**ON DILEPTON RADIATION OF THERMALIZED MATTER
PRODUCED IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS**

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Abstract

The use of a particular combination of dilepton yield and scaled rapidity density is proposed for the possible identification of dilepton radiation from thermalized matter produced in ultrarelativistic heavy-ion collisions. The method is based on the different multiplicity dependences of various production mechanisms for massive lepton pairs.

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The recent experiments of ultrarelativistic heavy-ion collisions have shown a wealth of new and interesting facts [1]. In the present state of both the experimental and theoretical search for deconfined matter however, an unambiguous signal of the predicted transient quark-gluon plasma creation seems to be missing. Among the promising signals for the diagnostics of properties of highly excited, strongly interacting matter, the observation of dileptons with high invariant mass (1 - 4 GeV) attracted much attention. While many investigations in this mass range are induced by the predicted and observed change of the J/ψ signal relative to the background, we here concentrate on the smooth continuum between the ρ , ω , ϕ , η bump and the J/ψ peak. Below and around 1 GeV the spectrum seems to be dominated by ordinary resonance (Dalitz) decays [2], and above 4 GeV the Drell-Yan production dominates.

The dileptons (as direct photons, but unlike hadrons) probe the entire space-time region of the interacting matter. This makes exact predictions somewhat difficult since one must convolute the space-time evolution with production rates. In doing so one has to resort to model quantities which are theoretically not completely controlled and experimentally only poorly known. Therefore, a useful strategy for looking at the spectrum of dileptons is the use of combined quantities where as many as possible yet uncertainly known quantities cancel out. We follow here such a strategy and (i) propose a way of identifying possible dilepton radiation from thermalized, strongly interacting matter, and (ii) show that the transverse spectra can be used for inferring certain temperatures, which in turn carry information on the initial temperature, in the case of pure hadron matter, or a critical temperature if there is a phase transition with large latent heat.

Due to the mentioned convolution of a space-time scenario and dilepton production rates, one must use some assumptions on the evolution of matter. We consider here a sufficiently small rapidity (y) interval on the peak of the rapidity distribution of all hadrons observed. For simplicity we assume approximate charge symmetry. The hadronic matter flows with the velocity $v = th^{-1}y = x/t$, and the rapidity distribution in this small interval is assumed to be approximately constant on the proper time surface $\tau = \sqrt{t^2 - x^2} = \text{const.}$ After a certain proper time $\tau_0 \approx 1 \text{ fm}/c$ the matter is assumed to be sufficiently near to a local equilibrium state and henceforth dissipative effects should not be important, i.e., the comoving entropy density remains constant, $s\tau = s_0\tau_0$. We assume for this matter a simple relation of entropy density s and temperature T , $s = \frac{4}{3}A_{\pi,qg}\pi^2T^3$ ($A_{\pi} = \frac{1}{10}$ for pion matter and $A_{qg} = \frac{37}{8}$ for quark-gluon matter).

In such a scenario the high mass dileptons come from three space-time regions: *I*: initial hard interactions around $x \approx t \approx 0$ (Drell Yan production); *II*: pre-equilibrium production till τ_0 ; *III*: equilibrium production after τ_0 . *I* is believed to be satisfactory under theoretical control (cf. [3] and Refs. therein), at least for pp and hA collisions. For *III* we assume $q\bar{q} \rightarrow \gamma^* \rightarrow l\bar{l}$ and/or $\pi^+\pi^- \rightarrow \rho \rightarrow \gamma^* \rightarrow l\bar{l}$ to be the dominant production channels of lepton pairs. On *II* we comment below.

As shown in previous work [4,5] the combination of dilepton yield $\frac{dN_{l\bar{l}}}{dM^2dy}$, at fixed invariant dilepton mass M , and associated pion rapidity density $\frac{dN_{\pi}}{dy}$ in the form

$$K = A^{2/3} \frac{dN_{l\bar{l}}}{dM^2dy} \left(\frac{dN_{\pi}}{dy} \right)^{-2} \quad (1)$$

has the advantage that the experimentally hardly controllable quantities τ_0 and R (being the transverse radius of the predominantly longitudinally expanding matter) for the stage *III* cancel out. Strictly speaking, this holds only for central AA collisions or for AB collisions with $A < B$ and full overlap of A and B; then $R = 1.15A^{1/3} \text{ fm}$. The full overlap is easily controlled, e.g., by E_{veto} , and it is assumed to hold in what follows. In fact, in scenario *III* we have

$$\frac{dN_{l\bar{l}}}{dM^2dy} = \frac{\alpha^2 R^2}{\pi^2} \frac{M}{2} \int d\tau T(\tau) K_1 \left(\frac{M}{T(\tau)} \right) \left[F_q x(\tau) + \frac{1}{14.4} F_{\pi} (1 - x(\tau)) \right] \quad (2)$$

$$= (s_0\tau_0)^2 R^2 M^{-4} \varphi(s_0, s_Q, s_H, s_f; M),$$

$$\frac{dN_{\pi}}{dy} = \frac{\zeta(3)}{4\zeta(4)} \pi R^2 (s_0\tau_0), \quad (3)$$

with K_1 as modified Bessel function and the notations

$$F_q = \frac{5}{9}, \quad F_{\pi} = \frac{1.2 m_{\rho}^4}{(m_{\rho}^2 - M^2)^2 + \Gamma_{\rho}^2 m_{\rho}^2}, \quad m_{\rho} = 0.77 \text{ GeV}, \quad \Gamma_{\rho} = 0.15 \text{ GeV}, \quad \alpha = \frac{1}{137},$$

$$x(\tau) = \Theta(s - s_Q) + \Theta(s_Q - s) \Theta(s - s_H) \frac{s - s_H}{s_Q - s_H} + \Theta(s_H - s), \quad s_{Q,H} = s_{qg,\pi}(T_c), \quad s_f = s_{\pi}(T_f).$$

Temperature $T(\tau)$ and phase weight $x(\tau)$ follow from the adiabaticity relation $s\tau = s_0\tau_0$ and the averaging $s = xs_{qg} + (1 - x)s_{\pi}$; for details cf.[3-7]. (Note that, contrary to the common belief, the yield increases more strongly than $\left(\frac{dN_{\pi}}{dy}\right)^2$ due to the thermal function φ . Only at very high s_0 does φ saturate.) Thus $K \propto \varphi$ as a function of the scaled multiplicity $A^{-2/3} \frac{dN_{\pi}}{dy}$ reflects only the dependence on the initial state at τ_0 . We assume here constant freeze-out temperature $T_f = 125 \text{ MeV}$ and constant initial time τ_0 for stage *III*; for another view see [6,7]. The function $K \left(A^{-2/3} \frac{dN_{\pi}}{dy} \right)$ is displayed in Fig. 1. In Ref. [5] it has been shown that the shapes of these curves suffer only little change when transverse expansion and a realistic initial distribution caused by geometric nuclear effects are included. Also displayed in Fig. 1 is the contribution of the stage *I*, i.e., the Drell-Yan part. In drawing the latter curve we used the estimate [7] for $M \ll \sqrt{s}$ and central collisions,

$$\frac{dM^{DY}}{dM^2dy} = 7.6 \cdot 10^{-8} M_{GeV}^{-4} A^{4/3} \text{ GeV}^{-2}, \quad (4)$$

and did not assume a correlation with the associated pion multiplicity. Using this and keeping A fixed, then K^{DY} will essentially decrease with increasing scaled multiplicity. Some impact parameter dependence of $\frac{dN_{l\bar{l}}^{DY}}{dM^2dy}$ will certainly weaken the decrease of K^{DY} [3], however, in case of the required full overlap of the nuclei the effect is not significant. In probing K the fluctuations of the multiplicity are mainly needed.

An important feature can be seen in Fig. 1: there is a clear turn-over from dominating Drell-Yan to dominating thermal production at a certain scaled multiplicity. The invariant dilepton mass should be in the interval $1.5 < M < 2.5 \text{ GeV}$ to avoid too strong

contaminations of the ρ , ω , ϕ , η bump and the J/ψ peak and Drell-Yan contributions as well. Integrating over M in this interval, in order to relax the trigger conditions for M , the shapes of the curves remain unchanged, but the crossing of $K^{thermal}$ and K^{DY} is shifted to two times higher scaled multiplicity.

In Refs. [4,5] the different shapes of the curves of K vs. scaled pion multiplicity have been proposed as a signal for the confinement transition. However in view of the large Drell-Yan contribution in the interesting region and the not too different shapes of the curves K_{π} and $K_{q+\pi}$ this seems to be a difficult task. In particular a rather large interval of scaled multiplicities must be covered (which could be accomplished, in principle, by combining different nuclei and energies). Given the uncertainties of the present model one should rather use the turn-over in $K(A^{-2/3} \frac{dN_{\pi}}{dy})$ to determine the onset of dominant thermal dileptons at appropriate invariant mass. This fixes the associated hadron multiplicity or in practice the E_T . Using this trigger one has then to sample the transverse dilepton yields at fixed M , or M in the given interval as a function of the transverse momentum p_t .

In our model the transverse spectrum in stage III is given by [4,6,7]

$$\begin{aligned} \frac{dN_{\bar{l}l}}{dM^2 dy dp_t^2} &= \pi R^2 \frac{\alpha^2}{(2\pi)^{5/2}} \int d\tau \tau (e^{M_l/T(\tau)} - 1)^{-1} \frac{T(\tau)}{p_t} \sqrt{\frac{T(\tau)}{M_t}} \left[x(\tau) F_q \log \left(\frac{ch(\frac{M_t + p_t}{2T(\tau)})}{ch(\frac{M_t - p_t}{2T(\tau)})} \right) \right. \\ &\quad \left. + (1 - x(\tau)) \frac{1}{12} F_{\pi} \log \left(\frac{(x_2 - e^{M_l/T(\tau)})(x_1 - 1)}{(x_1 - e^{M_l/T(\tau)})(x_2 - 1)} \right) \right], \end{aligned} \quad (5)$$

$$x_{1,2} = e^{-E_{1,2}/T}, \quad E_{\frac{1}{2}} = \frac{1}{2}(M_t \pm p_t), \quad M_t = \sqrt{p_t^2 + M^2}.$$

As seen in Fig. 2, for the given value of the associated pion multiplicity, the slopes of the transverse spectra reflect different temperatures; in the case of no deconfinement and dominant pion annihilation as the dilepton source, the transverse spectrum reflects the higher temperature at τ_0 . On the contrary, in the case of deconfinement and sufficiently large latent heat between the phases the slope reflects just the critical temperature. This is because the main contribution stems from quark fusion at T_c . Only at considerably larger $\frac{dN_{\pi}}{dy}$ is the initial entropy high enough for quark fusion above T_c to dominate the high p_t tail. When increasing the associated pion multiplicity, at fixed impact parameter and keeping A fixed, the initial entropy s_0 increases and correspondingly the absolute yield increases considerably. Therefore, due to this sensitive dependence on the multiplicity, one must trigger: the lower bound of $\frac{dN_{\pi}}{dy}$ separates the Drell-Yan contributions and the upper bound fixes the maximum entropy or initial temperature. Again the dilepton mass may still cover the range 1.5 - 2.5 GeV, since the shape of the spectra does not change essentially. However, when including also the higher values of M one has to go to higher scaled multiplicities in order to avoid the Drell-Yan contamination.

Discussing uncertainties of our approach, we first mention that the multiplicity dependence (and of course the A dependence) of the Drell-Yan rates has to be checked experimentally (at higher mass, say above 4 GeV) to ensure that the assumed quadratic decrease of K^{DY} vs. $A^{-2/3} \frac{dN_{\pi}}{dy}$ is sufficiently correct. This is a wide and interesting field

in itself, in particular with respect to possible nuclear soft initial state interactions which can affect the Drell-Yan rates [8].

Obviously our approximation for the high-temperature hadron gas is somewhat simplified with respect to the assumed pion density $\propto T^3$ and needs improvements. But we hope that this gives at least a qualitatively correct description.

Concerning the pre-equilibrium contributions from stage II, an estimate in line with the soft annihilation model of Ref. [9] points to a contribution $K^{nonther}(A^{-2/3} \frac{dN_{\pi}}{dy}) \approx const$, which is lower than the contribution of stage III, i.e., below the contribution from the mixed phase, where $0 < x < 1$.

In summary, we try to develop a way to identify a thermal dilepton component in ultrarelativistic heavy-ion collisions. Such (at least) near-to-equilibrium strongly interacting matter is a prerequisite for the transient creation of the quark-gluon plasma. Our proposed signal relies heavily on the different correlations between the various dilepton production processes with the associate hadron multiplicities, which have been also noticed qualitatively by previous authors. The key point is the achievement of sufficiently large variations of $\frac{dN_{\pi}}{dy}$ via fluctuations to overcome the Drell-Yan production. Once one has verified the thermal dileptons above a certain multiplicity or E_T threshold, the occurrence of a phase transition with large latent heat, i.e., the deconfinement transition, should show up as a constant slope of $\frac{dN_{\bar{l}l}}{dM^2 dy dp_t^2}$ vs. p_t at $p_t > 1$ GeV with the slope parameter of the order of $T_c \approx 200$ MeV, while a pure hadron source at the same associated multiplicity would give considerably higher apparent temperatures which increase strongly with increasing associate multiplicity. The proper invariant mass window is between the ρ, ω, ϕ, η signals and the J/ψ peak. The approach can also be applied to photons.

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FIGURE CAPTIONS

Fig. 1: The function K (eq.(1)) which describes the correlation between dileptons, at fixed invariant mass $M = 1.5$ GeV and in a narrow rapidity interval around the maximum rapidity density, and the associated pion multiplicity. π : only pion matter (formally $T_c \rightarrow \infty$, i.e., no deconfinement); $q + \pi$: pion matter below the critical temperature $T_c = 200$ MeV (dashed curve labelled by 4) plus deconfined matter above the critical temperature (1) plus mixed matter at critical temperature (2 - yield from quark-gluon matter; 3 - from pionic matter); DY: estimate of the Drell-Yan contribution according to eq. (4). With $A = 100$ the Drell-Yan curve crosses the thermal curves at a scaled multiplicity which corresponds to an entropy density $s_0 = 0.1$ GeV³. With respect to the results of Ref. [3] the Drell Yan yield seems to be somewhat underestimated by eq. (4).

Fig. 2: Transverse spectra from stage III according to eq. (5) for the invariant mass $M = 1.5$ GeV and fixed scaled pion multiplicity which corresponds to the entropy density $s_0 = 0.2$ GeV³ ($A = 100$). The high p_t tails can be fitted by $e^{-p_t/T_{app}}$ with $T_{app} = 400$ MeV(π) and 215 MeV($q + \pi$). The low p_t tail can be affected by a possible transverse expansion, but not the high p_t [7].

Fig. 1

Fig. 2