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Systematic analysis of the incoming quark energy loss in cold nuclear matter

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ABSTRACT

The investigation into the fast parton energy loss in cold nuclear matter is crucial for a good understanding of the parton propagation in hot-dense medium. By means of four typical sets of nuclear parton distributions and three parametrizations of quark energy loss, the parameter values in quark energy loss expressions are determined from a leading order statistical analysis of the existing experimental data on nuclear Drell–Yan differential cross section ratio as a function of the quark momentum fraction. It is found that with independence on the nuclear modification of parton distributions, the available experimental data from lower incident beam energy rule out the incident-parton momentum fraction quark energy loss. Whether the quark energy loss is linear or quadratic with the path length is not discriminated. The global fit of all selected data gives the quark energy loss per unit path length $\alpha = 1.21 \pm 0.09$ GeV/fm by using nuclear parton distribution functions determined only by means of the world data on nuclear structure function. Our result does not support the theoretical prediction: the energy loss of an outgoing quark is three times larger than that of an incoming quark approaching the nuclear medium. It is desirable that the present work can provide useful reference for the Fermilab E906/SeaQuest experiment.

1. Introduction

The parton energy loss in high energy collisions has attracted an increasing amount of attention from both the nuclear and particle physics communities for over two decades. There is a rich theoretical literature on in-medium parton energy loss extending back to Bjorken, who proposed the suppressed production of particles having large transverse momenta, known as jet-quenching, was the "smoking guns" of the Quark Gluon Plasma (QGP) formation in high energy nucleus–nucleus collisions [1]. The wealth of experimental data on jet-quenching from RHIC [2–7] and LHC [8] reflect clearly the energy loss of fast partons while traversing this hot and dense medium. However, a detailed understanding of the parton energy loss in hot and dense medium requires the good investigation into the fast parton propagation in cold nuclear matter because there are common elements between the two mediums.

Two sets of experimental data from the semi-inclusive deep inelastic scattering of lepton on nuclei and the Drell–Yan reaction [9] in hadron–nucleus collisions can provide the essential information on the energy loss of fast partons owing to multiple scattering and gluon radiation while traversing this cold nuclear medium. The semi-inclusive deep inelastic scattering on nuclear targets is an ideal tool to study the energy loss of the outgoing quark in the cold nuclear medium. In our recent article [10], the experimental data with quark hadronization occurring outside the nucleus from HERMES [11] and EMC [12] experiments are picked out by means of the short hadron formation time. A leading-order analysis is performed for the hadron multiplicity ratios as a function of the energy fraction on helium, neon, and copper nuclei relative to deuteron for the various identified hadrons. It is found that the theoretical results considering the nuclear modification of fragmentation functions due to the outgoing quark energy loss are in good agreement with the selected experimental data. The obtained energy loss per unit length is 0.38 ± 0.03 GeV/fm for an outgoing quark by a global fit.

The hadron-induced Drell–Yan reaction on nuclei is an excellent process to investigate the incoming quark energy loss in cold nuclear matter because the produced lepton pair does not interact strongly with the partons in the nucleus. A series of experiments [13] have been performed at Fermilab and CERN which presented the Drell–Yan differential cross section distributions in order to test the theoretical model, know the momentum distributions of the projectile and target quarks, and explore the nuclear target

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dependence. Four experimental collaborations have measured the Drell–Yan differential cross section ratio of two different nuclear targets bombarded by the same hadron at the same centre-of-mass energy in order to study the nuclear effects on Drell–Yan reaction. They are NA3 [14] and NA10 [15] Collaborations from CERN, and E772 [16] and E866 [17] Collaborations from Fermilab. The advantage of using the Drell–Yan differential cross section ratio at the same energy is that the differential cross section ratio can reduce the dependence on the beam hadrons, and cancel the most uncertainties regarding the lepton pair production. Additionally, the differential cross section ratio can avoid the influence of the QCD next-to-leading order correction. Theoretically, it has proved that the effect of next-to-leading order correction on the Drell–Yan differential cross section ratio as a function of the quark momentum fraction can be negligible for the 800 GeV proton beam at Fermilab and lower energy beam [18].

In our previous articles [19,20], the energy loss effect on the Fermilab E866 nuclear Drell–Yan differential cross section ratio was investigated as a function of the quark momentum fraction of the beam proton at the hadron level in the framework of the Glauber model, and at parton level by using two typical kinds of quark energy loss parametrization, respectively. It was confirmed that the energy loss effect can suppress evidently the differential cross sections versus the quark momentum fraction. In the recent work [21], the study on quark energy loss is extended to the E772 data without performing the global fit to E772 and E866 data. It is found that the quark energy loss effect on nuclear Drell–Yan cross section ratio becomes greater with the increase of quark momentum fraction in the target nuclei. The global analysis of nuclear parton distribution functions including E772 data overestimates the nuclear modification in the sea quark distribution if the quark energy loss effect is neglected. It is noticeable that the E772 and E866 Collaborations used the same 800 GeV proton beam incident on various nuclei. The measured momentum fraction of the target parton is in the range $0.01 < x_2 \leqslant 0.271$.

The main goal of the present work is to extract the incoming quark energy loss in cold nuclear matter systematically from a global analysis of these experimental results on nuclear Drell–Yan differential cross section ratio from NA3 [14] and NA10 [15] Collaborations at CERN, and E772 [16] and E866 [17] Collaborations at Fermilab. The main improvements over our earlier work are twofold: on one hand, the error estimate for the incoming quark energy loss is presented, and on the other hand, by adding the NA3 [14] and NA10 [15] data from CERN, the used experimental data can cover 140 GeV, 150 GeV, 286 GeV and 800 GeV incident hadron beam with the target-quark momentum fraction from 0.01 to 0.45. The extended beam energy and kinematic coverage significantly increase the sensitivity to incident parton energy loss and nuclear modification in the sea quark distribution. It is hoped to provide a good understanding of the parton energy loss in cold nuclear matter from the available data, and to facilitate the theoretical research on the energy loss of an incoming quark and outgoing quark in nuclear matter.

This Letter is organized as follows. A brief formalism for the differential cross section in nuclear Drell–Yan process is detailed in Section 2, followed by the data selection in Section 3. The obtained results are discussed in Section 4. Finally, the summary and concluding remarks are given in Section 5.

2. Dilepton production differential cross section in nuclear targets

At the leading order (LO) in perturbation theory, the lepton pair production differential cross section in hadron–nucleus collisions can be obtained from the convolution of differential partonic cross section $\bar{q}q \to l^+l^-$ with the parton distribution functions in the incident hadron h and the target nucleus A. With neglecting the incoming quark energy loss in cold nuclear matter, the differential cross section is written as

$$\frac{d^2\sigma}{dx_1\,dx_2} = \frac{4\pi\alpha_{em}^2}{9sx_1x_2}\sum_f e_f^2\big[q_f^h\big(x_1, Q^2\big)\bar{q}_f^{\mathrm{A}}\big(x_2, Q^2\big) + \bar{q}_f^h\big(x_1, Q^2\big)q_f^{\mathrm{A}}\big(x_2, Q^2\big)\big], \tag{1}$$

where x_1 (x_2) is the momentum fraction of the partons in the beam hadron (target), α_{em} is the fine structure constant, $\sqrt{s}$ is the center of mass energy of the hadronic collision, e_f is the charge of the quark with flavor f, Q^2 is the invariant mass of a lepton pair, $q_f^{h(\mathrm{A})}(x, Q^2)$ and $\bar{q}_f^{h(\mathrm{A})}(x, Q^2)$ are respectively the quark and anti-quark distribution function with Bjorken variable x and photon virtuality Q^2 in the hadron (nucleon in the nucleus A), and the sum is carried out over the light flavor.

In the hadron-induced Drell–Yan reaction on nuclei, the incoming quark can lose its energy ΔE_q, owing to multiple scattering on the surrounding nucleon and gluon radiation while propagating through the nucleus. The energy loss of an incoming quark results in an average change in its momentum fraction prior to the collision, $\Delta x_1 = \Delta E_q/E_h$, where E_h is the incident hadron energy. On the basis of theoretical research, three parametrizations for quark energy loss have been proposed separately by Brodsky and Hoyer [22], Baier et al. [23], and by Gavin and Milana [24]. One is $\Delta x_1 = \alpha\langle L\rangle_A/E_h$, where α denotes the incident quark energy loss per unit length in nuclear matter, $\langle L\rangle_{\mathrm{A}} = 3/4(1.2A^{1/3})$ fm is the average path length of the incident quark in the nucleus A. Another one is $\Delta x_1 = \beta\langle L\rangle_{\mathrm{A}}^2/E_h$. Obviously, the quark energy loss is quadratic with the path length. In what follows, the two different parametrizations are called the linear and quadratic quark energy loss, respectively. The third form is $\Delta x_1 = \kappa x_1 A^{1/3}$, which is named the incident-parton momentum fraction quark energy loss. In these three expressions, α, β and κ can be extracted by a global analysis to nuclear Drell–Yan experimental data on the differential cross section ratio, respectively.

The quark energy loss in target nucleus shifts the incident quark momentum fraction from $x_1' = x_1 + \Delta x_1$ to x_1 at the point of fusion. With adding the quark energy loss in the nucleus, the nuclear Drell–Yan differential cross section can be expressed as

$$\frac{d^2\sigma}{dx_1\,dx_2} = \frac{4\pi\alpha_{em}^2}{9sx_1x_2}\sum_f e_f^2\big[q_f^h\big(x_1', Q^2\big)\bar{q}_f^{\mathrm{A}}\big(x_2, Q^2\big) + \bar{q}_f^h\big(x_1', Q^2\big)q_f^{\mathrm{A}}\big(x_2, Q^2\big)\big]. \tag{2}$$

The parton distribution functions inside a nucleus from the Drell–Yan differential cross section have been found to differ notably from the corresponding ones in the free nucleon with the discovery of the nuclear EMC effect some twenty years ago (see Ref. [25], and references therein). Despite a significant worldwide effort in experiment and theory, there is as yet no consensus concerning the origin of this effect. In view of the importance for finding any new physical phenomena in the high-energy nuclear reactions, the global analyses of nuclear parton distribution functions, which parallel those for the free proton, have been performed in the past decade by different groups: HKM/HKN07 [26,27], nDS [28], and EPS09 [29]. The four sets of nuclear parton distribution functions employed the existing experimental data on nuclear structure functions from the electron and muon deep inelastic scattering. Unfortunately, the nuclear structure functions are composed of nuclear sea and valence quark distributions. The fact results in that the nuclear valence quark distributions are relatively

Table 1
Experimental data sets selected for the present analysis.

Exp.	E_{beam} (GeV)	Proj.	Target	x_1	No. data	x_2	No. data
NA10a [15]	140	π^-	D, W	0.39–0.82	5	0.163–0.360	4
NA3 [14]	150	π^-	H, Pt	0.25–0.95	8	0.074–0.366	7
NA10b [15]	286	π^-	D, W	0.22–0.83	9	0.125–0.451	6
E772 [16]	800	p	D, C, Ca, Fe, W	0.15–0.85	122	0.04–0.271	36
E866 [17]	800	p	Be, Fe, W	0.21–0.95	56	0.01–0.12	16

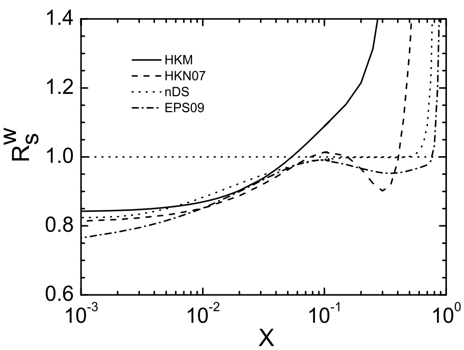

Fig. 1. The nuclear modification of sea quark distribution at $Q^2 = 50\ \mathrm{GeV}^2$ as a function of Bjorken variable x for tungsten nucleus. The solid, dashed, dotted and dash–dot lines correspond to the results given by HKM, HKN07, nDS and EPS09 nuclear parton distributions, respectively.

well determined except for the small Bjorken variable x region, and nuclear antiquark distributions in small x region. It is difficult to constraint the antiquark distributions at medium and large x region. It is expected that the nuclear Drell–Yan experimental data can pin down the nuclear valence quark distributions in the small x region and nuclear antiquark distributions in the medium x region $0.01 < x < 0.3$. For this reason, HKN07 and EPS09 added Fermilab E772 and E866 nuclear Drell–Yan data, and nDS included E772 experimental data with difference from HKM.

The quantitative comparison between the different sets of nuclear parton distribution functions shows that the nuclear modification for valence quarks agrees nicely in the large-x region $x > 0.3$. In other x region, HKN07, nDS and EPS09 give nuclear modifications relatively close to each other. Only the HKM displays a smaller antishadowing in the region $0.01 < x < 0.3$ than other sets, and no nuclear correction in $x < 0.01$. The nuclear modification of sea quark distribution for tungsten nucleus, $R_s^W(x, Q^2 = 50\ \mathrm{GeV}^2)$ is shown in Fig. 1, as a function of Bjorken variable x from the leading order HKM (solid line), HKN07 (dashed line), nDS (dotted line), and EPS09 (dash dot line) nuclear effects. It is found that the nuclear modifications from different sets are relatively close to each other in the region $0.01 < x < 0.08$, however gives a clear deviation in the region $x > 0.08$. It is apparent that the nuclear modifications with including nuclear Drell–Yan data do not give a good consistency in the medium x region from HKN07, nDS and EPS09 parameterizations. The fact goes contrary to one's wishes.

3. The experimental data

In our present analysis, the experimental data, providing the input for the value of the parameter in the three representative expressions of quark energy loss, are taken from NA3 [14] and NA10 [15] Collaborations at CERN, and E772 [16] and E866 [17] Collaborations at Fermilab. The experimental data sets used here are summarized in Table 1, in which the beam energy E_{beam} of incident hadron, the projectile/target species, the covered domain on the momentum fraction of the hadron and target parton, and the number N of points in each data sample are specified. In total, our analysis has 269 data points, and 6 nuclei from beryllium up to platinum.

Table 2
The χ^2/N-values computed using HKM, HKN07, nDS and EPS09 nuclear parton distribution functions without quark energy loss effect. The notation x_1 and x_2 indicate the momentum fraction of the incident hadron and target parton, respectively.

Exp. data	HKM	HKN07	nDS	EPS09
NA10a(x_1)	23.69	6.84	8.81	5.03
NA10a(x_2)	25.68	5.26	10.42	4.92
NA3(x_1)	5.99	4.81	4.45	3.68
NA3(x_2)	9.93	6.98	7.67	6.35
NA10b(x_1)	3.81	1.45	1.60	1.42
NA10b(x_2)	5.11	0.65	1.90	0.86
E772(x_1)	1.92	1.41	1.47	1.33
E772(x_2)	4.83	1.58	1.79	0.82
E866(x_1)	1.44	0.90	1.19	0.84
E866(x_2)	3.00	1.17	2.17	0.95

To be emphasized, NA3 and NA10 data used cover the momentum fraction of the target parton from 0.074 to 0.366, and from 0.125 to 0.451, respectively. In the region $x_2 > 0.1$, the nuclear modification to sea quark distribution given by the different sets displays a gradually large deviation from each other with the increase of the momentum fraction of the target parton. Therefore, NA3 and NA10 data can show better the difference between HKM, HKN07, nDS and EPS09 parameterizations. Meanwhile, the bigger range coverage on beam energy and momentum fraction of the target parton can make us to find very clearly the quark energy loss effect on the nuclear Drell–Yan differential cross section ratio.

4. Results and discussion

In order to study the quark energy loss effect in the hadron-induced Drell–Yan reaction on nuclei, determine the values of the parameters α, β and κ in quark energy loss expressions, and investigate the dependence of quark energy loss on the nuclear parton distribution functions, we calculate in perturbative QCD leading order(LO) the Drell–Yan cross section ratio $R^{theo}_{A_1/A_2}$ on two different nuclear targets bombarded by hadron

$$R^{theo}_{A_1/A_2}(x_{1(2)}) = \int dx_{2(1)} \frac{d^2\sigma^{h-A_1}}{dx_1\,dx_2} \Big/ \int dx_{2(1)} \frac{d^2\sigma^{h-A_2}}{dx_1\,dx_2}. \tag{3}$$

The comparison is performed with selected experimental data on the Drell–Yan differential cross section ratio. The integral range in above equation is obtained by means of the relative experimental kinematic region with neglecting the nuclear modifications in deuterium. In our calculation as following, we use the four sets of leading order nuclear parton distribution functions together with CTEQ6L parton density in the proton [30], and parton density in the negative pion [31].

When the incoming quark energy loss effect is neglected in the hadron-induced Drell–Yan reaction on nuclei, the calculated results are compared with the experimental data selected for our analysis on the Drell–Yan differential cross section ratio as a function of the momentum fraction of the incident hadron and target parton. The χ^2/N (N being the number of data points) computed are

Table 3
The values of α, β and κ, χ^2/ndf and S factors extracted from each data sample with HKM nuclear corrections. The bottom row corresponds to the global fit of all selected data.

Exp. data	α (χ^2/ndf, S)	β (χ^2/ndf, S)	κ (χ^2/ndf, S)
NA10a(x_1)	1.53 ± 0.14 (1.61, 1.27)	0.248 ± 0.022 (1.49, 1.22)	0.0152 ± 0.0015 (4.12, 2.03)
NA10a(x_2)	1.46 ± 0.16 (0.81, 1.00)	0.230 ± 0.025 (0.74, 1.00)	0.0210 ± 0.0030 (2.69, 1.64)
NA3(x_1)	1.82 ± 0.29 (1.69, 1.30)	0.310 ± 0.050 (1.44, 1.20)	0.0120 ± 0.0040 (3.40, 1.84)
NA3(x_2)	1.85 ± 0.36 (2.53, 1.59)	0.300 ± 0.060 (2.24, 1.50)	0.0130 ± 0.0050 (5.78, 2.40)
NA10b(x_1)	0.88 ± 0.20 (1.31, 1.14)	0.140 ± 0.030 (1.31, 1.14)	0.0070 ± 0.0015 (1.47, 1.21)
NA10b(x_2)	0.79 ± 0.14 (0.45, 1.00)	0.125 ± 0.023 (0.45, 1.00)	0.0083 ± 0.0016 (0.88, 1.00)
E772(x_1)	1.26 ± 0.16 (1.33, 1.15)	0.230 ± 0.030 (1.35, 1.16)	0.0042 ± 0.0005 (1.26, 1.12)
E772(x_2)	1.29 ± 0.13 (1.10, 1.05)	0.230 ± 0.030 (1.53, 1.24)	0.0066 ± 0.0006 (1.69, 1.30)
E866(x_1)	1.28 ± 0.22 (0.79, 1.00)	0.190 ± 0.030 (0.80, 1.00)	0.0026 ± 0.0004 (0.77, 1.00)
E866(x_2)	1.27 ± 0.23 (1.12, 1.06)	0.190 ± 0.030 (1.13, 1.06)	0.0035 ± 0.0006 (0.78, 1.00)
Global fit	1.21 ± 0.09 (1.07, 1.03)	0.190 ± 0.020 (1.11, 1.05)	0.0037 ± 0.0003 (1.21, 1.10)

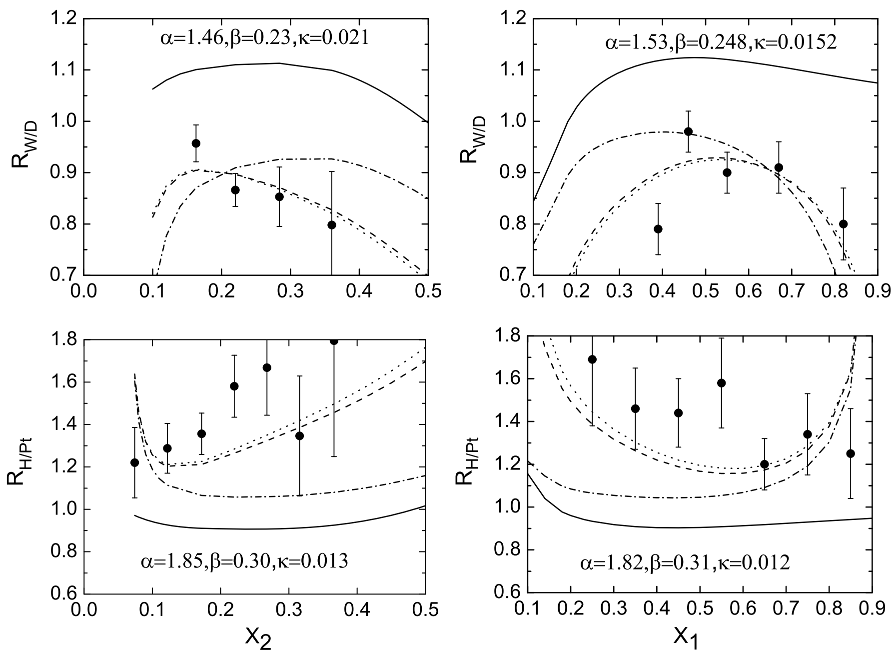

Fig. 2. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ and $R_{A_1/A_2}(x_2)$ by using HKM nuclear parton distributions. The solid curves correspond to the results with only nuclear effects of parton distributions. The dashed, dotted and dash–dot curves show the combination of nuclear effects of parton distributions with linear, quadratic and incident-parton momentum fraction quark energy loss, respectively. The relative optimal parameter is taken from the fit to corresponding data sample. The experimental data are taken from NA3 [14] and NA10a [15].

summarized in Table 2 by means of HKM, HKN07, nDS and EPS09 nuclear parton distribution functions, respectively. Usually, if the χ^2/N is not much larger than one, the theoretical results are considered as being statistically consistent with the experimental data. As seen from Table 2, each analysis on nuclear effects has consistently much larger χ^2/N values for NA3 and NA10a data from the negative pion incident Drell–Yan reaction on nuclei. Interestingly, very larger χ^2/N value is 23.69 and 25.68 for NA10a(x_1) and NA10a(x_2) data, respectively, from the HKM nuclear effects.

To determinate the optimal parameter from each experimental data set, we adopt the χ^2 analysis method described in Ref. [10]. The obtained results are summarized in Table 3 by combining the HKM cubic type of nuclear parton distributions with linear, quadratic and incident-parton momentum fraction quark energy loss, respectively. The values of α, β, κ extracted from the individual fit of each data sample, as well as their corresponding rescaled error, χ^2 per number of degrees of freedom (χ^2/ndf) and S factors, are listed in Table 3, in which the bottom row corresponds to the global fit of all selected data. As can be found from Table 3 compared with Table 2, χ^2 values with quark energy loss effect, overall, are much smaller than those with only HKM nuclear effects of parton distributions. The agreement of theoretical calculations with experimental data has a significant improvement. However, the computed results with the incident-parton momentum fraction quark energy loss have yet a significant deviation from NA3 and NA10a data sets.

Regarding the linear, quadratic and the incident-parton momentum fraction quark energy loss, the global fit of all data makes $\alpha = 1.21 \pm 0.09$ with the relative uncertainty $\delta\alpha/\alpha \simeq 7\%$ and $\chi^2/ndf = 1.07$, $\beta = 0.19 \pm 0.02$ with $\delta\beta/\beta \simeq 10\%$ and $\chi^2/ndf = 1.11$, and $\kappa = 0.0037 \pm 0.0003$ with $\delta\kappa/\kappa \simeq 8\%$ and $\chi^2/ndf = 1.21$.

To demonstrate intuitively the energy loss effect of an incoming quark on the nuclear Drell–Yan cross section ratio, the calculated results combining HKM cubic type of nuclear parton distributions are compared with NA10a and NA3 data in Fig. 2. It is necessary to note that NA3 Collaboration provided the negative pion incident Drell–Yan cross section ratio $R_{H/Pt}$ as a function of parton momentum fraction. If the ratio $R_{H/Pt}$ is transformed to $R_{Pt/H}$, the ratio $R_{Pt/H}$ has the same tendency as $R_{W/D}$ at the beam energy 140 GeV. It can be seen from Fig. 2 that the calculated differential cross section ratios are nearly same from the linear and quadratic quark energy loss. The theoretical prediction from the incident-parton momentum fraction quark energy loss is not in agreement with the NA3, NA10a(x_2) and NA10a(x_1) data in $x_1 < 0.4$. Therefore,

Table 4
The values of α, β and κ with χ^2/ndf and S factors extracted from the global fit of all data by using HKN07, nDS and EPS09 nuclear corrections, respectively.

	α^{HKN07} (χ^2/ndf, S)	α^{nDS} (χ^2/ndf, S)	α^{EPS09} (χ^2/ndf, S)
Global fit	0.64 ± 0.09 (1.09, 1.04)	0.73 ± 0.09 (1.08, 1.04)	0.23 ± 0.07 (1.05, 1.02)
	β^{HKN07} (χ^2/ndf, S)	β^{nDS} (χ^2/ndf, S)	β^{EPS09} (χ^2/ndf, S)
Global fit	0.103 ± 0.014 (1.09, 1.04)	0.122 ± 0.013 (1.08, 1.04)	0.042 ± 0.015 (1.05, 1.02)
	κ^{HKN07} (χ^2/ndf, S)	κ^{nDS} (χ^2/ndf, S)	κ^{EPS09} (χ^2/ndf, S)
Global fit	0.0023 ± 0.0003 (1.08, 1.04)	0.0026 ± 0.0004 (1.08, 1.04)	0.0009 ± 0.0004 (1.05, 1.02)

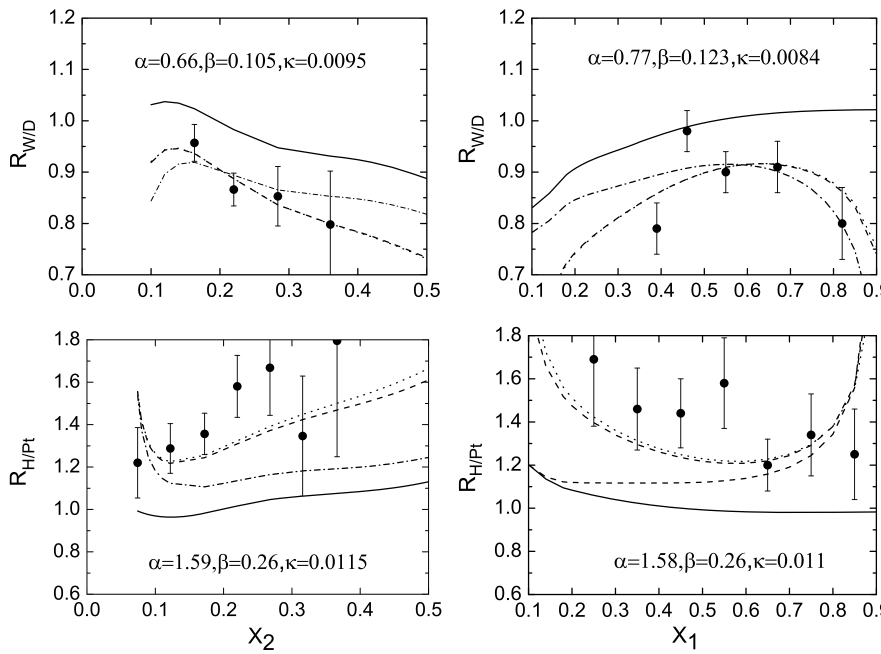

Fig. 3. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ and $R_{A_1/A_2}(x_2)$ by using HKN07 nuclear parton distributions. The other comments are the same as those in Fig. 2.

we can conclude apparently that the existing experimental data from lower incident beam energy rule out the possibility of the incident-parton momentum fraction quark energy loss. Whether the quark energy loss is linear or quadratic with the path length is not determined.

In order to quantify the sensitivity of our computed results on quark energy loss with respect to the strength of nuclear corrections to the parton distributions, the global fit analysis is carried out by using HKN07, nDS and EPS09 parameterizations. The results given from the three parametrizations of quark energy loss are summarized in Table 4 with the values of α, β and κ, their corresponding rescaled error, χ^2/ndf and S factors. It can be found that the obtained parameter values in three expressions for quark energy loss are smaller than that by HKM nuclear effects. It directly reflects the deviation between HKM nuclear corrects to sea quark distribution and other three sets. The calculated results are compared with NA3 [14] and NA10a [15] data including quark energy loss effect and nuclear effects of parton distributions from HKN07, nDS and EPS09 sets in Figs. 3, 4 and 5, respectively. It is shown from these figures that the computed results from the linear quark energy loss are identical to those from the quadratic quark energy loss. The theoretical prediction on $R_{\text{W/D}}$ from the incident-parton momentum fraction quark energy loss exists a significantly large deviation from that by the linear (or quadratic) quark energy loss in the region $x_2 > 0.3$ and $x_1 < 0.4$. The tendency of $R_{\text{W/D}}$ as a function of quark momentum fraction does not support the possibility of the incident-parton momentum fraction quark energy loss. Additionally, it can be found that with independence on the nuclear modification of parton distributions, NA3 experiment rules apparently out the incident-parton momentum fraction quark energy loss. In view of the large experimental error in NA3 and NA10 data, it is desirable to operate precise measurements on the nuclear Drell–Yan reactions from lower incident beam energy.

5. Summary and concluding remarks

In summary, the available data on nuclear Drell–Yan differential cross section ratio as a function of the quark momentum fraction have been analyzed with three parametrizations of quark energy loss and four typical sets of nuclear parton distribution functions. It is found that with independence on the nuclear modifications of parton distributions, the experimental data from lower incident beam energy rule out the possibility of the incident-parton momentum fraction quark energy loss. The existing experimental data do not distinguish between the linear and quadratic dependence of quark energy loss. It is worth to mention that the mean energy loss is employed in our calculations. In hot and dense matter, however, the mean energy loss of the highly energetic partons would be considered very simplistic. Rather, it is now accepted that at least the probability distribution $P(\Delta E, L)$ of energy loss ΔE given a path L is the relevant quantity, which then needs to be averaged over geometry, i.e. a calculation needs to include explicitly both dynamical fluctuations given the same path, and fluctuations of the path a quark takes through the medium. It is possible that the distinction between linear and quadratic energy loss as observed in present analysis is lost by not accounting for fluctuations. However, while the quadratic dependence of energy loss is argued to arise from the Landau–Pomeranchuk–Migdal effect, it is

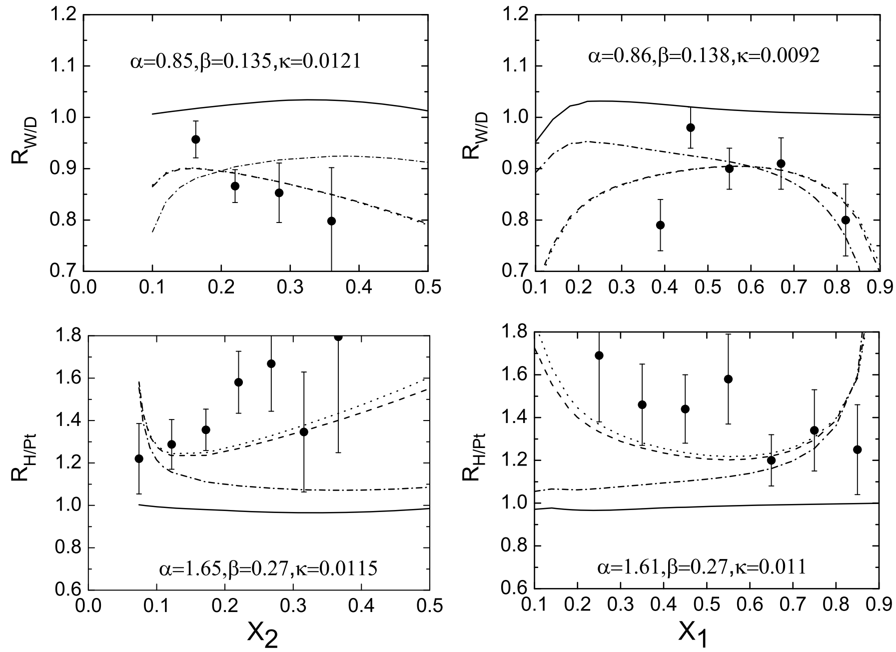

Fig. 4. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ and $R_{A_1/A_2}(x_2)$ by using nDS nuclear parton distributions. The other comments are the same as those in Fig. 2.

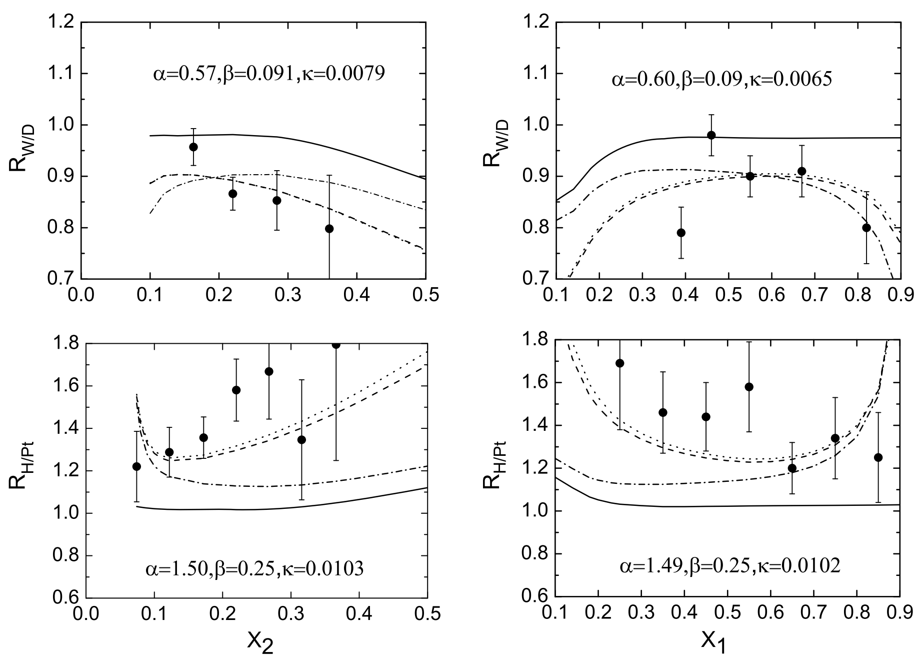

Fig. 5. The nuclear Drell–Yan cross section ratios $R_{A_1/A_2}(x_1)$ and $R_{A_1/A_2}(x_2)$ by using EPS09 nuclear parton distributions. The other comments are the same as those in Fig. 2.

now known that effectively due to finite energy corrections even a Landau–Pomeranchuk–Migdal-driven radiative energy loss reverts to an approximately linear dependence quickly [32,33].

From the global fit of all selected data, we obtain the quark energy loss per unit path length $\alpha = 1.21 \pm 0.09$ GeV/fm by HKM nuclear parton distribution functions. By combining our previous discussion on the semi-inclusive deep inelastic scattering of lepton on nuclear targets [10], our result on the mean energy loss per unit length of an incoming quark is not in support of the theoretical prediction: the mean energy loss of an outgoing quark is three times larger than that of an incoming quark approaching the medium [34]. In ultra-relativistic heavy-ion collisions, however, the medium-modified fragmentation function is obtained from a computation of an in-medium parton-shower followed by hadronization [35,36], i.e. what matters for the final state is not the energy loss of a single quark but rather the modified development of a parton shower. This virtuality evolution may explain the difference between the energy loss of incoming and outgoing quarks – while incoming quarks all in all probably can be considered on-shell, outgoing quarks are significantly off-shell due to the hard scattering.

In addition, the obtained value of the parameter in the quark energy loss expression from HKM nuclear effects is larger than that using other three sets of nuclear parton distribution. Our calculated results show that the energy loss effect of the incident quark has a distinct impact on the Drell–Yan cross section. It directly brings about an overestimation for nuclear correct to the sea quark distribution if leaving the quark energy loss effect out. Besides, the Drell–Yan single differential cross section as a function of the target parton momentum fraction is dominated by nuclear sea and valance quark distribution, which is similar to the nuclear structure function in charged-lepton deep inelastic scattering on nuclei. In order to make the flavor decomposition of nuclear parton distribution functions, we need to resort to the neutrino deep inelastic scattering data. Several works have studied the nuclear effects in the neutrino–nucleus charged-current inelastic scattering process [37–39]. We suggest that the new global analysis of nuclear parton distribution functions should employ the available experimental data on structure function from neutrino and charged-lepton deep inelastic scattering on nuclei.

It is worth noting that the fractional energy loss does not provide a good description of the data in hot-dense matter physics [40] because the fast parton propagation in cold nuclear and hot-dense matter contains different physics [41,42]. Moreover, in our present work, the used experimental data from NA10 Collaboration recorded the x_2 dependence of nuclear Drell–Yan cross section ratio from $0.12 < x_2 < 0.45$, which can be covered by Fermilab E906/SeaQuest experiment [43]. Therefore, we desire that our Letter can provide useful reference for E906's insight on the energy loss of an incoming quark propagating in cold nucleus.

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