Fate of the ρ – a_1 mixing in dilepton production

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Abstract. We investigate the effect of chiral mixing on dilepton production by combining the in-medium spectral function in the chiral effective field theory with the state-of-the-art fluid dynamical simulations. We compare the spectral functions with different chiral symmetry restoration scenarios: without chiral symmetry restoration, with chiral symmetry restoration, and the low-temperature mixing theory extrapolated to high-temperature. We find that the scenario with proper chiral symmetry restoration that takes into account the degenerate ρ and a_1 mesons leads to an increase of the yield in the window of $1.1 < M < 1.4$ GeV. Whereas, the extrapolated low-temperature theorem leads to a substantial overestimate at $M = 1.2$ GeV.

1 Introduction

Probing the chiral symmetry restoration (CSR) is one of the main goals in high-energy heavy-ion collisions. The QCD matter created in the high-energy heavy-ion collisions is expected to experience CSR in the QGP phase above the chiral temperature and the masses of chiral partners degenerate. On the other hand, when the chiral symmetry is broken in the hadronic phase, the mass difference of chiral partners becomes large. This degeneracy of the masses is the key for probing the chiral symmetry restoration. Given the difficulty of constructing the axial-vector spectrum in heavy-ion experiments, we focus on the phenomenon known as chiral mixing, where the vector meson mixes with the axial-vector meson in a medium via pion loops. In our study, we investigate the ρ–a_1 mixing because of their short lifetimes compared to the QGP created in heavy-ion collisions.

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In the low-temperature mixing theorem [1], the current correlators are the superposition of vector and axial vector correlators at zero temperature:

$$G_V(q;T) = (1-\epsilon)\,G_V(q;0) + \epsilon\,G_A(q;0)\,,$$
$$G_A(q;T) = \epsilon\,G_V(q;0) + (1-\epsilon)\,G_A(q;0)\,, \tag{1}$$

where $\mathrm{Im}\,G_V(q;0)$ and $\mathrm{Im}\,G_A(q;0)$ are the vector and the axial-vector spectral functions at zero temperature, respectively. The mixing parameter ϵ is given as $\epsilon = T^2/(6f_\pi^2)$ with the pion decay constant, $f_\pi = 92.4\,\mathrm{MeV}$. The naive extrapolation of the low-temperature mixing theorem is often argued to generate an increase of the dilepton yield by 20-30%. However, it is inappropriate to utilize the low-temperature expansion for high-temperature. Instead, there are two major approaches to embed the chiral mixing to high temperature. One is to build up the axial-vector spectrum from the Weinberg sum rules [2]. The other is to consider the chiral mixing at finite temperatures using the chiral perturbation theory with generalized hidden local symmetry [3], where the chiral mixing is included from chiral Lagrangian with a one-loop calculation and the degeneration of ρ and a_1 masses at high temperatures in the chiral limit.

The measurement of chiral symmetry restoration via chiral mixing is set with a high priority in the upcoming experiments. The purpose of this study is to evaluate the effect of CSR on dilepton invariant mass spectra. To investigate the effect, we combine the spectral function with the hydrodynamic model for the description of space-time evolution [4].

2 Model

The dilepton production rate from the hadronic matter is related to the imaginary part of the vector-current correlation function G_V via:

$$\frac{dR_{\mathrm{had}}}{d^4q}(q;T) = \frac{\alpha_{\mathrm{EM}}^2}{\pi^3 M^2}\,\frac{\mathrm{Im}G_V(q;T)}{e^{q_0/T}-1}\,. \tag{2}$$

We compare three CSR scenarios for the spectral function $\mathrm{Im}G_V(q;T)$. Figure 1 shows the

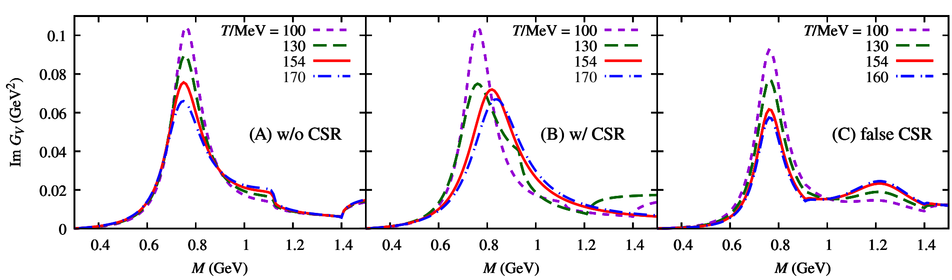

Figure 1. (Color online). The temperature dependence of vector spectral function (A) without chiral symmetry restoration, (B) with chiral symmetry restoration, and (C) with false chiral symmetry restoration.

spectral function for the three scenarios: (A) without chiral symmetry restoration, (B) with chiral symmetry restoration, and (C) with false chiral symmetry restoration. The spectral functions with scenarios A and B are calculated from Ref. [3] which include the thermal corrections via meson loops. For scenario A, we assume the ρ and a_1 masses are constant.

Scenario B is the proper CSR scenario where we take into account the degeneracy of ρ and a_1 mass by dropping a_1 mass. Here, the mass difference $\delta m = m_{a_1} - m_\rho$ decreases as temperature approaches T_χ. Scenario C is a false CSR that extrapolates the low-temperature mixing theorem, Eq. (1), to high-temperature. We integrate the dilepton production rate from initial time τ_0 until the system reaches the kinetic freeze-out temperature, $T_{\rm fo} = 116$ MeV [5]. We combine the dilepton production rate of the QGP phase and that of the hadronic phase smoothly where we assume a crossover between the two phases [6]:

$$\frac{dR}{d^4q} = \frac{1}{2}\left(1 - \tanh\frac{T - T_\chi}{\Delta T}\right)\frac{dR_{\rm had}}{d^4q} + \frac{1}{2}\left(1 + \tanh\frac{T - T_\chi}{\Delta T}\right)\frac{dR_{\rm QGP}}{d^4q}\,, \tag{3}$$

with $\Delta T = 0.1T_\chi$ and chiral crossover temperature $T_\chi = 154$ MeV. The dilepton production rate from the QGP medium due to $\bar{q}q$ annihilation in the Born approximation is given by:

$$\frac{d^4R_{\rm QGP}}{d^4q}(q;T) = \frac{\alpha_{\rm EM}^2}{6\pi^4}\frac{1}{e^{q^0/T} - 1}\left\{1 - \frac{2T}{|\boldsymbol{q}|}\ln\left[\frac{n_-}{n_+}\right]\right\}, \tag{4}$$

$$n_\pm = 1 + \exp\left[-\frac{q^0 \pm |\boldsymbol{q}|}{2T}\right]. \tag{5}$$

where $\alpha_{\rm EM} = e^2/4\pi$ represents the electromagnetic coupling constant and $M = \sqrt{q_0^2 - |\boldsymbol{q}|^2}$ the invariant mass with energy q_0 and three-momentum $\boldsymbol{q}$ of a virtual photon.

3 Results

We utilize the state-of-the-art relativistic viscous hydrodynamics model [5, 7] to describe the dynamical evolution of the QCD matter created in the high-energy heavy-ion collisions. The initial entropy density distribution at an initial time of $\tau_0 = 0.6$ fm is obtained from the initial condition model, TRENTo [8, 9]. For the equations of state, we employ the lattice QCD simulations parameterized in the hadronic and QGP phases [10]. We analyze the invariant mass spectra from 20 hydrodynamic events for Pb+Pb collisions with the collision energy $\sqrt{s_{\rm NN}} = 2.76$ TeV in the centrality window of 0–5%. We integrate the dilepton production rate over the rapidity η and transverse momenta p_T in the ranges of $|\eta| < 0.8$ and $0.2 < p_T < 5.0$ GeV. Figure 2 shows the invariant mass spectra obtained from the three CSR scenarios. The peak structure from the ρ mass is seen for all three cases at $M \sim 0.8$ GeV, while the effect of a_1 is seen between 1.0 and 1.5 GeV. In the spectra from scenario B, w/ CSR, we see a smooth enhancement between 1.1 and 1.4 GeV. This enhancement is the proper CSR signal, which is caused by the mass degeneration of ρ and a_1. In the spectra from scenario C, with false CSR, we see the enhancement between 1.1 and 1.3 GeV and becomes maximal at $M = 1.2$ GeV. This is an overestimate coming from the maximal mixing.

4 Summary

We have analyzed the dilepton production with three CSR scenarios taking account of space-time evolution with the viscous hydrodynamic model. We have shown the proper chiral symmetry restoration with degeneration of ρ and a_1 masses leads to a smooth enhancement in the dilepton yield between $1.1 < M < 1.4$ GeV. On the other hand, the low-temperature mixing theorem with maximal mixing overestimates at $M = 1.2$ GeV. As an outlook, we can work on spectral functions with ω and ϕ mesons. Also, chiral mixing in a dense medium is interesting for future work.

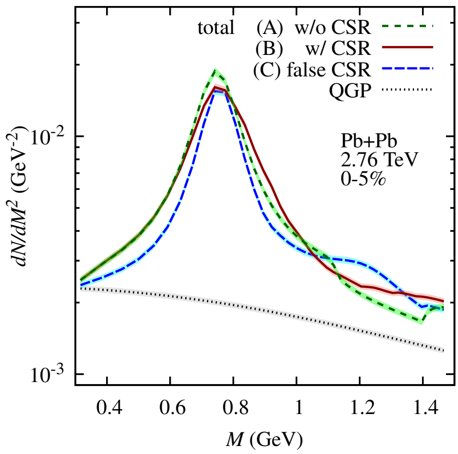

Figure 2. (Color online). The total dilepton yield in Pb+Pb collisions with collision energy $\sqrt{s_{\rm NN}}$ = 2.76 TeV for centrality 0–5% from the three hadronic spectral functions and that from the QGP medium [4]. The width represents the statistical errors.

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