Dilepton emission from an equilibrating non-abelian plasma

Gouranga C Nayak *
Department of Physics, Indian Institute of Technology, Kanpur – 208 016, INDIA

Abstract

We study dilepton production from a thermally equilibrating quark-gluon plasma expected to be formed in ultra relativistic heavy-ion collisions. The pre-equilibrium dynamics of quark-gluon plasma is studied within the color flux-tube model by solving non-abelian relativistic transport equations. This dilepton rate crucially depends on the collision time of the plasma. The results are compared with the Drell-Yan productions. We suggest that a measurement of this rate at RHIC and LHC will determine the initial field energy density.

Keywords: Dilepton, quark-gluon plasma, heavy-ion collision, color flux-tube model, QCD, hadronic colliders.

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*Electronic address: gcn@iitk.ernet.in

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One of the primary aims of the ultra relativistic heavy-ion collision experiment is to detect a new phase of matter, \textit{viz} quark-gluon-plasma (QGP). It is known from lattice quantum chromodynamics that hadronic matter undergoes a transition to this quark-gluon plasma phase at very high temperatures (\(\sim 200\text{MeV}\)) and densities (\(\sim 2\text{GeV/fm}^3\)) \[1\]. While such a phase did exist in the early universe, after \(\sim 10^{-4}\) seconds of the big bang, it is interesting if we can recreate the early universe and experimentally verify this QCD phase transition in the laboratory \textit{i.e.} in high energy heavy-ion collisions. In the near future, the relativistic heavy ion collider (RHIC) at BNL (Au-Au collisions at \(\sqrt{s} = 200\text{GeV}\)) and large Hadron Collider (LHC) at CERN (Pb-Pb collisions at \(\sqrt{s} \simeq 6.4\text{TeV}\)) \[2,3\] will provide the best opportunity to study such a phase transition. As this plasma exist for a very short time (\(\sim 10\text{fm}\)) and formed over a very small volume (\(\sim 100\text{fm}^3\)), the direct detection of this phase is not possible in these experiments. The proposed signatures for its detection are therefore indirect, and the prominent ones are: 1) \(J/\psi\) supression \[4\], 2) electromagnetic probes such as dilepton and direct photon production \[5,6\], and 3) strangeness enhancement \[7\].

It has been suggested by Matsui and Satz that \(J/\psi\) suppression is a good probe \[4\] for the detection of an equilibrated quark-gluon plasma. Their calculation is based on lattice QCD which assumes equilibration of the plasma. However, in heavy-ion collisions such as at RHIC and LHC the assumption of such an equilibration of quark-gluon plasma is only suggestive. One does not know exactly when the plasma equilibrates and there is no concrete calculation on this aspects. This sets an uncertainty in the calculation of \(J/\psi\) survival probability which is determined from screening. In this regard, there are calculations of \(J/\psi\) suppressions in the equilibrating quark-gluon plasma \[8,9\] using short-distance QCD, but the uncertainties in the \(J/\psi\) formation time and quark-gluon plasma equilibration time make it difficult to compare the results with the experiments (see Ref. \[8\] for the details). The suppression of \(J/\psi\) infact, been observed in reactions where there is no quark-gluon plasma phase, such as in p-A collisions and in collisions of light nucleus \[10\]. This suppression is well explained by the nuclear absorption of \(J/\psi\) \[11\]. Although, recently, NA50 collaboration \[12\] reports an excess...
in the suppression of $J/\psi$, it is still not clear if an equilibrated quark-gluon plasma has formed in this collisions. There are proposals that the data are explained by a deconfined partonic medium \cite{13}, or by a medium with high density \cite{14}; but there are also other calculations which explain the data without assuming any quark-gluon plasma phase \cite{15,16}. As far as the $J/\psi$ suppression in nucleus-nucleus collision is concerned, many aspects of it has to be studied in greater detail before unambiguous conclusions can be drawn about the existence of quark-gluon plasma. It thus appears that there is a need to study more than one signature if one has to detect QGP. With that in mind we investigate another signature, *i.e.* dilepton emission.

Dileptons and single photons have long been proposed as useful probes of the plasma \cite{3}, as once produced, they hardly interact with the strong matter and thus carry the details of the circumstances of their production. Being electromagnetic in nature, they do not suffer from the final state interactions (interactions with hadrons) and hence keep the memory of their formation surroundings (such as the information about the temperature and number density). The major processes for dilepton production in ultrarelativistic heavy-ion collisions (URHIC) are, (i) hard parton scattering, (ii) electromagnetic decay of hadrons and (iii) production from partons present in QGP (thermal production). The hard parton scatterings produce high $p_t$ lepton pairs which are calculated from pQCD, knowing the structure functions of partons inside nucleus. On the other hand, electromagnetic decay of produced hadrons is the main source of dilepton and photon production in heavy-ion collisions which obscure the signal of interest (thermal production), which are produced from QGP. The thermal emission of high invariant mass dilepton is calculated in the same way as that of hard parton scatterings by using the thermal distributions of partons inside QGP. It is expected that in high energy heavy-ion collisions such as at RHIC and LHC, the thermal production of dileptons will be more than that from other processes \cite{17}. On the experimental side, an enhancement of dilepton yield is observed in central 200A GeV S+Au \cite{18}, S+W \cite{19}, and 160A GeV Pb+Au \cite{20} collisions. However, these data are partially explained by the conventional mechanism of binary hadron collisions, *e.g.*, by $\pi\pi \rightarrow e^+e^-$ processes \cite{21,22}. 
and by the contribution of the collective bremsstrahlung mechanism \[24\]. In ultrarelativistic heavy-ion collisions such as at RHIC and LHC situation might be different and one may expect an enhancement of the dilepton production which can be due to the formation of quark-gluon plasma.

For a thermally equilibrated quark-gluon plasma, the distribution of dilepton is given by\[17\]

\[
\frac{dN}{dydM^2} = \pi R^2 \frac{3M^2\sigma(M)T_0^2\tau_0^2 T_0^4}{2(2\pi)^4} \frac{T_0^4}{M^4} \times \left[H\left(M/T_0\right) - H\left(M/T_c\right)\right]
\]

(1)

where \(T_c\) is the freeze-out temperature at which one stops the hydrodynamic evolution of the quark-gluon plasma, or perhaps the critical temperature if there is a phase transition. Here \(M\) is the invariant mass of the dilepton pair, \(R\) is the size of the nucleus and \(\sigma\) is the annihilation cross section for quark-antiquark into a dilepton pair. The function \(H\) is written in terms of Bessel function \(K_1\) as, \(H(z) = z^2(z^2 + 8)K_0(z) + 4z(z^2 + 4)K_1(z)\). Assuming a fast thermalisation and high initial temperature, enhancement in the dilepton rate was found by several authors \[17\]. However, it can be seen from the above equation that there is always an uncertainty in the dilepton rate because of the assumption of initial temperature \((T_0)\) and initial time \((\tau_0)\), at which quark-gluon plasma thermalise. The dilepton rate in any realistic calculation depends crucially on these initial conditions which determines the hydrodynamic evolution. For this reason a detailed calculation of the plasma evolution in different stages of ultrarelativistic heavy-ion collisions is necessary. The various stages by which the evolution of quark-gluon plasma is described in URHIC are, i) pre-equilibrium, ii) equilibrium, where one actually studies the equilibrated quark-gluon plasma, and iii) hadronisation. The pre-equilibrium stage of the collision which leads to thermal and then chemical equilibrium has a crucial role to play in the equilibration of the plasma and also on the calculation of different signatures. From this point of view it is necessary to study what happens to the dilepton production from different stages of QGP, rather than estimating it in an equilibrated quark-gluon plasma (Eqn.-1 ). In this paper we study the dilepton rate for a thermally equilibrating quark-gluon plasma in ultra relativistic heavy-ion collisions.
The rate of equilibration of quark-gluon plasma in URHIC is different for different models. One of the relevant models that describes the production and the equilibration of QGP in URHIC is the color flux-tube model \cite{25-27}. This model is a generalization of the familiar Lund string model widely used for $e^+e^-$ and $p-p$ collisions \cite{28}. Within this model, two nuclei that undergo a central collision at ultra high energies are highly lorentz-contracted as thin plates. When these two highly lorentz-contracted nuclei pass through each other they acquire a nonzero color charge ($<Q>=0$, $<Q^2>\neq0$), by a random exchange of soft gluons. The nuclei which act as color capacitor plates produce a chromo-electric field between them \cite{29,30}. This strong electric field creates $q\bar{q}$ and gluon pairs via the Schwinger mechanism \cite{31} which enforces the instability of the vacuum in the presence of an external field. The partons so produced, collide with each other and also get accelerated by the background field. In the case at hand, the color degree has a central dynamical role in the evolution of the plasma. In our recent studies we have incorporated this dynamics in the plasma evolution in heavy-ion collisions \cite{32,33}. The color charge($Q^a$) which is a vector in the color space obeys Wong’s equation \cite{34}:

$$\frac{dQ^a}{d\tau} = f^{abc}u^aQ^bA^{c\mu}. \tag{2}$$

where $A^{a\mu}$ is the gauge potential, and $f^{abc}$ is the structure constant of the gauge group. This equation describes the precission of the color charge in external chromo field. The non-abelian version of the Lorenz force equation

$$\frac{dp_{\mu}}{d\tau} = Q^aF^{a\mu\nu}u_\nu, \tag{3}$$

describes the acceleration of the color particles by the background chromo field $F^{a\mu\nu}$. Due to these dynamical nature of the color charge, the usual classical phase space of coordinate and momenta is extended to include color. The single particle distribution function $f(x,p,Q)$ of quark and gluon is then defined in the compact phase space of dimension 14 in SU(3). In this extended phase space a typical relativistic transport equation is written as \cite{35}

$$\left[p_\mu\partial^\mu + Q^aF^{a\mu\nu}\partial_\mu + f^{abc}Q^aA^{b\mu}\partial^\mu\right]f(x,p,Q) = C(x,p,Q) + S(x,p,Q). \tag{4}$$
One needs to solve this transport equation to study the non-equilibrium dynamics of the quark-gluon plasma expected to be formed in ultra relativistic heavy-ion collisions. The first term in the above non-abelian relativistic transport equation corresponds to the usual convective flow (free streaming expansion), the second term is the non-Abelian version of the Lorentz force term and the last term corresponds to the precession of the color charge as described by Wong’s equation. $S$ on the right hand side of equation (4) correspond to the source term for parton production from background chromoelectric field via Schwinger non-perturbative mechanism. $C$ corresponds to the collision term. In general we have to write separate equations for quarks, antiquarks and gluons since they belong to different representations of the gauge group. For anti-quarks the distribution function $\bar{f}(x, p, Q)$ obeys a similar equation, with $Q^a$ replaced by $-Q^a$ (i.e. the second term in the above equation changes sign). These equations, which are lorentz and gauge invariant [35], are closed with the Yang-Mills equation,

\[(D_\mu F^{\mu\nu})^a(x) = j_\nu(x) = g \int p^\nu Q^a[f_q(x, p, Q) - \bar{f}_q(x, p, Q) + f_g(x, p, Q)]dPdQ.\] (5)

to study the production and equilibration of quark-gluon plasma.

According to Bjorken’s proposal [36] the distribution function and other physical quantities are written in terms of the boost invariant parameters $\tau(= \sqrt{t^2 - z^2})$, $p_t$ and $\xi(= \eta - y)$. Here $\eta$ is the space time rapidity ($tanh\eta = z/t$) and $y$ is the momentum rapidity ($tanh y = p_z/p^0$). In our calculation we have employed a collision term in the relaxation time approximation:

\[C = -p^\mu u_\mu(f - f^{eq})/\tau_c,\] (6)

where $f^{eq}$ is the local equilibrium distribution function with explicit color dependences. This is given by [37]:

\[f^{eq}_{q,g} = \frac{2}{\exp((p^\mu - Q^a \cdot A^{\mu a})u_\mu/T(\tau)) \pm 1}.\] (7)

The $+(-)$ sign in the above expression is for quarks(gluons). The source term $S$ for $q\bar{q}$ and gluon pair production is obtained by the Schwinger mechanism of particle production.
In the process where field and particles are present, we use the energy momentum conservation equation:

$$\partial_\mu T^{\mu\nu}_{\text{matter}} + \partial_\mu T^{\mu\nu}_{\text{field}} = 0,$$

(8)

with $T^{\mu\nu}_{\text{matter}} = \int p^\mu p^\nu (2f_q + 2\bar{f}_q + f_g) d\Gamma dQ$ and $T^{\mu\nu}_{\text{field}} = \text{diag}(E^2/2, E^2/2, E^2/2, -E^2/2)$. Here $d\Gamma = d^3p/(2\pi)^3p_0 = p_t dp_t d\xi/(2\pi)^2$, and $dQ$ is the integral in the color space. The factor 2 in the above expression is for two flavors of massless quark. Equation (4) along with equation (8) is solved numerically by a double self consistent method [38] to study the equilibration of quark-gluon plasma in URHIC. In the earlier paper [33] we have studied the bulk properties and the equilibration of quark-gluon plasma (which occurs around 1 fm). Here we calculate the dilepton production rate using these distribution functions of partons $f(\tau, \xi, p_t, Q)$.

The dominant process which produces a dilepton pair $l^+l^−$ is

$$q + \bar{q} \rightarrow \gamma^* \rightarrow l^+ + l^−,$$

(9)

where $\gamma^*$ is the intermediate virtual photon. The dilepton emission rate $dN$ for such a process in a space time volume $d^4x$ is

$$\frac{dN}{d^2xd^4P} = \frac{1}{(2\pi)^6} \int d^3p_1 d^3p_2 dQ f(x, p_1, Q) f(x, p_2, Q) v_{\text{rel}} \sigma(M^2) \delta^4(P - p_1 - p_2).$$

(10)

Here $P^\mu$ is the four momentum of the lepton pair, $P_T$ is the transverse momentum, $M_T(=\sqrt{M^2 + P_T^2})$ is its transverse mass and $M$ is the invariant mass ($M^2 = P^\mu P_\mu$). $v_{\text{rel}}(=M^2/2E_1E_2)$ is the relative flux velocity of quark and antiquark pair in the above process.

The dilepton production cross section $\sigma(M^2)$ for the above reaction is

$$\sigma(M^2) = \frac{4\pi\alpha^2}{3M^2}[1 + \frac{2m_l^2}{M^2}][1 - \frac{4m_l^2}{M^2}]F_q,$$

(11)

with $F_q = N_s^2\frac{1}{N}\sum f e_f^2$ and $m_l$ is the mass of the lepton. Here, $N$ is the color averaging factor (which corresponds to the volume of the color space), $N_s$ is the spin degeneracy ($N_s = 2s + 1$) and $e_f$ is the fractional charge of the flavour. For dilepton pair of large invariant mass the emission rate in the midrapidity region ($Y = 0$) is given by:
\[
\frac{dN}{dM_T^2 dY dP_T^2} = \frac{5R^2 \alpha^2}{72 \pi^7} \int d\tau \tau W(f_1, f_2). \tag{12}
\]

where

\[
W(f_1, f_2) = \int_{-\infty}^{+\infty} d\eta \int_{-\infty}^{+\infty} d\xi_1 \int_{p_+}^{p_-} dp_{t1} \int dQ \left[ \frac{p_{t1} f(\tau, p_{t1}, \xi_1, Q) \tilde{f}(\tau, p_{t2}, \xi_2, Q)}{[P_{t1}^2 P_T^2 - [p_{t1} M_T \text{ch}(\eta - \xi_1) - \frac{1}{2} M^2]^2)^{3/2}} \right]. \tag{13}
\]

with \( p_{t2} = \sqrt{M_T^2 - 2 M_T p_{t1} \text{ch}(\eta - \xi_1) + p_{t1}^2} \), \( \text{sh} \xi_2 = \frac{1}{p_{t2}} (M_T \text{sh} \eta - p_{t1} \text{sh} \xi_1) \) and \( p_{\pm} = \frac{1}{2} M^2 [M_T \text{ch}(\eta - \xi_1) \mp P_T]^{-1} \). In equation (12) we have used \( d^4 x = \pi R^2 d\tau d\eta \) (where \( R \) is the radius of the nucleus). \( \alpha (= 1/137) \) is the coupling constant of the electromagnetic interaction.

It can be mentioned here that the thermal dilepton rate does not depend on \( M \) and \( P_T \) separately, but only on \( M_T \) \[39\]. However this \( M_T \) scaling is violated for an equilibrating plasma, which is seen in equation (12). In this case the dilepton rate depends on both \( M_T \) and \( P_T \). This would also be the case if one takes the transverse expansion of the plasma into account \[40\].

We will now present our results of the dilepton rate using the above non-equilibrium distribution function, \( f(\tau, \xi, p_t, Q) \), of quarks and antiquarks. In our calculation we have taken \( R = 7 \text{fm} \) and the initial field energy density \( \epsilon_0 (= 1/2 E_{\text{o}}^2) \) to be equal to 300 GeV/fm\(^3\) (see Ref. \[32\]). We have considered two different cases corresponding to two different relaxation times, \( \tau_c = 5 \text{fm} \) and \( \tau_c = 0.2 \text{fm} \). The relaxation time \( \tau_c = 5 \text{fm} \) corresponds to collisionless limit and \( \tau_c = 0.2 \text{fm} \) corresponds to a more realistic limit of equilibration \[41\].

We have calculated the dilepton rate as a function of \( M_T \) for \( P_T = 0 \) and 1 GeV respectively. In Fig-1 we have presented the results for \( \tau_c = 0.2 \text{fm} \). As can be seen from the figure, the dilepton yield becomes smaller for higher values of transverse momenta. In Fig-2 we have presented our results for \( \tau_c = 5 \text{fm} \) which corresponds to the collisionless limit. In this case the rate at higher \( M_T \) is found to be larger than that at \( \tau_c = 0.2 \text{fm} \). This is because the average energy per parton is higher at \( \tau_c = 5 \text{fm} \) than at \( \tau_c = 0.2 \text{fm} \) as observed earlier \[33\]. The average energy per parton is around 4 GeV for \( \tau_c = 5 \text{ fm} \) and is around 2 GeV for \( \tau_c = 0.2 \text{ fm} \). In the absence of any collision the partons come with higher energies than the
partons with collision. From this point of view it is crucial to determine the collision time accurately. We will mention here that a determination of the collision time $\tau_c$ is possible by a triple self consistent numerical method [12] instead of a double self consistent method (which we have employed here to solve the transport equations).

In order to get a feeling, how crucial the dilepton production from an equilibrating QGP is, we have compared our results with the Drell-Yan productions. The Drell-Yan results are taken from the Ref. [13]. These spectra are calculated at pp center-of-mass energy $\sqrt{s} = 200$ GeV scaled to UU central collisions assuming a simple factorisation of the nuclear mass dependences. It can be seen in Fig-3 that the dilepton rate from the pre-equilibrium stage is larger than the Drell-Yan production for very small transverse momentum ($P_T \simeq 0$ GeV). This is true when $M_T \leq 2$ GeV. For $M_T \geq 2$ GeV, the Drell-Yan production dominates over the pre-equilibrium dilepton production. For large transverse momentum ($P_T = 1$ GeV) of dilepton pair, the production from the pre-equilibrium stage is smaller than the Drell-Yan production in the whole range of dilepton transverse mass. This has been shown in Fig-4. This result is contrary to the earlier findings [14,15] where it is shown that dilepton production from the pre-equilibrium stage dominates over the Drell-Yan production. The partons formed are not too hard in the color flux-tube model, and one expects to have such a low rate in the dilepton spectra than the Drell-Yan emissions, which are produced from the primary hard scattering of partons. However, the comparisons are not very strict because the choice of initial field energy density $\epsilon_0 (= 1/2 E_0^2$, $E_0$ being the initial chromoelectric field) is arbitrary and there is no way of determining this. This is because one does not know how many soft gluons are exchanged (which determines the strength of the initial chromoelectric field) when two nuclei cross each other in ultra relativistic heavy-ion collisions. This initial condition can be determined from the measurement of some experimental signatures, such as dilepton production. However, the results we have found here do not seem unnatural. This is because, if one identifies the energy deposited at RHIC [34] (when two nuclei are in maximum overlap) with the initial field energy, the initial field energy density becomes $\sim 250$ GeV/$fm^3$ [11]. In any case, we hope to extract the initial field energy density from
the measurement of dilepton spectra at RHIC and LHC (this is done only after a careful substraction of the dilepton rates from other processes in different stages of quark-gluon plasma). After the determination of this initial field energy density, other bulk properties of the plasma can be determined accurately.

Summarizing the paper, we have calculated the dilepton spectra in ultra relativistic heavy-ion collisions within color flux-tube model, with non-abelian features explicitly incorporated. The production is larger in the collisionless limit of the plasma. After one determines the collision time accurately by a triple self consistent procedure \[42\], an experimental measurement of the dilepton spectra at RHIC and LHC will shed light on the determination of initial field energy density which we have assumed in our model. Only after this, the predictions of all the bulk properties of the plasma such as temperature and number density, will be determined accurately.
REFERENCES

[1] F. Karsch, Rep. Prog. Phys. 56, 1347 (1993).

[2] T. C. Awes et al.(eds.), Nucl. Phys. A544, 1c (1993).

[3] H. A. Gustafsson et al.(eds.), Nucl. Phys. A566, 1c (1994).

[4] T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).

[5] M. T. Strickland, Phys. Lett. B 331, 245 (1994).

[6] Jan-e Alam, Sibaji Raha and Bikash Sinha, Phys. Rep. 273, 243 (1996).

[7] J. Rafelski and B. Muller, Phys. Rev. Lett. 48, 1066 (1982),
    C. P. Singh, Phys. Rev. Lett. 56, 870 (1990).

[8] Gouranga C. Nayak, Journal of High Energy Physics, 02 (1998) 005, Report No: hep-ph/9704281.

[9] Xiao-Ming Xu et al., Phys. Rev. C 53, 3051 (1996).

[10] C. Baglin et al. Phys. Lett. B 270, 105 (1991);
    C. Baglin et al. ibid 345, 617 (1995).

[11] C. Gerschel and J. Hufner, Z. Phys. C 56, 171 (1992).

[12] M. Gonin et al. Nucl Phys. A 610, 404c (1996).

[13] D. Kharzeev, C. Lourenco, M. Nardi and H. Satz, Z. Phys. C 74, 307 (1997).

[14] J. P. Blaziot and J. Y. Ollitraraught, Phys. Rev. Lett. 77, 1703 (1996).

[15] R. C Hwa, T. Pisut and N. Pisutova, OITS 628 (1997).

[16] C. Y. Wong, Phys. Rev. C 55, 2621 (1997).

[17] J. Kapusta, L. McLerran and D. K. Srivastava, Phys. Lett. B283, 145 (1992).

[18] G. Agakishiev et al. CERES Collaboration, Phys. Rev. Lett. 75, 1272 (1995).
[19] M. Masera for the HELIOS-3 Collaboration, Nucl. Phys. A590, 93c (1995).

[20] G. Agakishiev et al. CERES Collaboration, Nucl. Phys. A610, 317c (1996).

[21] G. Q. Li, C. M. Ko and G. E. Brown, Phys. Rev. Lett. 75, 4007 (1995), C. M. Ko, G. Q. Li, G. E. Brown and H. Sorge, Nucl. Phys. A610, 342c (1996).

[22] W. Cassing, W. Ehehalt and C. M. Ko, Phys. Lett. B363, 35 (1995).

[23] L. A. Winckelmann et al., Nucl. Phys. A610, 116c (1996).

[24] I. N. Mishustin et al., Phys. Rev. C57, 1552 (1998).

[25] G. Baym, Phys. Lett. 138B, 18 (1984)

[26] K. Kajantie and T. Matsui, Phys. Lett. 164B, 373 (1985).

[27] B. Banerjee, R. S. Bhalerao and V. Ravishankar, Phys. Lett. B 224 16 (1989)

[28] B. Andersson et al. Phys. Rep. 97, 31 (1983), Nucl. Phys. B 281, 289 (1987).

[29] F. E. Low, Phys. Rev. D 12 163 (1975)

[30] S. Nussinov, Phys. Rev. Lett. 34, 1286 (1975).

[31] J. Schwinger, Phys. Rev. 82, 664 (1951)

[32] Gouranga C. Nayak and V. Ravishankar, Phys. Rev. D 55, 6877 (1997).

[33] Gouranga C. Nayak and V. Ravishankar, Phys. Rev. C. 58, 356 (1998), Report no: hep-ph/9710406.

[34] S. K. Wong, Nuovo Cemento A 65, 689 (1970)

[35] H-T Elze and U. Heinz, Phys. Rep. 183 81 (1989)

[36] J. D. Bjorken, Phys. Rev D 27, 140 (1983)

[37] U. Heinz, Ann. of Phys. (NY) 161 48 (1985).
[38] The numerical program is described in Ref. [32,33], where the determination of \( E \) and \( T \) is done by a double self consistent method. In this calculation an equilibration is assumed to relate temperature \( T \) to the particle energy density.

[39] L. D. McLerran and T. Toimela, Phys. Rev D 23 545(1985).

[40] K. Kajantie, M. Kajata, L. McLerran and P. V. Ruuskanen, Phys. Rev. D 34, 811 (1986).

[41] K. Geiger, Phys. Rep. 258, 237 (1995).

[42] The relaxation time \( \tau_c \) is determined in simillar way (see Ref. [38]) by relating \( \tau_c \) to the number density of the plasma, assuming equilibration.

[43] M. Asakawa and T. Matsui, Phys. Rev D 43, 2871 (1991).

[44] A. Bialas and J. P. Blaizot, Phys. Rev. D 32, 2954 (1985).

[45] K. Geiger and J. I. Kapusta, Phys. Rev. Lett 70, 1920 (1993).

**Figure captions**

**FIG. 1.** Dilepton rate from pre-equilibrium stage, as a function of \( M_T \) for \( \tau_c =0.2 \) fm.

**FIG. 1.** Dilepton rate from pre-equilibrium stage, as a function of \( M_T \) for \( \tau_c =5.0 \) fm (collisionless limit).

**FIG. 3.** Drell-Yan and pre-equilibrium dilepton rate as a function of \( M_T \) for \( \tau_c =0.2 \) fm \((P_T = 0 \) GeV\).

**FIG. 4.** Drell-Yan and pre-equilibrium dilepton rate as a function of \( M_T \) for \( \tau_c =0.2 \) fm \((P_T = 1 \) GeV\).
\[ \frac{dN}{dM_T^2 d^2 p_T} \]

Fig-1
\[ \frac{dN}{dM_T^2 dY dP_T} \] (GeV$^4$)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot}
\caption{\textit{Fig-2}}
\end{figure}
\[ \frac{dN}{dM_T^2 dY dP_T^2} \]

**Fig-3**

\[ P_T = 0 \text{ GeV} \]

Drell-Yan ---
Pre-equilibrium ---

**NAYAK**
Fig-4

NAYAK