Correlations and fluctuations with and without inverse magnetic catalysis effect

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Outline

1 background

2 inverse magnetic catalysis

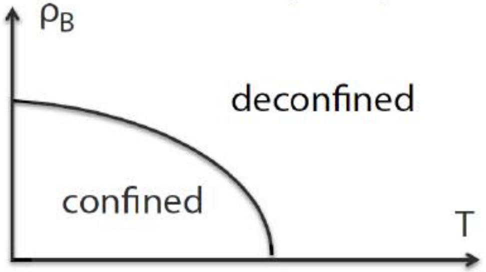
3 correlations and fluctuations

4 summary and outlook

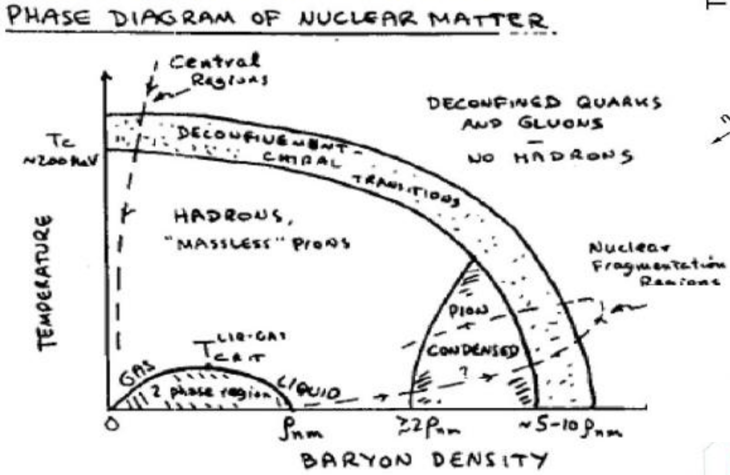
1 Background

QCD 相图

Deconfinement, *N.Cabbibo and G.Parisi, PLB59, 67(1975)*



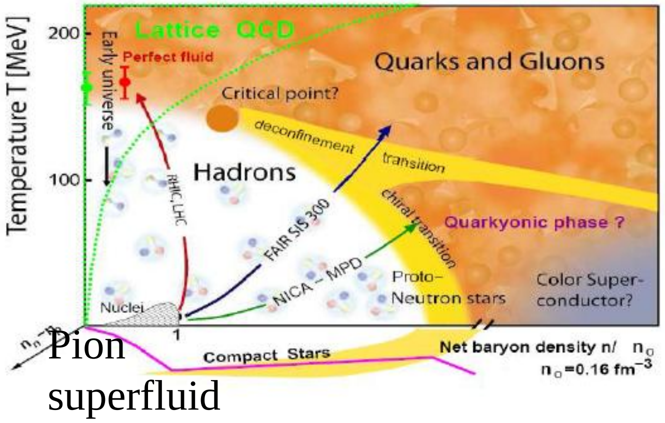
+ Chiral restoration *G.Baym, NSAC Long Rang Plan, 1983*



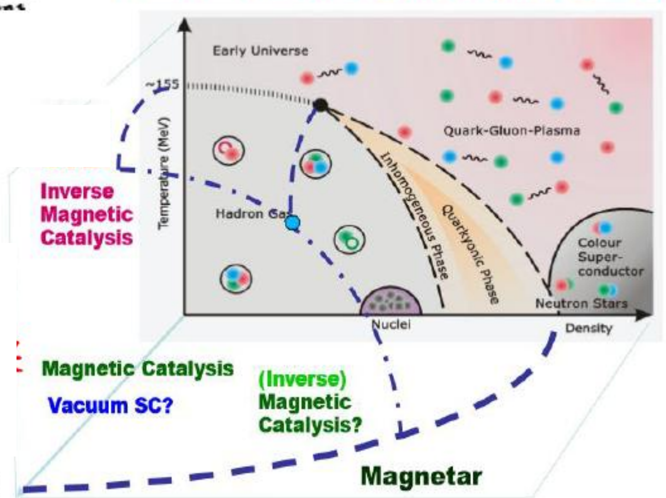
Theoretical Methods:

Lattice QCD
Functional RG
Resumed pQCD
Dyson-Schwinger equation
AdS/CFT
Effective models
Machine learning

+ CSC, quarkyonic phase and critical point, …… (1998)



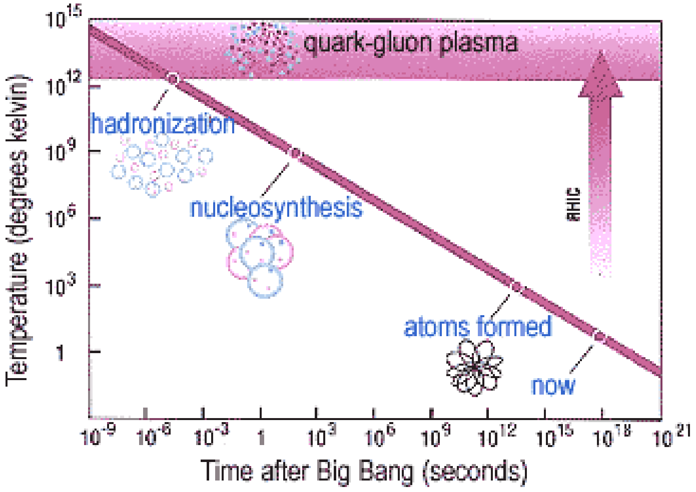
+ eB: IMC,Vacuum SC (2010)



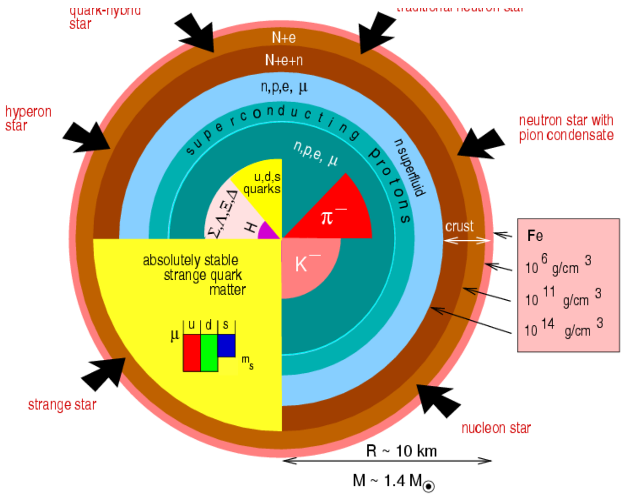
(E, R,) B

1 Background

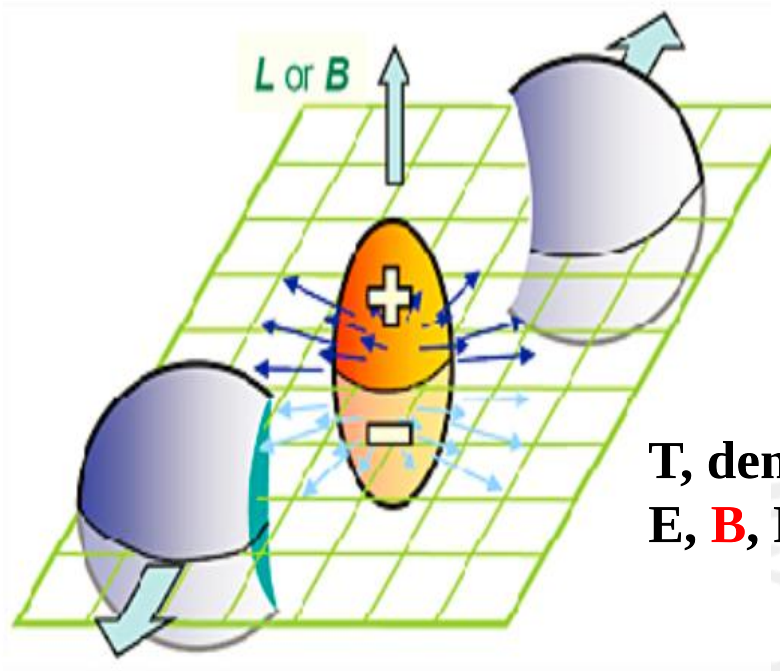
Early Universe (T, B)



Compact stars (Density, B, R)



HIC: LHC, RHIC, FAIR,NICA,HIAF, …



T, density,
E, B, R

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

2 Inverse Magnetic Catalysis (磁反催化)

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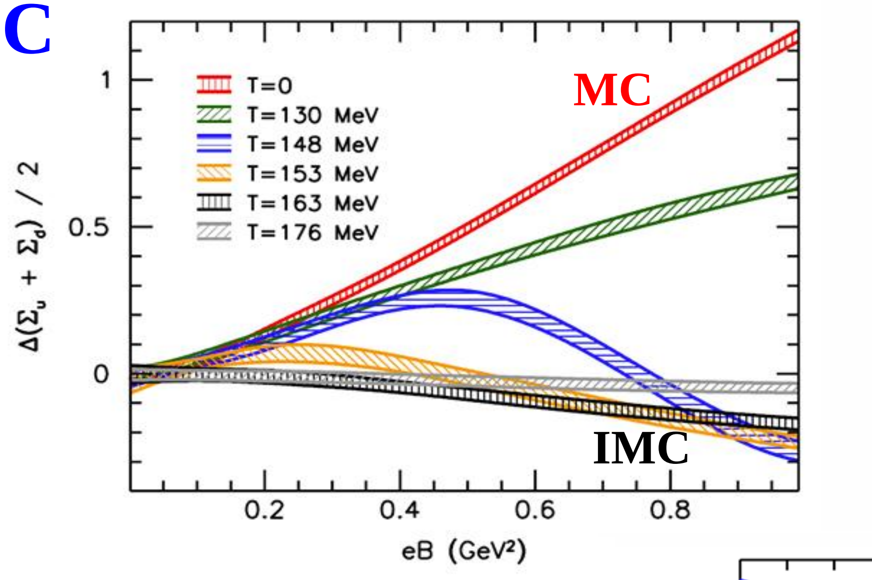
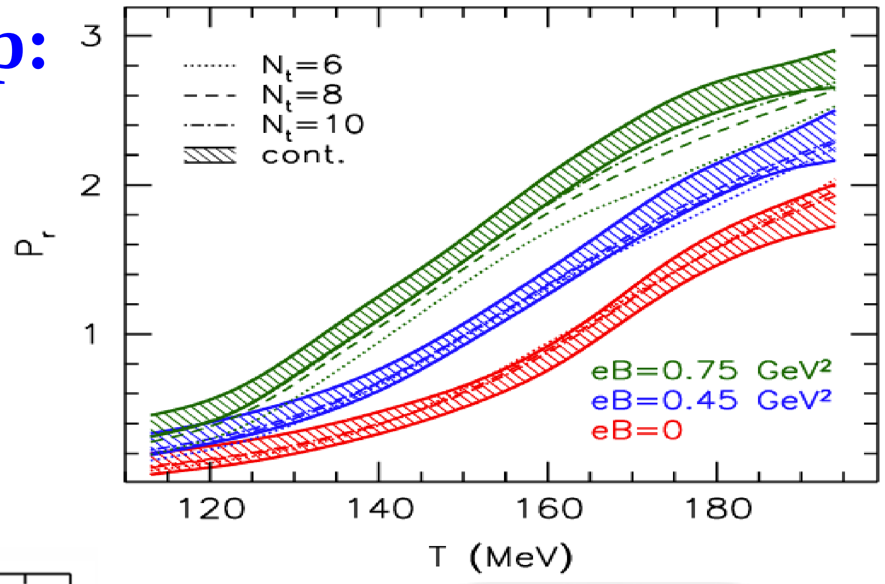
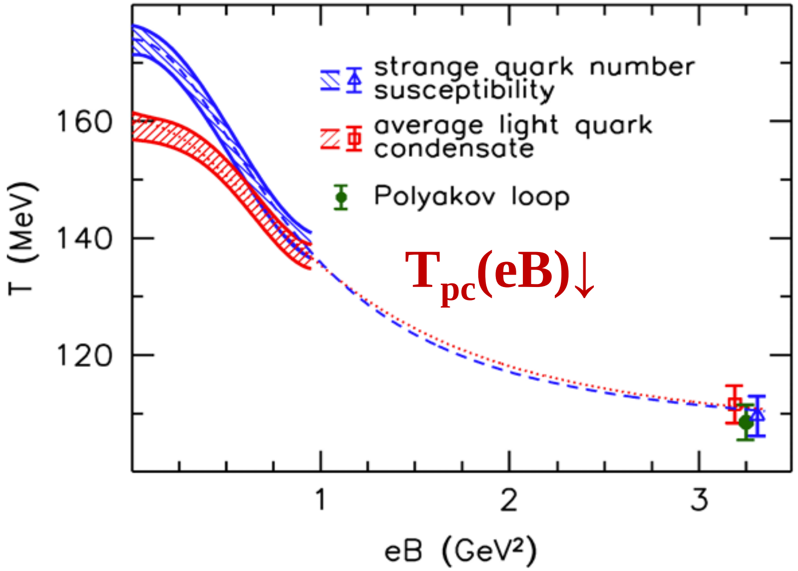
u,d: IMC



Polyakov loop: MC





LQCD results

G. Bali, et.al, PRD86, 071502(2012);
G. Bali, et.al, JHEP02,044(2012);
H.T. Ding, et.al, PRD105, 034514(2022);
M.D'Elia, et.al, PRD98, 054509(2018).

2 Analytical efforts for IMC 超出平均场效应

(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., PRD110, 034024(2024).

(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 (eB dependence) 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); Mao,arXiv:2406.13531.

(4) eB-dependent interaction between Polyakov loop and quarks

Fraga, PLB731, 154(2014); Ferreira, PRD89, 016002(2014); Mao, PRD110, 054002(2024).

(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) .

2.1 B influence the quark-gluon interaction

(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., PRD110, 034024(2024).

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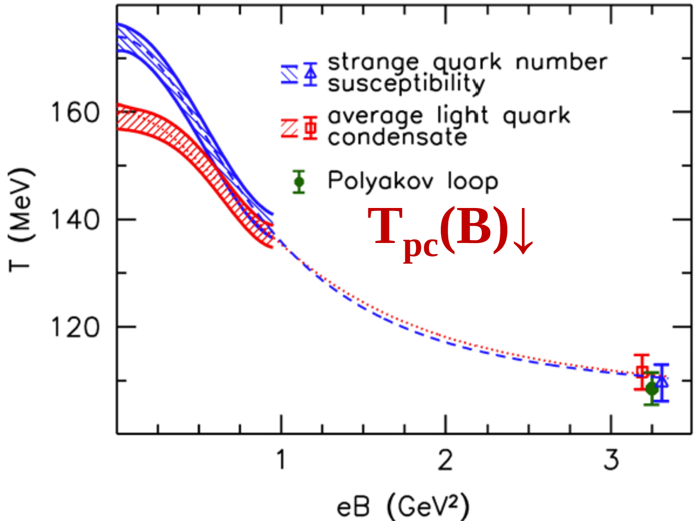
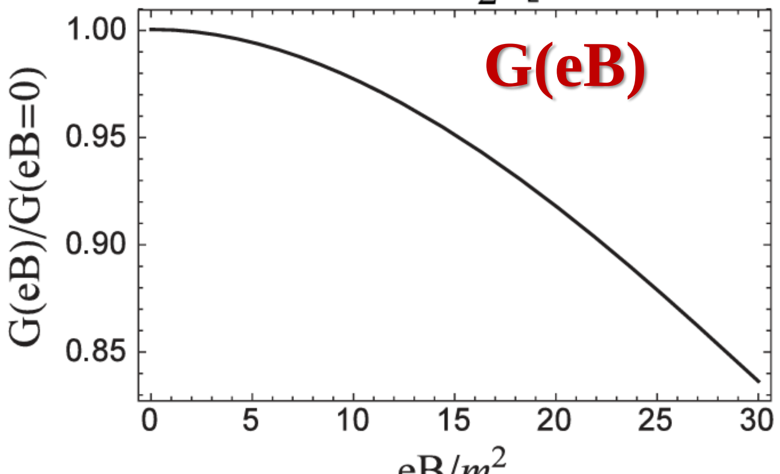


$$\mathcal{L} = \bar\psi(i\gamma_\mu D^\mu - \hat m_0)\psi + \frac{G}{2}\left[(\bar\psi\psi)^2 + (\bar\psi i\gamma_5\tau\psi)^2\right] - \mathcal{U}(\Phi,\bar\Phi)$$



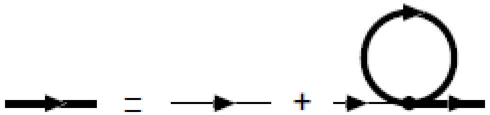
feeddown from pion G(eB)

PNJL model beyond mean field

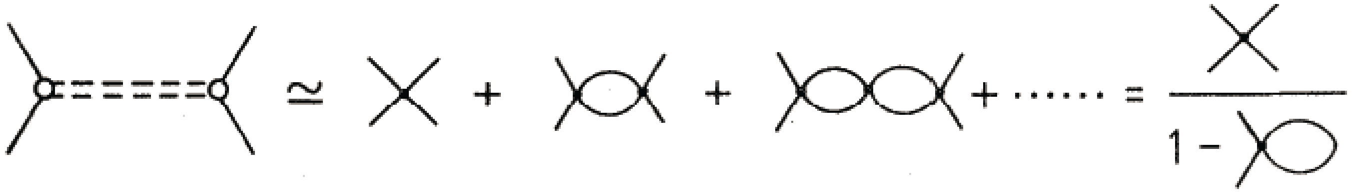
$$\mathcal{L} = i\bar{\psi}\gamma_\mu D^\mu \psi + \frac{G}{2}[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\boldsymbol{\tau}\psi)^2] - \mathcal{U}(\Phi, \bar{\Phi}) \qquad \mathbf{B} = (0, 0, B)$$

idea: strong interaction & strong correlation

(1)Quarks： mean field



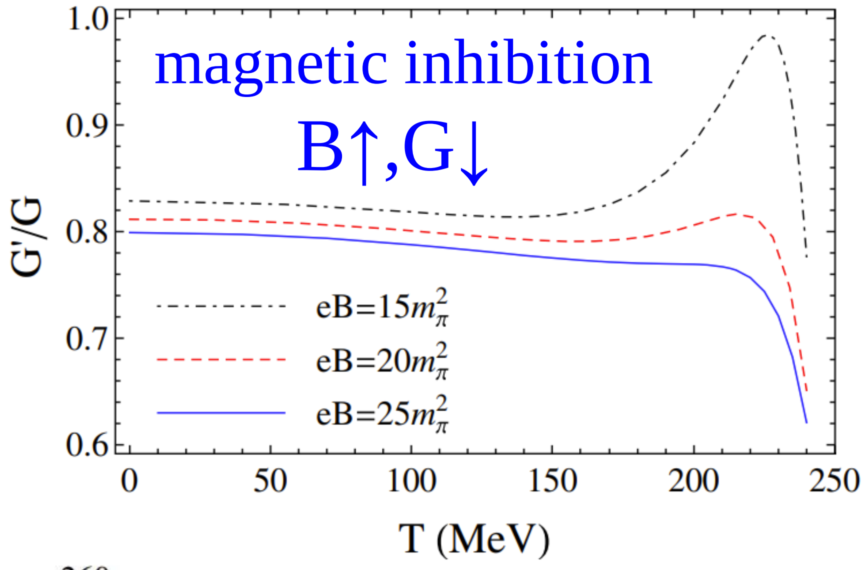
(2)Mesons: RPA resummation (quantum fluctuation)

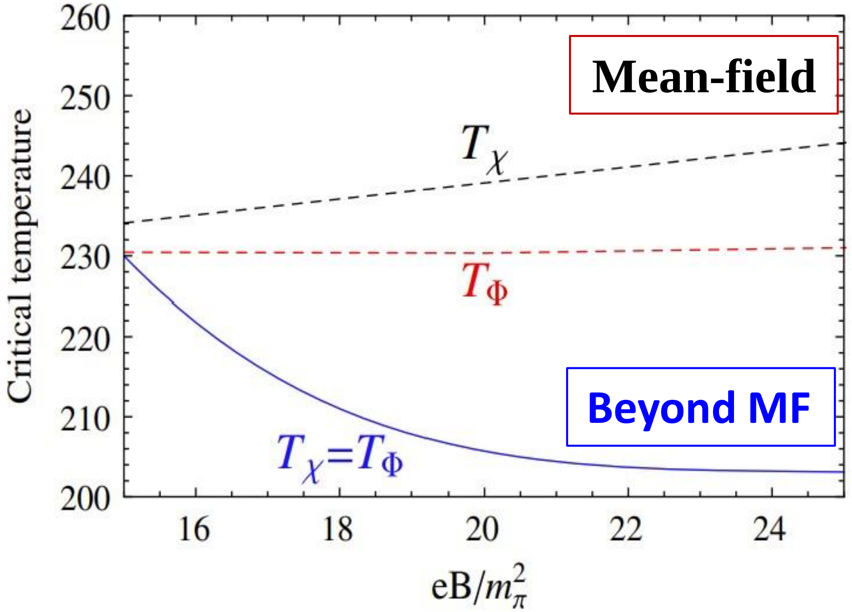


(3)Q-M system： $\Omega = \Omega_q + \Omega_M \rightarrow \Omega(G'), \; G'(B,T)$

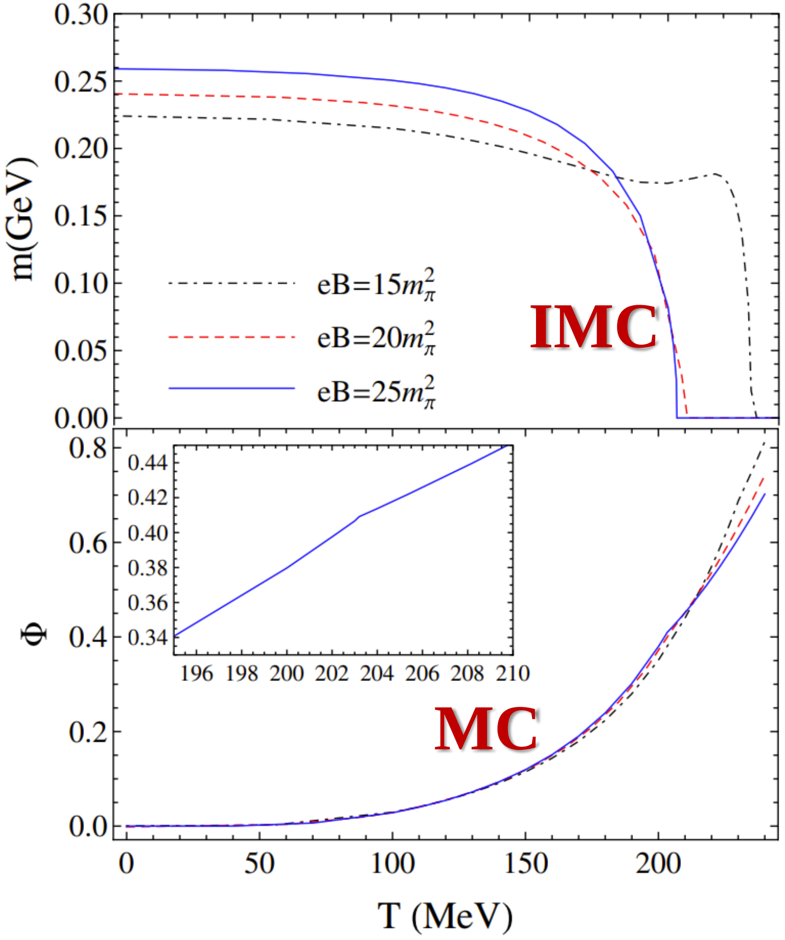
feed-down from mesons to quarks

2.1 Chiral limit eB VS G





order parameters



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

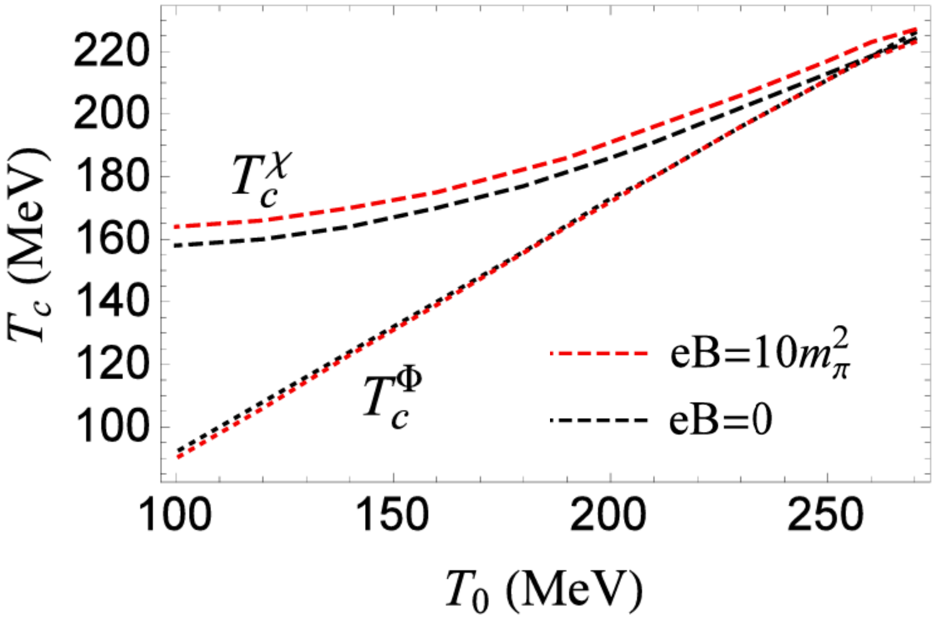
2.2 B influence the quark-gluon interaction

(4) eB-dependent interaction between Polyakov loop and quarks

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

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

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

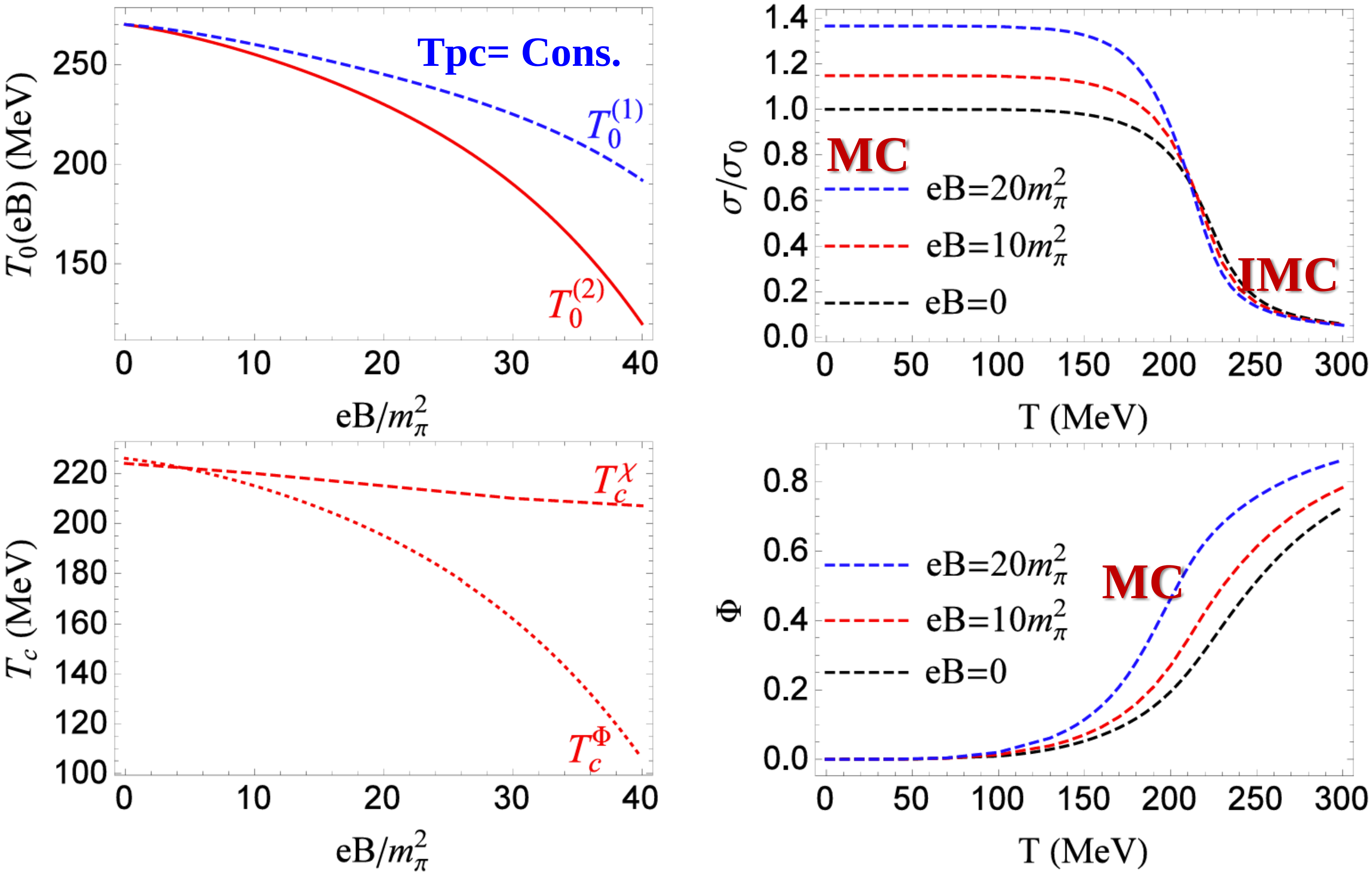


- T_0= 270MeV critical temperature of deconfinement in pure gauge field.
- coupling with quarks decreases T_0
- T_0 (eB) ↓ ⟹ T_{pc}(eB)↓

F.Bruckmann, et.al, JHEP04, 112(2013);
E.S.Fraga,et.al, PLB731, 154 (2014) ;Mao, PRD110, 054002(2024).

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

u, d quarks



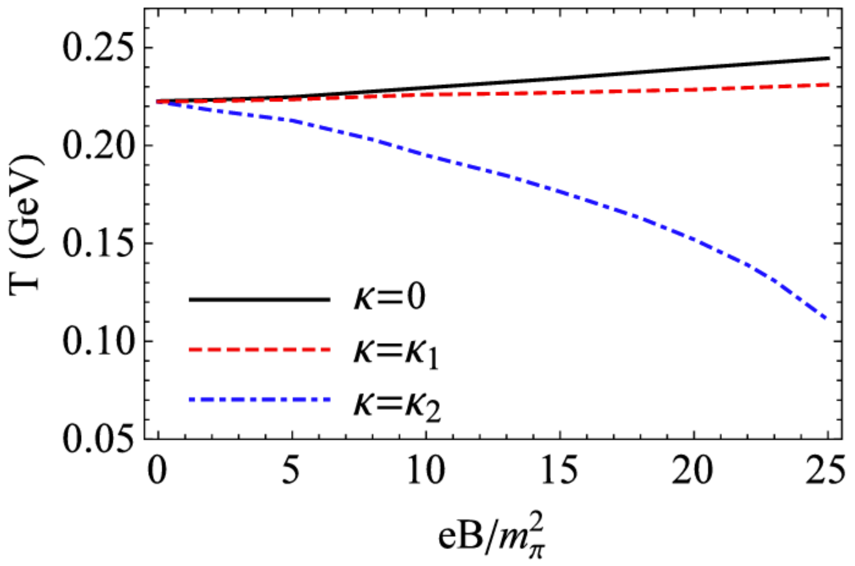
2.3 Analytical efforts for IMC

(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) .

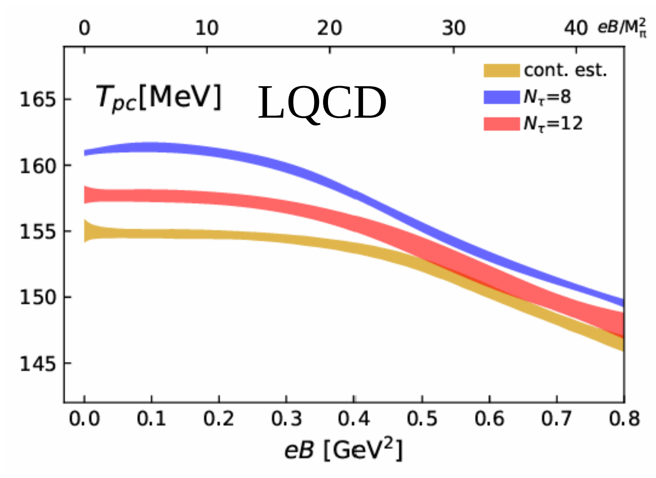


$\kappa_2 > \kappa_1 > \kappa_0$

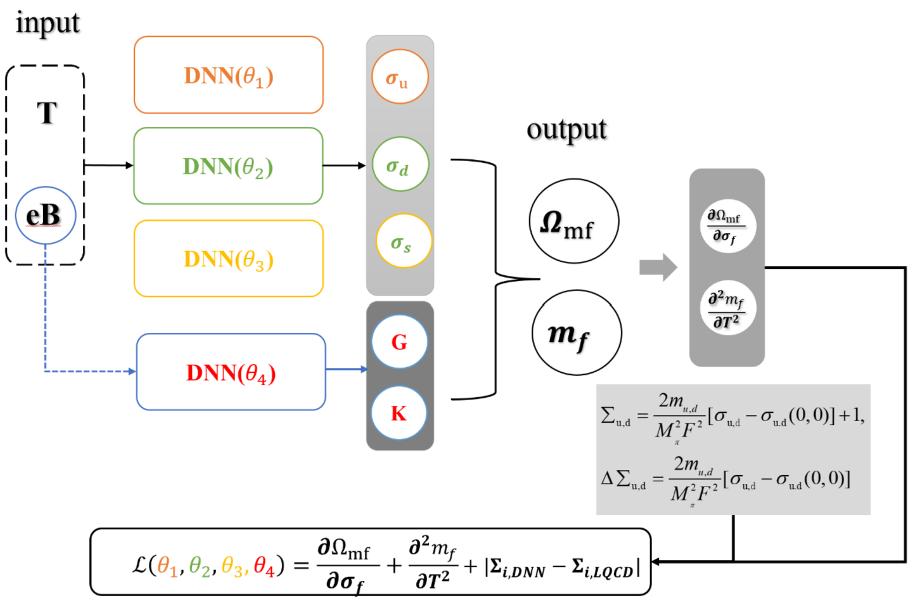
Large 夸克反常磁矩，$T_{pc}(B)\downarrow$

2 Analytical efforts for IMC 超出平均场效应

(1) magnetic inhibition: feedback from neutral pion to quarks
(2) thermo-magnetic effect: fluctuations @(P)QM
(3) weakening (eB dependence) of coupling between quarks
(4) eB-dependent interaction between Polyakov loop and quarks
(5) chirality imbalance
(6) quark anomalous magnetic moment



H.T.Ding,et.al, 2503.18467



F.P. Li, L.X. Wang and S.J. Mao, deep learning study of IMC effect, under preparation.

3

fluctuations and correlations with/without IMC

fluctuations and correlations with/without IMC

Fluctuations & correlations:

$$\chi_{i,j}^{B,Q,S} = -\frac{\partial^{i+j+k}(\Omega/T^4)}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\Big|_{\mu_X=0}$$

crossover

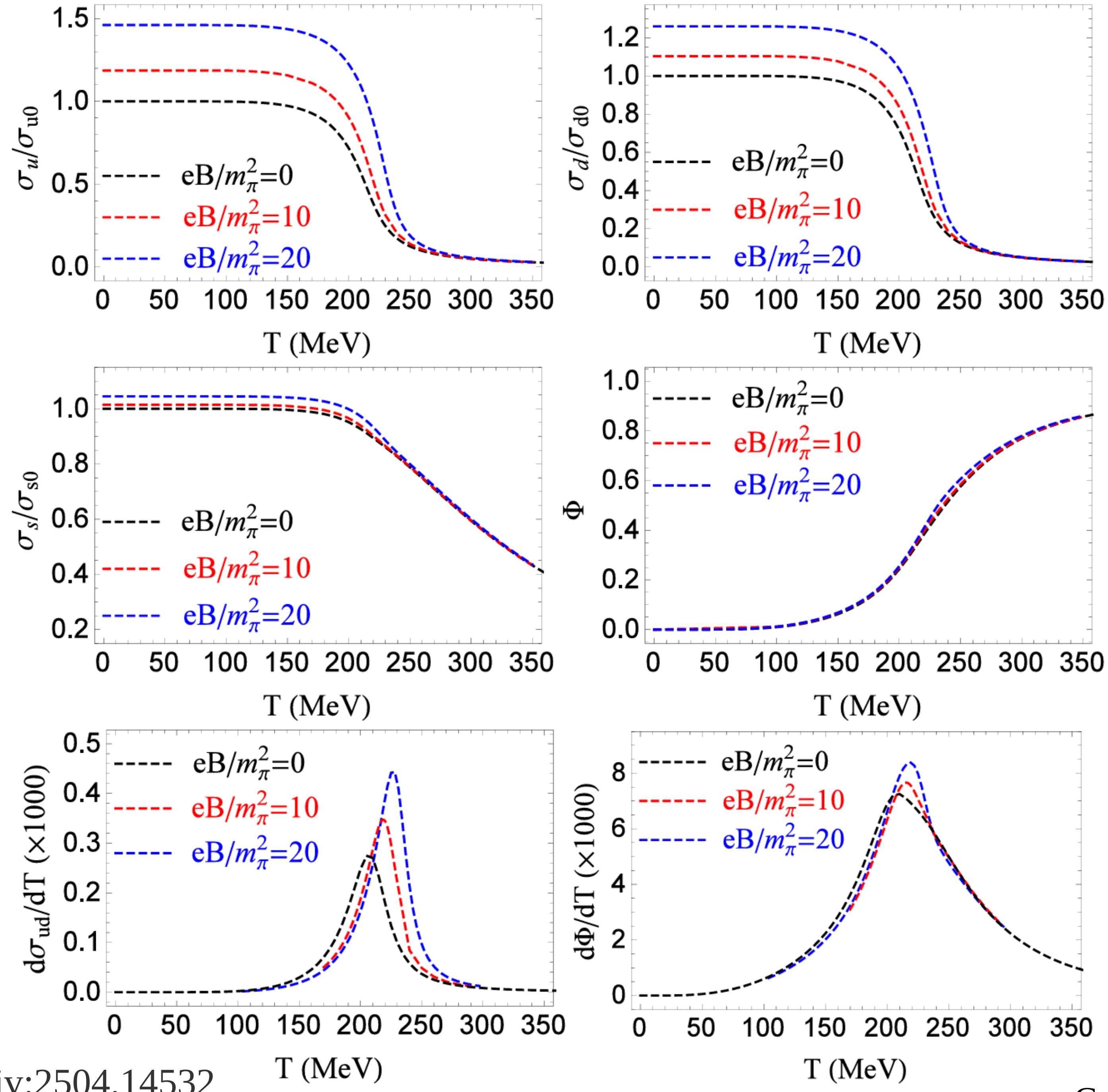
PNJL Lagrangian:

$$\begin{aligned}
\mathcal{L} &= \bar{\psi}\left(i\gamma^\mu D_\mu - \hat{m}_0\right)\psi + \mathcal{L}_4 + \mathcal{L}_6 - \mathcal{U}(\Phi,\bar{\Phi}), \\
\mathcal{L}_4 &= G\sum_{\alpha=0}^{8}\left[(\bar{\psi}\lambda_\alpha\psi)^2 + (\bar{\psi}i\gamma_5\lambda_\alpha\psi)^2\right], \\
\mathcal{L}_6 &= -K\left[\det\bar{\psi}(1+\gamma_5)\psi + \det\bar{\psi}(1-\gamma_5)\psi\right], \\
\mathcal{U}(\Phi,\bar{\Phi}) &= T^4\left[-\frac{b_2(t)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}\left(\bar{\Phi}^3+\Phi^3\right) + \frac{b_4}{4}\left(\bar{\Phi}\Phi\right)^2\right].
\end{aligned}$$

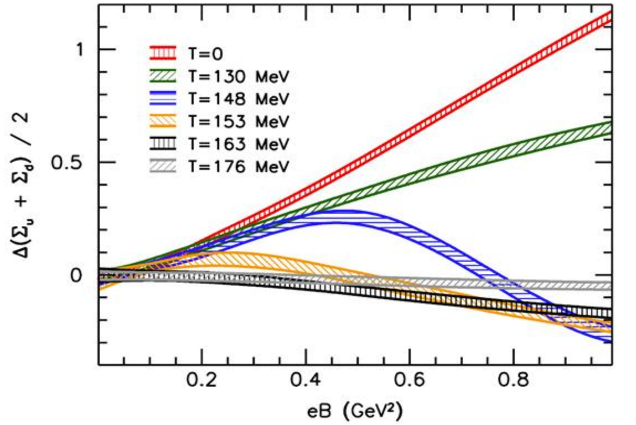
Thermodynamical potential:

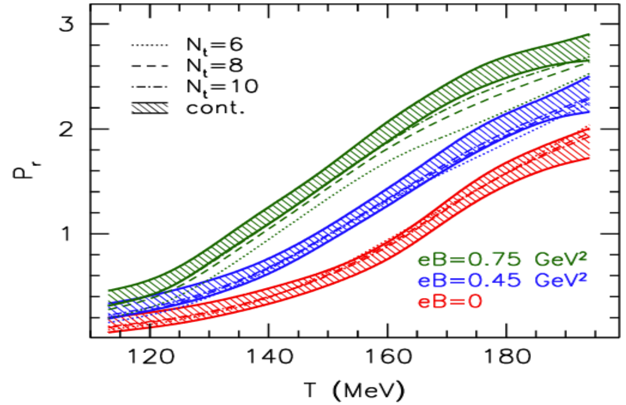
$$\begin{aligned}
\Omega &= 2G(\sigma_u^2+\sigma_d^2+\sigma_s^2) - 4K\sigma_u\sigma_d\sigma_s + \mathcal{U}(\Phi,\bar{\Phi}) + \Omega_q, \\
\Omega_q &= -\sum_{f=u,d,s}\frac{|Q_f B|}{2\pi}\sum_l \alpha_l \int\frac{dp_z}{2\pi}\Big[3E_f \\
&+ T\ln\left(1+3\Phi e^{-\beta E_f^+} + 3\bar{\Phi}e^{-2\beta E_f^+} + e^{-3\beta E_f^+}\right) \\
&+ T\ln\left(1+3\bar{\Phi} e^{-\beta E_f^-} + 3\Phi e^{-2\beta E_f^-} + e^{-3\beta E_f^-}\right)\Big],
\end{aligned}$$

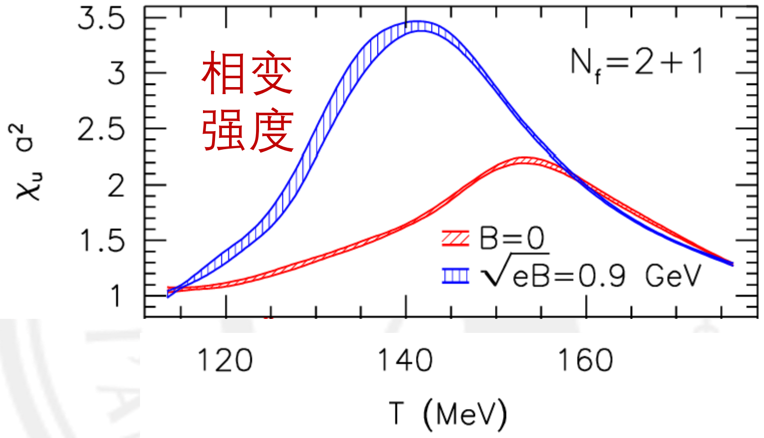
3.1



Mao,arXiv:2504.14532





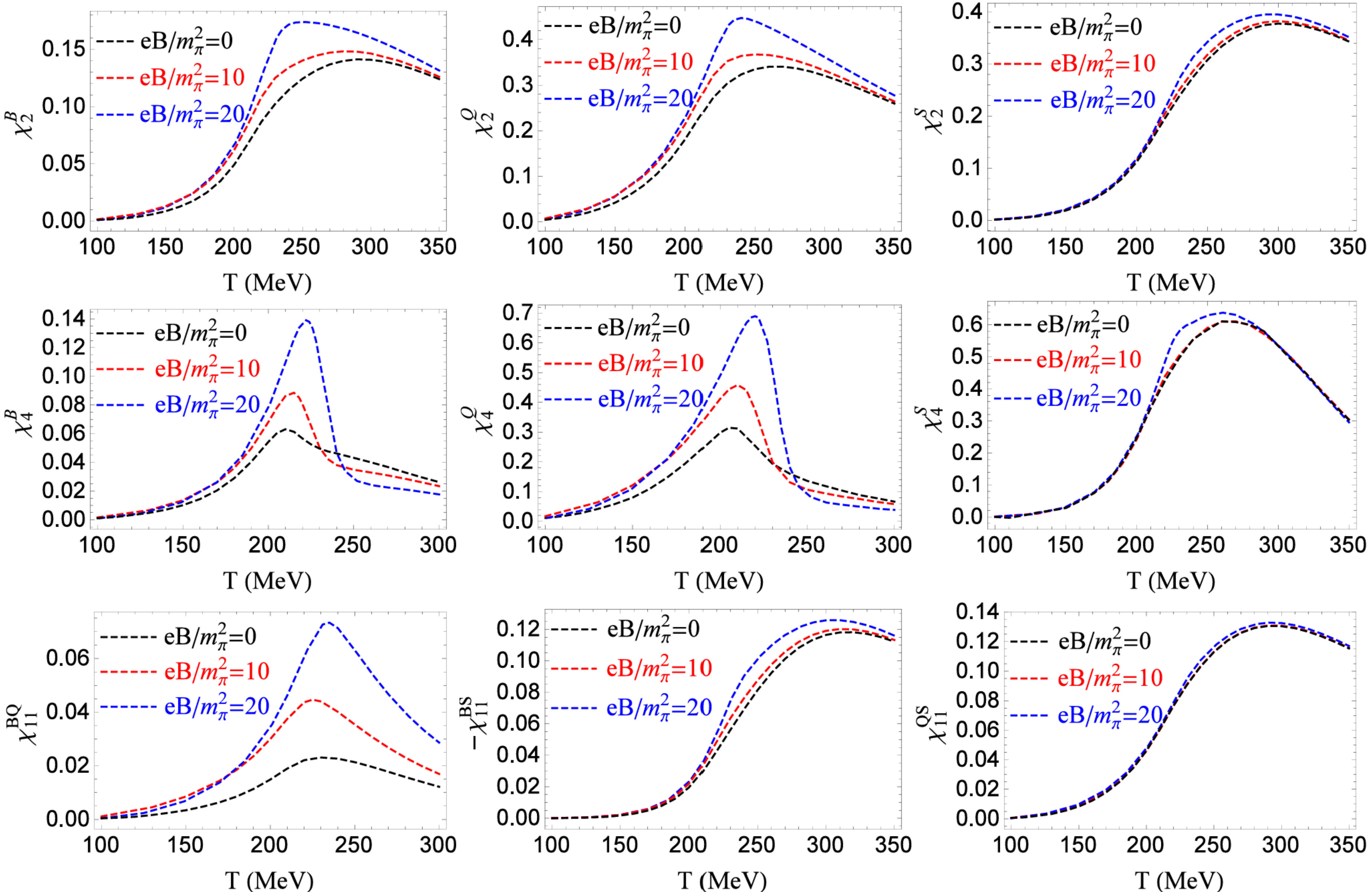


G. Bali, et.al, PRD86, 071502(2012);JHEP02,044(2012);

3.1 fluctuations and correlations without IMC

$$\chi_{i,j}^{B,Q,S} = -\frac{\partial^{i+j+k}(\Omega/T^4)}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\Big|_{\mu_X=0}$$

Mao,arXiv:2504.14532



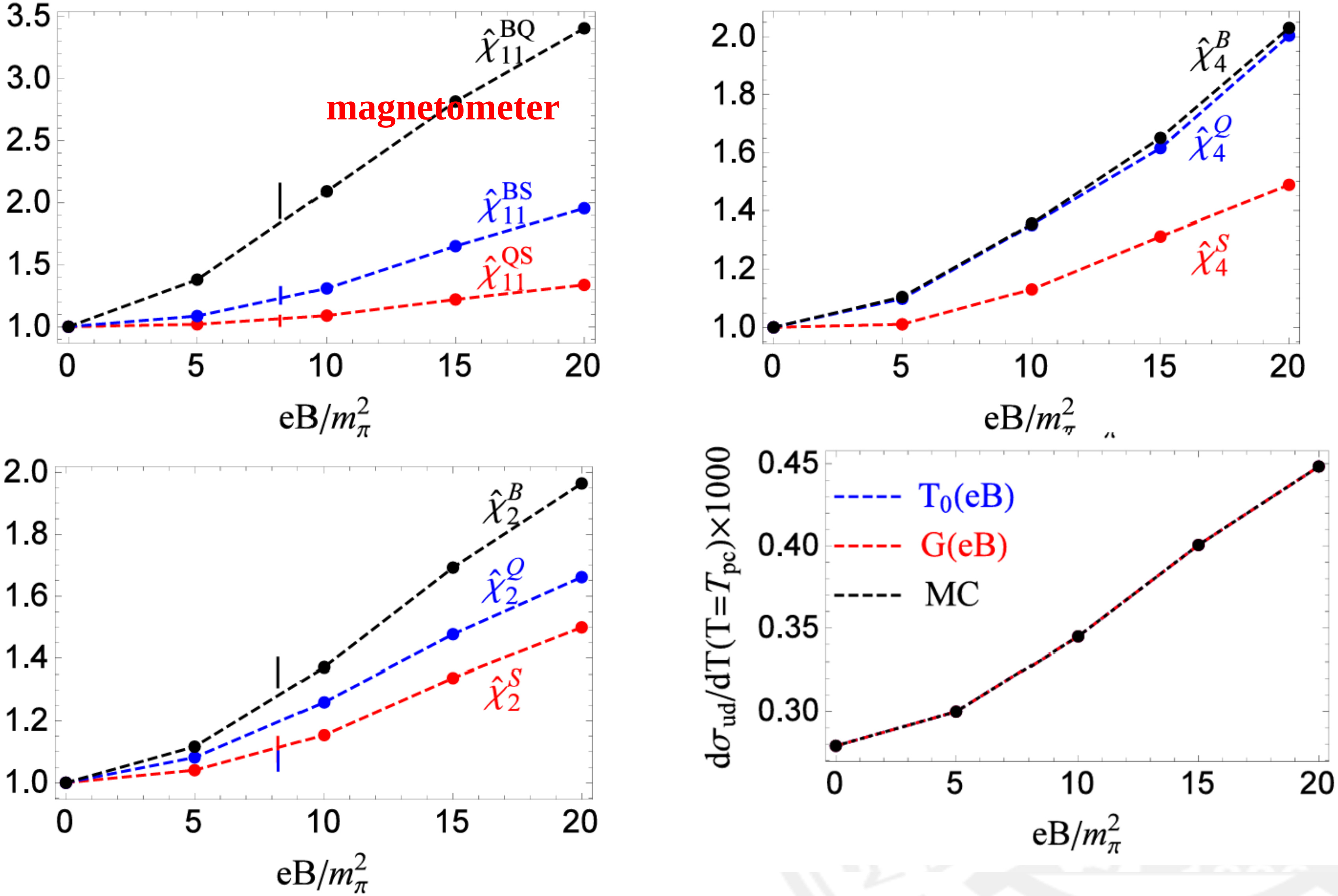
scaled fluctuations and correlations without IMC

Mao,arXiv:2504.14532

$$\hat{\chi}_{11}^{XY} = \frac{\chi_{11}^{XY}(eB, T_{pc}^c(eB))}{\chi_{11}^{XY}(eB=0, T_{pc}^c(eB=0))}$$

$$\hat{\chi}_{2,4}^{X} = \frac{\chi_{2,4}^{X}(eB, T_{pc}^c(eB))}{\chi_{2,4}^{X}(eB=0, T_{pc}^c(eB=0))},$$

$X, \ Y = B, \ Q, \ S$ and $X \neq Y$



3.2 introducing IMC: G(eB), T_0(eB)

Lagrangian density:

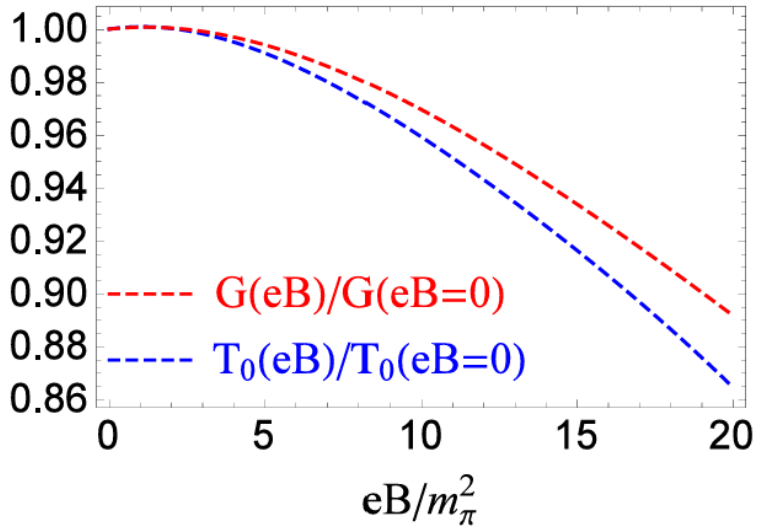
$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} - \hat{m}_0\right)\psi + \mathcal{L}_4 + \mathcal{L}_6 - \mathcal{U}(\Phi,\bar{\Phi}), \quad (1)$$

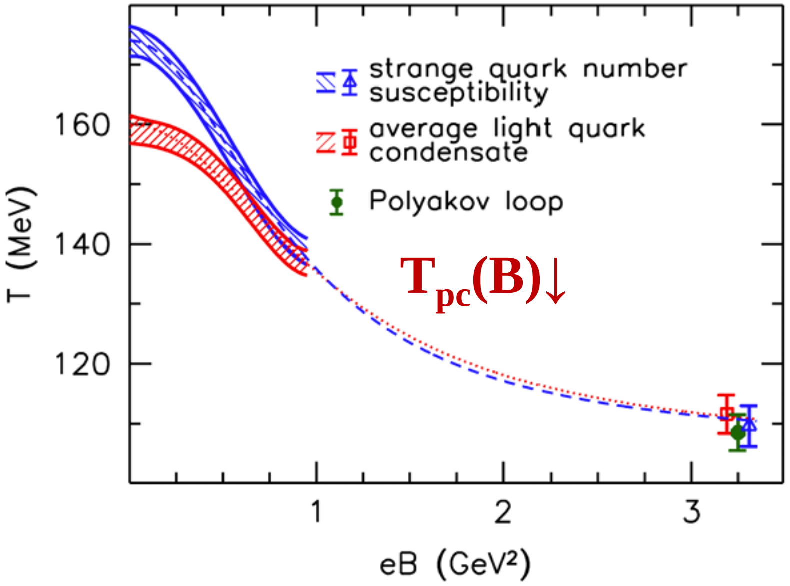
$$\mathcal{L}_4 = G\sum_{\alpha=0}^{8}\left[(\bar{\psi}\lambda_{\alpha}\psi)^2 + (\bar{\psi}i\gamma_5\lambda_{\alpha}\psi)^2\right],$$

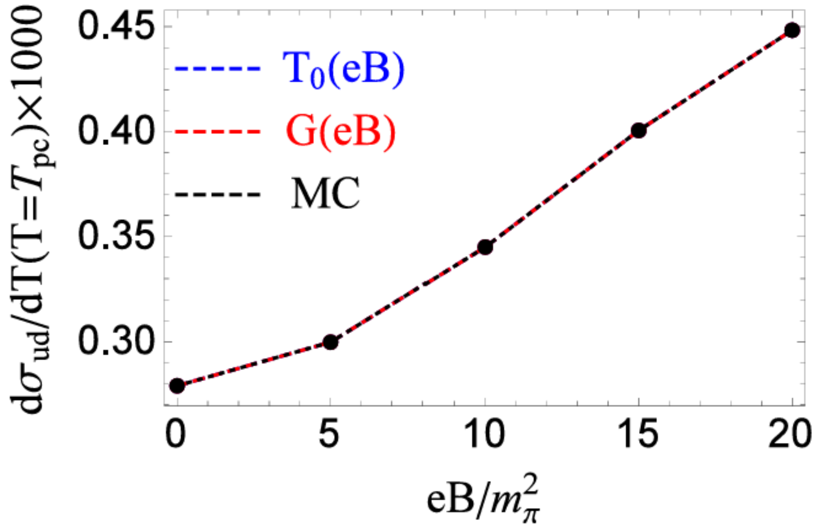
$$\mathcal{L}_6 = -K\left[\det\bar{\psi}(1+\gamma_5)\psi + \det\bar{\psi}(1-\gamma_5)\psi\right],$$

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

$$t' = T_0/T$$



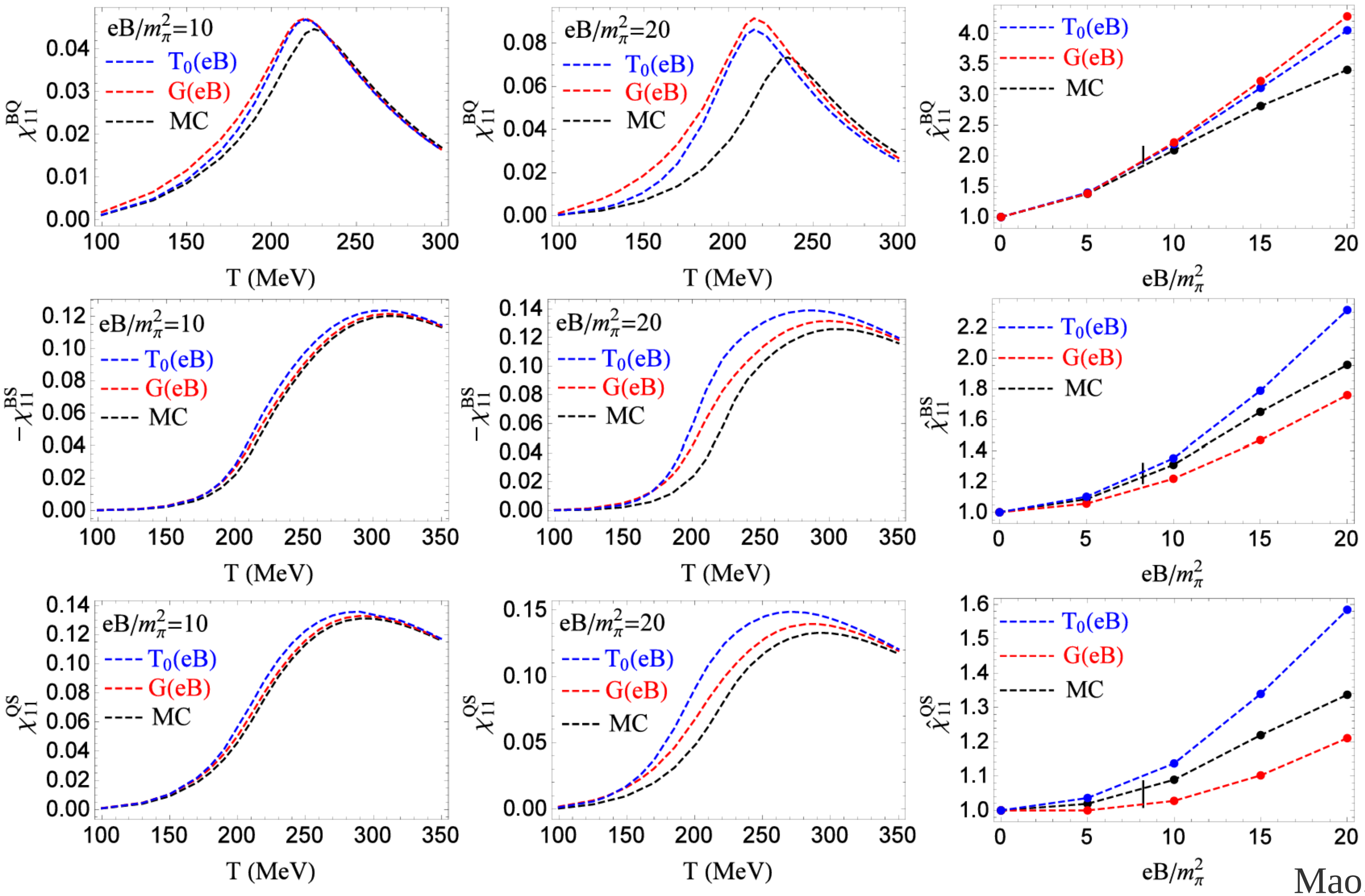




Mao,arXiv:2504.14532

3.2 correlations with IMC

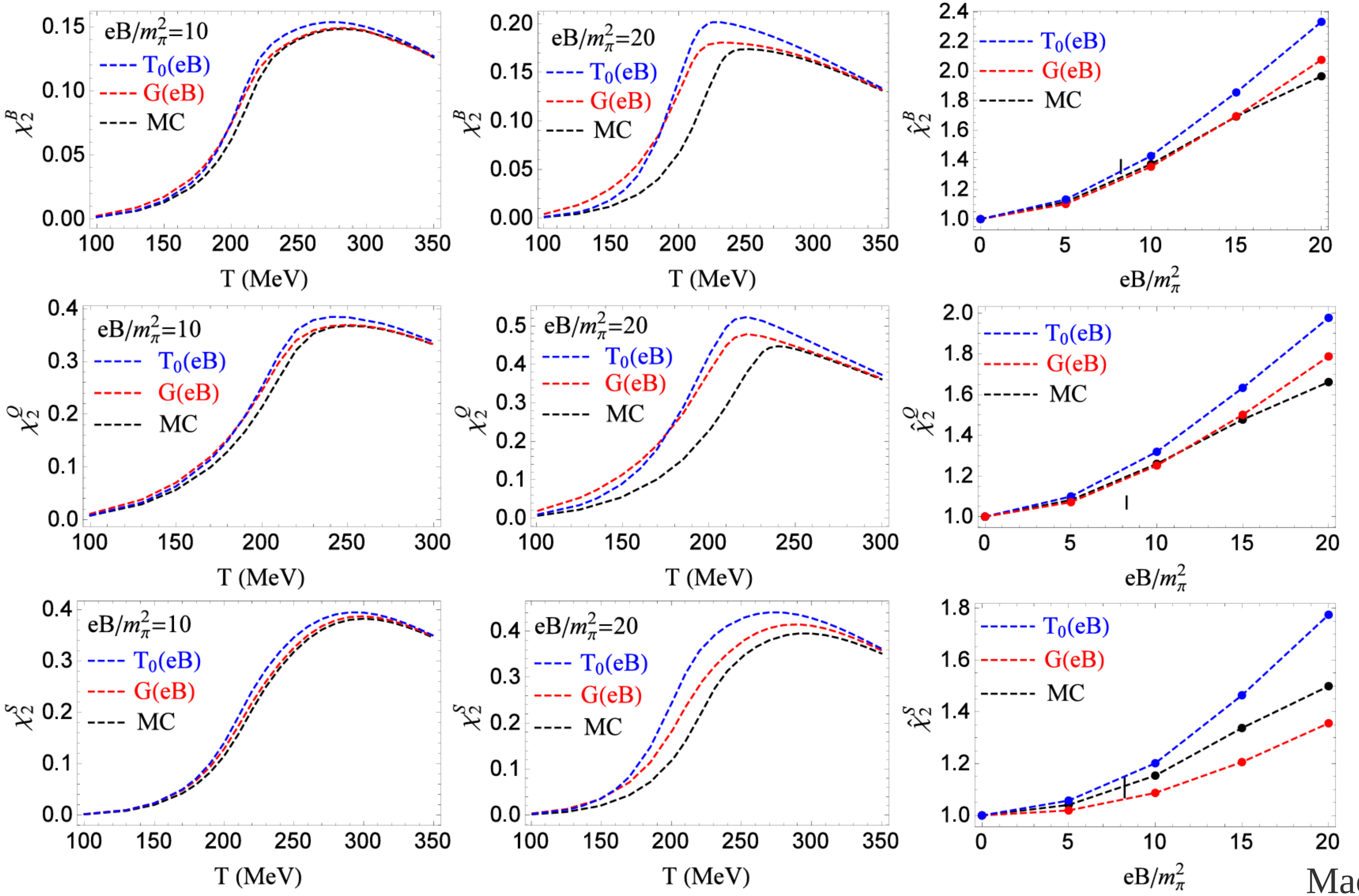
$$\chi^{B,Q,S}_{i,j} = -\frac{\partial^{i+j+k}(\Omega/T^4)}{\partial\hat{\mu}_B^i\,\partial\hat{\mu}_Q^j\,\partial\hat{\mu}_S^k}\bigg|_{\mu_X=0}$$



Mao,arXiv:2504.14532

3.2 fluctuations with IMC

$$\chi^{B,Q,S}_{i,j} = -\frac{\partial^{i+j+k}(\Omega/T^4)}{\partial\hat{\mu}^i_B\partial\hat{\mu}^j_Q\partial\hat{\mu}^k_S}\Bigg|_{\mu_X=0}$$



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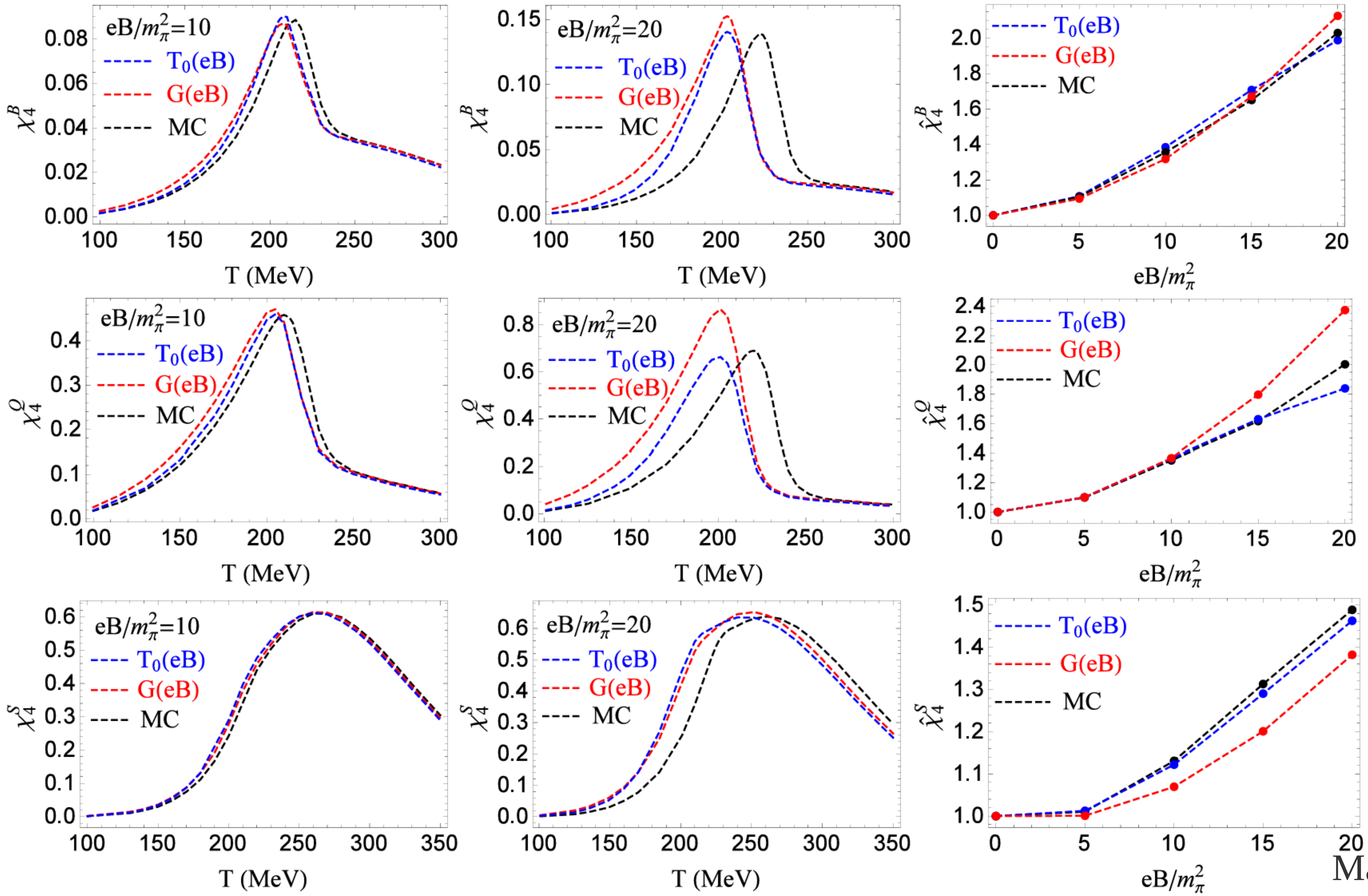
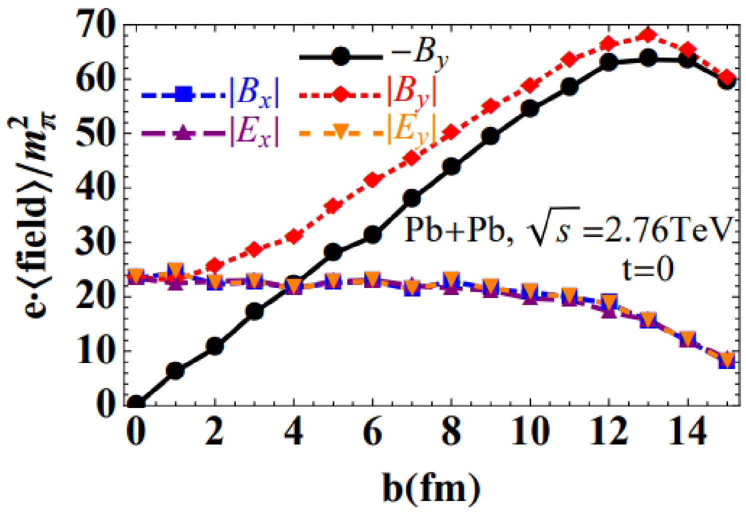


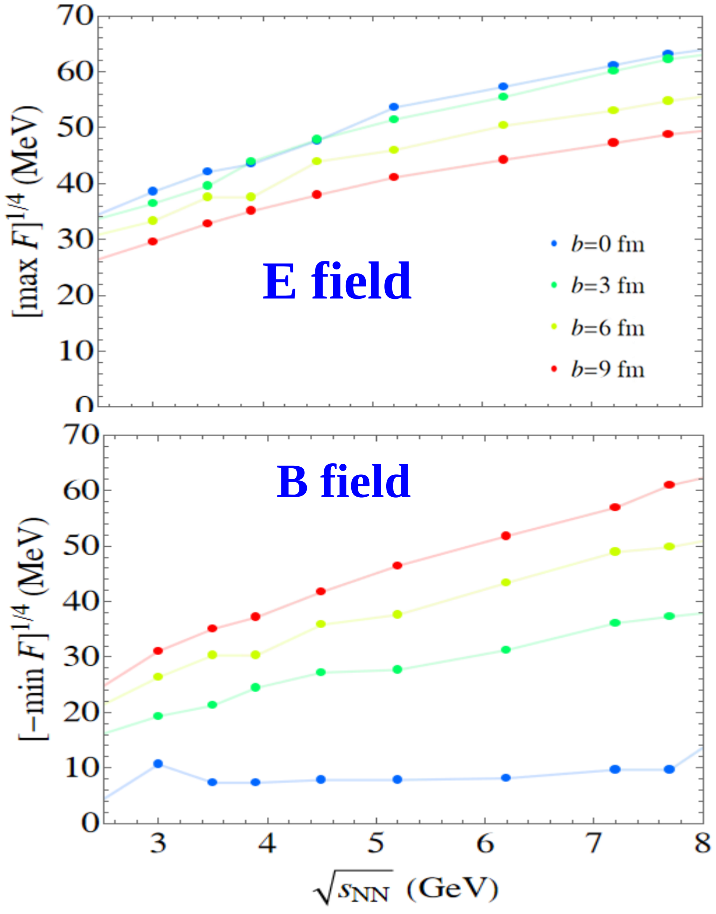
Mao,arXiv:2504.14532

4 summary and outlook

- **Not a single factor can explain IMC effect**
- **Fluctuations and correlations do not relay on IMC effect too much.**
- **E field needs more attention.**



Deng&Huang, PRC85, 044907(2012)



Taya,et.al,2402.17136; 2409.07685

https://indico.ihep.ac.cn/event/25561/

2025年中高能核物理暑期学校 @ 仙交大

2025年7月13日 到 2025年8月1日

Asia/Shanghai 时区

相对论重离子碰撞与夸克胶子等离子体是中高能核物理研究的重要前沿领域。随着实验的持续开展和未来更多大科学装置的运行，相对论重离子碰撞实验将提供丰富的数据，为研究中高能区QGP的演化、QCD的物态与相结构、末态强子与高密核物质的性质等提供重要机遇。

为了在该领域培养后备力量，我们拟在在西安举办“2025年中高能核物理暑期学校”，邀请领域知名专家学者为学员授课，课程涵盖基础知识与前沿讲座，具体包括：有限温度量子场论、重离子碰撞理论&实验、QGP演化与流体力学、QCD相结构、集体流、输运与极化理论、高密核物质、机器学习在核物理中的应用等方面的内容。

暑期学校暂定于7月13日 至8月1日举办。7月13日报到，8月1日课程结束。

我们诚挚邀请您的参与，并推荐优秀研究生、博士后和青年研究人员参加。暑期学校计划招收120名学员，学校报名网址：https://docs.qq.com/form/page/DQnhpVnFkd25YSHNz。

本次暑期学校得到国家自然科学基金委理论物理专款项目的支持，由西安交通大学物理学院举办。

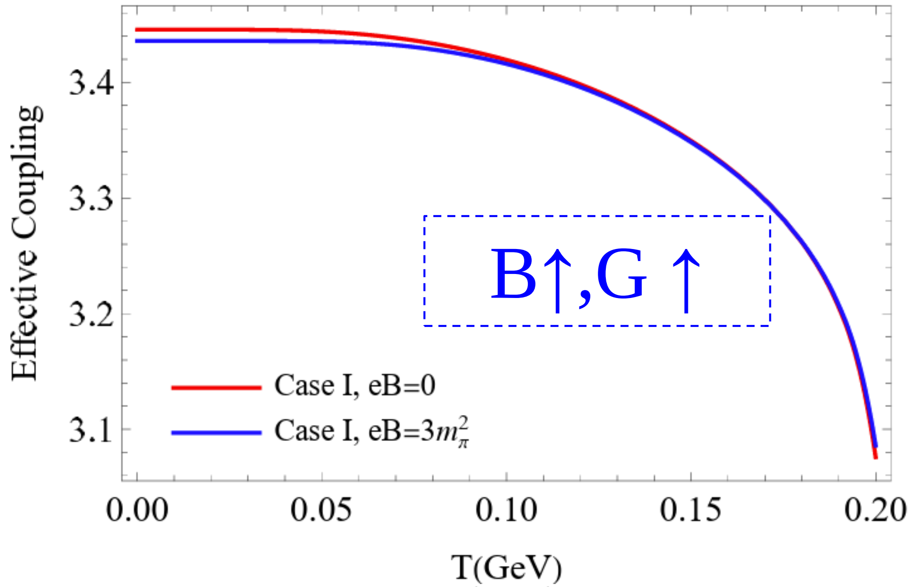
组委会：邵国运、毛施君、刘伯超、张盈

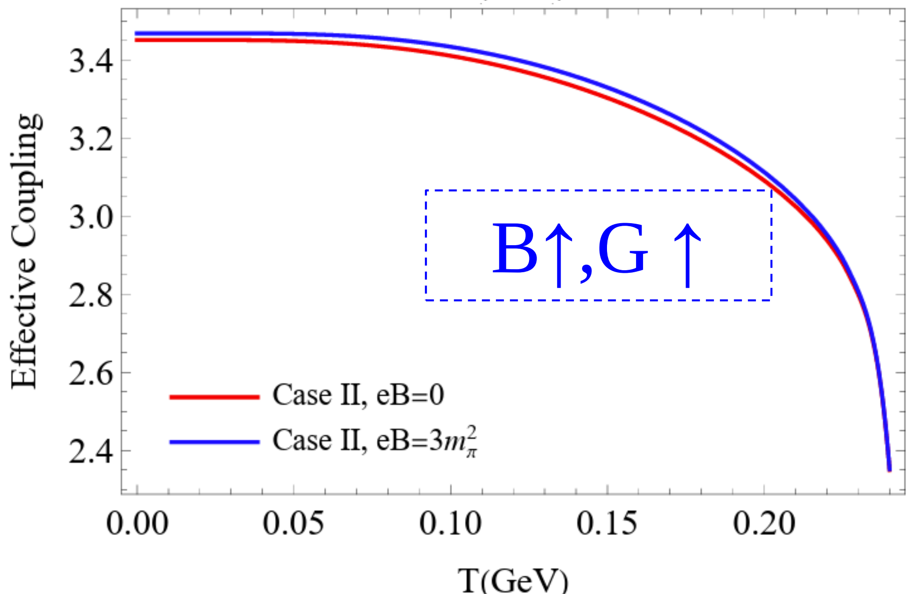
课程涵盖基础知识与前沿讲座，包括：

- 有限温度量子场论
- 重离子碰撞理论&实验
- QGP演化与流体力学
- QCD相结构
- 集体流
- 自旋与极化理论
- 高密核物质
- 机器学习与核物理交叉
- 等等

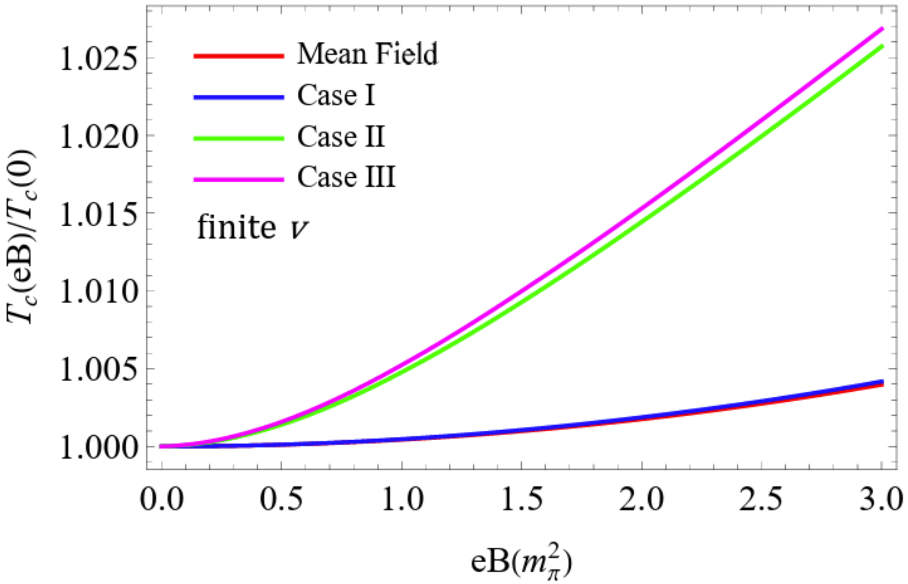
2.1 Physical case eB VS G

J.Mei, et.al, PRD110, 034024(2024)





Case	Included mesons
0	None
I	π_0 only
II	$\pi_\pm$ only
III	$\pi_0,\ \pi_\pm$



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