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Suppression of Nuclear Drell-Yan Ratios Due to Energy Loss Effect *

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Abstract The energy loss of the quark in the nuclear matter can be well described by the nuclear dependence in the high energy nuclear Drell-Yan process. In terms of the parametrization of the quark energy loss given in the literature and the nuclear parton distribution extracted from the experimental data of the deep inelastic scattering between lepton and nucleus only, the cross section ratios of lepton pair production in the nuclear Drell-Yan process induced by a proton of 800GeV bombarding on various nuclear targets at E772-FNAL are analyzed. It is shown that our results with the energy loss effect are in good agreement with the E772-FNAL data. Therefore, in order to extract the parton distribution functions in nucleus from the experimental data of the Drell-Yan process reliably, the energy loss effect should be taken into account.

Key words Drell-Yan, energy loss, nuclear parton distribution function

1 Introduction

In proton-proton collisions, the interactions between quarks and gluons that make up colliding nucleons[1] can be learned, parton distribution functions in nucleon can be extracted from the reaction data in relatively higher energies[2], and new physical phenomena might be revealed via precise calculations of cross sections. In the proton-nucleus collision, the parton distribution functions in nucleon would be modified, and the evolution of the strong interaction in space-time from early stages could be presented. Even in the nucleus-nucleus collision, the possible signal of the formation of the de-confined phase of QCD, the quark-gluon plasma[3], may be explored.

In the Drell-Yan prosess[4], only initial-state interactions are important, because the muon pair in the final state does not interact strongly with the partons in the nucleus. Thus, such a process can be an ideal place to study the energy loss of fast quarks[5]. Although this process is closely related to the deep inelastic scattering (DIS) of leptons, unlike DIS, it is sensitive to the antiquark contribution in the target parton distribution. When $x < 0.08$ in DIS, where x

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denotes the fraction of parton's momentum, the cross section per nucleon decreases with increasing nucleon number A due to the shadowing effect[6]. Such an effect should also occur in the dimuon production in the Drell-Yan process at small x_2, where x_2 represents the momentum fraction of the target parton. The theoretical calculation indicates that the shadowing effects in DIS and Drell-Yan processes have a common origin[7].

In 1990, E772 Collaboration at Fermilab[8] precisely measured the nuclear dependence of the Drell-Yan process by using an 800GeV proton beam. Muon pairs off the targets ^{2}H, C, Ca, Fe, and W, where the mass range is 4GeV$\leqslant M \leqslant$9GeV and $M \geqslant$11GeV were collected. In 2001, in terms of the global χ^2 analysis of the existing experimental data of nuclear structure functions except those in proton-nucleus Drell-Yan processes, Hirai,Kumano and Miyama (HKM)[9] proposed two types of nuclear parton distributions in which the weight function for nuclear effect was written by employing the quadratic and cubic expansion forms, respectively. The covered kinematic ranges were $10^{-9} \leqslant x \leqslant 1$ and $1\text{GeV}^2 \leqslant Q^2 \leqslant 10^5\text{GeV}^2$, and the target nucleus involved the lightest nucleus, deuteron, and some heavier ones. As a result, they obtained reasonable fit to the measured F_2. In this work, the nuclear dependence of the cross section ratios of the Drell-Yan process in the p-A collision are phenomenologically studied by combining the parametrization of quark energy loss proposed by G.T.Garvey and J.C.Peng[10] with the HKM's nuclear parton distribution.

2 Nuclear Drell-Yan process

In the Drell-Yan process, the leading-order contribution comes from the annihilation of quark and antiquark into a lepton pair. For the quark of flavor f, the annihilation cross section can be obtained by including a color factor of $\frac{1}{3}$ and a charge factor of $e_{\rm f}^2$ into the cross section of the $\rm e^+e^- \to \mu^+\mu^-$ process

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

where $\sqrt{\hat{s}} = (x_1x_2s)^{1/2}$ is the energy of the center of mass (CM) of the $\rm q\bar{q}$ system, $x_1(x_2)$ the momentum fraction carried by the projectile (target)parton, $\sqrt{s}$ the CM energy of the hadronic system, and M the invariant mass of the produced dimuon. The differential cross section of the hadronic Drell-Yan process is then obtained from the above-mentioned cross section of the partonic process with the quark distributions in both the beam and target particles:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}M} = K\frac{8\pi\alpha^2}{9M}\frac{1}{x_1 s}\sum_{\rm f} e_{\rm f}^2 \times \left[q_{\rm f}^p(x_1)\bar{q}_{\rm f}^A(x_2) + \bar{q}_{\rm f}^p(x_1)q_{\rm f}^A(x_2)\right], \tag{2}$$

where K is the high-order QCD correction, α denotes the fine-structure constant, the sum runs over the light flavor f=u,d,s, and $q_{\rm f}^{p(A)}(x)$ and $\bar{q}_{\rm f}^{p(A)}(x)$ represent the quark and anti-quark distributions in the proton (nucleon in the nucleus A), respectively. In order to obtain the x_1 dependence of Drell-Yan process, we calculate the differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1} = K\frac{8\pi\alpha^2}{9x_1 s} \times \sum_{\rm f} e_{\rm f}^2 \int \frac{\mathrm{d}M}{M}[q_{\rm f}^p(x_1)\bar{q}_{\rm f}^A(x_2) + \bar{q}_{\rm f}^p(x_1)q_{\rm f}^A(x_2)], \tag{3}$$

where the integration is taken over the invariant dimuon mass region according to the experimental data.

As for the energy loss of fast quarks moving through nucleus, a clear and simple model for the energy loss of the fast quark in cold nucleus was proposed by G.T.Garvey and J.C.Peng[10]. In their model, the energy loss of the incident quark in a unit length, α, in nuclear matter is assumed to be:

$$\Delta x_1 = \alpha\frac{\langle L\rangle_A}{E_{\rm p}}, \tag{4}$$

where $\langle L\rangle_A$ is the average path length of the incident quark in nucleus A, $E_{\rm p}$ denotes the energy of the incident proton. The value of the average path length is taken to be the conventional one, $\langle L\rangle_A = 3/4(1.2A^{1/3})$fm. If the energy loss of the quark in nucleus is considered, the momentum fraction of the quark would shift from $x_1' = x_1 + \Delta x_1$ to x_1 at the point of fusion. Thus, the production cross section in the pA Drell-Yan process can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1} = K\frac{8\pi\alpha^2}{9x_1 s}\sum_{\mathrm{f}} e_{\mathrm{f}}^2 \int \frac{\mathrm{d}M}{M}[q_{\mathrm{f}}^p(x_1')\bar{q}_{\mathrm{f}}^A(x_2) + \bar{q}_{\mathrm{f}}^p(x_1')q_{\mathrm{f}}^A(x_2)]. \quad (5)$$

In order to compare with the experimental data given by E772 Collaboration[8], we introduce the nuclear Drell-Yan ratio

$$R_{A_1/A_2}(x_1) = \frac{\mathrm{d}\sigma^{p-A_1}}{\mathrm{d}x_1} \Big/ \frac{\mathrm{d}\sigma^{p-A_2}}{\mathrm{d}x_1} \quad (6)$$

and the fitting error

$$\chi^2 = \sum_j \frac{\left(R^{\mathrm{data}}_{A_1/A_2,j} - R^{\mathrm{theo}}_{A_1/A_2,j}\right)^2}{\left(R^{\mathrm{err}}_{A_1/A_2,j}\right)^2}, \quad (7)$$

where $R^{\mathrm{data}}_{A_1/A_2,j}$ ($R^{\mathrm{theo}}_{A_1/A_2,j}$) indicates the experimental data (theoretical values), and $R^{\mathrm{err}}_{A_1/A_2,j}$ denotes the systematic errors in the experiment.

3 Results and discussion

By employing HKM's nuclear parton distribution functions[9] together with the parton distribution functions in proton given by Martin, Roberts, Stirling and Thorne (MRST)[11], the obtained χ^2 value with α=0.0 (without energy loss effects) for totally 122 data points is about 207.7. The χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} \simeq 1.7$. When α=0.9 (with energy loss effects), the obtained χ^2 per degree of freedom is $\chi^2/\mathrm{d.o.f.} \simeq 1.4$. The results obtained by employing HKM's quadratic expansion form in the nuclear parton distribution are almost the same as those shown above. The calculated Drell-Yan cross section ratios as the function of x_1 for various M values with HKM's cubic expansion form in the nuclear parton distribution for $C/^2H$ and $W/^2H$ are shown in Figs. 1 and 2, respectively. The dotted curves represent the ratios only with the nuclear effect on the parton distribution used in DIS process, and the solid curves denote the ratios with both the energy loss effect and the nuclear effect on the structure functions. Compared with the experimental data, our results are in good agreement with the E772 data, if the energy loss effect of quarks is considered.

In this work, the energy loss of the incident quark is employed with a linear dependence on the factor of $A^{1/3}$. In addition, the quark energy loss has a quadratic dependence on the medium size[12]. In current Fermilab proton energy, the nuclear Drell-Yan process does not discriminate the two types. Further experiments are needed about Drell-Yan reactions with a lower energy incident proton off nuclei.

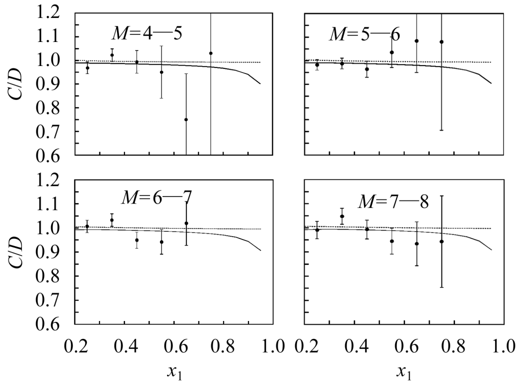

Fig. 1. The nuclear Drell-Yan cross section ratios $R_{A_1/A_2}(x_1)$ for $A_1/A_2 = C/^2H$ in various values of M. The dotted curves correspond to the nuclear effects on the structure function. Solid curves denote the case where both the energy loss and the HKM's cubic expansion form in the nuclear parton distribution are considered. The solid circles and corresponding error bars are the E772 experimental data taken from Ref. [9].

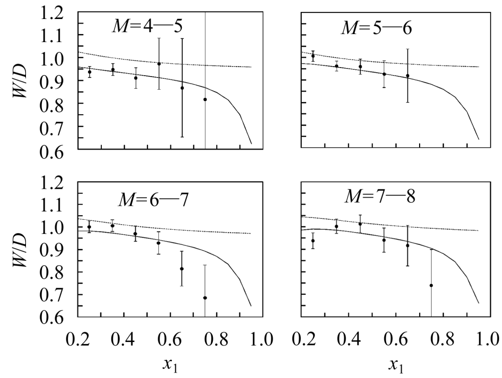

Fig. 2. Same as that in Fig. 1, except for $A_1/A_2 = W/^2H$.

In summary, a leading-order analysis of the E772 data is performed by taking into account the energy loss effect of fast quarks. By using the parameterized nuclear parton distributions obtained in the case without the nuclear Drell-Yan process and including the energy loss effect, the calculated results are in good agreement with the E772 data. Although the abundant data of the electron and the muon deep inelastic scattering off nuclei are currently available, valence quark distributions in the small x region and anti-quark distributions are still difficult to be extracted, and only valence quark distributions in large x region can relatively be well determined. In order to calculate the cross sections of nuclear reactions in high energies accurately and to find the signal of quark-gluon plasma in high energy heavy-ion collisions, one must have accurate nuclear parton distributions. Apparently, due to the energy loss of quark, its effect should be taken into account in extracting nuclear parton distribution functions from the experimental data of the Drell-Yan process. Moreover, accurate neutrino scattering experiments should further be used for measuring the structure functions $F_2(x,Q^2)$ and $xF_3(x,Q^2)$. In terms of the average of $xF_3^{\nu A}(x,Q^2)$ and $xF_3^{\bar{\nu} A}(x,Q^2)$, the distribution functions of valence quarks can be well determined. Combining inelastic scattering data of the lepton-nucleus with the neutrino-nucleus processes, the distribution functions of valence quark and anti-quark can be obtained. It would enrich our knowledge of the energy loss effect in the nuclear Drell-Yan process at high energies.

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能量损失效应引起的核Drell-Yan微分截面比的压低*

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摘要　核环境中夸克的能量损失可以通过高能核Drell-Yan过程的核依赖进行测量. 利用文献中给出的夸克能量损失公式和从轻子–原子核深度非弹性散射实验数据得到的束缚核子中的部分子分布函数, 计算了FNAL E772 800GeV的质子打击不同原子核的Drell-Yan过程截面比, 发现考虑能量损失的计算结果与FNAL E772实验数据符合甚好. 建议在利用核Drell-Yan过程实验数据抽取束缚核子内部分子分布函数时应该考虑能量损失效应.

关键词　Drell-Yan　能量损失　束缚核子部分子分布函数

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