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Drell-Yan dilepton production in relativistic heavy-ion collisions at RHIC*

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Abstract: We investigate the lepton pair production with the Drell-Yan process in relativistic heavy ion collisions by computing the double differential cross section $d\sigma/dM^2dy$ and $d\sigma/dM^2dx_F$ at the next-to-leading order in p+Au and Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV at RHIC. The resulting nuclear modification factors R^{pAu} and R^{AuAu} show strong sensitivity to the cold nuclear matter (CNM) effects and could probe the CNM effects at a very wide region of the longitudinal momentum fraction x. The variation of R with the invariant mass M, the rapidity y and the Feynman variable x_F is shown and we find that the nuclear modification factor for the double differential cross section could be smaller than 0.4 in some kinematic regions of high-energy nucleus-nucleus reactions at RHIC.

Key words: Drell-Yan process, heavy-ion collisions, cold nuclear matter effects

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1 Introduction

The production of a lepton pair in hadron-hadron collisions with large invariant mass has been studied experimentally for a long time [1], and theoretical computations with the collinear factorization formalism of perturbative Quantum Chromodynamics (pQCD) have been well known and could describe the experimental data of the Drell-Yan process very well, which in turn has provided complementary constraints on parton distribution functions (PDFs) in nucleons as other hard processes in $e^+ + e^-$ collisions and deeply inelastic scatterings (DIS) [2].

It will be of great interest to extend these studies to dilepton production in proton-nucleus and nucleus-nucleus collisions to test the validity of the generally assumed and widely used pQCD inspired parton-model in high-energy nucleus collisions. Moreover, in relativistic heavy-ion collisions a new kind of matter with deconfined partons, the quark-gluon plasma (QGP), is expected to be created. The formation of the QGP will modify the behaviors of many physics observables in high-energy nuclear collisions and the study of this alteration in the existence of the QGP is often complicated by the entanglement of the initial-state cold nuclear matter (CNM) effects and the final-state QGP medium effects [3, 4]. To study the formation and the properties of the QGP we need to have a reliable control of the initial-state CNM effects. The dilepton production of the Drell-Yan process with the large invariant mass in high-energy nuclear reactions therefore provides an excellent channel for studying the initial-state CNM effects because dilepton at large invariant mass does not interact with the hot QCD medium strongly and could disentangle the final-state QGP medium effects from the initial-state CNM effects [5–8].

In this paper we compute two sets of double differential cross sections for the Drell-Yan lepton pair production at the next-to-leading order in p+Au and Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV and obtain the resulting nuclear modification factor R. It is found that the nuclear modification R for the Drell-Yan process is very sensitive to the CNM effects and goes from larger than 1 to smaller than 0.4. By confronting the experimental measurements of the Drell-

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Yan in relativistic heavy-ion collisions with the theoretical investigations we may reduce the uncertainties in quantifying the CNM effects.

2 The Drell-Yan process in h+h collisions

The dilepton production in hadron-hadron collisions with a large invariant mass squared $M^2=q^2=(p_{l^+}+p_{l^-})^2$ in the Drell-Yan process at the leading order is given by the quark-antiquark annihilation process as shown in Fig. 1 (a) with q being the momentum of the virtual photon γ^*. The corresponding double differential cross section at the lowest order can be given as,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2\mathrm{d}y}=\sum_{\mathrm{q},\bar{\mathrm{q}}}\frac{4\pi e_{\mathrm{q}}^2\alpha^2}{9M^2s}f_{\mathrm{q}}(x_1,M^2)f_{\bar{\mathrm{q}}}(x_2,M^2), \quad (1)$$

where y is the rapidity of the lepton pair, s is the center of mass energy squared, $f_{\mathrm{q}(\bar{\mathrm{q}})}(x,\mu^2)$ is the (anti-) quark parton distribution functions in hadron with the longitudinal momentum fraction x. We have

$$x_1=\sqrt{\tau}\mathrm{e}^{y},\ \ x_2=\sqrt{\tau}\mathrm{e}^{-y},\ \ \tau=M^2/s\,. \quad (2)$$

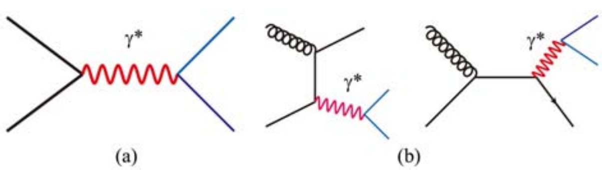

Fig. 1. (a) Feynman diagram for the Drell-Yan process at the leading-order; (b) The Compton process for higher order correction to the Drell-Yan process.

Moreover we can define the kinematics of the lepton pairs in terms of M and the Feynman variable x_{F} with

$$x_{\mathrm{F}}=2q_{\mathrm{L}}/\sqrt{s}\,, \quad (3)$$

where q_{L} is the longitudinal momentum of dilepton and x'_1,x'_2 as

$$x'_1x'_2=M^2/s,\ \ \ x_{\mathrm{F}}=x'_1-x'_2, \quad (4)$$

which gives

$$\begin{aligned} x'_1&=\sqrt{\frac{M^2}{s}+\frac{x_{\mathrm{F}}^2}{4}}+\frac{x_{\mathrm{F}}}{2},\\ x'_2&=\sqrt{\frac{M^2}{s}+\frac{x_{\mathrm{F}}^2}{4}}-\frac{x_{\mathrm{F}}}{2}. \end{aligned} \quad (5)$$

for a fixed M and x_{F}. Then we can express the double differential cross section with respect to M^2 and x_{F} as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2\mathrm{d}x_{\mathrm{F}}}=\sum_{\mathrm{q},\bar{\mathrm{q}}}\frac{4\pi e_{\mathrm{q}}^2\alpha^2}{9M^2s(x'_1+x'_2)}f_{\mathrm{q}}(x'_1,M^2)f_{\bar{\mathrm{q}}}(x'_2,M^2). \quad (6)$$

Please note that only at the leading order is it guaranteed $x_1=x'_1\,,x_2=x'_2$.

At the next-to-leading order we will get corrections from the annihilation process at the order $\mathcal{O}(\alpha^2\alpha_{\mathrm{s}})$ and from the Compton process illustrated in Fig. 1 (b). In these calculations the infrared divergence is canceled by the virtual corrections and the mass singularity by the renormalization of parton distribution functions according to the factorization of perturbative QCD [9, 10]. In the following calculations we utilize the analytical formulae of the Drell-Yan process at the next-to-leading order derived in [10] to calculate $\mathrm{d}\sigma/\mathrm{d}M^2\mathrm{d}y$ and $\mathrm{d}\sigma\mathrm{d}M^2\mathrm{d}x_{\mathrm{F}}$ for a lepton pair production in hadronic collisions.

In Fig. 2 we show a comparison of our numerical results of the Drell-Yan process at the next-to-leading order for 800 GeV proton bombardment of ^{2}H with the experiment data by Fermilab E772 [11]. In this calculation we use the CTEQ6 parametrization set of PDFs [12] and include the isospin effect of PDFs for deuteron. The renormalization and factorization scales is always set as $\mu_{\mathrm{R}}=\mu_{\mathrm{f}}=M$. It can be seen that the NLO calculation gives a good description of the experimental measurement by E772.

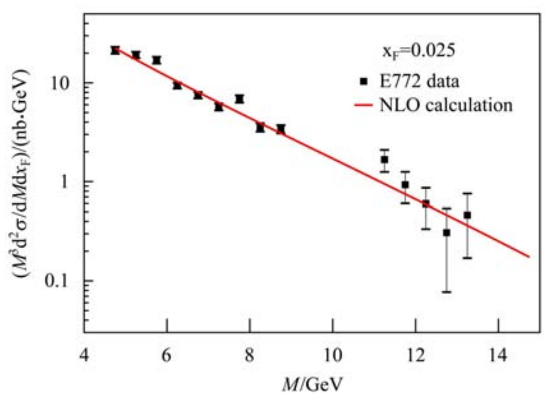

Fig. 2. Comparison of theoretical calculation at NLO for the Drell-Yan process for fixed target experiments p+D collisions with the experimental data at E772.

3 The Drell-Yan process in nuclear collisions

In relativistic heavy-ion collisions due to different cold nuclear matter effects, such as nuclear shadowing effect, anti-shadowing effect, EMC effect, etc. [5, 14–16], the PDFs of proton will be different from those of a nucleus. Taking into account different CNM effects phenomenologically, we can define the nuclear parton distribution functions (nPDFs) by [13, 18]

$$f_{\rm i}^A(x,Q^2) = R_{\rm i}^A(x,Q^2) f_{\rm i}^p(x,Q^2). \tag{7}$$

Here $f_{\rm i}^p(x,Q^2)$ is the PDF for a parton flavor i in a proton, $f_{\rm i}^A(x,Q^2)$ is the PDF of a proton bound to a nucleus with mass number A. $R_{\rm i}^A(x,Q^2)$ stands for the nuclear modification for this parton flavor and characterizes four typical nuclear effects at different regions of x: the shadowing effect ($x < x_{\rm S} \sim 0.1$); the anti-shadowing effect ($x_{\rm S} < x < x_{\rm E} \sim 0.3$); the EMC effect ($x_{\rm E} < x < x_{\rm M} \sim 0.8$) and the Fermi motion effect ($x_{\rm M} < x$). For different parton flavor i, $x_{\rm S}$, $x_{\rm E}$ and $x_{\rm M}$ will vary accordingly, but we always have $x_{\rm S} < x_{\rm E} < x_{\rm M}$.

The PDFs of neutron bound to the nucleus could be given with the isospin symmetry. Therefore we obtain the PDF for a u quark in a nucleus with mass number A and proton number Z as [13, 17, 18]

$$f_{\rm u}^A(x,Q^2) = Z f_{\rm u}^A(x,Q^2) + (A-Z) f_{\rm d}^A(x,Q^2). \tag{8}$$

The Drell-Yan process in p+A and A+A is an excellent channel for investigating the modification of PDF in a nucleus because the high energy virtual photon does not participate in the strong interactions between quarks and gluons, no matter whether it is in a cold or hot nuclear medium [5–7]. Here we will compute ${\rm d}\sigma^{AB}/{\rm d}M^2{\rm d}y$ and ${\rm d}\sigma^{AB}/{\rm d}M^2{\rm d}x_{\rm F}$ for the Drell-Yan lepton pair production at the next-to-leading order in relativistic heavy-ion collisions. To do so one needs to replace the relevant PDFs of a hadron in Eq. (1) and in Eq. (6) with the corresponding nPDF for the leading-order results and make similar changes for higher order corrections. Then we could obtain the nuclear modification factor R by

$$R(M,y) = \frac{\dfrac{{\rm d}\sigma^{AB}}{{\rm d}M^2{\rm d}y}}{\langle N_{\rm bin}\rangle \dfrac{{\rm d}\sigma^{pp}}{{\rm d}M^2{\rm d}y}},$$

$$\text{or} \quad R(M,x_{\rm F}) = \frac{\dfrac{{\rm d}\sigma^{AB}}{{\rm d}M^2{\rm d}x_{\rm F}}}{\langle N_{\rm bin}\rangle \dfrac{{\rm d}\sigma^{pp}}{{\rm d}M^2{\rm d}x_{\rm F}}},$$

where $\langle N_{\rm bin}\rangle$ gives the number of binary collisions in p+A and A+A collisions with Glauber model [14–16].

In Fig. 3 and Fig. 4 we show our numerical simulation of nuclear modification factor R for the Drell-Yan process at NLO p+Au and Au+Au collisions with $\sqrt{s_{\rm NN}} = 200$ GeV at RHIC where the EPS08 parametrization of nPDF [13] is used.

The variation of the nuclear modification factor $R(M,Y)$ with the invariant mass M and y is illustrated in two plots of Fig. 3. From the left panel of Fig. 3 we can see that in central rapidity $y=0$, $R^{\rm pAu}$ is smaller than 1 when $M<10$ GeV where the longitudinal momentum fraction x_1 (or x_2) in PDFs given by Eq. (2) at the leading-order is rather small and therefore we see the nuclear shadowing effect. At very large M we also see a significant suppression due to the EMC effect, while in the intermediate region of M the ratio R is enhanced slightly due to the anti-shadowing effect. In Au+Au collisions, these nuclear effects will be amplified a little bit due to the existence of two heavy nuclei. Please keep in mind that for higher order processes illustrated in Fig. 1 (b) the momentum fraction ξ in PDFs $f(\xi,\mu)$ has a relationship $1 \geqslant \xi \geqslant x_{1,2}$ because more energy will be needed to generate addition gluon radiation. Therefore for higher order corrections, the momentum fraction ξ may cover a large range from the small-x shadowing region to the large-x Fermi motion region. The left panel of Fig. 3 shows a monotonous decrease of R with increasing rapidity and it is smaller than 0.6 for Au+Au collisions when $y=2$.

The nuclear modification factor $R(M,x_{\rm F})$ as a function of M and the Feynman variable $x_{\rm F}$ is given in Fig. 4. It is observed that $R(M,x_{\rm F})$ is very sensitive to $x_{\rm F}$ and could be smaller than 0.4 when $x_{\rm F} \sim 0.75$ with $M = 10$ GeV for Au+Au collisions at RHIC. The underlying reason could be easily understood if we consider the leading-order contribution given by Eq. (5) and Eq. (6). One can see when $x_{\rm F}$ varies from 0 to ~ 1, $x'_{1,2}$ may change from very small ~ 0 to ~ 1 and therefore it can run almost the whole region of x and probe four typical CNM effects. The more dramatic variation of $R^{\rm AuAu}$ relative to $R^{\rm pAu}$ comes from the combined effect of two nuclear parton distribution functions such as the term $f_{\rm q}^A(x'_1,Q^2) f_{\bar{\rm q}}^A(x'_2,Q^2)$ at the leading order with $x'_1 = x'_2 + x_{\rm F}$.

Figure 3 and Fig. 4 demonstrate that the nuclear modification factors R for ${\rm d}\sigma/{\rm d}M^2{\rm d}y$ and ${\rm d}\sigma/{\rm d}M^2{\rm d}x_{\rm F}$ of the Drell-Yan process is very sensitive to the CNM effects. By measuring the alteration of R with the invariant mass M, rapidity y and the Feynman variable $x_{\rm F}$ at heavy-ion collisions and comparing the experimental data with the theoretical calculations we could significantly shrink the theoretical uncertainty in estimating the CNM effects and utilize them to distinguish different models or parameterizations of the CNM effects.

4 Summary

The dilepton production with large invariant mass

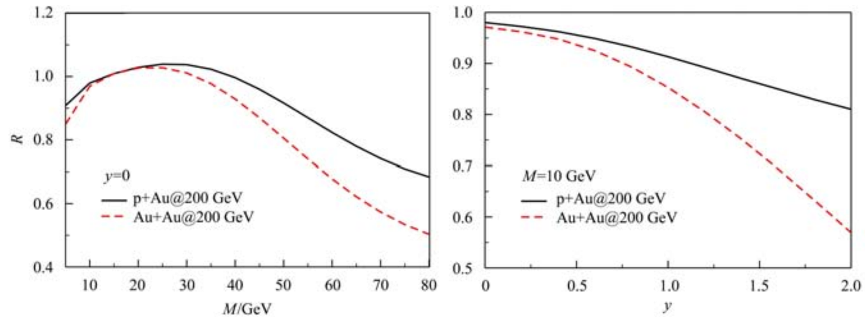

Fig. 3. Nuclear modification factor R as a function of M and y for p+Au and Au+Au collisions with $\sqrt{s_{\rm NN}}=$ 200 GeV at RHIC.

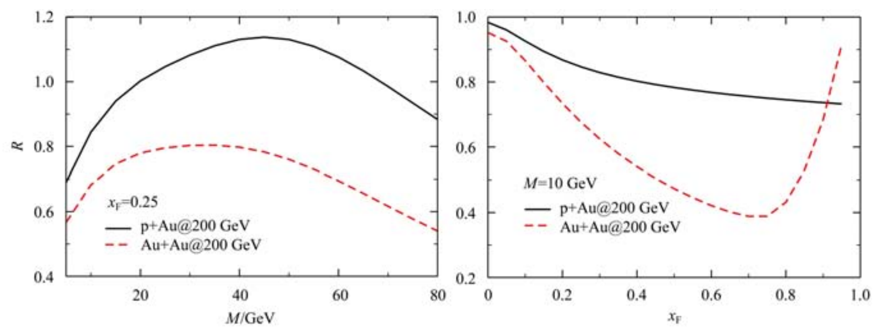

Fig. 4. Nuclear modification factor R as a function of M and $x_{\rm F}$ for p+Au and Au+Au collisions with $\sqrt{s_{\rm NN}}=200$ GeV at RHIC.

M in heavy-ion collisions provides an optimal facility for studying the cold nuclear matter effects because dilepton with large invariant mass M does not participate in the strong interaction between quarks and gluons in a nuclear environment[1)]. In this paper we have investigated the Drell-Yan process in relativistic heavy-ion collisions by calculating the double differential cross section $\mathrm{d}\sigma/\mathrm{d}M^2\mathrm{d}y$ and $\mathrm{d}\sigma/\mathrm{d}M^2\mathrm{d}x_{\rm F}$ at the next-to-leading order for p+Au and Au+Au collisions with $\sqrt{s_{\rm NN}}=200$ GeV at RHIC. The corresponding nuclear modification factors $R(M,y)$ and $R(M,x_{\rm F})$ are given, which show strong sensitivity to the initial-state CNM effects. Especially as a function of the Feynman $x_{\rm F}$ with not very large invariant mass M the suppression for the double differential cross section could approach 0.4 due to the CNM effects. A large variation of R as a function of $x_{\rm F}$ is found because when $x_{\rm F}$ varies from 0 to ~ 1 the CNM effects at a very wide range of longitudinal momentum faction x could be visited by the dilepton production.

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1) For dilepton production at small invariant mass M or transverse momentum $p_{\rm T}$ in high-energy nuclear collisions, the thermal dilepton production due to parton interactions in the QGP should be taken into account. However, the contribution of thermal dilepton to dilepton production at large M or $p_{\rm T}$ is very small and could be neglected