectively. The contribution from the order-α_s annihilation graphs is

$$\frac{d^2\sigma^{Ann}}{dx_1\,dx_2} = \int_{x_1}^{1} dt_1 \int_{x_2}^{1} dt_2 \times \left[\frac{d^2\hat{\sigma}^{Ann}}{dt_1\,dt_2} \sum_f e_f^2 q_f^p(t_1, Q^2) \bar{q}_f^A(t_2, Q^2) + \frac{d^2\hat{\sigma}^{Ann}}{dt_1\,dt_2}(t_1 \leftrightarrow t_2) \sum_f e_f^2 \bar{q}_f^p(t_1, Q^2) q_f^A(t_2, Q^2)\right], \tag{3}$$

with

$$\begin{aligned}\frac{d^2\hat{\sigma}^{Ann}}{dt_1\,dt_2} =& \sum_f \frac{8\alpha^2\alpha_s(Q^2)}{27Q^2}\delta(t_1 - x_1)\delta(t_2 - x_2) \\ &\times \left[1 + \frac{5}{3}\pi^2 - \frac{3}{2}\ln\frac{x_1 x_2}{(1-x_1)(1-x_2)} + 2\ln\frac{x_1}{1-x_1}\ln\frac{x_2}{1-x_2}\right] \\ &+ \sum_f \frac{8\alpha^2\alpha_s(Q^2)}{27Q^2}\delta(t_2 - x_2) \\ &\times \left[\frac{t_1^2 + x_1^2}{t_1^2(t_1 - x_1)_+}\ln\frac{2x_1(1-x_2)}{x_2(t_1+x_1)} + \frac{3}{2(t_1 - x_1)_+} - \frac{2}{t_1} - \frac{3x_1}{t_1^2}\right] + (1 \leftrightarrow 2) \\ &+ \sum_f \frac{16\alpha^2\alpha_s(Q^2)}{27Q^2} \\ &\times \left[\frac{(\tau + t_1 t_2)\left[\tau^2 + (t_1 t_2)^2\right]}{(t_1 t_2)^2(t_1 + x_1)(t_2 + x_2)[(t_1 - x_1)(t_2 - x_2)]_+} - \frac{2\tau(\tau + t_1 t_2)}{t_1 t_2 (t_1 x_2 + t_2 x_1)^2}\right].\end{aligned} \tag{4}$$

The contribution from the Compton scattering graphs is

$$\begin{aligned}\frac{d^2\sigma^{Comp}}{dx_1\,dx_2} =& \int_{x_1}^{1} dt_1 \int_{x_2}^{1} dt_2 \left\{\frac{d^2\hat{\sigma}^{Comp}}{dt_1\,dt_2} \times \sum_f e_f^2 g^p(t_1, Q^2)\left[q_f^A(t_2, Q^2) + \bar{q}_f^A(t_2, Q^2)\right]\right. \\ &\left. + \frac{d^2\hat{\sigma}^{Comp}}{dt_1\,dt_2}(t_1 \leftrightarrow t_2) \times \sum_f e_f^2\left[q_f^p(t_1, Q^2) + \bar{q}_f^p(t_1, Q^2)\right] g^A(t_2, Q^2)\right\},\end{aligned} \tag{5}$$

where $g(t, Q^2)$ is the gluon distribution in the beam proton and target nuclei, and

$$\begin{aligned}\frac{d^2\hat{\sigma}^{Comp}}{dt_1\,dt_2} =& \sum_f \frac{2\alpha^2\alpha_s(Q^2)}{9Q^2}\delta(t_2 - x_2) \\ &\times \left[\frac{x_1^2 + (t_2 - x_1)^2}{2t_1^3}\ln\frac{2x_1(1-x_2)}{x_2(t_1 + x_1)} + \frac{1}{2t_1} - \frac{3x_1(t_1 - x_1)}{t_1^3}\right] \\ &+ \sum_f \frac{2\alpha^2\alpha_s(Q^2)}{9Q^2} \\ &\times \left[\frac{x_2(\tau + t_1 t_2)\left[\tau^2 + (\tau - t_1 t_2)^2\right]}{t_1^3 t_2^2 (t_1 x_2 + t_2 x_1)(t_2 + x_2)(t_2 - x_2)_+} + \frac{\tau(\tau + t_1 t_2)\left[t_1 t_2^2 x_1 + \tau(t_1 x_2 + 2t_2 x_1)\right]}{(t_1 t_2)^2 (t_1 x_2 + t_2 x_1)^3}\right].\end{aligned} \tag{6}$$

Therefore, to the next leading order, the differential cross section in a Drell–Yan reaction can be written as

$$\frac{d^2\sigma^{NLO}}{dx_1\,dx_2} = \frac{d^2\sigma^{DY}}{dx_1\,dx_2} + \frac{d^2\sigma^{Ann}}{dx_1\,dx_2} + \frac{d^2\sigma^{Comp}}{dx_1\,dx_2}. \tag{7}$$

Calculating the integral of the differential cross section above in leading order (2) and next-to-leading order (7), the Drell–Yan production cross section is given by

$$\frac{d\sigma}{dx_{1(2)}} = \int dx_{2(1)} \frac{d^2\sigma}{dx_1\,dx_2}. \tag{8}$$

3 The influence of the QCD correction on the ratio of Drell–Yan cross sections

In the Drell–Yan reaction experiments, the ratios are measured of the Drell–Yan cross sections on two different nuclear targets bombarded by protons,

$$R_{A_1/A_2}(x_{1(2)}) = \frac{d\sigma^{p-A_1}}{dx_{1(2)}} \Big/ \frac{d\sigma^{p-A_2}}{dx_{1(2)}}. \tag{9}$$

In order to explore the influence of the QCD correction, we introduce the ratios

$$R^{NLO/DY}_{A_1/A_2}(x_{1(2)}) = R^{NLO}_{A_1/A_2}(x_{1(2)}) / R^{DY}_{A_1/A_2}(x_{1(2)}), \tag{10}$$

where $R^{NLO}_{A_1/A_2}(x_{1(2)})$ and $R^{DY}_{A_1/A_2}(x_{1(2)})$ are the ratios of the Drell–Yan differential cross section with QCD correction and with only a leading order contribution, respectively.

By taking advantage of the HKM cubic type of nuclear parton distribution functions [15], the ratios $R^{NLO/DY}_{Fe/Be}(x_{1(2)})$ and $R^{NLO/DY}_{W/Be}(x_{1(2)})$ for a proton beam incident on Be, Fe, W targets are calculated at the Fermilab

800 GeV proton beam energy in the range $4 < M < 8$ GeV. It is found that the differential cross section ratios in next-to-leading order are almost identical to those in leading order. Similar results are given for the lower energy proton bombarding of deuterium and tungsten at the Fermilab Main Injector (FMI,120 GeV proton beam) [18] and the Japan Proton Accelerator Research Complex (J-PARC, 50 GeV proton beam) [19, 20]. Therefore, it can be concluded that the QCD correction is negligible in the nuclear Drell–Yan reactions for the current Fermilab and lower energy proton beam. The production of lepton pairs in proton–nucleus collisions, the nuclear Drell–Yan process, is one of most powerful tools for probing the propagating of a quark through cold nuclei. The experimental study of the relatively low energy nuclear Drell–Yan process can give valuable insight in the quark energy loss dependence on the medium size [12–14]. Furthermore, the influence of the quark energy loss can be investigated on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton in leading order.

4 The impact of the quark energy loss on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton

The Fermilab E866 collaboration reported their measurement of the differential cross section ratios $R_{\mathrm{Fe/Be}}(x_2)$ and $R_{\mathrm{W/Be}}(x_2)$ for an 800 GeV proton beam bombarding Be, Fe and W nuclei [8]. By combining the HKM cubic type of nuclear parton distribution [15] with the quark energy loss, the global χ^2 analysis of the E866 experimental data is performed in perturbative QCD leading order. We introduce two typical kinds of quark energy loss expressions. One is rewritten as

$$\Delta x_1 = \alpha \frac{\langle L \rangle_A}{E_p}\,, \tag{11}$$

where α denotes 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. In addition to the linear quark energy loss rate, there is another one, expressed as

$$\Delta x_1 = \beta \frac{\langle L \rangle_A^2}{E_p}\,, \tag{12}$$

i.e., now the quark energy loss is quadratic in the path length. 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.

If the quark energy loss is not taken as input, the obtained χ^2 value is $\chi^2 = 48.06$ for the total of 16 data points. The χ^2 per degree of freedom is given by $\chi^2/\mathrm{d.o.f.} = 3.00$. It is apparent that the theoretical results without energy loss effects do not significantly agree with the E866 experimental data on the ratios $R_{A_1/A_2}(x_2)$. After adding the fast quark energy loss, the χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} = 1.12$ for the linear quark energy loss formula with $\alpha = 1.27$, and the χ^2 per degree of freedom is given by $\chi^2/\mathrm{d.o.f.} = 1.13$ for the quadratic quark energy loss expression with $\beta = 0.19$. By using the parameter values in the linear and quadratic expressions obtained by fitting the E866 experimental data on the ratios $R_{A_1/A_2}(x_1)$, the χ^2 per degree of freedom are $\chi^2/\mathrm{d.o.f.} = 1.69$ with $\alpha = 1.99$ and $\chi^2/\mathrm{d.o.f.} = 1.65$ with $\beta = 0.29$, respectively. The calculated results with the linear and quadratic 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

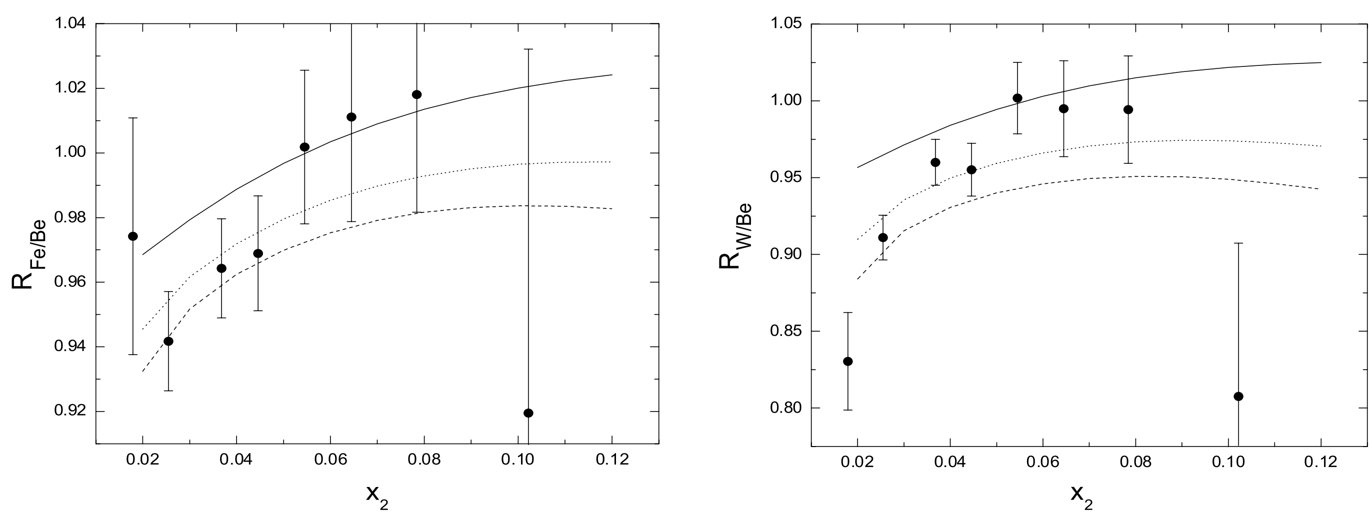

Fig. 1. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_2)$ on Fe to Be (*left*) and W to Be (*right*). *Solid curves* correspond to nuclear effects on the structure function. *Dotted* and *dashed curves* show the combination of the HKM cubic type of nuclear parton distributions with the linear energy loss with $\alpha = 1.27$ and 1.99, respectively. The experimental data are taken from the E866 experiment [8]

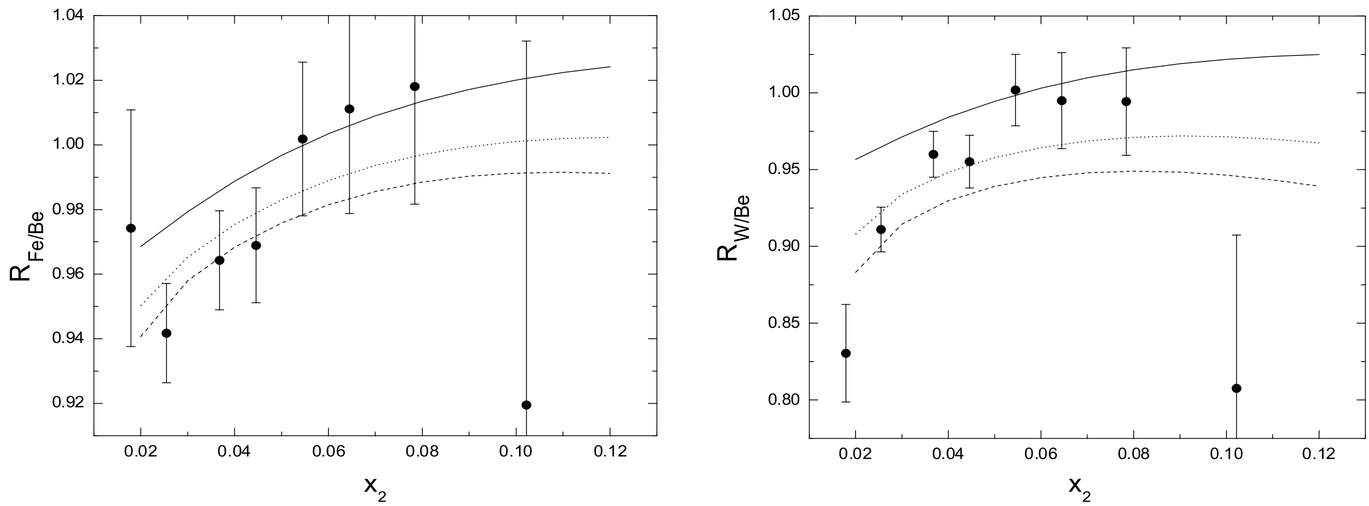

Fig. 2. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_2)$ on Fe to Be (*left*) and W to Be (*right*). *Solid curves* correspond to the nuclear effects on the structure function. *Dotted* and *dashed curves* show the combination of the HKM cubic type of nuclear parton distributions with the quadratic energy loss with $\beta = 0.19$ and 0.29, respectively. The experimental data are taken from the E866 experiment [8]

functions of x_2, respectively. The solid curves are the ratios with only the nuclear effect on the parton distributions as in deep inelastic scattering; the dotted and dashed curves respectively correspond to the linear energy loss with $\alpha = 1.27$ and $\alpha = 1.99$ in Fig. 1, and the quadratic energy loss with $\beta = 0.19$ and $\beta = 0.29$ in Fig. 2. By comparison with the experimental data, it is shown that our theoretical results with the energy loss effect are in good agreement with the Fermilab E866 data. Meanwhile, it is noticeable that the values of the parameter α (or β) are different by means of the global χ^2 analysis of the E866 experimental data on the ratios $R_{A_1/A_2}(x_1)$ and $R_{A_1/A_2}(x_2)$. The results may originate from the experimental precision. If the experimental data are sufficiently precise, the values of the parameter α (or β) in the quark energy loss expression should be the same as for fitting the ratios $R_{A_1/A_2}(x_1)$ or $R_{A_1/A_2}(x_2)$ from the nuclear Drell–Yan experiment.

In order to clarify the impact of the quark energy loss on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton, the ratios of $R_{A_1/A_2}(x_2)$ without quark energy loss to those with linear quark energy loss are calculated and tabulated in Table 1 for the kinematic ranges covered by the E866 experiment. Similar results can be obtained for the quadratic quark energy loss. It is shown that the quark energy loss effect has an obvious influence on the Drell–Yan differential cross section ratios $R_{A_1/A_2}(x_2)$. As for the ratios $R_{\mathrm{Fe/Be}}(x_2)$, the variation is approximately 2% to 4%. The extent to which the ratios $R_{\mathrm{W/Be}}(x_2)$ vary is roughly 4% to 8%. It can be deduced that the ratios of the Drell–Yan differential cross section for nuclei A versus deuterium, $R_{A/\mathrm{D}}(x_2)$, are affected largely because of the quark energy loss effect. In the global analysis of the nuclear parton distribution functions, the Drell–Yan data are taken mainly to determine the sea-quark modification in the small x region. It is obvious that, considering the existence of quark energy loss, the application of the nuclear Drell–Yan data is, remarkably, subject to a difficulty in the constraints of the nuclear antiquark distribution.

Table 1. The ratios of $R_{A_1/A_2}(x_2)$ without quark energy loss to those with linear quark energy loss

	x_2	0.03	0.05	0.07	0.09	0.12
$\alpha(1.27)$	Fe/Be	1.018	1.017	1.019	1.022	1.027
	W/Be	1.038	1.036	1.040	1.045	1.055
$\alpha(1.99)$	Fe/Be	1.029	1.027	1.030	1.035	1.042
	W/Be	1.061	1.058	1.064	1.072	1.088

The ratios of the Drell–Yan differential cross section for tungsten versus deuterium, $R_{\mathrm{W/D}}(x_2)$, are also calculated at 50 GeV and 120 GeV proton beam by means of the HKM cubic type of nuclear parton distribution functions [15] and the two kinds of quark energy loss expressions. It is indicated that the theoretical results with quark energy loss effect deviate significantly from those with only the nuclear effects on the structure function. As an example, Fig. 3 shows the ratios $R_{\mathrm{W/D}}(x_2)$ with and without linear quark energy loss at 50 GeV and 120 GeV proton beam, respectively. The kinematic ranges cover $4 < M < 8$ GeV in order to avoid contamination from charmonium decays. In these calculations, the energy loss per unit length α equals 1.27 GeV/fm and 1.99 GeV/fm, based on a good fit to the E866 data. Therefore, it is important to understand the energy loss effects for determining nuclear sea-quark distributions from future Drell–Yan experiments at the lower energy proton beams.

In addition, we calculate the ratios $R_{\mathrm{W/D}}(x_2)$ with the linear and quadratic energy loss formulae in the 50 GeV and 120 GeV proton beam bombarding of the deuterium and tungsten target. It turns out that the results with linear quark energy loss are almost identical to those with quadratic energy loss. The ratios $R_{\mathrm{W/D}}(x_2)$ do not deter-

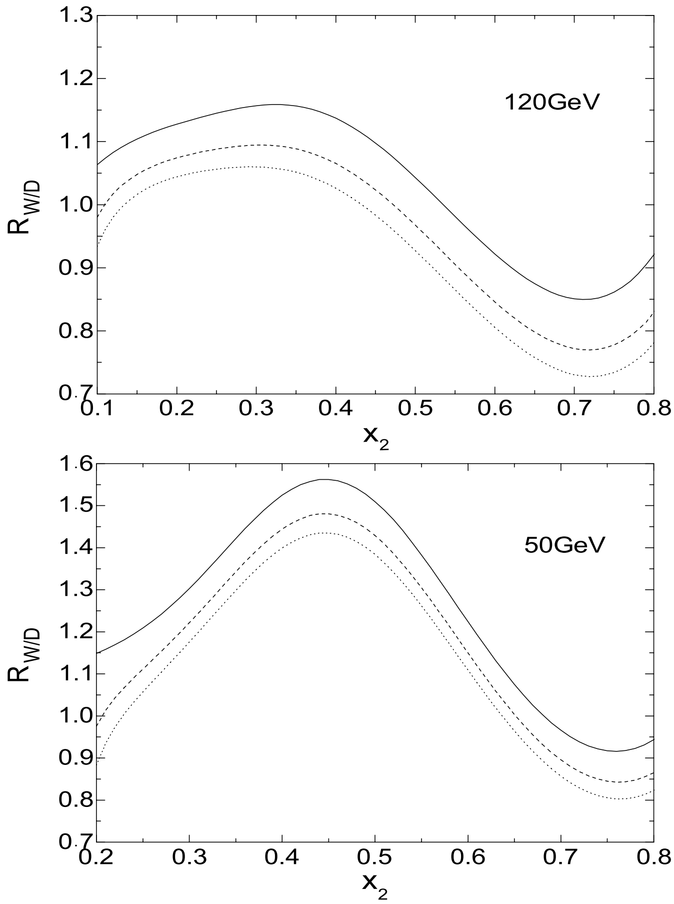

Fig. 3. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_2)$ on W to D at 120 GeV and 50 GeV incident proton beam with the linear energy loss $\alpha = 1.27$ GeV/fm (*dashed curves*) and $\alpha = 1.99$ GeV/fm (*dotted curves*). *Solid curves* correspond to the nuclear effects on the structure function

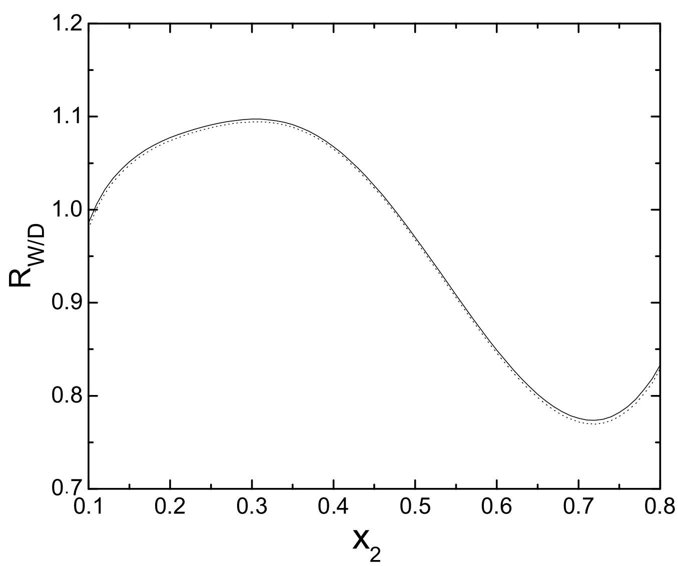

Fig. 4. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_2)$ on W to D at 120 GeV incident proton beam with the quadratic energy loss with $\beta = 0.19$ GeV/fm^2 (*solid curve*) and the linear energy loss with $\alpha = 1.27$ GeV/fm (*dotted curve*)

mine whether the energy loss is linear or quadratic with the path length. However, the ratios $R_{\mathrm{W/D}}(x_1)$ can easily distinguish between an L and L^2 dependence of the quark energy loss [12–14]. As an example, Fig. 4 shows the ratios $R_{\mathrm{W/D}}(x_2)$ of the Drell–Yan cross section per nucleon for a 120 GeV proton beam incident on D and W targets, where the solid and dotted lines correspond to a quadratic energy loss with $\beta = 0.19$ GeV/fm^2 and to a linear energy loss with $\alpha = 1.27$ GeV/fm, respectively.

5 Concluding remarks

In summary, a next-to-leading order and a leading order analysis are performed on the differential cross section ratios from the nuclear Drell–Yan process. The calculated results indicate that the QCD correction can be ignored in the nuclear Drell–Yan reactions for the current Fermilab and lower energy proton beam. Based on this view, the nuclear Drell–Yan process is one of most powerful tools for probing the propagating of quarks through cold nuclei. The experimental study of a relatively low energy nuclear Drell–Yan process can give valuable insight in the quark energy loss dependence on the medium size. Furthermore, we have made a leading order analysis of the E866 data on the Drell–Yan differential cross section ratios as a function of the momentum fraction of the target parton by taking into account the energy loss effect of fast quarks. It is found that the theoretical results with the quark energy loss are in good agreement with the Fermilab E866 experiment. The quark energy loss effect has an obvious impact on the Drell–Yan differential cross section ratios $R_{A_1/A_2}(x_2)$. Although there is an energy loss effect, the nuclear Drell–Yan experiment at the future lower energy proton beam should provide us with important information on the nuclear sea-quark distribution and the fast quark energy loss. In fact, by means of the structure function $xF_3(x,Q^2)$ in neutrino deep inelastic scattering only, the nuclear modifications to the valence quark distribution can very precisely be determined in the medium and large x regions [21]. Theoretically, the nuclear modifications to the sea-quark distribution in the medium and large x regions should be pinned down by using the structure functions $F_2(x,Q^2)$ from the neutrino's and charged-leptons' deep inelastic scattering off nuclei. In addition, the nuclear sea-quark distribution in the small-x regions can be relatively determined from the constraints of momentum conservation and the structure function in the small-x range. But accurate measurements must be provided in the future lepton–nuclei deep inelastic scattering. Therefore, we desire that the precise measurements will be performed in the experimental study of the relatively low energy nuclear Drell–Yan process in the near future. These new experimental data can shed light on the nuclear sea-quark distributions and the energy loss of fast quarks propagating in cold nuclei.

Acknowledgements. This work is partially supported by the Natural Science Foundation of China (10575028) and the Natural Science Foundation of Hebei Province (103143).

References

1. J.J. Aubert et al., Phys. Lett. B **123**, 275 (1983)
2. F. Carminati et al., J. Phys. G **30**, 1517 (2004)
3. H.K. Ackermann et al., Nucl. Instrum. Methods A **499**, 624 (2003)
4. S. Drell, T.M. Yan, Phys. Rev. Lett. **25**, 316 (1970)
5. D.M. Adle et al., Phys. Rev. Lett. **64**, 2479 (1990)
6. M. Ericson, A.W. Thomas, Phys. Lett. B **128**, 112 (1983)
7. C.E. Carlson, T.J. Havens, Phys. Rev. Lett. **51**, 261 (1983)
8. M.A. Vasiliev et al., Phys. Rev. Lett. **83**, 2304 (1999)
9. K.J. Eskola, V.J. Kolhinen, C.A. Salgado, Eur. Phys. J. C **9**, 61 (1999)
10. K.J. Eskola, V.J. Kolhinen, P.V. Ruuskanen, Nucl. Phys. B **535**, 351 (1998)
11. A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Eur. Phys. J. C **4**, 463 (1998)
12. C.G. Duan et al., Eur. Phys. J. C **39**, 179 (2005) [hep-ph/0601188]
13. C.G. Duan et al., Eur. Phys. J. C **29**, 557 (2003) [hep-ph/0405113]
14. C.G. Duan, H.M. Wang, G.L. Li, Chin. Phys. Lett. **19**, 485 (2002)
15. M. Hirai, S. Kumano, M. Miyama, Phys. Rev. D **64**, 034 003 (2001)
16. M. Hirai, S. Kumano, T.H. Nagai, Phys. Rev. C **70**, 044 905 (2004)
17. J. Kubar-Andre, J.C. Meunier, G. Plaut, Nucl. Phys. B **175**, 251 (1980)
18. D. Geesaman et al., Fermolab Proposal No. E906 (1999)
19. J.C. Peng et al., hep-ph/0007341
20. M. Asakawa et al., KEK Report No 2000-11
21. C.G. Duan et al., Eur. Phys. J. C **48**, 125 (2006) [hep-ph/0604146]