Quark-Gluon-Plasma Diagnostics: Measuring π^0/γ Ratio with Dileptons

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It is demonstrated that the π^0/γ ratio can never be a definite signal of the quark-gluon plasma but may be a rather useful diagnostic of the plasma only if measured in combination with dileptons in the kinematic regime $p_T \approx 2$–4 GeV/c.

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Experiments[1,2] are already planned to measure the π^0/γ ratio as a possible signature of the quark-gluon plasma (QGP). The neutral π mesons can be produced from the QGP by the "leakage" of quark-antiquark pairs from the surface of the QGP.[3] With the space-time evolution of the plasma, the QGP condenses to hadrons; the π mesons from the hadronic phase show up along with the π mesons from the QGP, the former more abundant at relatively low p_T, the latter dominating the high-p_T regime.[3]

The thermal photons from the QGP can be produced by two distinct processes,[4,5] $q\bar{q} \rightarrow \gamma g$ and $gq \rightarrow \gamma q$. The nonthermal photons, on the other hand, can have their origin from hard QCD processes[5]; with the quarks fragmenting into photons at relatively high p_T ($\gtrsim 5$ GeV/c) the photons which are the decay products of $\pi^0 \rightarrow 2\gamma$ show up abundantly in the low-p_T regime.

The kinematic behavior of the hard QCD photons being the same as the thermal photons[5] (both the cross sections $\sim p_T^{-4}$) from the QGP, it is crucial to choose the appropriate window, which necessarily filters out photons from both the hadronic phase and the hard QCD process.

It has already been suggested by one of the authors (B.S.)[6,7] that the $\mu^+\mu^-/\gamma$ and $\mu^+\mu^-/\pi^0$ ratios can be a useful signal of the QGP. As one transits from the hadronic phase to the QGP, the ratios just mentioned tend to saturate to a constant value beyond a certain critical temperature T_c, with the tacit assumption that these two states (hadronic phase and the QGP) are separated by a first-order phase transition at the critical temperature. The saturation is, as it were, a snapshot of the phase transition.[6]

In the real world, however, the QGP, with space-time evolution, condenses to the hadronic phase; the experimentally observable quantities are therefore products of the mixed phase. It was demonstrated recently[7] that the $\mu^+\mu^-/\gamma$ ratio as well as the $\mu^+\mu^-/\pi^0$ ratio, as functions of p_T, manifest the unique characteristic of saturating to a constant value around $p_T \sim 2$–4 GeV/c, the contribution from the mixed phase having turned rather negligible in this regime. It was observed[7] further that the ratios also turn independent of the initial temperature for values of initial temperatures larger than $\sim 5T_c$.

The essential motivation of this Letter is to demonstrate that measuring dileptons ($\mu^+\mu^-$ to be more precise), along with π^0/γ in the appropriate kinematic window, $p_T \sim 2$–4 GeV/c, will necessarily ensure a useful signature of the QGP, the dileptons acting as a filter for selection of the QGP signals and rejection of the signals from the hadronic world. The signal π^0/γ by itself, on the other hand, as will be shown in what follows, does not have this property; the ratio remains remarkably insensitive to p_T. In such circumstances, the background of the photons from π^0 decay as well as γ's from the hard QCD process tends to drown the thermal QGP (π^0/γ), thus rendering the signal by itself not so efficient a signature of the QGP.

The choice of the appropriate window is dictated by the need to make sure that signals from the QGP which involve photons do not get contaminated either by the soft photons originating from the decay of π mesons or by the hard QCD photons.

To conserve (transverse) momentum, the γ's (products of the decay of π^0) with a certain p_T will correspond to a parent π^0 with a transverse momentum $\sim 2p_T$; since the number of soft neutral pions $\propto e^{-10p_T}$, the number of π^0 with $p_T > 2$–3 GeV/c will be extremely small, rendering all the γ's with $p_T \gtrsim 3$ GeV/c primarily thermal photons from the QGP. On the other hand, the hard photons, products of quark fragmentation, populate a regime[5] $p_T > 5$ GeV/c; thus, the appropriate kinematic window for thermal photons from the QGP is in the regime $p_T \approx 2$–4 GeV/c.

With the tacit assumption[6,7] that the local thermodynamic equilibrium is maintained and that the space-time evolution can be described by the similarity hydrodynamical flow in the central region, the flux of hadrons with energy E per unit time per unit surface is given by[5,7]

$$E(dJ_\pi/dp^3) = [g_\pi p_T C/(2\pi)^3] f(M_T, Y), \tag{1}$$

where $f(M_T,Y)$ is a universal function, given by

$$f(M_T,Y) = \int_{-Y}^{Y} d\eta \left[\int_{T_c}^{T_i} dT\,(3/T^7)\exp[-T^{-1}M_T\cosh(Y-\eta)]\right] \tag{2}$$

for transverse mass M_T and rapidity Y; g_π is the statistical weight of the created particle (pions in our case). For the QGP, Eq. (1) corresponds to $g_\pi^h = 1$ and for the hadronic phase, $g_\pi^q = 1$; C is a constant which depends on the initial temperature and geometrical factors. The initial temperature, in turn, depends on the entropy and thus on the hadron distribution in the final phase,[5]

$$T_i^3 \tau = 5\times 10^5 A^{-2/3} S/2Y \tag{3a}$$

and

$$\frac{S}{2Y} \approx d\frac{S}{dY_\pi} \approx 3.6\left(\frac{dN}{dY_\pi}\right)^{AB\to\pi} \quad (b=0). \tag{3b}$$

Implicit in Eq. (1) is that the hadron (pion) leakage from the QGP is a surface and not a volume effect. The leptons and the photons, on the other hand, freely leave

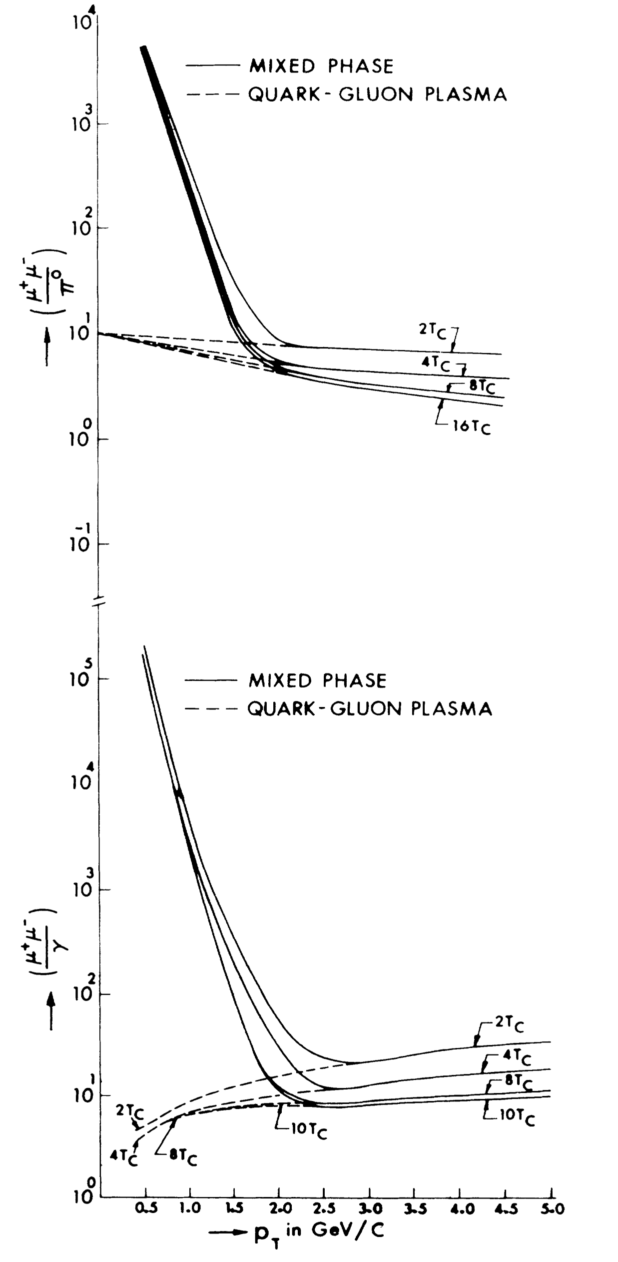

FIG. 1. The ratios of the production rate of $\mu^+\mu^-$ pairs to π^0's and thermal photons as a function of p_T.

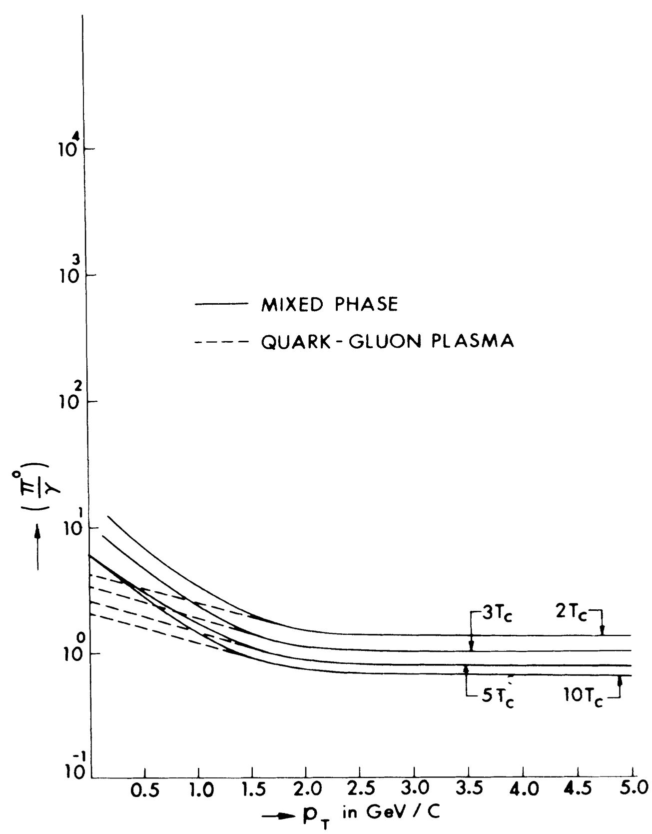

FIG. 2. The ratio of the production rate of π^0 to thermal photons (in arbitrary units) as a function of p_T. The numbers along the curves denote the initial temperature T_i in terms of critical temperature T_c.

the plasma from the entire volume of the plasma.[3,6]

The universal function $f(M_T,Y)$ is an integral characteristic of the hydrodynamic expansion and a direct consequence of the equipartition in phase space of different states with same energy—in other words, local thermodynamic equilibrium.

Neglecting transverse expansion for simplicity, we get, for π-meson leakage (with the reasonable assumption of cylindrical symmetry),

$$E\frac{d\sigma}{dp^3}\equiv\frac{1}{\pi}\frac{d\sigma}{dY dp_T^2}\approx\frac{g_\pi p_T C}{2r_0(2\pi)^3}f(M_T,Y), \tag{4}$$

where $r_0\sim 1/m_\pi$.

The cross section for thermal photons from the QGP is already calculated[5,7] for similar configuration. Thus, we now have the ratio

$$R\equiv(A^{\pi^0}/A^\gamma)=\mathcal{N}\frac{p_T\{(g_\pi^q/p_T^6)[F(4.5,p_T/T_c)-F(4.5,p_T/T_i)]+(5.0g_\pi^h/T_c^4)(p_T/T_c)^{1/2}e^{-p_T/T_c}\}}{(1/p_T^4)[F(3.5,p_T/T_c)-F(3.5,p_T/T_i)]} \tag{5}$$

where $A^x\equiv(d\sigma^x/dy\,dp_T^2)$; $x\equiv\pi^0$ or γ; $\mathcal{N}$ is a constant which depends on fundamental contents[5,7] and geometrical factors, not of great relevance for our purpose. The function F is defined as follows[5,7]:

$$F(Z,a_c)-F(Z,a_i)=\frac{1}{\Gamma(Z)}\int_{a_i}^{a_c}dZ\,Z^{t-1}e^{-t}. \tag{6}$$

The important advantage of our measuring the $\mu^+\mu^-/\gamma$ or the $\mu^+\mu^-/\pi^0$ ratio, or indeed π^0/γ, in contrast to the individual cross section for $\mu^+\mu^-$, π^0, or γ, is that the dependence of the ratios on the initial temperature [viz., Eq. (3)] through the entropy term gets mostly cancelled; the only dependence is through the $F(Z,a)$ functions, Eq. (6).

The exponential term in Eq. (5) is the contribution from the mixed phase; it turns negligible beyond $p_T\gtrsim 2$ GeV/c for currently acceptable[8] values of $T_c\sim 200$ MeV. In our evaluation of Eq. (5), it has been assumed that for pions $M_T\approx p_T$ since m_π is negligible in the kinematic regime 2–3 GeV/c. The A^{π^0} goes as p_T^{-5} ($p_T>2$ GeV/c) and A^γ goes as p_T^{-4}; thus the ratio A^{π^0}/A^γ goes as p_T^{-1} except for the $F(Z,a)$ terms; in the asymptotic case for $p_T>5T_i$, the ratio $F(Z,a)$ functions tend as p_T/T_i such that $A^{\pi^0}/A^\gamma\to 1/T_i$, turning independent of p_T. The ratios referred to above, $\mu^+\mu^-/\pi^0$ and $\mu^+\mu^-/\gamma$, have already been computed[6,7]; as shown in Fig. 1, beyond $p_T>2$ GeVc both these ratios saturate to a constant value, signalling the QGP, the contribution from the mixed phase having turned negligible. It is perhaps interesting to point out that for small p_T, where the contribution from the mixed phase is important, these ratios are noticeably different from their saturation values. However, the ratio $R\equiv A^{\pi^0}/A^\gamma$, as shown in Fig. 2, is remarkably insensitive to p_T (even for transverse momenta corresponding to mixed phase), rendering the signal by itself inefficient for the QGP.

Clearly, therefore, the π^0/γ ratio, insensitive to p_T, can never be a definite signal of the quark-gluon plasma but can become an efficient signal for the QGP only by measurement of $\mu^+\mu^-$ along with π^0/γ in the appropriate kinematic window $p_T\approx 2$–4 GeV/c, the dileptons acting as a filter for the QGP. This correlated measurement is thus a snapshot of the QGP, expected to be formed in ultrarelativistic heavy-ion collisions.

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