

# Influence of quark energy loss on extracting nuclear sea quark distribution from nuclear Drell-Yan experimental data<sup>\*</sup>

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**Abstract** By means of two typical kinds of quark energy loss parametrization and the nuclear parton distributions determined only with lepton-nuclear deep inelastic scattering experimental data, a leading order analysis is performed on the proton-induced Drell-Yan differential cross section ratios of tungsten versus deuterium as a function of the quark momentum fraction in the beam proton and target nuclei. It is found that the theoretical results with quark energy loss are in good agreement with the experimental data. The quark energy loss effect produces approximately 3% to 11% suppression on the Drell-Yan differential cross section ratios  $R_{W/D}$  in the range  $0.05 \leq x_2 \leq 0.3$ . The application of nuclear Drell-Yan data with heavy targets is remarkably subject to difficulty in the constraint of the nuclear sea quark distribution.

**Key words** Drell-Yan, energy loss, nuclear sea quark distribution

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## 1 Introduction

After the discovery of the EMC effect<sup>[1]</sup>, it is found that the parton distributions are modified in the nuclear environment. The origin of the nuclear effects is still under debate in theory, and it is considered that different mechanisms are responsible for the effects in the different regions of parton momentum fraction. Up to now, almost all of the data on nuclear dependence are from charged lepton deep inelastic scattering experiments, which are sensitive only to the charge-weighted sum of all quark and antiquark distributions. From the charged lepton deep inelastic scattering off nuclei, the nuclear valence quark distributions are relatively well determined in the medium and large Bjorken  $x$  regions. However, the charged lepton deep inelastic scattering experiment would not be sensitive to the nuclear sea quark distributions. In order to pin down the nuclear antiquark distributions,

it is desirable that the nuclear Drell-Yan reaction is an ideal complementary tool.

The production of large-mass lepton pairs from hadron-hadron inelastic collisions was first studied by Drell and Yan, which is the so-called Drell-Yan process<sup>[2]</sup>. 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 nuclear Drell-Yan reaction is a complementary tool to probe the structure of hadron and nuclei. The nuclear Drell-Yan experimental data can be used to research the anti-quark distributions in hadron and nuclei. However, it is indicated that the projectile rarely retains a major fraction of its momentum in traversing the nucleus in high energy inelastic proton-nucleus scat-

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tering. The quark and gluon in the induced proton can lose a finite fraction of its energy due to the multiple collisions in the nuclear target. In this respect, initial-state interactions should be important in the nuclear Drell-Yan process since the dimuon in the final state does not interact strongly with the partons in the nuclei. The quark energy loss effect in the nuclear Drell-Yan process is another nuclear effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering.

It is well known that precise nuclear parton distributions are very important to explain high energy nuclear scattering phenomena. As for the strong necessities, global analyses of nuclear parton distribution functions have been proposed in recent years. For example, global analyses of nuclear parton distribution functions are given by EKRS (Eskola, Kolhinen, Ruskonen and Salgado)<sup>[3]</sup>, HKN (Hirai, Kumano and Nagai)<sup>[4]</sup> and HKM (Hirai, Kumano and Miyama)<sup>[5]</sup>. It is noticeable that HKN employed Fermilab E772<sup>[6]</sup> and E866<sup>[7]</sup> nuclear Drell-Yan reaction data, EKRS included E772 experimental data, and HKM proposed the nuclear parton distributions which were determined by means of the existing experimental data on nuclear structure functions without including the proton-nucleus Drell-Yan process.

Because of the quark energy loss effect in the nuclear Drell-Yan reaction, there is the kind of nuclear effect on the differential cross section ratios as a function of the quark momentum fraction in the beam proton and target nuclei. In previous works<sup>[8–11]</sup>, the Fermilab E866<sup>[7]</sup> nuclear Drell-Yan reaction data were used to investigate quark energy loss effect. But, the impact of quark energy loss can be partly canceled out in the proton-induced Drell-Yan cross section ratios for Fe to Be and W to Be. In this paper, by combining two typical kinds of quark energy loss parametrization with the nuclear parton distributions determined only with lepton-nuclear deep inelastic scattering experimental data, a leading order analysis is performed on the differential cross section ratios of tungsten versus deuterium as a function of the quark momentum fraction in the beam proton and target nuclei for the proton-induced Drell-Yan process. The influence of quark energy loss is elucidated on extracting the nuclear sea quark distribution.

## 2 Brief formalism for differential cross section in Drell-Yan process

In the Drell-Yan process<sup>[2]</sup>, the leading-order contribution is quark-antiquark annihilation into a lepton pair. The annihilation cross section can be ob-

tained from the  $q\bar{q} \rightarrow l^+l^-$  cross section, which is

$$\sigma[q\bar{q} \rightarrow l^+l^-] = \frac{4\pi\alpha_{\text{em}}^2 e_f^2}{9M^2}, \quad (1)$$

where  $\alpha_{\text{em}}$  is the fine-structure constant,  $e_f$  is the charge of the quark and  $M$  is the invariant mass of the lepton pair. The nuclear Drell-Yan differential cross section can be written as

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha_{\text{em}}^2}{9s x_1 x_2} \sum_f e_f^2 [q_f^p(x_1, Q^2) \bar{q}_f^A(x_2, Q^2) + \bar{q}_f^p(x_1, Q^2) q_f^A(x_2, Q^2)], \quad (2)$$

where  $\sqrt{s}$  is the center of mass energy of the hadronic collision,  $x_1$  (Resp.  $x_2$ ) is the momentum fraction carried by the projectile (Resp. target) parton, the sum is carried out over the quark flavor  $f$ , and  $q_f^{p(A)}(x, Q^2)$  and  $\bar{q}_f^{p(A)}(x, Q^2)$  are respectively the quark and antiquark distributions in the proton (nucleon in the nucleus  $A$ ).

In order to take account of the energy loss of the fast quarks moving through the cold nuclei, we will introduce two typical kinds of quark energy loss expressions, which are based on the theoretical studies from Brodsky and Hoyer<sup>[12]</sup>, and Baier et al<sup>[13]</sup>. One can be rewritten as

$$\Delta x_1 = \alpha \frac{\langle L \rangle_A}{E_p}, \quad (3)$$

where  $\alpha$  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 by the conventional value,  $\langle L \rangle_A = 3/4(1.2A^{1/3})$  fm. In addition to the linear quark energy loss rate, the other is rewritten as

$$\Delta x_1 = \beta \frac{\langle L \rangle_A^2}{E_p}. \quad (4)$$

Obviously, the partonic energy loss is quadratic with the path length. With 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. Thus, the nuclear Drell-Yan differential cross section can be expressed as

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha_{\text{em}}^2}{9s x_1 x_2} \sum_f e_f^2 [q_f^p(x'_1, Q^2) \bar{q}_f^A(x_2, Q^2) + \bar{q}_f^p(x'_1, Q^2) q_f^A(x_2, Q^2)]. \quad (5)$$

After the integral of the above differential cross section, the nuclear Drell-Yan production cross section is given by

$$\frac{d\sigma}{dx_{1(2)}} = \int dx_{2(1)} \frac{d^2\sigma}{dx_1 dx_2}. \quad (6)$$

### 3 Results and discussion

The Fermilab Experiment 772 (E772)<sup>[6]</sup> reported the ratios of the proton-induced nuclear Drell-Yan differential cross section for tungsten to deuterium target,

$$R_{W/D}(x_{1(2)}) = \frac{d\sigma^{p-W}}{dx_{1(2)}} / \frac{d\sigma^{p-D}}{dx_{1(2)}}. \quad (7)$$

Muon pairs were recorded in the range  $4 \text{ GeV} \leq M \leq 9 \text{ GeV}$  and  $M \geq 11 \text{ GeV}$ . The covered kinematical range was  $0.04 < x_2 < 0.3$ . By combining the quark energy loss effect with HKM<sup>[5]</sup> cubic type of nuclear parton distributions determined only from lepton-nuclear deep inelastic scattering experimental data, a global  $\chi^2$  analysis is given to the experimental data on the ratios of the nuclear Drell-Yan differential cross section  $R_{W/D}(x_{1(2)})$ .

As for the ratios  $R_{W/D}(x_1)$ , the obtained  $\chi^2$  per degree of freedom is  $\chi^2/\text{d.o.f.} = 2.14$  for the 31 data points without energy loss effect. It is shown that the calculated results without energy loss effect are in disagreement with the experimental data. With the fast quark energy loss, the  $\chi^2$  per degree of freedom is  $\chi^2/\text{d.o.f.} = 0.84$  for the linear quark energy loss formula with  $\alpha = 1.28$ , and the  $\chi^2$  per degree of freedom is given by  $\chi^2/\text{d.o.f.} = 0.84$  for the quadratic quark energy loss expression with  $\beta = 0.2$ . It is found

that the results given by the linear quark energy loss are nearly the same as these from the quadratic quark energy loss. The nuclear Drell-Yan differential cross section ratios are shown in Fig. 1 as functions of  $x_1$  for various intervals of  $M$ , respectively. The solid curves are the ratios with only the nuclear effects on the parton distribution. The dotted curves correspond to the results by combining linear quark energy loss with nuclear effects on structure function. It is apparent that the results with energy loss effect are in good agreement with the experimental data.

For the nuclear Drell-Yan differential cross section ratios  $R_{W/D}(x_2)$ , the  $\chi^2$  per degree of freedom is given by  $\chi^2/\text{d.o.f.} = 4.85$  for the 9 data points if the quark energy loss is not put in. There appears to be a significant disagreement between the theoretical results without energy loss effect and the experimental data. With consideration of the fast quark energy loss, the  $\chi^2$  per degree of freedom is  $\chi^2/\text{d.o.f.} = 1.31$  for the linear quark energy loss formula with  $\alpha = 0.94$ , and the  $\chi^2$  per degree of freedom is  $\chi^2/\text{d.o.f.} = 1.32$  for the quadratic quark energy loss expression with  $\beta = 0.15$ . It is shown that the results given by the linear quark energy loss are nearly identical to those from the quadratic quark energy loss. In Fig. 2, the solid curve is the ratios with only the nuclear effects on the parton distributions, the dotted curve corresponds to the results with added linear energy loss. Compared with the experimental data, our results

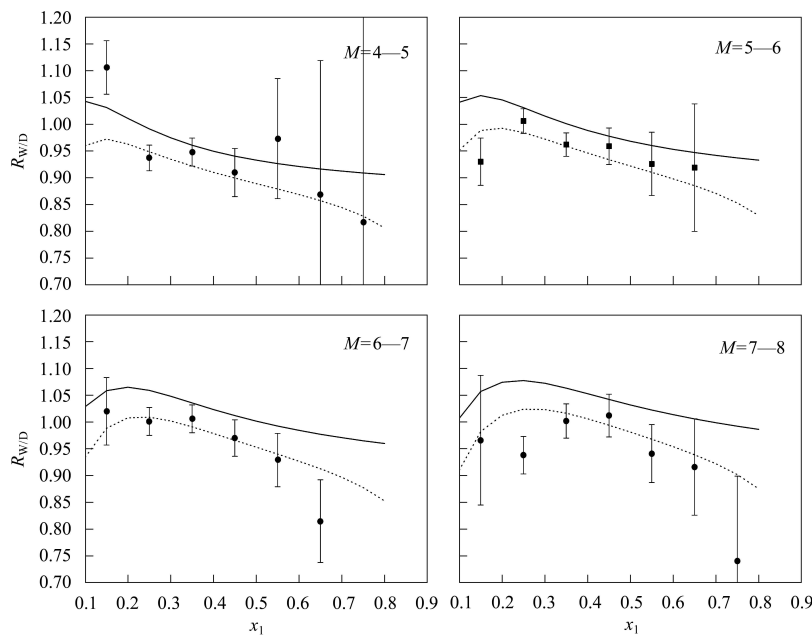


Fig. 1. The nuclear Drell-Yan cross section ratios  $R_{W/D}(x_1)$  for various intervals  $M$ . The solid curves correspond to the nuclear effects on structure function. The dotted curves show the combination of linear quark energy loss effect with HKM cubic type of nuclear parton distributions. The experimental data are taken from E772<sup>[6]</sup>.

with energy loss effect significantly agree with the experimental data. Meanwhile, it is noticeable that the values of the parameter  $\alpha$  (or  $\beta$ ) are different by means of the global  $\chi^2$  analysis to the ratios  $R_{W/D}(x_2)$  and  $R_{W/D}(x_1)$ . The results may originate from the experimental precision. If the experimental data are sufficiently precise, the values of the parameter  $\alpha$  (or  $\beta$ ) in the quark energy loss expression should be the same for fitting the ratios  $R_{W/D}(x_2)$  and  $R_{W/D}(x_1)$  from the nuclear Drell-Yan experiment.

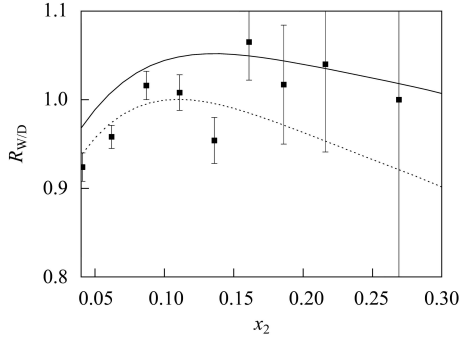


Fig. 2. The nuclear Drell-Yan cross section ratios  $R_{W/D}(x_2)$  of tungsten versus deuterium. The comments are the same as Fig. 1.

In order to clarify the influence of quark energy loss on the Drell-Yan differential cross section ratios as a function of the quark momentum fraction in target nuclei, the ratios on  $R_{W/D}(x_2)$  without quark energy loss to those with linear quark energy loss are calculated and tabulated in Table 1. The similar results can be obtained for the quadratic quark energy loss. It is found that the quark energy loss effect has an apparent influence on the Drell-Yan differential cross section ratios  $R_{W/D}(x_2)$ . The impact of quark energy loss on  $R_{W/D}(x_2)$  becomes larger with the increase of momentum fraction of the target parton. The quark energy loss effect produces approximately 3% to 11% suppression on the Drell-Yan differential cross section ratios  $R_{W/D}(x_2)$  in the ranges  $0.05 \leq x_2 \leq 0.3$ . Therefore, the application of nuclear Drell-Yan data with

heavy targets is remarkably subject to difficulty in the constraints of the nuclear antiquark distribution.

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

$x_2$	ratios of $R_{W/D}(x_2)$
0.05	1.03
0.10	1.04
0.15	1.05
0.20	1.07
0.25	1.09
0.30	1.11

## 4 Summary and concluding remarks

In summary, the quark energy loss effect in the nuclear Drell-Yan process is another nuclear effect apart from the nuclear effects on the parton distribution as in deep inelastic scattering. From the global  $\chi^2$  analysis on the ratios of nuclear Drell-Yan differential cross section  $R_{W/D}(x_{1(2)})$ , it is found that the theoretical results with quark energy loss are in good agreement with the experimental data. The quark energy loss effect has a significant impact on the Drell-Yan differential cross section ratio as a function of the quark momentum fraction in the beam proton and target nuclei. It is indicated that the influence of quark energy loss on the differential cross section ratios becomes greater with the increase of momentum fraction of the target parton. The application of nuclear Drell-Yan data with heavy targets is remarkably subject to difficulty in the constraint of the nuclear antiquark distribution. Therefore, we desire to take precise measurements of the experimental study from the relatively low energy nuclear Drell-Yan process at J-PARC<sup>[14]</sup> and Fermilab E906<sup>[15]</sup>. These new experimental data on nuclear the Drell-Yan reaction can shed light on the energy loss of fast quark propagating in a cold nucleus, and the impact of quark energy loss on the determination of nuclear sea quark distribution.

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