Chiral dynamics and gluodynamics under rotation

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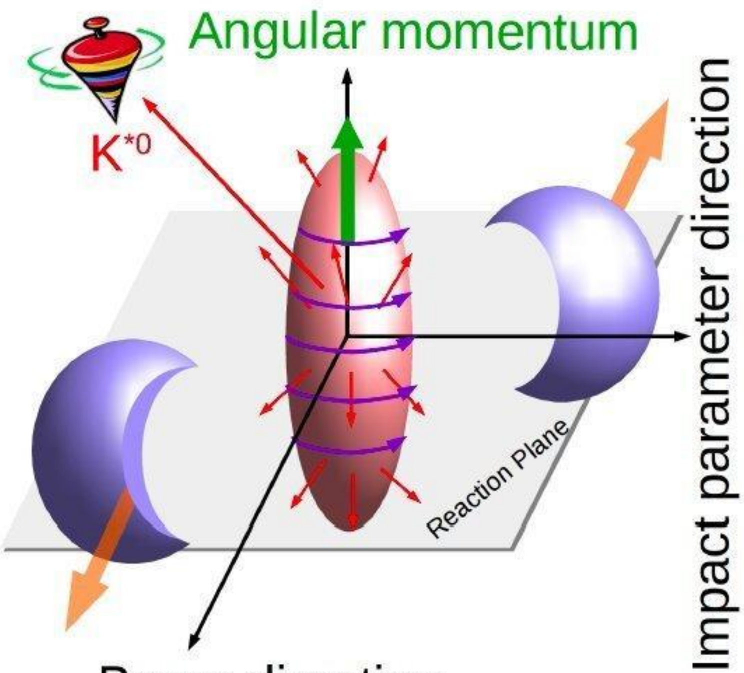
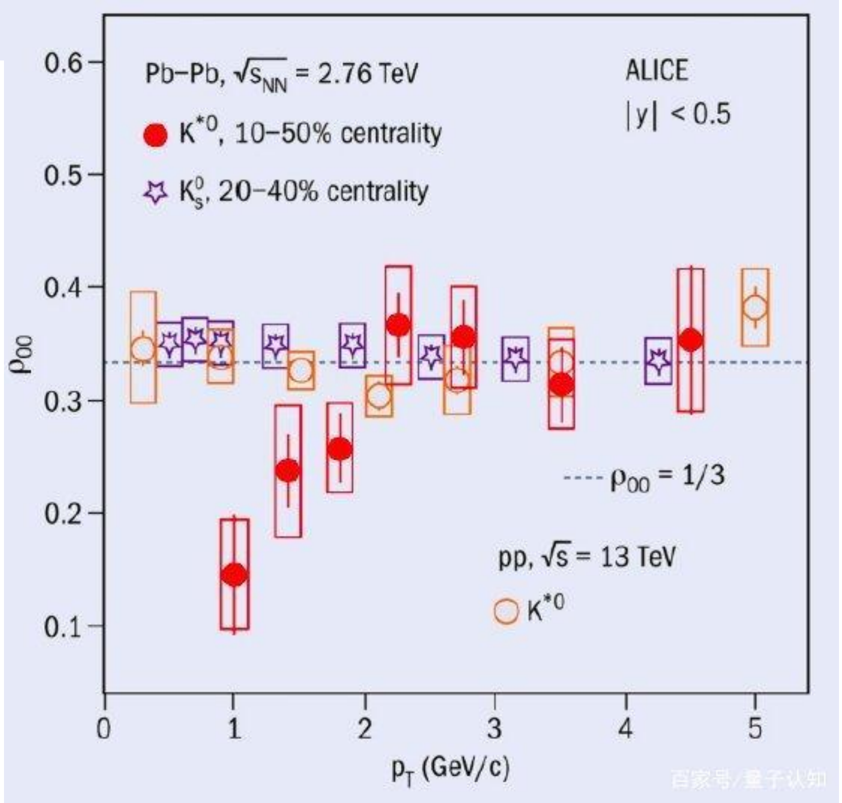
Content

I. Introduction

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





Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions, Physical Review Letters (2020). DOI: 10.1103/PhysRevLett.125.012301

II. Chiral dynamics under rotation

Xinyang Wang, Minghua Wei, Zhibing Li, M.H.
Phys.Rev.D 99 (2019) 1, 016018,e-Print: 1808.01931

Minghua Wei, Ying Jiang, M.H. to appear

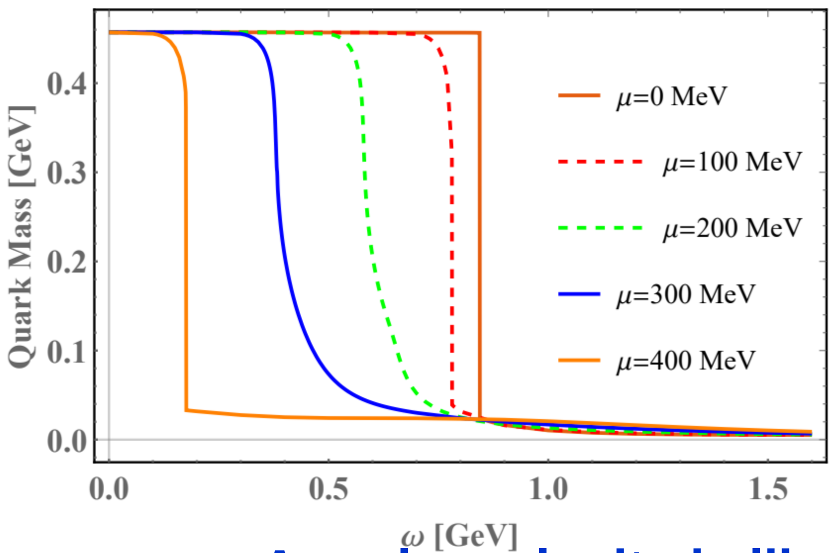
Chial dynamics under rotation from NJL model

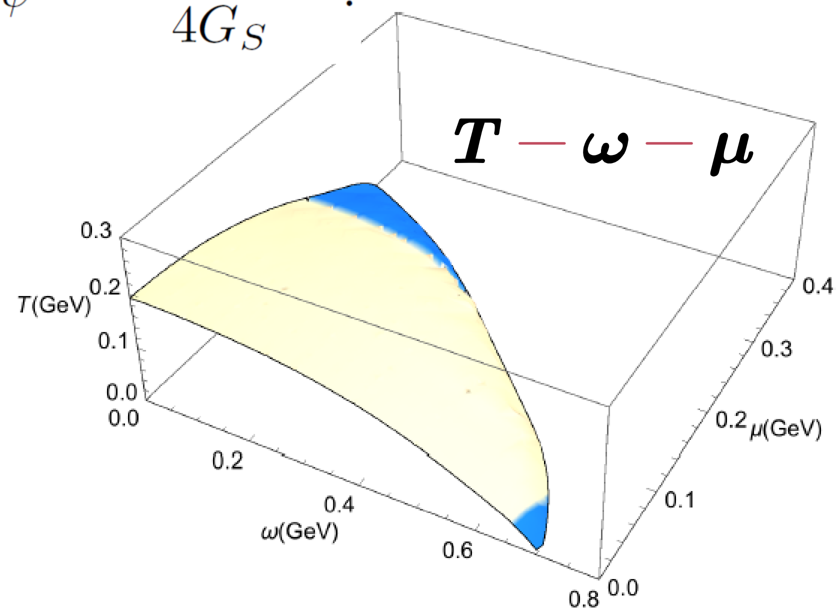
Yin Jiang, Jinfeng Liao PRL2015

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

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

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



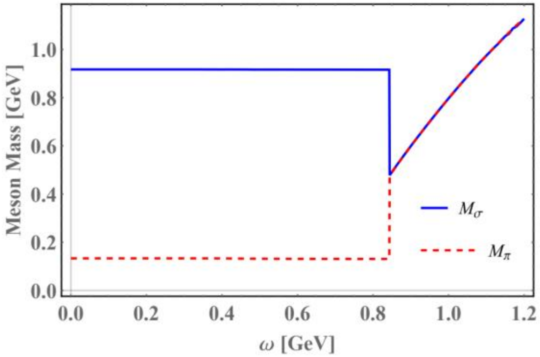


Angular velocity is like the chemical potential,
1st order phase transition in two corners!

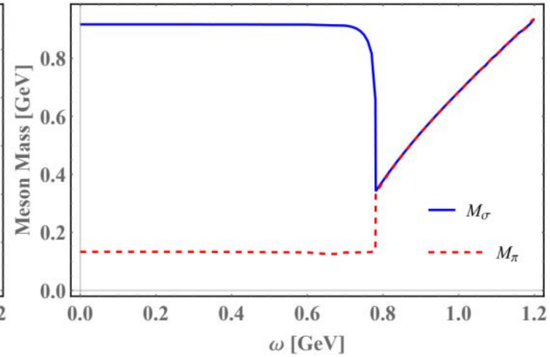
Minghua Wei, Ying Jiang,
M.H. to appear

Xinyang Wang, Minghua Wei,
Zhibin Li, Mei Huang PRD2019

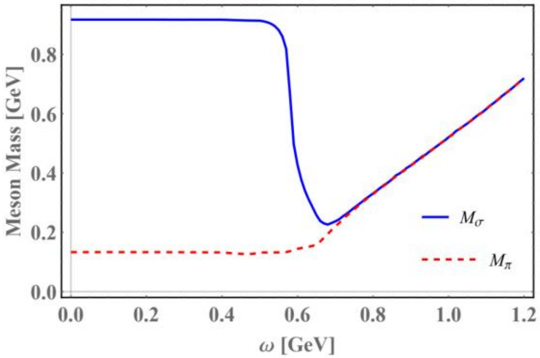
Scalar meson masses as functions of angular velocity



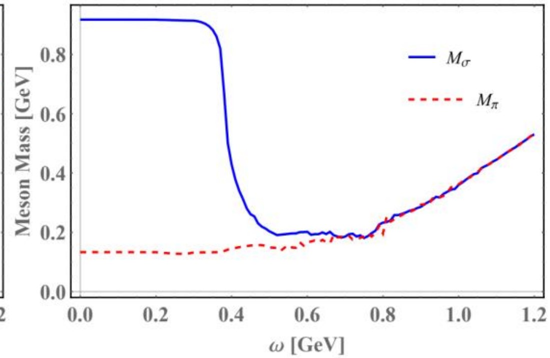
(a) scalar meson mass as a function of angular velocity at $\mu = 0MeV$



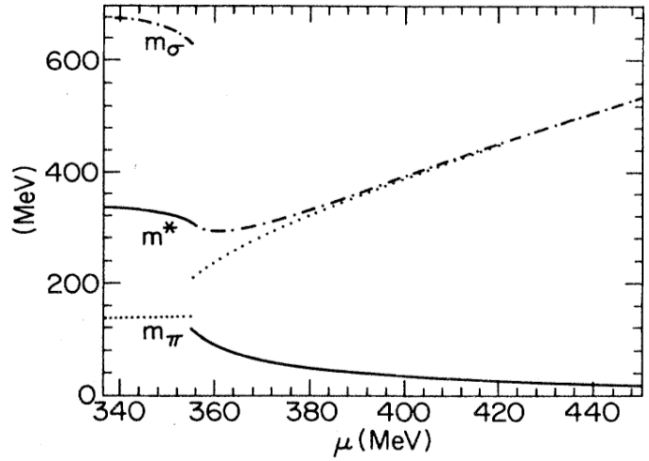
(b) scalar meson mass as a function of angular velocity at $\mu = 100MeV$



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



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

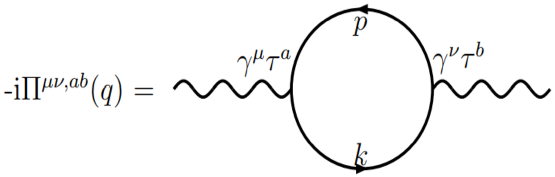


Minghua Wei, Ying Jiang, M.H. to appear

The effect of rotation on the scalar meson mass is similar to that of chemical potential !

Vector meson masses as functions of angular velocity

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



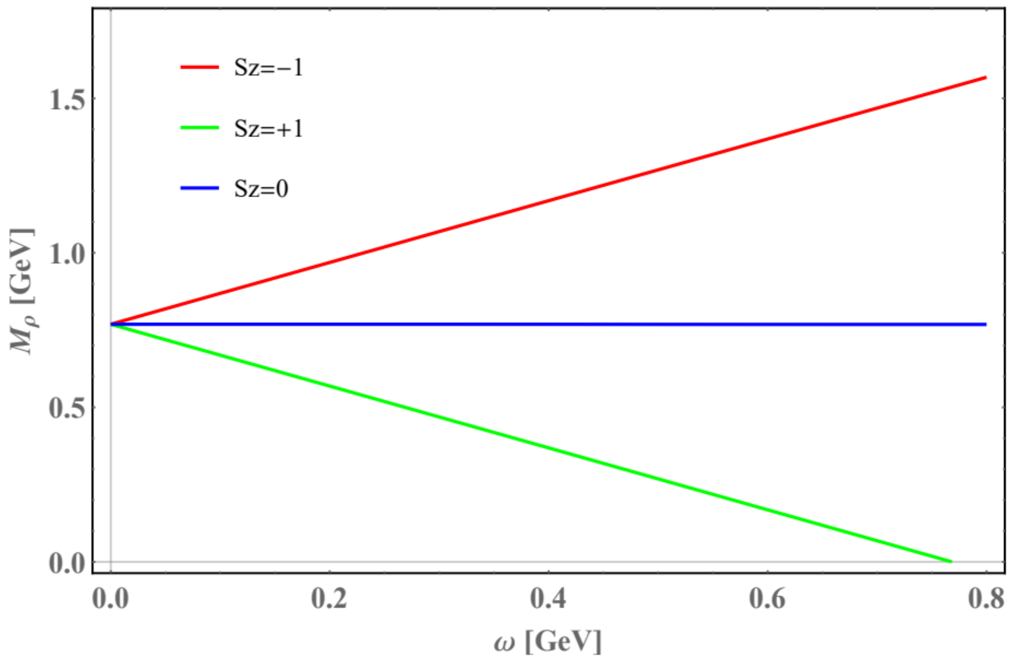
$$D^{\mu\nu}_\rho(q^2) = D_1(q^2)P^{\mu\nu}_1 + D_2(q^2)P^{\mu\nu}_2 + D_3(q^2)L^{\mu\nu} + D_4(q^2)u^\mu u^\nu$$

$$P^{\mu\nu}_1 = -\epsilon^\mu_1 \epsilon^\nu_1, (S_z = -1 \text{ for } \rho \text{ meson })$$
$$P^{\mu\nu}_2 = -\epsilon^\mu_2 \epsilon^\nu_2, (S_z = +1 \text{ for } \rho \text{ meson })$$
$$L^{\mu\nu} = -b^\mu b^\nu, (S_z = 0 \text{ for } \rho \text{ meson })$$

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

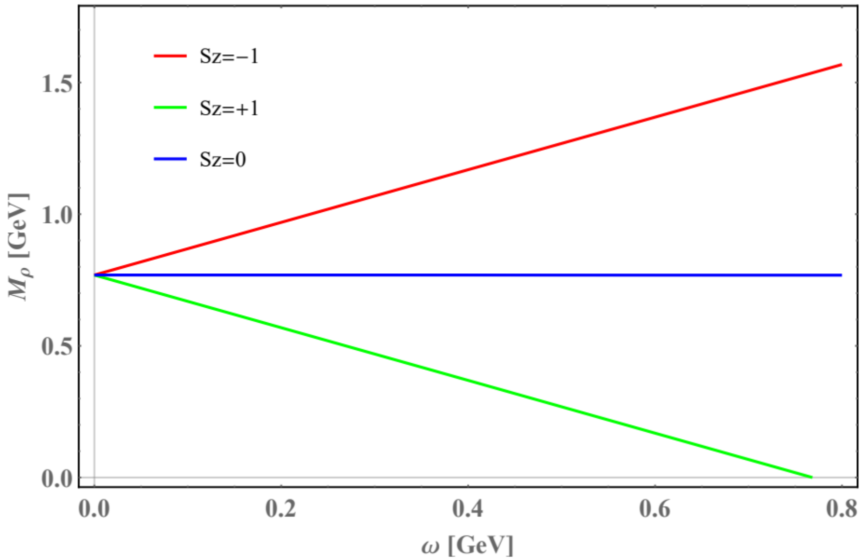
$$A_1^2 = -(\Pi_{11} - i\Pi_{12}), (S_z = -1 \text{ for } \rho \text{ meson })$$
$$A_2^2 = -\Pi_{11} - i\Pi_{12}, (S_z = +1 \text{ for } \rho \text{ meson })$$
$$A_3^2 = \Pi_{33}, (S_z = 0 \text{ for } \rho \text{ meson })$$

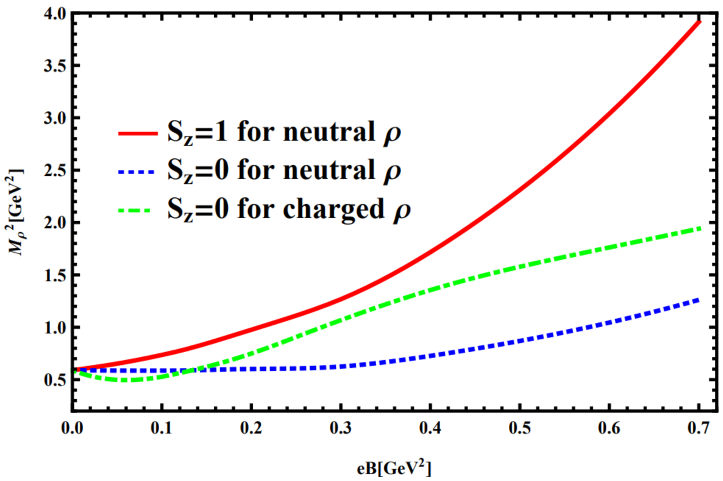
Zeeman splitting effect for different spin component!



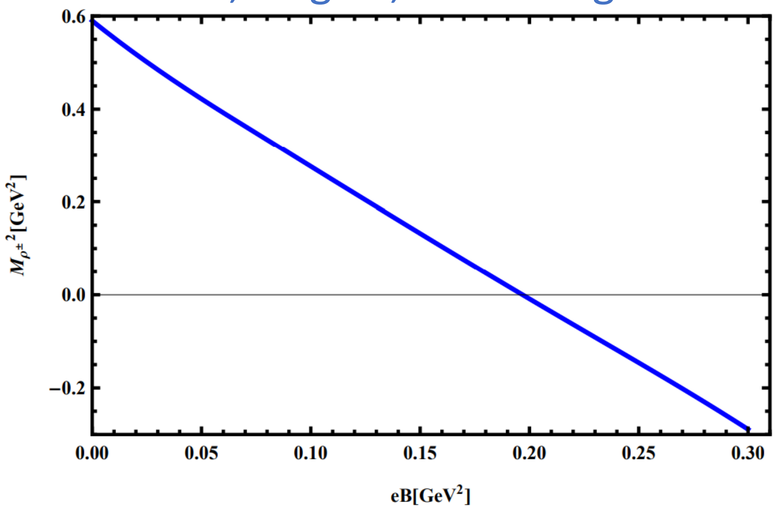
Minghua Wei, Ying Jiang, M.H. to appear

Vector meson masses as functions of angular velocity



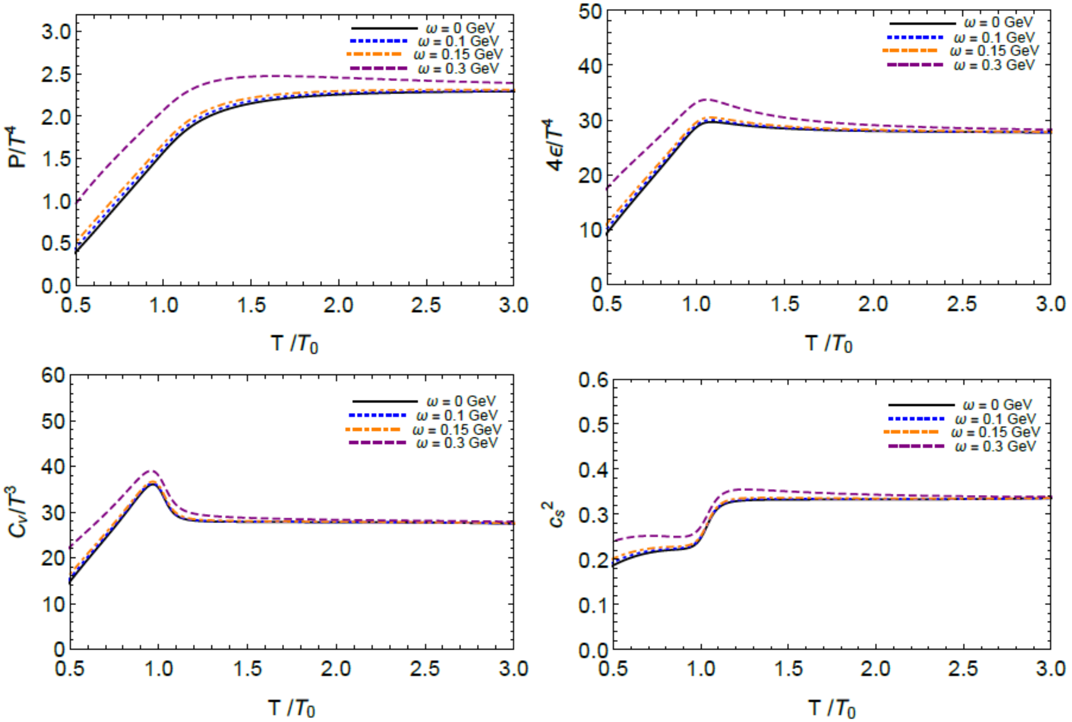


Hao Liu,Lang Yu,Mei Huang PRD2014



The effect of rotation on spin component of vector meson is similar to that of the magnetic field on charged vector mesons !

Enhancement of thermodynamical properties under rotation



Xinyang Wang, Minghua Wei, Zhibin Li, Mei Huang PRD2019

III. Gluodynamics under rotation

Xun Chen, Lin Zhang, Danning Li,
Defu Hou, M.H. arXiv: 2010.14478

Gluons are spin-1 particles, should be more sensitive to rotation!
No good 4D effective theory for gluodynamics, we use dynamical holographic QCD model!

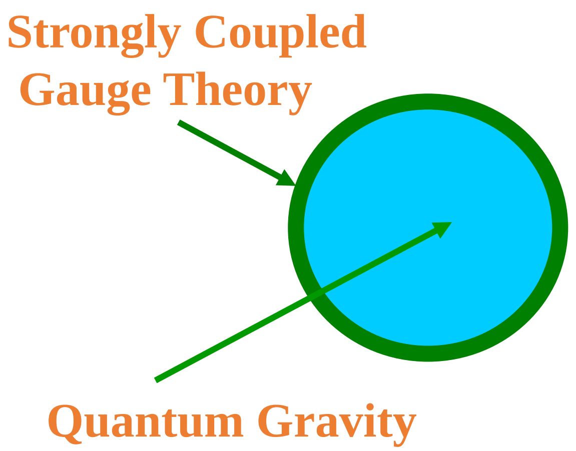
Holographic Duality: Gravity/QFT

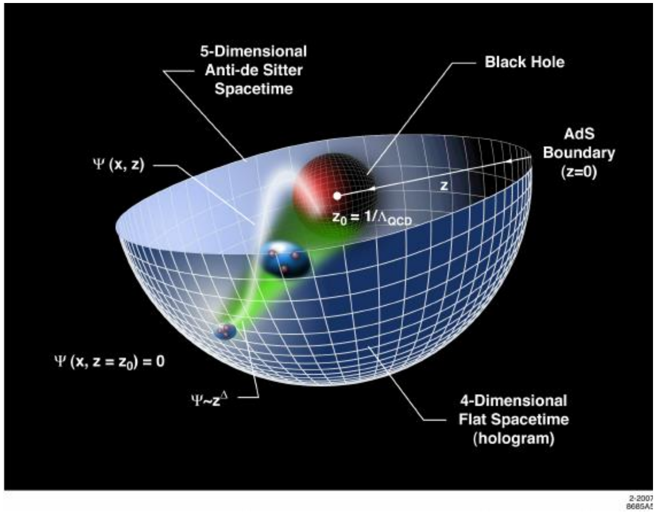
AdS/CFT : Original discovery of duality

Supersymmetry and conformality are required for AdS/CFT.

J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998)

Holographic Duality: (d+1)-Gravity/ (d)-QFT



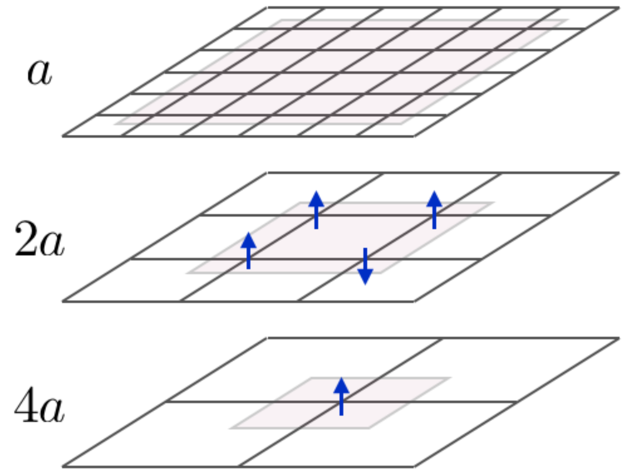


Holographic Duality & RG flow

Coarse graining spins on a lattice: Kadanoff and Wilson

$$H = \sum_{x,i} J_i(x)\mathcal{O}^i(x)$$

J(x): coupling constant or source for the operator



$$H = \sum_i J_i(x,a)\,\mathcal{O}^i(x)$$

$$H = \sum_i J_i(x,2a)\,\mathcal{O}^i(x)$$

$$H = \sum_i J_i(x,4a)\,\mathcal{O}^i(x)$$

$$u\frac{\partial}{\partial u}J_i(x,u) = \beta_i(J_j(x,u),u)$$

A.Adams, L.D.Carr, T.Shaefer, J.E.Thomas
arXiv:1205.5180

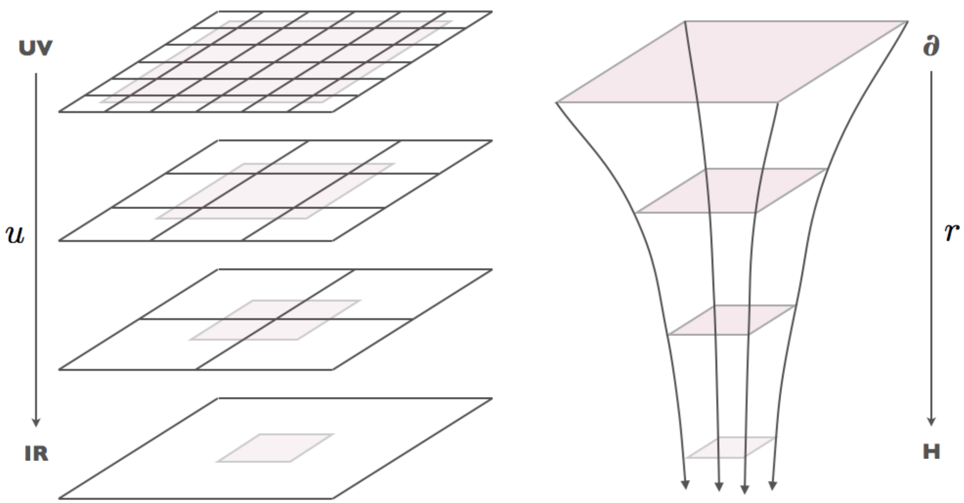
Dynamical holographic QCD !   Graviton-dilaton-scalar system

QFT on lattice equivalent to GR problem from Gravity

RG or energy scale → promote → an extra spatial dimension

Coupling constant → dynamical filed

$$J_i|_{UV} = \Phi_i|_\partial$$



A AdS_5 Dynamical

Bulk field/Operator correspondence

$\Phi(z)$	$\mathrm{Tr}\langle G^2\rangle$ $\langle g^2 A^2\rangle$
$\chi(z)$	$\langle \bar{q} q\rangle$

From UV to IR

Deformation of AdS_5

Dynamical holographic QCD   Graviton-dilaton-scalar system

D.N. Li, M.H., JHEP2013, arXiv:1303.6929

Gluonic background: Graviton-dilaton coupling

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R + 4\partial_M\Phi\partial^M\Phi - V_G(\Phi)\right)$$

Flavor background: Action for light hadrons (KKSS model)

5D linear sigma model

$$S_M = -\int d^5x\sqrt{g_s}e^{-\Phi}Tr(|DX|^2 + V_X(X^+X,\Phi) + \frac{1}{4g_5^2}(F_L^2 + F_R^2)).$$

Full Dynamics: $S = S_G + S_M$

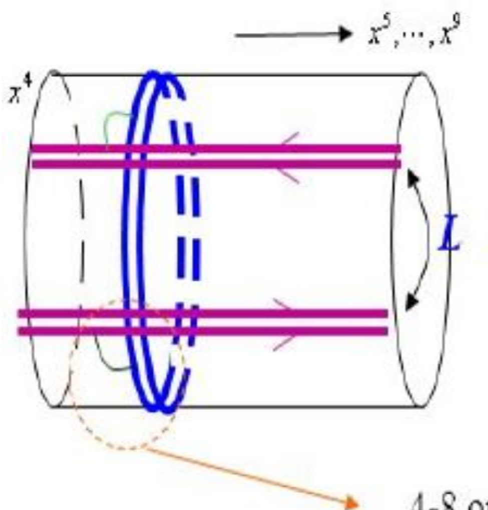
Interplay between gluodynamics and quark dynamics!!!

Dynamical holographic QCD   Graviton-dilaton-scalar system

	Gluodynamics	Quark dynamics
DhQCD	Dilaton background	Flavor background
SS:D4−D8 D3−D7	Dp brane: D4, D3	Dq brane: D8, D7
PNJL	Polyakov−loop potential	NJL model

Interplay between gluodynamics and quark dynamics!!!

Comparing with the Witten-Sakai-Sugimoto model



	0	1	2	3	4	5	6	7	8	9
N_c D4	o	o	o	o	o					
N_f $D8 - \overline{D8}$	o	o	o	o		o	o	o	o	o

4-8 open strings give chiral (from D8) and anti-chiral (from anti-D8) fermions in the fundamental representation.

Comparing with the Polyakov-loop NJL model

Quark dynamics:

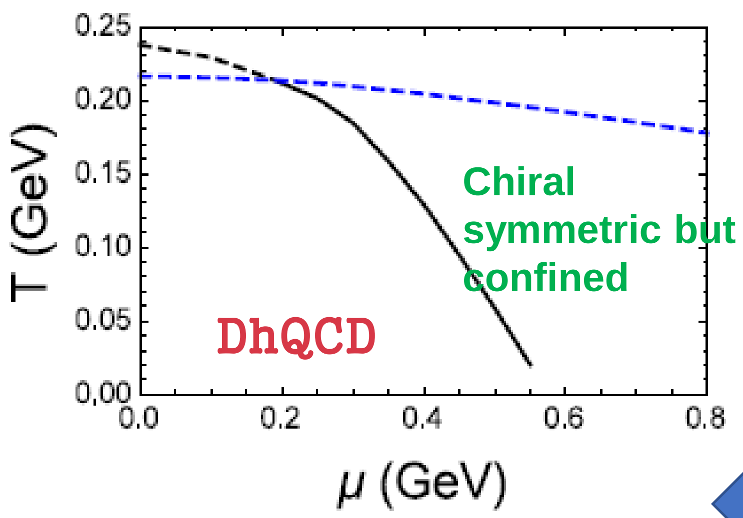
$$\mathcal{L}_{\rm NJL} = \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi + G_S[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] - G_V[(\bar{\psi}\gamma_\mu\psi)^2 + (\bar{\psi}\gamma_\mu\gamma_5\psi)^2]$$

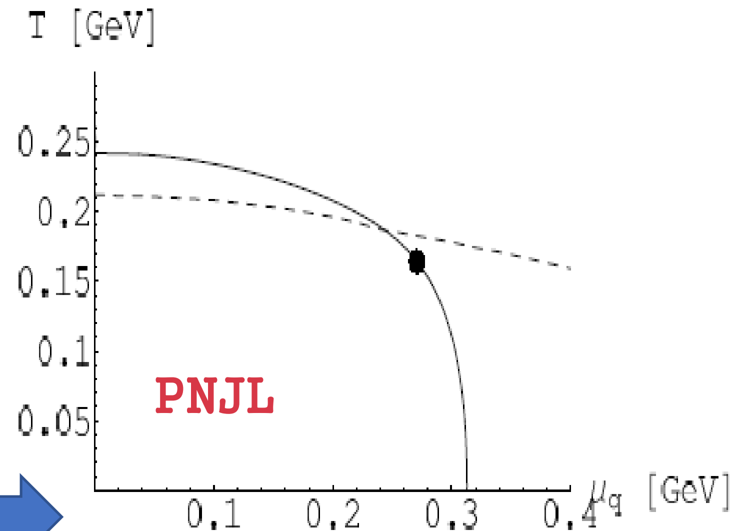
Gluon "dynamics": Polyakov-loop effective potential

$$\frac{\mathcal{U}(\Phi,\bar{\Phi},T)}{T^4} = -\frac{a(T)}{2}\bar{\Phi}\Phi + b(T)\ln[1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2]$$

$$\begin{aligned}\Omega_{PNJL} = {} & \mathcal{U}(\Phi,\bar{\Phi},T) - 2N_c\sum_{i=u,d}\int_0^\Lambda \frac{d^3p}{(2\pi)^3}[E_i] + G_S(\sigma_u+\sigma_d)^2 - G_V(\rho_u+\rho_d)^2 \\ & -2T\sum_{i=u,d}\int\frac{d^3p}{(2\pi)^3}[\ln(1+3\Phi e^{-\beta(E_i-\tilde{\mu}_i)} + 3\bar{\Phi}e^{-2\beta(E_i-\tilde{\mu}_i)} + e^{-3\beta(E_i-\tilde{\mu}_i)})] \\ & -2T\sum_{i=u,d}\int\frac{d^3p}{(2\pi)^3}[\ln(1+3\bar{\Phi} e^{-\beta(E_i+\tilde{\mu}_i)} + 3\Phi e^{-2\beta(E_i+\tilde{\mu}_i)} + e^{-3\beta(E_i+\tilde{\mu}_i)})]\end{aligned}$$

Quarkyonic phase in quenched DhQCD





Xun Chen, Danning Li, Defu Hou, M.H,
arXiv:1908.02000

Sasaki, Friman, Redlich,
hep-ph/0611147

4D effective theory mainly investigate chiral phase transition, HQCD can handle gluodynamics

Einstein-Maxwell-Dilaton system

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}[R - \frac{h(\phi)}{4}F^2 - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)].$$

$$ds^2 = \frac{e^{2A_e(z)}}{z^2}[-F(z)dt^2 + \frac{1}{F(z)}dz^2 + d\vec{x}^2]$$

$$A_e(z) = -\frac{3}{4}\ln\left(az^2+1\right) + \frac{1}{2}\ln\left(bz^3+1\right) - \frac{3}{4}\ln\left(dz^4+1\right)$$

$$h(z) = e^{-cz^2 - A_e(z)}.$$

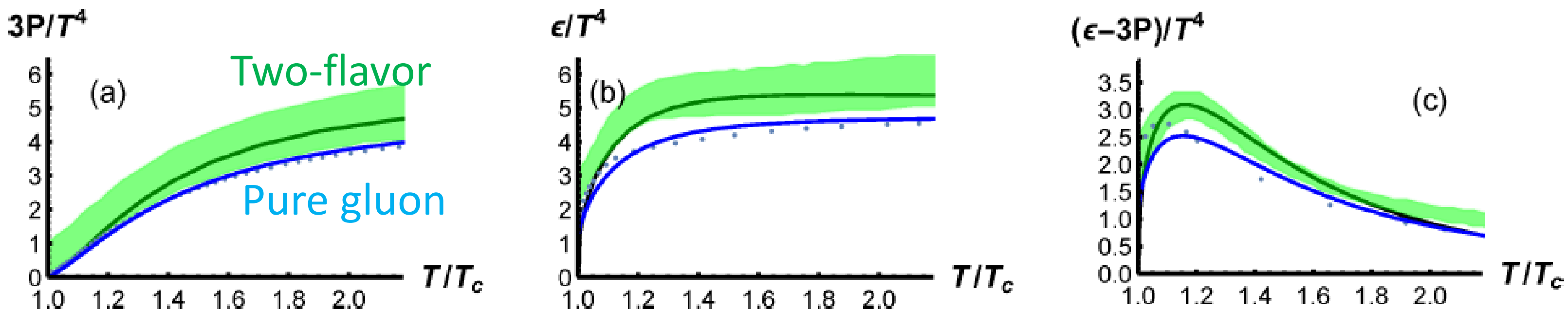
D. Dudal and S. Mahapatra, "Thermal entropy of a quark-antiquark pair above and below deconfinement from a dynamical holographic QCD model," Phys. Rev. D **96** (2017) no.12, 126010 [arXiv:1708.06995 [hep-th]].

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

ω is a dimensionless angular velocity parameter ranging from 0 to 1

Xun Chen, Lin Zhang, Danning Li, Defu Hou, M.H. arXiv: 2010.14478

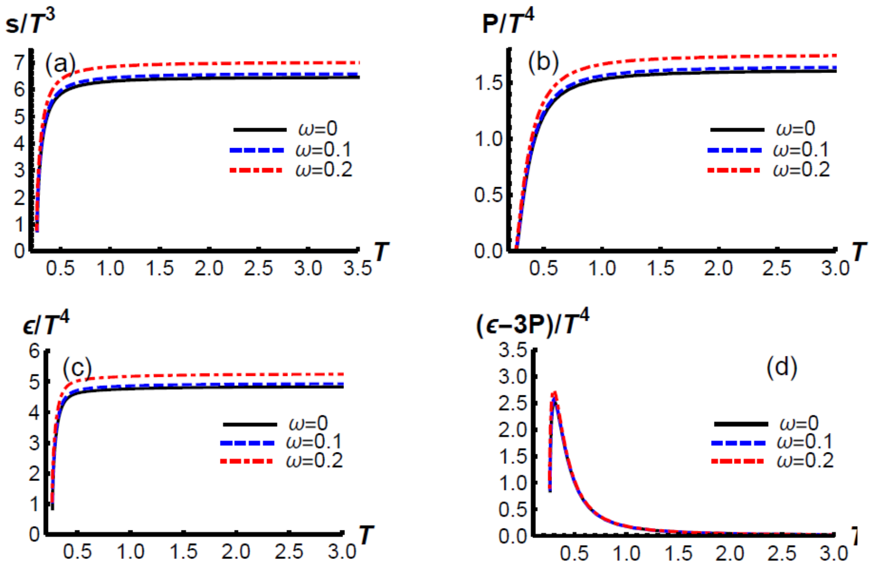
Fit parameters from lattice QCD results for pure gluon system and 2-flavor system

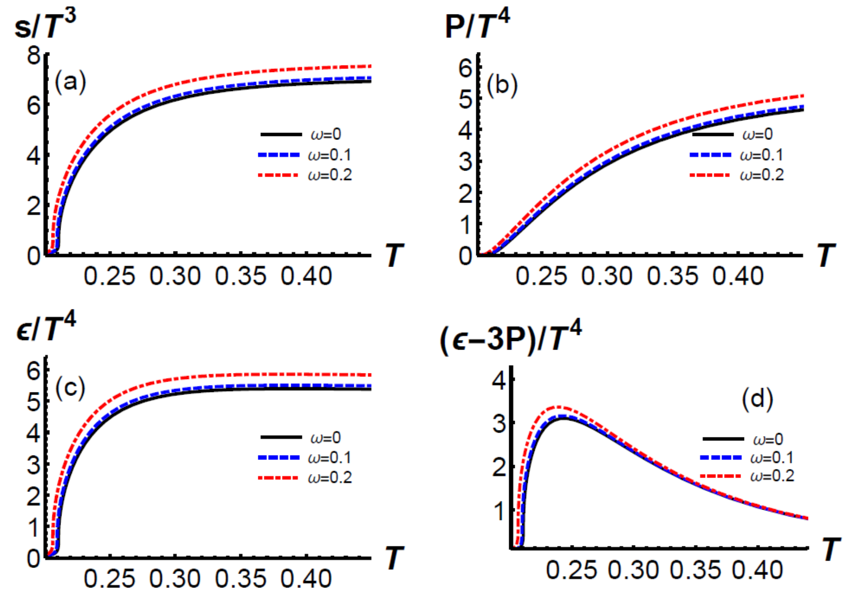


	c	a	b	d	G_5	T_c
$N_f = 2$	-0.227	0.01	0.045	0.035	1.1	211MeV
$N_f = 0$	1.16	0.075	0.12	0.075	1.2	265MeV

Xun Chen, Lin Zhang, Danning Li, Defu Hou, M.H. arXiv: 2010.14478

Enhancement of thermodynamical properties under rotation

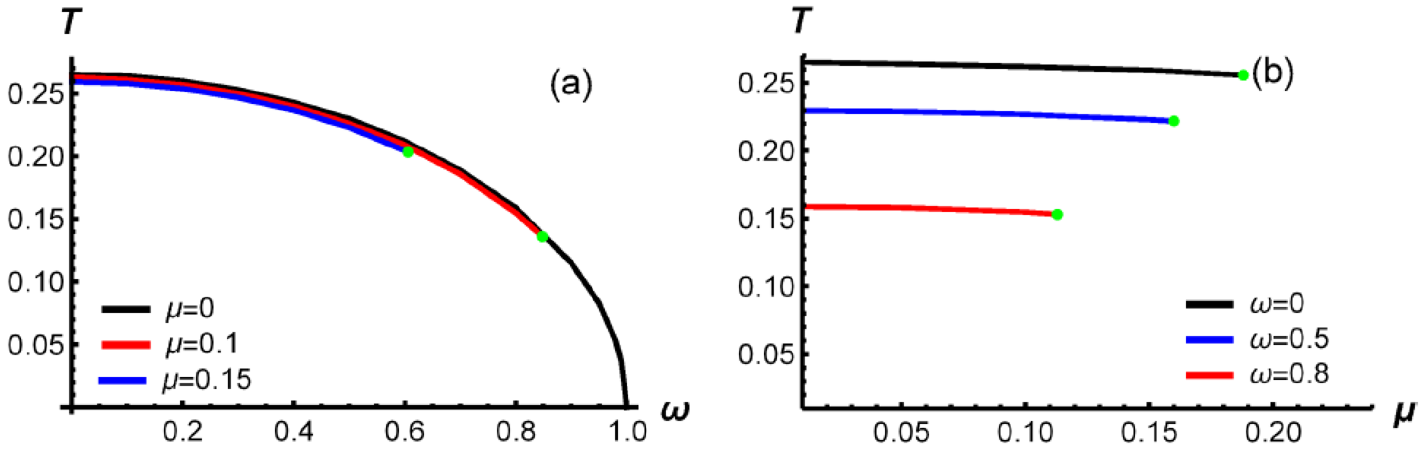




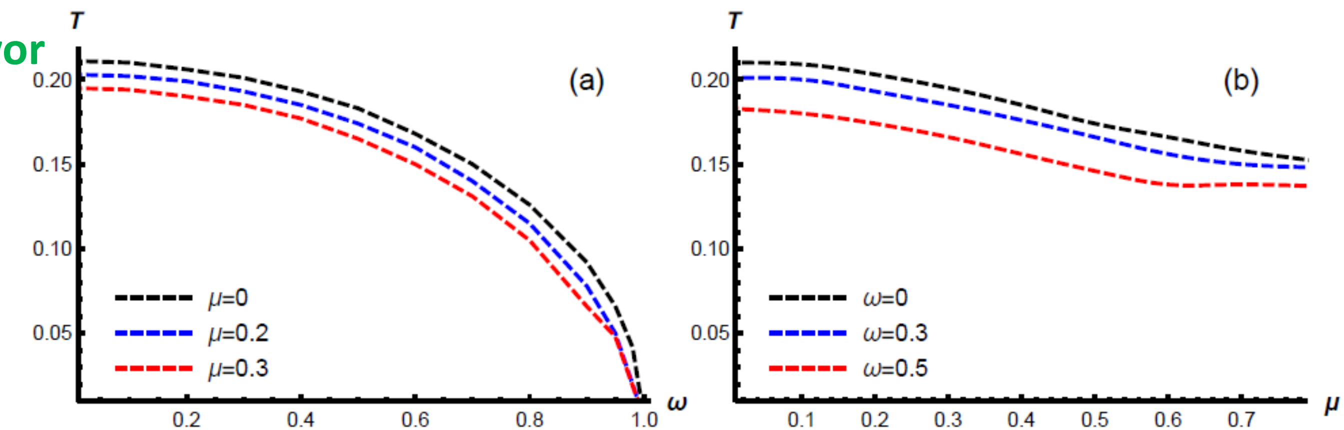
Xun Chen, Lin Zhang, Danning Li,
Defu Hou, M.H. arXiv: 2010.14478

Deconfinement phase transition under rotation

Pure gluon

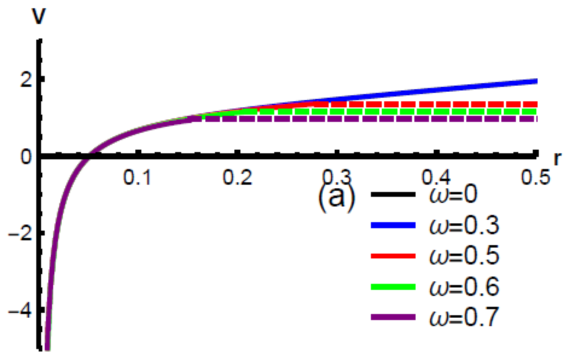


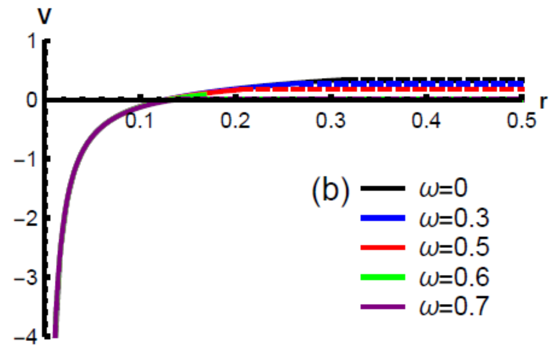
Two-flavor

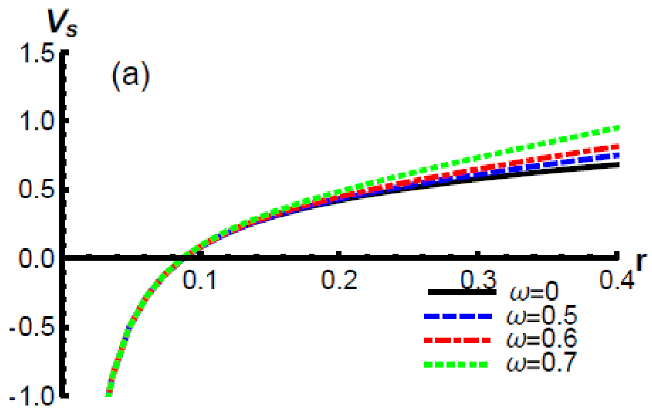


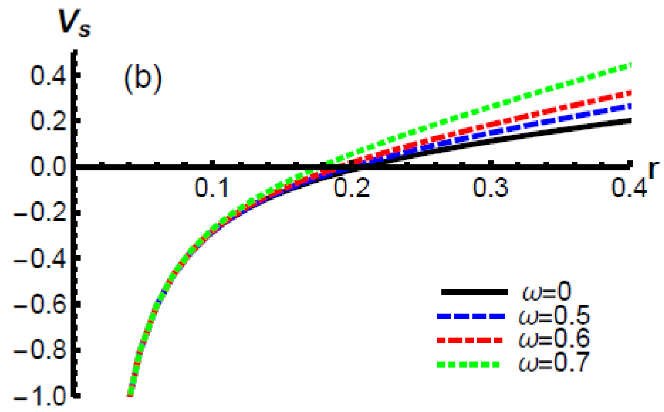
Xun Chen, Lin Zhang, Danning Li, Defu Hou, M.H. arXiv: 2010.14478

Heavy quark potential, spatial Wilson loop and Polyakov-loop under rotation









Xun Chen, Lin Zhang, Danning Li, Defu Hou, M.H. arXiv: 2010.14478

Heavy quark potential, spatial Wilson loop and Polyakov-loop under rotation

Pure gluon

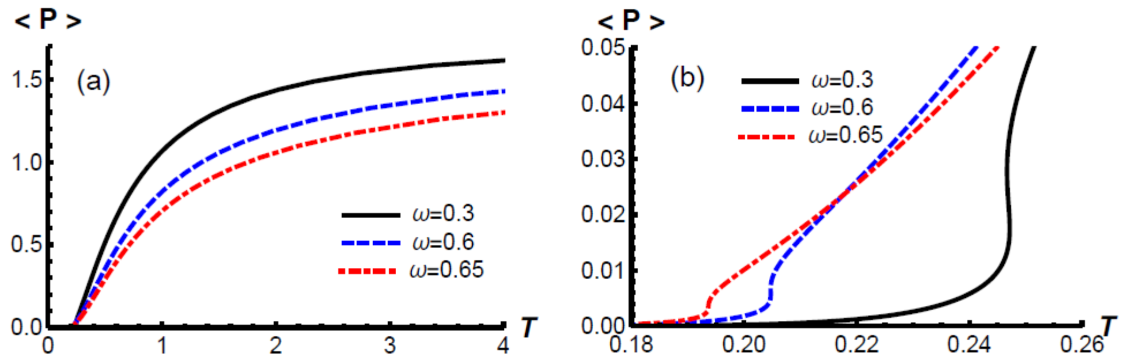


Figure 9. (a)In pure gluon system, the expectation value of a single Polyakov loop as a function of T at $\mu = 0.15GeV$ for different angular velocities of $\omega = 0$(solid black line), $\omega = 0.6$(dashed blue line) and $\omega = 0.65$(dot-dashed red line). (b) An enlarged view of (a).The unit for T, μ is in GeV.

Two-flavor

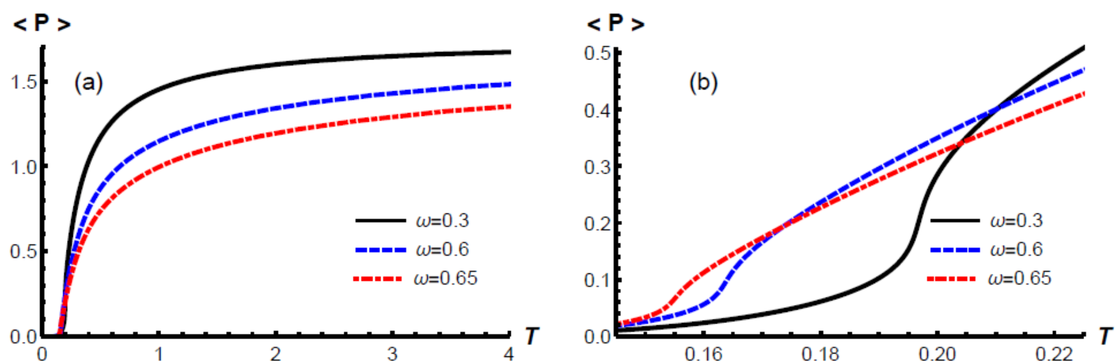


Figure 10. (a) In two-flavor system, the expectation value of a single Polyakov loop as a function of T at $\mu = 0.15GeV$ for different angular velocities of $\omega = 0$(solid black line), $\omega = 0.6$(dashed blue line) and $\omega = 0.65$(dot-dashed red line). (b) An enlarged view of (a).The unit for T, μ is in GeV.

Xun Chen, Lin Zhang, Danning Li, Defu Hou, M.H. arXiv: 2010.14478

IV. Summary

We investigated the effect of rotaion on chiral dynamics in the NJL model and gluodynamics in hQCD,

1, rotation plays the similar role as the chemical potential on thermodynamical properties, and scalar mesons,   while affect

vector mesons sensitively.

2, QCD phase structure under rotation

deconfinement phase transition & chiral phase transition

Outlook

1, inhomogeneous structure (vortex structure) under study

2, How to connect meson spectra of vector meson with the spin

polarization observables?(in progress)

Thanks for your attention!