Formation Time of QGP from Thermal Photon Elliptic Flow

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Abstract
We show that the transverse momentum dependent elliptic flow $v_2(p_T)$ of thermal photons is quite sensitive to the initial formation time ($\tau_0$) of Quark Gluon Plasma (QGP) for semi-central collision of gold nuclei at RHIC [1]. A smaller value of the formation time or a larger initial temperature leads to a significant increase in the thermal photon radiation from QGP phase, which has a smaller $v_2$. The elliptic flow of thermal photon is dominated by the contribution from the quark matter at intermediate and high $p_T$ range and as a result sum $v_2$ decreases with smaller $\tau_0$ for $p_T \geq 1.5$ GeV. On the other hand we find that the elliptic flow parameter for hadrons depends only marginally on the value of $\tau_0$.

1. Introduction

Heavy ion collisions at relativistic energies lead to formation of Quark-Gluon Plasma, a deconfined novel state of quarks and gluons in local thermal equilibrium. Interesting results of jet quenching due to parton energy loss in the medium [2] and elliptic flow of identified particles [3] at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab have provided significant evidence of the formation of QGP. However, one of the most important issues in this study, the initial formation time of the plasma, or the onset of collectivity and thermalization in the system, beyond which the powerful method of hydrodynamics can be used to describe its evolution is still not known precisely.

In a very simple treatment it is assumed that, the partons produced in the collisions have an average energy $\langle E \rangle$, and thus their formation time $\tau_0 \sim 1/\langle E \rangle$. Looking at the various treatments and perhaps complementary models available in the literature, a direct measurement of the formation time would be very desirable. We show that the elliptic flow of thermal photons using ideal hydrodynamics can be very useful to estimate the value of $\tau_0$ accurately [1].

2. $\tau_0$ sensitivity of the elliptic flow parameter at RHIC

It is quite well accepted that, photons are one of the most efficient probes to explore the properties of the hot and dense system produced in the collision of heavy nuclei at relativistic energies. Being electromagnetic in nature, they do not suffer any final state interactions and carry undistorted information about the circumstances of their production directly to the detector. Also, photons are emitted throughout the life time of the evolving system, whereas hadrons are emitted only from the surface of freeze-out.

In our earlier interesting work on elliptic flow of thermal photons at RHIC, we reported that the $v_2(p_T)$ of thermal photons using ideal hydrodynamics exhibits a completely different nature
Figure 1: $p_T$ spectra [left panel] and elliptic flow [right panel] of $\rho$ mesons considering different initial formation time $\tau_0$ of the plasma for 200A GeV Au+Au collisions at RHIC and at $b$=6 fm.

compared to the elliptic flow of hadrons at intermediate and large $p_T$ [4]. Thermal photon $v_2$ from quark matter is very small at large $p_T$ or early times, it gradually rises with smaller values of $p_T$ and then falls again as $p_T \to 0$ [see Fig. 3 of Ref. [4]]. The contribution to $v_2$ from hadronic matter photons rises monotonically with $p_T$, which is similar to the elliptic flow of hadrons predicted by hydrodynamics. The sum $v_2$ tracks the $v_2(p_T)$ from quark matter at large $p_T$ (inspite of very large $v_2$ values from hadronic matter) as the quark matter radiation dominates the spectra beyond $p_T$ value of about 1 GeV/$c$. Thus, the thermal photon $v_2$ at large $p_T$ reflects the momentum anisotropies of the partons produced at early times, soon after the collisions.

We follow the same treatment and initial conditions as used in Ref. [4] to calculate the $p_T$ spectra and elliptic flow of thermal photons at different $\tau_0$ for semi-central collision of Au nuclei at $\sqrt{s_{NN}}$ =200 GeV at RHIC. Cooper-Fry formulation is used to calculate the $p_T$ spectra for different hadrons considering the same initial conditions as for thermal photons. We assume that the system reaches a state of maximum entropy at the point of thermalization at a time $\tau_0$ and then follows an isentropic expansion. The initial entropy density $s_0$ is obtained by combining ‘hard’ and ‘soft’ contributions which are the contributions from binary collisions ($n_b$) wounded nucleons ($n_w$) respectively, and it follows the relation [5],

$$s(\tau_0, x, y, b) = \kappa [ \alpha n_w(x, y, b) + (1 - \alpha) n_b(x, y, b) ].$$

(1)

$\kappa$ and $\alpha$ (=0.75) are the constants in Eq.1 and Glauber model formulation is used to calculate the values of $n_b$ and $n_w$ at different points in the transverse plane for a particular impact parameter $b$. The value of $\kappa$ is obtained considering the initial entropy density at $x=y=b=0$ is about 117 fm$^{-3}$ when $\tau_0$ is 0.6 fm/$c$. [6]. We use boost invariant and impact parameter dependent azimuthally anisotropic hydrodynamics to model our system, where the plasma experiences a first order phase transition at a temperature of about 164 MeV and the freeze-out energy density is considered at 0.075 GeV/fm$^3$. Thermal photon emission from the quark matter and the hadronic matter are obtained by integrating the rates of emission over the space time volume $d^4x (= dx dy \tau d\eta)$. Photons from quark matter are calculated considering a complete leading order photon production rate from Arnold et al. [7] and we use the latest results by Turbide et al. [8] for thermal radiation from the hot hadronic gas. The elliptic flow parameter $v_2$, which directly reflects the
rescattering among the particles produced in the collisions, is obtained using the relation,
\[
\frac{dN(b)}{d^2p_T dy} = \frac{dN(b)}{2\pi p_T dp_T dy} \left[ 1 + 2v_2(p_T, b) \cos(2\phi) + \ldots \right].
\] (2)

2.1. Hadron spectra and \(v_2\) at different \(\tau_0\)

The \(p_T\) spectra and \(v_2(p_T)\) of several hadrons (nearly complete list available in the particle data book) are calculated at different \(\tau_0\) (ranging from 0.2 to 1.0 fm/c, in steps of 0.2 fm/c) by keeping the total entropy of the system fixed. Particle spectra and elliptic flow results for \(\rho\) mesons at different \(\tau_0\) for semi-central collision of Au nuclei are shown in Fig. [1]. The emission of hadrons is mainly governed by the conditions of the freeze-out hyper-surface or, in particular, the temperature at freeze-out \(T_f \sim 120\) MeV). We see that the heavier particles respond strongly to radial flow with changing \(\tau_0\), whereas the elliptic flow results for all the hadrons remain almost unaffected with changing initial formation time of the plasma. Early start of flow drives the freeze-out to happen sooner and hence the overall flow does not change significantly with changing \(\tau_0\) for them. We find the same insensitivity to \(\tau_0\) for all the hadrons in the particle data book. The effect of changing freeze-out conditions on the hadron spectra and elliptic flow are checked and resultant elliptic flow for \(\pi\) and \(\rho\) mesons are shown in left panel of Fig. [2]. We find that the flow parameter for hadrons essentially acquire its final value at some larger temperature and does not change significantly with changing freeze-out conditions.

2.2. Thermal photon spectra and elliptic flow at different \(\tau_0\)

We see that, the thermal photon spectra from hadronic phase at different \(\tau_0\) are almost independent of the value of \(\tau_0\) for \(p_T < 1.5\) GeV/c. Only at very large \(p_T\) \((\sim 5\) GeV/c\) values, the spectra at a smaller \(\tau_0\) is flatter than that at a larger \(\tau_0\) [see right panel of Fig. [2]. We know that the total entropy of the system is related to the particle number density and initial parameters by the relation, \(S(\eta) \propto dN/d\eta \propto T_0^4 \tau_0\), where, \(T_0\) is the initial temperature of the plasma at time \(\tau_0\). With smaller values of \(\tau_0\), the radiation from QGP phase increases significantly as the initial temperature of the system increases. As a result, the photon spectra at \(\tau_0 = 0.2\) fm/c is much flatter than the same at \(\tau_0 = 1.0\) fm/c and the two results differ by a few order of magnitudes at...
the intermediate and high $p_T$ range. Our results from hydrodynamics along with prompt photon results using NLO pQCD [9] and experimental data from PHENIX [10] are shown in left panel of Fig. 3. Although the thermal photon yield from quark matter increases with smaller $\tau_0$, the development of elliptic flow is not substantial at very early times and hence the $v_2(p_T)$ from quark matter decreases with smaller $\tau_0$. As the $v_2$ from hadronic matter is not affected significantly with changing $\tau_0$, the sum $v_2$ decreases with $\tau_0$ beyond a $p_T$ value of about 1.5 GeV/$c$ as shown in right panel of Fig. 3.

In conclusion, we show that the thermal photon $v_2$ is quite sensitive to the formation time of QGP and its value can be estimated precisely with the help of experimental determination of the flow parameter $v_2$, whereas the $v_2(p_T)$ for hadrons depends only marginally on the value of $\tau_0$.

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