Rotation effect on the spectral function of heavy vector mesons in holographic QCD

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1. Abstract

- Exploring heavy vector mesons of the J/ψ and Υ(1S) is crucial for understanding the quark gluon plasma (QGP) formed in heavy ion collisions. The influences of rotational effect on the properties of the J/ψ and Υ(1S) are investigated by incorporating rotation medium into the holographic QCD.
- It is found that temperature, chemical potential, and rotational radius effects enhance the dissociation process of the J/ψ and Υ(1S) states within the medium. This rotation-induced effect is more significant for heavy vector mesons in the transverse direction than that of the longitudinal direction. The first holographic study on the influence of the radius of a homogeneous rotating system on the vector meson spectrum is proposed. It is found that increasing in rotation radius promotes the dissociation of vector mesons of the J/ψ and Υ(1S). We also find that the dissociation perpendicular to the direction of rotational angular velocity is more significant than that parallel to it at large rational radius.

2. Introduction

- **Quark-Gluon Plasma (QGP):** QGP produced in relativistic heavy-ion collisions possesses extremely high temperature and density, and is accompanied by a strong magnetic field and significant rotational vortex characteristics.
- **Rotational Effects:** QGP produced in non-central collisions carries a huge angular momentum (10^4-10^5 ħ), with local angular velocities reaching 0.01 – 0.1 GeV.
- **Probe:** Heavy vector mesons (such as J/ψ and Υ(1S)) are important probes for investigating the properties of QGP.
- **Motivation:** To use Holographic QCD (gauge/gravity duality) to study the effects of rotation radius (l) and angular velocity (Ω) on heavy meson dissociation, particularly the anisotropic effects in finite-sized rotating systems.

3. Methods

Holographic QCD Theory

- **The soft wall model:** the vector meson is described by a vector field $V_m=(V_\mu,V_z)(\mu=0,1,2,3)$, which is dual to the current $J^\mu=\psi\gamma^\mu\psi$ of the gauge theory. The standard Maxwell action is

$$S=-\int d^4x\,dz\frac{Q}{4}F_{mn}F^{mn}\,, \qquad (1)$$

where $Q=\frac{\sqrt{-g}}{h(\phi)g_5^2}, h(\phi)=e^{\phi(z)}, F_{mn}=\partial_m V_n-\partial_n V_m$ and $\phi(z)$ the dilaton background.
the metric is given by in the background of a **charged black holes**

$$ds^2=\frac{R^2}{z^2}\left(-f(z)\,dt^2+\frac{dt^2}{f(z)}+d\vec{x}\cdot d\vec{x}\right), \qquad (2)$$

with

$$f(z)=1-\frac{z^4}{z_h^4}-q^2z_h^2z^4+q^2z^6, \qquad (3)$$

and

$$\phi(z)=k^2z^2+Mz+\tan h\left(\frac{1}{Mz}-\frac{k}{\sqrt{\Gamma}}\right), \qquad (4)$$

where k represents the quark mass, Mdenotes a large mass and Γis the string tension of the quark pair associated with the nonhadronic decays of heavy quarkonium. There is a matrix element $\langle 0|J_\mu(0)|\times X(1S)\rangle=\epsilon_\mu f_n m_n$(where represents the **heavy mesons**, ⟨0 is the hadronic vacuum and $J_\mu(0)$ is the hadronic current and f_n is the decay constant).

4. Rotation effect

Introduction of rotation

- we extend the holographic QCD model to include the case of a **rotating black hole** with a planar horizon.

$$\begin{aligned}ds^2=&(g_{\theta\theta}\Omega^2l^2-g_{ll})\gamma^2dt^2+2\gamma^2\Omega l^2(g_{\theta\theta}-g_{ll})dtd\theta\\&+\gamma^2(g_{\theta\theta}-\Omega^2l^2g_{tt})l^2d\theta^2+g_{zz}dz^2+g_{x_2x_2}dx_2^2\\&+g_{x_3x_3}dx_3^2.\end{aligned} \qquad (5)$$

- In the rotating frame, the rotating metric satisfies the same Einstein field equations as the rest frame metric. Thus, Hawking temperature and chemical potential can begiven as

$$T=\left(\frac{1}{\pi z_h}-\frac{q^2z_h^5}{2\pi}\right)\sqrt{1-\Omega^2l^2}, \qquad (6)$$

and

$$\mu=\tilde{\mu}\sqrt{1-\Omega^2l^2}, \qquad (7)$$

due to the limitation of the speed of light, it naturally leads to the restriction $\Omega l\le 1$.

5. Spectral Functions

The Membrane Paradigm

- The equations of motion obtained from Eq. (1) are as follows:

$$\partial_m(QF^{mn})=\partial_z(QF^{zn})+\partial_\mu(QF^{\mu m}), \qquad (8)$$

the conjugate momentum of the gauge field A^μ is given by the following equation:

$$j^\mu=-QF^{z\mu}. \qquad (9)$$

- Now we consider the plane wave solution of vector field A^μ propagates in the direction of x_1, and divide the equation of motion into a **longitudinal channel** and **transverse channel**

$$-\partial_z j^t-\frac{\sqrt{-g}}{h(\phi)}(g^{x_1x_1}g^{tt}+g^{x_1t}g^{tx_1})\partial_{x_1}F_{x_1t}=0, \qquad (10)$$

$$-\partial_z j^{x_1}+\frac{\sqrt{-g}}{h(\phi)}(g^{tt}g^{x_1x_1}+g^{tx_1}g^{x_1t})\partial_t F_{x_1t}=0, \qquad (11)$$

$$\partial_{x_1}j^{x_1}+\partial_t j^t=0.$$

It is possible to define the conductivity of the longitudinal channel and transverse channel

$$\sigma_L(\omega,z)=\frac{j^{x_1}(\omega,z)}{F_{x_1t}(\omega,z)}\,,\ \sigma_T(\omega,z)=\frac{j^{x_2}(\omega,z)}{F_{x_2t}(\omega,z)}. \qquad (12)$$

- The **spectral function** can be defined by the retarded Green's function as

$$\rho(\omega)\equiv -Im\,G_R(\omega)=\omega Re\,\sigma(\omega,0)\,. \qquad (13)$$

6. Results

- It would be interesting to explore how various thermodynamic quantities of strongly interacting rotating matter vary with the radius of the rotating system.

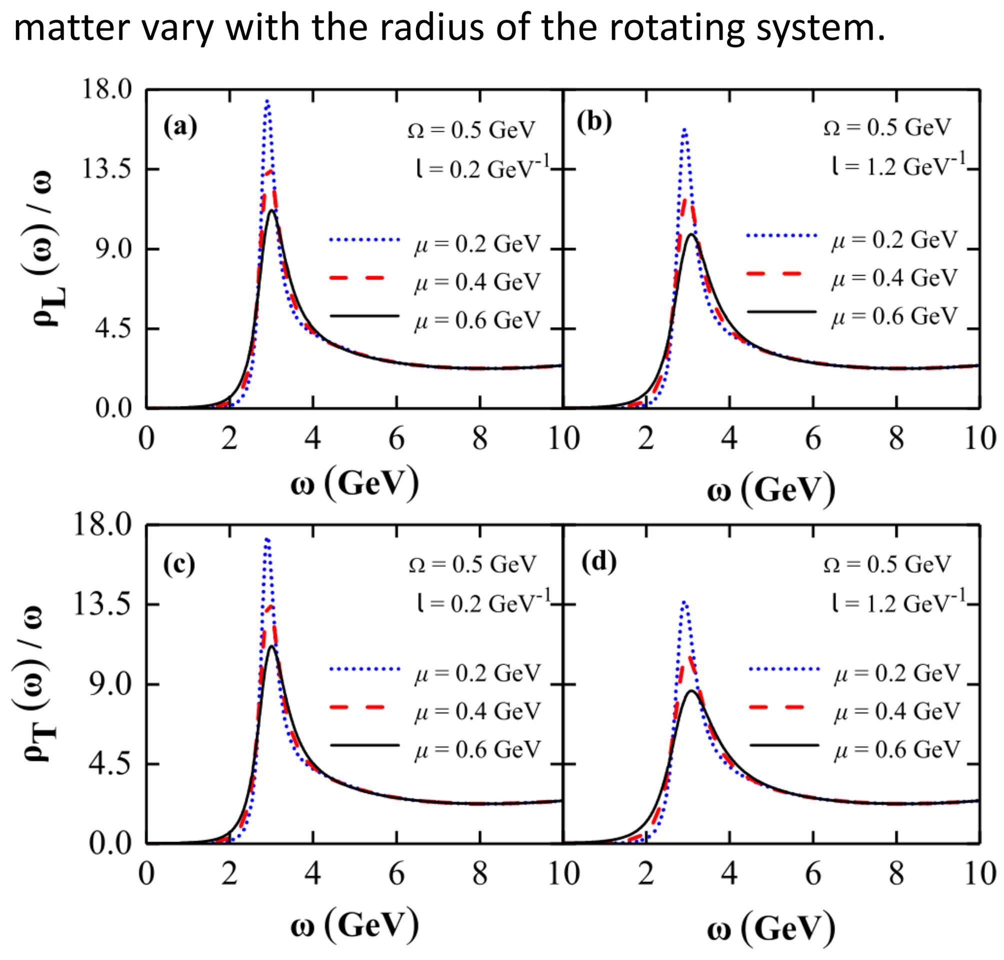

Fig1.Spectral functions of J/ψ at $T=0.2$ GeV, under different chemical potentials and rotational radius .

Discussion

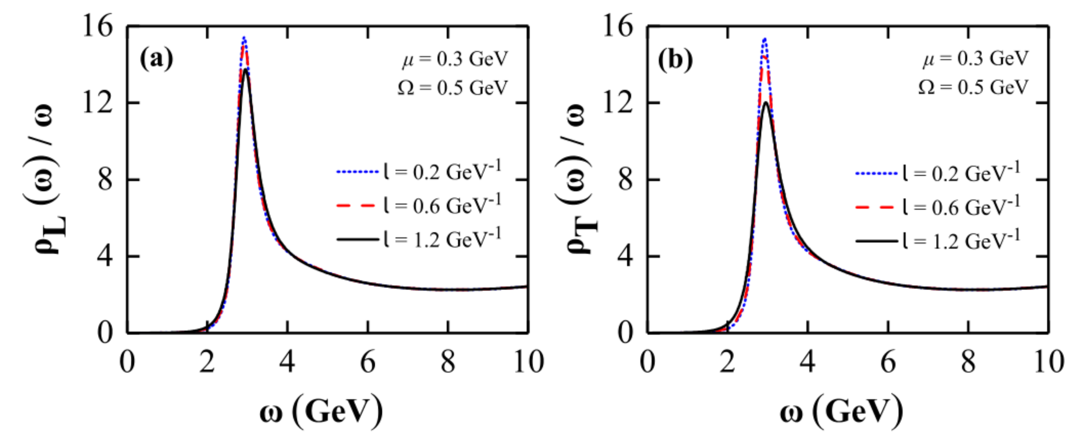

Fig.2 Spectral function of J/ψ for different rotation radii with parallel and perpendicular to the rotational angular velocity at $T=0.2$ GeV.

- Figure 1 presents the bell-shaped curve represents the resonance state, and the peak position corresponds to the resonance mass of the effective mass. As both the chemical potential μ and the rotational radius l increase, we observe that the peak decreases, broadens, and slightly shifts to the right. the chemical potential and rotational radius increase, they promote the dissociation of bound states and increase the decay width and effective mass.
- Figure 2 shows the **dissociation effect** in the transverse direction is more pronounced than in the longitudinal direction, and this effect becomes more prominent at **larger rotation radii**. Therefore, it can be concluded that increasing the rotation radius promotes the dissociation of bound states, and the dissociation perpendicular to the direction of rotational angular velocity is more significant than that parallel to it.

Effective Mass J/ψ

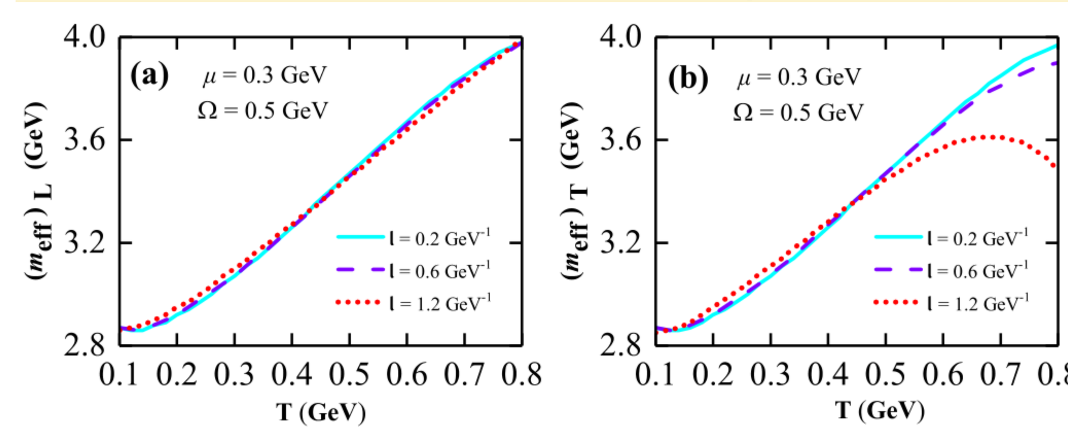

Fig.3 The effective mass on temperature under different rotation radius.

Effective Mass Υ(1S)

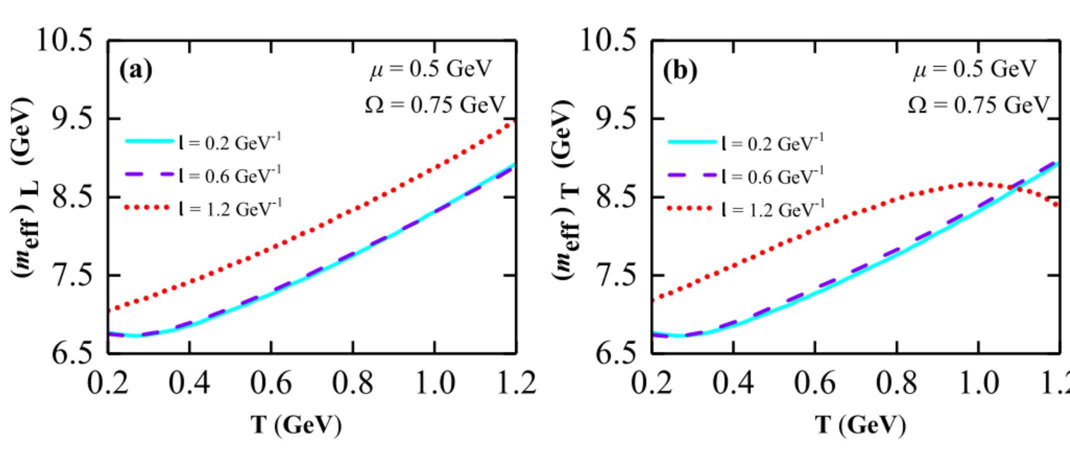

Fig.4 The effective mass on temperature under different rotation radius.

- In Figure 3 and Figure 4, when the rotation radius is small, the influence of the rotation radius on the relationship between effective mass and temperature is not significant in both longitudinal and transverse directions. However, as the **rotation radius increases**, the influence of the rotational radius on the relationship between effective mass and temperature becomes significant.

Future Plans

- In the subsequent work, we will conduct a more in-depth analysis of the spin polarization and alignment phenomena of heavy vector mesons within the holographic model.

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