Thermal Dilepton Production Rate from Dropping $\rho$ in the Vector Manifestation

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Abstract

In this write-up we summarize main points of our recent analysis on the thermal dilepton production rate from the dropping $\rho$ based on the vector manifestation (VM). In the analysis, we studied the effect of the strong violation of the vector dominance (VD), which is predicted by the VM, and showed that the effect of the violation of the VD substantially suppresses the dilepton production rate compared with the one predicted by assuming the VD together with the dropping $\rho$.

1 Introduction

Changes of hadron properties are indications of chiral symmetry restoration occurring in hot and/or dense QCD and have been explored using various effective chiral approaches \cite{2,3}. An enhancement of dielectron mass spectra below the $\rho/\omega$ resonance was first observed at CERN SPS \cite{4} and it is an indication of the medium modification of the vector mesons. The vector meson mass in matter still remains an open issue. Although there are several scenarios like collisional broadening due to interactions with the surrounding hot/dense medium \cite{3}, and dropping $\rho$ meson mass associated with chiral symmetry restoration \cite{5,7}, no conclusive distinction between them has been done. Indeed, the in-medium modification carried by $\rho$ near the critical point may not be apparent in the final yield depending on the fireball evolution under the CERN SPS condition \cite{6}. However, dropping masses of hadrons following the Brown-Rho (BR) scaling \cite{5} can be one of the most prominent candidates of the strong signal of melting quark condensate $\langle \bar{q}q \rangle$ which is an order parameter of spontaneous chiral symmetry breaking, if the signal is not washed out through the evolution, especially at RHIC.

The vector manifestation (VM) \cite{7} is a novel pattern of the Wigner realization of chiral symmetry in which the $\rho$ meson becomes massless degenerate with the pion at the chiral phase transition point. The VM is formulated \cite{8,9,10,11} in the effective field theory based on the hidden local symmetry (HLS) \cite{12,13}. The VM gives a field theoretical description of the dropping $\rho$ mass, which is protected by the existence of the fixed point (VM fixed point).

The dropping mass is supported by the mass shift of the $\omega$ meson in nuclei measured by the KEK-PS E325 Experiment \cite{14} and the CBELSA/TAPS Collaboration \cite{15} and also that of the $\rho$ meson observed in the STAR experiment \cite{16}. Recently NA60 Collaboration has provided data for the dimuon spectrum \cite{17} and it seems difficult to explain the data by a naive dropping $\rho$ \cite{18}. However, there are still several ambiguities which are not considered \cite{19,20,21}.

\footnote{Talk given by M. Harada at Mini-Workshop “Strongly Coupled Quark-Gluon Plasma: SPS, RHIC and LHC” (16-18 February 2007, Nagoya, Japan). This is based on the work done in Ref. \cite{1}.}
Especially, the strong violation of the vector dominance (VD), which is one of the significant predictions of the VM [22], plays an important role [19] to explain the data.

In Ref. [1], we studied the dilepton production rate from the dropping $\rho$ based on the VM using the HLS theory at finite temperature. We paid a special attention to the effect of the violation of the vector dominance (indicated by “VD”) which is due to the intrinsic temperature effects of the parameters introduced through the matching to QCD in the Wilsonian sense combined with the renormalization group equations (RGEs). We made a comparison of the dilepton production rates predicted by the VM with the ones by the dropping $\rho$ with the assumption of the vector dominance (VD). The result shows that the effect of the VD substantially suppresses the dilepton production rate compared with the one predicted by assuming the VD together with the dropping $\rho$.

This write-up is organized as follows: In section 2 we explain what the VM is. Section 3 is a main part in which we show the form factor and dilepton production rate. A brief summary and discussions are given in section 4.

2 Hidden Local Symmetry and Vector Manifestation

The vector manifestation (VM) was first proposed in Ref. [7] as a novel manifestation of Wigner realization of chiral symmetry where the vector meson $\rho$ becomes massless at the chiral phase transition point. Accordingly, the (longitudinal) $\rho$ becomes the chiral partner of the Nambu-Goldstone (NG) boson $\pi$. The VM is characterized by

\[(VM) \quad f_\pi^2 \to 0, \quad m_\rho^2 \to m_\pi^2 = 0, \quad f_\rho^2/f_\pi^2 \to 1, \quad (2.1)\]

where $f_\rho$ is the decay constant of (longitudinal) $\rho$ at $\rho$ on-shell. This is completely different from the conventional picture based on the linear sigma model where the scalar meson $S$ becomes massless degenerate with $\pi$ as the chiral partner:

\[(GL) \quad f_\pi^2 \to 0, \quad m_S^2 \to m_\pi^2 = 0. \quad (2.2)\]

In Ref. [8] this was called GL manifestation after the effective theory of Ginzburg–Landau or Gell-Mann–Levy.

We first consider the representations of the following zero helicity ($\lambda = 0$) states under $SU(3)_L \times SU(3)_R$; the $\pi$, the (longitudinal) $\rho$, the (longitudinal) axial-vector meson denoted by $A_1$ (a$_1$ meson and its flavor partners) and the scalar meson denoted by $S$. The $\pi$ and the longitudinal $A_1$ are admixture of $(8, 1) \oplus (1, 8)$ and $(3, 3^*) \oplus (3^*, 3)$ since the symmetry is spontaneously broken [23]:

\[
|\pi\rangle = |(3, 3^*) \oplus (3^*, 3)\rangle \sin \psi + |(8, 1) \oplus (1, 8)\rangle \cos \psi,
|A_1(\lambda = 0)\rangle = |(3, 3^*) \oplus (3^*, 3)\rangle \cos \psi - |(8, 1) \oplus (1, 8)\rangle \sin \psi, \quad (2.3)
\]

where the experimental value of the mixing angle $\psi$ is given by approximately $\psi = \pi/4$ [23]. On the other hand, the longitudinal $\rho$ belongs to pure $(8, 1) \oplus (1, 8)$ and the scalar meson to pure $(3, 3^*) \oplus (3^*, 3)$:

\[
|\rho(\lambda = 0)\rangle = |(8, 1) \oplus (1, 8)\rangle, \quad |S\rangle = |(3, 3^*) \oplus (3^*, 3)\rangle. \quad (2.4)
\]
When the chiral symmetry is restored at the phase transition point, it is natural to expect that the chiral representations coincide with the mass eigenstates: The representation mixing is dissolved. From Eq. (2.3) one can easily see that there are two ways to express the representations in the Wigner phase of chiral symmetry: The conventional GL manifestation corresponds to the limit \( \psi \rightarrow \pi/2 \) in which \( \pi \) is in the representation of pure \((3, 3^*) \oplus (3^*, 3)\) together with the scalar meson, both being the chiral partners:

\[
(\text{GL}) \quad \begin{cases} 
|\pi\rangle, |S\rangle & \rightarrow |(3, 3^*) \oplus (3^*, 3)\rangle, \\
|\rho(\lambda = 0)\rangle, |A_1(\lambda = 0)\rangle & \rightarrow |(8, 1) \oplus (1, 8)\rangle.
\end{cases}
\] (2.5)

On the other hand, the VM corresponds to the limit \( \psi \rightarrow 0 \) in which the \( A_1 \) goes to a pure \((3, 3^*) \oplus (3^*, 3)\), now degenerate with the scalar meson \( S \) in the same representation, but not with \( \rho \) in \((8, 1) \oplus (1, 8)\):

\[
(\text{VM}) \quad \begin{cases} 
|\pi\rangle, |\rho(\lambda = 0)\rangle & \rightarrow |(8, 1) \oplus (1, 8)\rangle, \\
|A_1(\lambda = 0)\rangle, |s\rangle & \rightarrow |(3, 3^*) \oplus (3^*, 3)\rangle.
\end{cases}
\] (2.6)

Namely, the degenerate massless \( \pi \) and (longitudinal) \( \rho \) at the phase transition point are the chiral partners in the representation of \((8, 1) \oplus (1, 8)\).

Next, we consider the helicity \( \lambda = \pm 1 \). Note that the transverse \( \rho \) can belong to the representation different from the one for the longitudinal \( \rho (\lambda = 0) \) and thus can have the different chiral partners. According to the analysis in Ref. [23], the transverse components of \( \rho (\lambda = \pm 1) \) in the broken phase belong to almost pure \((3^*, 3) (\lambda = +1) \) and \((3, 3^*) (\lambda = -1) \) with tiny mixing with \((8, 1) \oplus (1, 8)\). Then, it is natural to consider in VM that they become pure \((3, 3^*)\) and \((3^*, 3)\) in the limit approaching the chiral restoration point [8]:

\[
|\rho(\lambda = +1)\rangle \rightarrow |(3^*, 3)\rangle, \quad |\rho(\lambda = -1)\rangle \rightarrow |(3, 3^*)\rangle.
\] (2.7)

As a result, the chiral partners of the transverse components of \( \rho \) in the VM will be themselves.

The formulation of the VM was first done in the large flavor QCD [7], and then in the hot and dense QCD [9, 10]. The formulation was done within the framework of the hidden local symmetry (HLS) [12, 13], in which it is possible to perform a systematic derivative expansion (see Ref. [8] for a review).

At the leading order of the chiral perturbation with HLS the Lagrangian includes three parameters: the pion decay constant \( F_\pi \); the HLS gauge coupling \( g \); and a parameter \( a \). Using these three parameters, the \( \rho \) meson mass \( m_\rho \), the \( \rho-\gamma \) mixing strength \( g_\rho \), the \( \rho-\pi-\pi \) coupling strength \( g_\rho\pi\pi \) and the direct \( \gamma-\pi-\pi \) coupling strength \( g_{\gamma\pi\pi} \) are expressed as

\[
m_\rho^2 = g^2 a F_\pi^2, \quad g_\rho = g a F_\pi^2, \quad g_{\rho\pi\pi} = \frac{a}{2} g, \quad g_{\gamma\pi\pi} = 1 - \frac{a}{2}.
\] (2.8)

From these expression, one can easily see that the vector dominance (VD) of the electromagnetic form factor of the pion, i.e. \( g_{\gamma\pi\pi} = 0 \), is satisfied for \( a = 2 \). We would like to stress that the VD at zero temperature and density is accidentalaly satisfied: The parameter \( a \) is 4/3 at the bare level and it becomes 2 in the low-energy region by including the quantum correction [24]. This can be rephrased in the following way: the parameter \( a \) at the large \( N_c \) limit is 4/3 and it becomes 2 when the \( 1/N_c \) corrections are included [25].
The most important ingredient to formulate the VM in hot matter is the intrinsic temperature dependence of the parameters of the HLS Lagrangian \[9, 11\] introduced through the Wilsonian matching between the HLS and QCD: The Wilsonian matching near the critical temperature \(T_c\) provides the following behavior for the bare parameters \(a\) and \(g\):

\[
g(\Lambda; T) \sim \langle \bar{q}q \rangle \to 0, \quad a(\Lambda; T) - 1 \sim \langle \bar{q}q \rangle^2 \to 0, \quad \text{for } T \to T_c. \tag{2.9}
\]

It was shown \[8, 9, 10\] that these conditions are protected by the fixed point of the RGEs and never receives quantum corrections at the critical point. Thus the parametric vector meson mass determined at the on-shell of the vector meson also vanishes since it is proportional to the vanishing gauge coupling constant. The vector meson mass \(m_\rho\) defined as a pole position of the full vector meson propagator has the hadronic corrections through thermal loops, which are proportional to the gauge coupling constant \[9, 10, 22\]. Consequently the vector meson pole mass also goes to zero for \(T \to T_c\):

\[
m_\rho(T) \sim \langle \bar{q}q \rangle \to 0. \tag{2.10}
\]

We would like to stress that the VD is strongly violated near the critical point associated with the dropping \(\rho\) in the VM in hot matter \[22\]:

\[
a(T) \to 1, \quad \text{for } T \to T_c. \tag{2.11}
\]

### 3 Thermal Dilepton Spectra in the VM

We should note that the conditions in Eq. (2.9) hold only in the vicinity of \(T_c\): They are not valid any more far away from \(T_c\) where ordinary hadronic temperature corrections are dominant. For expressing a temperature above which the intrinsic effect becomes important, we introduce a temperature \(T_f\), so-called flash temperature \[26, 27\]. The VM and therefore the dropping \(\rho\) mass become transparent for \(T > T_f\). On the other hand, we expect that the intrinsic effects are negligible in the low-temperature region below \(T_f\): Only hadronic temperature corrections are considered for \(T < T_f\). Based on the above consideration, we adopt the following ansatz of the temperature dependences of the bare \(g\) and \(a\):\(^\#1\)

\[
\begin{align*}
g(\Lambda; T) &= \text{(constant)} \quad \text{for } T < T_f, \\
a(\Lambda; T) - 1 &= \text{(constant)} \quad \text{for } T > T_f.
\end{align*}
\]

Here we would like to remark that the Brown-Rho scaling deals with the quantity directly locked to the quark condensate and hence the scaling masses are achieved exclusively by the intrinsic effect in the present framework.

In Ref. \[1\], we calculated the mass and the width of \(\rho\) meson as well as the direct-\(\gamma\pi\pi\) coupling strength in hot matter using the in-medium parameters determined in the above way. We show the resultant temperature dependences in Fig. 1. Figures 1(a) and (b) show that, below the flash temperature \(T_f\), both the mass and width slightly increase with temperature caused by the hadronic temperature effects. For \(T > T_f\), on the other hand, the intrinsic effects

\(^\#1\) As was stressed in Refs. \[8, 11\], the VM should be considered only as the limit. So we include the temperature dependences of the parameters only for \(T_f < T < T_c - \epsilon\).
Figure 1: Temperature dependences of (a) the $\rho$ meson mass $m_\rho$, (b) the decay width $\Gamma_\rho$ and (c) the direct-$\gamma\pi\pi$ coupling $\bar{g}_{\gamma\pi\pi}$. The solid curves denote the full (both intrinsic and hadronic) temperature dependences. The curves with the dashed lines include only the hadronic temperature effects. Note that $\bar{g}_{\gamma\pi\pi}$ includes only the intrinsic effects.

become dominant and both the mass and width decrease rapidly toward zero. Figure 1(c) shows that, in the temperature region below $T_f$, $\bar{g}_{\gamma\pi\pi}$ is almost zero realizing the vector dominance (VD). Above $T_f$ the parameter $a$ starts to decrease from 2 to 1 due to the intrinsic effect. This causes an increase of $\bar{g}_{\gamma\pi\pi}$ toward $1/2$, which implies the strong violation of the VD.

Figure 2 shows the pion electromagnetic form factor for several temperatures. In Fig. 2(a)

Figure 2: Electromagnetic form factor of the pion as a function of the invariant mass $\sqrt{s}$ for several temperatures. The curves in the left panel (a) include only the hadronic temperature effects and those in the right panel (b) include both intrinsic and hadronic temperature effects.

only the hadronic temperature corrections are included in the form factor. There is no remarkable shift of the $\rho$ meson mass but the width becomes broader with increasing temperature, which is consistent with the previous study [28]. In Fig. 2(b) the intrinsic temperature effects are also included into all the parameters in the form factor. At the temperature below $T_f$, the hadronic effect dominates the form factor, so that the curves for $T = 0$, $0.4T_c$ and $0.6T_c$ agree with the corresponding ones in Fig. 2(a). At $T = T_f$ the intrinsic effect starts to contribute and thus in the temperature region above $T_f$ the peak position of the form factor moves as $m_\rho(T) \to 0$ with increasing temperature toward $T_c$. Associated with this dropping $\rho$ mass, the width becomes narrow, and the value of the form factor at the peak grows up as [9]

$$\frac{|g_\rho g_{\rho\pi\pi}|^2}{m_\rho \Gamma_\rho} \sim \left( \frac{g_\rho}{g_{\rho\pi\pi} m_\rho^2} \right)^2 \sim \frac{1}{g^2}.$$ (3.2)
Now, let us show the thermal dilepton production rate predicted in the VM. A lepton pair is emitted from the hot matter through a decaying virtual photon. The differential production rate in the medium for a fixed temperature $T$ is expressed in terms of the imaginary part of the photon self-energy $\text{Im}\Pi$ as

$$\frac{dN}{d^4q}(q_0, \vec{q}; T) = \frac{\alpha^2}{\pi^3 M^2} \frac{1}{e^{q_0/T} - 1} \text{Im}\Pi(q_0, \vec{q}; T),$$

where $\alpha = e^2/4\pi$ is the electromagnetic coupling constant, $M$ is the invariant mass of the produced dilepton and $q_\mu = (q_0, \vec{q})$ denotes the momentum of the virtual photon. We will focus on an energy region around the $\rho$ meson mass scale in this analysis. In this energy region it is natural to expect that the photon self-energy is dominated by the two-pion process and its imaginary part is related to the pion electromagnetic form factor $F(s; T)$ through

$$\text{Im}\Pi(s; T) = \frac{1}{6\pi\sqrt{s}} \left( \frac{s - 4m^2}{4} \right)^{3/2} |F(s; T)|^2,$$

with the pion mass $m_\pi$.

As noted, the vector dominance (VD) is controlled by the parameter $a$ in the HLS theory. The VM leads to the strong violation of the VD (indicated by “$\nabla$”) near the chiral symmetry restoration point, which can be traced through the Wilsonian matching and the RG evolutions. Thus the direct photon-$\pi$-$\pi$ $g_{\gamma\pi\pi}$ coupling yields non-vanishing contribution to the form factor together with the $\rho$-meson exchange. In Ref. [1], we compared the dilepton spectra predicted in the VM (including the effect of $\nabla$) with those obtained by assuming the VD, i.e. taking $g_{\gamma\pi\pi} = 0$. Figure 3 shows the form factor and the dilepton production rate integrated over three-momentum, in which the results with VD and $\nabla$ were compared. The figure shows a clear difference between the curves with VD and $\nabla$. In the low-temperature region $T \ll T_f$, the hadronic effects are dominant compared with the intrinsic ones, so both curves almost coincide. A difference between them starts to appear around $T = T_f$ and increases with temperature. It can be easily seen that the $\nabla$ gives a reduction compared to the case with keeping the VD. The features of the form factor as well as the dilepton production rate coming from two-pion annihilation shown in Fig. 3(a)-(e) are summarized below for each temperature:

(a) and (b) (below $T_f$): The form factor, which has a peak at the $\rho$ meson mass $\sqrt{s} \sim 770$ MeV, is slightly suppressed with increasing temperature. An extent of the suppression in case with $\nabla$ is greater than that with VD. This is due to decreasing of the $\rho$-$\gamma$ mixing strength $g_\rho$ at finite temperature. At $T < T_f$, $g_\rho$ mainly decreases by hadronic corrections. In case with VD, however, $g_\rho$ is almost constant. The dilepton rate (a) has two peaks, one is at the $\rho$ meson mass and another one is lying around low-mass region. The later peak comes from the Boltzman factor of Eq. (3.3). For a rather low-temperature the production rate is much enhanced compared with the $\rho$ meson peak since the yield in the higher-mass region is suppressed by the statistical factor. With increasing temperature those peaks of the production rate (b) are enhanced and the peak at $\sqrt{s} \sim m_\rho$ clearly appears. In association with decreasing $g_\rho$, one sees a reduction of the dilepton rate with $\nabla$.
Figure 3: Electromagnetic form factor of the pion (left) and dilepton production rate (right) as a function of the invariant mass $\sqrt{s}$ for various temperatures. The solid lines include the effects of the violation of the VD. The dashed-dotted lines correspond to the analysis assuming the VD. In the dashed curves in the right-hand figures, the parameters at zero temperature were used.
(c), (d) and (e) (above $T_f$) : Since the intrinsic temperature effects are turned on, a shift of the $\rho$ meson mass to lower-mass region can be seen. Furthermore, the form factor, which becomes narrower with increasing temperature due to the dropping $m_{\rho}$, exhibits an obvious discrepancy between the cases with VD and $\sqrt{\mathcal{D}}$. The production rate based on the VM (i.e., the case with $\sqrt{\mathcal{D}}$) is suppressed compared to that with the VD. We observe that the suppression is more transparent for larger temperature: The suppression factor is $\sim 1.8$ in (c), $\sim 2$ in (d) and $\sim 3.3$ in (e).

As one can see in (c), the peak value of the rate predicted by the VM in the temperature region slightly above the flash temperature is even smaller than the one obtained by the vacuum parameters, and the shapes of them are quite similar to each other. This indicates that it might be difficult to measure the signal of the dropping $\rho$ experimentally, if this temperature region is dominant in the evolution of the fireball. In the case shown in (d), on the other hand, the rate by the VM is enhanced by a factor of about two compared with the one by the vacuum $\rho$. The enhancement becomes prominent near the critical temperature as seen in (e). These imply that we may have a chance to discriminate the dropping $\rho$ from the vacuum $\rho$.

4 Summary and Discussions

We studied the pion electromagnetic form factor and the thermal dilepton production rate from the two-pion annihilation within the hidden local symmetry (HLS) theory as an effective field theory of low-energy QCD. In the HLS theory the chiral symmetry is restored as the vector manifestation (VM) in which the massless $\rho$ meson joins the same chiral multiplet as pions. In order to determine the temperature dependences of the parameters of the HLS Lagrangian, the Wilsonian matching to the operator product expansion at finite temperature was made by applying the matching scheme developed in the vacuum [29, 30] and at the critical temperature [9, 30, 22, 31].

In the notion of the Wilsonian matching to define a bare theory in hot environment, the bare parameters are dependent on temperature, which are referred as the intrinsic temperature effects. At low temperatures the chiral properties of in-medium hadrons are dominated by ordinary hadronic loop corrections. The dropping $\rho$ is realized in the HLS framework due to the intrinsic effects and thus they play crucial roles especially near the chiral phase transition. In order to see an influence of the intrinsic temperature effects, we presented the form factor including full temperature effects, i.e., the intrinsic and hadronic effects, and compared with that including only hadronic corrections. The $\rho$ meson mass $m_{\rho}$ is almost stable against the hadronic corrections and one does not obtain the dropping $m_{\rho}$. Accordingly the peak of the form factor including only the hadronic effects is located at around $\sqrt{s} \sim m_{\rho} \sim 770$ MeV even at finite temperature. The form factor is reduced with increasing temperature and correspondingly becomes broader. On the other hand, the Wilsonian matching procedure certainly involves the intrinsic temperature effects in the analysis and provides the dropping $m_{\rho}$ as the VM. The form factor above the flash temperature $T_f$ thus starts to present a shift of $m_{\rho}$ to lower invariant mass region. Associated with the dropping $\rho$, the form factor becomes sharp.

One of the significant predictions of the VM is a strong violation of the vector dominance
(VD) of the pion form factor. The VM predicts that the VD is violated near the transition temperature \( T_c \) in which the direct photon-\( \pi^-\pi^- \) coupling does contribute to the form factor in addition to the \( \rho \)-meson mediation. It crucially affects the analysis of dilepton yields. We presented the form factor and the dilepton production rate with and without the VD assumption together with the dropping \( \rho \). For \( T \ll T_f \) the result shows only a small difference between those two cases since the VD is still well satisfied in low temperatures. A clear difference can be seen for \( T > T_f \) where the intrinsic temperature effects contribute to the physical quantities. The form factor and consequently the dilepton production rate with taking account of the violated VD are reduced and exhibit an obvious difference near \( T_c \) compared to those with the VD.

Several comments are in order:

The HLS Lagrangian has only pions and vector mesons as physical degrees of freedom, and a time evolution was not considered in this work. Thus it is not possible to make a direct comparison of our results with experimental data. However a naive dropping \( m_\rho \) formula, i.e., \( T_f = 0 \), as well as VD in hot/dense matter are sometimes used for theoretical implications of the data. As we have shown in this paper, the intrinsic temperature effects together with the violation of the VD give a clear difference from the results without including those effects. It may be then expected that a field theoretical analysis of the dropping \( \rho \) as presented in this work and a reliable comparison with dilepton measurements will provide an evidence for the in-medium hadronic properties associated with the chiral symmetry restoration, if complicated hadronization processes do not wash out those changes.

Recently the chiral perturbation theory with including vector and axial-vector mesons as well as pions has been constructed \[32, 33\] based on the generalized HLS \[34, 13, 35\]. In this theory the dropping \( \rho \) and \( A_1 \) meson masses were formulated and it was shown that the dropping masses are related to the fixed points of the RGEs which gives a VM-type restoration and that the VD is strongly violated also in this case. Inclusion of the effect of \( A_1 \) meson as well as the effect of collisional broadening will be done in future work \[36\].

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