QCD matter under rotation

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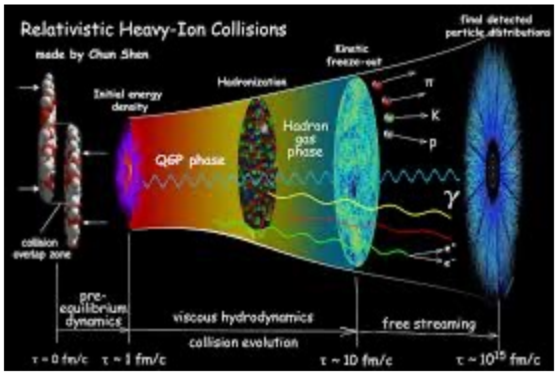
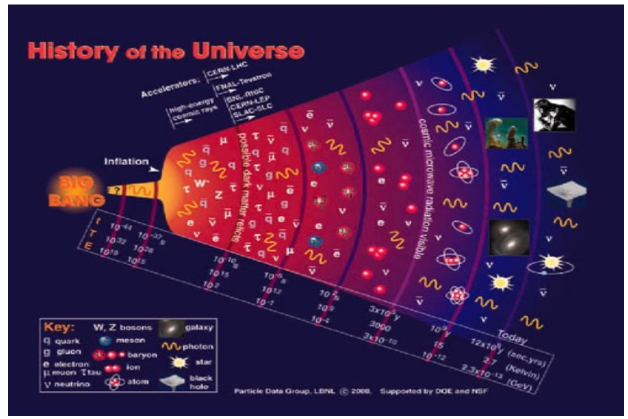
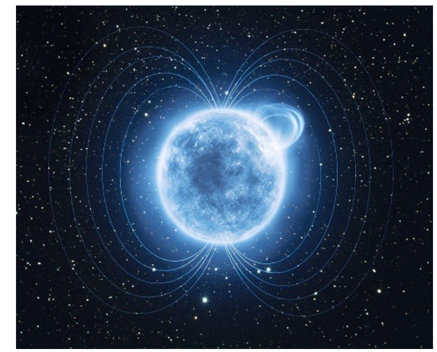
QCD matter under extreme conditions

$$\mathrm{T}, \mu_B, \mathbf{B}, \mathbf{E}\cdot\mathbf{B}, \boldsymbol{\omega}, \mu_{\mathrm{I}}, \boldsymbol{L}$$







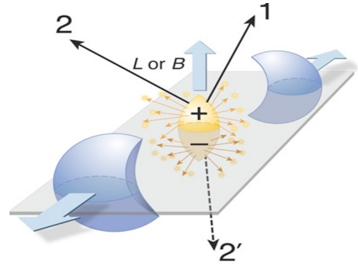
LHC,RHIC,FAIR,NICA,HIAF

Early universe

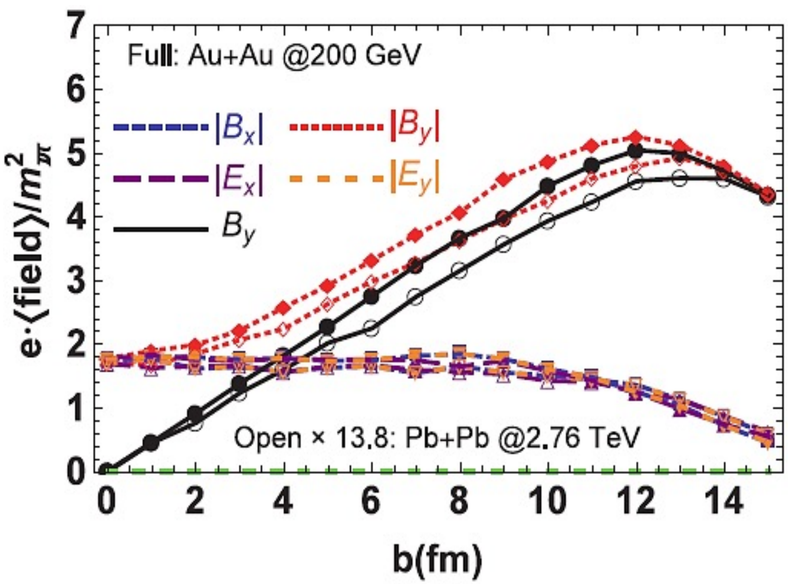
Neutron star

Neutron star merge→BH

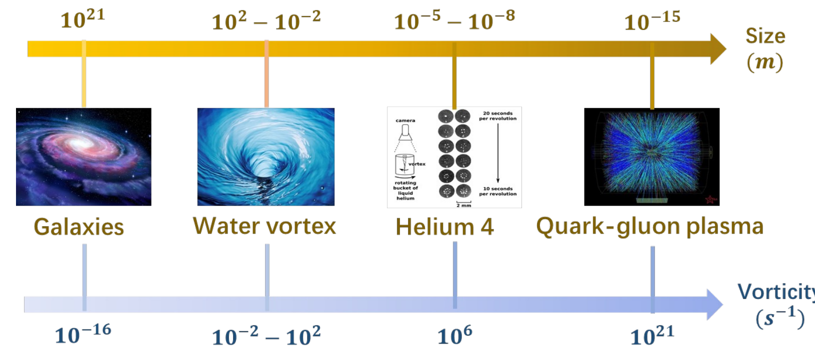
MAGNETIC FIELDS

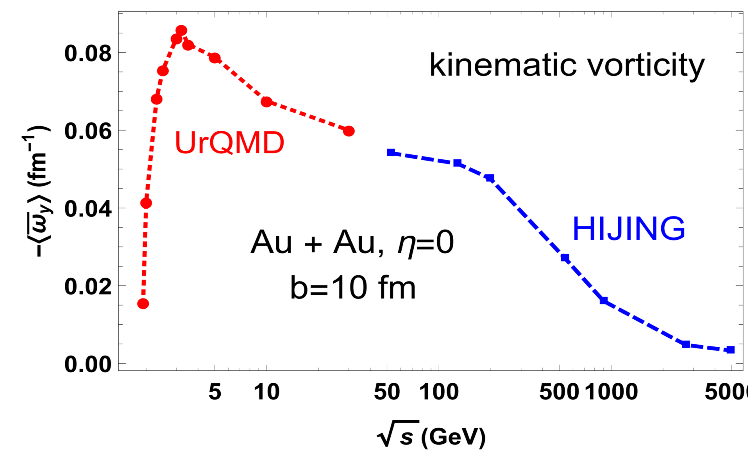


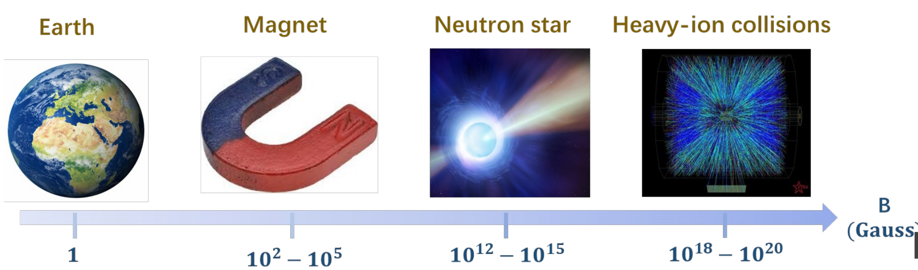
ROTATION



HIJING (Deng-XGHuang PRC2012)



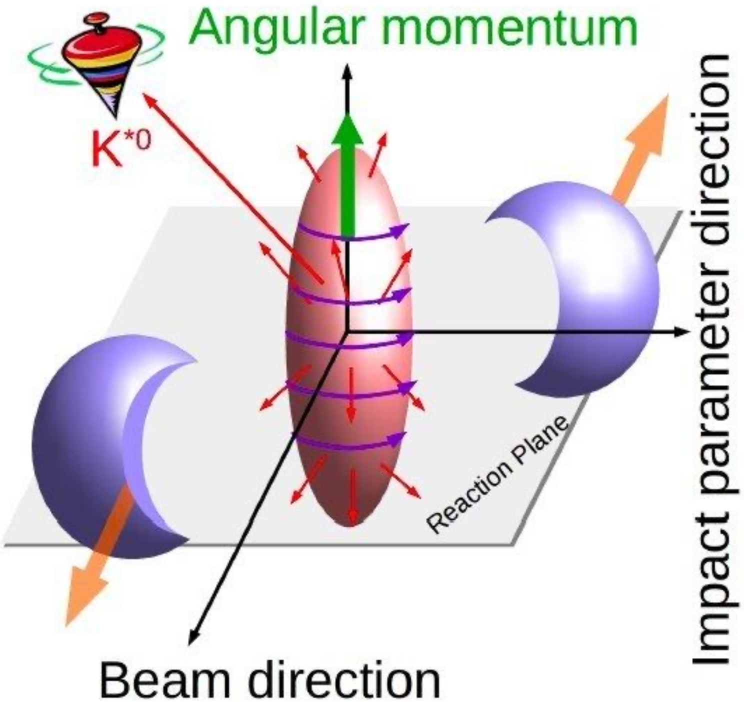


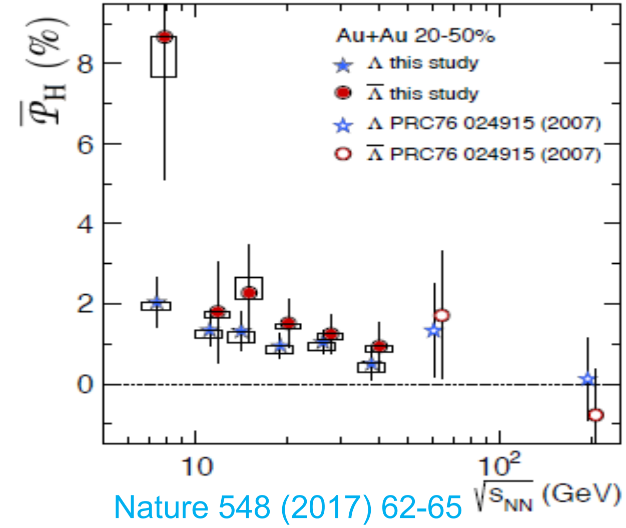


Deng-XGHuang PRC2016

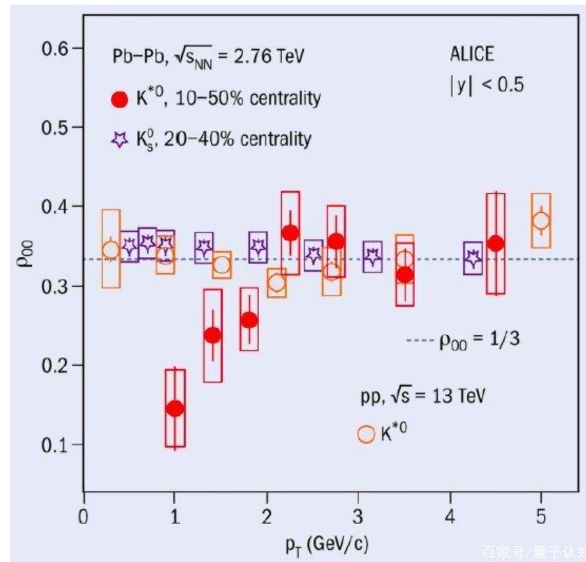
Deng-XGHuang-GLMa-Zhang PRC2020

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





Nature 548 (2017) 62-65



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

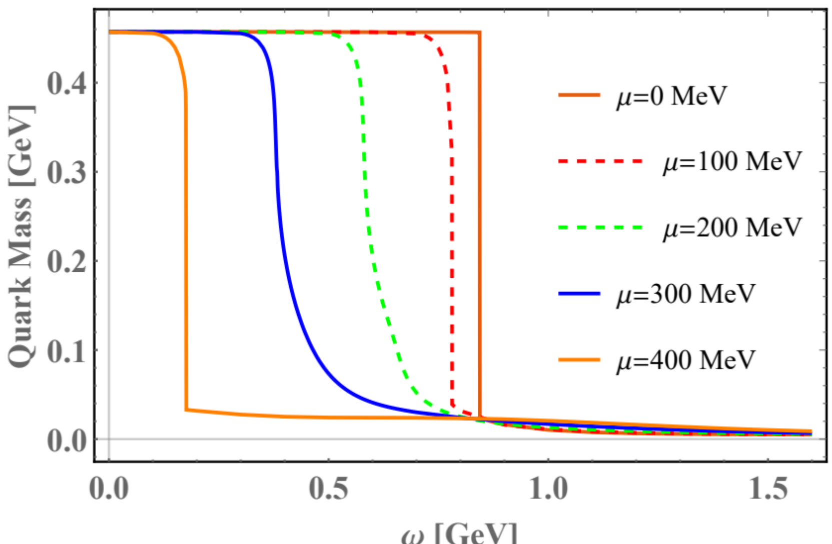
Chial dynamics under rotation from NJL model

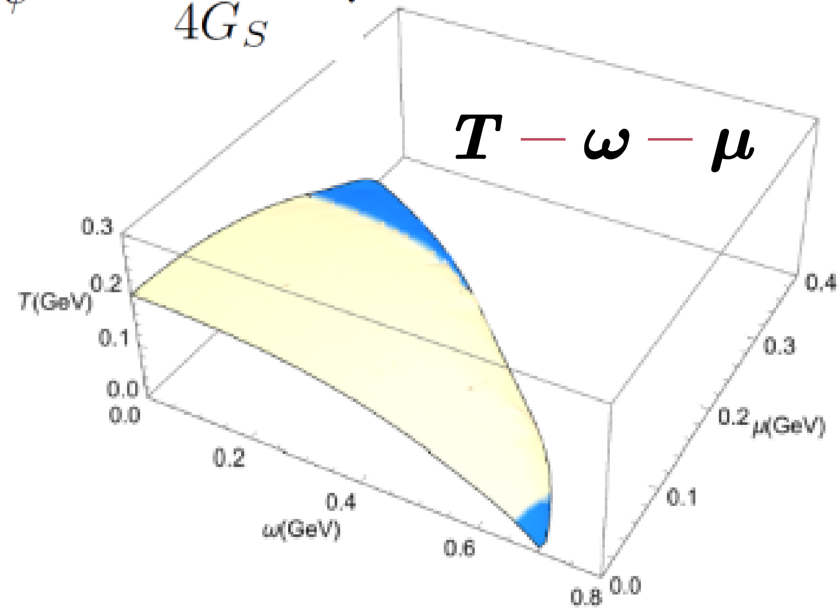
Yin Jiang, Jinfeng Liao PRL2015

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

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

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



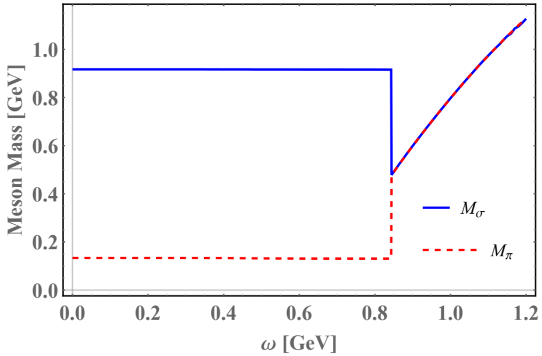


Angular velocity is like the chemical potential,
1st order phase transition in two corners!

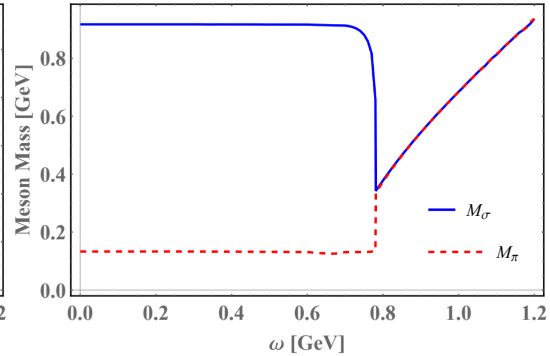
Minghua Wei, Ying Jiang,
M.H. 2011.10987

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

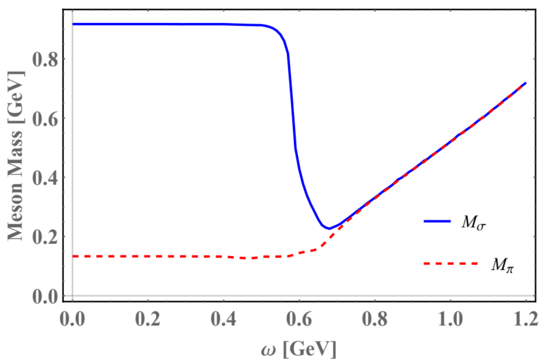
Scalar meson masses as functions of angular velocity



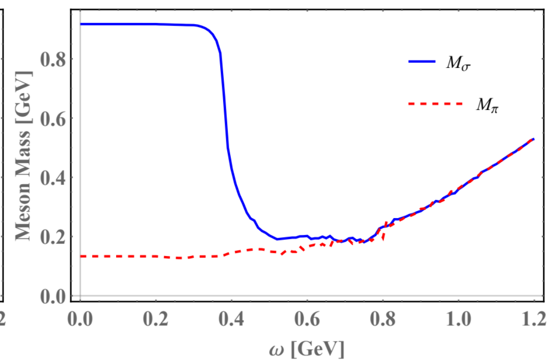
(a) scalar meson mass as a function of angular velocity at $\mu = 0MeV$



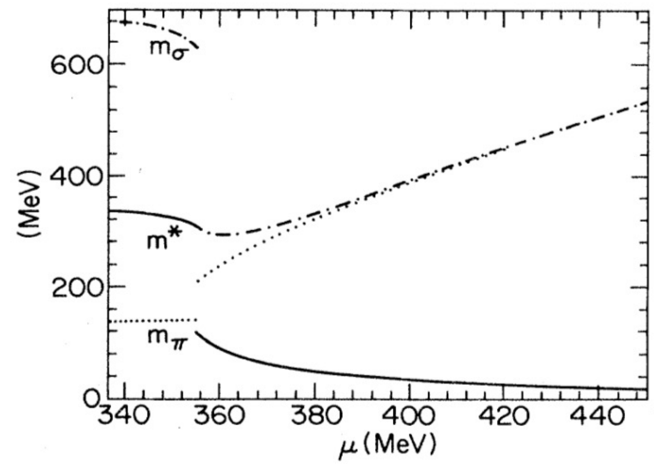
(b) scalar meson mass as a function of angular velocity at $\mu = 100MeV$



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



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



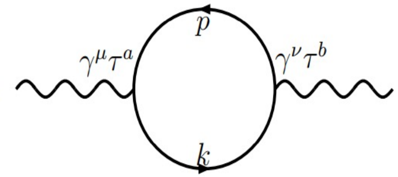
Minghua Wei, Ying Jiang, M.H. 2011.10987

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

Vector meson masses as functions of angular velocity

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

$-i\Pi^{\mu\nu,ab}(q) =$



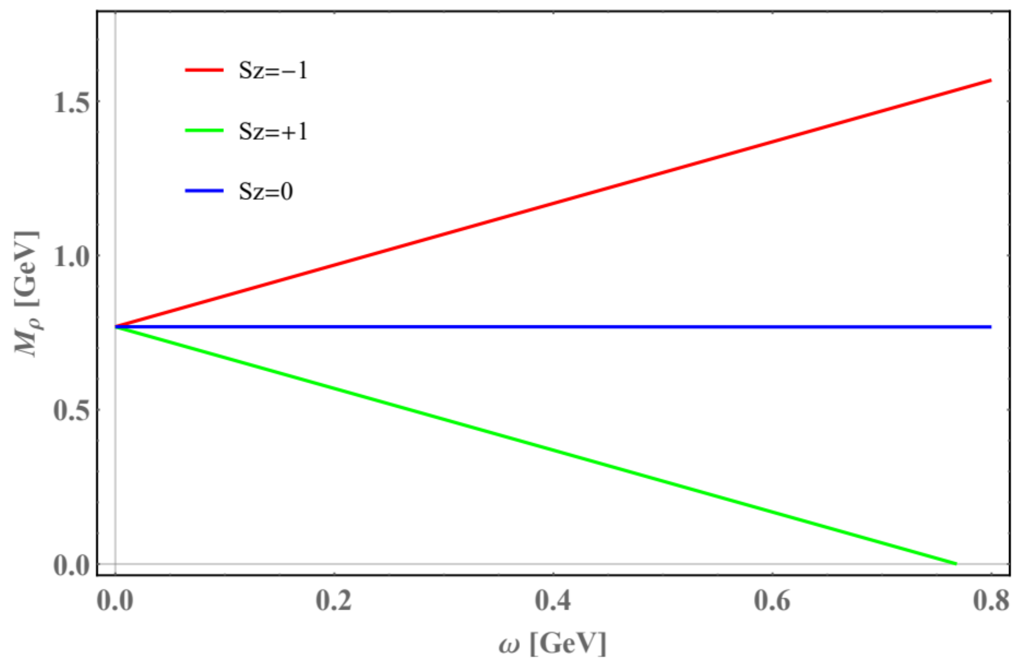
$$D_\rho^{\mu\nu}(q^2) = D_1(q^2)P_1^{\mu\nu} + D_2(q^2)P_2^{\mu\nu} + D_3(q^2)L^{\mu\nu} + D_4(q^2)u^\mu u^\nu$$

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

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

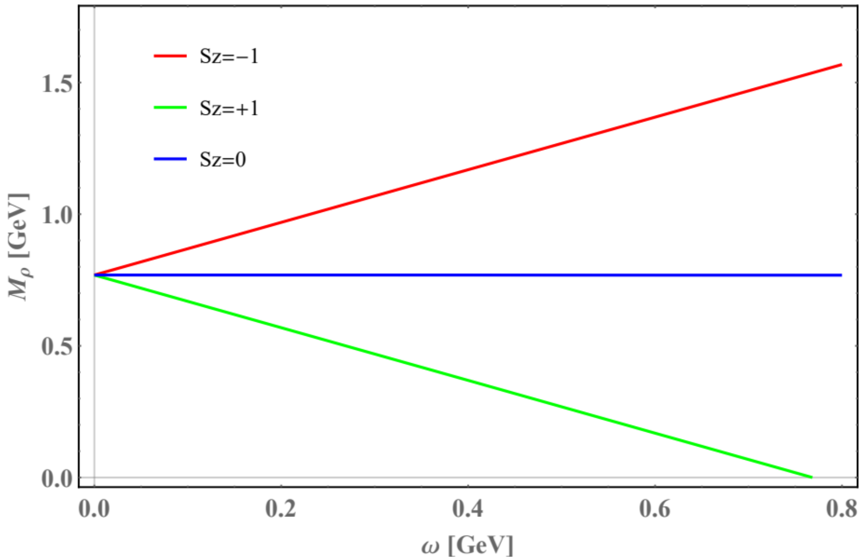
$$A_1^2 = -(\Pi_{11} - i\Pi_{12}), (S_z = -1 \text{ for } \rho \text{ meson })$$
$$A_2^2 = -\Pi_{11} - i\Pi_{12}, (S_z = +1 \text{ for } \rho \text{ meson })$$
$$A_3^2 = \Pi_{33}, (S_z = 0 \text{ for } \rho \text{ meson })$$

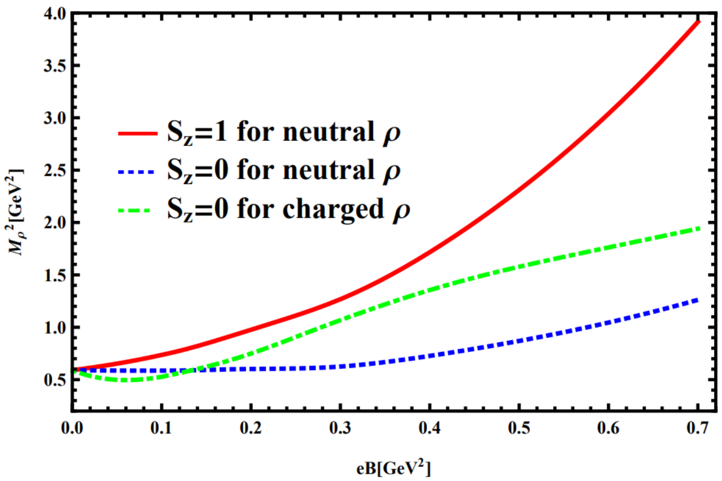
Zeeman splitting effect for different spin component!



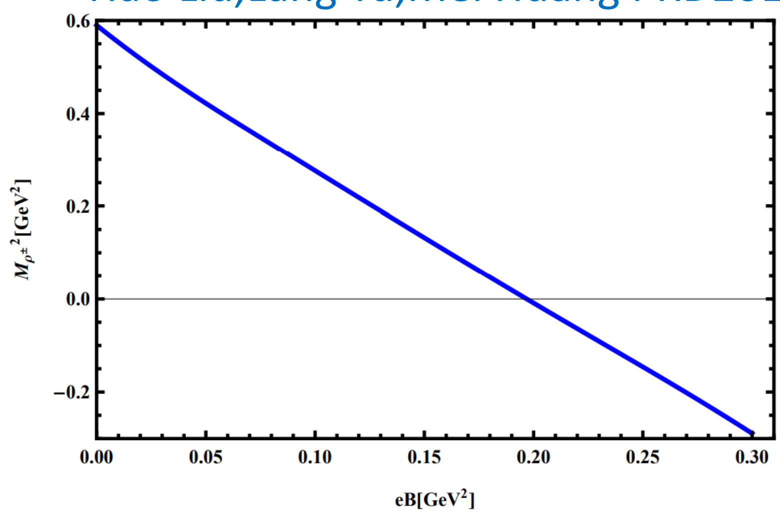
Minghua Wei, Ying Jiang, M.H. 2011.10987

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 !

Gluons are spin-1 particles, should be more sensitive to rotation than that of quarks! There are no 4D effective theory for gluodynamics, we use dynamical holographic QCD model!

III. Gluodynamics under rotation

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

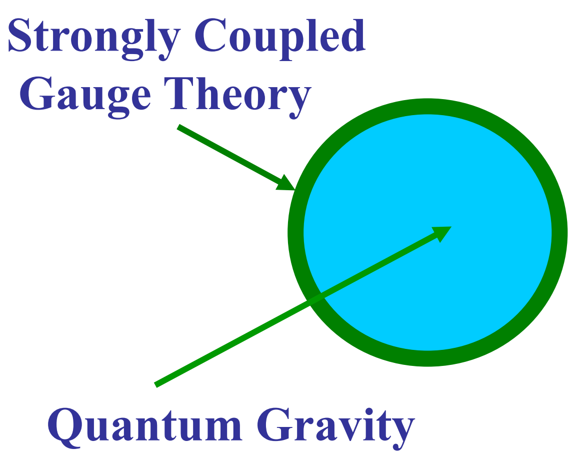
Holographic Duality: Gravity/QFT

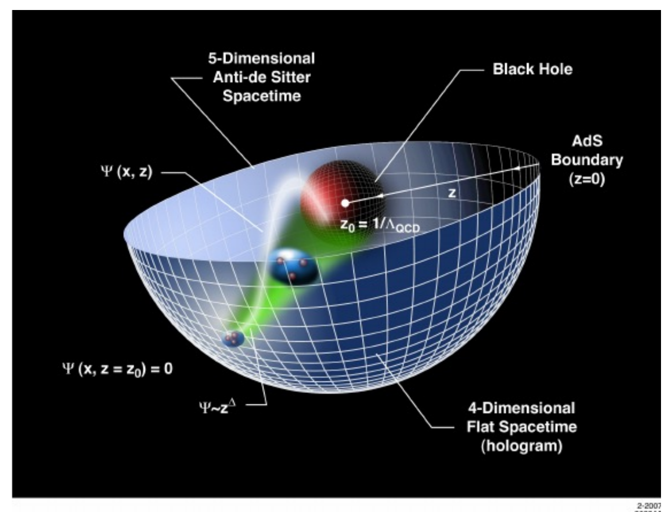
AdS/CFT : Original discovery of duality

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



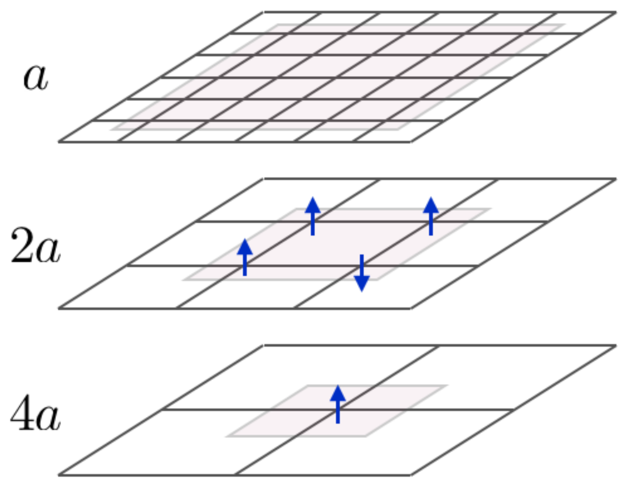


Holographic Duality & RG flow

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

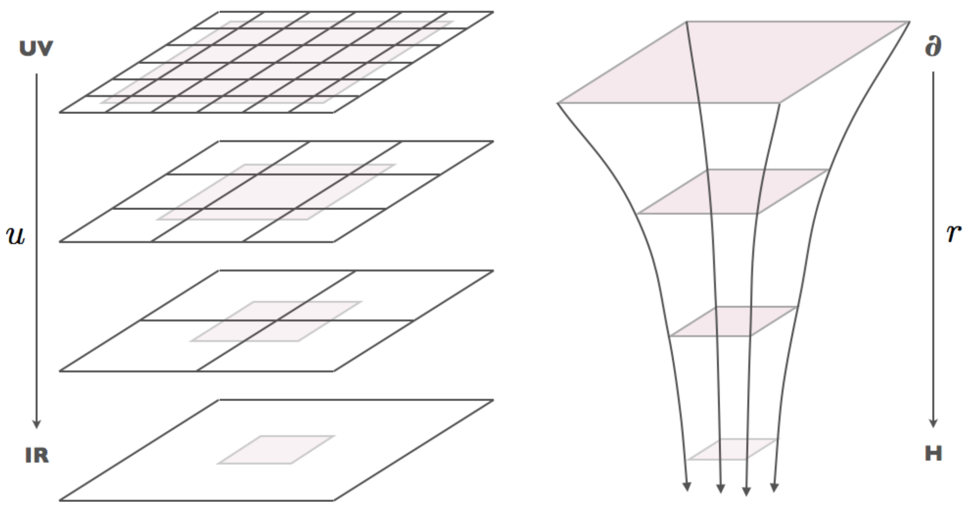
QFT on lattice equivalent to GR problem from Gravity

RG or energy scale → an extra spatial dimension

promote

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

5D linear sigma model

(KKSS 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:

$$S = S_G + S_M$$

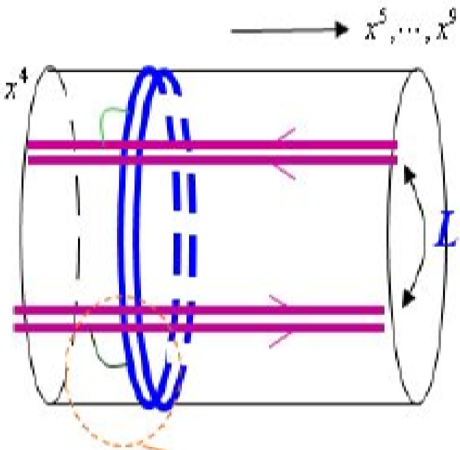
Interplay between gluodynamics and quark dynamics!!!

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:

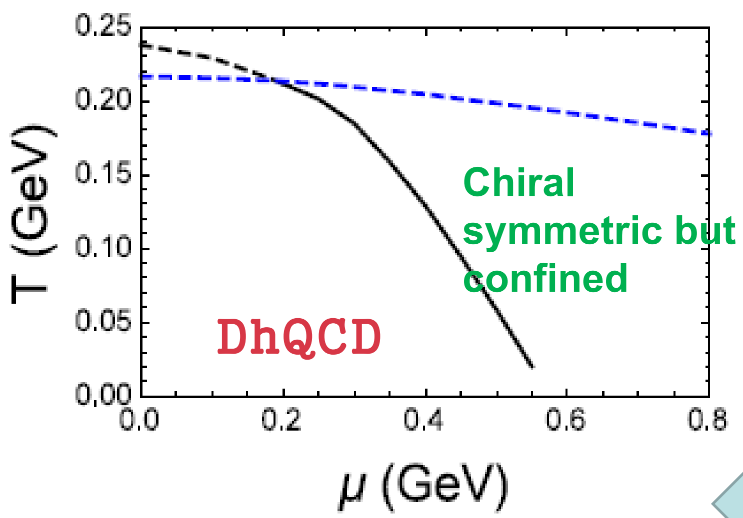
$$\mathcal{L}_{\rm NJL} = \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi + G_S[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\vec{\tau}\psi)^2] - G_V[(\bar{\psi}\gamma_\mu\psi)^2 + (\bar{\psi}\gamma_\mu\gamma_5\psi)^2]$$

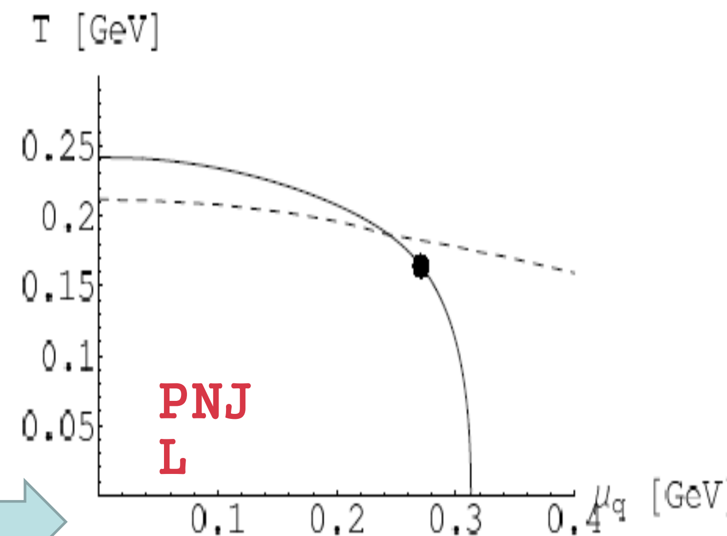
Gluon "dynamics": Polyakov-loop effective potential

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

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

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

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

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

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

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

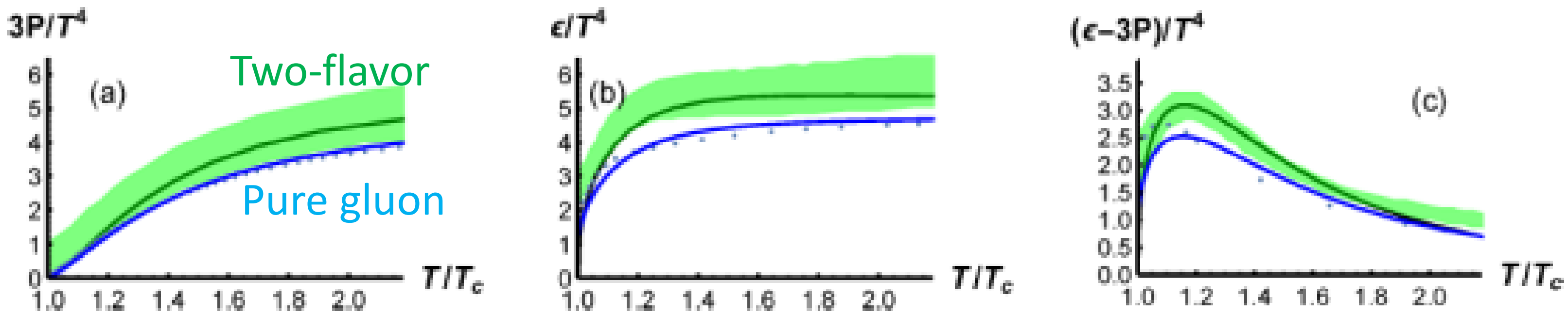
D. Dudal and S. Mahapatra, "Thermal entropy of a quark-antiquark pair above and below deconfinement from a dynamical holographic QCD model," Phys. Rev. D **96** (2017) no.12, 126010 [arXiv:1708.06995 [hep-th]].

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

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

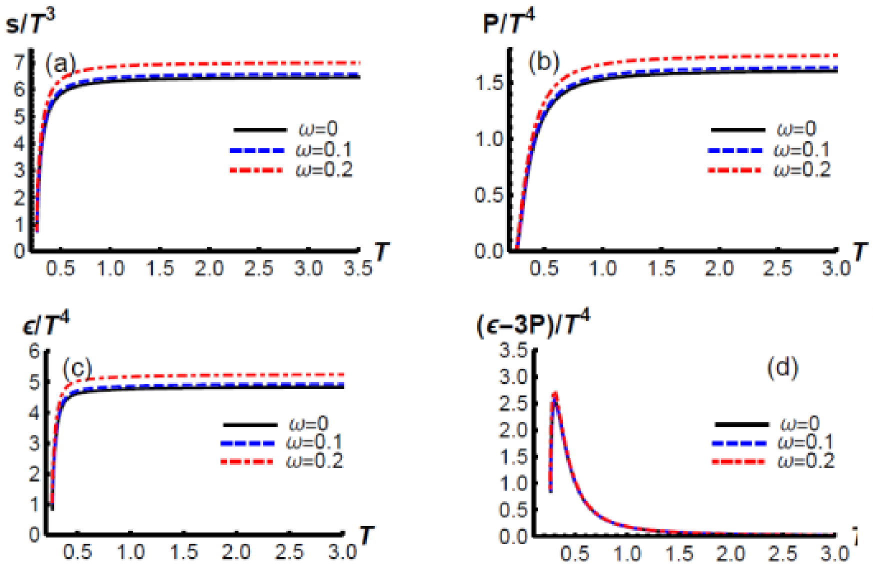
Fit parameters from lattice QCD results for pure gluon system and 2-flavor system

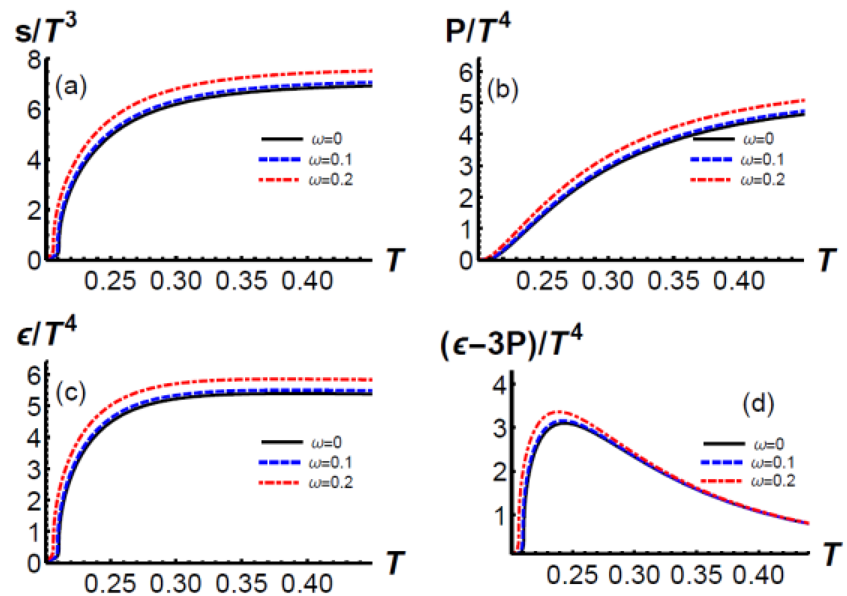


	c	a	b	d	G_5	T_c
$N_f = 2$	-0.227	0.01	0.045	0.035	1.1	211MeV
$N_f = 0$	1.16	0.075	0.12	0.075	1.2	265MeV

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

Enhancement of thermodynamical properties under rotation

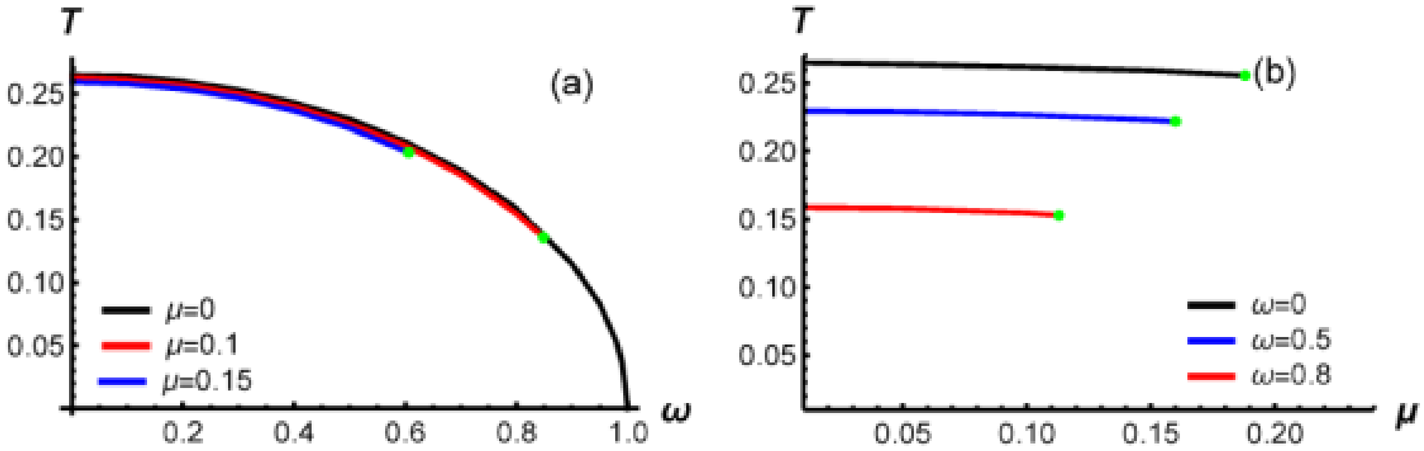




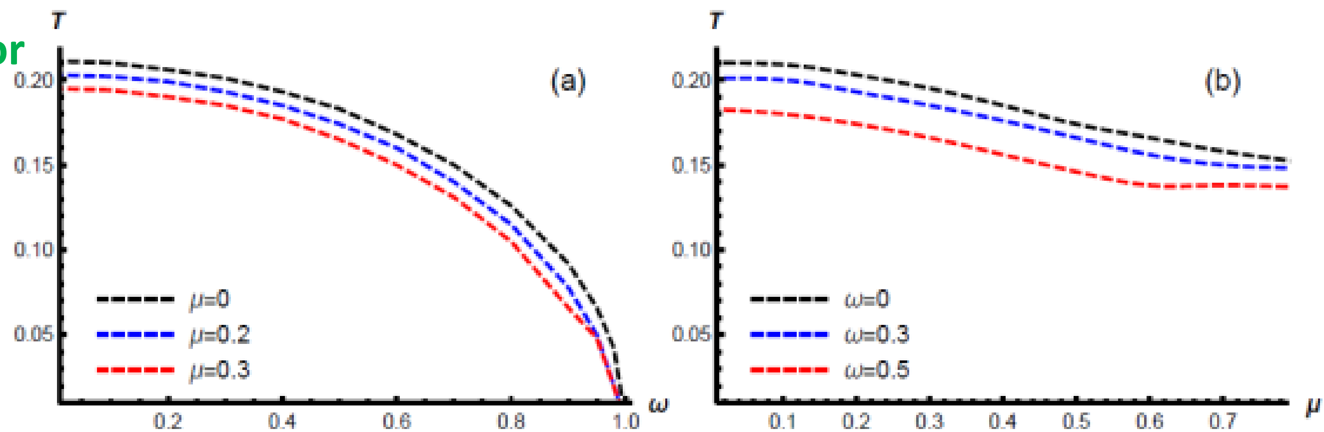
Xun Chen, Lin Zhang, Danning Li,
Defu Hou, M.H. arXiv: 2010.14478

Deconfinement phase transition under rotation

Pure gluon



Two-flavor



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

Critical temperature of deconfinement phase transition decreases with rotation in holography method! Confirmed by other studies! e.g.

Yanqing Zhao's talk

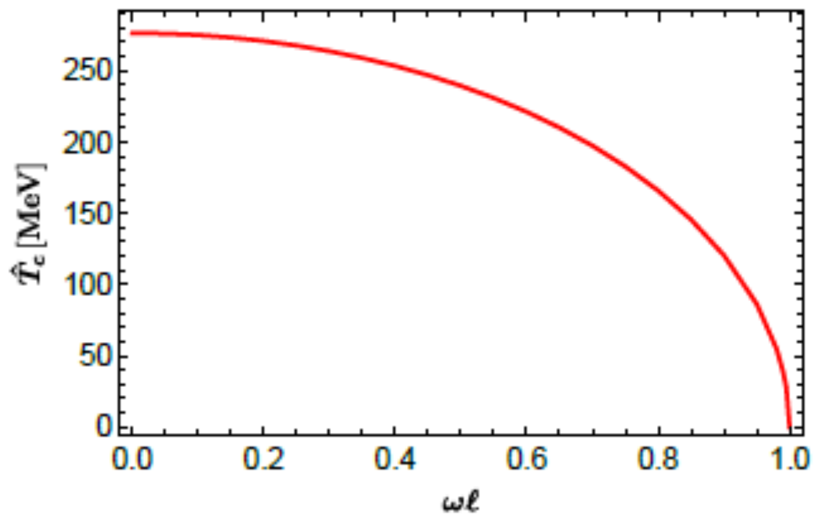


Figure 9: The $\hat{T}-\omega$ phase diagram of the pure gluon system. The critical temperature of the first-order phase transition decreases as ω is increased.

Phase diagram of holographic thermal dense QCD matter with rotation

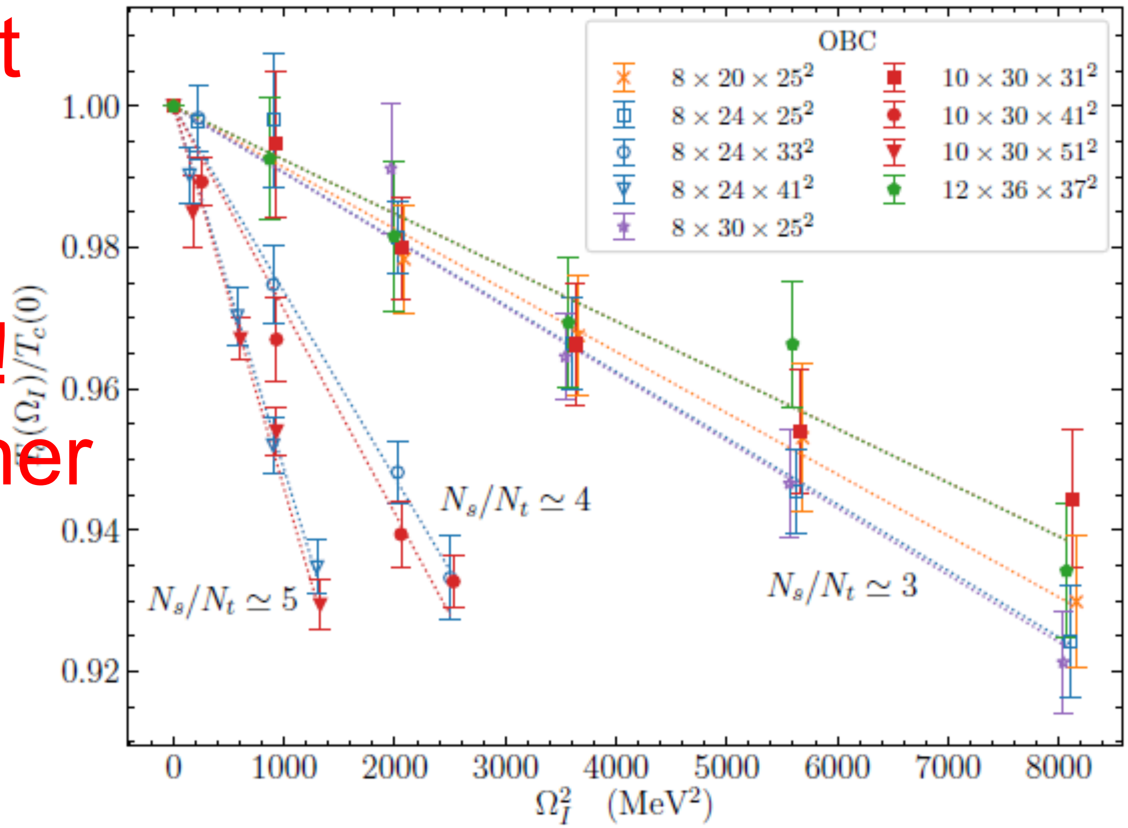
Yan-Qing Zhao[1]*, Song He[2,3]†, Defu Hou[1]‡, Li Li[4,5,6]§ and Zhibin Li[7]¶

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

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]

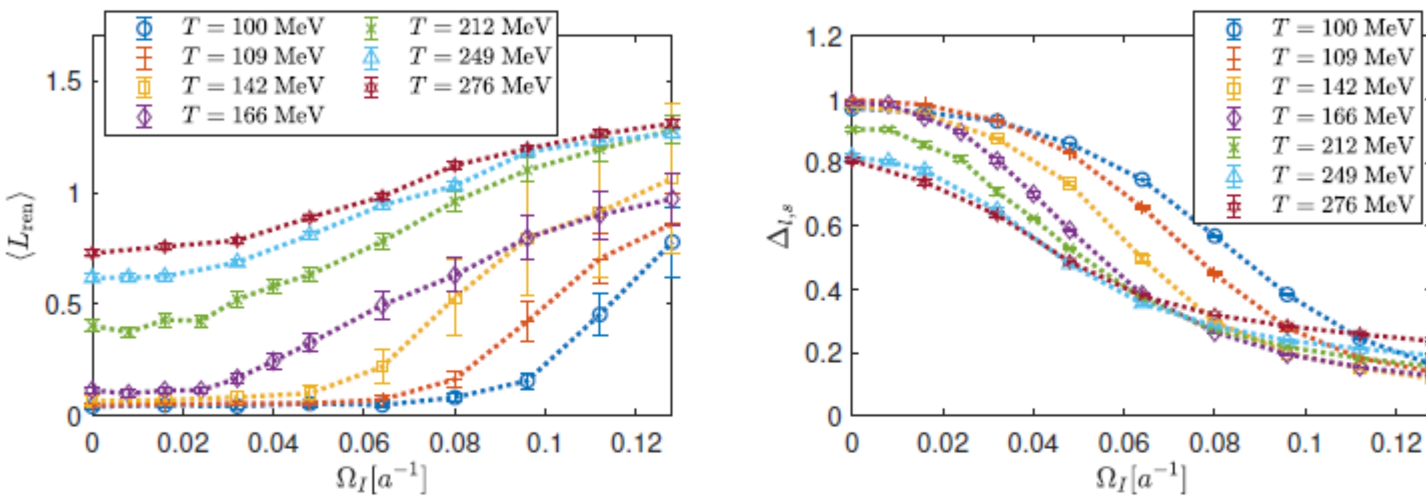


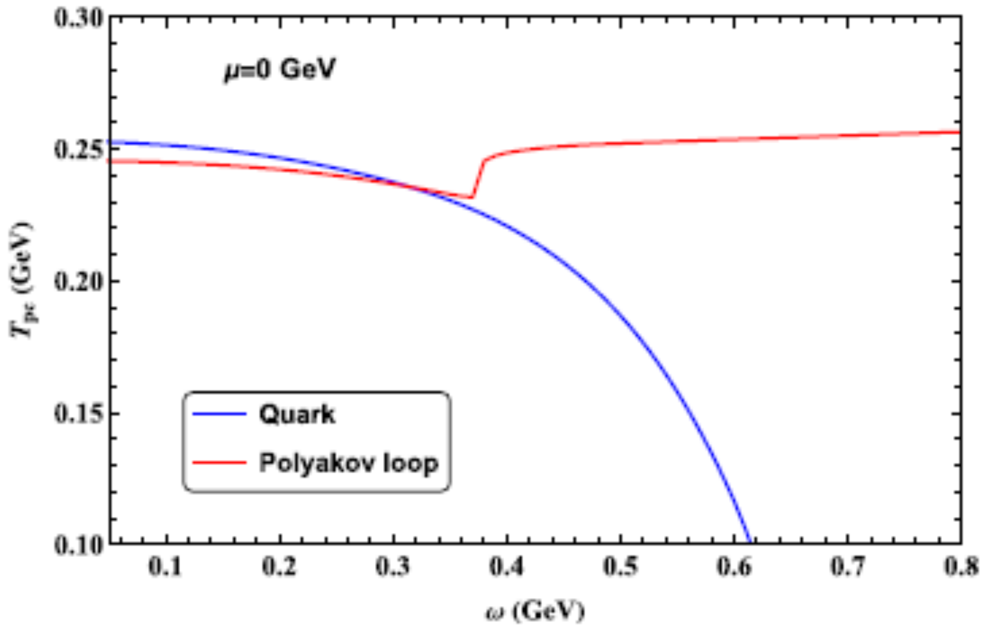
FIG. 4. The Polyakov loop and chiral condensate as functions of Ω_I.

Opposite results on the effect of rotation on the critical temperature of deconfinement phase transition in hQCD and lattice has attracted much attention in recent years!

Deconfinement phase transition under rotation in PNJL model

Fei Sun , Kun Xu, and Mei Huang， PHYSICAL REVIEW D 108, 096007 (2023), e-Print: 2307.14402 [hep-ph]

$$\mathcal{L}_{\mathrm{PNJL}} = \bar{\psi}[i\gamma^{\mu}D_{\mu} - m + \gamma^{0}\mu + (\gamma^{0})^{-1}((\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times4})]\psi + G(\bar{\psi}\psi)^{2} - \mathcal{U}(\Phi[A],\overline{\Phi}[A],T),$$



The effects of imaginary and real rotations on QCD matters

Gaoqing Cao
School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519088, China
(Dated: October 6, 2023)

e-Print: 2310.03310 [nucl-th]

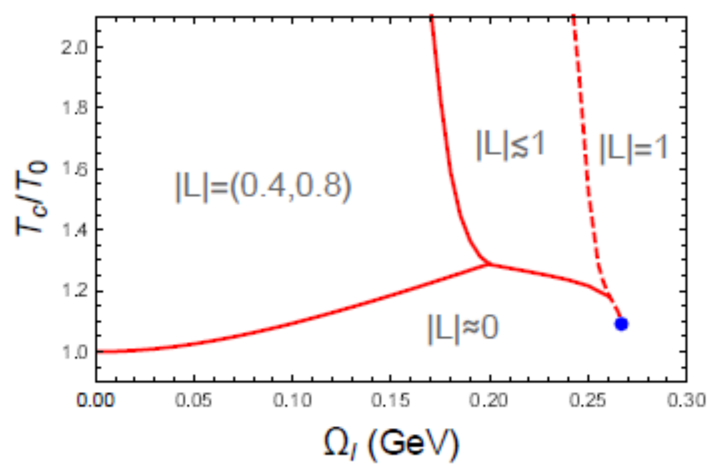


FIG. 3. The temperature-imaginary rotations ($T-\Omega_I$) phase diagram. The solid and dashed lines correspond to first- and second-order transitions, respectively, and the blue bullet is a critical end point.

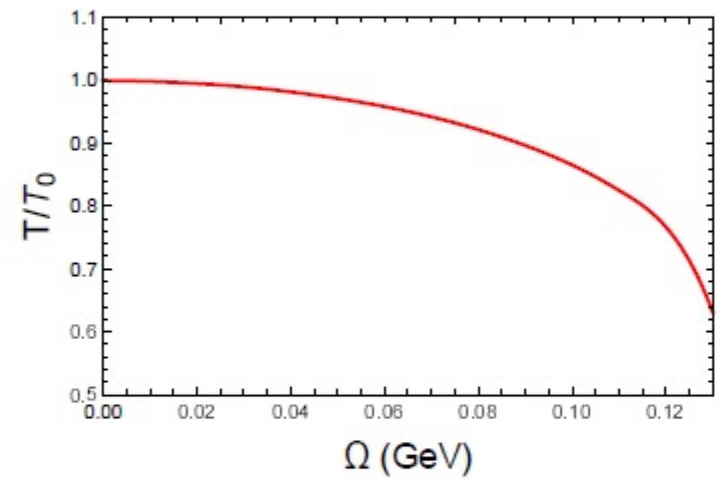


FIG. 5. The temperature-real rotations ($T-\Omega$) phase diagram with the transition of first order.

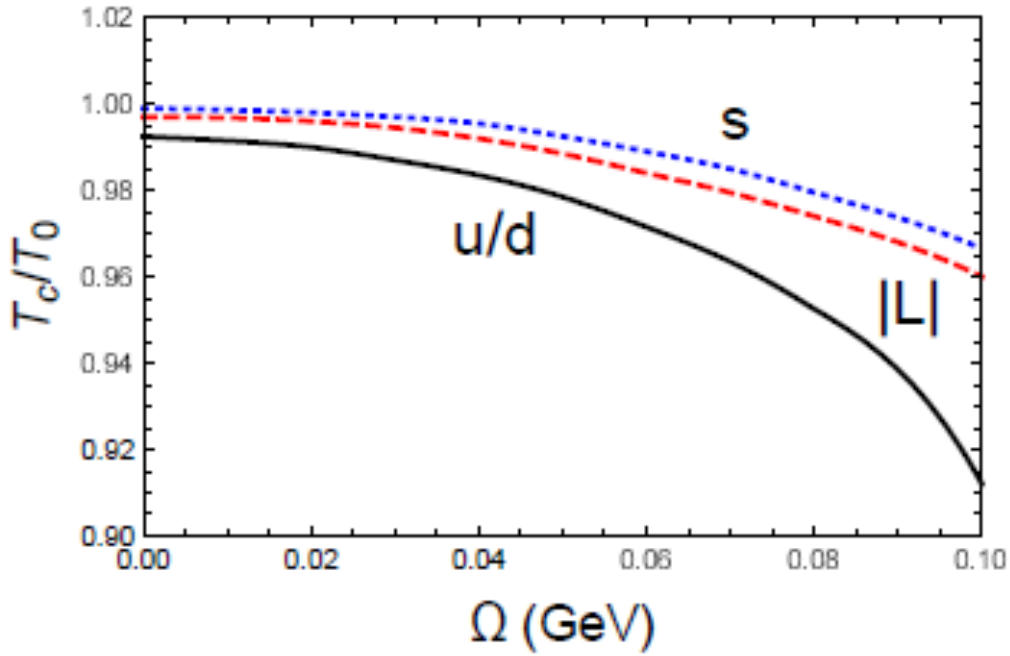


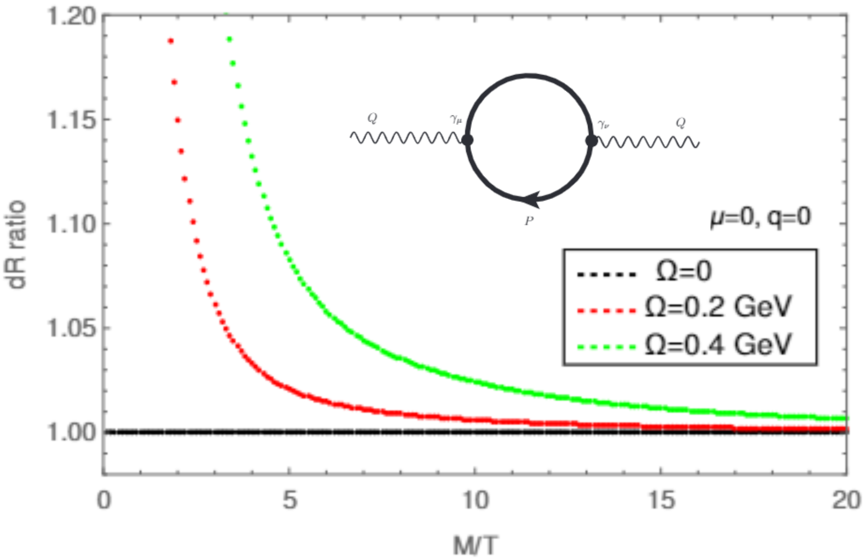
FIG. 14. The pseudocritical temperatures T_c as functions of real rotation Ω for $m_{u/d}$, m_s and $|L|$ in the PNJL model.

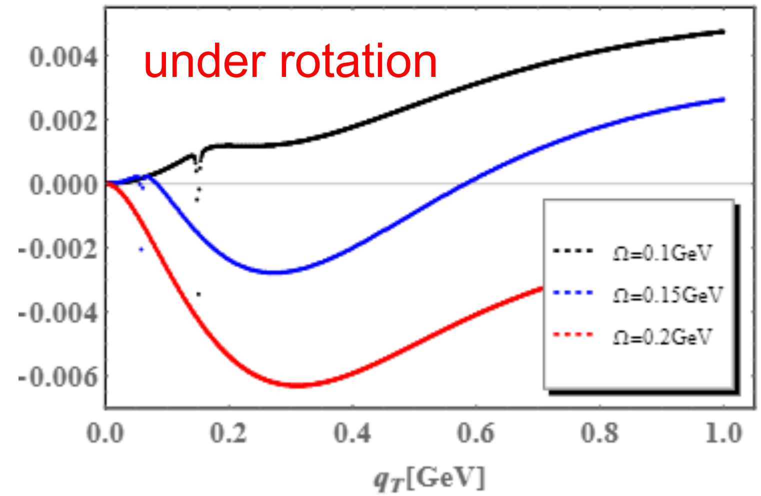
1, need to understand polarized gluodynamics under rotation;

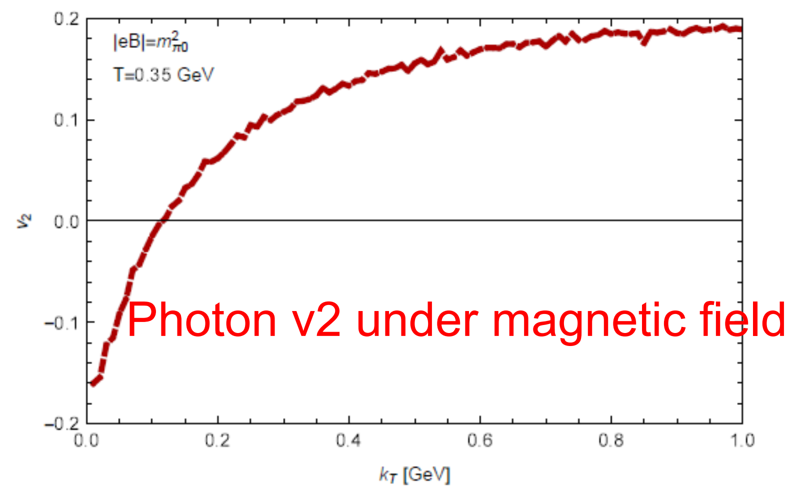
2, need to check carefully the calculation in hQCD and lattice QCD.

Dilepton rate and ellipticity under roation

Minghua Wei, Aminul Chowdhury, Mei Huang, arXiv: 2111.05192



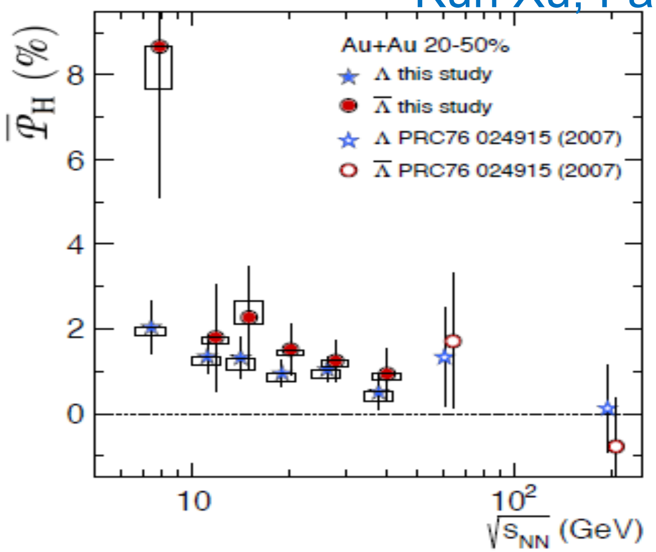


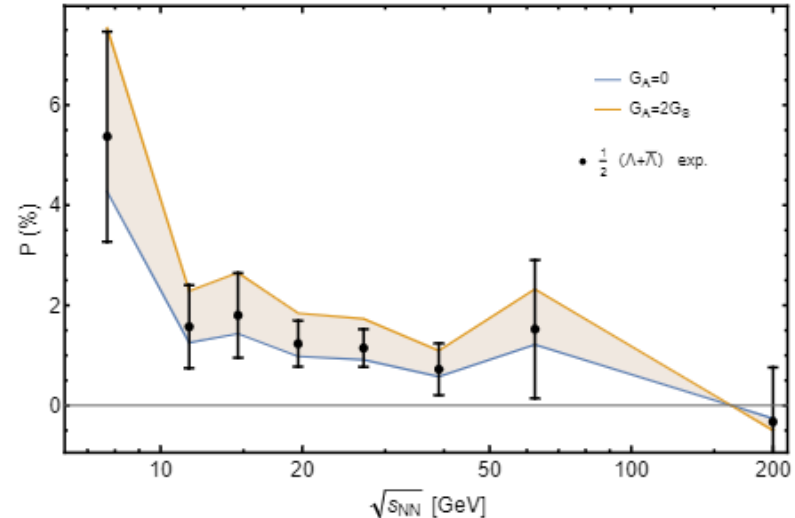


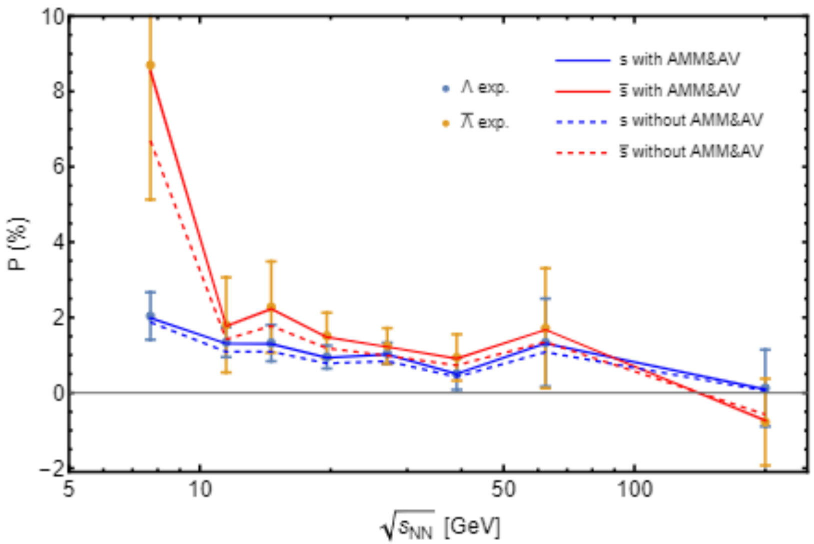
Xinyang Wang, Igor Shovkovy,Lang Yu, Mei Huang, arXiv: 2006.16254

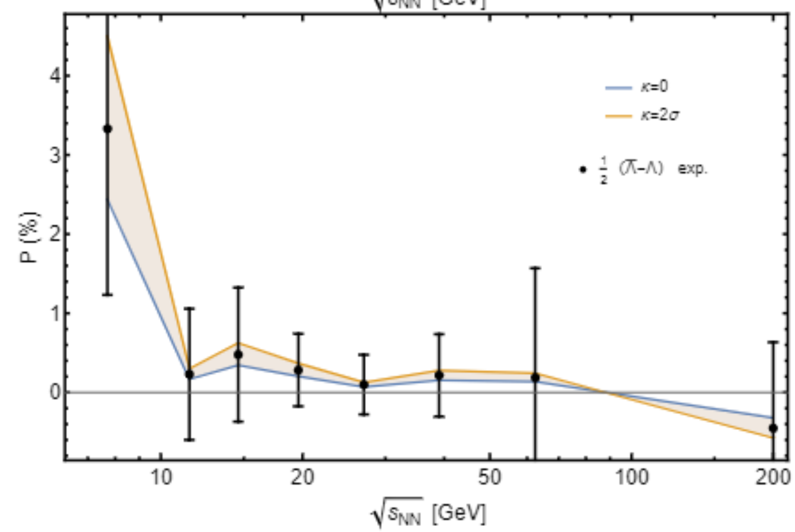
Global polarization induced by rotation, polarization difference of charged particles induced by magnetic field. SP and AMM plays important role.

Kun Xu, Fan Lin, Anping Huang, Mei Huang, to appear









Summary

1, Selfconsistent understanding on diamagnetism, IMC and meson spectra under magnetic field still need further studies.

2, Both rotation and magnetic field induces polarization, global polarization induced by rotation, polarization difference of charged particles induced by magnetic field. SP and AMM plays important role.