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Large Transverse Momentum Production of Lepton Pairs in Au-Au Collisions*

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Abstract：The large transverse momentum distribution of lepton pairs produced in heavy-ion collisions has been studied，making use of the perturbative QCD. The contribution of the two-parton production process into lepton pairs in Au-Au collisions is calculated. Lepton pair production with the direct single photon process and the resolved single photon process are introduced. We believe that the photon processes are significant. The complete processes at large transverse momentum are included，and moreover，the effect of shadowing and isospin of nucleus are also considered in heavy-ion collisions. Dilepton signals to regard the background of QGP have a good correction.

Key words：large transverse momentum；lepton pair production；Au-Au collision

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1　Introduction

Hadronic processes producing a large transverse momentum (P_T) photon play a fundamental role in heavy-ion collisions. Dilepton production in ultrarelativistic heavy-ion collisions is intimately related to many signals and their backgrounds for physics processes or new physics.

From the earlier Relativistic Heavy Ion Collider(RHIC) to the Large Hadron Collider(LHC)，many efforts have been trying to probe the properties of the quark-gluon plasma(QGP)，which has become the most important issue in the study of relativistic heavy-ion collisions[1-10]. In probing the properties of QGP，the production of lepton pairs is ineluctable at large transverse momentum. In the circumstances，we consider that the production of lepton pairs is not ignored at large transverse momentum. Dilepton signals produced from the initial nucleus-nucleus collisions are significant to regard the background of QGP.

The PHENIX collaboration at RHIC has recently measured the transverse momentum distribution of electron-positron pairs，with the pairs' invariant mass as low as 100 MeV$<M<$300 MeV，in both p-p and Au-Au collisions. Experimental results from the RHIC have established that in Au-Au collisions at $\sqrt{s}=200$ GeV matter is created with very high energy density[11-14].

In our case，a virtual photon could subsequently decay into a lepton pair，which can be detected. This case thus corresponds to a "Drell-Yan" type situation，with a lepton pair at large P_T[15-19]. Perturbative QCD theory should work well at large transverse momentum (P_T) in ultra-relativistic heavy-ion collisions. In our calculation，Au-Au scattering takes place in the region 1 GeV

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$\leqslant P_T \leqslant 10$ GeV.

We further calculate the dilepton production in Au-Au collisions，making use of nuclear parton distribution functions. Inside，parton distribution functions are from Ref. ［20］，parton distributions of real and virtual photons are from Ref. ［21］. The total energy of nucleon-nucleon collisions is $\sqrt{s} = 200$ GeV at large transverse momentum distributions of lepton pairs in Au-Au collisions. We discuss the whole processes of the lepton pair production at large transverse momentum in Au-Au collisions at RHIC. Then the contribution of above processes is calculated.

In Sec. 2，we discuss the whole processes of the lepton pair production at large transverse momentum in Au-Au collisions. There are four major processes in here. The effect of shadowing and isospin of nucleus are introduced in the parton model. In Sec. 3，the numerical results are displayed. In order to compare with data from RHIC，we deal with results which are calculated. Finally，Sec. 4 presents our summary and conclusions.

2　Lepton Pair Production at Large Transverse Momentum

The process for Drell-Yan type inclusive lepton pair production in hadronic collisions is $A + B \to \gamma^* (\to l^+ l^-) + X$. We can express in terms of the cross section for producing a virtual photon that decays into the observed lepton pair. The cross section is in the following：

$$\frac{d\hat{\sigma}_{AB\to l^+l^- X}}{dM^2\, d\hat{t}} = \frac{\alpha}{3\pi M^2} \frac{d\hat{\sigma}_{AB\to\gamma^* X}}{d\hat{t}} \quad , \qquad (1)$$

where the variables M is the invariant mass of a lepton pair.

2.1　Lepton pair production with the leading order process

In the process，parton-parton is a direct process without the fragmentation of parton. There are two channels in here ($q + \bar{q} \to \gamma^* (\to l^+ l^-) + g$，$q + g \to \gamma^* (\to l^+ l^-) + q$). The cross sections of the two channels are in the following[22]：

$$\frac{d\sigma}{dM^2\, dy\, d^2 P_T} = \frac{1}{\pi} \int_{x_a^{\min}}^{1} dx_a G_{A/a}(x_a, Q^2) \times G_{B/b}(x_b, Q^2) \frac{x_a x_b}{x_a - x_1} \frac{d\hat{\sigma}_{ab\to l^+ l^- x}}{dM^2\, d\hat{t}} \quad , \qquad (2)$$

where $d\hat{\sigma}_{ab\to\gamma^* x}/d\hat{t}$ [22] is for parton scattering. For the rapidity y is zero，$\sqrt{s}$ and P_T are the total energy of nucleon-nucleon collisions and transverse momentum of the lepton pair，respectively. We have the Mandelstam variables in the cross section as $\hat{s} = x_a x_b s$, $\hat{t} = -x_a s x_2 + M^2$ and $\hat{u} = -x_b s x_1 + M^2$. Besides，$\tau = M^2/s$, $x_T = 2P_T/\sqrt{s}$, $x_1 = x_2 = (x_T^2 + 4\tau)^{1/2}/2$ and $x_b = (x_a x_2 - \tau)/(x_a - x_1)$. The minimum momentum fraction in the integral is $x_a^{\min} = (x_1 - \tau)/(1 - x_2)$.

For the nucleus-nucleus collisions，we choose the parton distribution $G(x, Q^2)$ of the nucleus from M. Gluck et al.[20] in the following：

$$G(x, Q^2) = R(x, A)[Z P(x, Q^2) + (A - Z) N(x, Q^2)] \quad , \qquad (3)$$

where $R(x, A)$ is the EMC shadowing factor[23]，Z is the proton number of the nucleus，A is the nucleon number，$P(x, Q^2)$ is the proton distribution and $N(x, Q^2)$ is the neutron distribution. Since protons and neutrons have different up and down valence quark distribution，the isospin of the nucleus can be represented by the sum of the proton and neutron distribution[24].

2.2　Lepton pair production with the fragmentation process

In this process，lepton pairs emit from the fragmentation of quarks in the final state. There are six channels ($qq' \to qq'$，$qq \to qq$，$q\bar{q} \to q'\bar{q}'$，$q\bar{q} \to q\bar{q}$，$gq \to gq$ and $gg \to q\bar{q}$) about large transverse momentum. The cross sections of the six channels are in the following：

$$\frac{d\sigma}{dM^2\, dy\, d^2 P_T} = \frac{1}{\pi} \int_{x_a^{\min}}^{1} dx_a \int_{x_b^{\min}}^{1} dx_b G_{A/a}(x_a, Q^2) \times G_{B/b}(x_b, Q^2) D_q^{\gamma}(z_c, Q^2) \frac{x_a x_b}{z_c (x_a x_b - \tau)} \frac{d\hat{\sigma}_{ab\to cd}}{dM^2\, d\hat{t}}, \qquad (4)$$

where $\mathrm{d}\hat{\sigma}_{\mathrm{ab}\to\mathrm{cd}}/\mathrm{d}\hat{t}$ [25] is for parton scatterings is . We have the Mandelstam variables in the cross section as $\hat{s}=x_{\mathrm{a}}x_{\mathrm{b}}s$, $\hat{t}=-sx_2(x_{\mathrm{a}}/z_{\mathrm{c}})$ and $\hat{u}=-sx_1(x_{\mathrm{b}}/z_{\mathrm{c}})$. Besides, $x_{\mathrm{a}}^{\min}=(\tau+x_1)/(1-x_2)$, $x_{\mathrm{b}}^{\min}=(\tau+x_{\mathrm{a}}x_2)/(x_{\mathrm{a}}-x_1)$ and $z_{\mathrm{c}}=(x_{\mathrm{a}}x_2+x_{\mathrm{b}}x_1)/(x_{\mathrm{a}}x_{\mathrm{b}}-\tau)$.

A factor of $\pi\alpha_{\mathrm{s}}^2/s^2$ which is used in the process has been factored out of the purely strong-interaction process[25]. Here the strong running coupling constant is

$$\alpha_{\mathrm{s}}=\frac{4\pi}{\beta_0\ln(Q^2/\Lambda^2)} \quad , \tag{5}$$

where the QCD scale parameter $\Lambda=0.2$ GeV , $\beta_0=11-2n_{\mathrm{f}}/3$, and n_{f} is the flavor number of quarks.

The fragmentation function of photons is given by the following:

$$D_{\mathrm{q}}^{\gamma}(z_{\mathrm{c}},Q^2)=\frac{\alpha e_{\mathrm{q}}^2}{2\pi z_{\mathrm{c}}}\ln\frac{Q^2}{\Lambda^2}[1+(1-z_{\mathrm{c}})^2], \tag{6}$$

and one should note that $D_{\mathrm{g}}^{\gamma}(z_{\mathrm{c}},Q^2)=0$ due to a photon is not coupled with a gluon directly[24].

2.3 Lepton pair production with the direct single photon process

In the process, a photon which is fragmented from a parton reacts with the other parton ($\gamma+\mathrm{q}\to\mathrm{l}^+\mathrm{l}^-+\mathrm{q}$). The cross section is in the following:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2\mathrm{d}y\mathrm{d}V^2P_{\mathrm{T}}}=\frac{2}{\pi}\int_{x_{\mathrm{a}}^{\min}}^{1}\mathrm{d}x_{\mathrm{a}}\times$$
$$\int_{x_{\mathrm{b}}^{\min}}^{1}\mathrm{d}x_{\mathrm{b}}G_{\mathrm{A/a}}(x_{\mathrm{a}},Q^2)G_{\mathrm{B/b}}(x_{\mathrm{b}},Q^2)D_{\mathrm{q}}^{\gamma}(z_{\mathrm{c}},Q^2)\times$$
$$\frac{x_{\mathrm{a}}x_{\mathrm{b}}z_{\mathrm{c}}}{x_{\mathrm{a}}x_{\mathrm{b}}-x_{\mathrm{a}}x_2}\frac{\mathrm{d}\hat{\sigma}_{\gamma\mathrm{q}\to\mathrm{l}^+\mathrm{l}^-\mathrm{q}}}{\mathrm{d}M^2\mathrm{d}\hat{t}} \quad , \tag{7}$$

where $\mathrm{d}\hat{\sigma}_{\gamma\mathrm{q}\to\gamma^*\mathrm{q}}/\mathrm{d}\hat{t}$ is for parton scattering. We have the Mandelstam variables in the cross section as $\hat{s}=x_{\mathrm{a}}x_{\mathrm{b}}z_{\mathrm{c}}s$, $\hat{t}=M^2-sx_{\mathrm{a}}x_2z_{\mathrm{c}}$, $\hat{u}=M^2-x_{\mathrm{b}}sx_1$. Besides, $x_{\mathrm{a}}^{\min}=(x_1-\tau)/(1-x_2)$, $x_{\mathrm{b}}^{\min}=(x_{\mathrm{a}}x_2-\tau)/(x_{\mathrm{a}}-x_1)$ and $z_{\mathrm{c}}=(x_{\mathrm{b}}x_1-\tau)/(x_{\mathrm{a}}x_{\mathrm{b}}-x_{\mathrm{a}}x_2)$.

2.4 Lepton pair production with the resolved single photon process

In the process, a parton of photon which is fragmented from a parton reacts with the other parton. Principle allows a photon for a short time also to fluctuate into a quark-antiquark pair. Therefore a high energy photon looks like surrounded by a quark cloud, and can be interpreted that it has a inner parton structure. There are two channels in here ($\mathrm{q}_{\gamma}+\bar{\mathrm{q}}\to\mathrm{l}^+\mathrm{l}^-+\mathrm{g}$, $\mathrm{q}_{\gamma}+\mathrm{g}\to\mathrm{l}^+\mathrm{l}^-+\mathrm{q}$). The cross sections of the two channels are in the following:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2\mathrm{d}y\mathrm{d}^2P_{\mathrm{T}}}=\frac{2}{\pi}\int_{x_{\mathrm{a}}^{\min}}^{1}\mathrm{d}x_{\mathrm{a}}\int_{x_{\mathrm{b}}^{\min}}^{1}\mathrm{d}x_{\mathrm{b}}\times$$
$$\int_{z_2^{\min}}^{1}\mathrm{d}z_2G_{\mathrm{A/a}}(x_{\mathrm{a}},Q^2)G_{\mathrm{B/b}}(x_{\mathrm{b}},Q^2)D_{\mathrm{q}}^{\gamma}(z_{\mathrm{c}},Q^2)\times$$
$$G_{\mathrm{q}/\gamma}(z_2,Q^2)\frac{x_{\mathrm{a}}x_{\mathrm{b}}z_{\mathrm{c}}z_2}{x_{\mathrm{a}}x_{\mathrm{b}}z_2-x_{\mathrm{a}}z_2x_2}\frac{\mathrm{d}\hat{\sigma}_{\mathrm{ab}\to\mathrm{l}^+\mathrm{l}^-\mathrm{x}}}{\mathrm{d}M^2\mathrm{d}\hat{t}}, \tag{8}$$

where $\mathrm{d}\hat{\sigma}_{\mathrm{ab}\to\gamma^*\mathrm{x}}/\mathrm{d}\hat{t}$ [22] is for parton scattering. We have the Mandelstam variables in the cross section as $\hat{s}=x_{\mathrm{a}}x_{\mathrm{b}}z_{\mathrm{c}}z_2s$, $\hat{t}=M^2-x_{\mathrm{a}}z_{\mathrm{c}}z_2sx_2$ and $\hat{u}=M^2-x_{\mathrm{b}}sx_1$. Besides, $x_{\mathrm{a}}^{\min}=(x_1-\tau)/(1-x_2)$, $x_{\mathrm{b}}^{\min}=(x_{\mathrm{a}}x_2-\tau)/(x_{\mathrm{a}}-x_1)$, $z_2^{\min}=(x_{\mathrm{b}}x_1-\tau)/(x_{\mathrm{a}}x_{\mathrm{b}}-x_{\mathrm{a}}x_2)$ and $z_{\mathrm{c}}=(x_{\mathrm{b}}x_1-\tau)/(x_{\mathrm{a}}x_{\mathrm{b}}z_2-x_{\mathrm{a}}z_2x_2)$.

2.5 Other process

In addition, the two processes are not calculated because they are far smaller than the resolved single photon process, much less the leading order process. The two processes are the resolved two-photon process and the commixing process which includes direct and resolved mechanism.

3 Numerical Results

In this section, we discuss the dilepton production in Au-Au collisions at RHIC. We define the invariant cross section for producing lepton pairs in a mass range between $M_{\min}$ and $M_{\max}$ [15].

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}^2P_{\mathrm{T}}}=\int_{M_{\min}^2}^{M_{\max}^2}\mathrm{d}M^2\frac{\mathrm{d}\sigma}{\mathrm{d}M^2\mathrm{d}y\mathrm{d}^2P_{\mathrm{T}}} \quad , \tag{9}$$

where 0.2 GeV$\leqslant M\leqslant$0.3 GeV, 0.3 GeV$\leqslant M\leqslant$0.5 GeV and 0.5 GeV$\leqslant M\leqslant$0.75 GeV.

In order to present our results in a way that allows them to be compared with data from RHIC, we will study the invariant yield which is given by:

$$Y_{\mathrm{ield}}=\frac{1}{N_{\mathrm{part}}/2}\frac{1}{2\pi P_{\mathrm{T}}}\frac{\mathrm{d}^2N}{\mathrm{d}P_T\mathrm{d}y}$$

$$= \frac{1}{N_{\mathrm{part}}/2}\,\frac{1}{\sigma_{\mathrm{total}}}\,\frac{1}{2\pi P_{\mathrm{T}}}\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}P_{\mathrm{T}}\mathrm{d}y}\ , \qquad (10)$$

where $\sigma_{\mathrm{total}} \sim 4\pi R^2 \sim 1.4\times 10^4[\mathrm{GeV}^{-2}]$, The data from PHENIX correspond to a minimum bias situation, so the collisions considered have centrality in the range 0—92% which corresponds to $N_{\mathrm{part}} = 109$[26—29].

In Fig. 1, the contribution of the fragmentation process at large transverse momentum production of lepton pairs in Au-Au collisions is changing along with the increase of transverse momentum. The contribution of the fragmentation process exceeds the contribution of the leading order process when the transverse momentum is not very high. The contribution of the leading order process is the biggest when the transverse momentum is high. In addition, the resolved single photon process is smaller than the direct single photon process at large transverse momentum production of lepton pairs in Au-Au collisions. At large transverse momentum, it is not neglected to consider the low-order processes. In the condition, the result will be exact as having the contribution of the low-order processes.

The calculated mass range is various (0.2 GeV⩽M⩽0.3 GeV, 0.3 GeV⩽M⩽0.5 GeV and 0.5 GeV⩽M⩽0.75 GeV). At invariant mass between 0.2 GeV and 0.75 GeV, the experimental data at PHENIX is higher than the the oretical prediction. The dilepton production sources in the energy region are: thermal dileptons which are produced in the QGP phase; the hadronic cocktail which is decayed from the hadronic phase; the cold component which is emitted from the initial parton collisions. Discussing the production of lepton pairs from the initial parton collisions will help us to comprehend the above phenomenon.

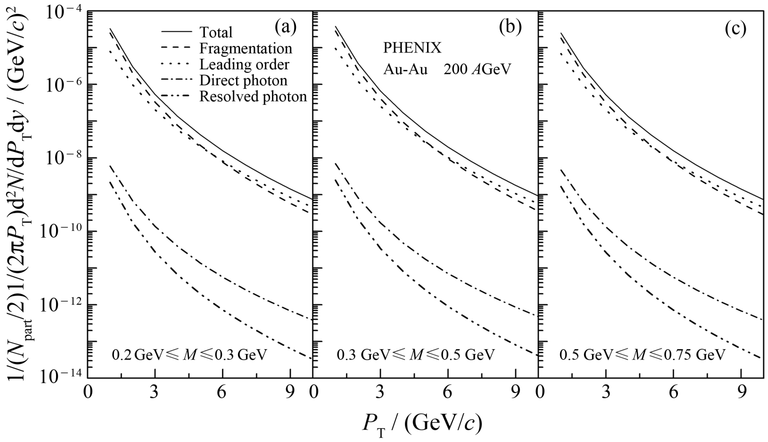

Fig. 1 The large transverse momentum production of lepton pairs in Au-Au collisions at $\sqrt{s}=200$ GeV, $y=0$.

Moreover, the direct photon process and the resolved photon process are the important part of constituting theory. Through the research of the resolved photon process, we can prove the character of distribution and structure as a parton of photon. High energy heavy-ion collisions can create the experimental condition. The high energy photons produced from the hard parton-parton collisions may be hadron-like.

4 Summary

The production of lepton pairs is discussed at large transverse momentum in Au-Au collisions. The complete processes are considered. Inside, the four major processes of large P_{T} lepton pair production are calculated in the region 1 GeV⩽P_{T}⩽10 GeV. The total energy of nucleon-nucleon collisions is $\sqrt{s} = 200$ GeV. Invariant mass which is considered is low. In the parton model, the effect of shadowing and isospin of nucleus are introduced. The data which is calculated is exact as some effects and complete mechanisms in the processes are included.

In our results, the contribution of the production of lepton pairs in Au-Au collisions is substantial. Dilepton signals are comparable with QGP signals. So regarding the cold dilepton signals as QGP background is necessary while we try to probe the properties of QGP.

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Au-Au 碰撞中大横动量双轻子对的产生*

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摘　要：运用微扰 QCD 讨论了重离子碰撞中大横动量轻子对的分布，计算了 Au-Au 碰撞中两个部分子产生的轻子对的贡献。引入了轻子对产生的直接单光子过程和分解单光子过程。大横动量情况下的所有过程都包括在内，而且考虑了核遮蔽效应和同位旋效应，作为 QGP 背景的双轻子信号有了一个好的修正。

关 键 词：大横动量；轻子对产生；Au-Au 碰撞

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