Dilepton radiation measured in PHENIX probing the strongly interacting matter created at RHIC

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Abstract

PHENIX has measured $e^+e^-$ pairs from $p+p$ and Au+Au collisions as function of mass and $p_T$. The data can be used to probe the properties of dense matter formed in Au+Au collision. The relation between electron pairs and virtual photons is discussed.

1. Introduction

It is now well established that high density partonic matter is formed in collisions of heavy nuclei at RHIC[1]. Photons and lepton pairs are the cleanest probes of the dense matter. Since these electromagnetic probes have little interaction with the matter, they carry direct information deep inside of the medium. From the emission rate of photons and dileptons, we can directly probe the temperature of the medium, the properties of hadrons inside of the medium, and the matter’s properties.

2. Relation between dilepton and virtual photon

The thermal emission rate of electron pairs per space-time volume can be described in terms of the electromagnetic (EM) spectral function as [2]

$$\frac{dR_{ee}}{d^4q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M)}{M^2} \text{Im}\Pi^\mu_{em,\nu}(M, q; T)f_\text{B}(q_0, T),$$

(1)

$$L(M) = \sqrt{1 - \frac{4m_e^2}{M^2}(1 + \frac{2m_e^2}{M^2})}.$$  

(2)

Here $\Pi^\mu_{em,\nu}$ is the in-medium EM spectral function and $f_\text{B}(q_0, T) = 1/(e^{q_0/T} - 1)$ is the Boltzmann factor. The equation shows that from the emission rate we can probe the medium property encoded in the EM spectral function as well as its temperature in the Boltzmann factor. The EM spectral function in vacuum for the low mass region is well described as a sum of contributions of the low mass vector mesons ($\rho, \omega$, and $\phi$). Modification of the properties of these mesons shows up as modification of the EM spectral function.

Using the same notation, the emission rate of virtual photons is described as [2,3]

$$\frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2} \text{Im}\Pi^\mu_\text{em,\nu}(M, q; T)f_\text{B}(q_0, T).$$

(3)
The virtual photon and the electron pair emission rate are related as
\[ q_0 \frac{dR_{ee}}{dM^2 dq} = \frac{1}{2} \frac{dR_{ee}}{d^2q} = \frac{\alpha}{3\pi} \frac{L(M)}{M^2} q_0 \frac{dR_{\gamma^*}}{d^3q}. \]  
(4)

The same relation holds for the yield of photons and electron pairs after space-time integration. This relation between the virtual photon and electron pair emission is exact to the order of \( \alpha \) in QED and is exact to all orders of strong couplings. For \( M \to 0 \), the virtual photon yield becomes the real photon yield \( (N_{\gamma^*} \to N_{\gamma}) \). Thus this relation can be used to determine the yield of real photons. Recently, PHENIX measured the yield of direct photon in Au+Au from the yield of low mass \( e^+e^- \) pairs using this relation.\[4\].

The equation (4) can be rewritten as
\[ q_0 \frac{dN_{\gamma^*}}{d^3q} \approx \frac{3\pi}{2\alpha} Mq_0 \frac{dN_{ee}}{d^3q} dM. \]  
(5)

This equation can be used to convert the yield of \( e^+e^- \) pair to virtual photon yield. Such conversion is useful since the virtual photon emission rate is just the product of the EM spectral function and the Boltzmann factor.

Figure 1: Electron pair emission rate (left panel) and virtual photon emission rate (right panel) calculation by R. Rapp[5]. The solid and dashed curve uses the EM spectral function in the medium and in vacuum, respectively. The dotted curve shows \( q\bar{q} \) annihilation contribution.

Figure 1 illustrates the relation between electron pair mass spectrum and virtual photon yield. The left panel of the figure shows the differential electron pair spectrum, \( (1/p_T) dN_{ee}/dM dp_T dy \) at \( p_T = 1.025 \text{ GeV}/c \) from a model calculation of electron pair production by Rapp. The dashed and solid curve show electron pairs from hadronic gas, while the dotted curve show the contribution from the leading order (LO) \( q + \bar{q} \) corrected with a Hard Thermal Loop (HTL) correction. The dashed curve uses the EM spectral function \( \Pi_{EM} \) that is unchanged from its vacuum value so the line shapes of vector mesons (\( \rho, \omega, \phi \)) are unmodified. In the solid curve the spectral function is calculated by hadronic many body theory (HMT), and the vector mesons are broadened due to the interactions. It also includes the contributions like \( a_1(1260) \to \pi + e^+e^- \), \( \rho \to \pi + e^+e^- \), and \( N + \pi \to N^* \to N\gamma e^+e^- \). These contributions filled the low mass regions below the two-pion threshold. In the low mass region, the mass spectrum steeply increases with decreasing \( M \). This behavior is due to the \( 1/M \) factor in \( \gamma^* \to e^+e^- \).
The right panel of Fig. 1 shows the same calculations presented as the yield of virtual photon. The steep $1/M$ behavior of the electron pair spectrum is removed, and much more smooth behavior of the virtual photon spectrum is revealed. The plot shows that the virtual photon yield is almost constant as a function of $M$. The value of the solid curve at $M = 0$ should correspond to the real photon yield. This illustrates that in a consistent theory calculation the yield of virtual photon is a smooth function of $M$ and it becomes the real photon yield in the limit of $M = 0$.

The quark annihilation contribution, shown as dotted curve, behaves as $\propto M^2$ in the right panel at low mass region since $q\bar{q}$ contribution to $\Pi_{EM}$ is proportional to $M^2$. Thus it is strongly suppressed and have little contribution in the low mass region. In the high mass region, the $M^2$ behavior of the quark annihilation is suppressed by the Boltzmann factor.

It should be noted that the dotted curve does not include processes like $q + g \rightarrow q + \gamma^*$ that are associated with real direct photon production in QGP. This is because HTL calculation of thermal radiation from QGP is only available in the real photon case. Turbide, Gale, and Rapp \[6\] calculated real photon production in an hadronic gas using the same model and compared it with real photon production in QGP phase using the complete leading order HTL analysis. They found that real photon from the QGP outshines that of hadronic gas for $p_T > 1.5$ GeV/c in Au+Au collisions at RHIC. This means that contribution from processes associated with real photon production in QGP can be as large as that of HMT (solid curve) and can be much larger than that of the LO $q\bar{q}$ annihilation (dotted).

3. $e^+e^-$ mass spectra in $p + p$ and Au+Au

PHENIX measured the $e^+e^-$ pair production in Au+Au and in $p + p$ at $\sqrt{s_{NN}}=200$ GeV \[7, 8\]. In $p + p$ the measured mass spectrum in low mass ($M < 1$ GeV/$c^2$) is well described by the sum of light hadron decay contributions. The high-mass region is dominated by the contribution of the correlated decays of charm and bottom. From the measured mass spectrum the charm cross section is determined as $\sigma_{c\bar{c}} = 544 \pm 39 \pm 142\mu b$, which is consistent with that obtained from single electron measurement. The bottom cross section is determined as $\sigma_{b\bar{b}} = 3.9 \pm 2.5\pm 3\mu b$, which is consistent with that obtained from $e - h$ correlation \[10\].

Figure 2 compares the $e^+e^-$ pair mass distributions in $p + p$ and Au + Au collisions and hadronic cocktail for $M < 1.2$ GeV/$c^2$. The $p + p$ and Au+Au data are normalized in Dalitz pair
mass region ($M < 30$ MeV/c$^2$). While the $p + p$ data is well described by the cocktail shown in solid curve, the Au+Au data show a large enhancement over the cocktail. The enhancement is larger in the low $p_T$ region ($p_T < 0.7$ GeV/c) shown in the left panel of the figure.

The left panel of Fig. 3 shows the $e^+ e^-$ mass distribution for $p_T > 1.5$ GeV/c. The enhancement in Au+Au is still visible for $M > 0.1$ GeV/c$^2$ but its magnitude is much reduced. In the left panel, $M \times dN_{ee}/dM$ of the excess yield of the $e^+ e^-$ pair in the Au+Au for $1.5 < p_T < 2.0$ GeV/c is shown. Following Eq. 4 this corresponds to the yield of virtual photons. The figure shows that the yield of virtual photon is approximately constant for $M > 0.1$ GeV/c, which is consistent with the constant behavior of the HMT calculation by R. Rapp shown in Fig. 1. This could be interpreted that the virtual photon emission in the high $p_T$ region ($p_T > 1.5$ GeV/c) is dominated by hadronic scattering process like $\pi + \rho \rightarrow \pi + \gamma^*$ or partonic processes like $q + g \rightarrow q + \gamma^*$. Both of these processes give a constant contribution to the EM spectral function at low mass. Since the virtual photon yield is almost constant, it can be reliably extrapolated to $M = 0$. This should give the real photon emission rate.

In contrast, the mass distribution in Au+Au at low $p_T$ shown in the right panel of Fig. 3 is quite different. The shape of the excess seems to be incompatible with a constant virtual photon emission rate. The data might suggest that a large enhancement of the EM spectral function at low mass and low $p_T$ in Au+Au collisions.

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