Dilepton Rates at RHIC and LHC are Big

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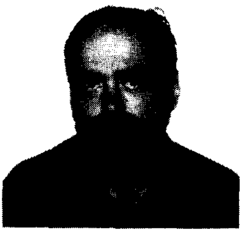

ABSTRACT

We study the problem of dilepton production in heavy ion collisions at RHIC and LHC energies. We find that, due to the expected enhanced multiplicities and larger transverse momenta of hadrons arising from minijet production, the dilepton production rate dramatically increases.

Early in the discussion of ultrarelativistic heavy ion collisions photons and dileptons were proposed as probes of the collision dynamics, and by some even as signals for the production of a quark-gluon plasma [1]-[8]. It was suggested by Shuryak and others that a window for observing such dileptons exists for masses between the ρ and the J/Ψ [2]. Subsequent computations have shown that continuum pairs and contributions from hadronic matter may obscure a signal of quark-gluon plasma here [8].

On the other hand, since the original computations of thermal dilepton production from a quark-gluon plasma were carried out, our understanding of the production of quarks and gluons in the early stages of the collisions has much improved. The original computations were also tailored in large part for experiments at SPS energies. Recent studies of particle production suggest that, to some degree at RHIC and to a much greater degree at LHC, both the central region multiplicity and the average p_t per particle should substantially increase at these higher energies. Since the magnitude of the dilepton rate from thermal emission is proportional to $(dN/dy)^2$, where dN/dy is the hadron multiplicity per unit rapidity, the increased multiplicity at these energies should greatly increase the rate. In addition, the increase of transverse momenta of produced quarks and gluons should also make it possible for dileptons produced in secondary scatterings to be produced at higher masses and transverse momenta than was originally believed.

The average transverse momentum of particles produced in a high multiplicity environment in almost all models of particle production should scale roughly as

$$< p_t > \sim \kappa \left(\frac{dN/dy}{\pi R^2} \right)^{1/2} . \tag{1}$$

This follows on dimensional grounds since this density provides the only scale in the limit that the multiplicity density becomes large. It is a valid relation in minijet models [9]-[10] as well as string models of multiparticle production [11]. If one takes a typical multiplicity density at SPS energies as about 500 for central gold-gold collisions, this relation gives an average transverse momentum of order 500 MeV, if κ is chosen to be about 3. At LHC energies, on the other hand, many event generators predict hadron multiplicity densities as large as 5000, so that we expect an increase in the average transverse momentum of about a factor 2-3. The corresponding p_t is therefore of order 1-2 GeV.

If the typical energy scale of produced quarks and gluons at RHIC or LHC energies is significantly increased, then we expect that the typical production time of partons will be decreased. This follows from an uncertainty principle argument which suggests that the production time τ_o for quarks and gluons should be related to their average energy $< E >$ by

$$\tau_o < E > \sim 1 \tag{2}$$

By production time we mean the time after which coherence effects in the nuclear wavefunction for the hadrons can be ignored. This is the time after which we can reasonably talk about secondary scatterings. This time scale is not the same as the time at which the produced quarks and gluons thermalize (if they ever do). Nevertheless, we expect that after this time the quarks can electromagnetically annihilate to produce dilepton pairs.

We can now ask: What is the interesting range of dilepton masses at RHIC and LHC energies? If we take a characteristic quark transverse momentum to be of order 1-2 GeV, then the resulting characteristic dilepton mass will be of order 2-4 GeV. This is in the region of the J/Ψ. We will later see that a more careful calculation gives a signal which is larger than that of continuum dileptons associated with the Drell-Yan process for masses in the range 2-4 GeV for RHIC energies and 2-10 GeV for LHC energies. The region of interest therefore extends from somewhere between the ρ and

J/Ψ, as is true at lower energies, to somewhere between the J/Ψ and the Υ resonances. Given the problems of background mentioned above, the region above the J/Ψ would be a good one for experimental study of quark and gluon dynamics at high energy density.

To study quantitatively the problem of dilepton production associated with secondary particle collisions is difficult, and probably requires use of an event generator for parton cascades [12]. As a temporary measure we will consider two different models as extreme limits. The truth is probably inbetween these extremes, and will only become known after much more theoretical and experimental study. We will not attempt here to make one of these extremes more credible than the other.

The first extreme is to assume thermalization of quarks and gluons immediately upon production, at the proper time τ_o. We further assume that the mean free path for quark and gluon scattering is so small that they remain in local thermal equilibrium as the system expands. This hydrodynamic description of the evolution of the produced matter [13] is the canonical description of the production of dileptons from a quark-gluon plasma. As it turns out, the typical formation time for the matter distribution at RHIC and LHC energies is quite small, $\tau_o \sim 0.10$ fm/c, compared to what has been conventionally assumed in the literature, $\tau_o \sim 1$ fm/c. The assumption that the matter can maintain thermal equilibrium at such early times certainly pushes the limit of credibility of hydrodynamics, although for later times hydrodynamics may be a very good first approximation.

To relate the initial times and temperatures in a central collision to multiplicities under the assumption of instant thermalization, we recall that the initial multiplicity of quarks plus gluons (partons) is

$$\frac{dN_p}{dy} = \frac{12N_f + 16}{\pi^2} T_o^3 \tau_o \, \pi R^2 \tag{3}$$

where N_f is the number of relevant flavors of quarks, which we choose to be three, T_o is the initial temperature, τ_o is the formation time and R is the nuclear radius. We have neglected the effects of Bose or Fermi statistics here for simplicity. The initial parton rapidity density can be related to the final total pion multiplicity using entropy conservation as [6] $dN_p/dy = dN/dy$. If we further use the fact that the average energy per (massless) particle is about $< E >\sim 3T$ we find that the initial time is about

$$\frac{1}{\tau_o} \sim 2.26 \left(\frac{dN/dy}{\pi R^2}\right)^{1/2} \tag{4}$$

Assuming, for example, a rapidity density in the central region of about 5600 as may be appropriate for gold collisions at LHC energies we find $\tau_o \sim 0.073$ fm/c and $T_o \sim 900$ MeV. On the other hand, for a hadron rapidity density of 625 in gold collisions at SPS energies, we find $\tau_o \sim 0.22$ fm/c and $T_o \sim 300$ MeV. Of course, at SPS energies the space-time picture used to derive this relationship is not valid, since the Lorentz contracted size of the nuclei is a few fermis. These considerations become more relevant at RHIC energies where the Lorentz contracted nuclear size is of the order of $R/\gamma \sim 0.07$ fm.

Next, we ask what initial conditions are reasonable for the free-streaming case. Initially there ought to be fluctuations in the transverse momentum of produced partons which is of the order of their average transverse momentum. At the time of formation it is therefore not unreasonable to assume a distribution which is exponential in the total energy in a local co-moving frame. This is the distribution which maximizes the entropy for a given energy and appears to be consistent with the invocation of the uncertainty principle as used in eq. (2). As time goes on the matter free-streams and a strong correlation develops between position and momentum.

Continuing our discussion of free-streaming, we therefore assume that at the time $t = \tau_o$ and the position $z = 0$ in the center-of-mass frame of a central heavy ion collision, the distribution is exponential,

$$\frac{dN}{d^3pd^3x} = e^{-E/T_o} \tag{5}$$

where $E = \sqrt{p_t^2 + p_z^2}$ for massless particles. In the analysis which follows below, we assume Boltzmann statistics, which for our purposes should be sufficiently accurate. Since the distribution function is exponential at the initial time, the initial time and initial temperature (slope of the E_t distribution) are the same as what was computed earlier using the local thermalization assumption.

For free-streaming particles the phase space distribution function, or Wigner distribution,

$$\frac{dN}{d^3pd^3x} = f(p,x) \tag{6}$$

satisfies the equation

$$p \cdot \partial_x f(p,x) = 0. \tag{7}$$

Assuming boost invariance along the z (beam) axis restricts $f(p,x)$ to be of the form

$$f(p,x) = f(p_t, p_z t - Ez). \tag{8}$$

The solution which satisfies the boundary condition at $z = 0, t = \tau_o$ and has a uniform rapidity density is

$$f(p,x) = exp(-\sqrt{p_t^2 + (p_z t - Ez)^2/\tau_o^2}/T_o). \tag{9}$$

This distribution function may also be obtained by direct calculation.

The distribution function for free-streaming particles may be simplified a little using

$$\begin{aligned} p_z &= p_t \, sinh(y) \\ E &= p_t \, cosh(y) \\ z &= \tau \, sinh(\eta) \\ t &= \tau \, cosh(\eta) \end{aligned} \tag{10}$$

where y is the ordinary rapidity,

$$\tau = \sqrt{t^2 + z^2} \tag{11}$$

is the proper time, and

$$\eta = \frac{1}{2} \, ln \left(\frac{t+z}{t-z} \right) \tag{12}$$

is the space-time rapidity. In terms of these variables

$$f(p, x) = \exp\left[-\frac{p_t}{T_o}\sqrt{1 + \tau^2 sinh^2(y-\eta)/\tau_o}\right] \tag{13}$$

Notice that the correlation between momentum-space and space-time rapidity becomes stronger at later times.

We have used the above results to compute dilepton production at RHIC and LHC energies. We will not present the details of this analysis here. It is straightforward and involves convoluting the single particle distribution function with the cross section for quark antiquark annihilation into dilepton pairs.

To compare with what is expected from experiment we have considered central gold on gold collisions at SPS, RHIC and LHC energies. We have taken the expected hadron multiplicity from a compendium of event simulators and phenomenological extrapolations.

At SPS energy we assume a central dN/dy of 624 particles which implies an initial temperature of about 300 MeV. In Fig. 1 we plot the mass distribution. The dotted curve is the Drell-Yan distribution. The dashed curve is the thermalized, hydrodynamically evolving quark-gluon plasma, and the solid curve is the free-streaming gas. Only for masses below 3 GeV does the Drell-Yan contribution lose out. The shape of the free-streaming and quark-gluon plasma distributions are remarkably similar.

In Fig. 2 we do the same analysis at RHIC energy. Here the dN/dy is assumed to be 1735 corresponding to an initial temperature of 500 MeV. The quark-gluon plasma and free-streaming distributions are larger than that of the Drell-Yan out to about 5 GeV. The thermal and free-streaming distributions are again remarkably similar.

At LHC energy, shown in Fig. 3, the dN/dy was taken as 5624 with an initial temperature of 900 MeV. The quark-gluon plasma and free-streaming distributions are similar except at low and high masses. They are both larger than the Drell-Yan distribution up to masses of about 9-10 GeV.

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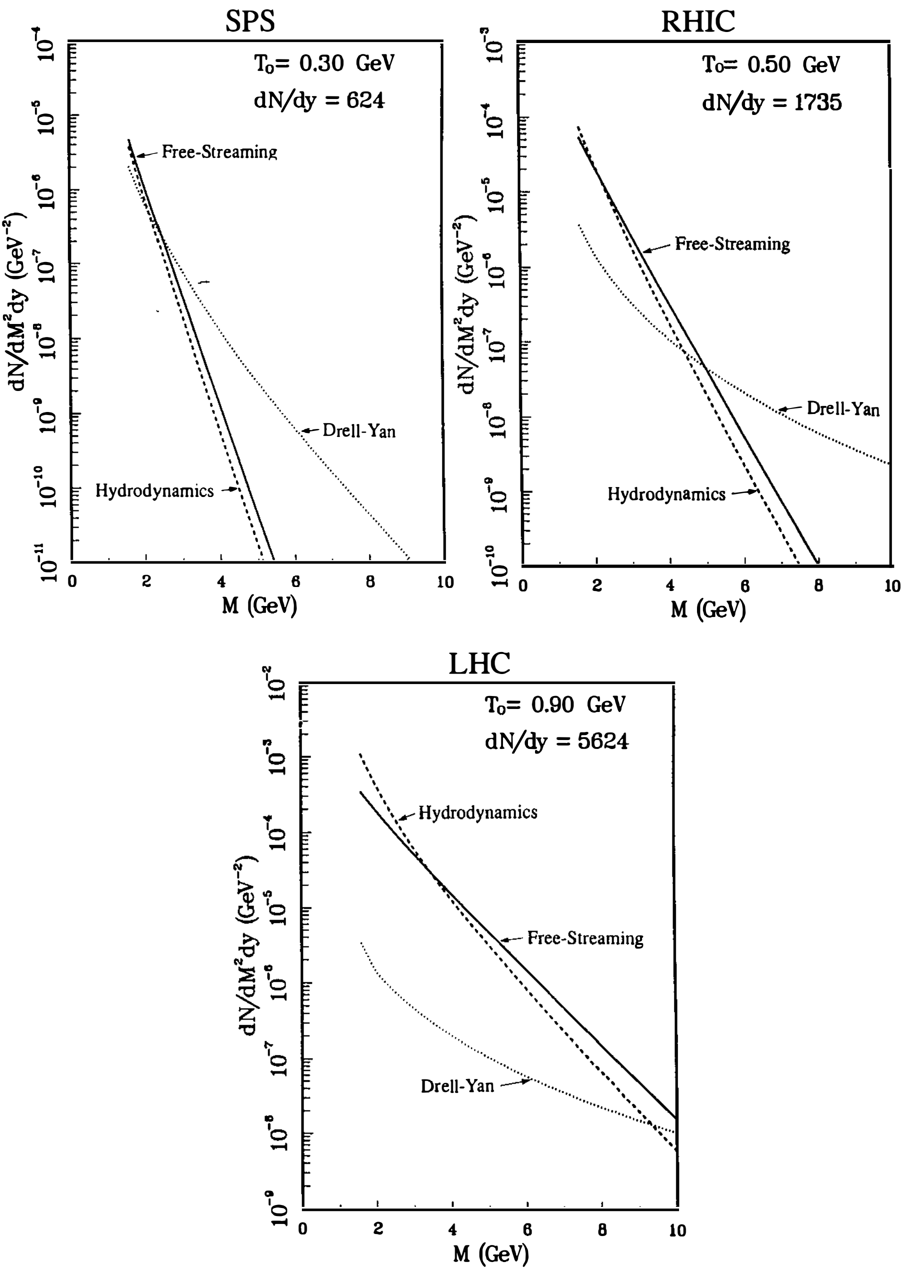
The Figure Captions

1) Dilepton production for central gold on gold collisions at SPS energy. The dotted line is Drell-Yan, the dashed a quark-gluon plasma and the solid a free-streaming distribution of partons. The hadron multiplicity is 624 corresponding to an initial temperature of 300 MeV.

2) Dilepton production at RHIC. Labels are as in Fig. 1.

3) Dilepton production at LHC. Labels are as in Fig. 1.



SPS
T_0= 0.30 GeV
dN/dy = 624
Free-Streaming
Drell-Yan
Hydrodynamics
dN/dM²dy (GeV⁻²)
M (GeV)
RHIC
T_0= 0.50 GeV
dN/dy = 1735
Free-Streaming
Drell-Yan
Hydrodynamics
dN/dM²dy (GeV⁻²)
M (GeV)
LHC
T_0= 0.90 GeV
dN/dy = 5624
Hydrodynamics
Free-Streaming
Drell-Yan
dN/dM²dy (GeV⁻²)
M (GeV)