Characterizing quark gluon plasma by thermal photons and lepton pairs

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The photon spectra measured by the ALICE collaboration in Pb+Pb collisions at Large Hadron Collider (LHC) energies has been analyzed with a view of extracting the properties of thermal system formed in these collisions. The results of the analysis are compared with the previously studied spectra measured at Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC) energies. The thermal dilepton spectra from the Pb+Pb collision at LHC energy has been predicted for the initial conditions constrained by the thermal photon spectra at the same collision conditions. The slope of the photon has been used to estimate the rise in the effective degeneracy with the charged particle multiplicity of the system. The slopes of the lepton pair spectra for different invariant mass windows have been used to conjecture the average radial flow velocity of the high temperature phase.

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I. INTRODUCTION

The main aim of colliding heavy nuclei at relativistic energies is to create a hot and/or dense thermal phase of matter where the quarks and gluons are not confined inside hadrons but move within nuclear volume. Such a phase of matter is called quark gluon plasma (QGP). The detection of QGP in heavy ion collisions (HIC) at RHIC and LHC energies is one of the most challenging jobs both for experimentalists and theorists working in this field primarily because of the extremely transient nature of the QGP. The QGP evolves dynamically in space and time due to high internal pressure, due to which the system cools and reverts to hadronic matter. The electromagnetically interacting particles, photons and dileptons see, for review are considered to be penetrating probes of the matter formed in the collisions of heavy ions at relativistic energies because (i) they are produced at each space-time point of the system and (ii) their mean-free paths are much larger than the system-size and hence bring the information of the production points very efficiently.

The efficiency of photons for being considered as an competent probe of QGP largely depends on the ability to disentangle the photons produced from various stages of evolution of the system formed in HIC. Therefore, first we identify the possible sources of photons above those coming from the decays of $\pi^0$ and $\eta$ mesons etc, as provided by the data because photons from these decays are already eliminated and hence need not be considered in the present analysis. Photons produced from the evolving matter under consideration are:

(i) due to the initial hard collisions of the partons from the nucleons of the colliding nuclei. This contribution may be estimated by using the techniques of perturbative QCD (pQCD) and the data from pp collisions may be used to validate such calculations.

The $p_T$ distributions of photons from proton+proton (pp) collisions at a given energy can be used as a benchmark for the hard contribution in HIC. Therefore, estimation of these contributions with minimal model dependence is important. In view of this, in the present analysis we estimate the light $p_T$ contributions in HIC by using the experimental data obtained in pp collisions as described in section III.

(ii) Photons are also produced from the interactions of the ‘yet-to-be equilibrated’ partons i.e. from the time span between the collision point and the onset of thermalization. In case where the thermalization time scale is very small the contributions from this interval will be insignificant and hence can be neglected.

(iii) Thermal photons originating from the interactions of the (a) quarks and gluons in the bath and (b) thermal hadrons ($\pi$, $\rho$, $\eta$, $\omega$, $a_1$ etc). The estimation of the thermal contribution depends on the space-time evolution scenario that one considers. In case of a deconfinement phase transition, which seems to be plausible at RHIC energies (see for a review), one assumes that QGP is formed initially. The equilibrated plasma then expands, cools, and reverts to hadronic matter and finally freezes out at a temperature, $T_f \sim$, called freeze-out temperature. Evidently there will be thermal radiation from QGP as well as from the luminous hadronic fireball which has to be estimated as accurately as possible in order to have a reliable estimate of the initial temperature.

The momentum distributions of photons (and dileptons) produced from a thermal system depend on the temperature ($T$) of the source through the thermal phase space factors of the participants of the reactions. Consequently, the transverse momentum ($p_T$) spectra of photon reflects the temperature of the source. For an expanding system the situation is, however, far more complex. The thermal phase
space factor changes - by several factors e.g. the transverse kick received by low \( p_T \) photons due to flow originating from the low temperature hadronic phase (realized when \( T < T_c \)) populates the high \( p_T \) part of the spectra \cite{10}. As a consequence the intermediate or the high \( p_T \) part of the spectra contains contributions from both QGP as well as hadrons. The photon spectra measured experimentally represents the space-time integrated yield from the matter that evolves from an initial hot and dense phase to a comparatively cooler and diluted phase of hadronic gas. Therefore, the temperature extracted from such spectra will exhibit the average temperature of the system.

The experimental data on the \( p_T \) distributions of photons from various collision energies and colliding systems have been analyzed by using different kinds of models \cite{11–18} mainly to extract the temperature of the hot phase formed after the collisions. In the present work the slope of the photon spectra has been used to estimate the enhancements of the effective degeneracy with increased multiplicity. The photon production per unit space-time volume per unit four momentum volume is given by \cite{1–3} (see \cite{5} for a review):

\[
E \frac{dR}{dp} = \frac{g^{\mu\nu}}{(2\pi)^3} \text{Im} \Pi_{\mu\nu}^R f_{BE}(E, T) \tag{1}
\]

where \( \text{Im} \Pi_{\mu\nu}^R \) is the imaginary part of the retarded photon self energy and \( f_{BE}(E, T) \) is the thermal phase space distribution for Bosons. For an expanding system, the energy \( E \) should replaced by \( u^\mu p_\mu \), where \( p^\mu \) and \( u^\mu \) are the four momentum and the hydrodynamic four velocity respectively.

The Hard Thermal Loop \cite{19} approximations has been used by several authors \cite{20} to evaluate the photon spectra originating from the interactions of thermal quarks and gluons. The complete calculation of emission rate of photons from QGP to order \( O(\alpha_s) \) has been done by resuming ladder diagrams in the effective theory \cite{21}, which has been used in the present work. A set of hadronic reactions with all possible isospin combinations have been considered for the production of photons \cite{22, 24} from hadronic matter. The effect of hadronic dipole form factors has been taken into account in the present work as in \cite{24}.

### B. Sources of thermal dileptons

The dominant source of the thermal dileptons from QGP is the \( q\bar{q} \) annihilation \cite{22}. For the low mass dilepton production from HM the decays of thermal light vector mesons namely \( \rho, \omega \) and \( \phi \) have been considered. The change of spectral function of \( \rho \) due to its interaction with \( \pi, \omega, a_1, h_1 \) (see \cite{26, 27} for details) and baryons \cite{28} have been included in evaluation of lepton pairs from HM. For the spectral function \( \omega \) the width at non-zero temperature is taken from Ref. \cite{29} and no medium effect has been considered for \( \phi \). The continuum part of the spectral function of \( \rho \) and \( \omega \) have also been included in the dilepton production rate \cite{6, 30}. The model employed in the present work leads to a good agreement with NA60 dilepton data \cite{31} for SPS collision conditions \cite{32}.

### II. EXPANSION DYNAMICS

The space time evolution of the system formed in \( \text{Pb+Pb} \) collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) has been studied by using relativistic hydrodynamics with longitudinal boost invariance \cite{33} and cylindrical symmetry \cite{34}. We assume that the system reaches the state of equilibrium at a time \( \tau_i \) after the collision. The initial temperature, \( T_i \), can be related to the measured hadronic multiplicity \( (dN/dy) \) by the following relation for system undergoing isentropic expansion:

\[
\frac{dN}{dy} = \pi R_A^2 a_q T_i^3 \tau_i / c \tag{2}
\]

where \( R_A \) is the radius of colliding nuclei, \( c \) is a constant \( \sim 4 \) and \( a_q = (\pi^2/90)g_q \) where \( g_q = (2 \times 8 + 7 \times 2 \times 2 \times 3 \times N_F/8) \) is the degeneracy of quarks and gluons in QGP, \( N_F \)= number of flavours. The value of \( dN/dy \) can be calculated from the following equation \cite{35}:

\[
\frac{dN}{dy} = (1 - x) \frac{dn_{pp}}{dy} < N_{part} > \frac{2}{2} + x \frac{dn_{pp}}{dy} < N_{coll} > \tag{3}
\]

\( N_{coll} \) is the number of collisions and contribute to \( x \) fraction to the multiplicity \( dn_{pp}/dy \) measured in
TABLE I: The values of various parameters - thermalization time ($\tau_i$), initial temperature ($T_i$) and hadronic multiplicity $dN/dy$ - used in the present calculations.

| $\sqrt{s_{NN}}$ | 2.76 TeV |
|-----------------|---------|
| centrality      | 0-40%   |
| $dN/dy$         | 1212    |
| $\tau_i$       | 0.1 fm  |
| $T_i$           | 553 MeV |
| $T_c$           | 175 MeV |
| $T_f$           | 100 MeV |
| EoS             | Lattice QCD |

TABLE II: The values the $\langle p_T \rangle$ for different collision energies obtained from the direct photon data at low $p_T$ by fitting with $a_0 \times \exp[-p_T/a_1]$.

| $\sqrt{s_{NN}}$ | 2.76 TeV |
|-----------------|---------|
| $(1/N_{part})(dN_{ch}/d\eta)$ | $\langle p_T \rangle$ |
| 1.214           | 245 MeV |
| 1.77            | 265 MeV |
| 3.47            | 300 MeV |

$pp$ collision. The number of participants, $N_{part}$ contributes a fraction $(1 - x)$ of $dn_{pp}/dy$. The values of $N_{part}$ and $N_{coll}$ are estimated by using Glauber Model and the results are in agreement with $[^{36}]$. We have used $dn_{pp}/dy = 4.31$ and $x = 0.1$ at $\sqrt{s_{NN}} = 2.76$ TeV. It should be mentioned here that the values of $dN/dy$ (through $N_{part}$ and $N_{coll}$ in Eq. 3) and hence the $T_i$ (through $dN/dy$ in Eq. 2) depend on the centrality of the collisions. The values of $R_A$ for a given centrality has been evaluated by using the relation - $R_A \sim 1.1N_{part}^{1/3}$.

We use the lattice QCD EoS $[^{37}]$ for the QGP phase and hadronic resonance gas EoS for the hadronic phase $[^{38}]$. The kinetic freeze out temperature, $T_f = 100$ MeV is constrained by the $p_T$ spectra of hadrons. The ratios of various hadrons measured experimentally at different $\sqrt{s_{NN}}$ indicate that the system formed in heavy ion collisions chemically decouple at $T_{ch}(> T_f)$. Therefore, the system remains out of chemical equilibrium from $T_{ch}$ to $T_f$. The deviation of the system from the chemical equilibrium is taken in to account by introducing chemical potential for each hadronic species $[^{39}]$.

III. RESULTS AND DISCUSSION

A. $p_T$ distributions of photons and dileptons

The direct photon spectra from Pb+Pb collisions is measured at $\sqrt{s_{NN}} = 2.76$ TeV. However, no data at this collision energy is available for pp interactions. Therefore, prompt photons from $p+p$ collisions...
collision at $\sqrt{s_{NN}} = 7$ TeV has been used to estimate the hard contributions for nuclear collisions at $\sqrt{s_{NN}} = 2.76$ TeV by using the scaling (with $\sqrt{s_{NN}}$) procedure used in \cite{7}. For the Pb+Pb collisions the result has been scaled up by the number of collisions at this energy (this is shown in Fig. 4 as prompt photons). The high $p_T$ part of the data is reproduced by the prompt contributions reasonably well. At low $p_T$ the hard contributions underestimate the data indicating the presence of a possible thermal source.

The thermal photons with initial temperature $\sim 553$ MeV along with the prompt contributions explain the data well (Fig. 4), with the inclusion of non-zero chemical potentials for all hadronic species considered \cite{39} (see also \cite{40}).

It is well known that transverse momentum spectra of photons act as a thermometer of the interior of the plasma. The inverse slope of the thermal distribution is a measure of the average (over evolution) effective (containing flow) temperature of the system. We have extracted the average effective temperature ($\sim <p_T>$) from the thermal distributions of photons at different collision energies - i.e. for SPS, RHIC and LHC energies. Fig. 5 shows the variation of $<p_T>$ with multiplicity for different collision energies. To minimize the centrality dependence of the results the $dN_{ch}/d\eta$ is normalized by $N_{part}$. The results clearly indicate a significant rise in the average $p_T$ ($<p_T>$) while going from SPS to RHIC to LHC. The values of $<p_T>$ for different collision energies are given in the table \ref{tab:1}. Since photons are emitted from each space time point of the system, therefore, the measured slope of the $p_T$ spectra represents the average effective temperature of the system.

The quantity, $\rho_{eff}^{\gamma}$ = $1/N_{part}(dN_{ch}/d\eta)$ is proportional to the entropy density. Therefore, $\rho_{eff}^{\gamma}/<p_T>^3$ is a quantity which changes drastically if the colour degrees of freedom are deconfined i.e. if a phase transition takes place in the system. We find that the entropy density ($s \sim g_{eff}T^3$) at LHC increases by almost 96% compared to RHIC and there is an enhancement of 46% at RHIC compared to SPS. However, part of this increase is due to the increase in the temperature and part is due to increase in degeneracy. To estimate the increase in the degeneracy we normalize the quantity $\rho_{eff}^{\gamma}/<p_T>^3$ by $<p_T>^3$. Therefore, we estimate $\rho_{eff}^{\gamma}/<p_T>^3$ from the analysis of the experimental data and found that there is a 15% increase in this quantity from SPS to RHIC and 35% increase from RHIC to LHC.

We evaluate the invariant mass ($M$) spectra, and the transverse mass ($M_T$) spectra of lepton pairs with initial conditions, EoS etc constrained by the measured photon spectra at $\sqrt{s_{NN}} = 2.76$ TeV. The emission processes from QGP and the hadronic phases are taken from Ref. \cite{26}, therefore, we do not repeat the details here to save space. The $M_T(=\sqrt{M^2_{av}+p_T^2})$ spectra is evaluated for different $M$ windows ($M$ ranging from $M_1$ to $M_2$, with $M_{av} = (M_1 + M_2)/2$). The $M$ spectra displayed in Fig. 5 indicates that by selecting $M_1$ and $M_2$ appropriately, one can extract the properties of QGP ($M_{av} > 1.5$ GeV) or hadronic system ($M_{av} \sim m_{\pi}$, $\rho$ mass). Therefore, for example, the slope of the $M_T$ spectra (Fig. 5) at $M_{av} \sim 2$ GeV and 0.77 GeV provide information about the average temperature and flow of the QGP and hadronic phases respectively.

In Fig. 5 the slope of the $M_T$ spectra, $T_{eff}$ for different $M$ windows has been plotted. To understand the effect of flow on the slope of the spectra we evaluate the spectra and hence estimate the slope by switching on and off the radial flow. The results with (solid line) and without (dashed line) flow are depicted in Fig. 5. The slope, $T_{eff}$ with flow ($v_r \neq 0$) may be parametrized as $T_{eff} = T_f + M_{av} < v_r >^2$. The difference in the slope due to non-zero $v_r$ and

**FIG. 4:** The transverse mass distribution of thermal lepton pairs for Pb+Pb collision at LHC.

**FIG. 5:** The variation of effective slope with invariant mass bins for Pb+Pb collision at LHC. The dashed line is obtained by setting radial velocity, $v_r = 0$. 

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**TABLE I**

| Energy (GeV) | $dN_{ch}/d\eta$ | $N_{part}$ | $s/\rho^{\gamma}$ |
|-------------|------------------|------------|-------------------|
| SPS         | 1.74             | 1          | 0.10              |
| RHIC        | 2.00             | 2          | 0.20              |
| LHC         | 3.00             | 3          | 0.30              |
the observation of the dominance of the QGP phase at large $M$ help in estimating the radial flow of the QGP phase. The estimated value of $< v_r > \sim 0.065$ for $M = 2$ GeV. A very small value of 0.065 is justified because the $M \sim 2$ GeV range correspond to very early time when flow is not fully developed. However, for $M \sim 1.6$ GeV we found $< v_r > \sim 0.24$ where QGP phase contributions dominate, indicating the fact that the QGP formed at LHC collision conditions undergo significant radial flow. Similarly, the value of $< v_r >$ for the hadronic phase (near the $\rho$ peak) is 0.46. The value of $< v_r >$ in the hadronic phase at freeze-out will be more than 0.46 as this is the average value of the hadronic matter. The $< v_r > \sim 0.37$ for $M \sim 1.3$ GeV where the QGP and the hadronic matter contribute almost equally (see Fig. 3).

IV. SUMMARY AND DISCUSSIONS

In summary, we have analyzed the photon spectra measured by ALICE collaboration in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with a view of extracting the properties of thermal system formed in these collisions. The slope of the photon spectra have been compared with the previously measured spectra at Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC) energies. The thermal lepton pair spectra from the Pb+Pb collision at LHC energy has been estimated with the same initial condition that is used to reproduce the thermal photon spectra at the same collision conditions. The increase in the effective statistical degeneracy at RHIC and LHC relative to SPS have been estimated from the slope of the photon spectra. The radial flow velocity of the QGP and hadronic phases have been assessed from the invariant mass and transverse momentum distributions of the lepton pairs. As the data from ALICE collaboration is well reproduced by the sources of photons described above, photons from other sources e. g. due to jet-thermal parton interactions [41] and induced emissions by the hard partons due to multiple interactions in the QGP [42] are ignored in the present analysis. These processes do not appear to be essential for the present range of transverse momentum.

[1] L. D. McLerran and T. Toimela, Phys. Rev. D 31 (1985) 545.
[2] C. Gale and J.I. Kapusta, Nucl. Phys. B 357 (1991) 65.
[3] H.A. Weldon, Phys. Rev. D 42 (1990) 2384.
[4] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25 (2000) 1.
[5] J. Alam, S. Raha and B. Sinha, Phys. Rep. 273 (1996) 243.
[6] J. Alam, S. Sarkar, P. Roy, T. Hatsuda and B. Sinha, Ann. Phys. 286 (2001) 159.
[7] M.M. Aggarwal et al. (WA98 Collaboration), Phys. Rev. Lett. 85 (2000) 3595.
[8] I. Arsene et al. (BRAHMS Collaboration), Nucl. Phys. A 757 (2005) 1; B. B. Back et al. (PHOBOS Collaboration), Nucl. Phys. A 757 (2005) 28; J. Adams et al. (STAR Collaboration), Nucl. Phys. A 757 (2005) 102; K. Adcox et al. (PHENIX Collaboration), Nucl. Phys. A 757 (2005) 184.
[9] C. Y. Wong, Introduction to High Energy Heavy Ion Collisions, World Scientific, Singapore, 1994.
[10] J. Alam, D. K. Srivastava, B. Sinha and D. N. Basu, Phys. Rev. D 48, 1117 (1993).
[11] J. Alam, S. Sarkar, T. Hatsuda, T. K. Nayak and B. Sinha, Phys. Rev. C 63 (2001) 021901 (R); J. Alam, P. Roy, S. Sarkar and B. Sinha, Phys. Rev. C 67 (2003) 054901; S. Sarkar, P. Roy, J. Alam and B. Sinha, Phys. Rev. C 60, 054907 (1999).
[12] D. K. Srivastava and B. Sinha, Phys. Rev. C 64, (2001) 034902; D. K. Srivastava and B. Sinha, Phys.Rev.Lett. 73, 2421 (1994).
[13] P. Huovinen, P. V. Ruuskanen and S. S. Rasanen, Phys. Lett. B 535 (2002) 109.
[14] K. Gallmeister, B. Kämpfer and O. P. Pervelenko, Phys. Rev. C 62 (2000) 057901.
[15] F. D. Steffen and M. H. Thoma, Phys. Lett. B 510, 98 (2001).
[16] D. G. d’Enterria and D. Peressounko, Eur. Phys. J. C 46, 451 (2006); DOI: 10.1140/epjc/s2006-02504-0.
[17] J. Alam, J. K. Nayak, P. Roy, A. K. Dutt-Mazumder and B. Sinha, J.Phys. G 34, 871 (2007); DOI: 10.1088/0954-3899/34/5/008.
[18] J. K. Nayak and B. Sinha, Phys. Lett. B 719, 110 (2013).
[19] E. Braaten and R. D. Pisarski, Nucl. Phys. B 337 (1990) 569; ibid 339 (1990) 310.
[20] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D 44 (1991) 2774; R. Bair, H. Nakagawa, A. Niegawa, and K. Redlich, Z. Phys. C 53 (1992) 433; P. Aurenche, F. Gelis, R. Kobes, and H. Zaraket, Phys. Rev. D 58 (1998) 085003.
[21] P. Arnold, G.D. Moore, and L.G. Yaffe, J. High Energy Phys. 0111 (2001) 057; P. Arnold, G.D. Moore, and L.G. Yaffe, J. High Energy Phys. 0112 (2001) 009; P. Arnold, G.D. Moore, and L.G. Yaffe, J. High Energy Phys. 0206 (2002) 030.
[22] S. Sarkar, J. Alam, P. Roy , A. K. Dutt-Mazumder, B. Dutta-Roy, B. Sinha, Nucl. Phys. A 634 (1998) 206.
[23] P. Roy, S. Sarkar, J. Alam and B. Sinha, Nucl. Phys. A 653 (1999) 277.
[24] S. Turbide, R. Rapp and C. Gale, Phys. Rev. C 69 (2004) 014903.
[25] J. Cleymans, J. Fingberg and K. Redlich, Phys. Rev. D 35, 2153 (1987).
[26] S. Ghosh, S. Sarkar and J. Alam, Eur. Phys. J. C 71, 176 (2011).
[27] S. Ghosh, S. Mallik and S. Sarkar, Eur. Phys. J. C 70 (2010) 251.
[28] S. Ghosh and S. Sarkar, Nucl. Phys. A 870, 94 (2011).
[29] S. Ghosh and S. Sarkar, Eur. Phys. J. C 70 (2010) 251.
[30] E. V. Shuryak, Rev. Mod. Phys. 65 (1993) 1.
[31] R. Arnaldi et al. for NA60 Collaborations, Phys. Rev. Lett. 96, 162302 (2006); Phys. Rev. Lett. 100, 022302 (2008).
[32] S. Ghosh and S. Sarkar, J. Phys. Conf. Ser. 374 (2012) 012010.
[33] J. D. Bjorken, Phys. Rev. D 27 (1983) 140.
[34] H. von Gersdorff, M. Kataja, L. D. McLerran and P. V. Ruuskenn, Phys. Rev. D 34 (1986) 794.
[35] D. Kharzeev and M. Nardi, Phys. Lett. B 507 (2001) 121.
[36] K. Aamodt et al. (for ALICE collaboration), Phys. Rev. Lett. 106, 032301 (2011).
[37] C. Bernard et al., Phys. Rev. D 75 (2007) 094505.
[38] B. Mohanty and J. Alam, Phys. Rev. C 68, 064903 (2003).
[39] T. Hirano and K. Tsuda, Phys. Rev. C 66 (2002) 054905.
[40] T. Renk, Phys. Rev. C 71, 064905 (2005; T. Renk, J. Phys. G 30, 1495 (2004).
[41] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. Lett. 90, 132301 (2003).
[42] B. G. Zakharov JETP Lett. 80, 1 (2004).