Empirical estimation the effects of flow on thermal photon angular distribution and spectra in nucleus-nucleus collisions at RHIC and LHC

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Experimental data for hadron radial and elliptic flow are used to investigate their influence on the shape of the thermal photon spectrum at RHIC. Leaving alone the actual mechanism of photon production and its time evolution, we concentrate on the spectrum shape. Radial and longitudinal flow of the bulk can change significantly the observed photon energy spectrum via the Doppler Effect. Experimental thermal photon data are described by local frame temperature parameter which depends on the assumption of longitudinal and radial flow. From the observed hadron elliptic flow we estimate the modulation of radial flow parameter versus the angle relative to the reaction plane. Based on this we calculate elliptic flow parameter for thermal photons, which was found to be very close to that for hadrons. Considering very similar amplitude for hadron elliptic flow at LHC and RHIC, we demonstrate that thermal photons at LHC should show large elliptic flow as well. All of these considerations are also valid for the low invariant mass dilepton pairs.

Measurements of the photons radiated in nucleus-nucleus collisions are of great current interest. This interest stems from good photon penetration through strongly interacting matter. From a theoretical point of view, the way to study thermal photons would be to perform a full hydrodynamic calculation. Nevertheless, such calculations use many assumptions and parameters such as the initial energy and density profile, equation of state, treatment of exact photon production channels, initial temperature profile, equilibration time, consideration of the quark-gluon and hadron phases and many others; these assumptions can serve to mask many of the general features of photon emission. One of the common effect on top of all these assumptions is the relativistic radial and longitudinal expansion of the system. Such expansions can induce a Doppler Effect with red and blue shifts for radiated thermal photons. Here, we investigate the influence of such effects on the emission spectrum for thermal photons. We do not pretend to calculate the exact photon yield nor specify the actual mechanisms for photon production.

One can distinguish two types of photons: prompt or direct photons, produced by primary partons in the initial stage of a collision, and thermal photons radiated by hot and dense matter after the system thermalizes. We limit ourselves to consideration of the latter type. We start from a simple system with fixed temperature, that expands in the transverse and longitudinal directions. Then, we examine how additional assumptions can change this simple picture.

The non-relativistic Doppler Effect for a frequency change from a moving source, say, towards an observer is $\omega = \omega_0/(1 - v/c)$, where ω_0 is the original frequency in the rest frame of the source, v is source velocity and c is the speed of the signal in the medium. For the relativistic case, this formula changes to:

$$\omega = \omega_0 \frac{\sqrt{1 - \beta^2}}{1 - \beta cos\theta}. \tag{1}$$

Here β is speed of the source relative to the speed of light and $cos\theta$ is the angle between the direction of the moving source and the observer. One can see an additional factor $\sqrt{1 - \beta^2}$ for the relativistic case.

For non-relativistic case, if the radiation spectrum has a simple Boltzman exponential shape with temperature T,

$$dN/d\omega_0 = exp(-\omega_0/T), \tag{2}$$

using relations $\omega_0 = \omega(1 - \beta)$ and $d\omega_0/d\omega = 1 - \beta$, we get radiation spectrum seen in the laboratory frame:

$$dN/d\omega = \frac{dN}{d\omega_0}\frac{d\omega_0}{d\omega} = (1 - \beta)exp(-\frac{\omega}{T/(1 - \beta)}). \tag{3}$$

For relativistic kinematics and photons with energy $E = \hbar\omega$ the last formula changes to:

$$dN/dE = \frac{1 - \beta cos\theta}{\sqrt{1 - \beta^2}}exp(-\frac{E(1 - \beta cos\theta)}{T\sqrt{1 - \beta^2}}). \tag{4}$$

To separate longitudinal and transverse expansion in nucleus-nucleus collisions, we describe a boos in the transverse direction by velocity β_T or rapidity y_T, and expansion in longitudinal direction by velocity β_L and rapidity y_L. The rapidity and velocity are related by the formula $\beta = tanh(y)$, where $tanh$ is a hyperbolic tangent. The total rapidity y can be calculated via Pifagora's relation in hyperbolic rapidity space: $cosh(y) = cosh(y_T) \cdot cosh(y_L)$. For an observer at mid-rapidity, radial expansion of the created matter will lead to a blue shift of the spectrum when matter moves exactly towards the observer. In contrast it will induce a red shift for photons

produced from the medium, which expands in opposite to the observer direction. This expansion in a direction opposite to the observer is very similar to astrophysical expansion of our Universe. For different cells of the medium the vectors for radial flow are oriented at some angle to the observer, this effect will be controlled by the $\beta_T cos\theta$ component of the flow. Thus we can write:

$$dN/dE = \frac{1 - \beta_T cos\theta}{\sqrt{1 - \beta^2}} exp(-\frac{E(1 - \beta_T cos\theta)}{T\sqrt{1 - \beta^2}}). \quad (5)$$

To make quantitive estimates for nucleus-nucleus collisions we run a simple simulation. We use a density profiles of wounded nucleons for Au+Au collisions in $x - y$ plane transverse to the beam direction from work [1], which were also used later in paper [2]. These profiles were generated for different centralities assuming Woods–Saxon density distribution of the colliding nuclei. We use a linear transverse velocity profile for radial flow which rises from zero at the center of the collision zone to a maximum value of β_T=0.75c [3]. This value describes well the momentum spectra of identified secondary hadrons produced in Au+Au collisions at RHIC. The main results of our calculation do not change much by changing β_T in the range 0.7–0.8c. Then, each point in $x - y$ plane was taken with the weight of relevant participant nucleon density. For simplicity we consider the most central 0-5% events and set the observer in x direction in reaction plane of the collision. For each point we estimate the distance from the collision center, calculate the radial boost $\beta(r) = \beta_T \cdot r/R$ and its projection to the observer direction $\beta_T \cdot cos\theta$, where the angle θ in our set is the angle relative to the reaction plane (usually marked as ϕ). To compare with experimental data we have to use the invariant yield by multiplying Eq. 5 by factor $E/p^2 = 1/E$ for massless photons.

In Fig. 1 we present results of the calculation. The curves were normalized to the first experimental point at 1.2 GeV [4]. We fit data for β_L=0.5. In this case the shape of the experimental spectrum could well be described at temperature T=0.17 GeV. There is a significant blue shift of the spectrum at high energy and observable red shift at low energy. From the formulas presented above, one can see that there is a strong correlation between parameters T and β_L. Thus, for β_T=0.75c the same result could be obtained for different parameter combinations, like T=0.2 GeV, β_L=0.7c and T=0.3 GeV, β_L=0.88c or with no longitudinal flow when β_L=0c, we get T=0.15 GeV. The experimental data and our estimation for E below 2.5 GeV are very close. Deviations from experimental points at higher energy could be explained by a significant contribution from direct photons, whose yield could be estimated by using p+p data from [4] and scaled by the number of binary nucleon-nucleon collisions, thin solid line in figure. The yield of direct photons becomes dominant for photon energy

above 2.7 GeV. In addition, we check how our results may change by the varying transverse velocity profile (from liner to quadratic) and by introducing a temperature profile (more hot in the center and colder at the edges). We did not find a significant change of the results with these assumptions.

In nucleus-nucleus collisions the produced matter definitely expands in the longitudinal direction and $\beta_L > 0$, so T=0.15 GeV is the lowest estimate of the mean possible temperature of the system. At the same time, it is hard to get the actual temperature from the experimental spectrum without knowing the value of the longitudinal expansion.
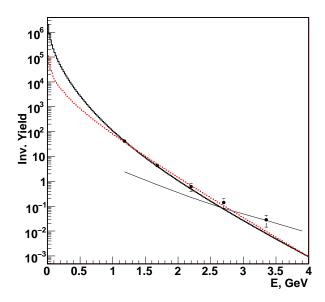

FIG. 1: Fig.1. Invariant thermal photon yield for central 0–5% Au+Au collisions versus the observed photon energy in laboratory frame for the original source temperature T=0.17 GeV, β_T=0.75c and β_L=0.5 – thick solid line. The yield was normalized to the first experimental point at 1.2 GeV. Points are experimental data for central 0–20% Au+Au collisions from [4]. Thin solid line is for the experimental data for p+p collisions from the same measurement scaled by the mean number of binary nucleon-nucleon collisions at this centrality. Dashed line is an estimate of photon yield at very early times of the collision just after thermalization occure with temperature 0.27 GeV but with no flow.

Another test of our model assumptions is the consideration of elliptic flow for thermal photons. We can make an empirical estimation of the elliptic flow parameter for thermal photons using experimental data for hadron elliptic flow. For hadrons produced in A+A collisions we can attribute the observed azimuthal anisotropy to an amplitude modulation of the radial flow versus the reaction plane. Elliptic flow is usually described by the parameter v_2 as: $\sigma(\phi) = const \cdot (1 + 2 \cdot v_2 cos(2\phi))$, where ϕ is the angle with respect to the reaction plane. For

hadrons,the azimuthal parameter v_2, scales with number of constituent quarks and transverse kinetic energy per quark [5]. The value of v_2 per quark saturates at about v_2=0.07 at kinetic energy around 1 GeV per quark for mid-central collisions. We use this to estimate the difference of radial flow *in* and *out* of the reaction plane, β^{in} and β^{out}, to get a value of v_2. The parameter v_2 by itself defines the relative variation of the production cross section σ with respect to the reaction plane orientation. So, the difference from the average yield for in-plane or out-plane is $\Delta\sigma/\sigma = 2 \cdot v_2$.

Knowing the shape of the cross section spectrum versus the kinetic energy we can estimate what should be the difference in kinetic energy to get such cross section change. In the kinetic energy range under consideration the cross section has an exponential shape with the inverse slope parameter T around 200 MeV for pions and 300–330 MeV for protons [3, 6]. Thus, for the spectrum of constituent quarks the inverse slope parameter T_q would be around 100 MeV. If the cross section is described by a simple exponent, $\sigma = const \cdot exp(-E_{kin}/T_q)$, then its relative variation for an energy change ΔE_{kin} will be $\Delta\sigma/\sigma = \Delta E_{kin}/T_q$. To satisfy these changes we get the necessary relation with v_2:

$$\Delta E_{kin} = 2 \cdot T_q \cdot v_2. \qquad (6)$$

If a quark with mass m_q moves with velocity β and $\gamma = 1/\sqrt{1-\beta^2}$, then its kinetic energy E_{kin} will be $E_{kin} = m_q(\gamma - 1)$ and we can estimate $\Delta\gamma$ from the relation $\Delta E_{kin} = m_q \cdot \Delta\gamma = 2 \cdot T_q \cdot v_2$.

At our maximum transverse boost value β =0.75 (averaged over all angles versus the reaction plane), γ=1.51. If T_q=0.1 GeV, v_2=0.07 and taking a constituent quark mass $m = 0.3$ GeV we get $\Delta\gamma$=0.047. This gives estimates of the maximum velocity boost β^{in}=0.77 and β^{out}=0.73. Now we can estimate elliptic flow for thermal photons. Fig. 2 shows the value of v_2 for 30-35% centrality Au+Au collisions assuming m_q=0.3 GeV (dashed line) versus photon energy for the case of β_T=0.75c, T=0.2 GeV and β_L=0.7c. We use the similar wounded nucleon distribution in the $x - y$ plane as before by calculating the photon spectrum. For comparison we plot the experimental data of v_2 for inclusive hadrons versus hadron transverse kinetic energy [5]. We see significant value of v_2 for thermal photons, which is comparable with that for hadron v_2 and then significantly overshoots hadron points at larger energy. We have to take into account that in actual experiments, for photon energies above 2 GeV, there is a significant contribution from direct photons (thin line in Fig. 1) for which v_2 is about zero [7], this dilutes the total photon v_2. We get an estimation of the relative direct photon yield from experimental results [4]. Thus, the measured value of photon v_2 could be surprisingly close (or even larger) to the hadron v_2. At low energy, where the spectrum is red shifted, v_2

gets negative. Selection of $m_q = 0.3$ GeV is quite arbitrary, so we also made calculations for $m_q = 0.07$ GeV. In this case we get $\Delta\gamma$=0.2, β^{in}=0.81 and β^{out}=0.65. As one can see, v_2 for thermal photons does not change much on the assumption of constituent quark mass in hadron. Very much the same results we get for combinations T=0.17 GeV, β_L=0.5c, or T=0.15 GeV and β_L=0.
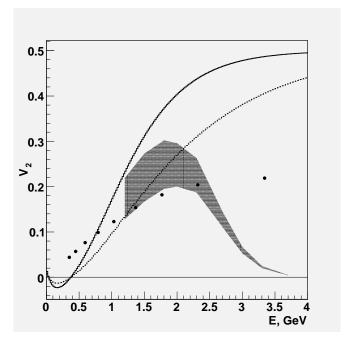

FIG. 2: Fig.2. Azimuthal asymmetry parameter v_2 for thermal photons versus photon energy in 30-35% centrality Au+Au collisions. Solid line – for evaluation using the constituent quark mass $m_q = 0.1$ GeV, dashed line – for $m_q = 0.3$ GeV. Experimental points for non-identified hadrons in Au+Au collisions at centrality 30-40% versus hadron transverse kinetic energy are from [5]. Shaded area shows change of the result if we take into account the contribution from direct photons.

Resent experimental data for $Pb+Pb$ collisions at LHC energy show large hadron v_2 [8] with similar values as at RHIC. Thus, we can also expect large and at about the same value of v_2 for thermal photons at LHC and red/blue shift effects as well. Similar features, seen for thermal photon spectrum, should also be observed for low invariant mass dilepton pairs.

In conclusion, based on a simple assumption that in nucleus-nucleus collisions most of the thermal photons are produced at the stage when the bulk flow is already developed, we have examined the resulting change in the photon spectrum due to longituidinal and transverse expansion. The observed picture is very similar to the astrophysical expansion. Strong correlation was found between the temperature and the longitudinal flow parameters. In the absence of longitudinal flow, which is definitely not the case, we get the lowest estimate for

the thermal photon temperature of about 0.15 GeV. We attribute the observed elliptic flow for hadrons to some amplitude modulation of the radial flow. From this we estimate the photon flow parameter v_2 for mid-central collisions, which are found to be large. Because of some contribution to the yield from thermal photons, which were produced before bulk flow developed, we can consider our estimates for v2 as upper limits. On the other hand, if in experiment we will see significant photon elliptic flow, it means that the most of photons are produced when radial and longitudinal flow are already developed. Unfortunately we can not distinguish contributions from the quark-gluon or hadron gas stages.

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