Spin Alignment and Phase Transition of QGP in the Presences of Vorticity Fields

1. The Spin Alignment and Phase Structure of Thermal QGP under Rotation
2. Spectral signatures of heavy quarkonia in a rotating and anisotropic QGP: A holographic study
3. Summary and Conclusions

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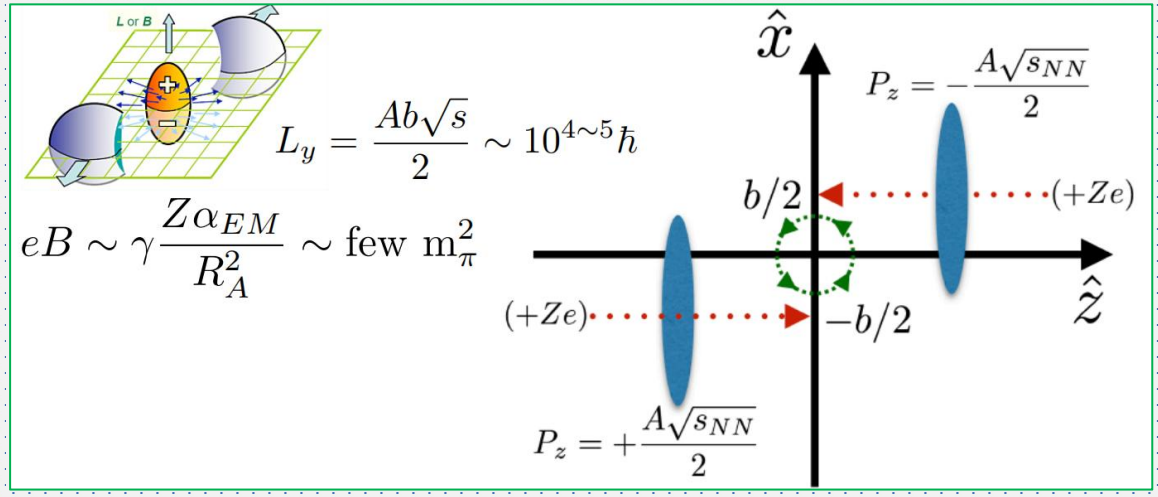
中国物理学会高能物理分会第十二届全国会员代表大会, 广州 2026.7.14-19

Extremal Vorticity and Magnetic Fields in Relativistic HIC

For non-central high-energy collisions, the dense matter produced in the overlapped region of the collision will carry a global angular momentum along the direction opposite to the reaction plane (− y) . Assuming that a partonic system is formed immediately following the initial collision, interactions among produced partons will lead to formation of a quark – gluon plasma (QGP) .



Vorticity fields $\omega \sim 10^{21} s^{-1}$

STAR, Nature 548 (2017) 62-65;
Becattini, Liao, Lisa,
Lect.Notes Phys. 987 (2021).

Magnetic fields $B \sim 10^{18} Gauss$

W. T. Deng, X. G. Huang,
PRC 85, 044907 (2012).

QCD

- **Phase structure**
- **Spin polarization**
- **Jet quenching**
- **Meson/baryon mass**
- ⋮

- **NJL model**
- **Quark meson model**
- **Lattice QCD**
- **Holographic model**
- ⋮

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1. The Spin Alignment and Phase Structure of Thermal QGP under Rotation

(1) Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025);

(2) Y.-R. Bao and S.-Q. Feng, Phys. Rev. D 109, 096033 (2024).

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From Gluon Topology to Quark Charality

$$Q_w = \frac{1}{32\pi^2}\int d^4x F^{a\mu\nu}\tilde{F}^a_{\mu\nu}$$

In the quark–gluon plasma (QGP), once these gluon configurations are excited at a certain spacetime point, the topological charge of the vacuum around that point will be altered by these gluon configurations. The chirality imbalance $N_5 = N_R - N_L = -2Q_w$ is induced by the nonzero topological charge through the axial anomaly of QCD.

A non-zero Q_W will induce a corresponding fluctuation in the quark chiral imbalance N_5. This process will result in chiral imbalance between right and left quarks, leading to the violation of parity (P) and charge-parity (CP) symmetry in the thermal plasma.

The effects of a chiral imbalance in a medium can be implemented in the grand canonical ensemble by introducing a chiral chemical potential μ_5.

The Lagrangian of NJL model with the chiral chemical potential μ_5

The QCD matter produced in heavy-ion non-central collisions can rotate rapidly with local angular velocities ranging from 0.01 to 0.1 GeV. The Lagrangian of two flavors under the mean field approximation of the NJL model is given

chiral imbalance | Orbital motion | Spin motion

$$\mathcal{L}_{MFA}=\bar{\psi}\left[i\gamma^{\mu}\partial_{\mu}-M+\mu\gamma^{0}+\mu_5\gamma^{0}\gamma^{5}+\left(\gamma^{0}\right)^{-1}\left(\left(\vec{\omega}\times\vec{x}\right)\cdot\left(-i\vec{\partial}\right)+\vec{\omega}\cdot\vec{S}_{4\times4}\right)\right]-G_s\sigma^{2}$$

In cylindrical coordinates, the general positive-energy solutions for the quark field from the Dirac equation corresponding to the above Lagrangian is given as

$$\psi\left(\theta,r\right)=e^{-iEt+iP_z z}\begin{pmatrix} ce^{in\theta}J_n\left(p_t r\right)\\ ide^{i(n+1)\theta}J_{n+1}\left(p_t r\right)\\ c'e^{in\theta}J_n\left(p_t r\right)\\ id'e^{i(n+1)\theta}J_{n+1}\left(p_t r\right)\end{pmatrix}$$

Reference:

(1). Y. Jiang and J. Liao, Phys. Rev. Lett. 117, 192302 (2016);

(2). Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025)

The energy level, thermodynamic potential and chiral charge density

Through the calculation of the finite temperature field, the energy level and thermodynamic potential by rotation are obtained as follows:

$$E_{n,s}=\sqrt{\left(\sqrt{p_t^{\,2}+p_z^{\,2}}-s\mu_5\right)^2+M^2}-\left(n+\frac{1}{2}\right)\omega$$

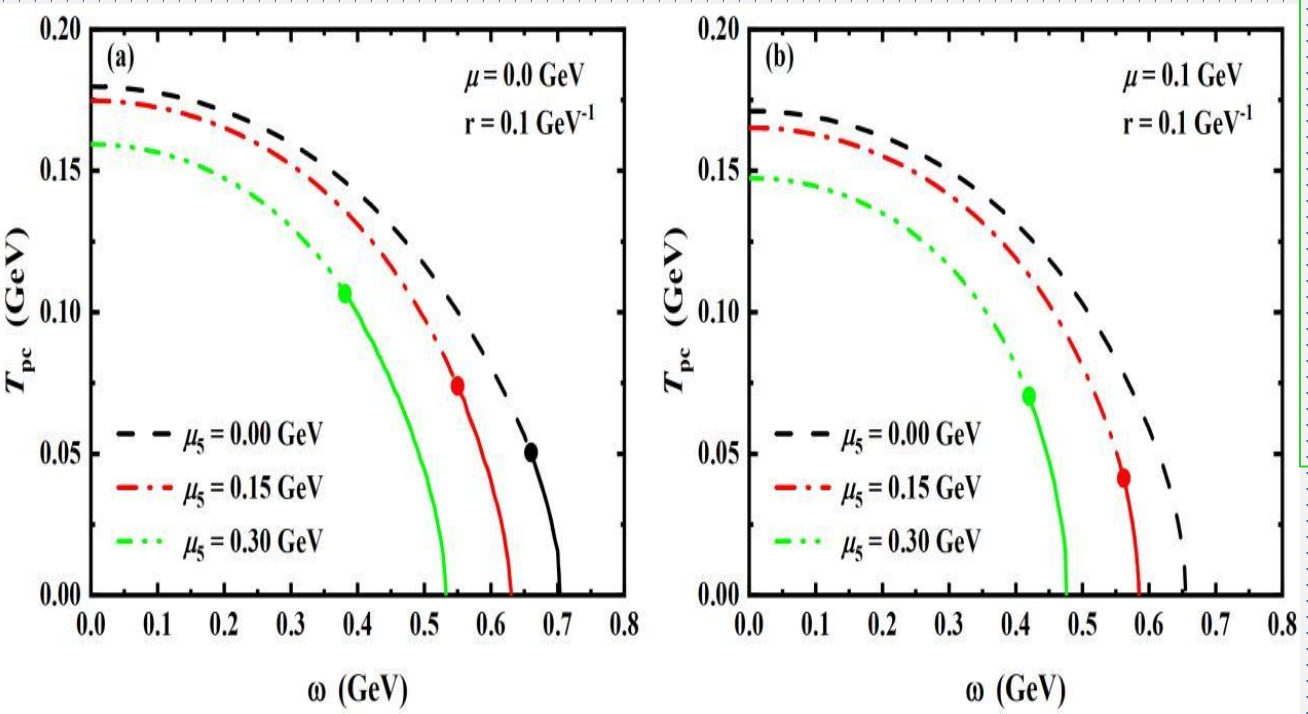
$$\Omega=\frac{(M-m)^2}{4G_s}-\frac{N_f N_c}{8\pi^2}\sum_{n=-\infty}^{+\infty}\sum_{s=\pm1}\int dp_t^{\,2}dp_z W_{n,s}\left\{E_{n,s}+T\ln\left[1+e^{-\beta(E_{n,s}-u)}\right]+T\ln\left[1+e^{-\beta(E_{n,s}+u)}\right]\right\}$$

$$W_{n,s}=\left[J_n^2(p_t r)+\lambda^2 J_{n+1}^2(p_t r)\right]\Big/\left(1+\lambda^2\right)$$

Gap equation: $\dfrac{\partial\Omega}{\partial M}=0,\quad \dfrac{\partial^2\Omega}{\partial M^2}>0$

The chiral charge density n_5 is defined by : $n_5=-\dfrac{\partial\Omega}{\partial\mu_5}$

The phase structure of T - ω plane with chiral chemical potential



This figure illustrates the chiral phase diagram in the $T_{pc}-\omega$ plane for varying chiral chemical potentials μ_5. The critical temperature T_{pc} decreases with increasing μ_5, but the critical end point (CEP) shifts toward higher T and lower ω.

It resolves how chiral imbalance alters the order and criticality of the chiral phase transition under rotation, providing insights into the interplay of vorticity and parity violation in quark-gluon plasma (QGP).

Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025).

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Spin Alignment of ρ Mesons

The ρ meson is a vector meson composed of a quark and an antiquark with parallel spins (total spin $s = 1$). In extreme environments such as the rotating quark-gluon plasma (QGP) produced in non-central heavy-ion collisions, ρ mesons may exhibit spin alignment — a phenomenon where their spin states correlate with the direction of system rotation.

The key observable for studying spin alignment is the spin density matrix element ρ_{00}, which describes the probability of the meson being in the spin states $s_z = 0$.

In the absence of polarization, $\rho_{00} = 1/3$ indicating isotropic spin distribution. A deviation from 1/3 signals spin polarization along a specific direction.

Spin Alignment of ρ Mesons

The spin alignment ρ_{00} is derived using a quark recombination model, where polarized quarks and antiquarks combine to form ρ mesons:

$$\rho_{00} = \frac{1 - P_q P_{\bar{q}}}{3 + P_q P_{\bar{q}}} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}$$

P_q and $P_{\bar{q}}$ are the polarization of quarks and antiquarks, respectively.

Spin Alignment of ρ Mesons

According to the quark recombination model [1, 2], the spin alignment of fermions is composed of the particle number densities of quarks and antiquarks, which is given by the partial derivative of the thermodynamic potential with respect to the chemical potential:

$$N_{\uparrow}^{+}=\frac{N_f N_c}{4\pi^2}\sum_{n=-\infty}^{+\infty}\sum_{s=\pm1}\int dp_t dp_z p_t \frac{J_n^2(p_t r)}{1+\lambda^2}\frac{e^{-\beta(E_{n,s}-\mu)}}{1+e^{-\beta(E_{n,s}-\mu)}}$$

$$N_{\downarrow}^{+}=\frac{N_f N_c}{4\pi^2}\sum_{n=-\infty}^{+\infty}\sum_{s=\pm}\int dp_t dp_z p_t \frac{\lambda^2 J_{n+1}^2(p_t r)}{1+\lambda^2}\frac{e^{-\beta(E_{n,s}-\mu)}}{1+e^{-\beta(E_{n,s}-\mu)}}$$

$$N_{\uparrow}^{-}=-\frac{N_f N_c}{4\pi^2}\sum_{n=-\infty}^{+\infty}\sum_{s=\pm1}\int dp_t dp_z p_t \frac{J_n^2(p_t r)}{1+\lambda^2}\frac{e^{-\beta(E_{n,s}+\mu)}}{1+e^{-\beta(E_{n,s}+\mu)}}$$

$$N_{\downarrow}^{-}=-\frac{N_f N_c}{4\pi^2}\sum_{n=-\infty}^{+\infty}\sum_{s=\pm1}\int dp_t dp_z p_t \frac{\lambda^2 J_{n+1}^2(p_t r)}{1+\lambda^2}\frac{e^{-\beta(E_{n,s}+\mu)}}{1+e^{-\beta(E_{n,s}+\mu)}}$$

[1] Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005);
[2] Z.-T. Liang and X.-N. Wang, Phys. Lett. B 629, 20 (2005).

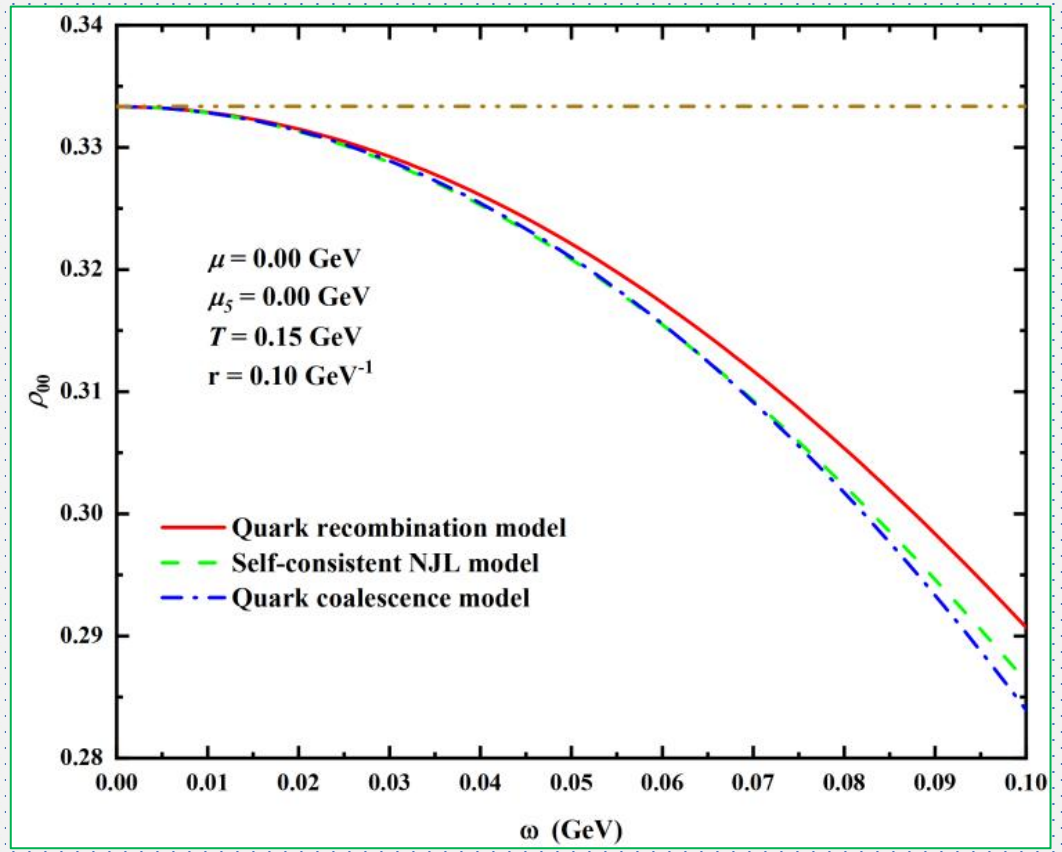
Comparison with other models

When studying the spin alignment of vector mesons ρ, besides our quark recombination model, there is also the quark condensation model [1]. The spin alignment corresponding to vector mesons ρ can take the following form

$$\rho_{00} = \frac{1}{3} - \frac{4}{9}(\beta\omega)^2$$

Another spin polarization model is self-consistent NJL model [2], the alignment of vector mesons (including ρ and ϕ) ($T = 150$ MeV), exhibits the following relationship:

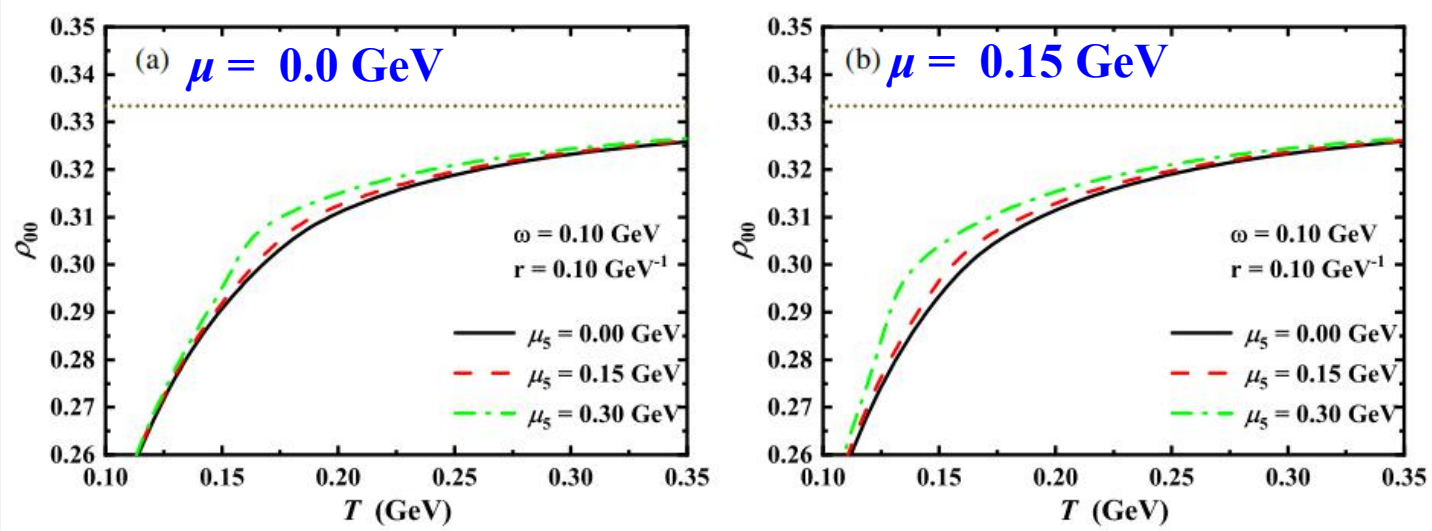
$$\rho_{00} = \frac{1}{3} - 5.10\omega^2 + 39.62\omega^4$$



[1] Y.-G. Yang, R.-H. Fang, Q. Wang, and X.-N. Wang, Phys. Rev. C 97, 034917(2018);

[2] M. Wei and M. Huang, Chin. Phys. C 47, 104105(2023).

The relationship between spin alignment ρ_{00} and temperature T



Spin alignment ρ_{00} of ρ mesons as a function of temperature T

ρ_{00} approaches 1/3 (isotropic spin alignment) at high T, while deviating 1/3 near the phase transition temperature.

Increasing μ_5 enhances ρ_{00}, reducing spin polarization.

Innovation & Impact: This is the first work to connect chiral imbalance (μ_5) with vector meson spin alignment, showing that μ_5 counteracts rotation-induced polarization near T_{pc}.

Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025).

Key Problem Solved: It explains how chiral imbalance moderates spin polarization in a temperature-dependent manner, crucial for interpreting experimental ρ_{00} data in QGP.

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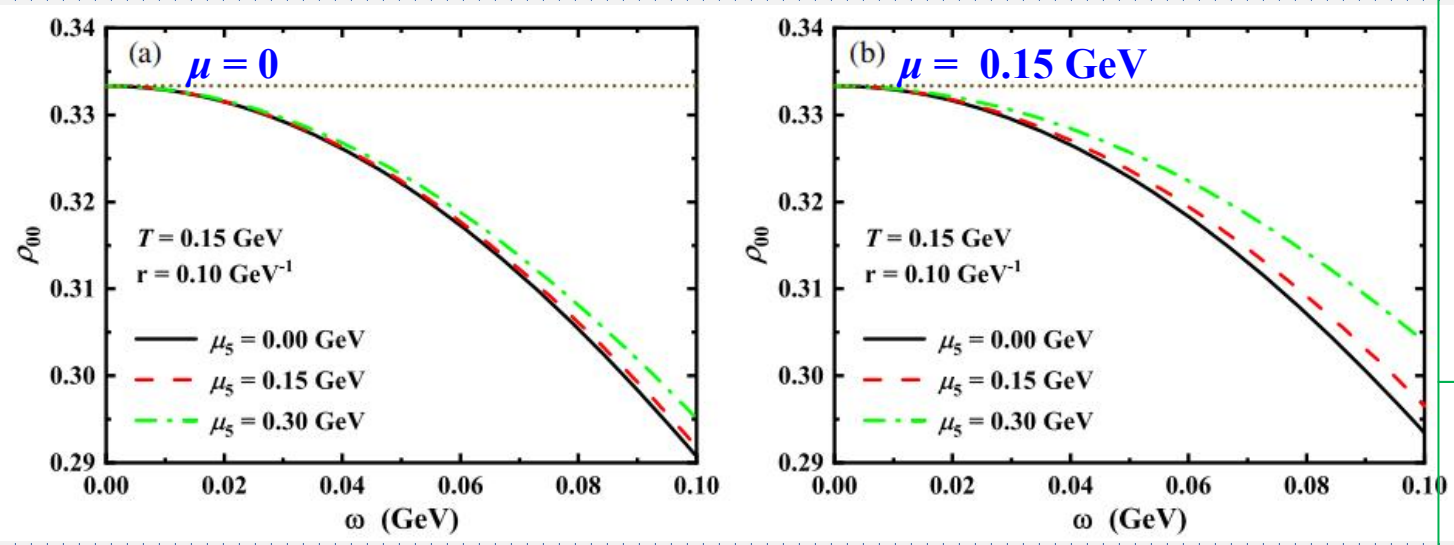
The relationship between spin alignment ρ_{00} and rotational velocity ω



Spin alignment ρ_{00} of ρ mesons as a function of ω

Research Content: ρ_{00} decreases with ω, deviating from 1/3 (indicating polarization). large ω makes more polarization, but larger μ_5 reduces this deviation, particularly at high ω, makes less polarization.

Innovation & Impact: It demonstrates that chiral imbalance suppresses rotation-induced spin polarization, offering a mechanism to tune meson spin states via μ_5

Key Problem Solved: It resolves how competing effects of rotation and chiral imbalance determine the net polarization of vector mesons, vital for probing spin-orbit coupling in QCD matter.

Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025).

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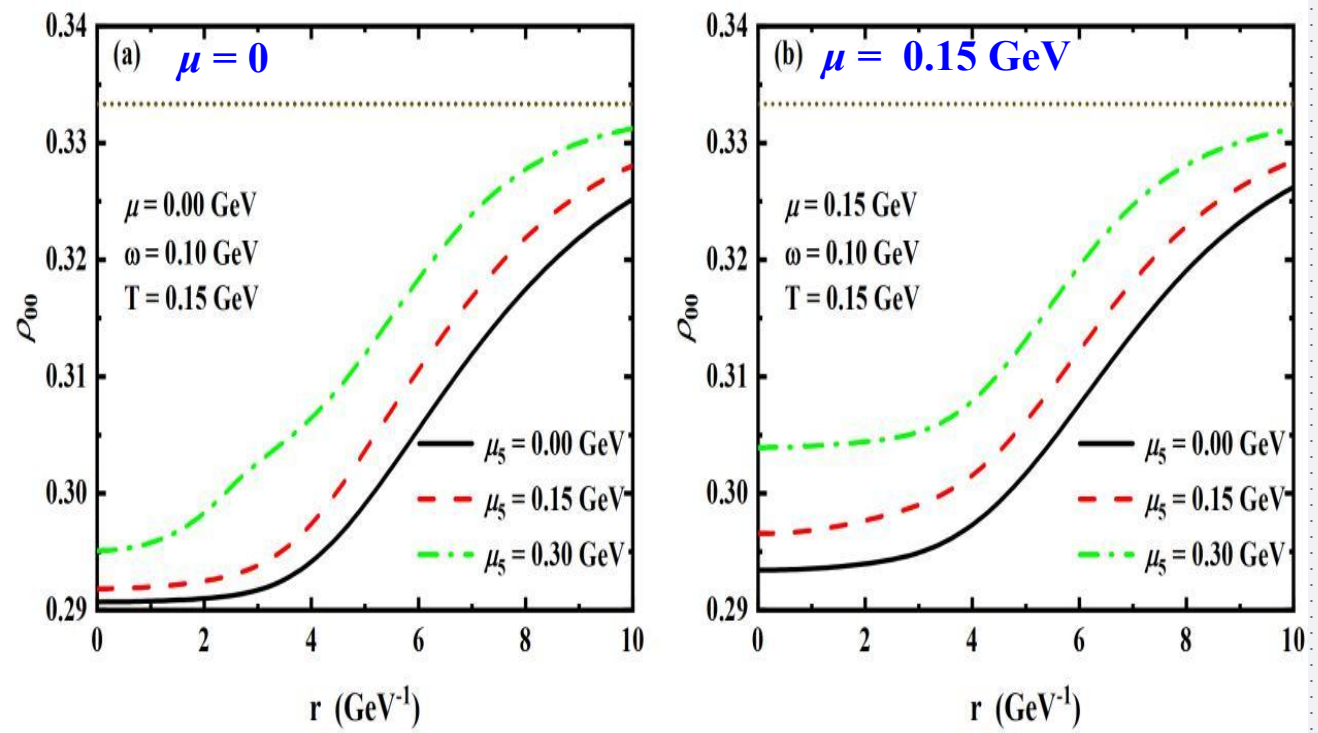
The relationship between spin alignment ρ_{00} and rational radius



Spin alignment ρ_{00} of ρ mesons as a function of radius r

Research Content: ρ_{00} increases with r, approaching 1/3, showing reduced polarization away from the rotation center. μ_5 enhances ρ_{00} at all r, especially near T_{pc}.

Innovation & Impact: This study pioneers the spatial analysis of spin alignment in rotating systems, revealing radial gradients in polarization and the moderating role of μ_5.

Key Problem Solved: It identifies the spatial inhomogeneity of spin polarization in vortical QGP, essential for understanding local spin dynamics in finite-size systems like heavy-ion collisions.

Y. Hua and S.-Q. Feng, Phys. Rev. D 111, 036012 (2025).

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2. Spectral signatures of heavy quarkonia in a rotating and anisotropic quark-gluon plasma: A holographic study

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

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Global rotation and Spatial anisotropy

Non-central heavy-ion collisions produce a strongly coupled QGP with:

Global rotation (angular velocity $\omega \sim 0.01 - 0.1$GeV)

Spatial anisotropy (expansion along collision axis)

Heavy quarkonia (J/Ψ, $\Upsilon(1S)$) are sensitive probes of the QGP medium.

Key Questions:

How do rotation and anisotropy jointly modify in-medium spectral functions and effective masses?

Do they exhibit directional selectivity in dissociation?

Is their effect additive or competitive?

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Theoretical Framework – Holographic Setup

Gauge/Gravity Duality (AdS/CFT) used as a non-perturbative tool

5D Einstein-Dilaton-Two-Maxwell action

First Maxwell field → finite chemical potential μ

Second Maxwell field → spatial anisotropy

Dilaton field $\phi(z)$ with parameters fitted to charmonium/bottomonium spectra.

Anisotropic metric (stationary frame):

$$d\tilde{s}^2 = \frac{b(z)}{z^2}\left[-g(z)dt^2 + dx_1^2 + z^{2-2/\nu}(dx_2^2 + dx_3^2) + \frac{dz^2}{g(z)}\right]$$

x_1 : longitudinal (anisotropy axis);

x_2, x_3 : transverse;

ν : anisotropy parameter ($1 < \nu \leq 4.5$);

$b(z) = e^{\frac{1}{2}cz^2}$: warp factor.

Rotation introduced via Lorentz boost along angular direction → rotating metric with ωl.

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

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The key steps for computing the spectral functions

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

1. Set up the holographic model

2. Introduce rotation

Apply a Lorentz boost along the angular coordinate to the static metric, obtaining a rotating frame metric with angular velocity ω. The Hawking temperature and chemical potential are rescaled by $\sqrt{1-\omega^2 l^2}$

3. Derive the flow equations for conductivities

For a vector field (dual to heavy quarkonia), decompose fluctuations into longitudinal (along the anisotropy direction x_1) and transverse (x_2, x_3) channels. Using the membrane paradigm, derive first-order differential equations for the longitudinal/transverse conductivities $\sigma_{L,T}(\varepsilon, z)$: $\partial_z \sigma = i\varepsilon \Delta (\sigma^2 - \Sigma^2)$, with Δ and Σ given by the metric coefficients and dilaton background.

4. Solve the flow equations

Impose regularity at the horizon ($\partial_z \sigma = 0$ at $z = z_h$) and integrate numerically from the horizon to the boundary ($z \to 0$) to obtain the boundary conductivities $\sigma_{L,T}(\varepsilon, 0)$.

5. Extract the spectral function

The spectral function is obtained via the retarded Green's function: $\rho(\varepsilon) \equiv -\mathrm{Im}\, G_R(\varepsilon) = \varepsilon\, \mathrm{Re}\, \sigma(\varepsilon, 0)$.

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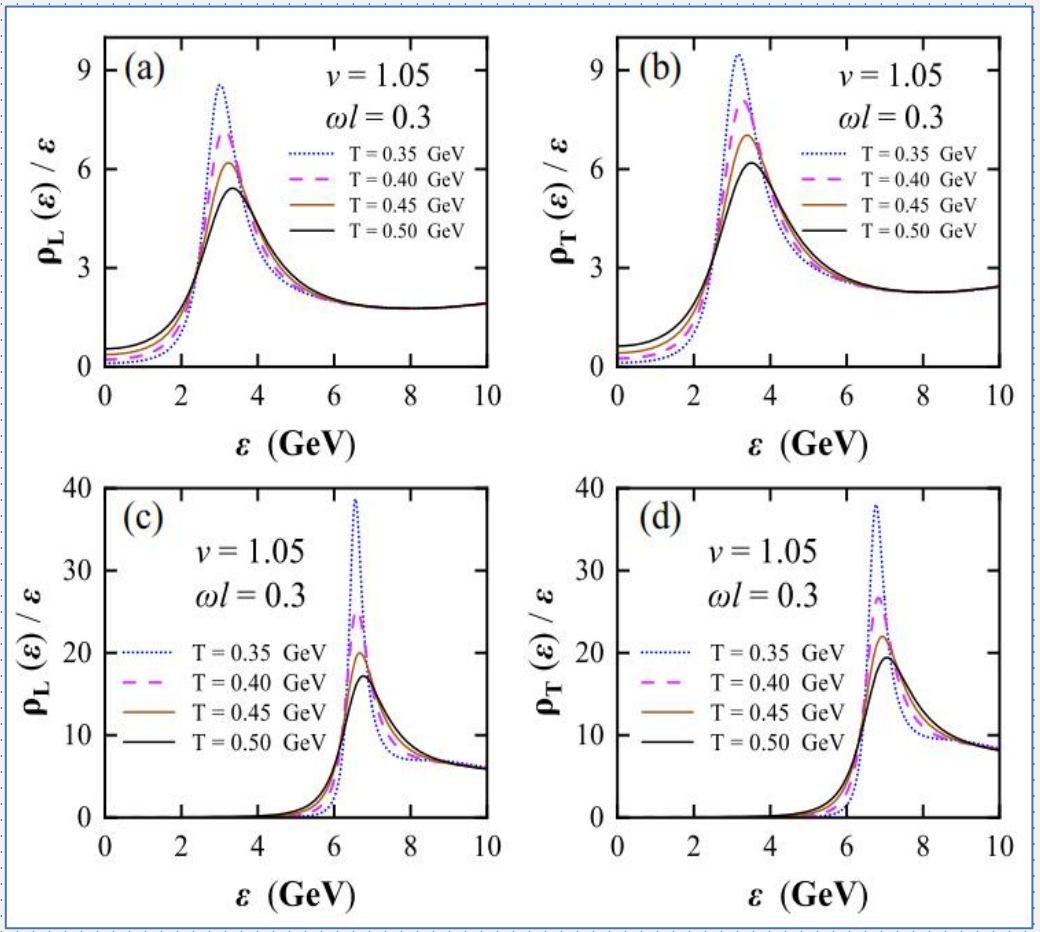
Temperature dependence of heavy quarkonium spectral functions in a rotating and anisotropic QGP



Temperature dependence: In a background that simultaneously **includes rotation and anisotropy, raising the temperature systematically suppresses the spectral peaks and broadens the widths for both polarizations. Crucially, the suppression is marginally stronger in the longitudinal (anisotropy-parallel) channel than in the transverse one, revealing that thermal dissociation acquires a subtle directional imprint even when rotation is present.** Additionally, **the much taller and narrower peaks of $\Upsilon(1S)$ compared to J/ψ confirm the expected heavy-quark mass suppression resistance.**

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

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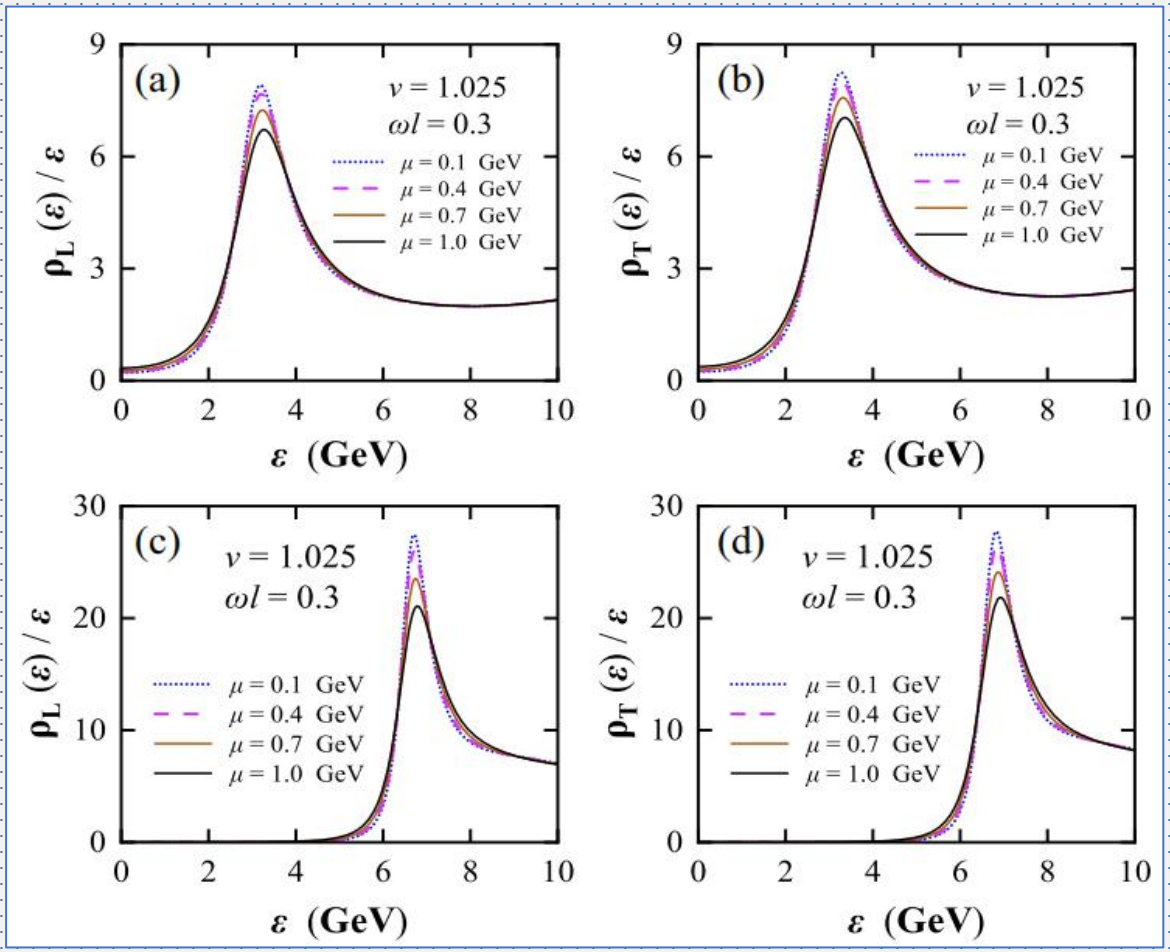
Chemical potential dependence of heavy quarkonium spectral functions in a rotating and anisotropic QGP



Chemical-potential dependence: At fixed temperature, increasing the baryon chemical potential μ also suppresses peaks and broadens widths in both longitudinal and transverse polarizations.

The key novelty is that density-driven dissociation remains robust in the rotating-anisotropic medium, acting as an independent melting agent via enhanced color screening.

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

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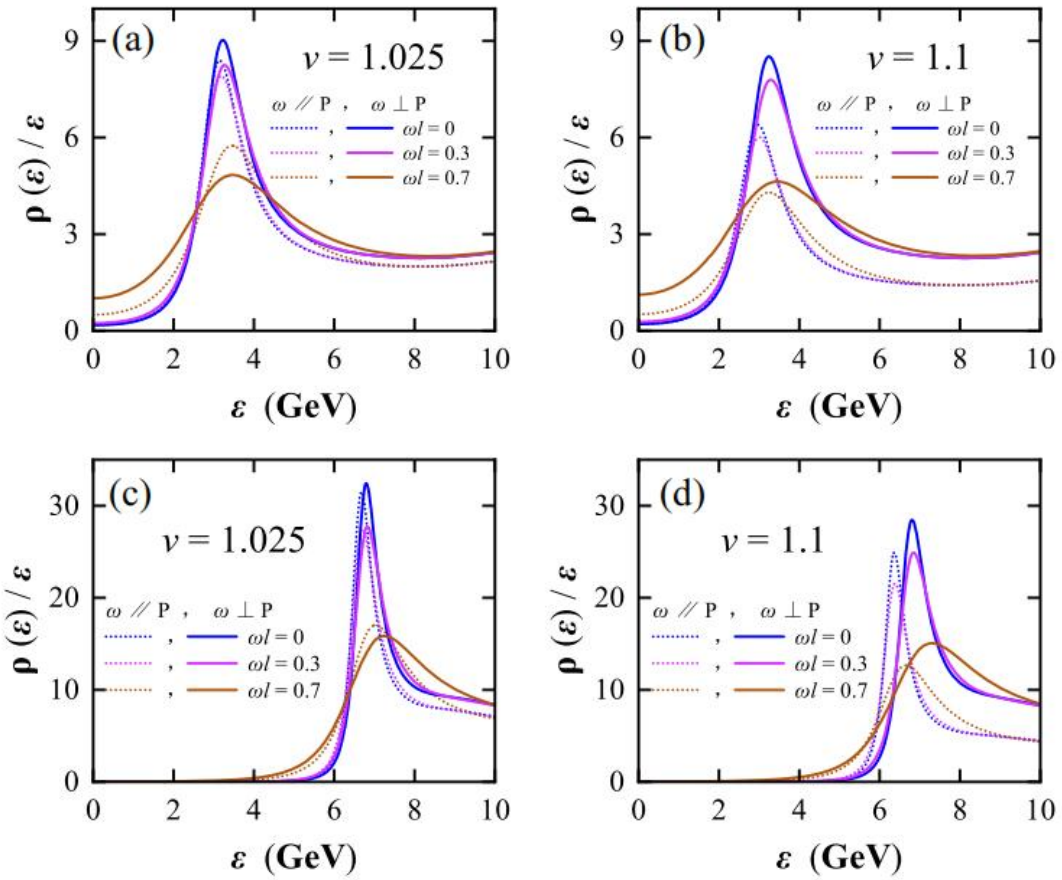
Competitive modulation of heavy quarkonium spectral functions and polarization-dependent dissociation by anisotropy and rotation



(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

(1) Global rotation and spatial anisotropy act not additively, but competitively.

(2) The directional suppression pattern of quarkonia in noncentral heavy-ion collisions reflects a dynamical battle between initial-state spatial deformation (anisotropy, which preferentially disrupts longitudinal polarizations) and later-stage collective vorticity (rotation, which more strongly affects transverse polarizations).

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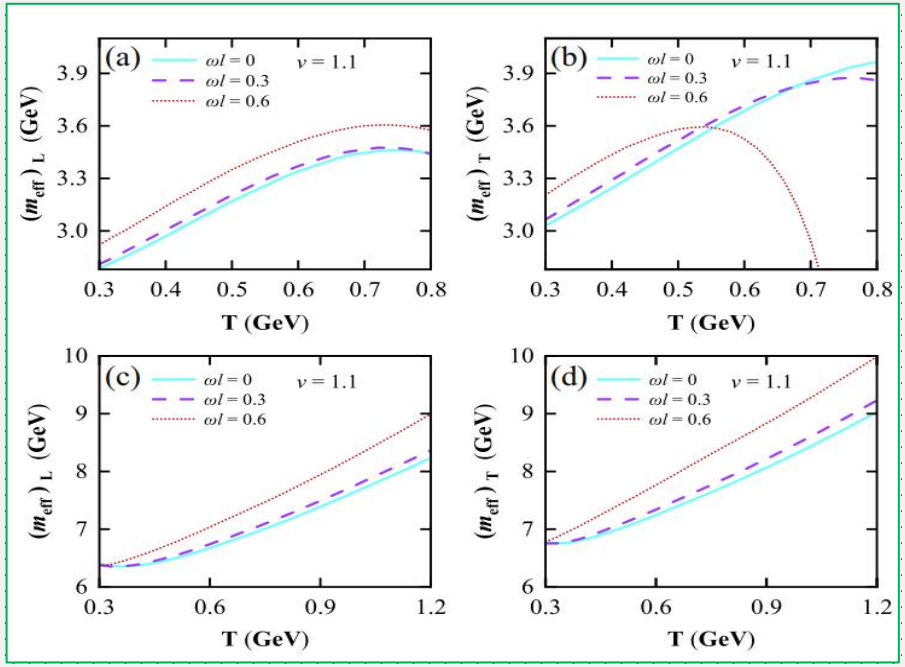
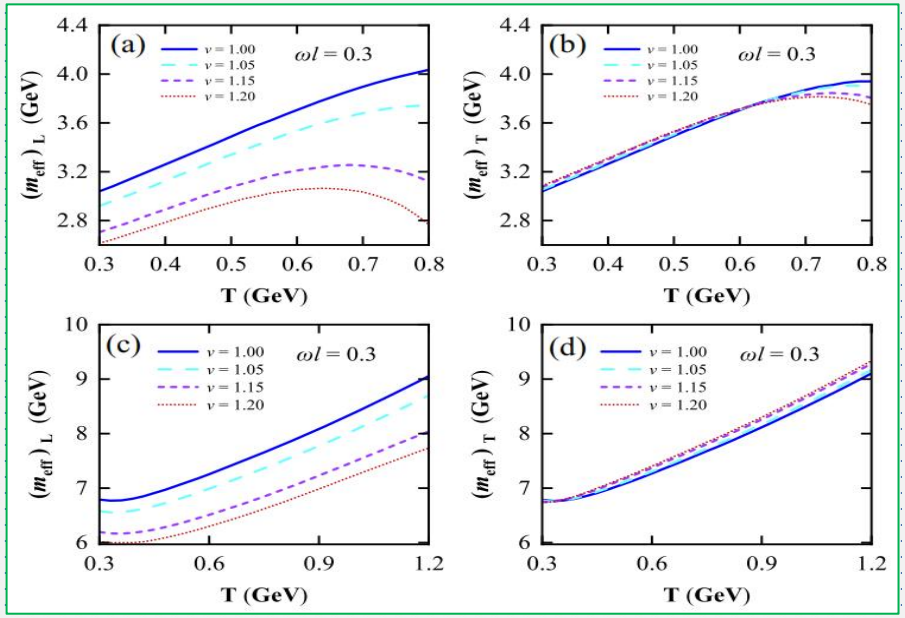
Modulation of heavy-quarkonium effective masses with temperature by rotation and anisotropy





The in-medium mass shift of heavy quarkonia is not merely thermal but is modulated by distinct directional geometric and dynamical distortions – rotation generates centrifugal effects in the transverse direction, whereas anisotropy stretches the medium along its axis.

Moreover, they uncover polarization-dependent nonmonotonic behavior that is state-sensitive: only the lighter J/ψ exhibits such complexity, while the heavier $\Upsilon(1S)$ remains largely monotonic. These findings provide a holographic explanation for the polarization-dependent mass modifications expected in noncentral heavy-ion collisions.

(1) X.-W. Shi and S.-Q. Feng, Phys. Rev. D 113, 096006 (2026)

(2) X.-L. Wang and S.-Q. Feng, Phys. Rev. D 110, 086018 (2024)

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3. Summary and Conclusions

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Summary and conclusions

1. The spin alignment of η_{00} and phase structure of thermal QGP under rotation are investigated. It is found that chiral imbalance have some effects on phase structure of QGP medium. We also study some dependences of spin alignment of η_{00} with temperature, angular velocity, rotational radius on chiral imbalance.

2. This holographic study examines spectral functions and effective masses of J/ψ and Υ(1S) in a rotating and anisotropic QGP, using a five-dimensional Einstein-dilaton-two-Maxwell model. We find that both rotation and anisotropy individually enhance quarkonium dissociation (peak suppression and broadening), but with opposite directional biases: anisotropy preferentially suppresses longitudinal polarizations, while rotation more strongly affects transverse ones.

Thanks !

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