Exploring properties of rotating Magnetized QCD matter

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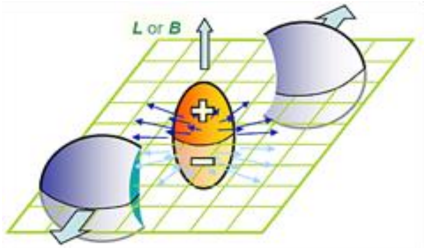
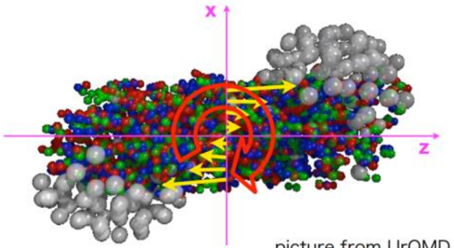
原子核结构与相对论重离子碰撞前沿交叉研讨会

Outlines

- **Introduction and motivation**
- **Phase structure under rotation and Magnetic field**
- **Transport properties rotating magnetized matter**
- **Summary**

QCD under new extreme conditions





picture from UrQMD

$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

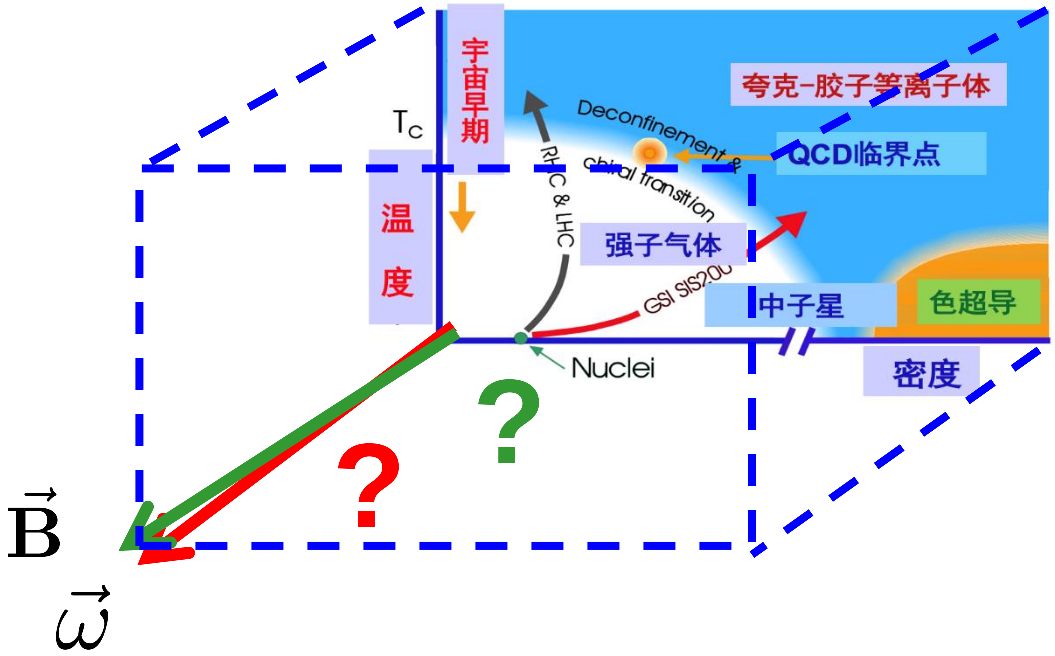
$$L \approx \frac{A\sqrt{s_{NN}}}{2} b\hbar \sim 10^6 \hbar$$

传统看法: 电磁场 / 转动的影响 << 强相互作用，可以忽略。

不可忽略！热力学平衡性质？动力学输运性质？可观测实验信号？

Talks in this WS: Zhuang, M. Huang, L. Chen, X.Huang , Y. Ma, G. Ma , Pu, Lin , Cao, Chen, Gao

Explore the new dimensions of the QCD phase diagram



New theoretical techniques needed!

Lattice QCD

difficulty with Finite baryon density, Real time dynamics Continuum

Phenom. models: (p)NJL、(p)QMC...

Field Theory: HD(T)L , pQCD , Chiral Perturbation,

DS Equations

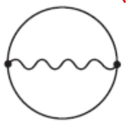
Functional Renormalization Group, Sum rules ....

AdS/CFT, AdS/QCD

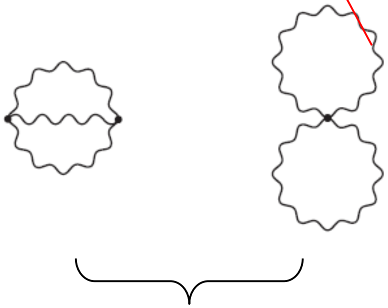
CJT effective action of QCD

$$\Gamma[\bar{D},\bar{S}] = \frac{1}{2}\{Tr\ln\bar{D}^{-1} + Tr(D^{-1}\bar{D}-1) - Tr\ln\bar{S}^{-1} - Tr(S^{-1}\bar{S}) - 2\Gamma_2[\bar{D},\bar{S}]$$

2-loop approximation



Order of g² μ^4



Powers of T

Stationary points

$$\left.\frac{\delta\Gamma}{\delta\bar{\mathcal{D}}}\right|_{\bar{\mathcal{D}}=\mathcal{D},\bar{\mathcal{S}}=\mathcal{S}} = 0\,, \qquad \left.\frac{\delta\Gamma}{\delta\bar{\mathcal{S}}}\right|_{\bar{\mathcal{D}}=\mathcal{D},\bar{\mathcal{S}}=\mathcal{S}} = 0$$

$\Downarrow$ $\qquad$ $\Downarrow$

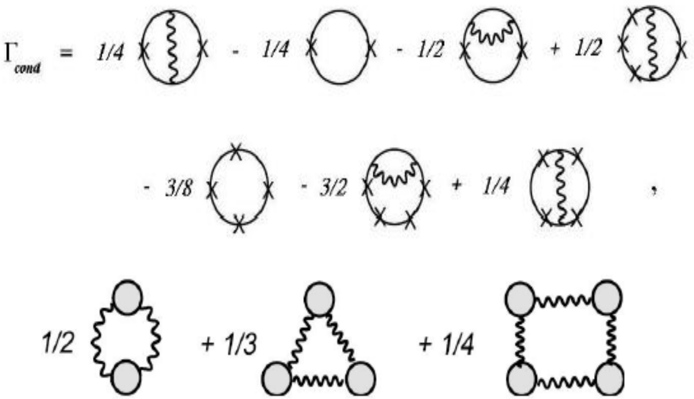
$$\mathcal{D}^{-1} = D^{-1} + \Pi[\mathcal{S}] \qquad \mathcal{S}^{-1} = \mathcal{S}_0^{-1} + \Sigma$$

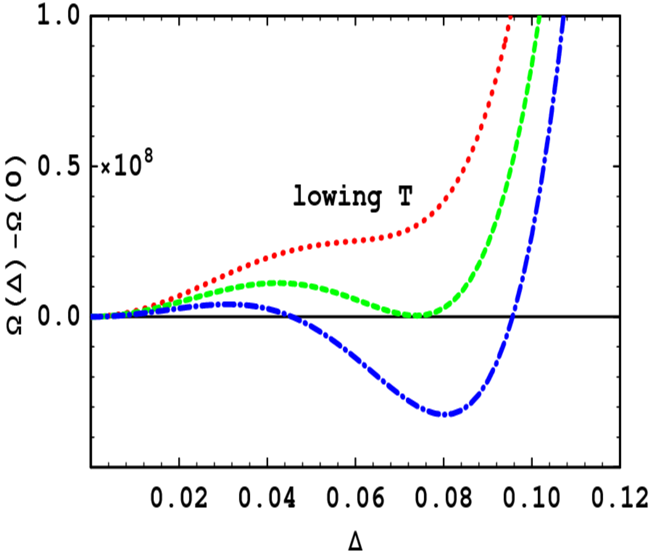
$$\Gamma_2[\bar{\mathcal{D}},\bar{\mathcal{S}}] = -\frac{1}{2}\,\mathrm{Tr}\{\bar{\mathcal{D}}\,\Pi[\bar{\mathcal{S}}]\}$$

D. Rischke Prog. Part. Nucl. Phys. 52 197 (2004)

Gauge field fluc. induce 1st order PT of CSC in dense QCD

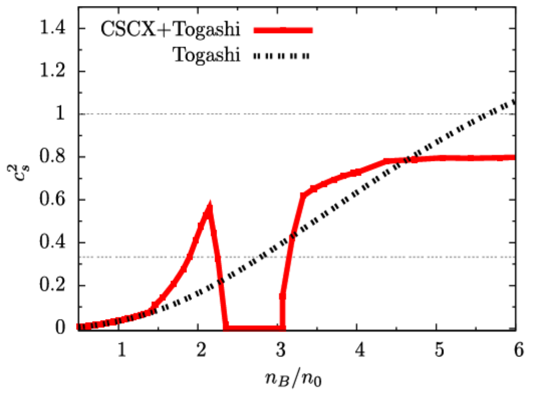
Ginnakis, Hou, Ren, Rischke, PRL 93 (04) ; PRD73 (06)

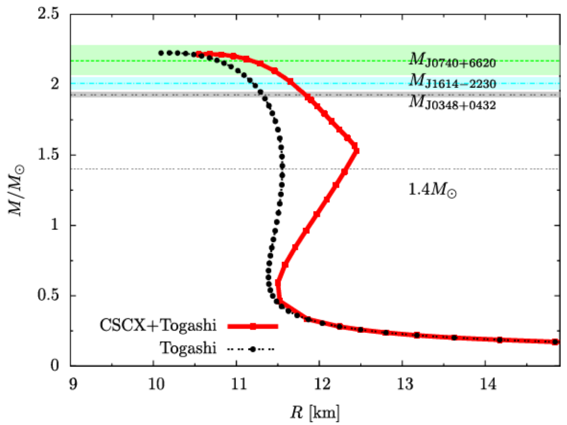




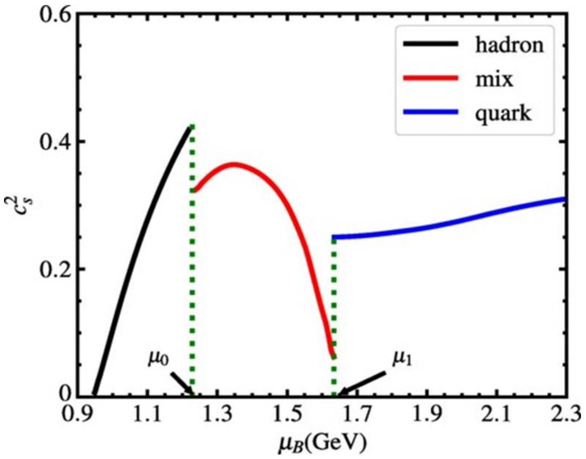
Introduction of Δ^3 term in free energy by flucts. Inducing 1st order PT in stead of 2nd order PT in MFA

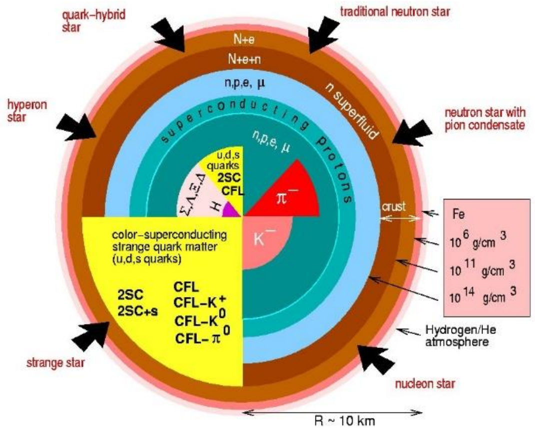
QCD物质的状态方程与中子星结构





T. Kojo， DF Hou, etc.
PRD 104 (2021) 063036



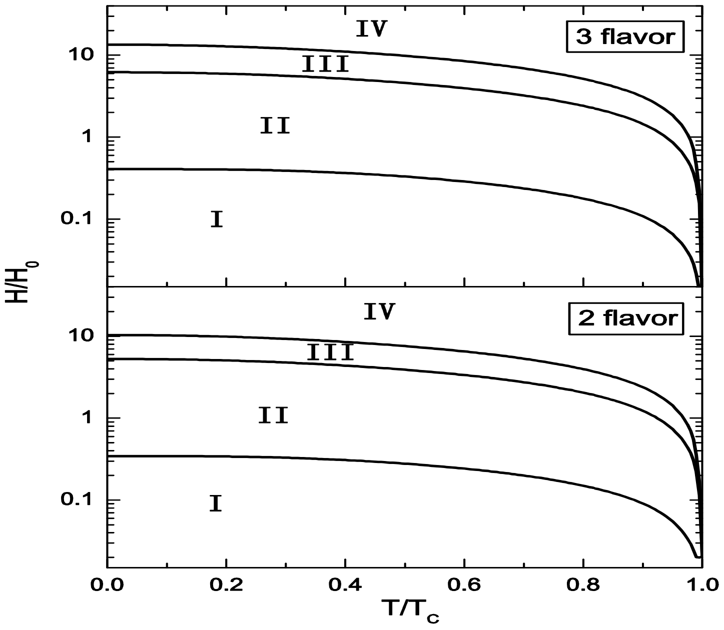


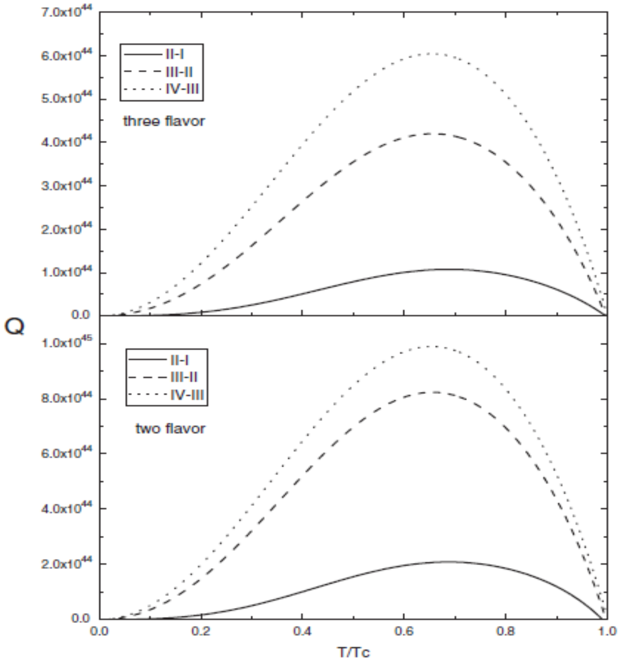
Talks in this WS:
LW Chen, Y. Ma, Huan Chen

Zhan Bai, Yuxin Liu , PRD 108, 014018 (2023)

Nonspherical states in dense QCD with B

	I	II	III	IV	$T_C(10^{-1}$ MeV)
Two-flavor	CSL_u, CSL_d	$(polar)_u$, $(planar)_d$	$(normal)_u$, $(polar)_d$	$(normal)_u$, $(normal)_d$	1.35
Three-flavor	CSL_u, $CSL_{d,s}$	$(polar)_u$, $(planar)_{d,s}$	$(normal)_u$, $(polar)_{d,s}$	$(normal)_u$, $(normal)_{d,s}$	0.49



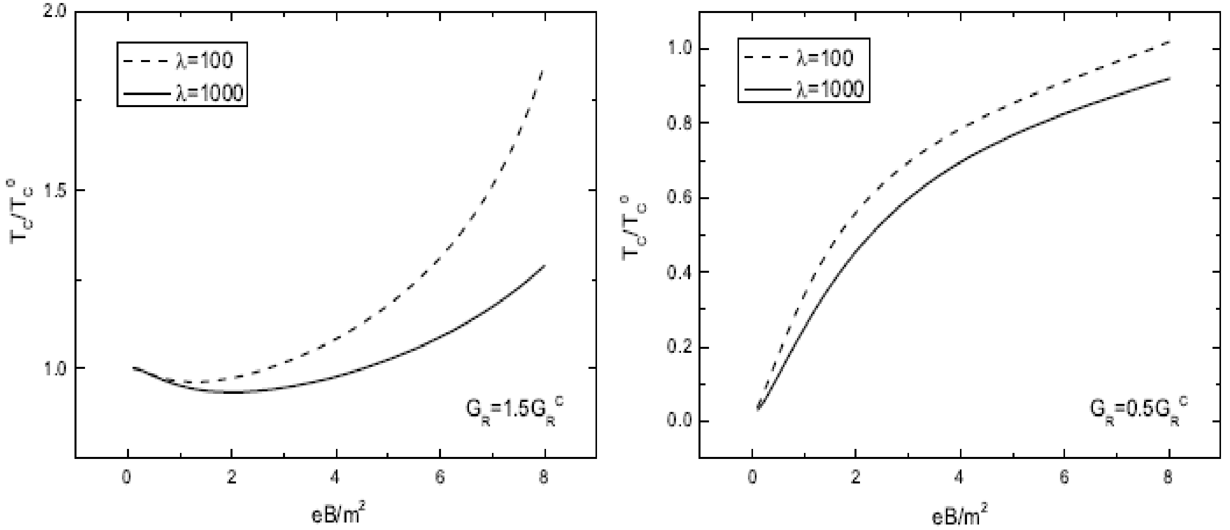


H0=5.44×10ˆ14　G, 1.97×10ˆ14　G

Feng, Hou, Ren,Wu, PRL 105(2010)

Wu, He, Hou, Ren, PRD84 (2011)

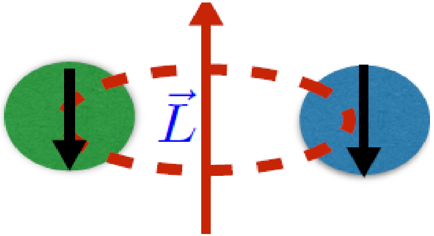
Magnetic (Inverse) BEC catalysis at W/S coupling

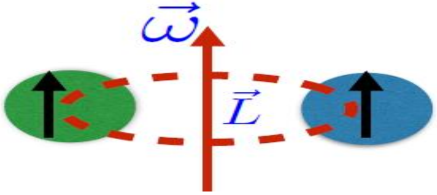


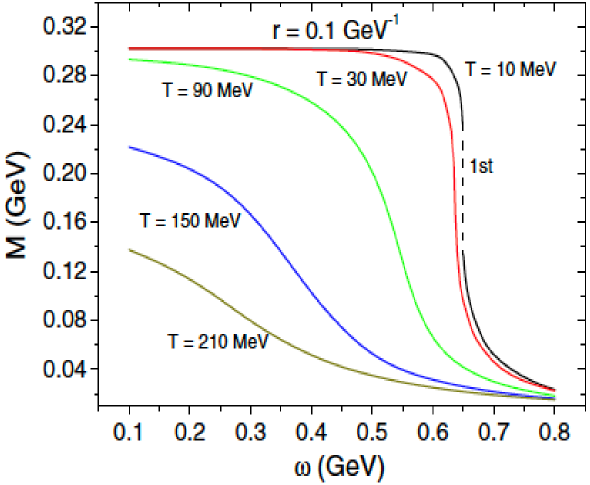
Condensation temperature versus the dimensionless magnetic field

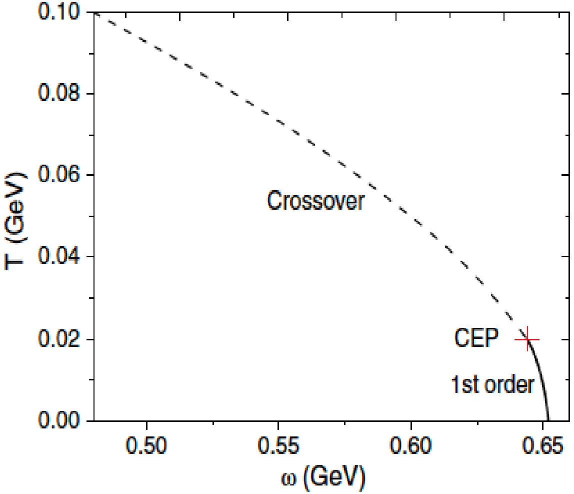
Feng, Hou, Ren , Wu, **PRD 93 (2016)085019**

Phase structure under rotation





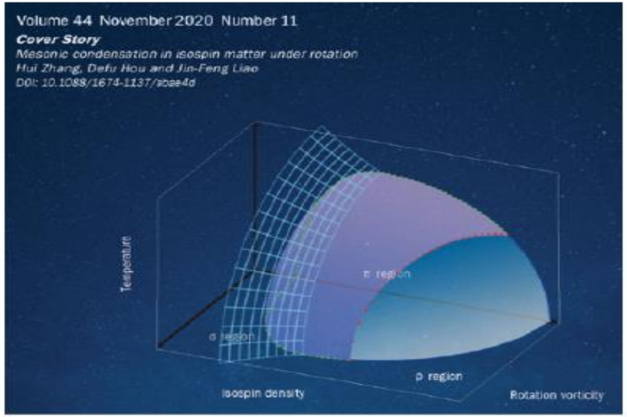


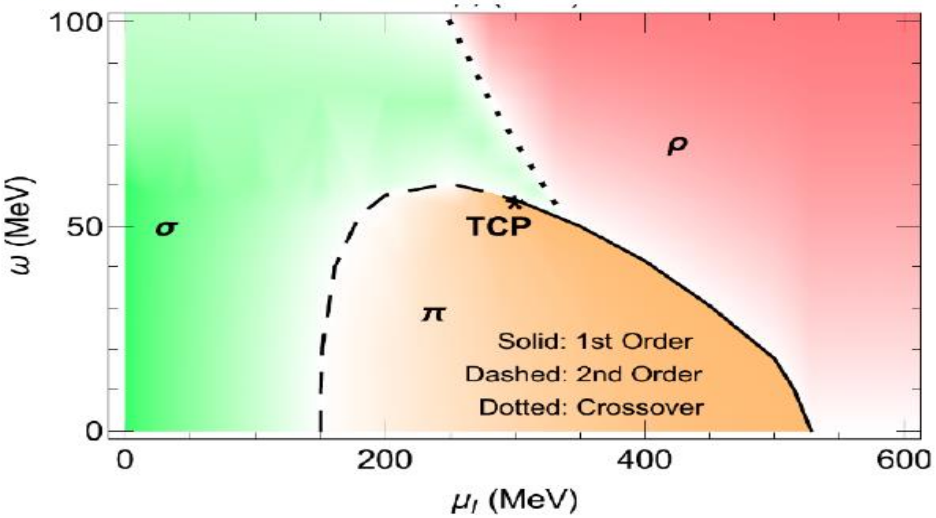


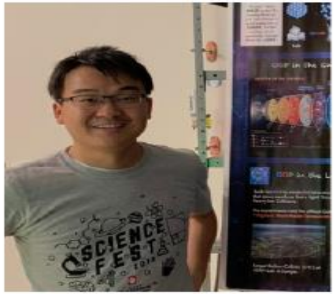
Jiang,Liao: PRL117(2016)192303

Isospin Matter under Rotation

Vacuum: sigma condensate;
Static isospin matter: pion superfluidity;
Isospin matter under rotation: emergence of rho condensate!





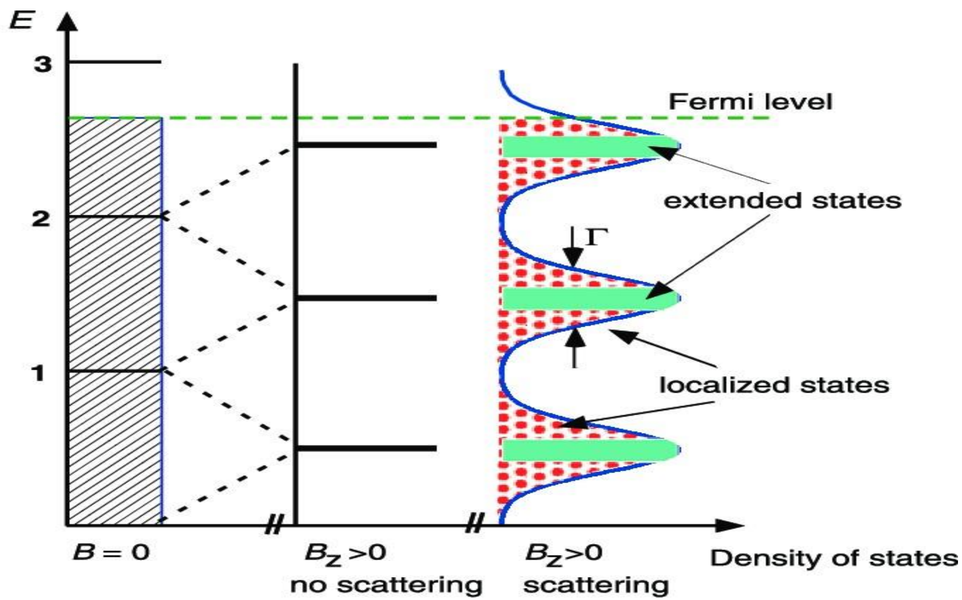


Rich phase structures found;
Could be relevant to low energy HIC
or neutron star matter

[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

De Hass-van Alphen Effect (\mu, B)

W. J. De Haas and P. M. Van Alphen, in Comm. NO. 212a from the Phys. Lab, Leiden (1930).



The dHvA effect in a degenerated system of charged fermions is the consequence of filling discrete but highly degenerate Landau levels in a magnetic field.

De Hass-van Alphen Effect with Rotation

Shu-Yun Yang, Ren-Da Dong, DF Hou, Hai-Cang Ren, PRD 107, 076020 (2023)

finite T

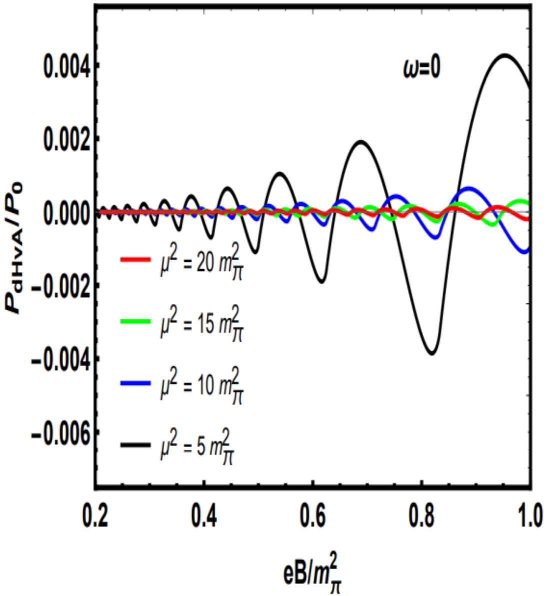
$$P_{\mathrm{dHvA}} = -\frac{(eB)^{\frac{1}{2}}}{2\pi^2 R^2}\sum_{l=1}^{\infty}\frac{1}{l^{3/2}}\sum_{M>0}\frac{\cos\left[\frac{l\pi}{eB}(\mu+M\omega)^2-\frac{\pi}{4}\right]}{\sinh\frac{2l\pi^2 T(\mu+M\omega)}{eB}}.$$

Zero T:

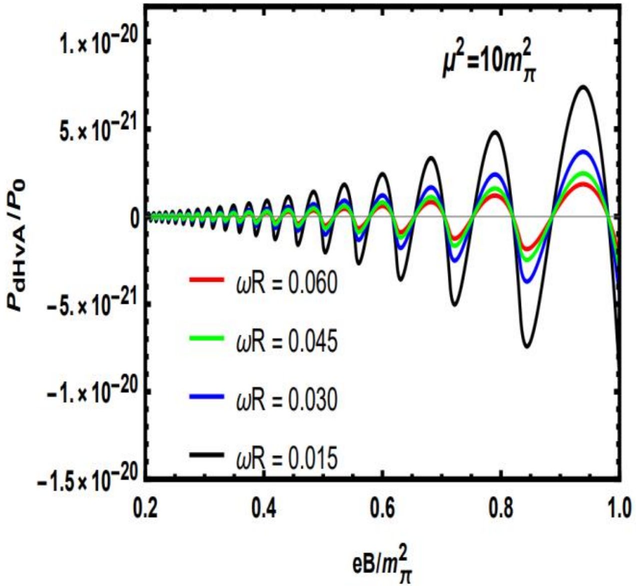
$$P_{\mathrm{dHvA}} = -\frac{(eB)^{\frac{3}{2}}}{4\pi^4 R^2}\sum_{M>0}\frac{1}{\mu+M\omega}\sum_{l=1}^{\infty}\frac{1}{l^{5/2}}\cos\left[\frac{l\pi}{eB}(\mu+M\omega)^2-\frac{\pi}{4}\right]$$

In rotation, the thermodyn Equl. is established under a AM. The equal distrib. of different AM states within a LL is offset by the nonzero AV with higher AM more favored than lower ones, which amounts to lifting the degeneracy of LL. The dHvA oscillation is thereby expected to be reduced by rotation

De Hass-van Alphen oscillation



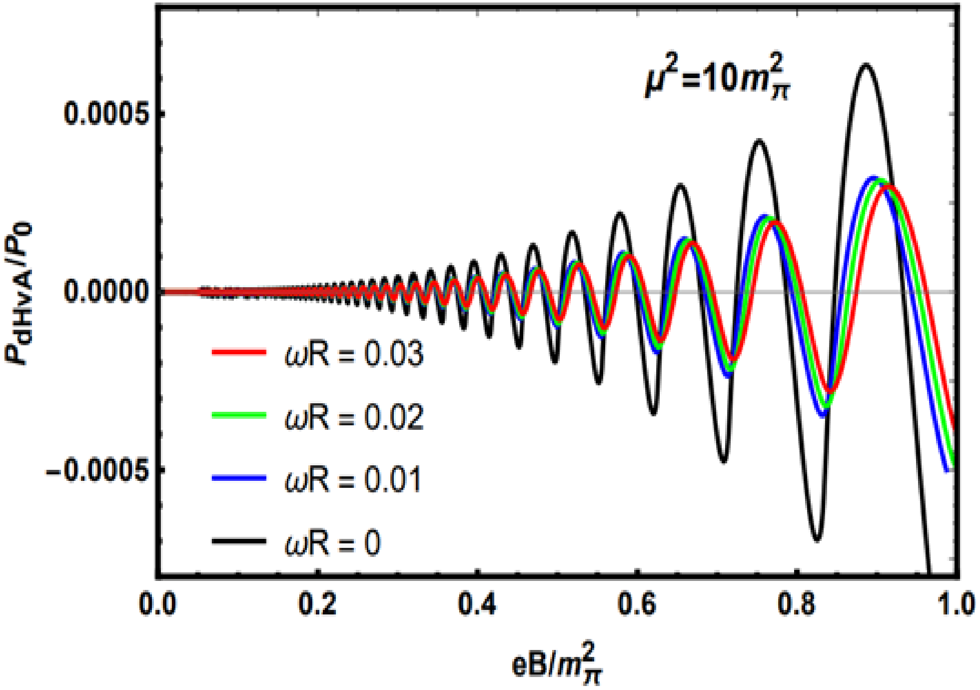
dHvA in NS with rotation (R=1km)



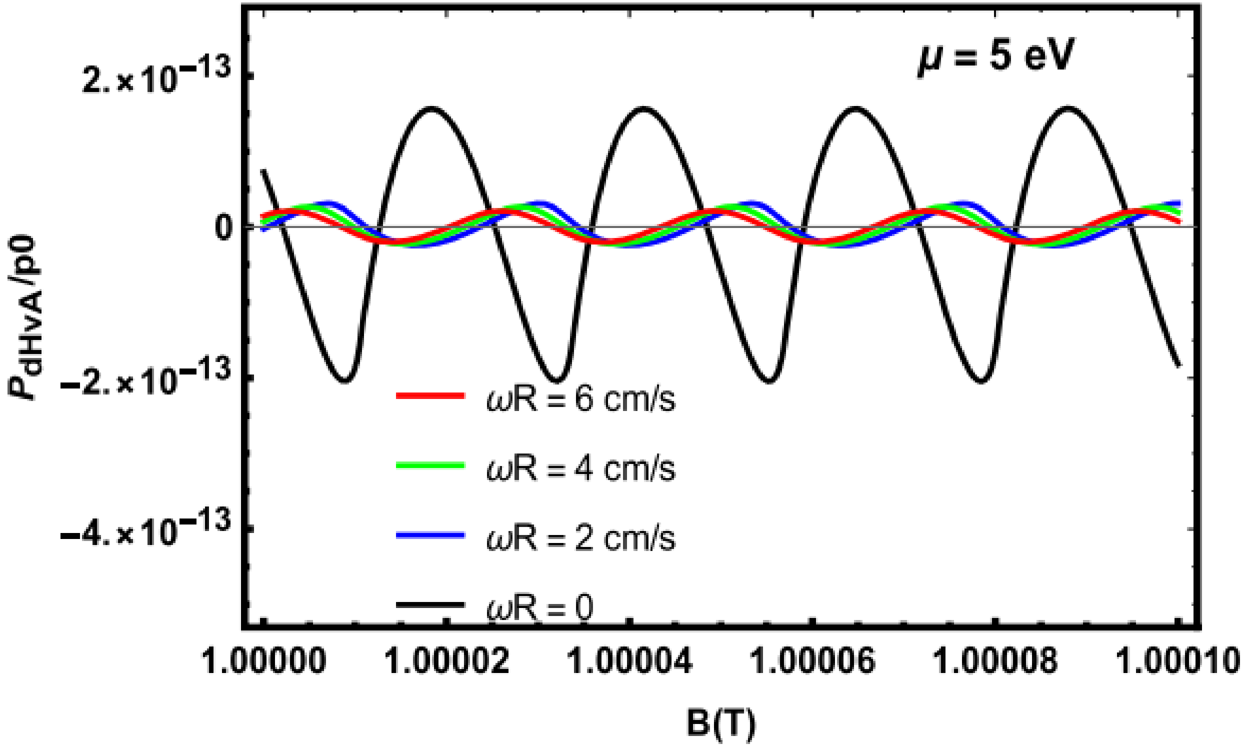
Huge suppression of dHvA oscill. (17 order)
due to large size

Shu-Yun Yang, Ren-Da Dong, DF Hou, Hai-Cang Ren, PRD 107, 076020 (2023)

dHvA oscillation in cold & dense QGP droplet (R=10fm)



the variation of dHvA oscillation with angular velocity appears detectable (oscillation remains)

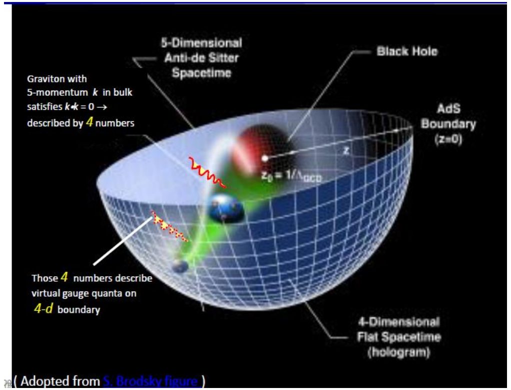


a typical electron gas in a good metal, the variation of dHvA oscillation with AM appears detectable, via magnetization and/or magnetic susceptibility.

QCD Phase Diagram with rotation

Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li, *JHEP 04 (2023) 115*

AdS/CFT correspondence

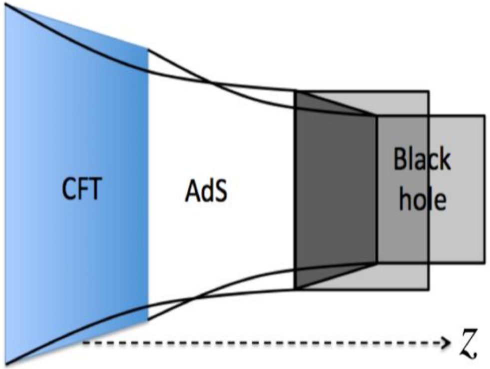


4dim. Large-Nc strongly coupled SU(Nc) N=4 SYM (finite T).

Maldacena '97 ↕

conjecture

Witten '98

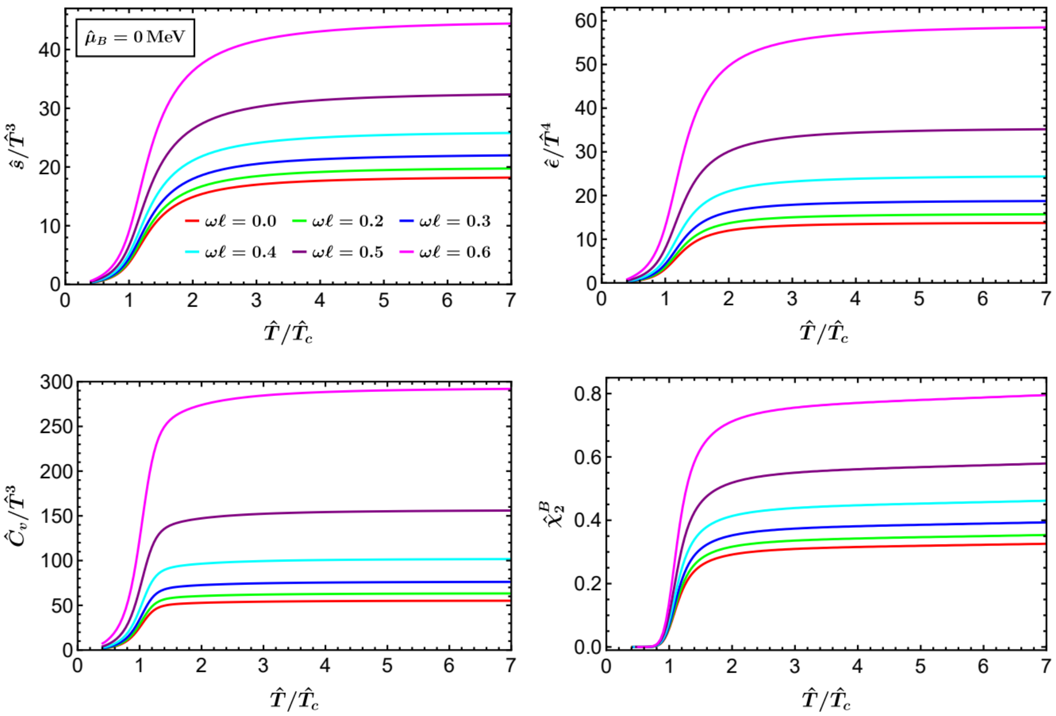


Type II B Super String theory on AdS5-BH×S5

Some complicated Field theory calculations become simple "geometric' problems in higher dimensions

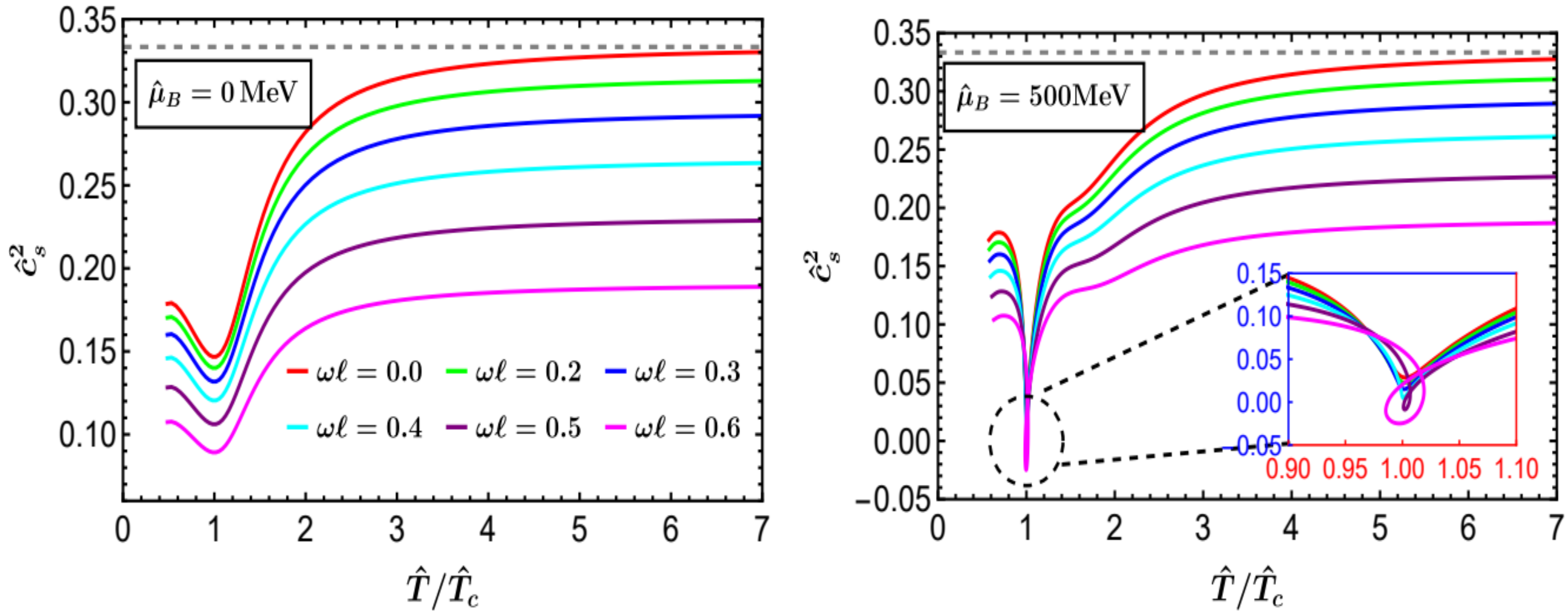
Phase diagram @2+1 flavor

- Thermodynamics *with rotation*:



Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li, JHEP 04 (2023) 115 • e-Print: 2212.14662

➢ Thermodynamics *with rotation*:



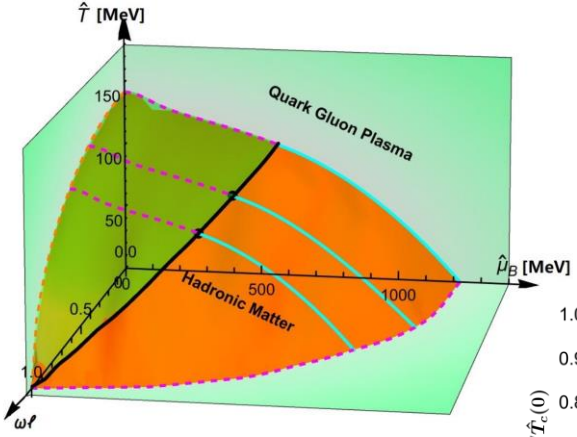
Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li, JHEP 04 (2023) 115 • e-Print: 2212.14662

ID: Yan-Qing Zhao, Song He, Defu Hou, Li Li, Zhibin Li, JHEP 04 (2023) 115 • e-Print: 2212.14662

➢ 2+1 flavor:

➢ Pure gluon($\hat{\mu}_B = 0$):

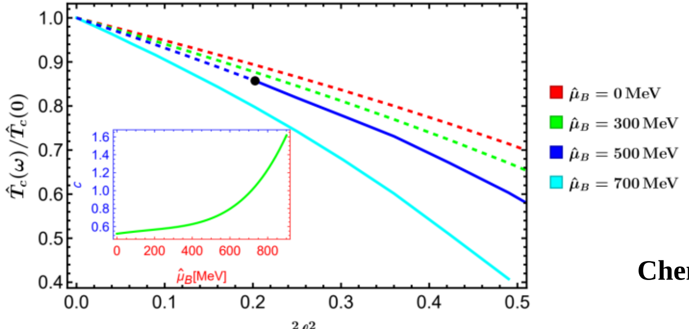
- ✓ **black solid line:** denoting the location of CEP.
- ✓ At high $\hat{T}$ and small $\hat{\mu}_B$: **Being the smooth crossover.**
- ✓ At low $\hat{T}$ and large $\hat{\mu}_B$: **Being 1st-order transition.**
- ✓ $\omega \uparrow$ ⟹ $\hat{T}_c \downarrow$, $\hat{\mu}_c \downarrow$, $\hat{T}_{cep} \downarrow$, $\hat{\mu}_{cep} \downarrow$.



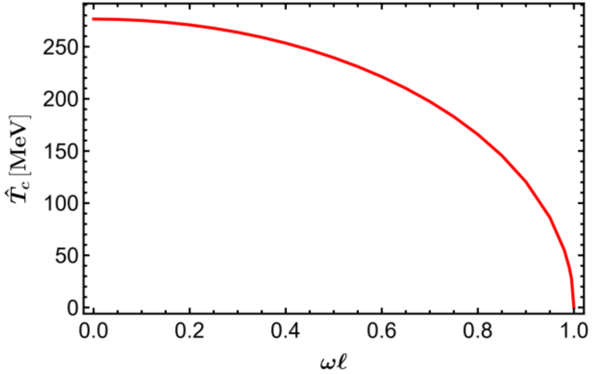
$$\hat{T}_c(\omega)/\hat{T}_c(0) \approx 1 - c\,\omega^2$$

- ✓ At finite $\hat{\mu}_B$ **and smaller ω.**

The value of c depends on $\hat{\mu}_B$.



Analytically: $\hat{T}_c(\omega) = T_c\sqrt{1-\omega^2\ell^2}$



Chen, Zhang, Li, Hou , M.Huang ,JHEP 07 (2021) 132

Phase Structure with magnetic field

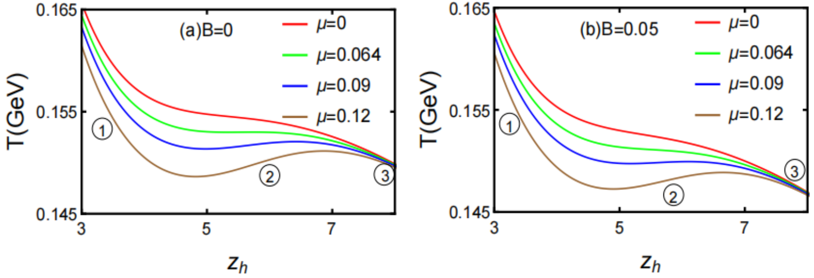


图1. 化学势对温度的影响

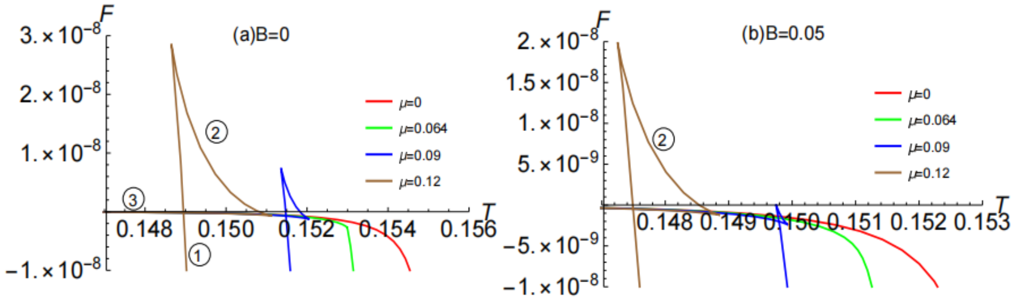


图2. 化学势对吉布斯自由能的影响

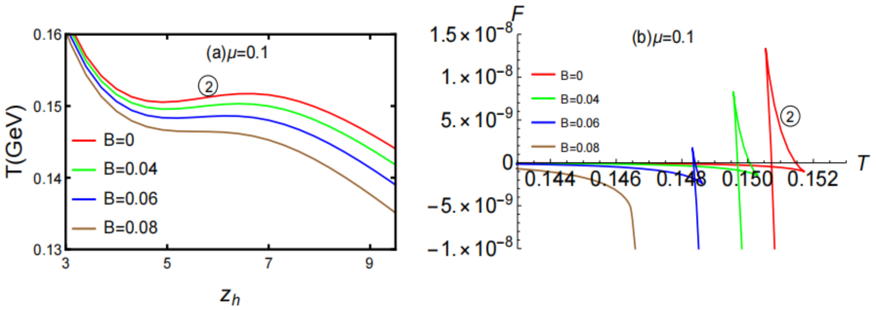


图3. 磁场对温度、自由能的影响

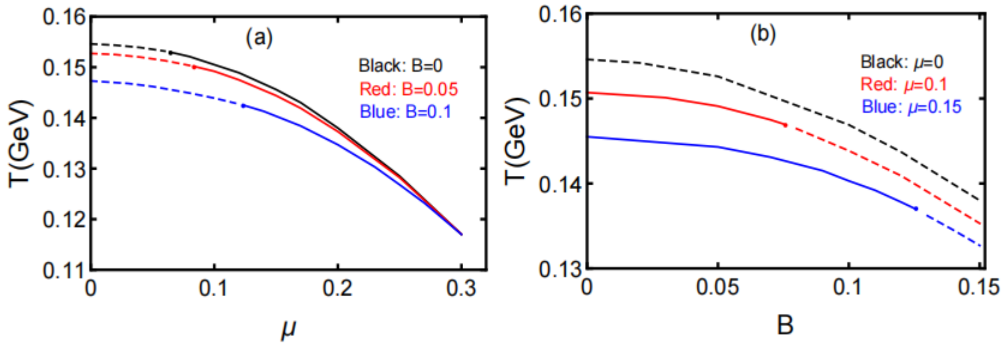
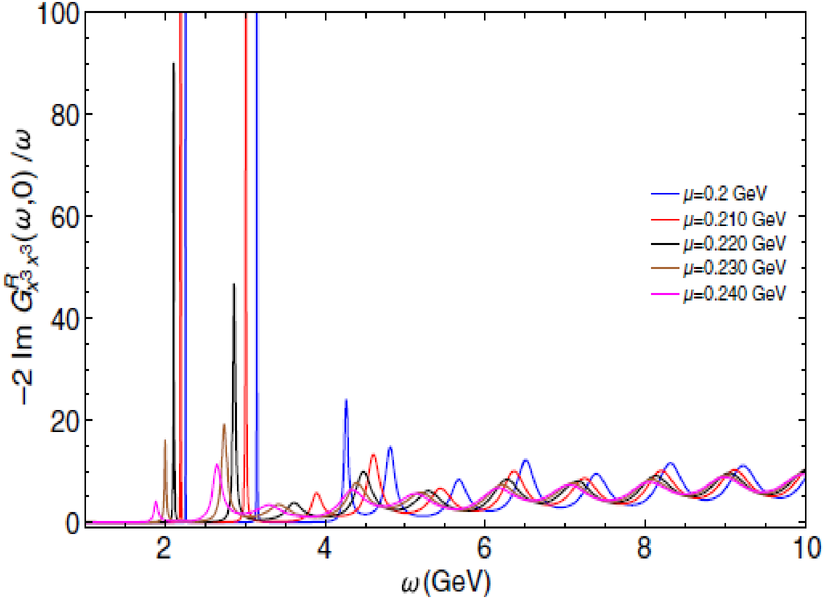


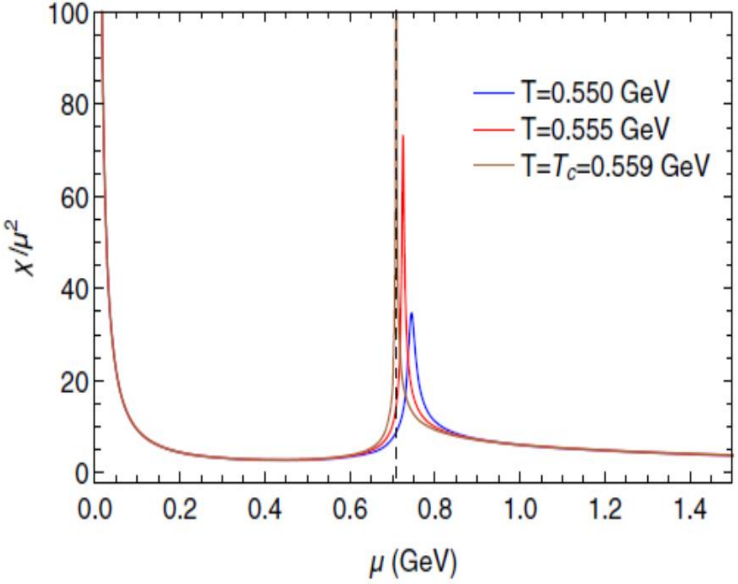
图4. 相图

Zhou-Run Zhu, De-fu Hou, Inverse magnetic catalysis and energy loss in holographic QCD model, (arXiv:2305.12375).

The spectral function of heavy vector mesons

Mamani , Hou, Braga, PRD 105, 126020 (2022)



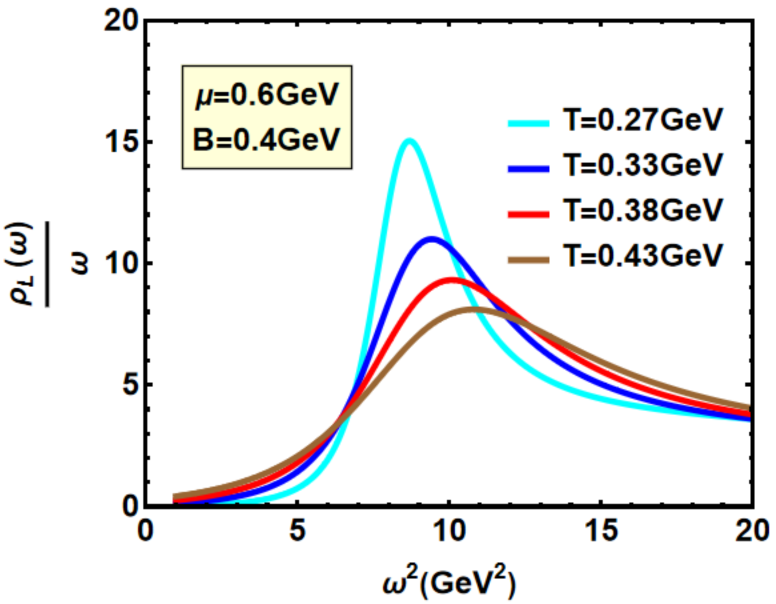


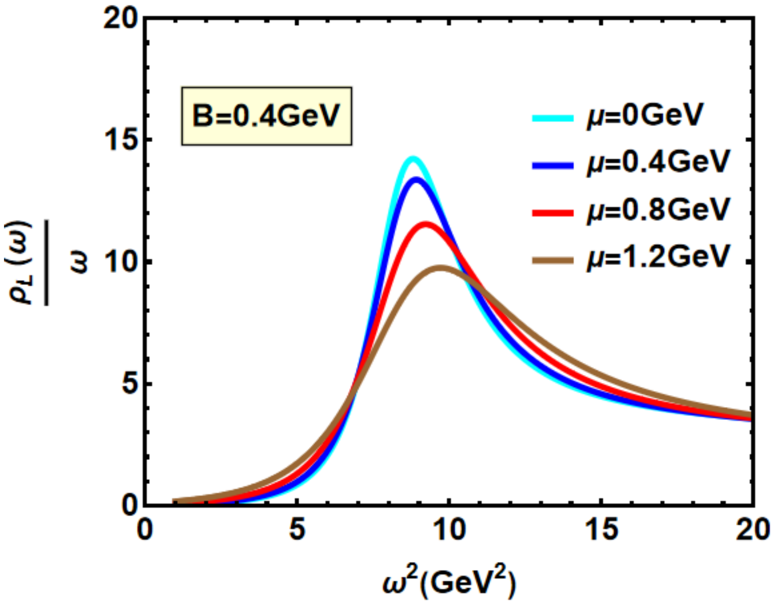
J/Ψ

- **Spectral function:**

Yan-Qing Zhao, Defu Hou, Eur.Phys.J.C 82 (2022) 12, 1102 • e-Print: 2108.08479

As increasing temperature and chemical potential，the dissociation effect increases.



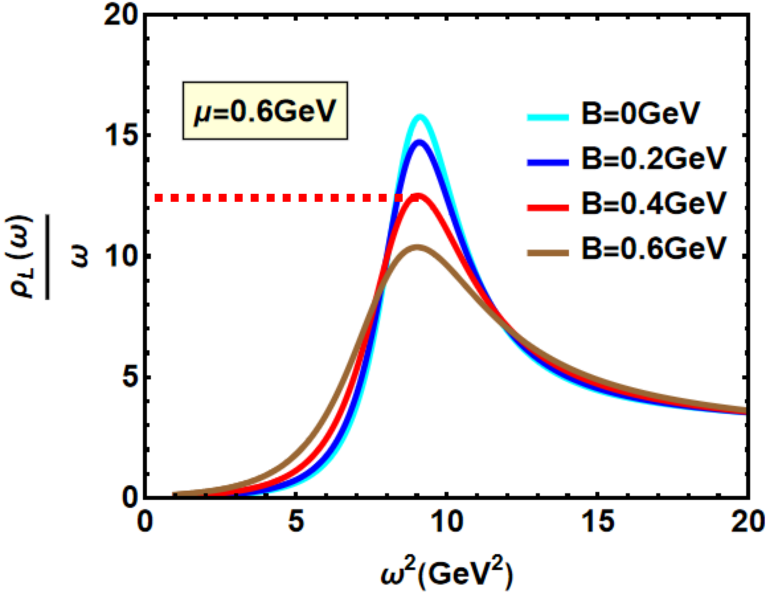


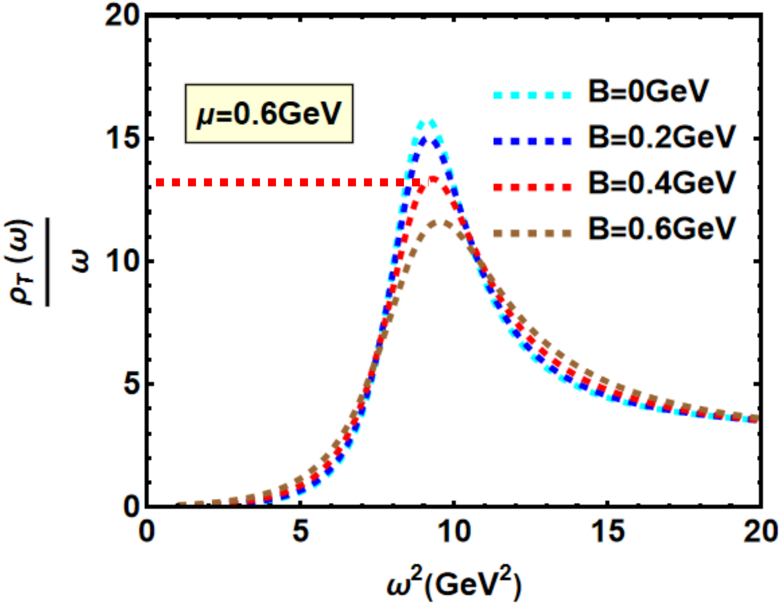
J/Ψ

- **Spectral function:**

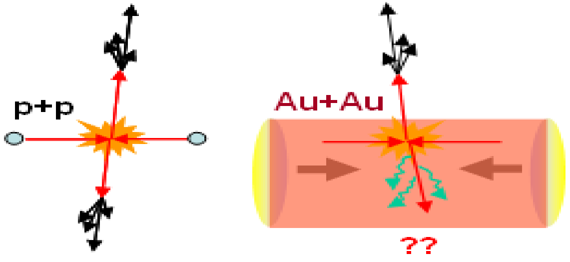
Yan-Qing Zhao, Defu Hou, Eur.Phys.J.C 82 (2022) 12, 1102 • e-Print: 2108.08479

As increasing magnetic field, the dissociation effect increases and it is stronger for the parallel case.



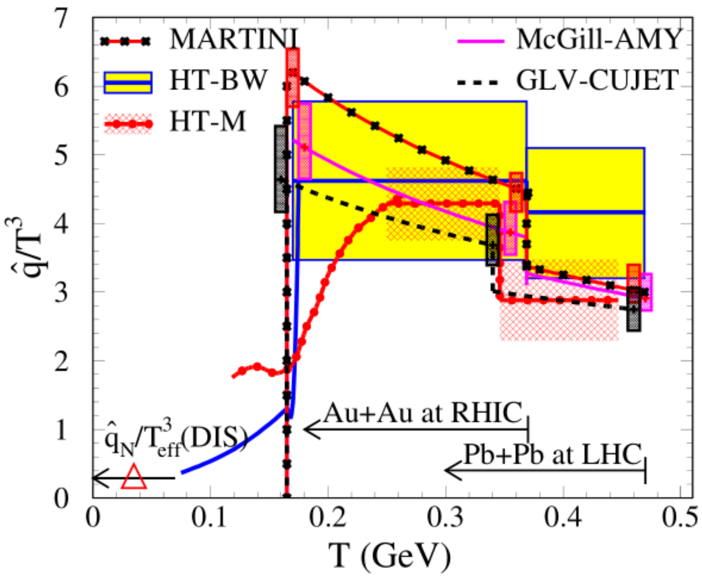


Jet quenching in QGP



$$\Delta E \approx -\frac{\alpha_S}{2\pi} N_C \, \hat{q} \, L^2$$

Baier, Dokshitzer, Mueller,Peigne, Schiff (1996):



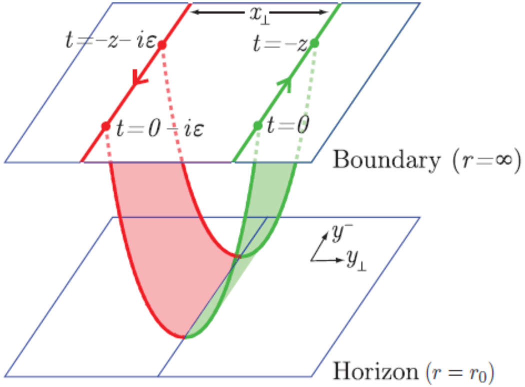
Jet Collaboration, PRC 90,014909(2014)

Talks in this WS: Zhang, Qin

Energy loss and jet quenching

$$\langle W^A[C]\rangle \approx exp(-\frac{1}{4\sqrt{2}}\hat{q}L_-L^2) \quad \langle W^F[C]\rangle \approx exp[-S_I]$$

$$\hat{q}_0 = \frac{\pi^{3/2}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3$$



H. Liu, K. Rajagopal, and U. A. Wiedemann, Phys. Rev. Lett. 97, 182301 (2006).

NL correction to jet quenching parameter

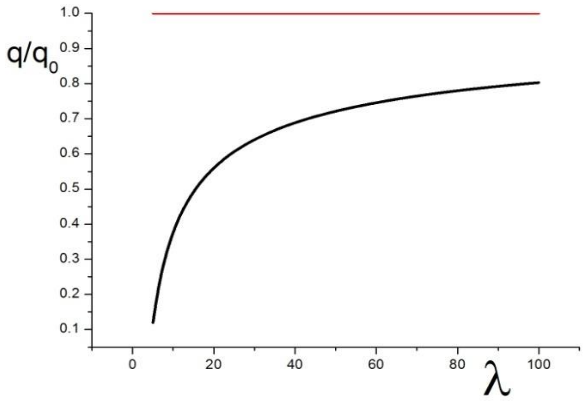
Zhang, Hou, Ren, JHEP1301 (2013) 032

dominant

$$\hat{q} = \frac{\pi^{3/2}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda}T^3[1-1.97\lambda^{-1/2}+O(\lambda^{-1})]$$

$$1 - 1.765\lambda^{-3/2}.$$

Armesto et al JHEP09 (06)



相变温度附近的喷注淬火参数

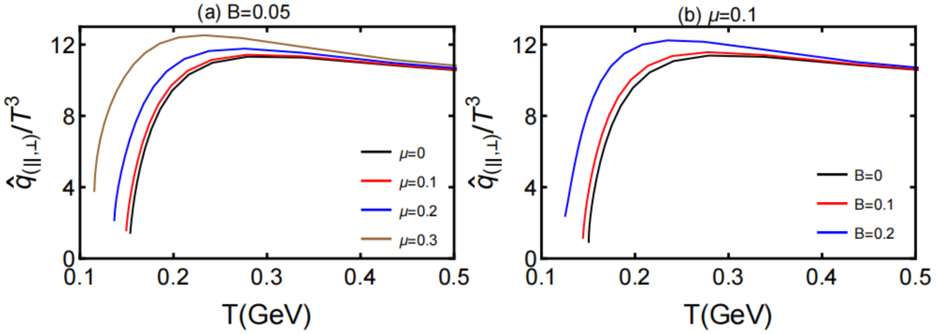


图10. $\hat{q}_{(\parallel,\perp)}$

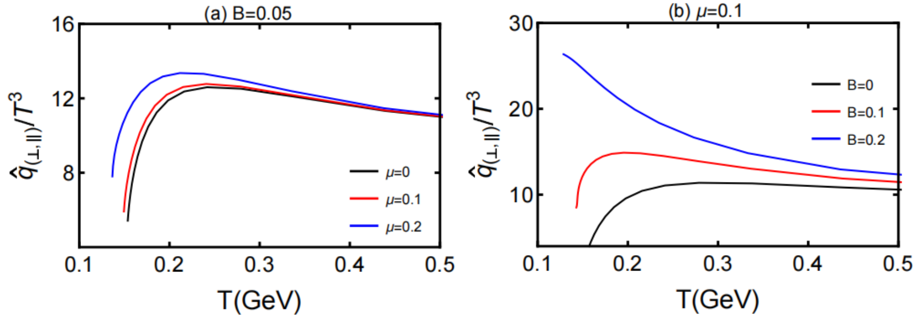


图11. $\hat{q}_{(\perp,\parallel)}$

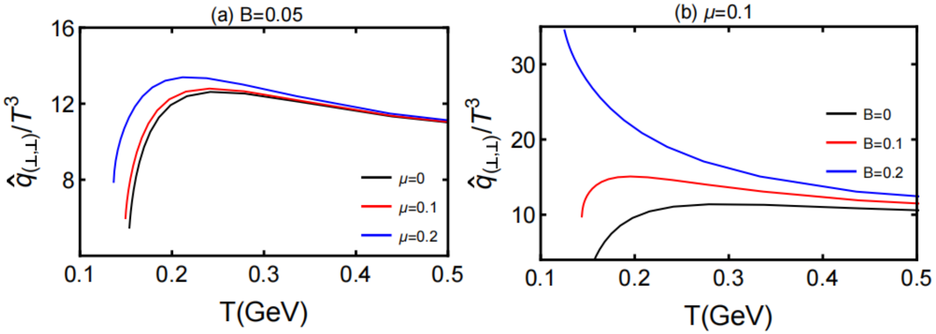


图12. $\hat{q}_{(\perp,\perp)}$

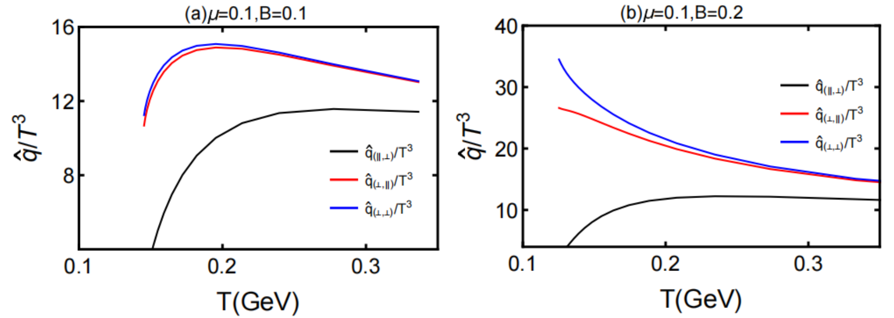


图13. $\hat{q}/T^3$

图10-12：$\hat{q}$在T_c附近有增强，与格点(150-250MeV)相符合*；
峰值所对应温度随μ/B增加而降低；μ、B增强了$\hat{q}$

图13： $\hat{q}_{(\perp,\perp)} > \hat{q}_{(\perp,\parallel)} > \hat{q}_{(\parallel,\perp)} \longrightarrow \hat{q}_{\perp} > \hat{q}_{\parallel}$

Amit Kumar, Abhijit Majumder, and Johannes Heinrich Weber. PRD 106 (2022) 3, 034505

Zhou-Run Zhu, De-fu Hou, Inverse magnetic catalysis and energy loss in holographic QCD model, (arXiv:2305.12375).

相变温度附近的重夸克能损

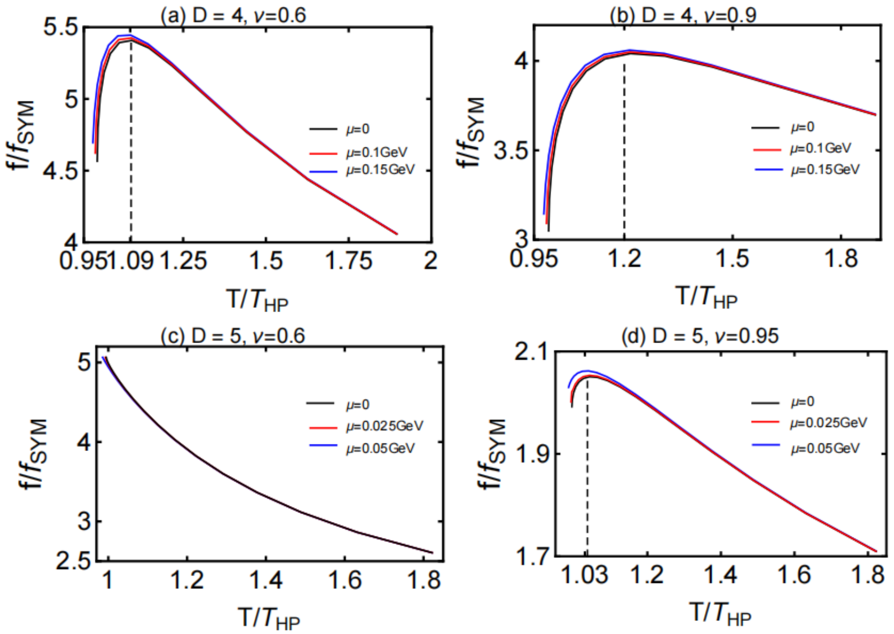


图24. 化学势的对能损的影响

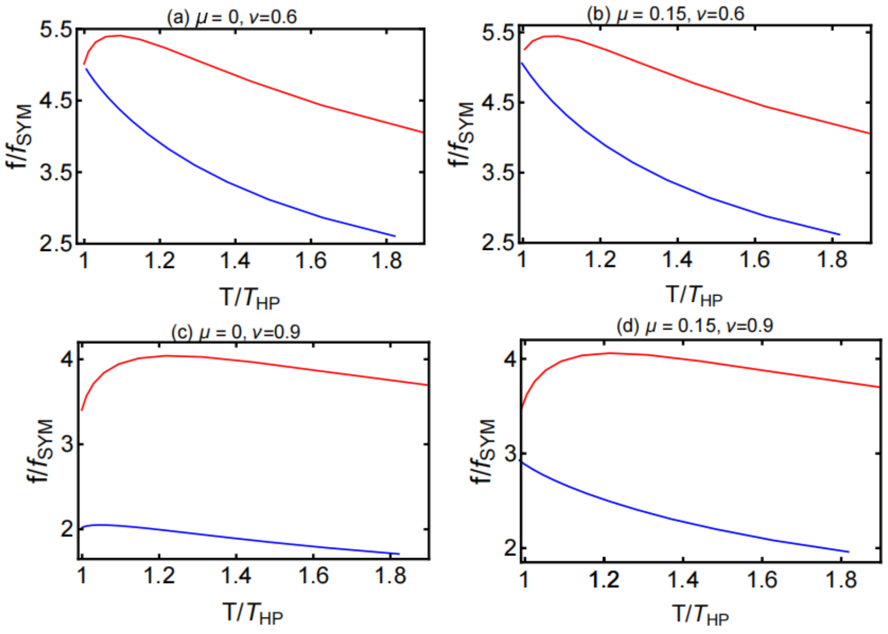


图25. 不同维度下的能损

1) 在T_c附近有增强，峰值所对应温度随μ增加而降低；
2)在较低维度时，重夸克损失更多能量。

Zhou-Run Zhu, Jun-Xia Chen, Xian-Ming Liu, De-fu Hou, Eur.Phys.J.C 82 (2022) 6,560.

Summary

Properties of strongly interacting matter under magnetic field and rotation are very interesting!

- **QCD Phase diagram under rotation and Magnetic field**
- **Transport properties of rotating magnetized matter**

Heavy quarkonia

Jet quenching and energy loss

Thank you very much for your attention!