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Numerical Simulation of Azimuthal Anisotropy of Direct Photons in High Energy Nucleus-nucleus Collisions*

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Abstract: The azimuthal anisotropy of high p_T direct photons is investigated by using the coefficient of elliptic flow ν_2 in non-central nucleus-nucleus collision at LHC energies. These photons come from radiation induced by the interaction between jet and hot/dense medium. There is $\pi/2$ difference between direct photons and hadrons for the azimuthal elliptic flow ν_2. Such photons are the main source of the negative part of ν_2 for direct photons. The dependence of the direct photon ν_2 on the transverse momentum p_T at LHC energy is found to be consistent with the experimental results at RHIC energy. Furthermore, we find that the value of the direct photon ν_2 at LHC energy is smaller than that at RHIC energy. The value of the transverse momentum at which the direct photon ν_2 changes from negative value to positive at LHC is higher than that at RHIC. It's found the enhanced jet-quenching effect and enhanced contribution for the elliptic flow ν_2 of the direct photons emitted from surface at LHC energy.

Key words: direct photon; high energy nucleus-nucleus collision; jet-quenching; azimuthal anisotropy

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1　Introduction

Experiments performed at the Relativistic Heavy Ion Collider (RHIC) and newly started the Large Hadron Collider (LHC), are providing evidence for the production of quark-gluon plasma (QGP) in nuclear-nuclear collisions at ultrarelativistic energies[1]. Penetrating probes, such as direct photons and leptons, provide insight into the early stage of heavy ion collisions since they are essentially unaffected by the surrounding hadronic matter. Thus they are able to carry to the detectors information about the state of the system at the time they were created[2]. Photons and lep-tons thus constitute a unique class of penetrating probes. The two most interesting sources of photons are those where the plasma is directly involved in the emission. These are the thermal radiation from the hot QGP[3] and the radiation induced by the passage of high energy jets through the plasma[4－6]. The thermal radiation is emitted predominantly with low transverse momentum p_T and has to compete with photon[7, 8]. Photons from jets are an important source at intermediate p_T, where they compete with photons from primary hard scatte-

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rings between partons of the nuclei[9]. They probe the thickness of the medium: the longer the path of the jet, the more photons are emitted.

Obviously, measuring photons from either of the sources involving the QGP would be an important approach toward establishing its existence and would provide a crucial test of the reaction dynamics. We refer the reader to Ref. [6] for a discussion of the different photon sources. Recently, the PHENIX collaboration at RHIC published their first results on direct photons measured in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}=200$ GeV[10]. It should be mentioned that direct photons here are defined as the total inclusive photon yield minus the photons originating from the decay of hadrons like π^0 and η. The sources discussed above will contribute to the direct photon signal. The data involves the intermediate and high-p_{T} range where thermal photons are not a leading source. This makes it particularly attractive to look for photons from jet-plasma interactions. nucleus-nucleus collisions at finite impact parameter $b>0$ start out in an initial state which is not azimuthally symmetric around the beam axis. Instead, the initial overlap zone of the two nuclei has an “almond” shape. Therefore particle spectra measured in the final state are not necessarily isotropic around the beam axis. It has been argued that the translation of the original space-time asymmetry into a momentum space anisotropy can reveal important information about the system[11]. Two different mechanisms are important here: hydrodynamic pressure for the bulk of the matter, at low-to intermediate-p_{T}, and a simple optical-depth argument for intermediate-to high-p_{T} particles. The third mechanism is introduced by Gale[12] and this mechanism is expected to exhibit an inverse optical anisotropy ($\nu_2<0$).

2 Direct Photons Production and Elliptic Flow

One can define the reaction plane as the plane spanned by the beam axis and the impact parameter of the colliding nuclei. For the bulk of the dense matter, the initial space time asymmetry leads to an anisotropic pressure gradient which is larger where the material is thinner, i. e. in the event plane. This translates into a larger flow of matter in this direction. The anisotropy is analyzed in terms of Fourier coefficients ν_k defined from the particle yield $\mathrm{d}N/p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}\phi$ as Ref. [13].

$$\frac{\mathrm{d}N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}\phi}=\frac{\mathrm{d}N}{2\pi p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}}\left[1+\sum_k 2\nu_k(p_{\mathrm{T}})\cos(k\phi)\right], \tag{1}$$

where the angle ϕ is defined with respect to the event plane. At midrapidity all odd coefficients vanish for symmetry reasons, leaving the coefficient ν_2 to be the most important one. Its size determines the ellipsoidal shape of the anisotropy. It is clear that the elliptic asymmetry coefficient ν_2 is always positive for hadrons at low and intermediate p_{T} due to the hydrodynamic flow. On the other hand, a direction where the medium is thicker for jets to pass leads to more energy losing, i. e. out of the reaction plane. The stronger jet quenching leads to fewer hadrons at intermediate and high p_{T} emitted into this direction. This “optical ν_2” is not associated with flow but with absorption and implies positive ν_2 for hadrons from jets. Measurements at RHIC for several hadron species confirm this behavior[14, 15].

In this paper, we discuss ν_2 of direct photons. The intermediate and high p_{T} and the ν_2 from all the relevant processes will be concentrated on. We define a mechanism that works by absorption of particles or jets going through the medium as optical. It turns out that in some cases a new inverse-optical mechanism is in place for photons: there are more of them emitted into the direction where the nuclear overlap zone is thicker, thus leading to a situation where the anisotropy is shifted by a phase $\pi/2$. Correspondingly ν_2 is negative in this case.

There are different contributions to the direct photon spectrum. Direct photons from primary hard Compton and annihilation processes ($a+b\rightarrow\gamma+c$) produced symmetrically with

$$\frac{dN^{N\text{-}N}}{p_T dp_T d\phi} = T_{AB} f_{a/A} \otimes \sigma_{a+b\rightarrow\gamma+c} \otimes f_{b/B}, \qquad (2)$$

$\sigma_{a+b\rightarrow\gamma+c}$ is the cross section between partons, $f_{a/A}$, $f_{b/B}$ are parton distribution functions in the nuclei A and B and T_{AB} is the overlap factor of the nuclei. The primary hard direct photons do not suffer any final state effect and do not exhibit any elliptic asymmetry.

Jets from processes ($a+b\rightarrow\gamma+c$) are also produced symmetrically, however they are quenched once they start to propagate through the plasma. This is the optical mechanism that leads to positive ν_2 for hadrons fragmentation from jets. We expect photons from such jets in the vacuum ($c\rightarrow c+\gamma$, after c propagated through the medium) to exhibit the same anisotropy. Their yield at midrapidity is given by

$$\frac{dN^{\text{jet-frag}}}{p_T dp_T d\phi} = \sum_f \left.\frac{dN^f(\phi)}{dq}\right|_{q=p_T/z} \otimes D_{f/\gamma}(z, p_T), \qquad (3)$$

where $dN^f(\phi)/dq$ is the distribution of jet partons f with momentum q traveling into the direction given by the angle ϕ, and D is the photon fragmentation function.

The interaction of jets with the medium can also produce photons in different ways: (i) scattering off plasma components can induce photon bremsstrahlung; (ii) hard leading partons may annihilate with thermal ones ($(q+\bar{q}\rightarrow\gamma+g)$), or they can participate in Compton scattering ($q(\bar{q})+g\rightarrow q(\bar{q})+\gamma$). The latter case is also called jet-photon conversion, because the cross section is dominated by transfer of the entire jet momentum to the photon, $p_\gamma \approx p_{\text{jet}}$. The jet-photon conversion yield at midrapidity is given by[16]

$$\frac{dN^{\text{jet-th}}}{p_T dp_T d\phi dy} = \int d^4x \frac{\alpha\alpha_s T^2}{8\pi^2} \sum_q \left(\frac{e^q}{e}\right)^2 \times$$

$$f_q(x;\ p_T,\ \phi,\ y)\left[2\ln\frac{4E_\gamma T}{m^2} - C\right] \qquad (4)$$

with $C = 2.332$ and $m^2 = 4\pi\alpha_s T^2/3$. The distribution of jet partons $f_q(x;\ p_T,\ \phi,\ y)$ at a space-time point x is determined from the time dependent spectrum of jet partons propagating in the plasma, $dN^q/dq(\tau)$, as discussed in Refs. [4, 6]. The time dependence is governed by the energy loss through induced gluon radiation, obtained with the complete leading order description by Arnold, Moore and Yaffe(AMY, Arnold-Moore-Yaffe formalism)[16]. It is clear that an anisotropy in ϕ is introduced by the different path lengths for jets traveling in and out of the event plane, leading to an increased probability for a jet-photon conversion in the direction where the medium is thicker. Such an inverse optical effect has not been observed before.

Medium induced bremsstrahlung ($q\rightarrow\gamma+q$) is implemented directly in the AMY formalism through splitting function $d\Gamma^{q\rightarrow q\gamma}/dkdt$. The photon yield from this process is obtained by

$$\frac{dN^{\text{jet-b}\gamma}}{dp_T d\phi} = \int d^2\gamma_\perp\ p(\gamma_\perp) \int_0^d dt dk \frac{dN^q}{dq} \frac{d\Gamma^{q\rightarrow q\gamma}(q,\ k)}{dkdt}, \qquad (5)$$

there $p(\gamma_\perp)$ is the spatial distribution of hard processes creating jets in the transverse plane and $d = d(\gamma_\perp,\ \phi)$ is the distance the jet has to travel from $\gamma_\perp$ into the direction of the angle ϕ to leave the fireball. Again it is obvious that the probability for induced bremsstrahlung to occur increases with the path length d of the jet. Hence these photons are preferentially emitted into the direction where the medium is thicker, leading to negative ν_2.

As mentioned above, two processes which are expected to exhibit an inverse optical anisotropy ($\nu_2 < 0$), are induced bremsstrahlung from jets and jet-photon conversion; Photons from fragmentation show the regular optical anisotropy ($\nu_2 > 0$), while primary hard and thermal photons do not contribute to ν_2 at intermediate and high p_T. In the followed chapter, we will use the introduced method to calculate direct photon ν_2 at LHC energy and compare them to the corresponding results based on the RHIC experiment data.

3 Calculation and Results

Firstly, we show the result by S. Turbide for Au+Au collisions at RHIC($\sqrt{s_{\mathrm{NN}}}=200$ GeV)[12]. Photon spectra at midrapidity with their dependence on the azimuthal angle ϕ are calculated as described above for three different centrality classes. The modeling of the nucleus-nucleus collision is introduced in Ref. [6]. With fixed initial time $\tau_{\mathrm{i}}=0.26$ fm/c, the initial temperatures are $T_{\mathrm{i}}=370$, 360 and 310 MeV for centrality classes 0—20%, 20% —40% and 40%—60%, respectively. Comparing with measured photon spectra, a good agreement is obtained, for all centrality classes. Details will appear elsewhere[17, 18]. The coefficients ν_2 can then be calculated by using

$$\nu_2(p_{\mathrm{T}})=\frac{\int \mathrm{d}\phi\cos(2\phi)\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\phi}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}}\,. \tag{6}$$

In order to analyze the mechanism of direct photon's ν_2, we will compare the direct photon's ν_2 at RHIC and LHC energies. We take the direct photon ν_2 results at RHIC from Ref. [12] (seen in Fig. 1). Fig. 1 shows the coefficient ν_2 as a function of p_{T} for Au+Au collisions at RHIC and for the centrality classes 0—20%, 20%—40% and 40%—60%. The dotted lines give the results for primary hard direct photons and photon fragmentation. As expected photons from fragmentation lead to a positive ν_2 which is diluted by adding primary hard photons. Solid lines are the results when bremsstrahlung, jet-photon conversion and thermal photons are included. They meet our expectations for ν_2 of the direct photons including all source discussed above. The ν_2 for induced bremsstrahlung and jet-photon conversion is indeed negative. Together they are able to overcome the positive ν_2 from fragmentation, leading to an overall negative elliptic asymmetry for the direct photons at moderate p_{T}. Only above 8 GeV/c the direct photon's ν_2 is again positive, because the yield of photons from fragmentation is dominating over medium induced bremsstrahlung[6] in this range. The dashed lines in Fig. 1 show the ν_2 for the direct photons with no

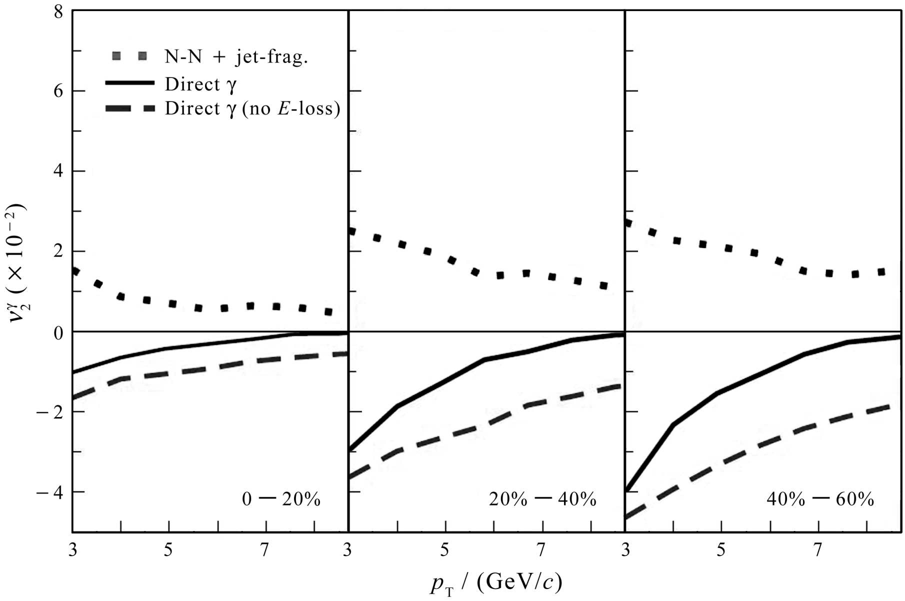

Fig. 1 Elliptic flow ν_2 of photon as a function of p_{T} in different centralities for Au+Au collisions at RHIC. The dotted lines show ν_2 for primary hard photons and jet fragmentation only, and the solid lines show ν_2 for all direct photons. Energy loss is included in both cases. The dashed lines are the same as the solid line but without energy loss of jets taken into account.

jet energy loss included. In this case, the photons from fragmentation do not exhibit an anisotropy and the elliptic asymmetry is only due to jet-photon conversion. Measurements of ν_2 with sufficient accuracy could therefore constrain models for jet energy loss. The absolute size of ν_2 is not large, about 2%—3% for the 20%—40% centrality bin around $p_{\mathrm{T}}=4$ GeV/c and up to 5% for the more peripheral bin. The reason is that the signal is diluted by isotropic photons(primary hard and thermal) and partially cancelled between the optical and inverse optical mechanisms.

Then we carry out the same numerical calculation at LHC energy. The parton distribution function is extended to Pb + Pb collisions at LHC ($\sqrt{s_{\mathrm{NN}}}=5.5$ TeV). Photon spectra at midrapidity with their dependence on the azimuthal angle ϕ are caculated for three centrality classes measured above (0—20%, 20%—40% and 40%—60%). For such higher LHC energy, we fixed initial time $\tau_{\mathrm{i}}=0.12$ fm/c. Theoretically the average thermalization temperature at LHC is estimated between 500—800 MeV, so we respectively fix system temperature at 740, 720 and 600 MeV for three centrality. Fig. 2 shows the coefficient ν_2 as a function of p_{T} for Pb+Pb collision in three centrality classes at LHC energy. The doted line are the results when bremsstrahlung, jet-photon conversion and thermal photon are included.

For checking and comparision, we recalculate the S. Turbide's results in Fig. 1. The solid and dashed line are the S. Turbide's results at RHIC in Fig. 1 respectively corresponding to the inclusive direct photon ν_2 and ν_2 for direct photon with no jet energy loss included. One can find that the function behavior of inclusive photon ν_2 as a function of p_{T}(doted line) at LHC energy is similar to that at RHIC energy(solid line), but LHC inclusive photon's ν_2 is smaller than RHIC inclusive photon's ν_2 at the same p_{T}. Furthermore, compare solid and dashed lines one can see negative to positive inverting value of direct photon's ν_2 at the LHC energy is higher than that at RHIC energy. The conceivable reason is that at LHC energy much more harder jets lead to the p_{T} range dominated by photons exhibiting an inverse optical anisotropy shifts higher. Fig. 2 also shows ν_2 value of the direct photons at LHC energy is closed to the ν_2 value of the direct photons with no energy loss at RHIC energy. It's because of that at LHC energy, the direct photon from whether bremsstrahlung or jet photon conversion is produced by jet emitting at the edge of bulk of the matter. Such more edge emitting jets is due to the LHC's hotter and denser bulk of matter. The jets born innerly in the matter is more possibly absorbed by the matter. It present that surface emitting effect is prominent at LHC energy.

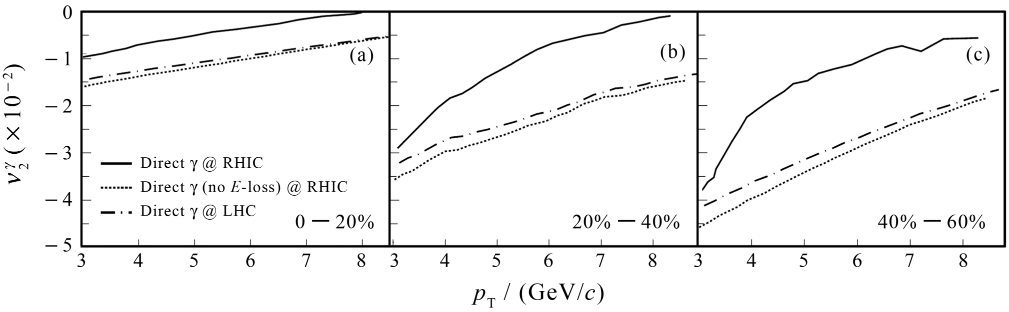

Fig. 2 Elliptic flow ν_2 of direct photons as a function of transverse momentum p_{T} in different centralities. The solid and dotted lines show the ν_2 for inclusive and direct photons in Au+Au collisions at RHIC. The dot-dashed lines show the ν_2 for direct photons in Pb+Pb collisions at LHC energy in the same centralities.

4 Summary

We briefly introduce the production of the direct photons in high energy nucleus-nucleus collision and method to calculate the signal ν_2 of the direct photons. We calculate the azimuthal asymmetry coefficient ν_2 for the direct photons at Pb+Pb collisions at LHC ($\sqrt{s_{\mathrm{NN}}}=5.5$ TeV). We find the inclusive direct photon ν_2 at LHC energy is smaller than inclusive direct photon ν_2 at RHIC and negative to positive inverting value of the direct photon ν_2 is higher at LHC energy than the negative to positive inverting value at RHIC. The visible jet quenching effect at LHC presupposes surface emitting direct photons will contribute more to the ν_2 signal. Finally we qualify that surface emitting effect is in evidence in LHC.

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高能核-核碰撞中直接光子各向异性的数值模拟研究*

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摘　要：通过计算给出了在 LHC 能区非对心核-核碰撞中由椭圆流 ν_2 表示的高横动量直接光子的方位角不对称性。该高横动量光子是由喷注与热密介质相互作用而辐射出来的。光子椭圆流与强子椭圆流 ν_2 相差 $\pi/2$ 的相位，是直接光子椭圆流中负值的来源。同时，计算表明 LHC 能区直接光子 ν_2 随粒子横动量 p_{T} 的变化趋势与 RHIC 上的实验结果一致，但 LHC 能区较 RHIC 能区有更低的直接光子流 ν_2 值，且 ν_2 值由负到正对应的转换 p_{T} 值更高。这表明在 LHC 能区喷注淬火效应更为明显，表面发射的直接光子对光子椭圆流的贡献份额增强。

关 键 词：直接光子；高能核-核碰撞；喷注淬火；各向异性

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