Transverse-Mass $M_\perp$ Dependence of Dilepton Emission from Preequilibrium and Quark-Gluon Plasma in High Energy Nucleus-Nucleus Collisions

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The dependence on invariant mass M and transverse momentum $q_\perp$ of lepton pairs emitted by quarks during the early stage of central collisions between gold nuclei at $\sqrt{s} = 200A$ GeV is investigated within the parton cascade model. For fixed transverse mass $M_\perp$ between 2 and 3 GeV, the spectrum is thermal shaped at low $q_\perp$ and exhibits a power law behavior at larger $q_\perp$. A suspected $M_\perp$ scaling is not observed in the calculated distribution, but the significant shape of the spectrum and the large yield from preequilibrium emission may nevertheless serve as a characteristic signal for a parton plasma formation.

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The problem of how to gather unambiguous information about the predicted QCD phase transition to a locally deconfined quark-gluon plasma (QGP) in ultrarelativistic heavy ion collisions is a long-standing one. One of the most prominent suggested signals for a QGP formation is the production of lepton pairs [1] during these collisions. In principle the production of dileptons is ideal for probing the dynamics and the composition of the dense matter in the central collision region, because they almost always leave the hadronic matter without any further interactions, so that they carry information about the conditions in the matter at the time of their production to the detectors. In reality, however, the problem is to read out the complex space-time history of the collisions, because of the existence of several sources which produce lepton pairs before, during, and after the hot stage of the reactions. Since detectors can only record the dilepton count rates in a space-time integrated way, the task is to disentangle the contributions from different sources by finding out if they are either dominant in some part of phase space, or have such distinct properties that they can be separated. In particular, it is of great importance to investigate the characteristc features of dileptons produced by quark-gluon interactions during the very early preequilibrium stage and the thermalized QGP stage, in order to separate them from those pairs emitted due to hadronic interactions and decays during the later stages of the nuclear collision. A successful distinction of the various contributions to the experimentally observed total dilepton spectrum would not only provide the possibility to detect a QGP formation, but also could serve as a "moving picture" of the space-time evolution since the lepton pair emission from the various sources is associated with different stages of the space-time history.

The purpose of this Letter is to investigate the transverse mass dependence of the dilepton production by partons in AA collisions at collider energies during the first few fm/c. Differentiating the commonly studied invariant mass distribution per unit rapidity of lepton pairs, dN/dM^2dy, with respect to the transverse momentum $q_\perp$ of the pairs, $dN/dM^2dyd^2q_\perp$, allows a more sensitive diagnosis than the spectrum integrated over all $q_\perp$. In general, this differential dilepton spectrum depends on both the transverse momentum $q_\perp$ and the transverse mass $M_\perp = \sqrt{M^2 + q_\perp^2}$, where M is the invariant mass of the lepton pair. However, as was recognized in earlier investigations [2–4], under certain conditions the dilepton spectrum scales with the transverse mass, $dN/dM^2dyd^2q_\perp = F(M_\perp)$, where y is the rapidity of the pair and F is a function of $M_\perp$ alone. That is, at a fixed value of $M_\perp$, the spectrum does not depend on $q_\perp$. The conditions under which this $M_\perp$ scaling is true are [2] local thermalization, a longitudinally boost invariant expansion, no radial flow, and no other scales but the temperature T. Consequently, the differential dilepton yield per unit rapidity from an ideal QGP for which these conditions hold would be flat when plotted versus $q_\perp$. In reality, this scaling will be broken at the later stage of the space-time evolution, due to the onset of transverse expansion and due to the appearance of additional mass scales associated with the formation of hadronic matter. These scale breaking effects were most recently investigated quantitatively in Refs. [5,6] within hydrodynamical models.

In the present paper I will show that the $M_\perp$ scaling is also strongly violated during the very early stage of a nuclear collision [7], when the highly nonthermal initial partons of the incident nuclei evolve from their first interactions, through a preequilibrium stage, into a fully thermalized plasma. Therefore the conclusion is that the experimentally observable, space-time integrated dilepton spectrum is very unlikely to exhibit a scaling behavior at all, because it can occur only in a narrow time interval and will be covered up by the large scale breaking contribution from preequilibrium during early times, and at later times due to radial expansion as well as due to the contribution from the hadronic phase. However, in contrast to Ref. [6] I argue that an unobservable $M_\perp$ scaling does *not* mean that a QGP is not created. Rather than

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that I will show that the copious production of dileptons from the preequilibrium and thermal stage results in a characteristic spectrum that may serve as a signature for the actual establishment of a parton plasma.

To calculate the production of lepton pairs from the initial nuclear contact, via preequilibrium, towards plasma formation, I used the parton cascade model (PCM) [8]. In this approach the initial parton distributions are evolved smoothly in complete phase space and time by tracing multiple parton scatterings, emission and absorption processes within improved perturbative QCD, and relativistic kinetic theory. No assumptions about formation time, initial temperature, entropy and energy density are involved, because these quantities are determined self-consistently by the dynamics itself. In a preceding paper [9] the application of the PCM to lepton pair production in heavy ion collisions was presented and it was found that the spectrum of dileptons produced during the early stage of the parton cascade evolution exhibits a rather different behavior than the spectra obtained in the standard thermal scenario [3,4]. The distribution of emitted pairs evolves smoothly from the initial Drell-Yan type reactions involving primary partons, all the way towards equilibrium emission. The contributions from reactions involving "hot" secondary partons during the preequilibrium and thermal stage are dominant. Qualitatively similar results have been found in related analyses addressing the effects of preequilibrium dynamics on dilepton production [10].

The experimentally observable, space-time integrated number distribution of l^+l^- pairs, produced between proper time τ_c (the moment of nuclear contact) and some $\tau > \tau_c$, with invariant mass squared M^2, rapidity y, and transverse momentum $q_\perp \equiv |\mathbf{q}_\perp|$ is obtained from

$$\frac{dN(\tau)}{dM^2dyd^2q_\perp} = \int_{\tau_c}^{\tau} \tau' d\tau' d\eta d^2r_\perp \, \frac{dR^{l^+l^-}}{dM^2dyd^2q_\perp} \, , \quad (1)$$

where η is the usual space-time rapidity and $\mathbf{r}_\perp$ the transverse coordinate. The general form of the differential rest frame rate $dR^{l^+l^-} \equiv dR^{l^+l^-}(y, \mathbf{q}_\perp; \eta, \mathbf{r}_\perp, \tau)$ for parton interactions involving $n_{\rm in}$ partons coming into a vertex and $n_{\rm out}$ partons emerging from the vertex plus a lepton pair l^+l^-, is given by

$$dR^{l^+l^-} = \sum_{i,j,k} \Bigg\{ \frac{1}{S_{\rm in}} \left(\prod_i^{n_{\rm in}} \int \frac{d^3p_i}{(2\pi)^3 2E_i} F_i \right) \left(\prod_j^{n_{\rm out}} \int \frac{d^3p_j}{(2\pi)^3 2E_j} [1+\theta_j F_j] \right) \frac{d^3p_{l^+}}{(2\pi)^3 2E_{l^+}} \frac{d^3p_{l^-}}{(2\pi)^3 2E_{l^-}} [1-F_{l^+}][1-F_{l^-}]$$
$$\times |\bar{M}^{(k)}_{i\to j+l^+l^-}|^2 \, (2\pi)^4 \, \delta^4\left(\sum_i^{n_{\rm in}} p_i - \sum_j^{n_{\rm out}} p_j - p_{l^+} - p_{l^-} \right) \Bigg\} . \quad (2)$$

Here the spin and color averaged squared matrix elements $|\bar{M}^{(k)}|^2$ for the various l^+l^- production processes k are weighted by the phase-space distributions $F_i(E_i, \mathbf{p}_i; \mathbf{r}, \tau)$ for the incoming particles and $[1+\theta_j F_j(E_j, \mathbf{p}_j, \mathbf{r}, \tau)]$ for the outgoing particles, where $\theta_j = -1$ for quarks and $\theta_j = +1$ for gluons. The statistical factor $S_{\rm in}$ is given by $S_{\rm in} = m_{\rm in}! m_{\rm out}!$ when there are $m_{\rm in}$ ($m_{\rm out}$) identical particles coming in (going out) of the vertex. For further details see Ref. [9]. By integrating over the complete space-time history of the partons' evolution in phase space from τ_c up to τ, one obtains the cumulative yield of dileptons from the various production processes $i \to f + l^+l^-$, as the system develops from the first nuclear contact, via preequilibrium towards thermalization.

The following results were obtained from Monte Carlo simulations with the PCM for Au+Au collisions with zero impact parameter at energy of the BNL Relativistic Heavy Ion Collider (RHIC), $\sqrt{s} = 200A$ GeV [9]. To demonstrate the vivid difference between nucleon-nucleon collisions and nucleus-nucleus reactions, I also calculated the lepton pair production in $p+p$ collisions at corresponding energy $\sqrt{s} = 200$ GeV. In order to allow for a fair comparison, in this case it was averaged over impact parameters, because in $A+A$ collisions with $A>1$ the nucleons have different impact parameters, even when the two nuclei collide head on. The proper time τ is defined as [11,12] $\tau = \mathrm{sgn}(t-t_0)\sqrt{(t-t_0)^2 - z^2}$, where t is the center-of-mass time and t_0 is the moment of maximum overlap of the colliding nuclei. In the center of mass, at $z=0$, the initial nuclear contact occurs at $\tau = \tau_c$ and the maximum density is achieved at $\tau = 0$. For the considered collider energy $\sqrt{s}/A = 200$ GeV, $\tau_c = -0.8$ fm/c for Au+Au [11] and $\tau_c = -0.5$ fm/c for $p+p$.

Figure 1 shows the invariant mass distribution of muon pairs, dN/dM^2dy, in the central rapidity unit around $y=0$, integrated over the whole $q_\perp$ range and over space-time from τ_c up to $\tau = 2.2$ fm/c for Au+Au [Fig. 1(a)] and $\tau = 1$ fm/c for $p+p$ [Fig. 1(b)]. One observes a significantly enhanced $\mu^+\mu^-$ yield up to masses of $M \simeq 8$ GeV in Au+Au relative to $p+p$, which is due to the copious preequilibrium and thermal emission of pairs in the case of Au+Au [9]. For comparison I also indicated the "standard Drell-Yan" result of the simple parton model (dashed lines), evaluated for $p+p$ collisions and scaled to Au+Au [13]. The terminology standard Drell-Yan refers here to the usual way to calculate the Drell-Yan cross section by convoluting the proton structure functions with the elementary parton cross section for $q\bar{q} \to \gamma^* \to l^+l^-$ only (i.e., assuming it to be the dominant contribution over all other partonic production processes), and multiplying it with a K factor of $\simeq 2$ to account for next-to-leading order corrections [14]. This case compares to the full PCM calculations as taking into account solely

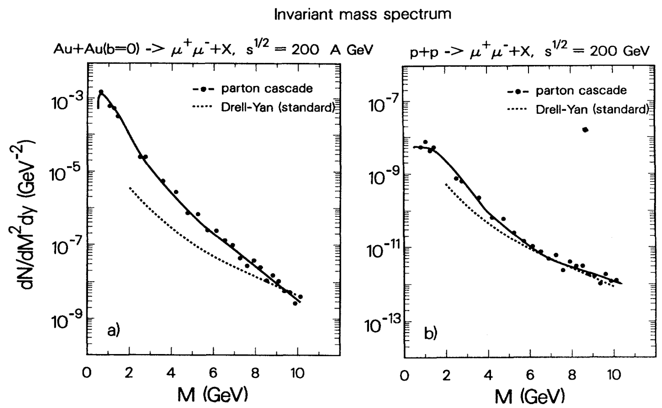

FIG. 1. Invariant mass spectrum $dN(\tau)/dM^2dy$ of $\mu^+\mu^-$ pairs in the central rapidity region in (a) Au+Au collisions at $\sqrt{s} = 200A$ GeV ($\tau = 2.2$ fm/c) and (b) $p+p$ collisions at $\sqrt{s} = 200$ GeV ($\tau = 1$ fm/c). The data points result from the parton cascade simulation; the full lines are interpolations to guide the eye. The dashed lines represent the "standard Drell-Yan" result of the simple parton model obtained by convoluting the proton structure functions with the $q\bar{q} \to \mu^+\mu^-$ cross section.

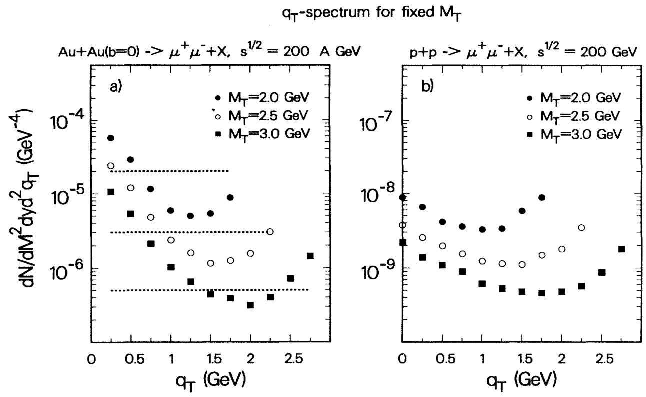

FIG. 2. Differential $\mu^+\mu^-$ spectrum $dN(\tau)/dM^2dyd^2q_\perp$ at fixed values of $M_\perp = 2, 2.5, 3$ GeV, in correspondence to Fig. 1, for (a) Au+Au ($\tau = 2.2$ fm/c) and (b) $p+p$ ($\tau = 1$ fm/c). In (a) the dashed lines indicate the $M_\perp$ scaling expected for a boost invariant ideal QGP with temperature $T \simeq 300$ MeV corresponding to the temperature of the actual parton plasma at $\tau = 2.2$ fm/c, as obtained from the parton cascade simulation.

primary $q\bar{q}$ annihilations without subsequent cascading and gluon bremsstrahlung (the same nucleon structure function parametrization of Glück, Reya, and Vogt [15] was employed). Evidently, in the case of $p+p$ collisions the simple parton model estimate agrees with the PCM result at larger invariant masses $M \gtrsim 5$ GeV, but exhibits a growing deviation at lower masses. This difference arises, because especially in this mass region lepton pair production is enhanced in the PCM due to multiple parton scatterings, the inclusion of various l^+l^- production processes involving both quarks and gluons, as well as bremsstrahlung by quarks.

Figure 2 exhibits the transverse mass dependence of the differential $\mu^+\mu^-$ spectrum $dN/dM^2dyd^2q_\perp$, Eq. (1), at fixed values of $M_\perp = 2, 2.5, 3$ GeV, again for Au+Au [Fig. 2(a)] and $p+p$ [Fig. 2(b)]. Comparing the two cases, in Au+Au collisions a clear enhancement in the low $q_\perp$ region ($q_\perp \lesssim 1$ GeV/c) is obvious for the reasons mentioned before. At these low $q_\perp$ values the spectrum in Fig. 2(a) is thermal shaped, i.e., approximately exponential, a behavior that is absent in Fig. 2(b). On the other hand, at larger $q_\perp \gtrsim 1$–1.5 GeV/c, the spectra for Au+Au and $p+p$ qualitatively resemble each other, and behave in both cases roughly as $\propto 1/M^4$ which is characteristic for the primary Drell-Yan type processes. Also indicated in Fig. 2(a) are the flat distributions of a QGP with $M_\perp$ scaling (dashed lines) for the same fixed $M_\perp$ values. These curves correspond to the temperature $T \simeq 300$ MeV of the actual parton plasma at $\tau = 2.2$ fm/c, as obtained from the parton cascade simulation. Note that local thermalization sets in already around $\tau \simeq 0.3$ fm/c at $T \simeq 600$ MeV [12]. One can definitely conclude that the realistic evolution of partons through preequilibrium and QGP formation does not exhibit a scaling behavior in the space-time integrated dilepton spectrum at all.

Finally, Fig. 3 displays, for central Au+Au$\to \mu^+\mu^- + X$, the distribution (1), $dN(\tau)/dM^2dyd^2q_\perp$, integrated over space-time up to different times $\tau = 0, 0.5, 2.2$ fm/c and at fixed $M_\perp = 2$ GeV [Fig. 3(a)] and $M_\perp = 3$ GeV [Fig. 3(b)]. It is obvious from the development of the distribution with time that pairs with larger $q_\perp$ are favorably produced at very early times, mostly by primary parton collisions, whereas the low $q_\perp$ region is populated later mainly by softer collisions involving secondary par-

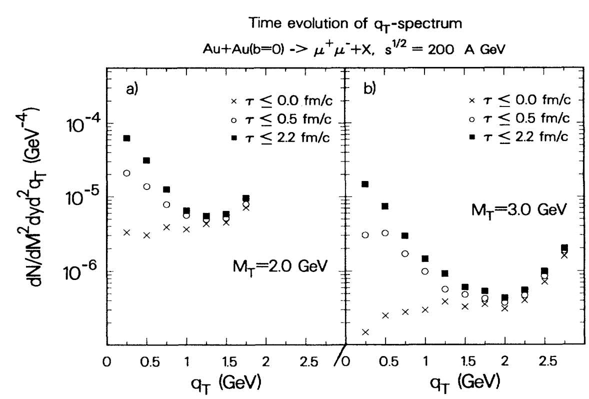

FIG. 3. Time development of the differential $\mu^+\mu^-$ spectrum $dN(\tau)/dM^2dyd^2q_\perp$ in central Au+Au collisions at $\sqrt{s} = 200A$ GeV. The pair production rate is integrated over space-time up to different times $\tau = 0, 0.5, 2.2$ fm/c and at fixed transverse mass (a) $M_\perp = 2$ GeV and (b) $M_\perp = 3$ GeV. Note that the nuclei begin to overlap at $\tau = -0.8$ fm/c so that $\tau = 0$ is the moment of maximum compression.

tons. The large yield at the low end of the spectrum comes essentially from photon bremsstrahlung by quarks and from thermal production of lepton pairs by scatterings of partons with low energies $\sim 3T$. The values of the temperature T, extracted from the space-time evolution of the parton density [11,12] at times $\tau = 0$, 0.5, 2.2 fm/c, are $T(\tau) \simeq 950$, 500, 300 MeV, respectively, and correspond to the actual temperatures effective in the central collision region.

In summary, the investigation of the transverse mass dependence of lepton pair yield in central Au+Au collisions at RHIC with the PCM shows a smooth development of the differential $\mu^+\mu^-$ mass spectrum $dN/dM^2dyd^2q_\perp$ from primary Drell-Yan processes, via preequilibrium, to plasma formation. The spectrum is dominated by low-$q_\perp$ pair production and is far from exhibiting $M_\perp$ scaling. Since $M_\perp$ scaling can only be expected for a perfectly thermalized and chemically equilibrated plasma of massless partons, which in addition must be longitudinally boost invariant with vanishing radial flow, it is not surprising that the results of the PCM calculations violate $M_\perp$ scaling. The reasons are the following: (i) During the very early stage when most of the pairs with appreciable $q_\perp$ are produced by primary parton collisions (Fig. 3, crosses), the system is not yet fully thermalized. (ii) The chemical composition of the parton matter is strongly dominated by the gluons that outweigh the quarks, and a full chemical equilibration cannot be established [12] (at least at RHIC energy). The time evolution of thermodynamic quantities, as the effective temperature and the parton densities, does not follow exactly the one of a boost invariant, perfect plasma, but is controlled by the time dependent relative admixtures of quarks and gluons [16]. (iii) In the PCM the temperature is not the only scale in the plasma evolution (as would be required for $M_\perp$ scaling). During the nuclear collision a large number of gluons acquire a timelike virtual mass through scatterings, resulting in a continuous, time dependent mass spectrum. This mass spectrum is associated with the Sudakov form factors of the partons [8] that account for the higher order QCD corrections to the lowest order Born amplitudes. (iv) Other additional mass scales in the model are the two infrared cutoff parameters [8], with values of 1.5 GeV and 1 GeV, necessary to regularize the perturbative QCD divergences of the partons' cross sections and bremsstrahlung amplitudes. This has the effect of imposing a mass threshold for l^+l^- production and affects particularly lepton pairs with masses comparable to the cutoffs and with very small $q_\perp$. Therefore a violation of $M_\perp$ scaling in the low $q_\perp$ region, where most of the pairs at later times are produced (Fig. 3, circles and boxes), is plausible.

The essential conclusion is although in the PCM the parton matter evolves rather rapidly via a preequilibrium stage into a thermalized state, $M_\perp$ scaling cannot be established due to the aforementioned properties of the underlying microscopic dynamics that result in a nontrivial dependence of the dilepton spectrum on M *and* on $q_\perp$. Although there might be a temporary region during which the dilepton emission approximately scales and is independent of $q_\perp$, it is impossible to observe such an effect in the space-time integrated spectrum, because the spectrum reflects the cumulation of the complete space-time history of the first 2 fm/c with dominantly scale breaking contributions. Nevertheless, the $1/M^4$ behavior for $q_\perp \to M_\perp$ from very early times and the $\exp(-bq_\perp)$ dependence for $q_\perp \to 0$ from later times result in a unique shape of the $M_\perp$ spectrum, which together with the large dilepton yield in the region $q_\perp$ up to 1–1.5 GeV/c and $M_\perp$ = 2–3 GeV may serve as a characteristic signature reflecting a plasma formation at RHIC if it can be detected with sufficient statistics. Therefore it is desirable to build detectors for RHIC that allow us to separate dileptons with different transverse momenta at least up to the J/ψ mass.

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