

## Suppression of dilepton production in hot hadronic matter

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Dilepton production from pion-pion annihilation in a hot hadronic matter is studied using an effective chiral Lagrangian that includes explicitly vector mesons. We find that the production rate for dileptons with invariant masses around the  $\rho$ -meson resonance is suppressed as a result of the modification of the pion electromagnetic form factor at finite temperature. The relevance of this phenomenon to the partial restoration of chiral symmetry in hot hadronic matter is discussed.

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Dileptons from relativistic heavy ion collisions have continually attracted great interest because once produced, they would escape from the collision region without further interactions and are thus ideal probes of the hot dense matter formed in the initial stage of the collision [1]. In hot dense matter, chiral symmetry is expected to be partially restored and the deconfinement transition to the quark-gluon plasma will occur once the temperature and density become sufficiently high. Therefore, based on the study of dileptons a number of signatures for these new phases of hadronic matter have been proposed [2–7].

One suggestion has been that the masses of vector mesons would change as the hadronic matter approaches the chirally symmetric phase, leading to a shift of the vector meson peaks in dilepton spectra from heavy ion collisions [8]. However, based on the partially conserved axial-vector current and current algebra it has been shown that up to  $T^2$ , where  $T$  is the temperature, there is no change in vector meson masses but only a mixing between the vector and axial vector correlators [9]. This result should be satisfied by any models that include the symmetry properties of low energy hadronic physics. Indeed, results from both QCD sum-rule calculations [10,11] and effective chiral Lagrangian approaches [12] are consistent with this temperature dependence. Thus, the vector meson masses obtained from these models do not change appreciably unless the temperature of the hadronic matter is very close to the critical temperature of the phase transition.

In the present paper, we shall study the pion electromagnetic form factor at finite temperature as it is needed for calculating the dilepton production rate from pion-pion annihilation in hot hadronic matter [2–5]. In the vector dominance model (VDM) [13], the pion electromagnetic form factor is obtained by assuming that the photon first converts into a  $\rho$  meson which subsequently interacts with the pion, i.e.,

$$F_{\pi}(q^2) = \frac{g_{\rho\pi\pi}}{g_{\gamma\rho}} \frac{m_{\rho}^2}{m_{\rho}^2 - q^2 - im_{\rho}\Gamma_{\rho}}, \quad (1)$$

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where  $g_{\gamma\rho}$  is the photon- $\rho$ -meson coupling constant,  $g_{\rho\pi\pi}$  is the pion- $\rho$ -meson coupling constant, and  $\Gamma_{\rho}$  is the neutral  $\rho$  meson decay width. Assuming the universality of  $\rho$  couplings, i.e.,  $g_{\gamma\rho} = g_{\rho\pi\pi}$ , then Eq. (1) agrees with the experimental measurement to within 10–20%. The discrepancy can be attributed to the internal quark-gluon substructure of the pion as shown by Brown, Rho, and Weise [14] using topological chiral models with the vector dominance idea [15].

To study the temperature dependence of the pion electromagnetic form factor we shall use an effective chiral Lagrangian that includes explicitly the vector mesons and also gives the correct isospin mixing at finite temperature. In this approach, we have thus neglected the temperature effect on the quark-gluon substructure of the pion. Our study indicates that not only is the photon- $\rho$ -meson coupling modified at finite temperature but there also exist effects due to vertex corrections and changes of the pion- and  $\rho$ -meson properties in hot hadronic matter. Using the temperature-dependent form factor, we shall then study its effect on the dilepton production rate from  $\pi\pi$  annihilation in hot matter.

In the literature, two methods have been introduced to include the vector mesons and photon field in the chiral Lagrangian; the massive Yang-Mills approach [16,17] and the hidden gauge approach [18]. In the massive Yang-Mills approach,  $\rho$  and  $a_1$  mesons are introduced as external gauge fields of the chiral group and the photon field is introduced via VDM. In the hidden gauge approach, vector mesons are introduced as gauge fields of the hidden local symmetry and the photon is introduced as an external gauge field. These two methods have been shown to be gauge equivalent and to have identical symmetry properties at finite temperature [12].

We shall follow the hidden gauge approach by considering the  $[\text{SU}(2)_L \times \text{SU}(2)_R]_{\text{global}} \times [\text{SU}(2)_V]_{\text{local}}$  “linear”  $\sigma$  model. It is constructed with two  $\text{SU}(2)$ -matrix valued variables  $\xi_L(x)$  and  $\xi_R(x)$ , which transform as  $\xi_{L,R}(x) \rightarrow \xi'_{L,R}(x) = h(x)\xi_{L,R} g_{L,R}^\dagger$  under  $h(x) \in [\text{SU}(2)_V]_{\text{local}}$  and  $g_{L,R} \in [\text{SU}(2)_{L,R}]_{\text{global}}$ . Introducing the vector meson  $V_{\mu}$  as the gauge field of the local symmetry and the photon  $\mathcal{B}_{\mu}$  as an external gauge field of the global symmetry, we have the following chirally invariant Lagrangian,

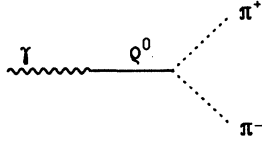


FIG. 1. The pion electromagnetic form factor at tree level.

$$\begin{aligned} \mathcal{L} = & f_\pi^2 \text{tr} \left[ \frac{1}{2i} (\mathcal{D}_\mu \xi_L \xi_L^\dagger - \mathcal{D}_\mu \xi_R \xi_R^\dagger) \right]^2 \\ & + a g^2 f_\pi^2 \text{tr} \left[ V_\mu - \frac{1}{2i} (\mathcal{D}_\mu \xi_L \xi_L^\dagger + \mathcal{D}_\mu \xi_R \xi_R^\dagger) \right]^2 \\ & + \mathcal{L}_{\text{kin}}(V_\mu, \mathcal{B}_\mu), \end{aligned} \quad (2)$$

where  $f_\pi = 93$  MeV is the pion decay constant, and the covariant derivative,  $\mathcal{D}_\mu \xi_{L,R}$ , is given by

$$\mathcal{D}_\mu \xi_{L,R} = \partial_\mu \xi_{L,R} + i e \xi_{L,R} \mathcal{B}_\mu \tau_3 / 2. \quad (3)$$

This effective Lagrangian with  $a=2$  is known to give the universality of  $\rho$  couplings ( $g_{\rho\pi\pi}=g$ ), the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin relations, and the  $\rho$ -meson dominance of the pion electromagnetic form factor ( $g_{\gamma\pi\pi}=0$ ). We shall use  $a=2$  throughout this paper. The Lagrangian has been extended to include the anomalous interactions and axial vector mesons. However, these effects are not included in present calculations.

In this effective Lagrangian, the pion electromagnetic form factor in free space can be obtained at tree level from the diagram shown in Fig. 1. One sees that the vector meson dominance appears naturally so a photon converts into a  $\rho$  meson which then interacts with the pion. The resulting pion electromagnetic form factor is exactly the same as Eq. (1) assumed in VDM. The temperature effect on the pion electromagnetic form factor can then be studied via thermal loops in the hot matter. We include only one-loop diagrams as the hadronic matter is rather dilute at temperatures considered here. For simplicity, we carry out the calculation in the rest frame of the photon and neglect the small finite pion mass.

First, we consider the temperature effect on the photon- $\rho$ -meson coupling as shown in Fig. 2(a). This correction is related to the mixing of the vector and axial vector current correlators in hot matter and is given by

$$F_\pi^{(1)}(q, T) = -F_\pi(q^2) \frac{\epsilon}{2}, \quad (4)$$

where  $q$  is the photon four momentum,  $\epsilon = T^2/6f_\pi^2$ , and  $F_\pi(q^2)$  is the pion electromagnetic form factor in free space given by Eq. (1). We see that, contrary to the modification of the vector meson mass in hot matter, the pion electromagnetic form factor has a  $T^2$ -dependence correction.

The change of  $\rho$  meson properties in hot matter gives the correction in Fig. 2(b). In Figs. 2(c)–2(f), we show the vertex corrections. The contribution from Fig. 2(f) is suppressed by the large vector meson mass and will be neglected. In a medium, a pion changes its properties through interactions with thermal pions and  $\rho$  mesons. This leads to the modifi-

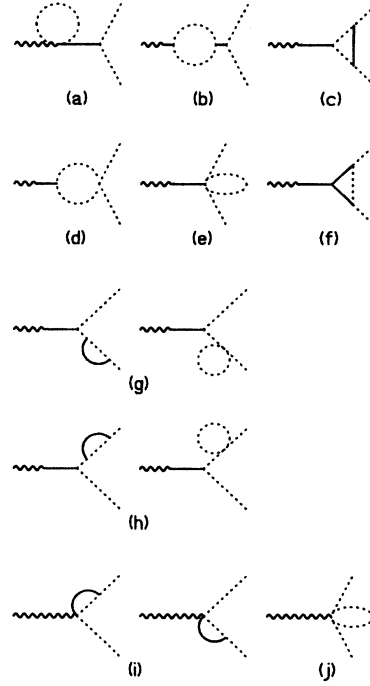


FIG. 2. One-loop corrections to the pion electromagnetic form factor. Solid, wavy, and dotted lines denote, respectively, the vector meson, photon, and pion.

cation of the form factor shown in Figs. 2(g) and 2(h). In the hidden gauge approach, there is also a direct photon-pion coupling at finite temperature as shown in Figs. 2(i) and 2(j), which explicitly modifies the notion of vector meson dominance. Details of our calculations will be reported elsewhere.

Contributions from thermal  $\rho$  mesons in the loop corrections are very small due to their large masses in the Boltzmann factor and are neglected in the study. Additional diagrams should be considered when we include anomalous interactions, such as the  $\pi\rho\omega$  coupling, and axial vector mesons. However, these effects will be suppressed by the large masses of the vector and axial vector mesons.

Figure 3 shows the  $q$  dependence of the pion electromagnetic form factor around the  $\rho$  resonance for different temperatures. The form factor is seen to be reduced near the resonance as temperature increases. We obtain a reduction of the form factor by 40% at  $q \sim m_\rho$  when  $T=180$  MeV. This result is comparable with that obtained using the QCD sum-rule approach which shows that at  $q^2 \sim (1 \text{ GeV})^2$ , the form factor at  $T \sim 0.9T_c$  is about half its value at  $T=0$  [19]. It is also consistent with that based on the perturbative QCD at high  $q^2$  [20].

The reduction of the pion electromagnetic form factor at finite temperature is mainly due to the modification of the photon- $\rho$ -meson coupling, the increase of the  $\rho$ -meson width, and the vertex corrections. The photon- $\rho$ -meson coupling is modified due to the isospin mixing at finite temperature which has been regarded as a possible signature for the partial restoration of chiral symmetry in hot matter. The resonance width has also been expected to increase in hot hadronic matter as a result of the chiral symmetry restoration

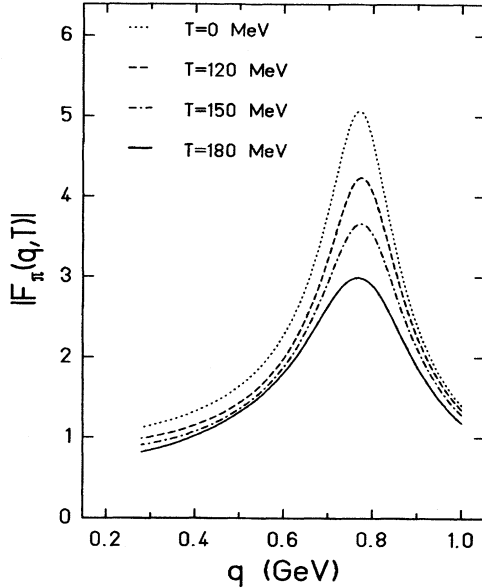


FIG. 3. The pion electromagnetic form factor at finite temperature.

[21]. The vertex corrections, which lead to a reduction of the  $\rho$ -pion coupling constant at finite temperature, may be related to the recent suggestion that the pion-vector meson coupling constant vanishes when chiral symmetry is restored in the vector limit [22]. Thus, the reduction of the pion electromagnetic form factor at finite temperature is probably related to the partial restoration of chiral symmetry in hot hadronic matter. Such a possible relation has also been suggested in studies based on QCD sum rules [19] and the QCD factorization formula [20].

Using the temperature-dependent pion electromagnetic form factor, we have calculated the dilepton production rate from pion-pion annihilation in hot hadronic matter. The production rate of dileptons with vanishing three momentum in hot hadronic matter is then given by [23,24]

$$\left. \frac{d^4 R}{d^3 q dM} \right|_{q=0} = \frac{\alpha^2}{3(2\pi)^4} \frac{|F_\pi(M, T)|^2}{(e^{\omega/T} - 1)^2} \sum_k \frac{k^4}{\omega^4} \left| \frac{d\omega}{dk} \right|^{-1}, \quad (5)$$

where  $M$  is the dilepton invariant mass. The momentum and energy of the pion are denoted by  $k$  and  $\omega$ , respectively, and are related by its dispersion relation in the medium. The last factor takes into account this effect. The sum over  $k$ 's is restricted by  $\omega(k) = M/2$ . However, the modification of the pion dispersion relation at finite temperature is small [25] and will be neglected.

The dilepton production rate is shown in Fig. 4 for  $T = 180$ . The result obtained with the modified pion form factor (solid line) is compared with that calculated using the form factor in free space (dotted line). It is seen that near the  $\rho$ -meson resonance the dilepton production rate at  $T = 180$  MeV is reduced by almost a factor of 3.

Recently, there are experiments at CERN on both photon and dilepton production from high energy nucleus-nucleus collisions [26,27]. For photons, theoretical results based on

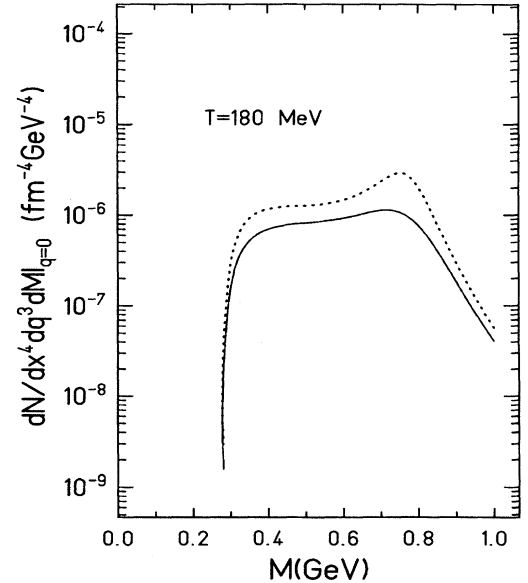


FIG. 4. The thermal dilepton production rate from pion-pion annihilation at  $T = 180$  MeV. Solid and dotted lines are results obtained with modified and free form factors, respectively.

the scenario that a quark-gluon plasma has been formed in the collision agree with the observations [28]. In these studies, there is appreciable contribution to the production of photons with the transverse energy less than about 2 GeV coming from the period of a two-phase coexistence, i.e., from hadronic matter at temperatures 160–180 MeV. We expect this to be the case also for dilepton production. Our results then imply that the dilepton production rate will be suppressed as a result of the temperature dependence of the form factor. It is thus important to include this effect in studying photon and dilepton production from heavy ion collisions.

Also, it is of interest to extend present calculations to the SU(3) limit. This will allow us to study the temperature dependence of the form factor needed in  $\bar{K}$ - $K$  annihilation. This will be relevant to the study of double  $\phi$  meson peak in dilepton spectra, which has recently been suggested as a possible signal for the phase transition in hot matter [6]. The second  $\phi$  peak in the dilepton spectrum is from the decay of  $\phi$  mesons in the mixed phase, which have reduced masses as a result of partial restoration of chiral symmetry.

In summary, we have studied the pion electromagnetic form factor in hot hadronic matter using an effective Lagrangian with vector mesons. We find that there is a reduction in the magnitude of the form factor, which could be understood in terms of the partial restoration of chiral symmetry in hot hadronic matter. The reduction in the electromagnetic form factor then leads to a suppression of dilepton production from pion-pion annihilation in hot matter. This effect needs to be included in future studies of dilepton production from heavy ion collisions.

We have neglected the internal quark-gluon substructure of hadrons and their changes with temperature. This should be reasonable at low temperatures. When the temperature is high, its effect cannot be ignored. In this respect, models

based on explicit quark-gluon degrees of freedom, such as that developed in Ref. [15], will be useful if extended to finite temperature. However, we do not expect that it will qualitatively modify our conclusion as our results are already consistent with those from analyses that are based on the QCD [19,20].

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