Chiral phase structure under external magnetic field

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第2届 超边缘碰撞物理研讨会 合肥 中国科技大学 2024年4月

Outline

1 **Background**

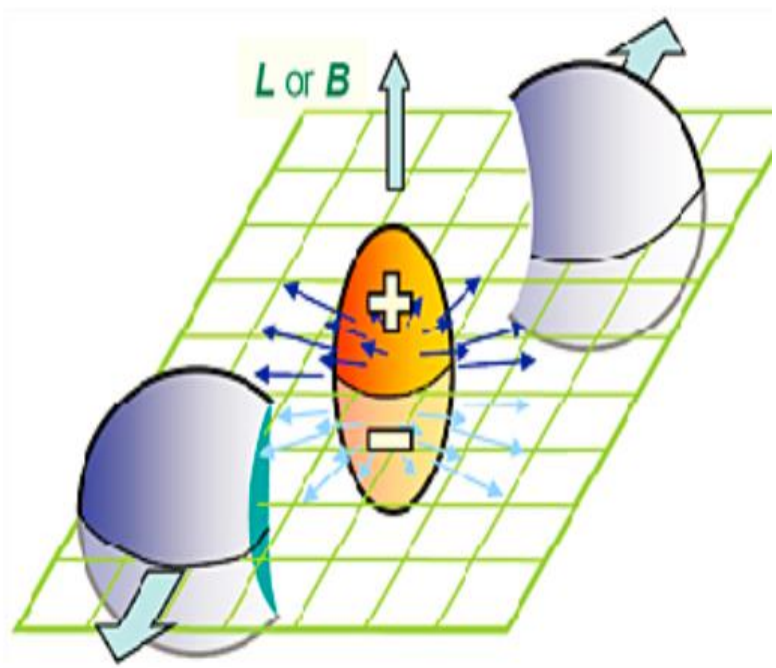
2.1 **Mesons feed-back effect**

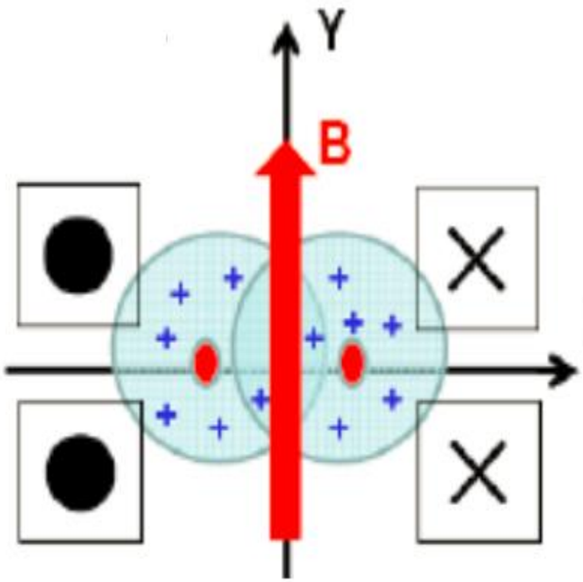
2.2 **Interaction of P and quarks**

2.3 **Weakening of quark coupling**

3 **Comment and outlook**

1 Extremely strong E, B, R



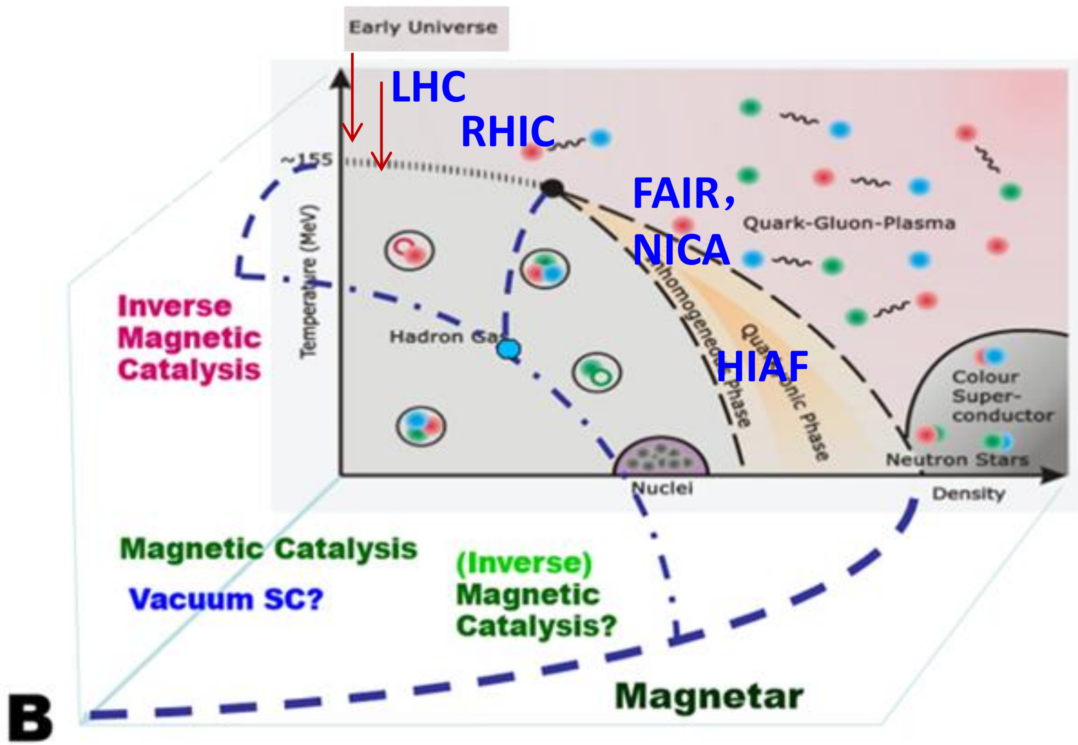


$$B, E \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 10^{18\sim20}\text{Gauss}$$

实验室 $\sim 10^{6-7}$Gauss，地磁场 $\sim 10^{-1}$Gauss

太阳 $\sim 10^{3}$Gauss，致密星 $\sim 10^{10\sim15}$Gauss

1 QCD phase structure



- chiral restoration
  (chiral symmetry)
- deconfinement
  (center symmetry)
- QCD superconduct
  /superfluid
  (color/isospin symmetry
- $U_A(1)$ restoration

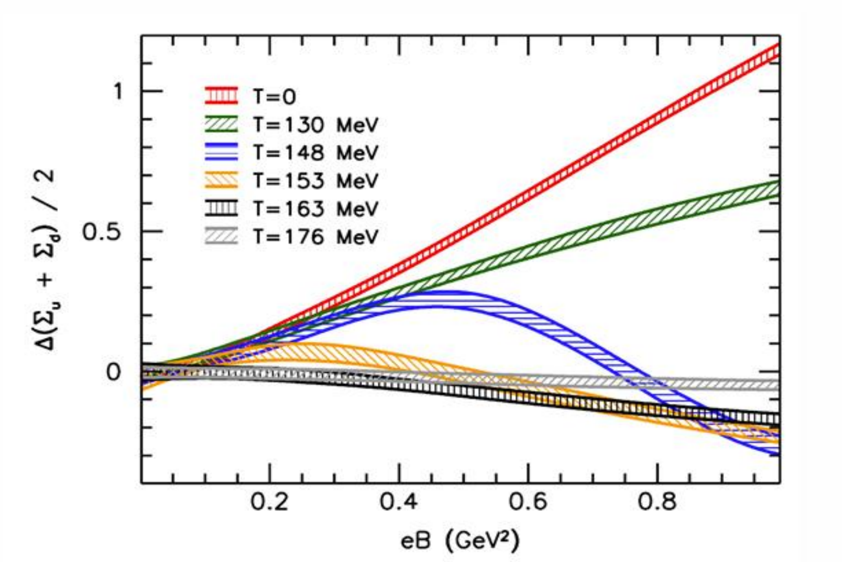
……

strong coupling & strong correlation

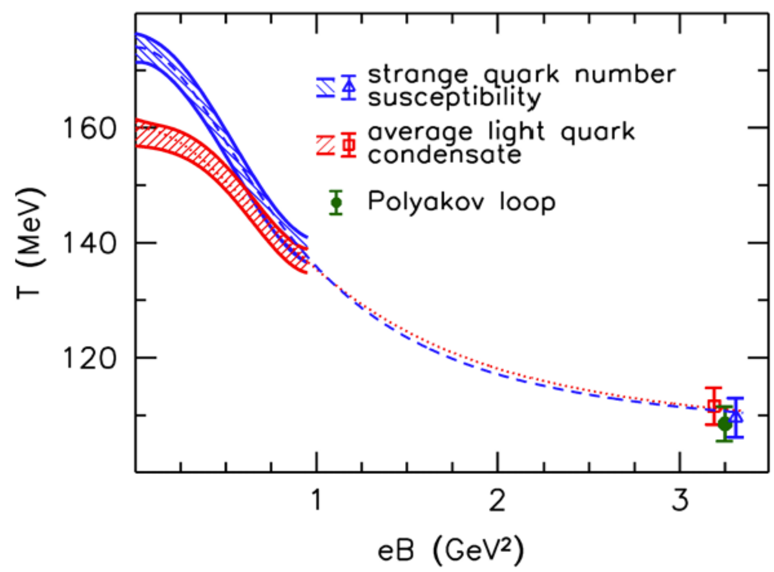
methods： LQCD;
effective models:(P)NJL, DS, (P)QM…

1 Lattice QCD @ B

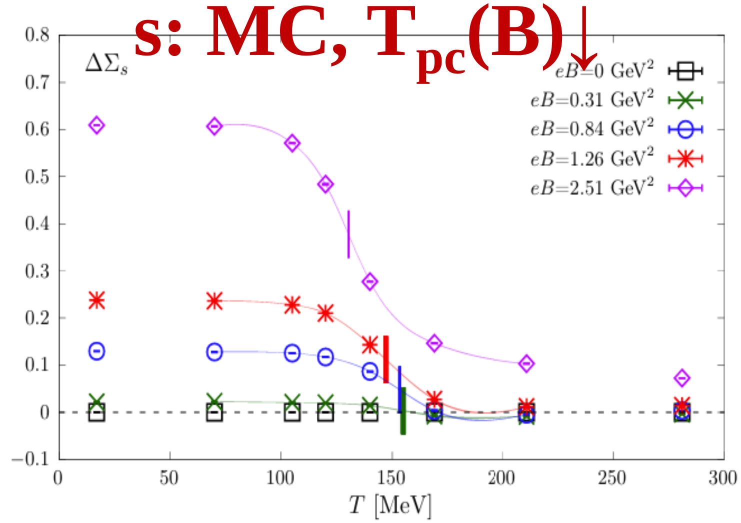
G. Bali, et.al, PRD86, 071502; JHEP02,044(2012)



u,d: IMC, $T_{pc}(B)$↓

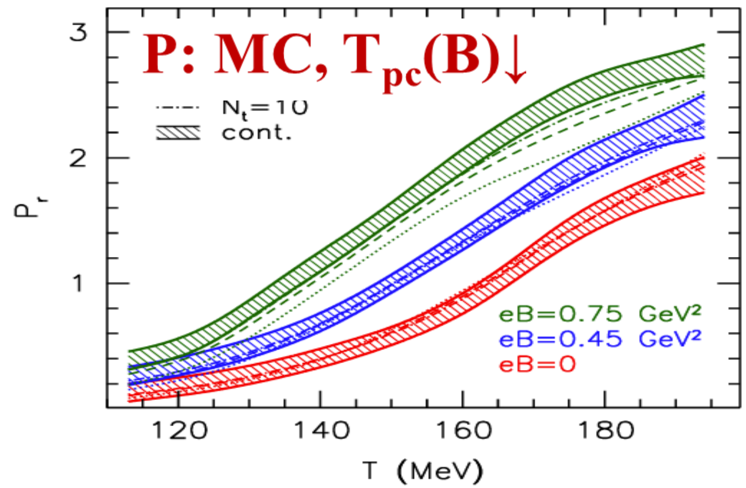


s: MC, $T_{pc}(B)$↓



原因 ???

P: MC, $T_{pc}(B)$↓



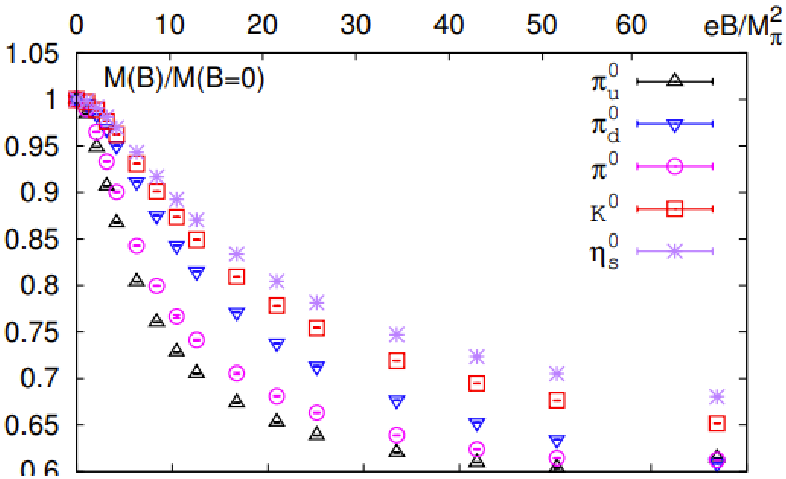
H.T. Ding, et.al, PRD105, 034514(2022);
M.D'Elia, PRD98, 054509(2018)

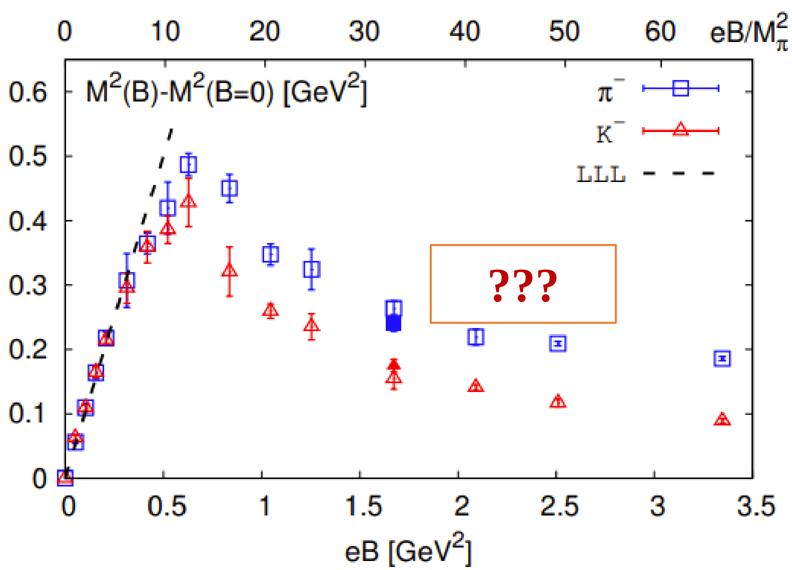
1 Lattice QCD @ B

H.T. Ding, et al, PRD 104, 014505(2021)

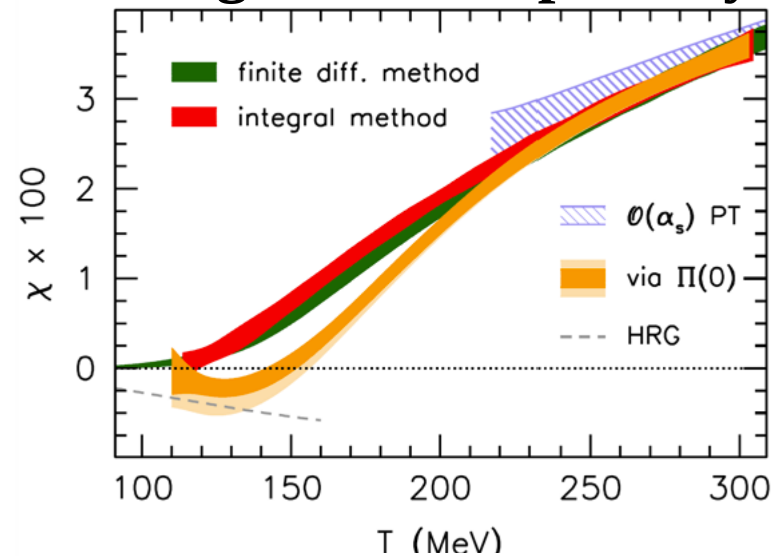
G. S. Bali, et al, JHEP08, 177(2014); JHEP07, 183(2020)

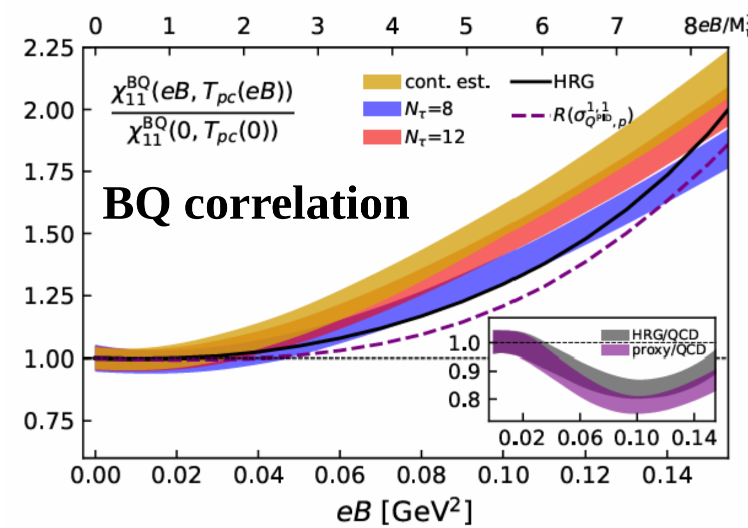
Mass spectra of meson nonet @eB





magnetic susceptibility





2 Analysis based on effective models

- (Inverse) magnetic catalysis
- Reduction of T_{pc}
- Mass spectra of meson nonet

2.1 (P)NJL model

手征恢复相变 &
因禁解除相变

2-flavor Nambu--Jona-Lasinio model

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi + \frac{G}{2}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right]$$

$$\mathbf{B} = (0, 0, B)$$

NJL模型受BCS理论的启发, 被广泛用来研究手征对称性(手征凝聚) (2008, Nobel Prize)。

2-flavor Polyakov loop extended NJL model

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi + \frac{G}{2}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right] - \mathcal{U}(\Phi, \bar{\Phi})$$

$$\frac{\mathcal{U}(\Phi, \bar{\Phi})}{T^4} = -\frac{b_2(t)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\bar{\Phi}^3 + \Phi^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2$$

$$t = T_0/T \qquad b_2(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

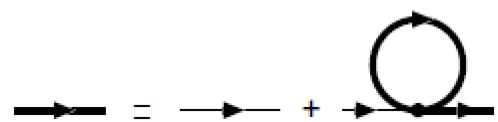
2.1 feedback from pion

PNJL model beyond mean field

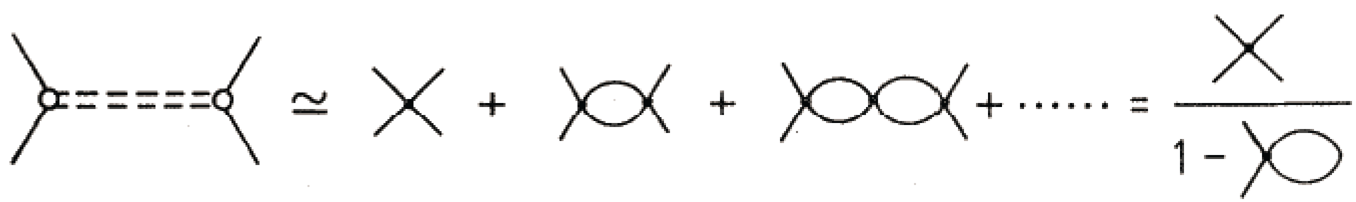
$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi + \frac{G}{2}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right] - \mathcal{U}(\Phi,\bar{\Phi}) \qquad \mathbf{B} = (0,0,B)$$

idea: 涨落在相变中的关键作用!!!

(1)Quarks：mean field



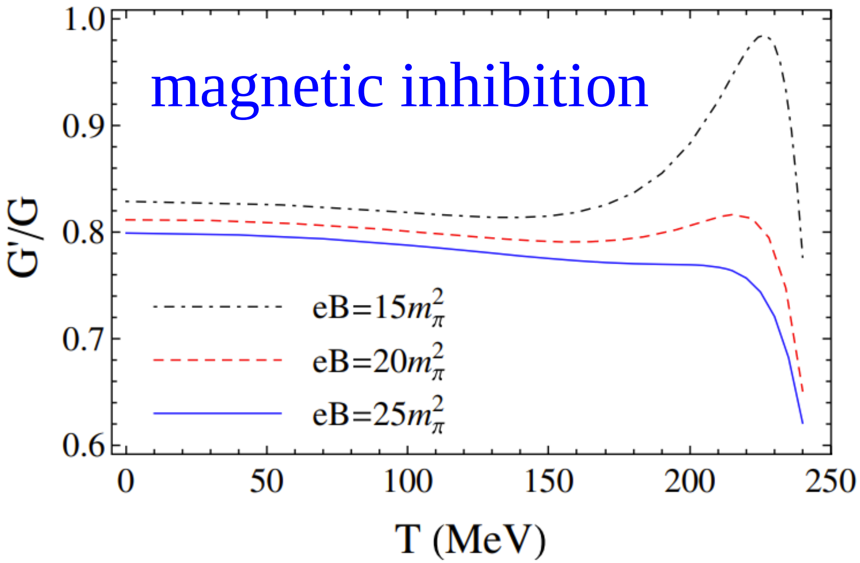
(2)Mesons：RPA resummation (quantum fluctuation)

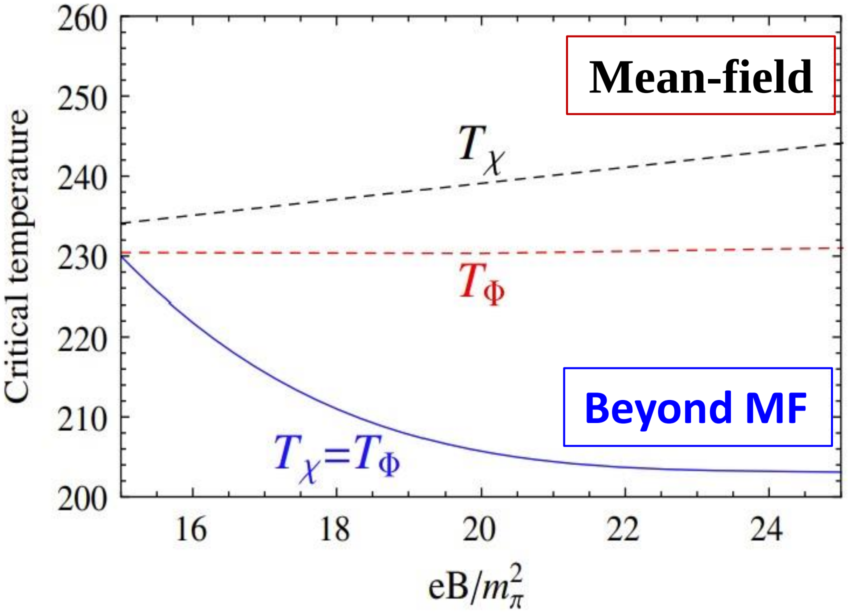


(3)Q-M system：$\Omega = \Omega_q + \Omega_M \rightarrow \Omega(G^{'}),\ G^{'}(B,T)$

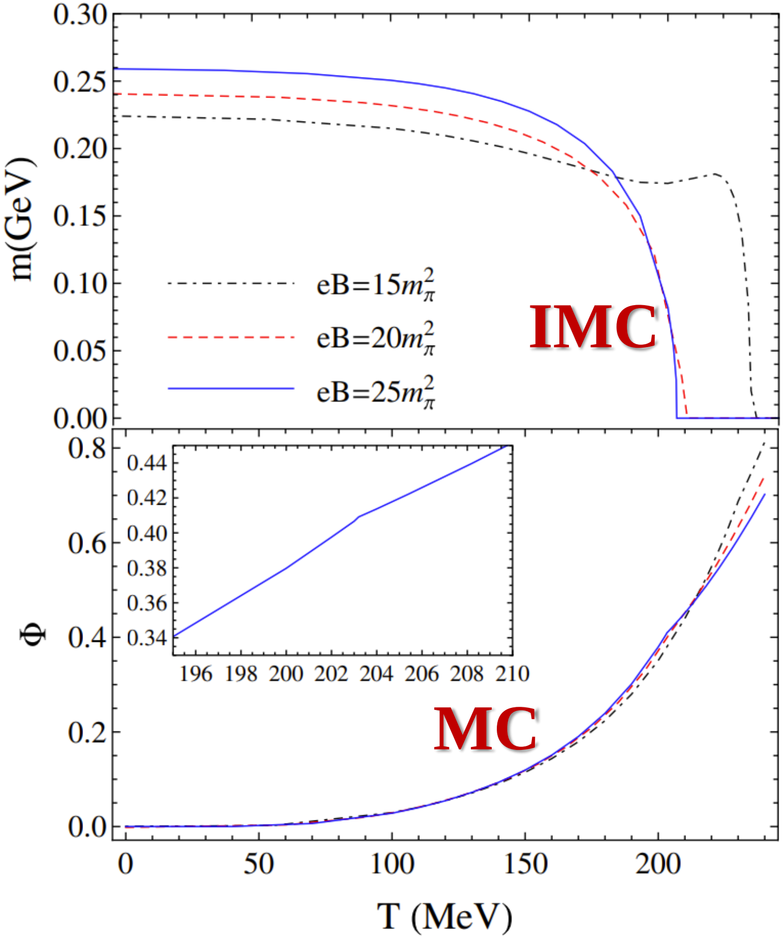
feed-down from mesons to quarks

2.1 Chiral limit





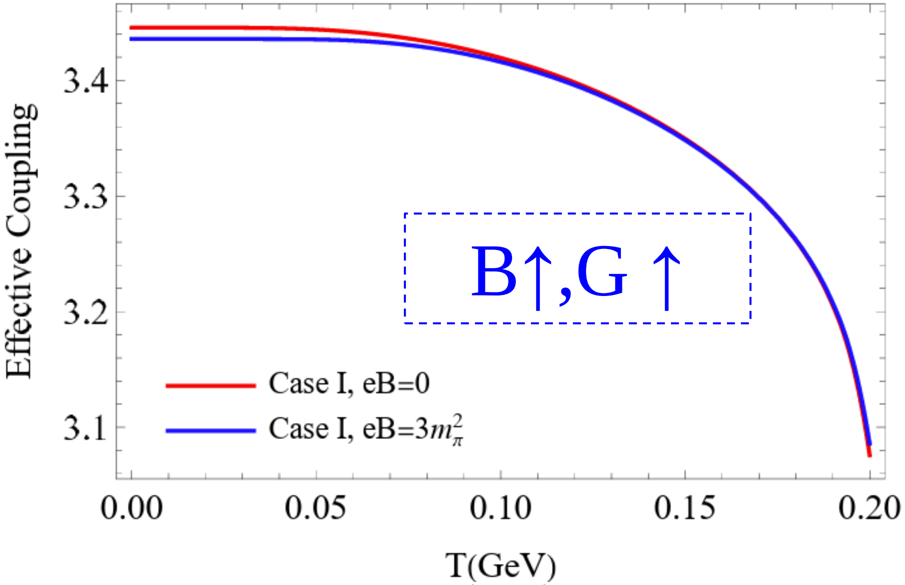
order parameters



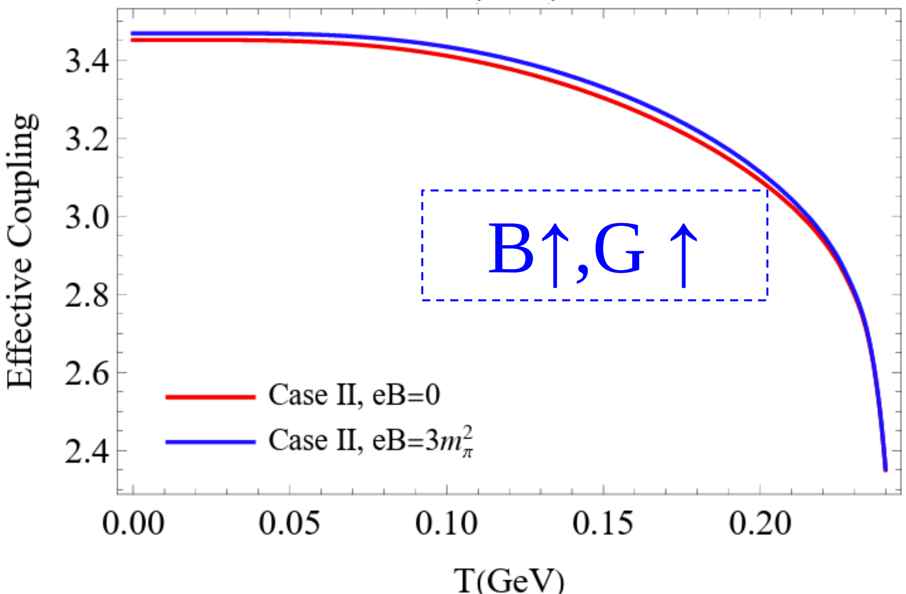
Phys. Lett. B758, 195-199 (2016);
Phys. Rev. D94, 036007 (2016);
Phys. Rev. D97, 011501 (2018) 快讯;

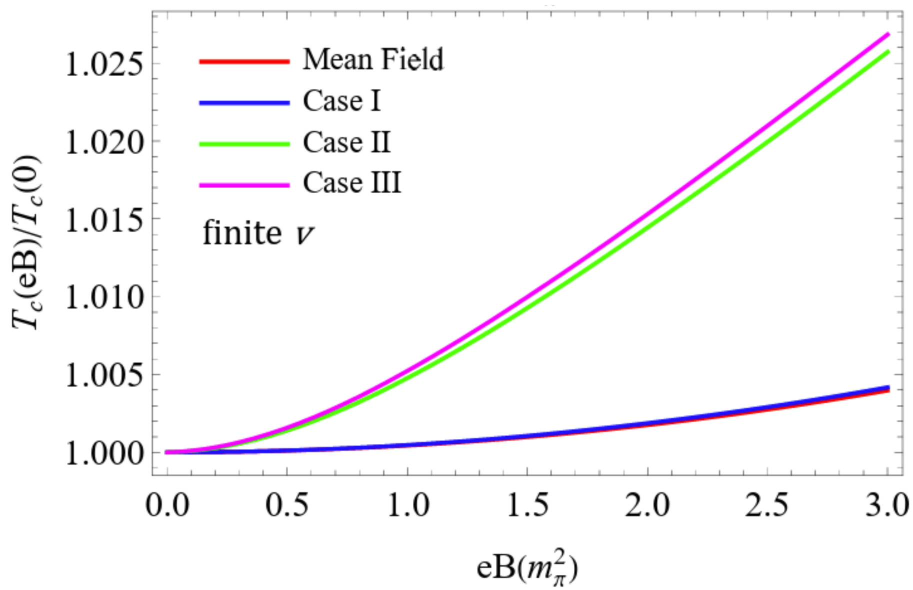
Physical case

arXiv: 2402.19193



Case	Included mesons
0	None
I	π_0 only
II	$\pi_\pm$ only
III	π_0, $\pi_\pm$





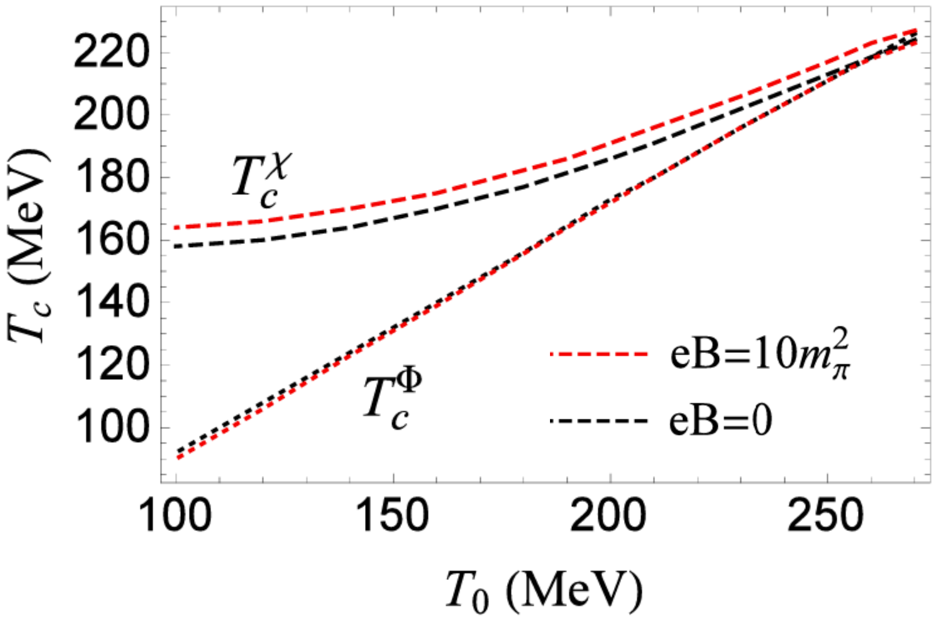
stronger eB case, &3-flavor case， under consideration

2.2 T_0 (eB)---interaction between Polyakov loop and quarks

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi + \frac{G}{2}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right] - \mathcal{U}(\Phi, \bar{\Phi}) \quad \mathbf{B} = (0, 0, B)$$

$$\frac{\mathcal{U}(\Phi,\bar{\Phi})}{T^4} = -\frac{b_2(t)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}(\bar{\Phi}^3 + \Phi^3) + \frac{b_4}{4}(\bar{\Phi}\Phi)^2 \qquad t = T_0/T$$

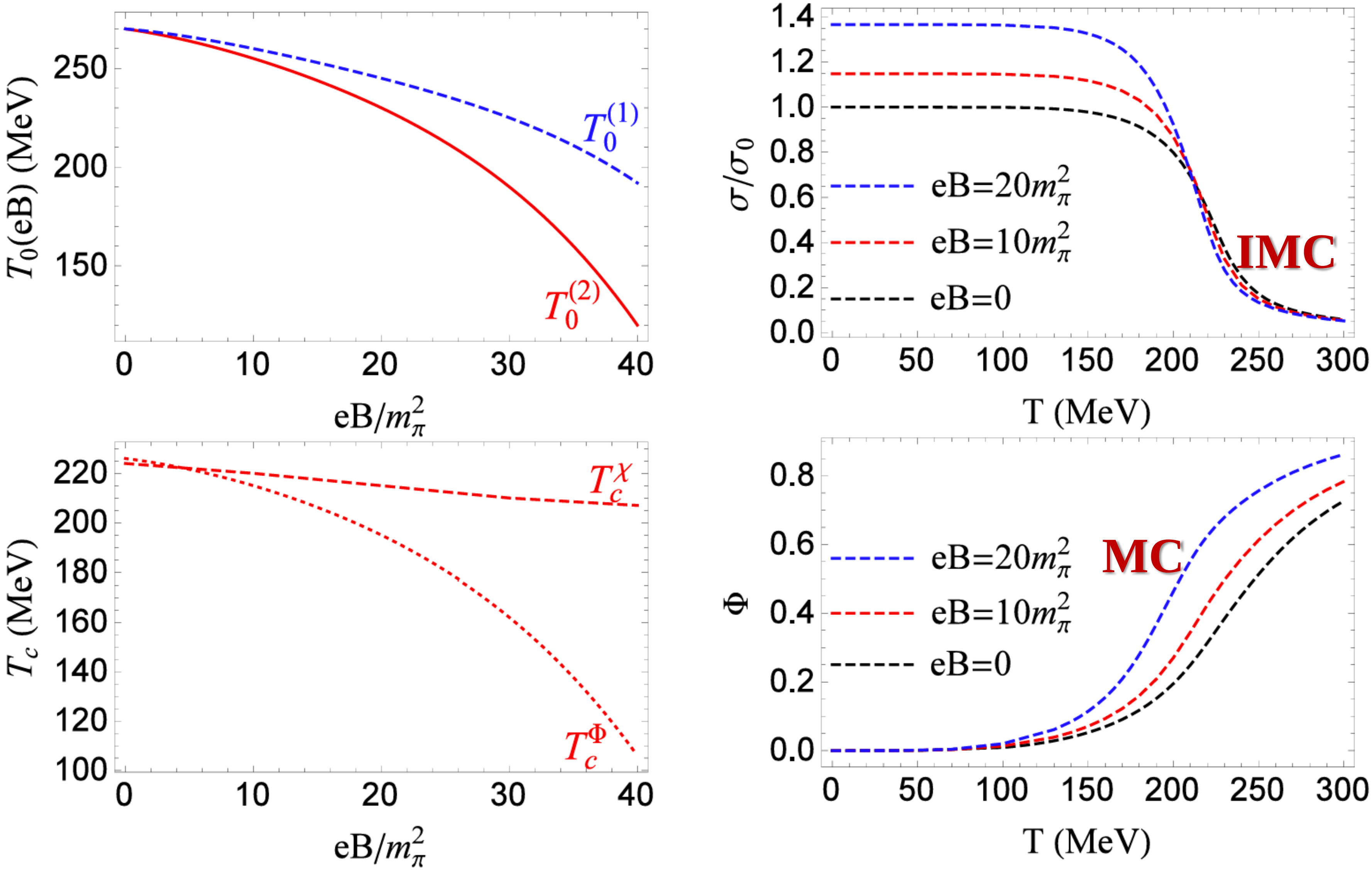
$$b_2(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$



- T_0= 270MeV critical temperature of deconfinement in pure gauge field
- coupling with quarks decreases T_0
- T_0 (eB) ↓

Mao, arXiv: 2404.05294

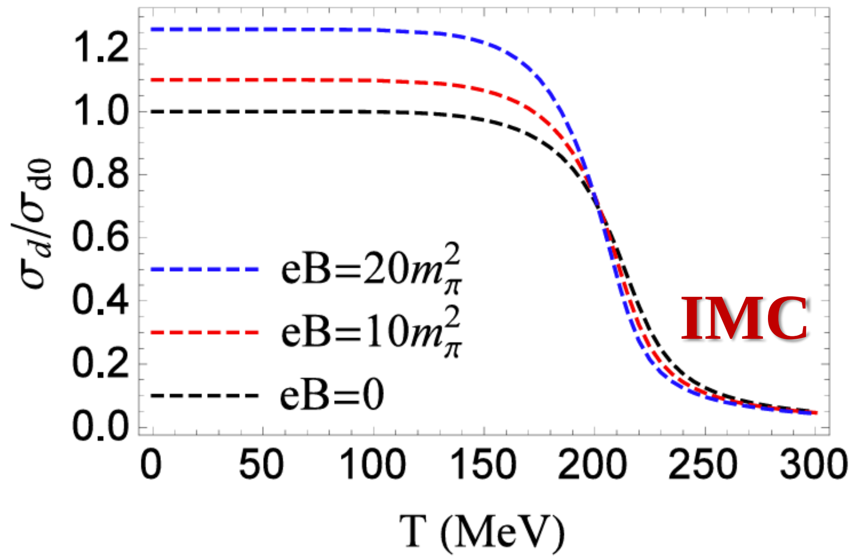
2.2 T_0 (eB)---interaction between Polyakov loop and quarks

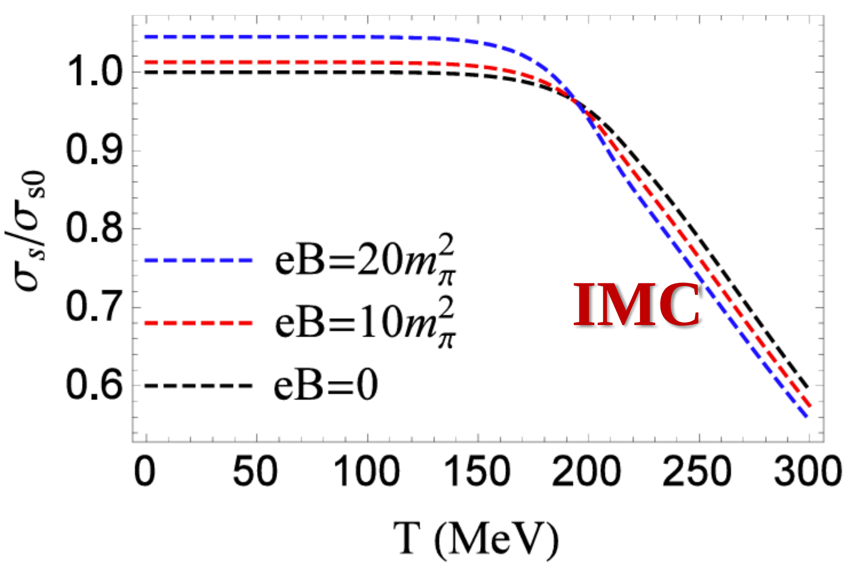


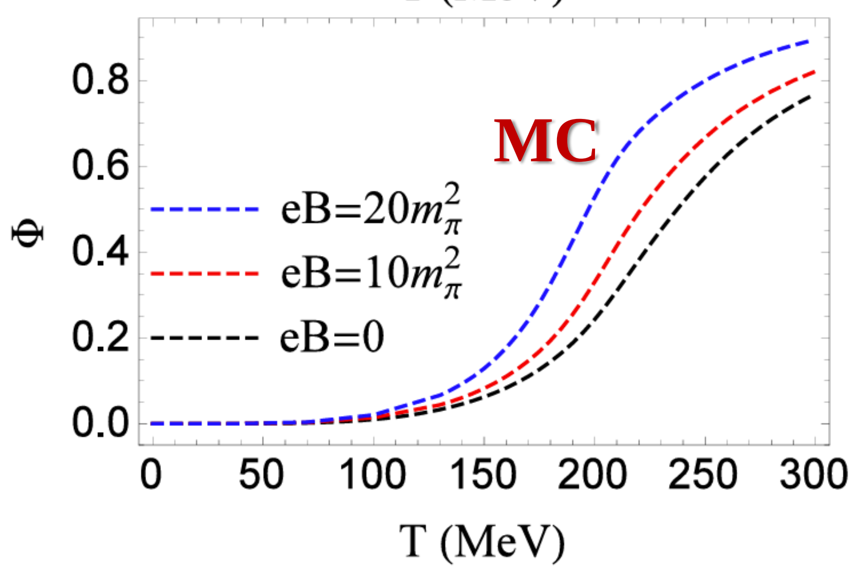
2.2 T_0 (eB)---interaction between Polyakov loop and quarks

3味情形：

eB (m_π^2)	$T_0(eB)$ (MeV)	T_c^u (MeV)	T_c^d (MeV)	T_c^s (MeV)	T_c^Φ (MeV)
0	270	215	215	268	216
10	255	212	211	261	207
20	230	209	208	253	192
30	190	205	203	241	160

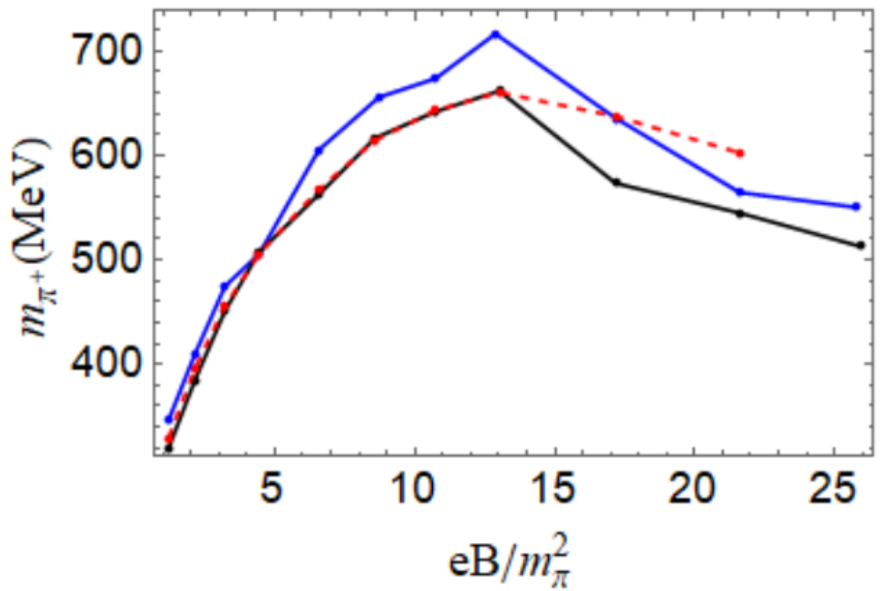




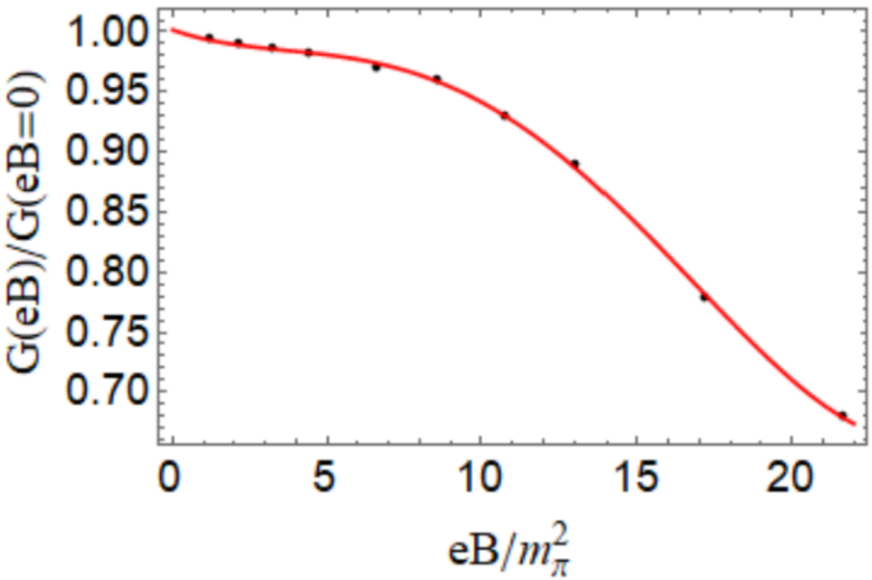


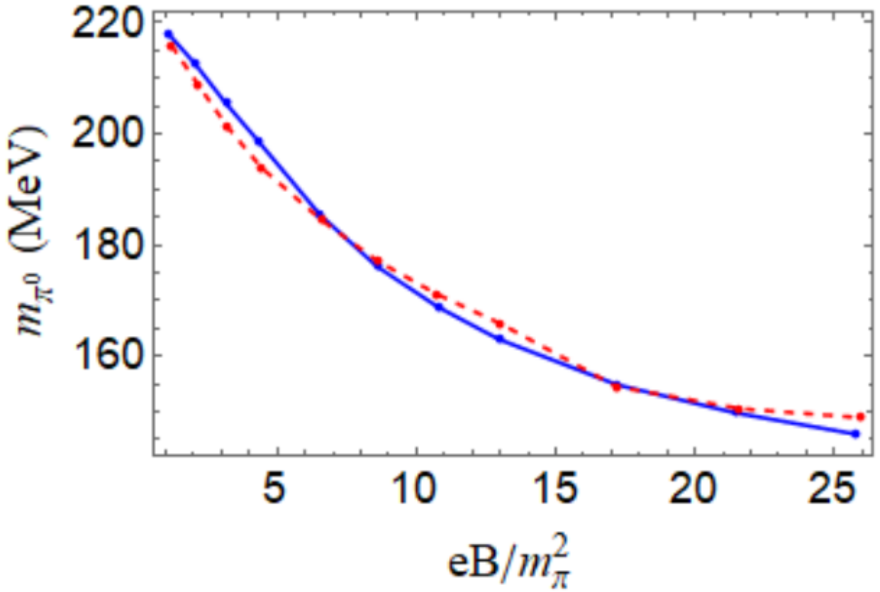
2.3 Weakening of quark coupling in (P)NJL model

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi + \frac{G}{2}\left[\left(\bar{\psi}\psi\right)^2 + \left(\bar{\psi}i\gamma_5\tau\psi\right)^2\right]$$



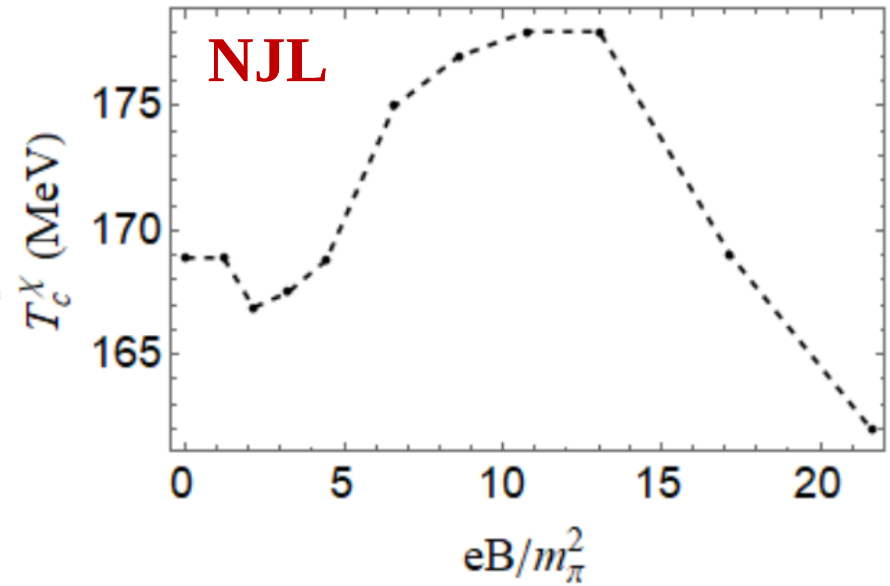
LQCD constrained G(eB)



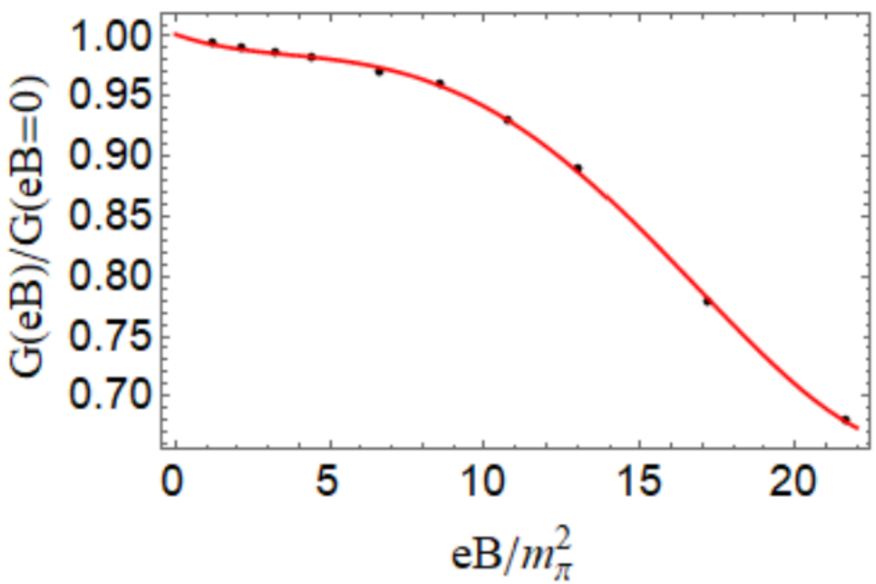


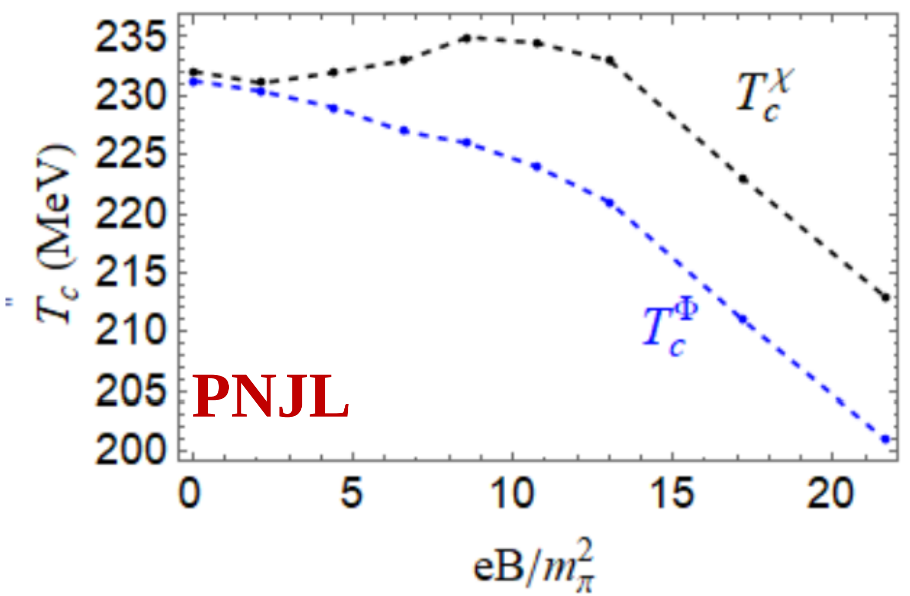
2.3 Weakening of quark coupling in (P)NJL model

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu D^\mu - \hat{m}_0)\psi - \mathcal{U}(\Phi, \bar{\Phi}) + \frac{G}{2}\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right]$$



LQCD constrained G(eB)





2.3 Weakening of quark coupling in (P)NJL model

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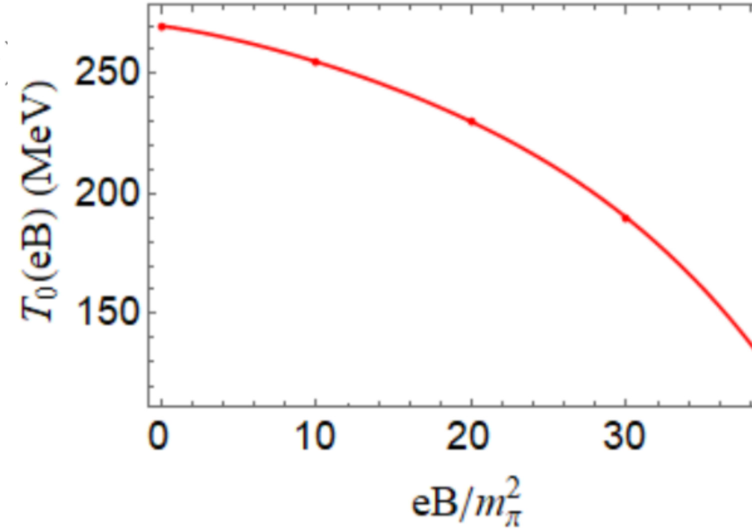
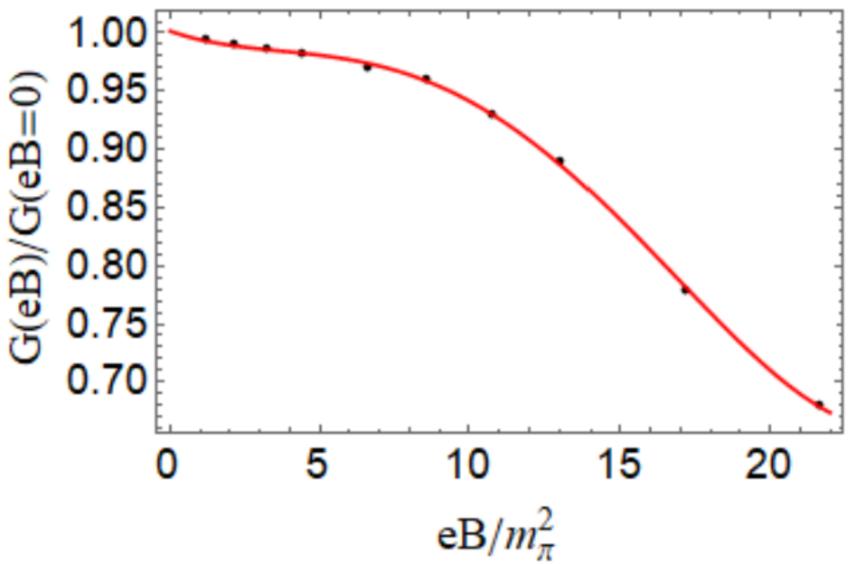
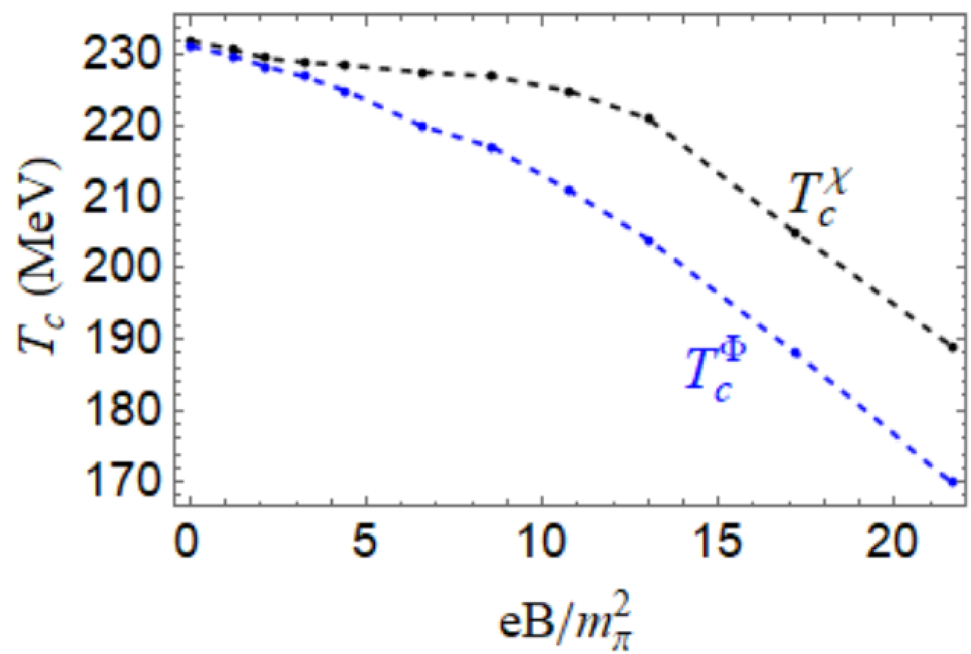
$$b_2(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \qquad t' = T_0'/T$$



LQCD constrained G(eB)





3 Comment and outlook

(1) magnetic inhibition: feedback from neutral pion to quarks

Fukushima et al., PRL110, 031601 (2013); Mao, PLB758,195(2016); PRD94,036007(2016); PRD97,011501(2018); Mei, Mao, Huang et al., arXiv: 2402.19193.

(2) thermo-magnetic effect: fluctuations @(P)QM

Kamikado et al. , JHEP 03,009(2014); Ayala et al.PRD90,036001(2014); PRD89,116017(2014); PRD92,096011(2015); EPJA 57, 234(2021).

(3) weakening of coupling between quarks

Farias et al. , PRC 90, 025203 (2014); Ferreira et al. , PRD89,116011(2014); PRD89, 036006(2014); PRD89,016002(2014); PRD89, 056013(2014); Mueller et al. , PRD91,116010(2015); Braun et al. , PLB755, 265(2016).

(4) interaction between Polyakov loop and quarks

Fraga, PLB731, 154(2014); Ferreira, PRD89, 016002(2014); Mao, arXiv:2404.05294

(5) chirality imbalance:

Chao, Huang et al. , PRD88, 054009 (2013); Fukushima PRD81, 114031 (2010); Mao et.al JPS Conf. Proc. 20, 011009 (2017).

(6) quark anomalous magnetic moment:

Chaudhuri et al. , PRD99, 116025 (2019); EPJA 56, 213 (2020); PRD103, 096021 (2021); Mao et al. , PRD102, 114035 (2020); PRD106, 034018 (2022); Ghosh, PRD103, 116008 (2021); Xu, Chao, Huang, PRD103,076015(2021); Feng, PRD**107**, 076004(2023); Tavares, PRD109, 016011 (2024) .

3 Comment and outlook

- Regularization schemes
- Not a single factor can explain results @ B
- s quark part needs more attention
- Chiral condensate & meson nonet & bulk properties

2.4 夸克反常磁矩

PNJL model beyond mean field

$$\mathcal{L}=\bar{\psi}(x)\left(i\gamma^{\mu}D_{\mu}+\frac{1}{2}a\sigma^{\mu\nu}F_{\mu\nu}\right)\psi(x)+\frac{G}{2}\{[\bar{\psi}(x)\psi(x)]^2+[\bar{\psi}(x)i\gamma_5\vec{\tau}\psi(x)]^2\}-\mathcal{U}(\Phi,\bar{\Phi})$$

夸克反常磁矩与磁场相互作用

spin tensor $\sigma_{\mu\nu}=\frac{i}{2}[\gamma_\mu,\gamma_\nu]$,

strength tensor $F_{\mu\nu}=\partial_{[\mu,}A_{\nu]}$

夸克的能量本征值：

$$E_f=\sqrt{p_z^2+\left(\sqrt{(2n+1-s\xi_f)|Q_fB|+m^2}-s\kappa_fQ_fB\right)^2}$$

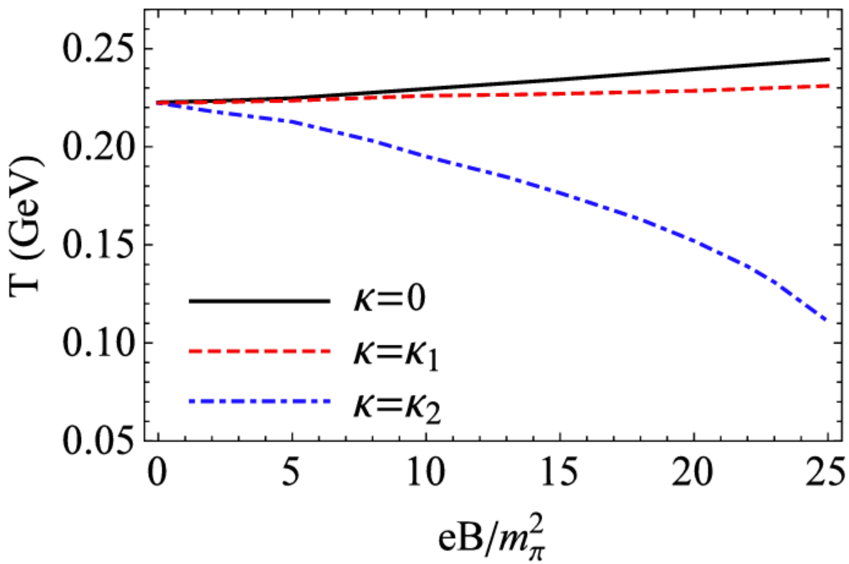
$$a=Q\kappa$$

最低阶朗道能级：

$$E_f=\sqrt{p_z^2+m_{\rm eff}^2},\quad m_{\rm eff}=m-\kappa_f|Q_fB|.$$

夸克反常磁矩，
减小夸克质量，
可能实现T_{pc}下降。

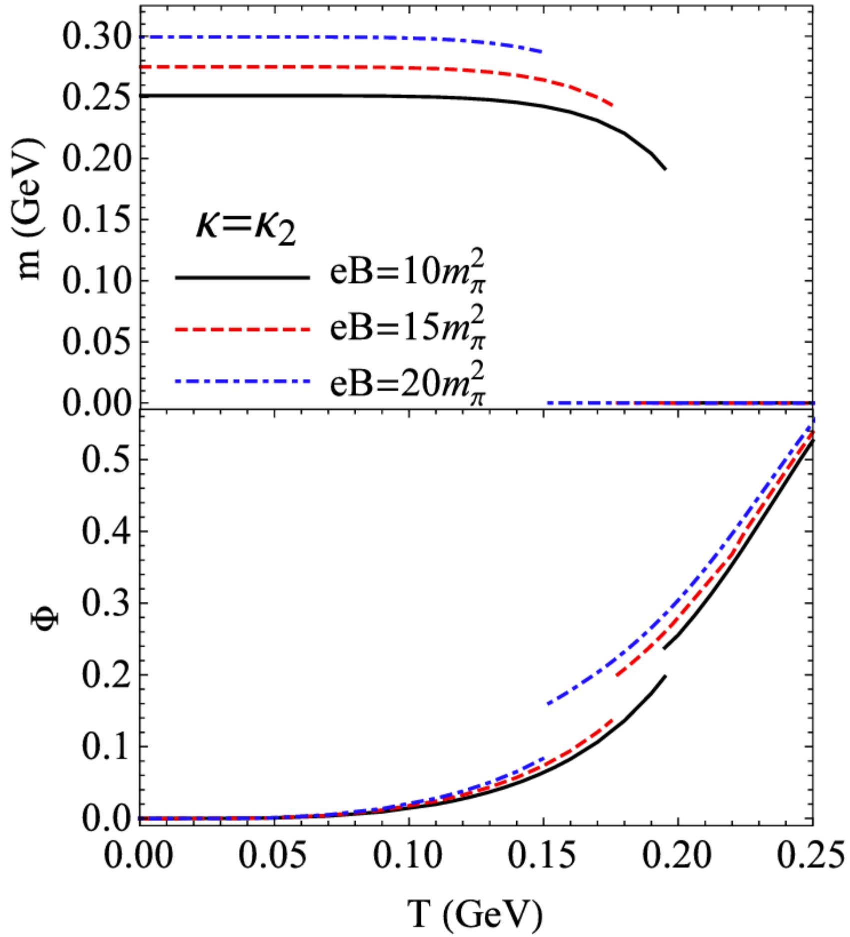
2.4 磁反催化现象----夸克反常磁矩



$$\kappa_2 > \kappa_1 > \kappa_0$$

大反常磁矩，**$T_c(B)\downarrow$**

序参量：MC



Phys. Lett. B 792, 149-155 (2019);
Phys. Rev. D 102, 114035 (2020);
Phys. Rev. D 106, 034018 (2022).

3味，见冯老师报告。