Gluon polarization under rotation and its contribution to phase transitions and vector meson spin alignment

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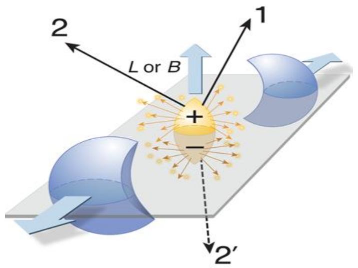
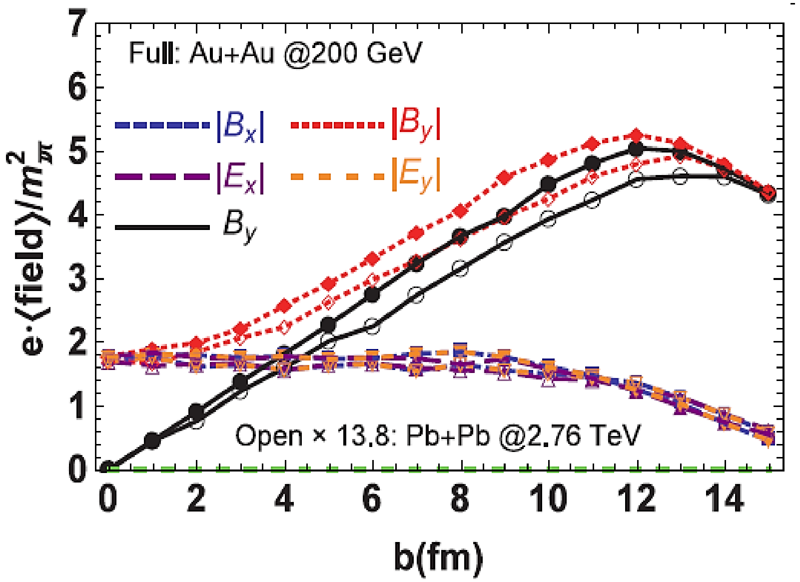
HOLOGRAPHIC PERSPECTIVES ON CHIRAL TRANSPORT AND SPIN DYNAMICS, MAR.24-29,2025

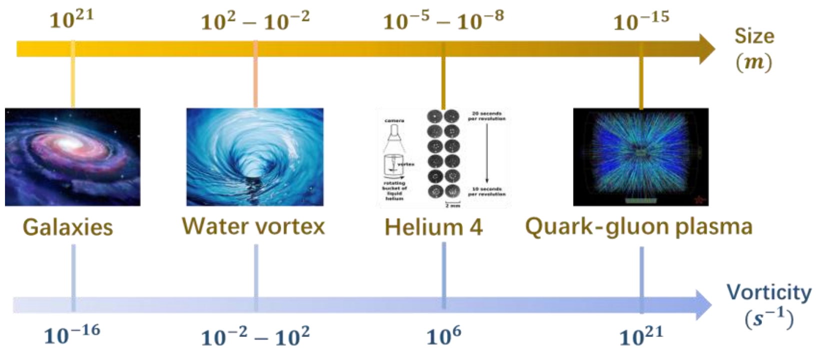
MAGNETIC FIELDS

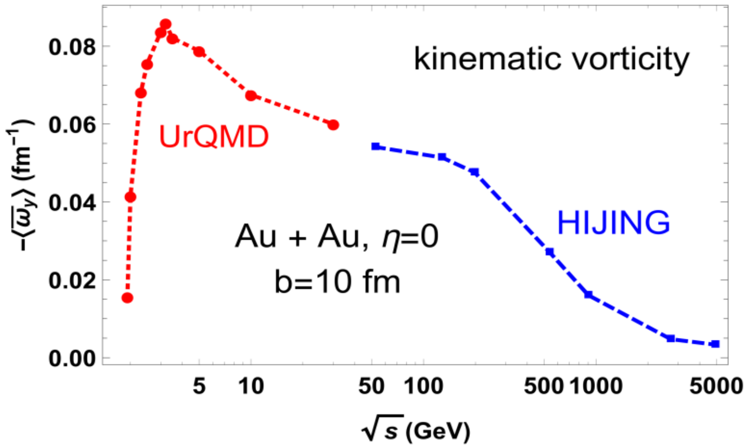


ROTATION

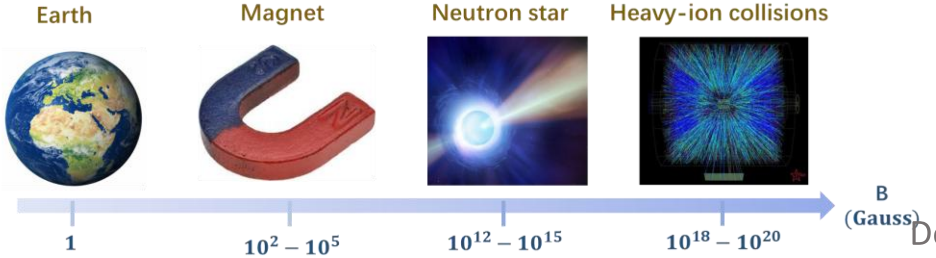


HIJING (Deng-XGHuang PRC2012)



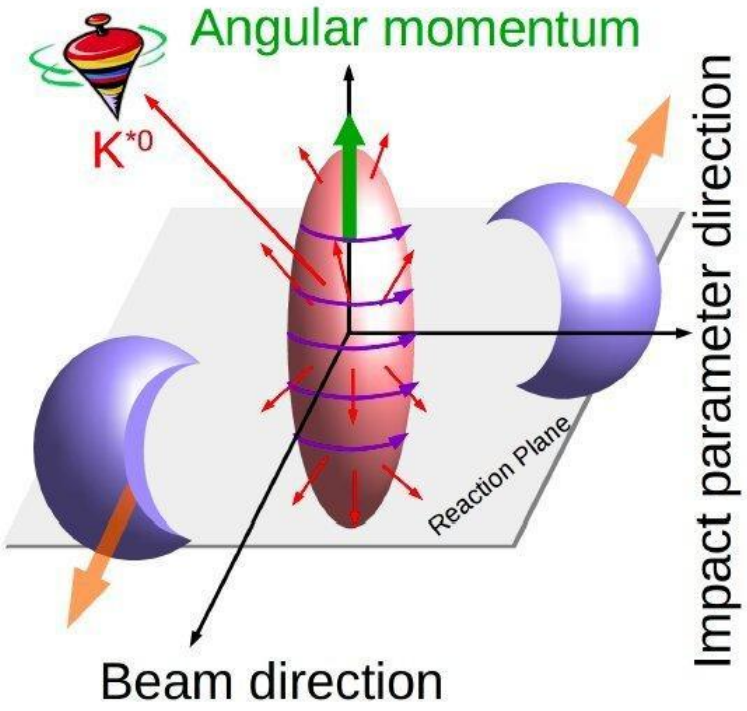


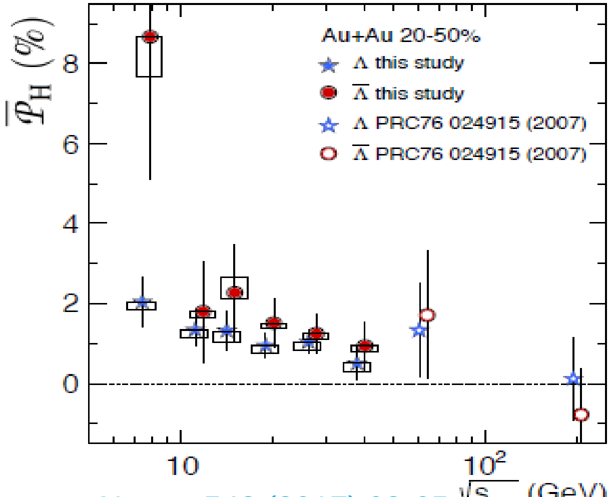
Deng-XGHuang PRC2016



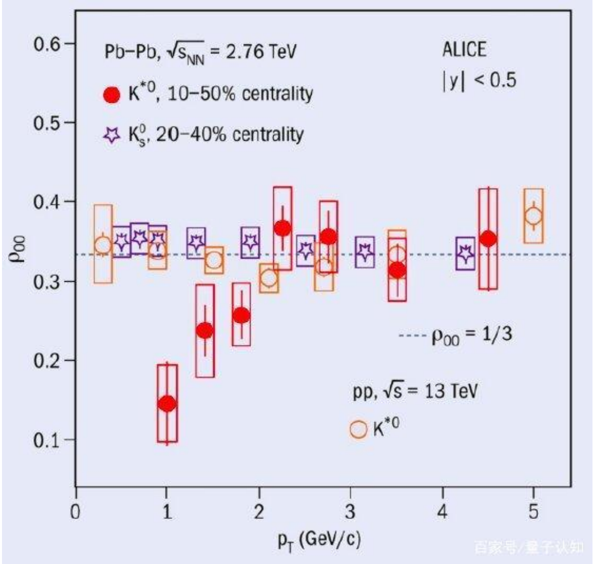
Deng-XGHuang-GLMa-Zhang PRC2020

$O(10^4)-O(10^5)\hbar$





Nature 548 (2017) 62-65



Physical Review Letters (2020).
DOI: 10.1103/PhysRevLett.125.012301

1, QCD phase transitions under rotation,

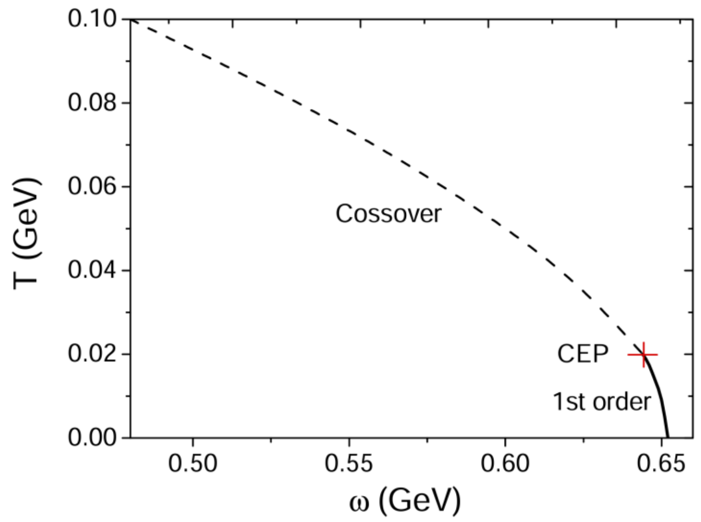
2, Spin alignment

Chial dynamics under rotation from NJL model

$$\mathcal{L} = \bar{\psi}[i\bar{\gamma}^{\mu}(\partial_\mu + \Gamma_\mu) - m]\psi + G_S[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] - G_V[(\bar{\psi}\gamma_\mu\psi)^2 + (\bar{\psi}\gamma_\mu\gamma_5\psi)^2].$$

$$\Gamma_\mu = \frac{1}{4}\times\frac{1}{2}[\gamma^a,\gamma^b]\Gamma_{ab\mu} \qquad \Gamma_{ab\mu} = \eta_{ac}\left(e^c_\sigma G^\sigma_{\mu\nu}e^\nu_b - e^\nu_b\partial_\mu e^c_\nu\right)$$

$$\mathcal{L} = \bar{\psi}[i\gamma^\mu(\partial_\mu + \gamma^0\omega\hat{J}_z) - M]\psi - \mu\psi^\dagger\psi - \frac{(M-m)^2}{4G_S}.$$



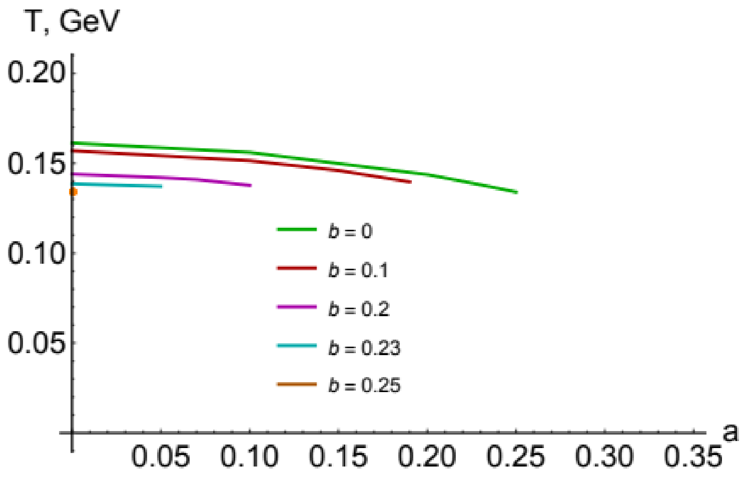
Yin Jiang, Jinfeng Liao PRL2016

Angular velocity is similar to the chemical potential, critical temperature decreases with angular velocity.

Consistent with many other effective model results, many references should be here.

Holographic results: critical temperature decreases with angular velocity

Kerr-AdS black holes



A

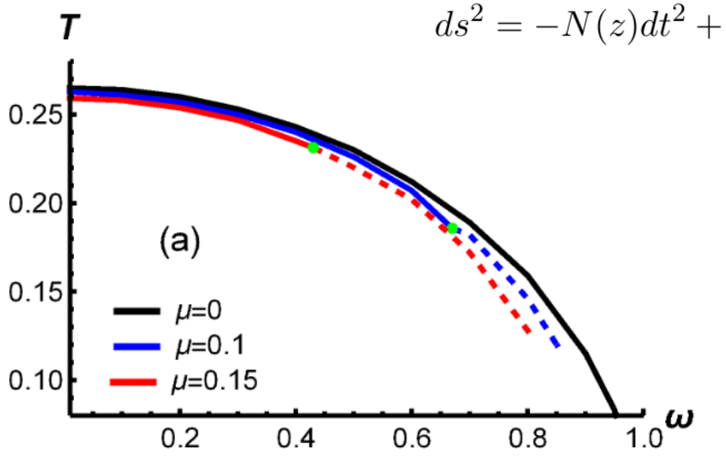
I.Y. Aref'eva, et al., e-Print: 2004.12984, JHEP (2021),
Confirmed by many results in this framework

Doing a local Lorentz boost

Pure gluon system

$$t \to \frac{1}{\sqrt{1-(\omega l)^2}}(t+\omega l^2\theta), \phi \to \frac{1}{\sqrt{1-(\omega l)^2}}(\theta+\omega t).$$

$$ds^2 = -N(z)dt^2 + \frac{H(z)dz^2}{G(z)} + R(z)(d\theta + P(z)dt)^2 + H(z)\sum_{i=1}^{2} dx_i^2,$$



$$N(z) = \frac{H(z)G(z)(1-\omega^2 l^2)}{1-G(z)\omega^2 l^2},$$

$$H(z) = \frac{L^2 e^{2A_e(z)}}{z^2},$$

$$R(z) = H(z)\gamma^2 l^2 - H(z)G(z)\gamma^2\omega^2 l^4,$$

$$P(z) = \frac{\omega - G(z)\omega}{1-G(z)\omega^2 l^2},$$

$$\gamma = \frac{1}{\sqrt{1-\omega^2 l^2}}.$$

Xun Chen, Lin Zhang, Danning Li,
Defu Hou, MH, arXiv: 2010.14478, JHEP (2021)
Confirmed by many results in this framework

Influence of relativistic rotation on the confinement/deconfinement transition in gluodynamics

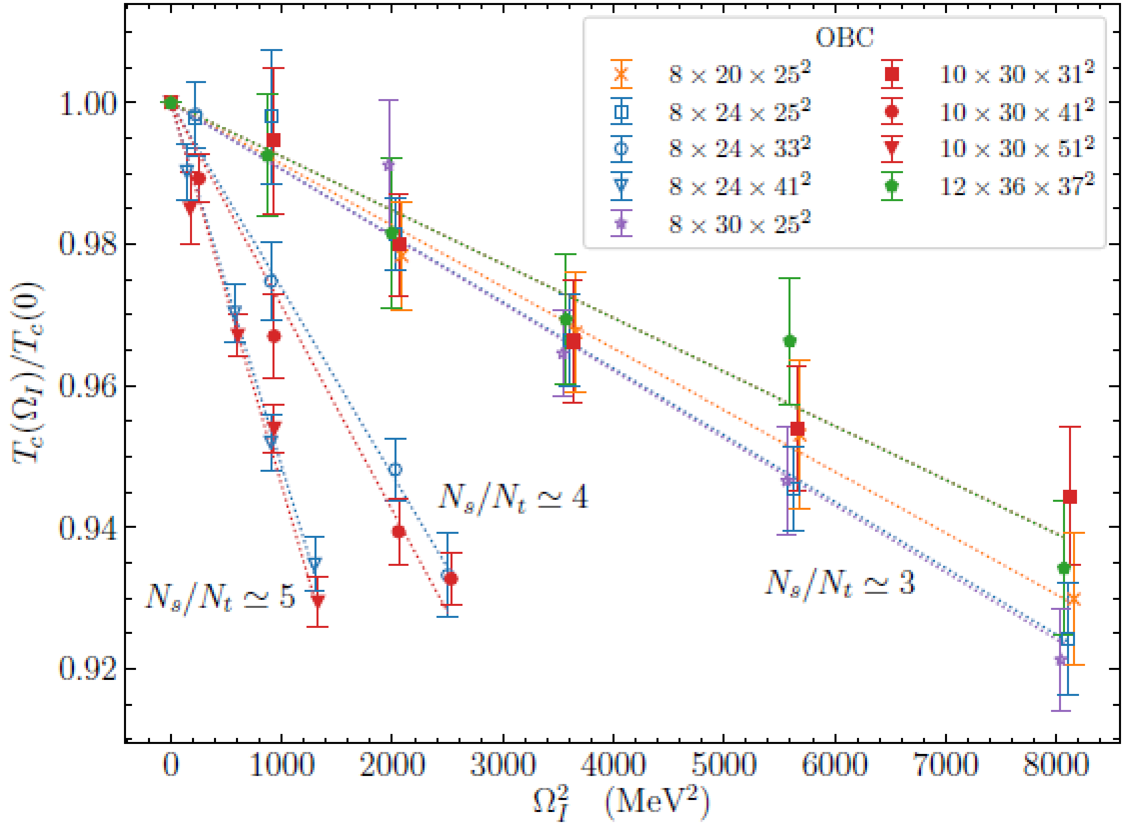
V. V. Braguta,[1,2,3,*] A. Yu. Kotov,[4,†] D. D. Kuznedelev,[3,‡] and A. A. Roenko[1,§]

Phys.Rev.D 103 (2021) 9, 094515,
e-Print: 2102.05084

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2\Omega^2 & \Omega y & -\Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

imaginary angular velocity $\Omega_I = -i\Omega$

$$\frac{T_c(\Omega_I)}{T_c(0)} = 1 - C_2\Omega_I^2 \qquad\qquad \frac{T_c(\Omega)}{T_c(0)} = 1 + C_2\Omega^2$$



Critical temperature of deconfinement phase transition increases with rotation in lattice! Confirmed by other lattice studies!

Ji-Chong Yang,Xu-Guang Huang e-Print: 2307.05755 [hep-lat]

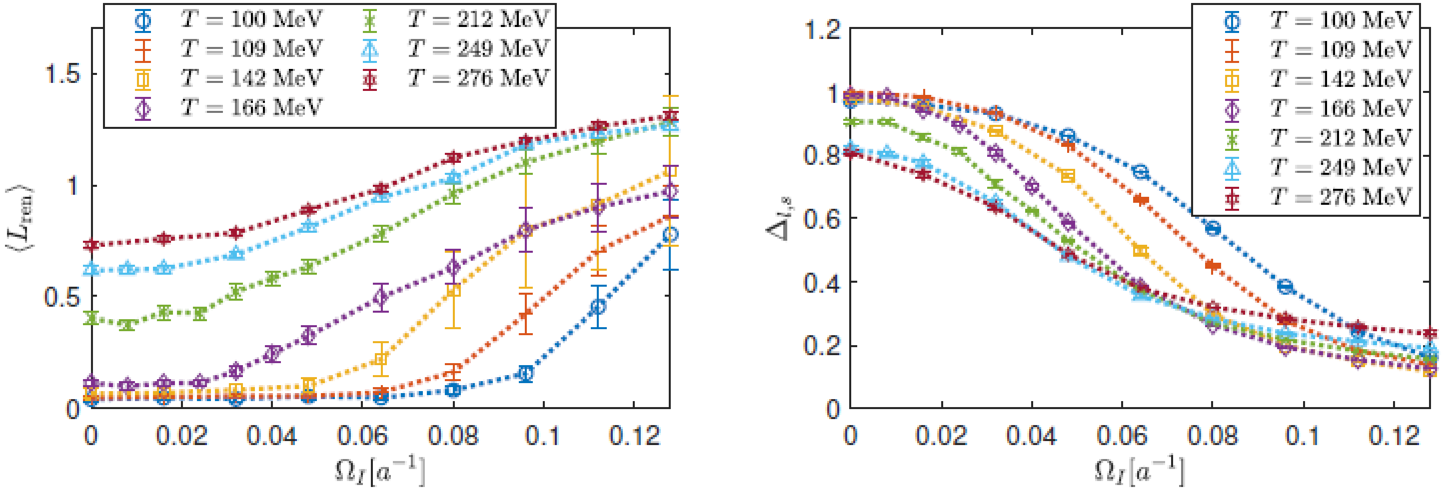


FIG. 4. The Polyakov loop and chiral condensate as functions of Ω_I.

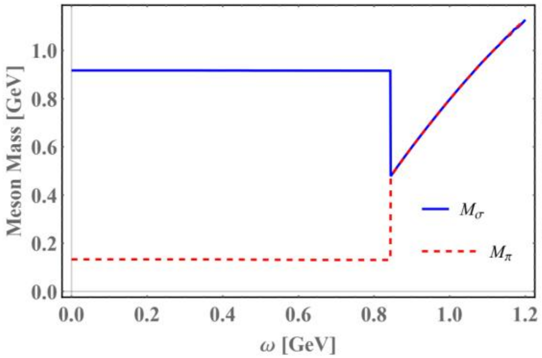
Opposite results on the effect of rotation on the critical temperature of deconfinement phase transition in hQCD and lattice has attracted much attention ! What’s missing?

XXXII International (online) Workshop on High Energy Physics “Hot problems of Strong Interactions”, Nov.9-13, 2020

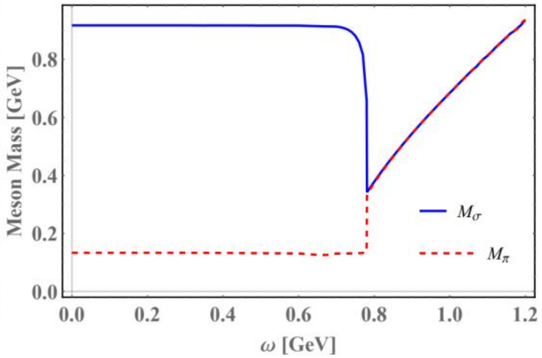
Victor Ambrus, *Phys.Lett.B* 855 (2024), e-Print: 2502.09738,…
Maxim Chernodub, Phys.Rev.D 103 (2021), *Phys.Rev.D* 110 (2024),…
Kenji Fukushima, *Phys.Lett.B* 859 (2024),…
Matthias Kaminski *Phys.Rev.D* 108 (2023), …
Gaoqing Cao, e-Print: 2310.03310,…
Yin Jiang, Phys.Lett.B 862 (2025),…
……

What’s missing?

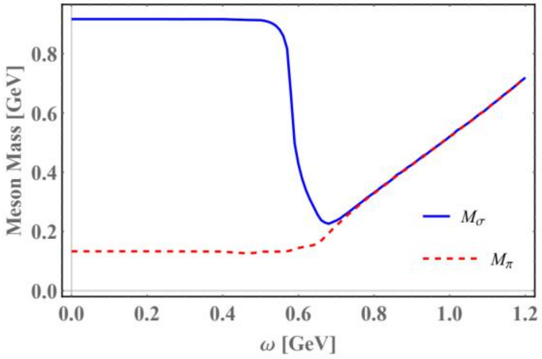
Minghua Wei, Ying Jiang, MH 2011.10987
mesons under rotation in the NJL model



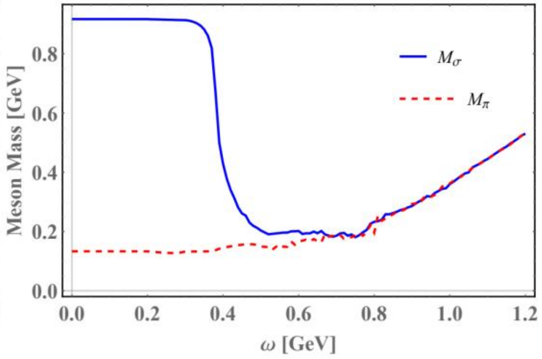
(a) scalar meson mass as a function of angular velocity at $\mu = 0MeV$



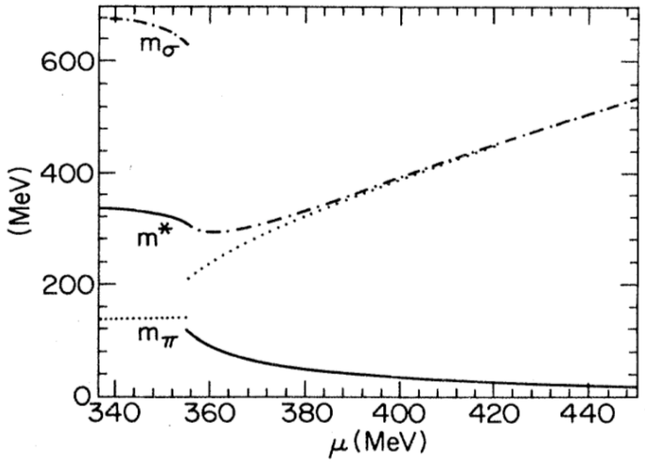
(b) scalar meson mass as a function of angular velocity at $\mu = 100MeV$



(c) scalar meson mass as a function of angular velocity at $\mu = 200MeV$



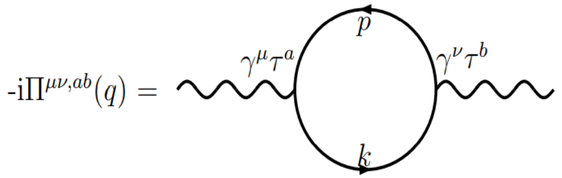
(d) scalar meson mass as a function of angular velocity at $\mu = 300MeV$



Scalar meson masses as functions of angular velocity. The effect of rotation on the scalar meson mass is similar to that of chemical potential !

Vector meson masses as functions of angular velocity

$$\Pi^{\mu\nu,ab}(q) = -i \int d^4\tilde{r} Tr_{sfc}[i\gamma^\mu \tau^a S(0;\tilde{r}) i\gamma^\nu \tau^b S(\tilde{r};0)] e^{q\cdot\tilde{r}}$$

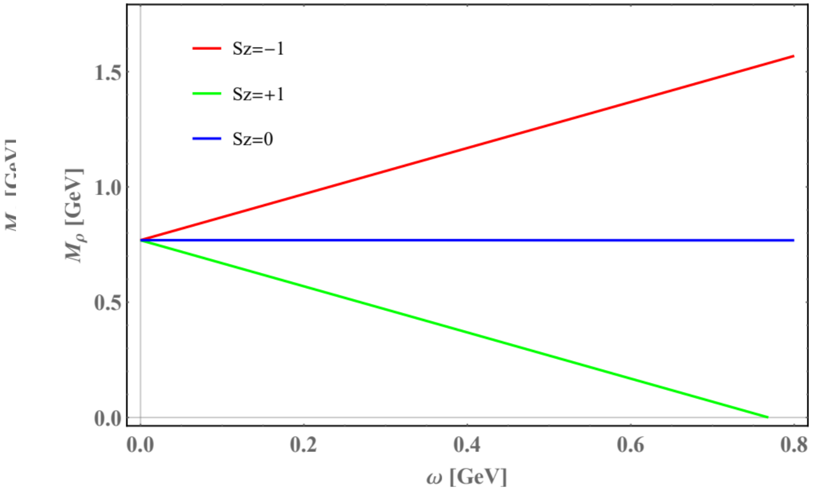


$$D_\rho^{\mu\nu}(q^2) = D_1(q^2)P_1^{\mu\nu} + D_2(q^2)P_2^{\mu\nu} + D_3(q^2)L^{\mu\nu} + D_4(q^2)u^\mu u^\nu$$

$$P_1^{\mu\nu} = -\epsilon_1^\mu \epsilon_1^\nu, (S_z = -1 \text{ for } \rho \text{ meson}$$
$$P_2^{\mu\nu} = -\epsilon_2^\mu \epsilon_2^\nu, (S_z = +1 \text{ for } \rho \text{ meson}$$
$$L^{\mu\nu} = -b^\mu b^\nu, (S_z = 0 \text{ for } \rho \text{ meson })$$

$$1 + 2G_V A_i^2 = 0$$

$$A_1^2 = -(\Pi_{11} - i\Pi_{12}), (S_z = -1 \text{ for } \rho \text{ mes}$$
$$A_2^2 = -\Pi_{11} - i\Pi_{12}, (S_z = +1 \text{ for } \rho \text{ meson })$$
$$A_3^2 = \Pi_{33}, (S_z = 0 \text{ for } \rho \text{ meson })$$



Minghua Wei, Ying Jiang, MH, 2011.10987

Zeeman splitting effect for different spin component! Mass of spin component +1 vector meson decreases with rotation. Rotation is charge blind, rho meson can be regarded as a gluon.

For massless gluon, will have BEC. (corresponding to Nielson-Olesson instability by Kenji?

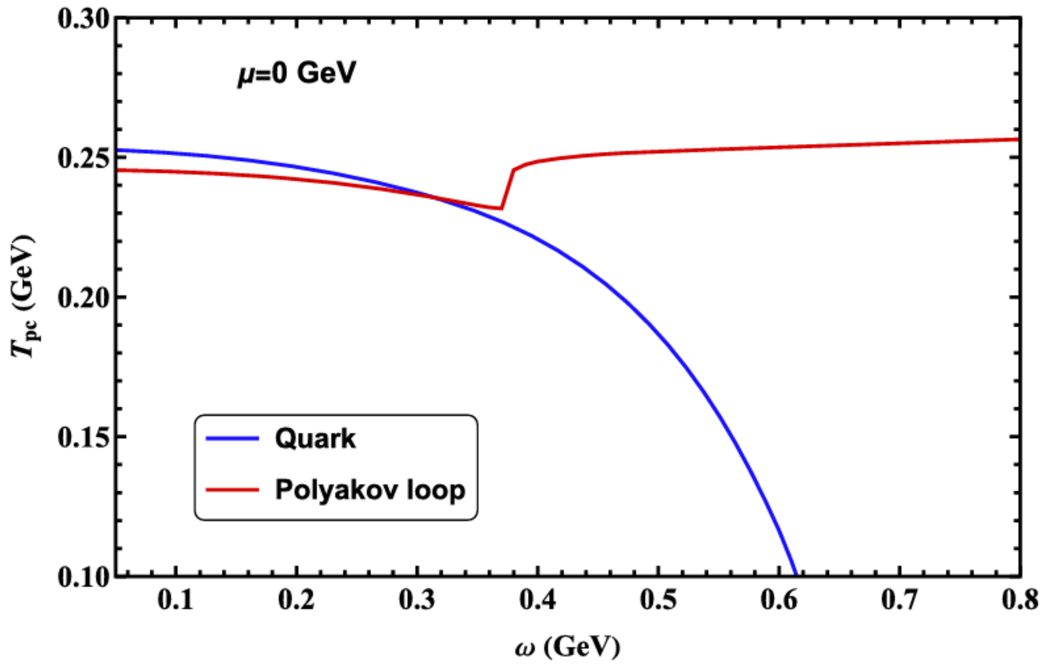
Gluons are spin-1 particles, should be more sensitive to rotation than that of quarks!

Add gluodynamics under rotation in PNJL

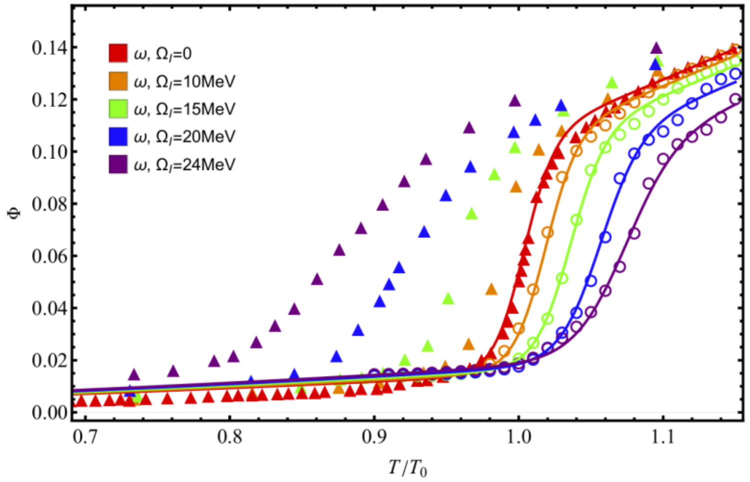
$$\mathcal{L}_{\rm PNJL} = \mathcal{L}_{\rm NJL} + \bar{\psi}\gamma^{\mu}A_{\mu}\psi - \mathcal{U}(\Phi, \bar{\Phi}, T),$$

Splitting of chiral and deconfinement phase transitions induced by rotation!

Fei Sun, Kun Xu, MH, e-Print: 2307.14402, PRD2023



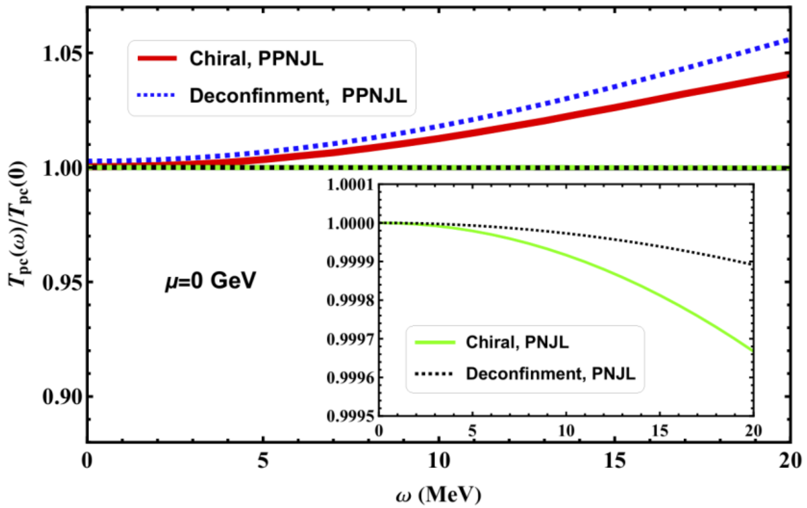
Polarized-Polyakov-loop Nambu–Jona-Lasinio model under rotation



$$\frac{\mathcal{U}\left(\Phi,\bar{\Phi},T,\omega\right)}{T^4} = -Cf\left(T,\omega\right)\left(\frac{T}{T_0}\right)^2\Phi\bar{\Phi} - \frac{1}{3}\left(\Phi^3+\bar{\Phi}^3\right) + C^{-1}f^{-1}\left(T,\omega\right)\left(\frac{T}{T_0}\right)^{-2}\Phi^2\bar{\Phi}^2,$$

$$\Phi\left(T,\omega\right) = \left(\frac{T}{T_0}\right)^2 f\left(T,\omega\right)$$

Fit Lattice data V. V. Braguta PRD2021



Both chiral and deconfinement PTs critical temperatures increase with rotation!

Lesson: Polarized gluons should be taken into account under rotation!

Fei Sun, Jingdong Shao, Rui Wen, Kun Xu,
and MH, e-Print: 2402.16595, PRD 2024

Holographic QCD Model Nf=2

$$S^s_{\rm tot} = S^s_G + S^s_M,$$
$$S^s_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g^s}e^{-2\Phi}\left[R^s + 4\partial_M\Phi\partial^M\Phi - V^s(\Phi) - \frac{h(\Phi)}{4}e^{\frac{4\Phi}{3}}F_{MN}F^{MN}\right],$$
$$S^s_M = -\int d^5x\sqrt{-g^s}e^{-\Phi}{\rm Tr}\left[\nabla_M X^\dagger\nabla^M X + V_X(|X|, F_{MN}F^{MN})\right],$$

Anisotropic background under rotation, cylindrical coordinate

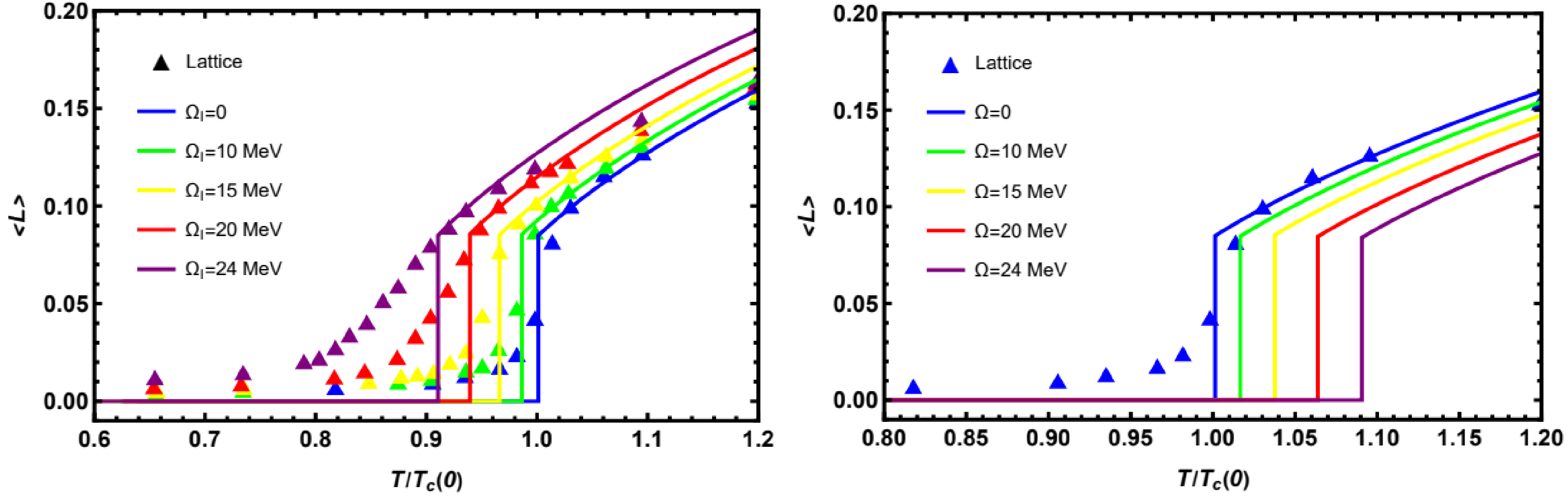
$$ds^2 = \frac{L^2e^{2A_e(z)}}{z^2}[-f(z)dt^2 + \frac{dz^2}{f(z)} + e^{B(z)}dr^2 + r^2e^{B(z)}d\theta^2 + e^{-2B(z)}dx_3^2],$$

$$A_M = (A_t, 0, 0, A_\theta, 0), \qquad A_\theta = \Omega r^2, \qquad A_\theta \sim \Omega r^2 + \rho_\theta(r, z).$$

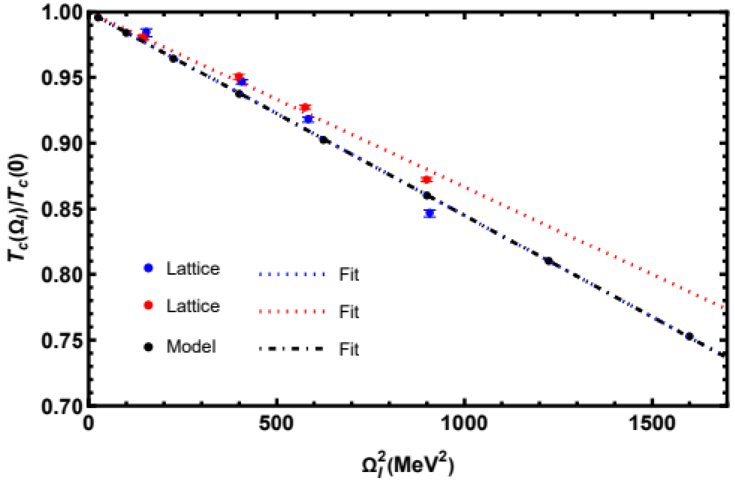
Polarized gluodynamics represented by arotation-dependent dilation field

$$\Phi = (\mu_G + \mu_\Omega\Omega^2)^2 z^2 \tanh(\mu^4_{G^2} z^2/(\mu_G + \mu_\Omega\Omega^2)^2).$$

Y. Chen, X. Chen, D. Li and MH, arXiv:2405.06386, Phys.Rev.D 111 (2025)



(a) imaginary rotation (b) real rotation



$$T_c(\Omega_I)/T_c(0) = 1 - C_2\Omega_I^2$$

The only parameter μ_Ω to be determined in the DHQCD model is based on the relationship between the phase transition temperature $T_c(\Omega_I)$ and the imaginary angular velocity predicted by lattice QCD.

Y. Chen, X. Chen, D. Li and MH, arXiv:2405.06386, Phys.Rev.D 111 (2025)

Results

Y. Chen, X. Chen, D. Li and MH, arXiv:2405.06386, Phys.Rev.D 111 (2025)

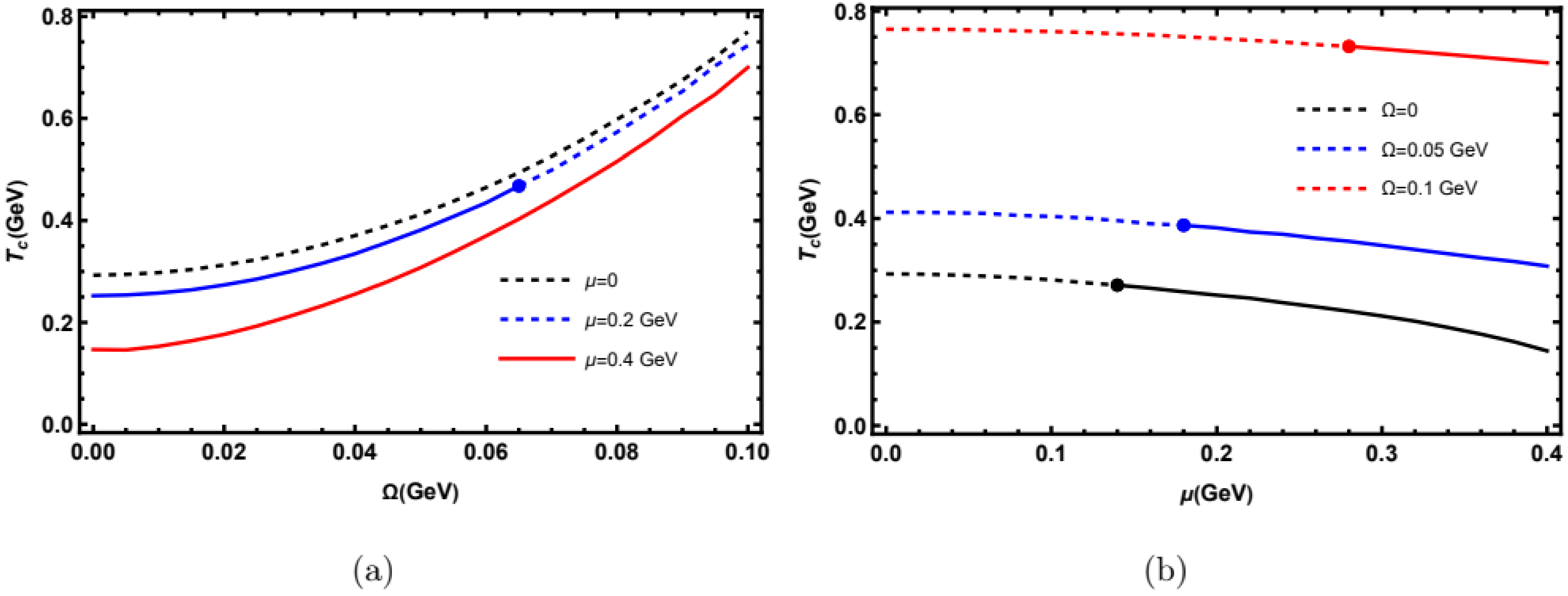
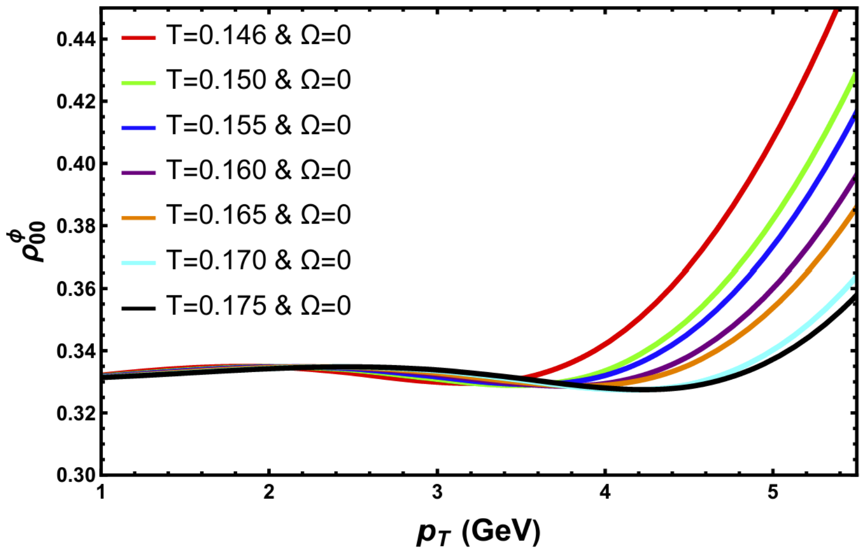


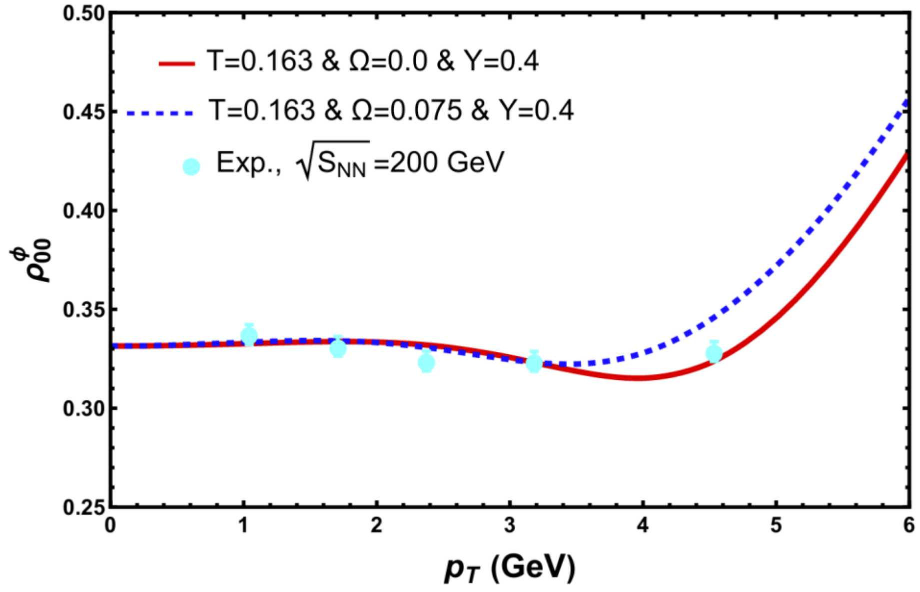
FIG. 7. The $T - \Omega$ and $T - \mu$ phase diagrams of chiral phase transition for 2-flavor system.

Spin alignment in Holographic QCD Model Nf=2+1+1

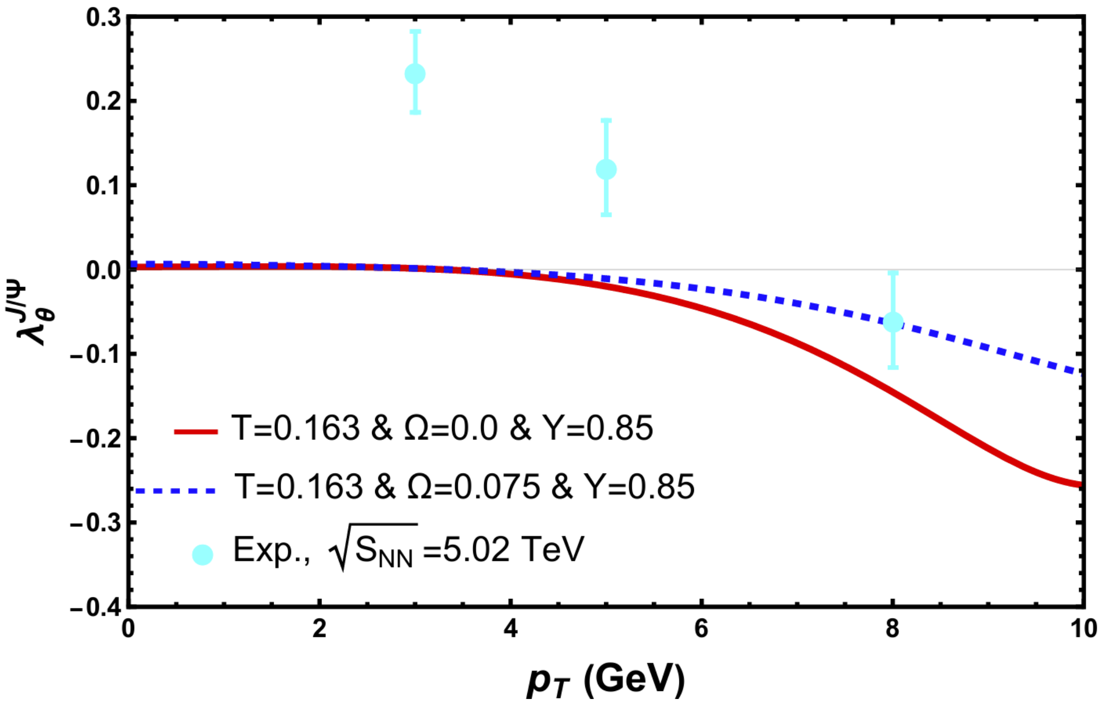
Hiwa A. Ahmed, Yidian Chen, and MH, arXiv:2501.13401, PRD2025

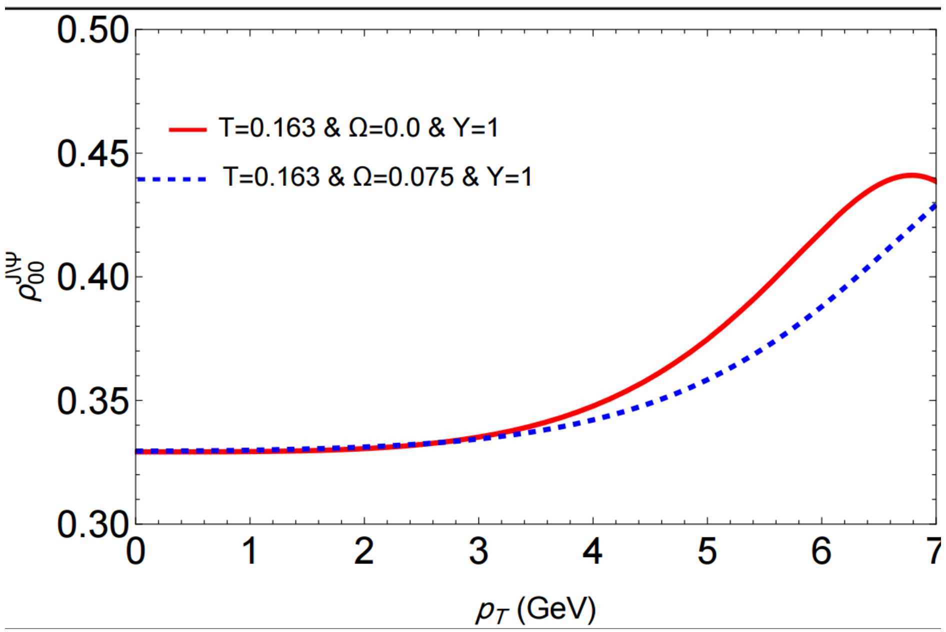
$$\varrho^{\mu\nu}(x,p) = \sum_{\lambda,\lambda'=0,\pm 1} v^{\mu}(\lambda,p) v^{*\nu}(\lambda',p)\, \tilde{\varrho}_{\lambda\lambda'}(x,p),$$





For the ϕ meson, the averaged ρ00 over the full range of azimuthal angle shows weak temperature dependence at low transverse momentum (pT), but significant suppression at high pT, aligning with experimental observations





The J/Ψ meson, however, displays insensitivity to temperature and rotation up to pT = 5 GeV

Summary

1, The puzzle on critical temperature of QCD PTs under rotation is understood by considering polarized gluon DOF!

2, More elegant framework taking into account of polarized gluodynamics under rotation is needed.

https://indico.ihep.ac.cn/event/24476/

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Welcome to join us at UCAS, Beijing!

Thank you for your attention!

Inhomogeneous condensation

Y. Chen, Danning Li and M. Huang, Phys.Rev.D (2022)

Parameters $(m_q, v_3, v_4) = (0, -3{,}8)$, $\mu_0 = (0.43\ GeV)^2, \mu_1 = (0.83\ GeV)^2, \mu_2 = (0.176\ GeV)^2$

$$T_c \simeq 174 MeV$$

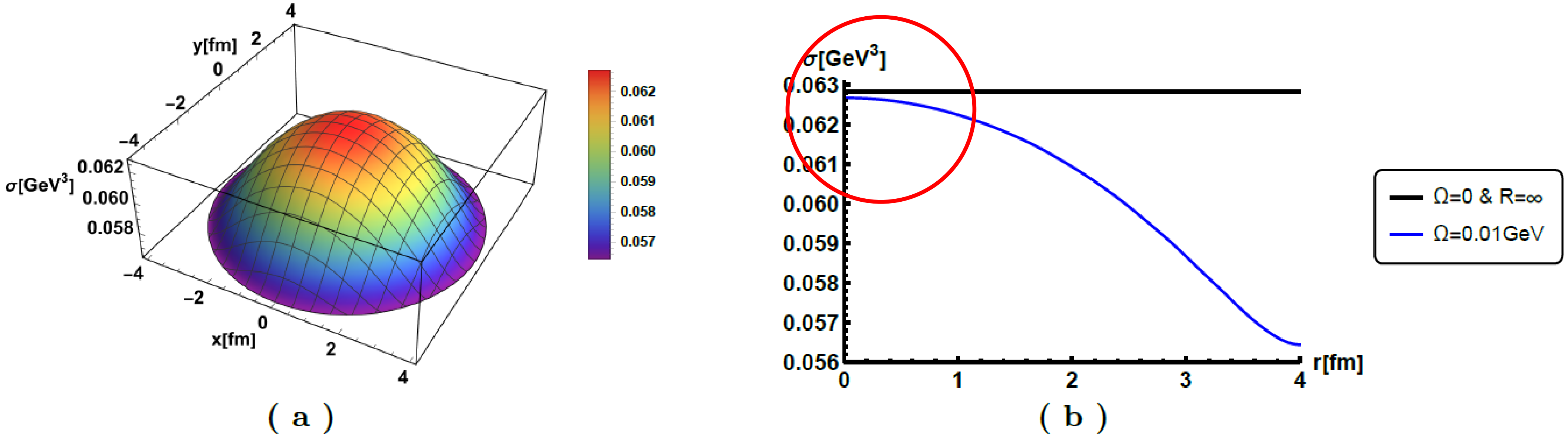

Figure 2. 3D and 2D plots of chiral condensation as a function of radial r at $T = 170$MeV and $\Omega = 0.01$ GeV with NBC and $(m_q, v_3, v_4) = (0, -3, 8)$. In Fig.(b), the black line indicates the value of condensation at the same temperature without rotation and finite size.