DILEPTON PRODUCTION AT FINITE TEMPERATURE QUARK GLUON PLASMA

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Abstract

We study a statistical model of hot nuclear matter in a hadronic medium. The dilepton production and integrated yeilds at a critical temperature $T_c \sim 170\ MeV$ and completely freeze out temperature $T = 150\ MeV$ with initial temperatures as $T_0 = 570, 400\ and\ 250\ MeV$ are calculated with the introduction of parametrization in the value of quark mass. We consider that quark mass is dependent on the coupling value and temperature with the effect of parametrization value. This parametrization value is to take care of the hydrodynamical flow of this hot nuclear matter so called Quark-Gluon Plasma(QGP). The rate of production is shown for low invariant mass M as well as transverse momentum P_T at the particular value of $E = \ 3.0\ GeV$, which is considered to scale the spectra of dilepton from plasma. It shows a very significant production of leptons in the process for small value of low invariant mass and highly suppressed of low momentum of these thermal mass model. Moreover, it shows a very good results in the case of particle yeilds with the evolution of time.

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Introduction: The theory of strong iinteractions so called quantum chromodynamics(QCD) [**?**] predicts the existence of a phase transition from a confined state of hadronic matter to a hot deconfined state of nuclear matter so called quark-gluon plasma (QGP). The transition is observed at the temperature $T_c \sim (150-170)\ MeV$ from the confined hadronic matter to the deconfined state, in which quark and gluon become the relevant degrees of freedom of this newly created nuclear matter. Perhaps, it is believed that it occured in the beginning of the early universe just after the event of Big Bang with the life span of few micro seconds ($10\mu s$). The evolution of such matter is believed to exist in the interior core of neutron star, which is considered to be highly dense matter. Presently, the experimental program of ultra-relativistic nucleus-nucleus collision at RHIC and LHC at CERN indicate the presence of these strongly interacting matter at very high energy density and temperature. However, finding its evidence and ultimately proof , for the creation and evolution of this deconfined state of matter is an open problem linking experimental observations to quantities measured in lattice calculations, and it has been recognized for a long time that electromagnetic radiation from relativistic heavy ion collisions experiments would yield a proper understanding for the formation of these hot and dense plasma of quark and gluon, consequent to quark-hadron phase transition. But there are other possibilities to show the signal of formation of this new state of matter. In fact, these formation of new state are enhanced by production of strangeness [**?**], a suppression of J/ψ [**?**], radiation of photons and dileptons [**?**] and hydrodynamical flow results etc. Among these probable probes, dilepton and photon production are considered to be most promising signal as they are being subject to electromagnetic interactions. So, they directly carry the whole information of plasma state without further scattering as their mean free path in the fireball matter is very large which yields interaction coverage over a large range of expected plasma temperature and it shows much wider region than spatial dimension of the system. This production is observed throughout evolution of this plasma state. Further, on the experimental side [**?**], it is reported that in the $NA50$ experiments, the collisions predict the excessive production of dileptons in the intermediate mass range, and $NA60$ collaborations [**?**] in central $In-In$ collision at the CERN-SPS also show dimuon spectra from a hot and dense hadron medium. In this way, several research groups have seen these spectra for the same collision [**?**].

Thus, so far, the production of dilepton and photon in a QGP with a finite temperature is studied by many authors and this temperature is related to the energy density ϵ given by the Stefan Boltzmamn law, $\epsilon \sim T^4$, and their thermodynamic properties are governed by $T\frac{dP}{dT} - P = \epsilon; P = \frac{1}{3}\sigma T^4 - AT$, where $'A'$ is a constant in the non-perturbative term of the pressure. On the basis of these studies, we first consider a non-baryonic QGP fireball of statistical model to study the dilepton spectra and integrated yeilds with variation of time. In this model of QGP formation we introduce a parametrization factor $\gamma_{q,g}$ which has the function to take care of deviations from linearity and other expected plasma characteristics of the QGP 'fluid' and to obtain the finite value of quark mass. The parametrization factor becomes the controlling factor in the dynamics of QGP fluid. It is given as:

$$\gamma_{q,g} = \sqrt{2}\sqrt{\frac{1}{\gamma_g^2} + \frac{1}{\gamma_q^2}}\,, \tag{1}$$

where, $\gamma_g = 6\ \gamma_q\ or\ 8\ \gamma_q$ with $\gamma_q = 1/6$. This value is used to find a finite value of quark mass from massless quark and the finite value of quark mass is obtained through the technique of Braaten and Pisarki [?]. Now this quark mass is given by $m^2(T) = \frac{1}{6}g^2T^2$, and it is completely dependent on coupling parameter $'g'$ and temperature. The coupling parameter is given by [?],

$$g^2 = \frac{N}{ln(1 + \frac{p^2}{\Lambda^2})} \tag{2}$$

with the QCD parameter $\Lambda = 150 MeV$ and $p = (\frac{\gamma_{q,g} N^{\frac{1}{3}} T^2 \Lambda^2}{2})^{\frac{1}{4}}$ is low momentum cut-off value with $N = \frac{16\pi}{27}$. Moreover, it is found that this coupling parameter g is mildly stronger compared to other coupling values and it is completely dependent on the momentum of the fireball. Thus, we obtain a QGP fireball in which quark mass is dependent on the factors of parametrization through coupling and temperature. Then we look at the production rate of dilepton with low invariant mass and with transverse momentum. In the conclusion of the paper we see the variation of the integrated yields with the evolution time τ of the fireball with the effect of finite value of quark mass and at the end, we conclude our results with the comparative statement of the standard results produced by many authors [7, 14].

Dilepton production at finite temperature QGP: There exists extensive literature in dilepton production from the hot quark-gluon plasma and hadronic system. Whenever there is a new model for plasma evolution, then its impact on dilepton and virtual photon production are assessed. Moreover, it is expected, that in heavy-ion collisions such as RHIC at BNL and SPS at CERN, [?] the thermal production of dileptons will be more focusing than other processes. Thus, on the basis of these informations, we focus our statistical model of QGP fireball evolution in a hadronic medium and in this new model, we consider mass of the quark as temperature dependence. We look at the calculation of dilepton production from the hot thermalised quark-gluon plasma with initial temperatures $T_0 = 570,\ 400\ (250) MeV$ to transition temperature $T_c = (150-170)\ MeV$, before it completely freezes out to hadrons. So, we use dominant reaction for thermal emission of dilepton pairs [**?**] which is the Drell-Yan mechanism $q\bar{q} \to l^+l^-$ as annihilation process or $q(\bar{q})g \to q(\bar{q}) + l^+l^-$ as Compton process. But, we exclusively use $q\bar{q} \to l^+l^-$ reaction for this calculation as mentioned, that at thermal equilibrium, dilepton production is domonated by $q\bar{q} \to l^+l^-$. The dilepton production rate $\frac{dN}{d^4X}$(i.e the number of dilepton produced per space time volume) is given [**?**] by:

$$\begin{aligned}\frac{dN}{d^4X} &= \int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3} f_q(p_1,T) f_{\bar{q}}(p_2,T)\\ &\times\ v_{q\bar{q}}\sigma_{q\bar{q}}(M^2)\end{aligned} \tag{3}$$

where, $f_q(p_1,T)$ and $f_{\bar{q}}(p_2,T)$ are distribution functions of quark and antiquark, $v_{q\bar{q}}$ is relative velocity between quark and antiquark pair, P_μ is four momentum of lepton pair, $E\ (= \sqrt{M^2+P_T^2})$ is the energy, P_T is transverse momentum and $M^2 = P^\mu P_\mu$ is invariant lepton pair mass, and $\sigma_{q\bar{q}\to l\bar{l}}$ is the electromagnetic annihilation cross section which is given as:

$$\begin{aligned}\sigma_{q\bar{q}\to l^-l^+}(M^2) &= \frac{4\pi\alpha^2}{3}\sum_{f=1}^{2}(\frac{e_f}{e})^2\frac{1}{M^2}\\ &\times\ (1-\frac{4m^2}{M^2})^{-1/2}\sqrt{(1-\frac{4m_l^2}{M^2})}\\ &\times\ (1+2\frac{m^2+m_l^2}{M^2}+4\frac{m^2m_l^2}{M^2})\end{aligned} \tag{4}$$

where $(\frac{e_f}{e})^2 = \frac{5}{9}$, the electric charge of quark in the units of electron charge, $\alpha = \frac{1}{137}$ and m_l is the lepton mass which we take as zero($m_l = 0$). Substituting the frequency distribution functions f_q and $f_{\bar{q}}$ for quark(q) and antiquark($\bar{q}$) in the equation (3), and integrating over p_1 and p_2, and subsequent integrating over space and time with a change of variable $d^4x = dx_p\tau d\tau dy$, we obtain the dilepton production rate as:

$$\begin{aligned}\frac{dN}{dM^2dy} &= \frac{5\alpha^2}{6\pi^2}\frac{\tau^2R^2T_0^6}{M^4}(1+\frac{2m^2}{M^2})\\ &\times\ \int_{\frac{M}{T_0}}^{\frac{M}{T_c}} z^4K_1(z)dz\end{aligned} \tag{5}$$

$$\frac{dN}{dP^2dy} = \frac{5\alpha^2}{12\pi^2}\frac{\tau^2R^2T_0^6}{E^6}(M^2+2m^2ln(M^2)) \times \int_{\frac{E}{T_0}}^{\frac{E}{T_c}} z^5K_0(z)dz \tag{6}$$

where, in the above expression $K_1(z)$ is a modified Bessel's function of first order and R is the quark droplet size. The integral can be evaluated analytically with a value given by $-z^2(8+z^2)K_0(z)-4z(4+z^2)K_1(z)$ in which we have defined $z=M/T$ whereas in another expression, $K_0(z)$ is the analytic solution of the Bessel's function in which $z=E/T$. The creation and evolution of plasma is transient with a characteristic time, $\tau \sim 1fm/c$ and, finally attains a temperature $T_c \sim (150-170)MeV$.

Results and Conclusions: In this short article, we have attempted to evaluate the dilepton production from a statistical model of QGP fireball in the hadronic medium. We have also considered quark mass dependence on coupling parameter and thermal temperature so that the massless quark has obtained a finite value. But this coupling parameter is obtained through a parametrization factor of fireball formation. First we look at the dilepton production rate with the variation of low invariant mass and low transverse momentum at the finite value of quark mass and subsequently integrated yeilds with the variation of time. The results of dilepton production rate with the corresponding variations are shown in Figs$[1-4]$. The production rates of dilepton with invariant mass at $T_c = 0.15\ GeV\ and\ T_c = 0.17\ GeV$ with energy $E = 3.0\ GeV$ are shown in Fig [1] and Fig [2] respectively. Here, we consider the value of energy which is used to scale the spectra of dilepton production from the plasma. Thus, we consider the initial temperatures as $T_0 = 570, 400$ and $250\ MeV$ and the final temperature as $T = 170\ MeV$ and $T = 150\ MeV$ for our calculation. The calculation at these two final temperatures indicate a slight difference in the production rate with the low invariant mass. The production rate at free-out,$T = 150\ MeV$ is slighly higher compared to transition temperature at $T_c = 170\ MeV$. This implies that near the hadronic phase, its production is more enhanced with the effect of thermal mass model of quark. However, the emission of these dilepton particles at low invariant mass region viz. $M = (0-3.0)\ GeV$ has good significant output with the recent results of dilepton production. Similarly, in the Figs$[3-4]$ we plot the dilepton production rate with low transverse momentum for the same initial and final temperatures. The production rate are almost similar for these two final temperatures and it is a very mild nature of higher production for the temperature $T = 150\ MeV$. Overall, it indicates that our result with the finite value of quark mass seem to be in good accord with various results for the low invariant mass and dilepton production with low transverse momentum is highly suppressed produced by other workers[13, 14]. Again, we look at the integrated yield with variation of time from $\tau = 0\ fm$ to $\tau = 3.0\ fm$ for these transition and free out temperature. They are shown in Figs.[5 − 6]. There is a very slight difference for these integrated yields at these two temperatures. It exhibits nice scenarios of integrated yeilds in these time regions. There is overall agreement with the recent results of Zejun He et al.[**?**] and the model with the introduction of parametrization in the quark mass satisfies the dilepton production and integrated yields.

Acknowledgments

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Figure Captions

Fig1:Variation of the dilepton emission rate with lepton pair mass $at\ T_c = 0.15\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

Fig2: Variation of the dilepton emission rate with lepton pair mass $at\ T_c = 0.17\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

Fig3:Variation of the dilepton emission rate with transverse momentum $at\ T_c = 0.15\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

Fig4:Variation of the dilepton emission rate with transverse momentum $at\ T_c = 0.17\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

Fig5: The integrated yield as function of τ $at\ T_c = 0.15\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

Fig6: The integrated yield as function of τ $at\ T_c = 0.17\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Dashed line: $T_0 = 0.25\ GeV$.

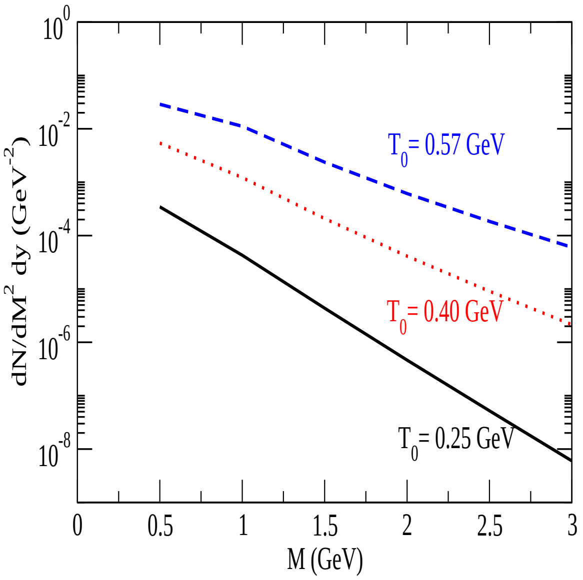

FIG. 1: Variation of the dilepton emission rate with lepton pair mass *at* $T_c = 0.15\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

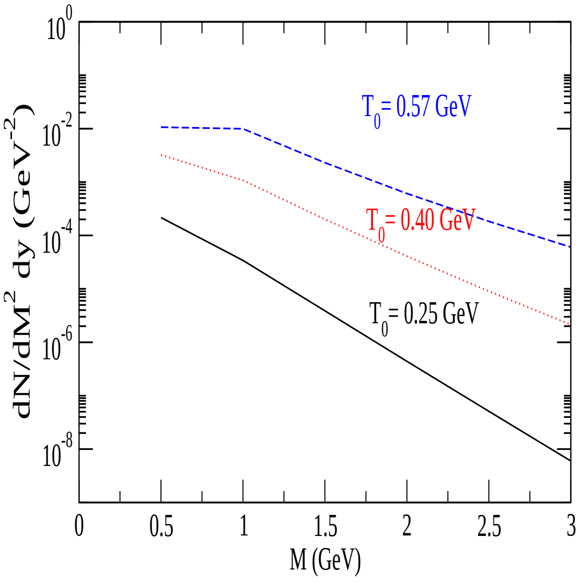

FIG. 2: Variation of the dilepton emission rate with lepton pair mass *at* $T_c = 0.17\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

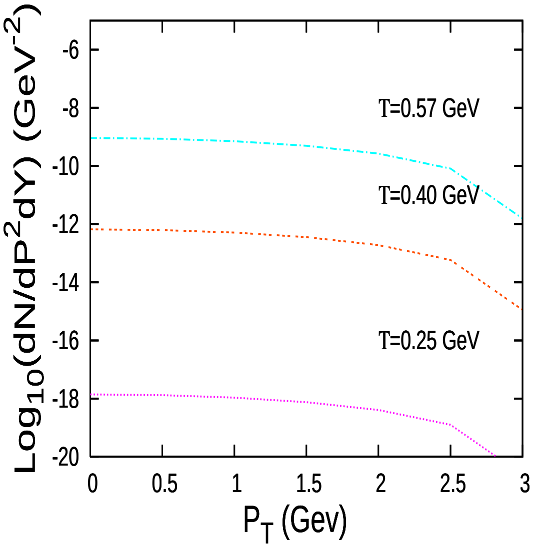

FIG. 3: Variation of the dilepton emission rate with transverse momentum *at* $T_c = 0.15\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

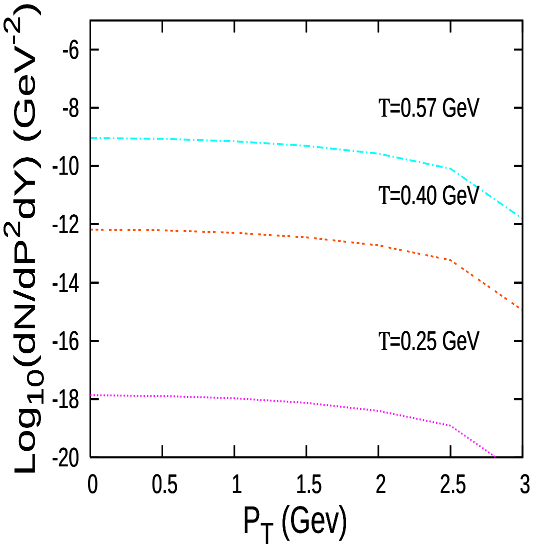

FIG. 4: Variation of the dilepton emission rate with transverse momentum *at* $T_c = 0.17\ GeV$ and $E = 3.0\ GeV$ with initial temperature T_0. Dashed line: $T_0 = 0.57\ GeV$ Dotted line: $T_0 = 0.40\ GeV$ Solid line: $T_0 = 0.25\ GeV$.

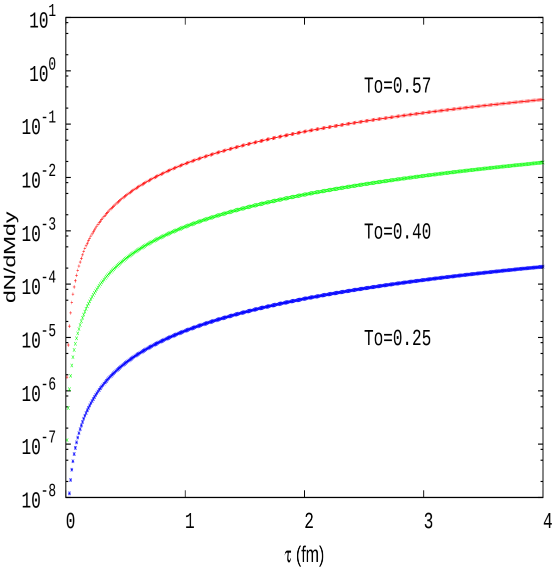

FIG. 5: The integrated yield as function of τ at $T_c = 0.15$ GeV and $E = 3.0$ GeV with initial temperature T_0. Dashed line: $T_0 = 0.57$ GeV Dotted line: $T_0 = 0.40$ GeV Solid line: $T_0 = 0.25$ GeV.

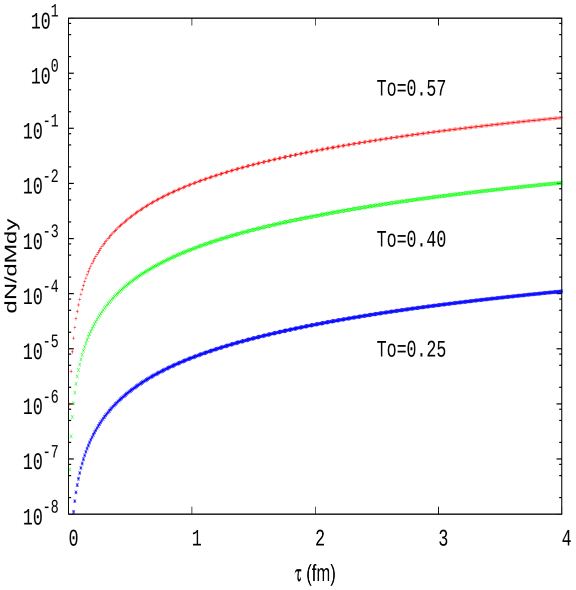

FIG. 6: The integrated yield as function of τ at $T_c = 0.17$ GeV and $E = 3.0$ GeV with initial temperature T_0. Dashed line: $T_0 = 0.57$ GeV Dotted line: $T_0 = 0.40$ GeV Dashed line: $T_0 = 0.25$ GeV.