Spin polarization condensation and chiral condensation in a (2 + 1)-flavor NJL model at finite temperature in the presence of magnetic field

1. Introductions
2. The (2 + 1) flavors NJL model with TSP and AMM under a magnetic field
3. The chiral phase transition with the contributions from the TSP and the AMM
4. Summary and conclusions

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1. Introductions

1. Introductions

By Considering the response of QGP in relativistic heavy-ion collisions

Here we stress the study of the magnetic field of non-central heavy-ion collisions, which comes from the laboratory of mankind.

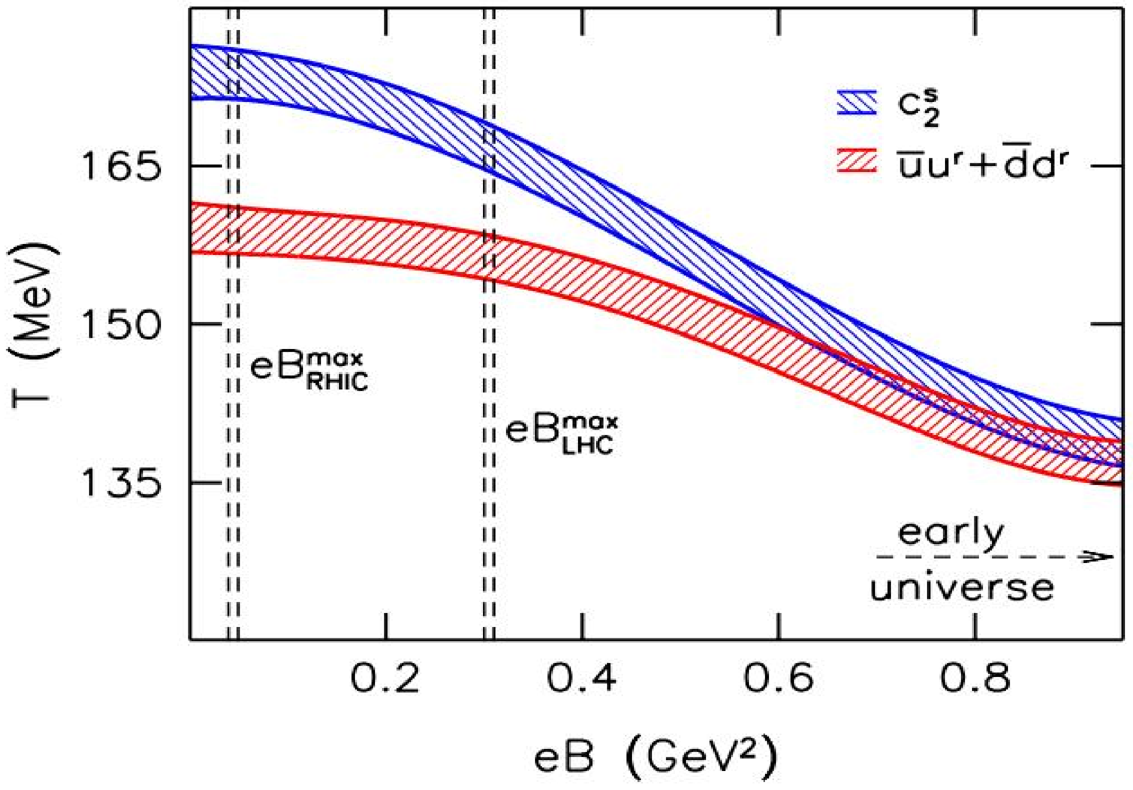
(1) The magnetic field reaches up to $\sqrt{eB} \sim 0.1$ GeV Au-Au collisions for RHIC and $\sqrt{eB} \sim 0.5$ GeV Pb - Pb collisions for LHC in non-central heavy-ion collisions. This magnetic field is external since it is generated by the spectators, and therefore it has a very short lifetime .

(2) The presence of the quark-gluon plasma (QGP) medium response effect, substantially delays the decay of these time-dependent magnetic fields. This is why in most cases, the effect of constant and uniform magnetic fields is taken.

D. She, S. -Q. Feng, European Physical Journal A 54: 48 (2018)
Y. Guo, S. Shi, S.-Q. Feng, and J. Liao, Phys. Lett. B 798, 134929 (2019).

Lattice Result in Phase Transition

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



Lattice result: the QCD phase diagram in the magnetic field-temperature plane.

Some effective field theories predict that the external magnetic field causes the magnetic catalytic feature of chiral symmetry breaking, namely the magnetic catalytic(MC). However, lattice theory provides different results, especially the corresponding inverse magnetic catalytic (IMC) of chiral symmetry breaking near the phase transition. This is an interesting question.

By introducing of tensor spin polarization (TSP) and **anomalous magnetic moment** (AMM) respectively in the background magnetic field, we will analyze the impact on the magnetic catalytic characteristics of chiral symmetry breaking and puase transition.

NJL model with Tensor Spin Polarization (TSP)

E. J. Ferrer, V. de la Incera, I. Portillo etal., Phys. Rev. D 89, 085034 (2014).
Yi-Wei Qiu and Sheng-Qin Feng, Phys. Rev. D 107, 076004 (2023)

The interaction term of NJL Lagrangian:

$$L_{\text{int}}^{\text{NJL}} = \frac{g}{2\Lambda^2}\left(\bar{\psi}\gamma^{\mu}\psi\right)\left(\bar{\psi}\gamma_{\mu}\psi\right).$$

Anisotropic coupling →

$$L_{\text{int}}^{\text{NJL}} = \frac{g_{\parallel}}{2\Lambda^2}\left(\bar{\psi}\gamma_{\parallel}^{\mu}\psi\right)\left(\bar{\psi}\gamma_{\mu}^{\parallel}\psi\right) + \frac{g_{\perp}}{2\Lambda^2}\left(\bar{\psi}\gamma_{\perp}^{\mu}\psi\right)\left(\bar{\psi}\gamma_{\mu}^{\perp}\psi\right).$$

The Fierz identities connecting the different Dirac ring elements:

$$\left(\Gamma_A\right)_{ij}\left(\Gamma^B\right)_{kl} = \frac{1}{16}Tr\left[\Gamma^A\Gamma_C\Gamma_B\Gamma_D\right]\left(\Gamma^D\right)_{il}\left(\Gamma^C\right)_{kj},$$

where $\left\{\Gamma^A\right\} = \left\{1,\gamma_5,\gamma^{\mu},\gamma_5\gamma^{\mu},\sigma^{\mu\upsilon}\right\}.$

For the particle-antiparticle channel the anisotropic Fierz identities in the presence of a constant and uniform magnetic field are

$$\begin{pmatrix} (1)_{ij}(1)_{kl} \\ (\gamma^{\parallel})_{ij}(\gamma_{\parallel})_{kl} \\ (\gamma^{\perp})_{ij}(\gamma_{\perp})_{kl} \\ (\sigma^{30})_{ij}(\sigma_{30})_{kl} \\ (\sigma^{\perp\parallel})_{ij}(\sigma_{\perp\parallel})_{kl} \\ \frac{1}{2}(\sigma^{\perp\perp})_{ij}(\sigma_{\perp\perp})_{kl} \\ (\gamma^{\parallel}\gamma_5)_{ij}(\gamma^{\parallel}\gamma_5)_{kl} \\ (\gamma^{\perp}\gamma_5)_{ij}(\gamma_{\perp}\gamma_5)_{kl} \\ (\gamma_5)_{ij}(\gamma_5)_{kl} \end{pmatrix} = \begin{pmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} \\ \frac{1}{2} & 0 & -\frac{1}{2} & -\frac{1}{2} & 0 & \frac{1}{2} & 0 & -\frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & 0 & \frac{1}{2} & 0 & -\frac{1}{2} & -\frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} \\ 1 & 0 & 0 & -1 & 0 & -1 & 0 & 0 & -1 \\ \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & -\frac{1}{2} & \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ -\frac{1}{2} & 0 & -\frac{1}{2} & \frac{1}{2} & 0 & -\frac{1}{2} & 0 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 & \frac{1}{2} & -\frac{1}{2} & 0 & -\frac{1}{2} \\ -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} \end{pmatrix} \begin{pmatrix} (1)_{il}(1)_{kj} \\ (\gamma^{\parallel})_{il}(\gamma_{\parallel})_{kj} \\ (\gamma^{\perp})_{il}(\gamma_{\perp})_{kj} \\ (\sigma^{30})_{il}(\sigma_{30})_{kj} \\ (\sigma^{\perp\parallel})_{il}(\sigma_{\perp\parallel})_{kj} \\ \frac{1}{2}(\sigma^{\perp\perp})_{il}(\sigma_{\perp\perp})_{kj} \\ (\gamma^{\parallel}\gamma_5)_{il}(\gamma^{\parallel}\gamma_5)_{kj} \\ (\gamma^{\perp}\gamma_5)_{il}(\gamma_{\perp}\gamma_5)_{kj} \\ (\gamma_5)_{il}(\gamma_5)_{kj} \end{pmatrix}.$$

At last, Lagrangian density within (2+1)-flavor NJL model in the presence of an external magnetic field can be given by:

$$L_{TSP} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} + \gamma^0\mu - m\right)\psi + G_s\sum_{a=0}^{8}\left[\left(\bar{\psi}\lambda_a\psi\right)^2 + \left(\bar{\psi}i\gamma^5\lambda_a\psi\right)^2\right]$$
$$G_t\sum_{a=0}^{8}\left[\left(\bar{\psi}\Sigma_3\lambda_a\psi\right)^2 + \left(\bar{\psi}\Sigma_3 i\gamma^5\lambda_a\psi\right)^2\right] - K\left[\det\bar{\psi}\left(1+\gamma_5\right)\psi + \det\bar{\psi}\left(1-\gamma_5\right)\psi\right],$$

Where the quark field ψ_f^c carries a flavor iso-doublet ($f = u, d, s$) and three color ($c = r, g, b$), current quark mass m is considered as $m_u = m_d$ for maintain isospin symmetry, covariant derivative $D_{\mu} = \partial_{\mu} + iQA_{\mu}^{ext}$ introducing magnetic field, the charge metrix in flavor space .

The 2 + 1 Flavors NJL Model with TSP under a Magnetic Field

The Lagrangian density of the (2 + 1)-flavor NJL model by considering TSP:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{TSP}} = & \bar{\psi}(i\gamma^{\mu}D_{\mu} + \gamma^{0}\mu - m)\psi \\
& + G_s \sum_{a=0}^{8} [(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma^5\lambda_a\psi)^2] \\
& + G_t \sum_{a=0}^{8} \{(\bar{\psi}\Sigma_3\lambda_a\psi)^2 + (\bar{\psi}\Sigma_3 i\gamma^5\lambda_a\psi)^2\} \\
& - K\{\det[\bar{\psi}(1+\gamma_5)\psi] + \det[\bar{\psi}(1-\gamma_5)\psi]\}.
\end{aligned}
$$

Yi-Wei Qiu and Sheng-Qin Feng, Phys. Rev. D 107, 076004 (2023)
Xueqiang Zhu and Sheng-Qin Feng, Phys. Rev. D 107, 016018 (2023)

The coupling constant G_s in the scalar/pseudoscalar channel is closely related to the spontaneously chiral symmetry breaking, which produces a dynamical quark mass, and the tensor/pseudotensor channels term $G_t\sum_{a=0}^{8}[(\bar{\psi}_f^c\Sigma^3\lambda_a\psi_f^c)^2+(\bar{\psi}_f^c i\Sigma^3\gamma^5\lambda_a\psi_f^c)^2]$ is closely related to the spin-spin interaction, which causes spin-polarization condensation.

The 2 + 1 Flavors NJL Model with TSP under a Magnetic Field

The effective potential of using a standardized process is given

$$\Omega_{\mathrm{TSP}} = G_s \sum_{f=u,d,s} \langle\bar{\psi}\psi\rangle_f^2 + G_t\langle\bar{\psi}\lambda_3\Sigma^3\psi\rangle^2 + G_t\langle\bar{\psi}\lambda_8\Sigma^3\psi\rangle^2 - \frac{N_c}{2\pi}\sum_{f=u,d,s}|q_f B|\sum_{l=0}^{\infty}\alpha_l\int_{-\infty}^{\infty}\frac{dp_z}{2\pi}$$
$$\times\left\{\varepsilon_{f,l,\eta} + T\ln\left[1+\exp\left(\frac{-\varepsilon_{f,l,\eta}-\mu}{T}\right)\right] + T\ln\left[1+\exp\left(\frac{-\varepsilon_{f,l,\eta}+\mu}{T}\right)\right]\right\}$$
$$+ 4K\langle\bar{\psi}\psi\rangle_u\langle\bar{\psi}\psi\rangle_d\langle\bar{\psi}\psi\rangle_s$$

Note that the breaking of energy spectrum degeneracy caused by spin known as Zeeman effect. Therefore, the contributions of spin come not only from the ground state of Landau level, but also from the whole excited states of Landau level.

Yi-Wei Qiu and Sheng-Qin Feng, Phys. Rev. D 107, 076004 (2023);
Xueqiang Zhu and Sheng-Qin Feng, Phys. Rev. D 107, 016018 (2023)

where $l = 0, 1, 2 \ldots$ represents the quantum number of Landau level, and $\eta = \pm 1$ corresponds to the two kinds of spin direction of quark-antiquark pair. Contribution of non-degenerate particles due to spin difference at non-lowest Landau energy levels should be taken into account with the definition of this new operator $\alpha_l = \delta_{0,l} + \Delta(l)\sum_{\eta=\pm 1}$

$$\varepsilon_{u,l=0}^2 = p_z^2 + \left(M_f + \left(F_3 + \frac{F_8}{\sqrt{3}}\right)\right)^2,$$

$$\varepsilon_{u,l\neq 0,\eta}^2 = p_z^2 + \left(\left(M_f^2 + 2|q_f B|l\right)^{1/2} + \eta\left(F_3 + \frac{F_8}{\sqrt{3}}\right)\right)^2,$$

$$\varepsilon_{d,l=0}^2 = p_z^2 + \left(M_f + \left(F_3 - \frac{F_8}{\sqrt{3}}\right)\right)^2,$$

$$\varepsilon_{d,l\neq 0,\eta}^2 = p_z^2 + \left(\left(M_f^2 + 2|q_f B|l\right)^{1/2} + \eta\left(F_3 - \frac{F_8}{\sqrt{3}}\right)\right)^2,$$

$$\varepsilon_{s,l=0}^2 = p_z^2 + \left(M_f + \left(\frac{2F_8}{\sqrt{3}}\right)\right)^2,$$

$$\varepsilon_{s,l\neq 0,\eta}^2 = p_z^2 + \left(\left(M_f^2 + 2|q_f B|l\right)^{1/2} + \eta\left(\frac{2F_8}{\sqrt{3}}\right)\right)^2.$$

The 2 + 1 Flavors NJL Model with TSP under a Magnetic Field

The tensor condensate parameter F_3 and F_8 are self-consistently satisfied the minimum of the thermodynamic potential, five coupling gap equations as:

$$\frac{\partial\Omega_{TSP}\left(M_f, F_3, F_8\right)}{\partial M_f} = 0.$$

and

$$\frac{\partial\Omega_{TSP}\left(M_f, F_3, F_8\right)}{\partial F_3} = \frac{\partial\Omega_{TSP}\left(M_f, F_3, F_8\right)}{\partial F_8} = 0$$

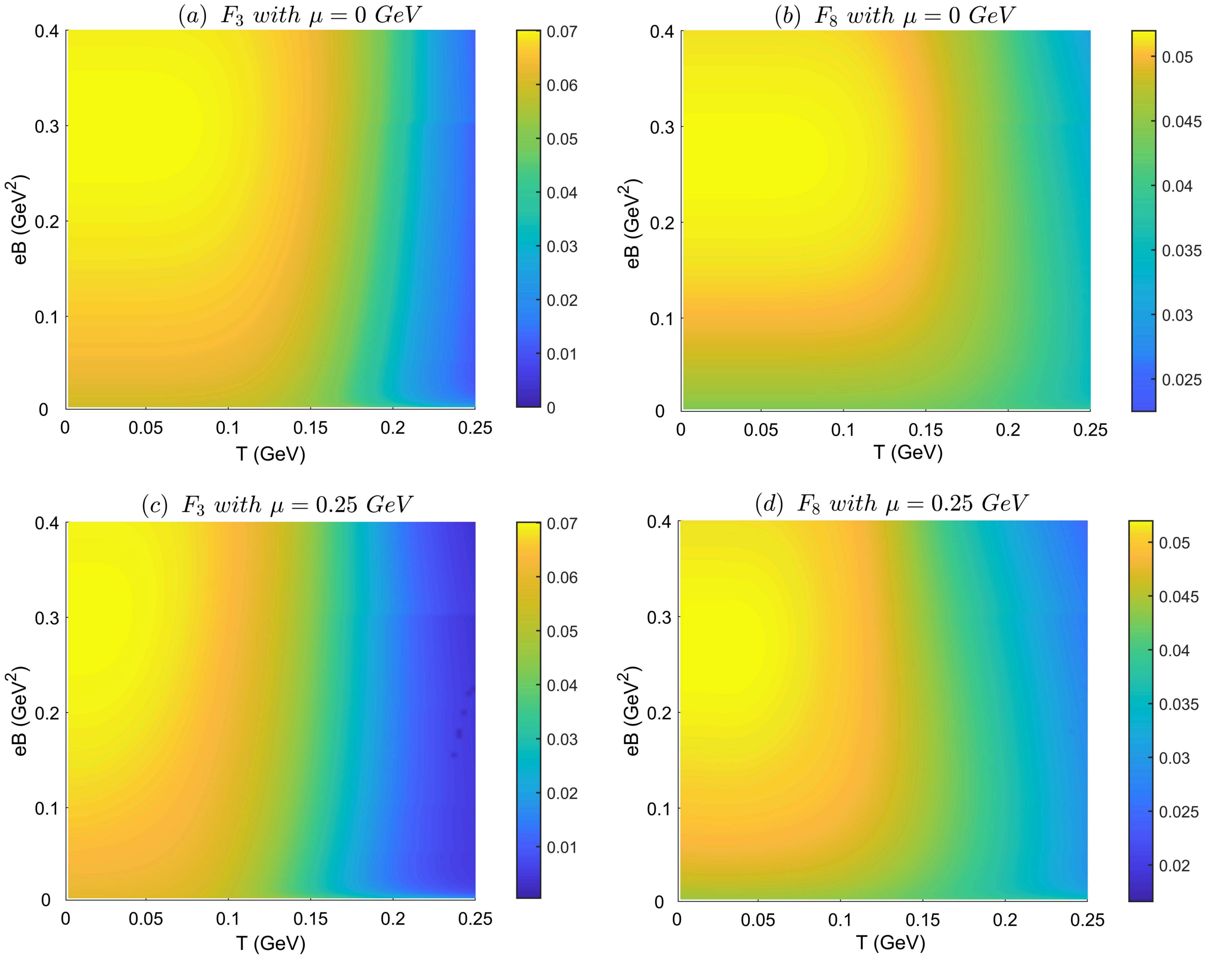
$$F_3 = -2G_t\left\langle\bar{\psi}\Sigma^3\lambda_3\psi\right\rangle,$$
$$F_8 = -2G_t\left\langle\bar{\psi}\Sigma^3\lambda_8\psi\right\rangle.$$

The scheme dealing with the sums of all Landau levels within the integrals by means of the Hurwitz zeta function.

(1) D. P. Menezes et.al., Phys. Rev. C 79, 035807(2009).
(2) R. M. Aguirre, Phys. Rev. D 102, 096025 (2020).

For the (2 + 1)-flavor NJL model, tensor-type interaction at the mean field level leads to the two types of spin polarization as

$$F_3 = -2G_t \left\langle \bar{\psi}\Sigma^3\lambda_3\psi \right\rangle,$$
$$F_8 = -2G_t \left\langle \bar{\psi}\Sigma^3\lambda_8\psi \right\rangle.$$



(1) Both F_3 and F_8 become stronger at low temperatures, especially with the increase of the magnetic field.

(2) F_3 is almost zero at high temperature, and F_8 is very small but not zero at high temperature.

(3) The polarizations become weak at high temperatures. It thus can be concluded that it is more difficult to be polarized in the hot QGP background. It is characterized by ferromagnetism, and ferromagnetic spin polarization is zero at high temperature.

Intrducing Anomalous Magnetic Moment (AMM)

In the case of strong magnetic field, the anomalous magnetic moment (AMM) effect of quarks has aroused great interest, and the inverse catalytic property (IMC) effect appears [1-5]. Dynamic chiral symmetry breaking is one of the most important characteristics of QCD, which enables quarks to obtain the dynamic mass of QCD. The AMM of quarks can also be generated like the dynamic quark mass M. Therefore, once quarks obtain kinetic mass due to condensation, they should also obtain kinetic AMM $\boxed{\frac{1}{2}q\kappa F_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi \ \left(\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]\right)}$**. The coefficient *κ* of quark AMM in a magnetic field is introduced to study the magnetic catalytic effect at finite temperature. For QCD, spontaneous chiral symmetry breaking results in quark AMM, also known as dynamic AMM.**

1. S. Fayazbakhsh and N. Sadooghi, Phys. Rev. D 90, 105030(2014).
2. N. Chaudhuri, S. Ghosh, S. Sarkar, and P. Roy, Phys. Rev. D 99, 116025 (2019).
3. S. Ghosh, N. Chaudhuri, S. Sarkar, and P. Roy, Phys. Rev. D 101, 096002 (2020).
4. K. Xu, J. Chao, and M. Huang, Phys. Rev. D 103, 076015 (2021).
5. Yi-Wei Qiu and Sheng-Qin Feng, Phys. Rev. D 107, 076004 (2023).

The（2 + 1） Flavors NJL model with AMM

The effect Lagrangian density of the (2 + 1)- flavor NJL model with AMM is given as

$$\mathrm{L}_{\mathrm{AMM}} = \bar{\psi}\left(i\gamma^{\mu}D_{\mu} + \gamma^{0}\mu - m + \frac{1}{2}q_f\kappa\sigma^{\mu\nu}F_{\mu\nu}\right)\psi + G_s\sum_{a=0}^{8}\left[\left(\bar{\psi}\lambda_a\psi\right)^2 + \left(\bar{\psi}i\gamma^5\lambda_a\psi\right)^2\right] - K\left[\det\bar{\psi}(1+\gamma_5)\psi + \det\bar{\psi}(1-\gamma_5)\psi\right],$$

The effective potential with AMM can be taken as

$$\Omega_{\mathrm{AMM}} = G_s\sum_{f=u,d,s}\left\langle\bar{\psi}\psi\right\rangle_f^2 + 4K\left\langle\bar{\psi}\psi\right\rangle_u\left\langle\bar{\psi}\psi\right\rangle_d\left\langle\bar{\psi}\psi\right\rangle_s - \frac{N_c\sum_{f=u,d,s}\left|q_fB\right|}{2\pi}\sum_{l=0}^{\infty}\sum_{t=\pm1}\int_{-\infty}^{\infty}\frac{dp_z}{2\pi}\left\{E_{f,l,t} + T\ln\left[1+\exp\left(\frac{-E_{f,l,t}-\mu}{T}\right)\right] + T\ln\left[1+\exp\left(\frac{-E_{f,l,t}+\mu}{T}\right)\right]\right\},$$

where $E_{f,l,t} = \sqrt{p_z^2 + \left(\left(M_f^{\,2} + 2|q_fB|l\right)^{1/2} - t\kappa_f q_f eB\right)^2}$ **is the energy spectrum under different Landau energy levels and corresponds to the two kinds of spin direction of quark-antiquark pair.**

The（2 + 1） Flavors NJL model with AMM

$$\frac{\partial \Omega_{AMM}}{\partial M_f} = 0,$$

where $f = u, d, s$ for the three different flavors. We can obtain three dynamical quark mass as

$$M_u = m_u - 4G_s \langle \bar{\psi}\psi \rangle_u + 2K \langle \bar{\psi}\psi \rangle_d \langle \bar{\psi}\psi \rangle_s,$$

$$M_d = m_d - 4G_s \langle \bar{\psi}\psi \rangle_d + 2K \langle \bar{\psi}\psi \rangle_u \langle \bar{\psi}\psi \rangle_s,$$

$$M_s = m_s - 4G_s \langle \bar{\psi}\psi \rangle_s + 2K \langle \bar{\psi}\psi \rangle_u \langle \bar{\psi}\psi \rangle_d,$$

and

$$\langle \bar{\psi}\psi \rangle_f = \frac{N_c G_s}{2\pi} \sum_{l=0}^{\infty} \alpha_l \, |q_f B| \int_{-\infty}^{+\infty} \frac{dp_z}{2\pi} \frac{M_f}{\varepsilon_{f,l,t}} \left(1 - \frac{s\kappa_f q_f B}{\hat{M}_{f,l,t}}\right) \left\{1 - \frac{1}{e^{\frac{\varepsilon_{f,l,t}+\mu}{T}} + 1} - \frac{1}{e^{\frac{\varepsilon_{f,l,t}-\mu}{T}} + 1}\right\}.$$

corresponds to chiral condensation of different quark flavors ($f = u, d, s$).

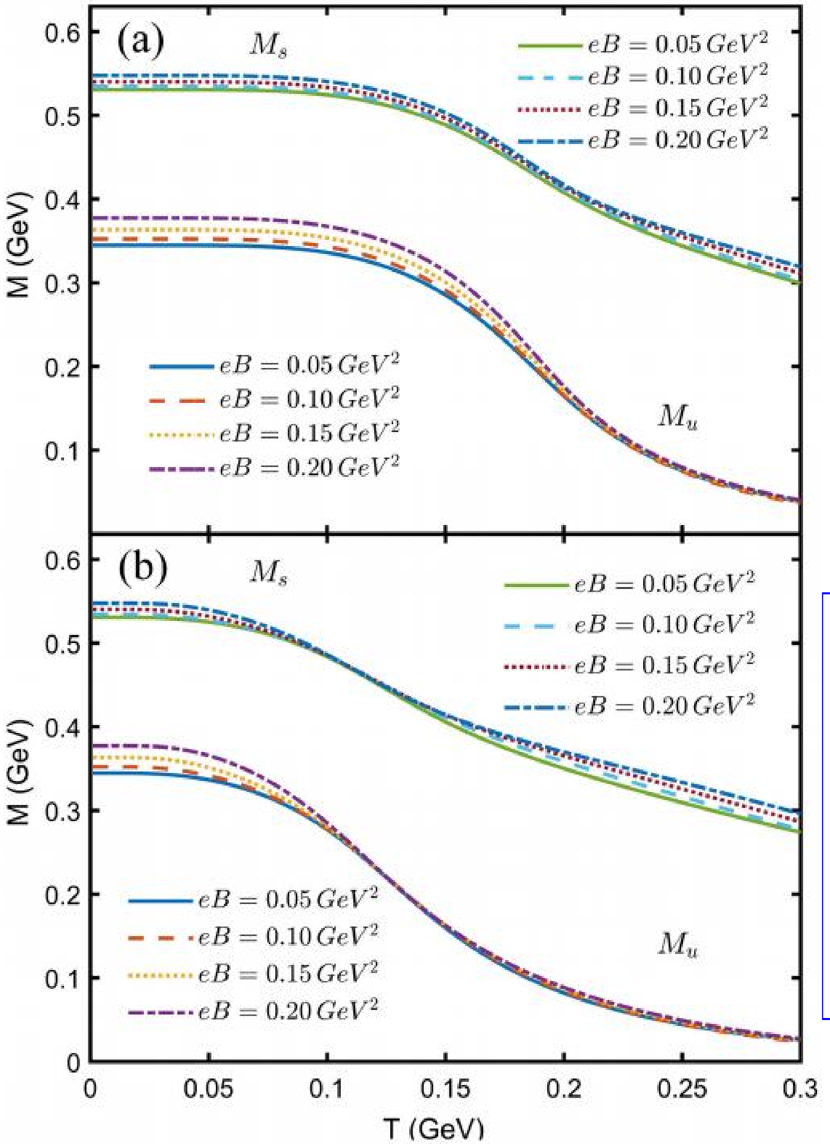


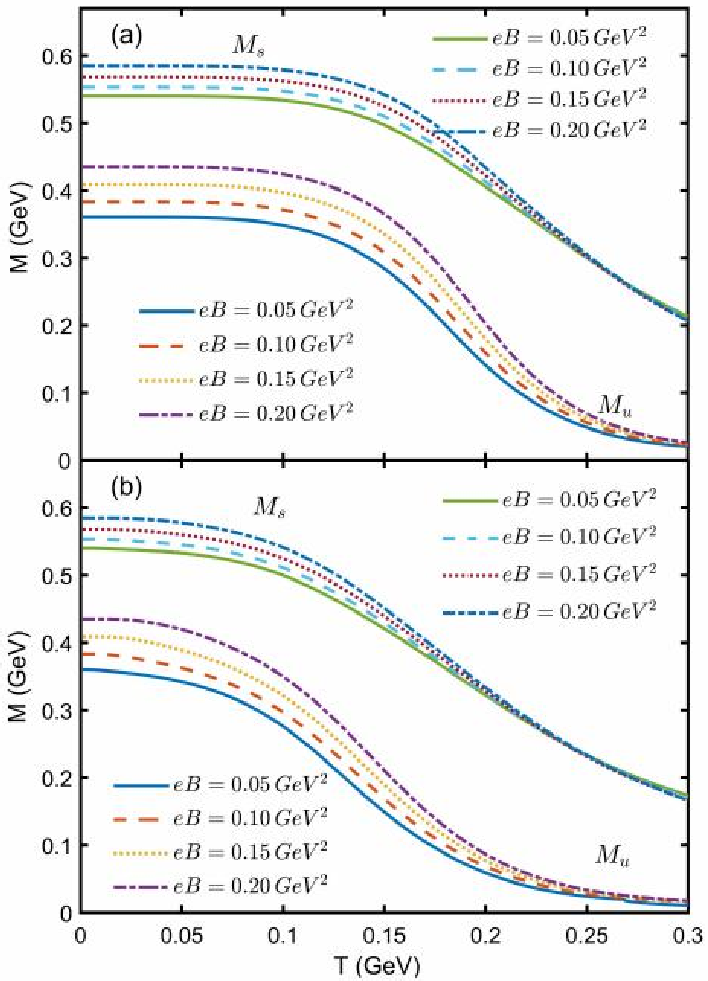
Fig. 3 The dynamical quark masses M of *u*, d and s quarks ***by without considering AMM and TSP***

Without considering AMM and TSP

The dynamical quark masses M of *u, d* and *s* quarks without considering AMM and TSP are manifested as decreasing *smooth functions* of temperatures at μ = 0 GeV (a) and μ = 0.25 GeV (b), which indicates a *chiral crossover*. The dynamical mass *M* is apparently enhanced by increasing the magnetic field.

The larger the magnetic field is, the larger the corresponding chiral condensation is. *This phenomenon is manifested as magnetic catalysis,* which accounts for the magnetic field has a strong tendency to enhance (or catalyze) spin-zero quark-antiquark condensates.

The influence of dynamical mass M by considering TSP of quarks

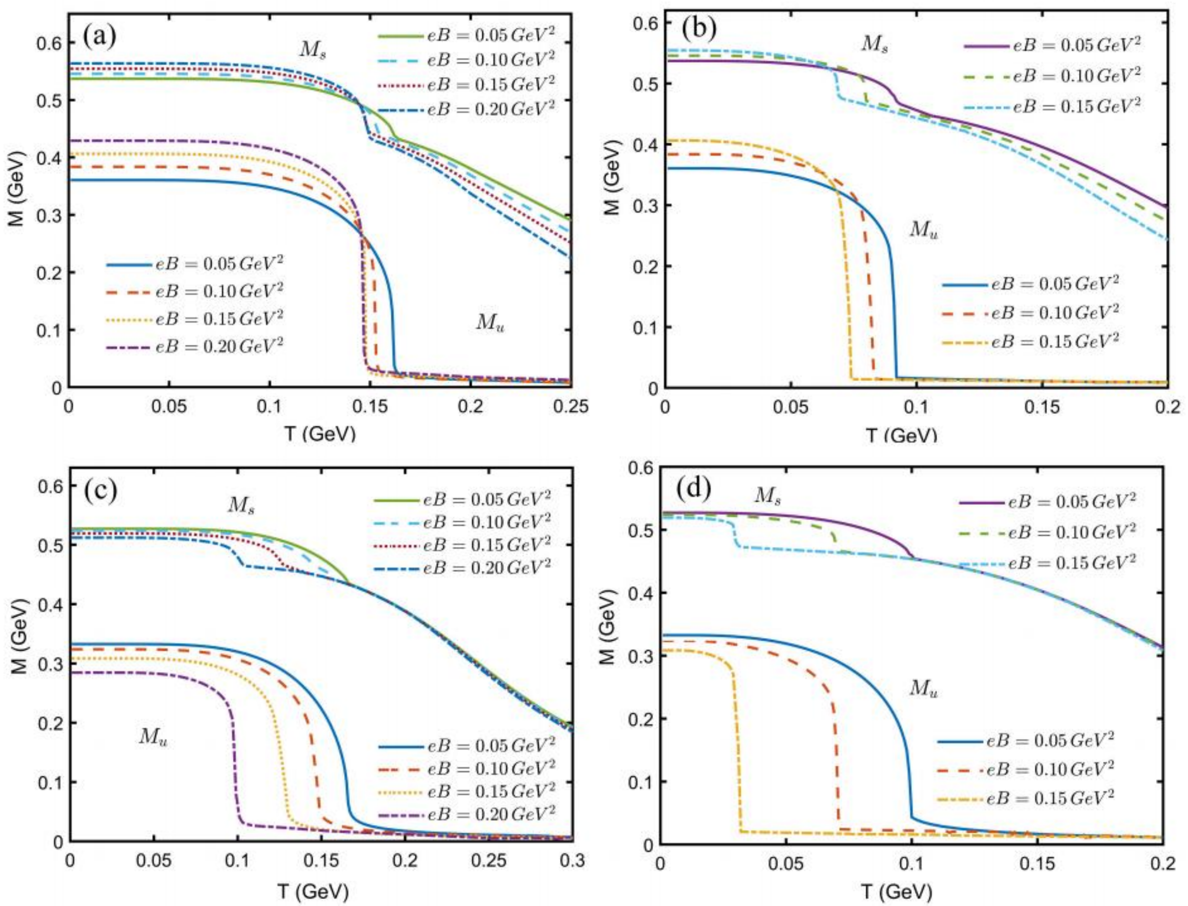


$\mu = 0$ (a) and $\mu = 0.25$ GeV (b) , respectively *by considering TSP of quarks, .*

(1) The dynamical mass M by considering TSP of quarks is manifested as a decreasing smooth function of temperatures for different magnetic fields and chemical potentials, which corresponds to a chiral crossover.

(2) Compared to not considering TSP, considering TSP results will enhance magnetic catalytic effect.

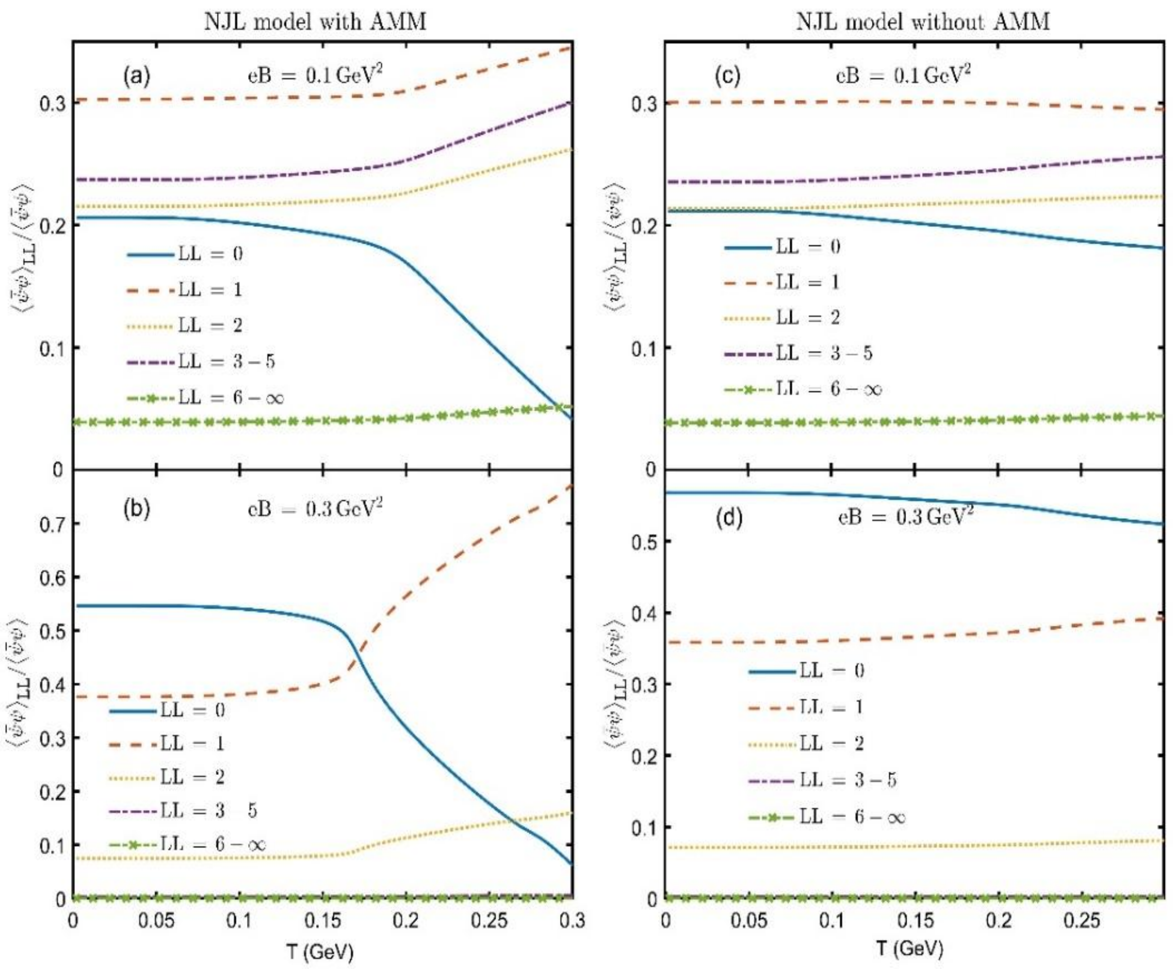
The influence of dynamical mass M by considering AMM of quarks



by considering the different sets of AMM. (a, b) are for $\mu = 0$ and $\mu = 0.25$ GeV respectively with AMM1 set as $\kappa_u = \kappa_d = 0.38$, $\kappa_s = 0.25$. (c, d) for AMM2 set as $\kappa_u = 0.123$, $\kappa_d = 0.555$, $\kappa_s = 0.329$.

The generation of dynamical quark mass from the dimensional reduction from 3 + 1 D to 1 + 1 D is predominated by LLL at the low temperature region. That effect can be reflected in AMM1 obviously. If the role of the AMM item is enough to alter the nature of the medium in the $T = 0$ like the case of AMM2, the IMC effect characteristics of the AMM2 will be more significant.

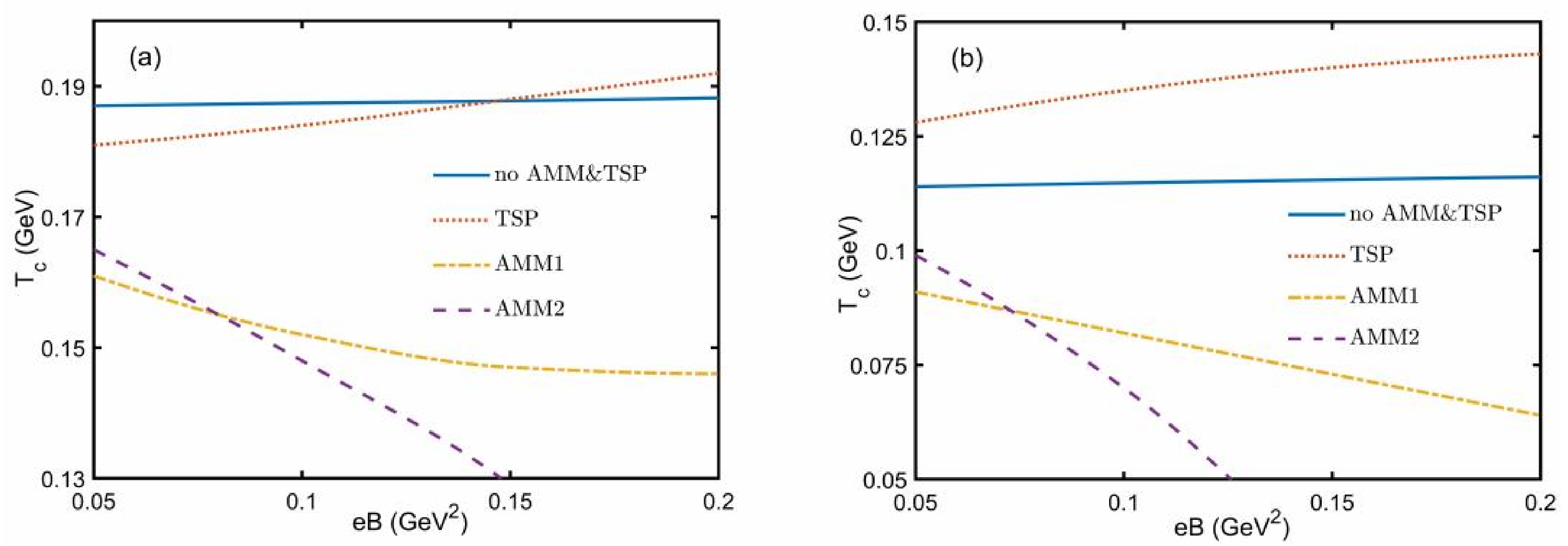
The dependent of ratio of chiral condensate on Landal Energy Levels by considering AMM of quarks



It is found that as the temperature increases, after reaching the chiral phase transition temperature, the contribution of the lowest Landau level to chiral condensation **decreases significantly by considering AMM as shown in (a, b),** while the contribution of the excited Landau level increases accordingly. Therefore, we can believe that the effect of AMM can make particles with the lowest Landau level more easily excited to higher excited energy level at high temperatures. And as the magnetic field increases, this effect becomes more pronounced. It is believed that this may be the reason for the formation of inverse magnetic catalysis (IMC) at high temperatures after the introduction of AMM.

3. The chiral phase transition with the contributions from the TSP and the AMM

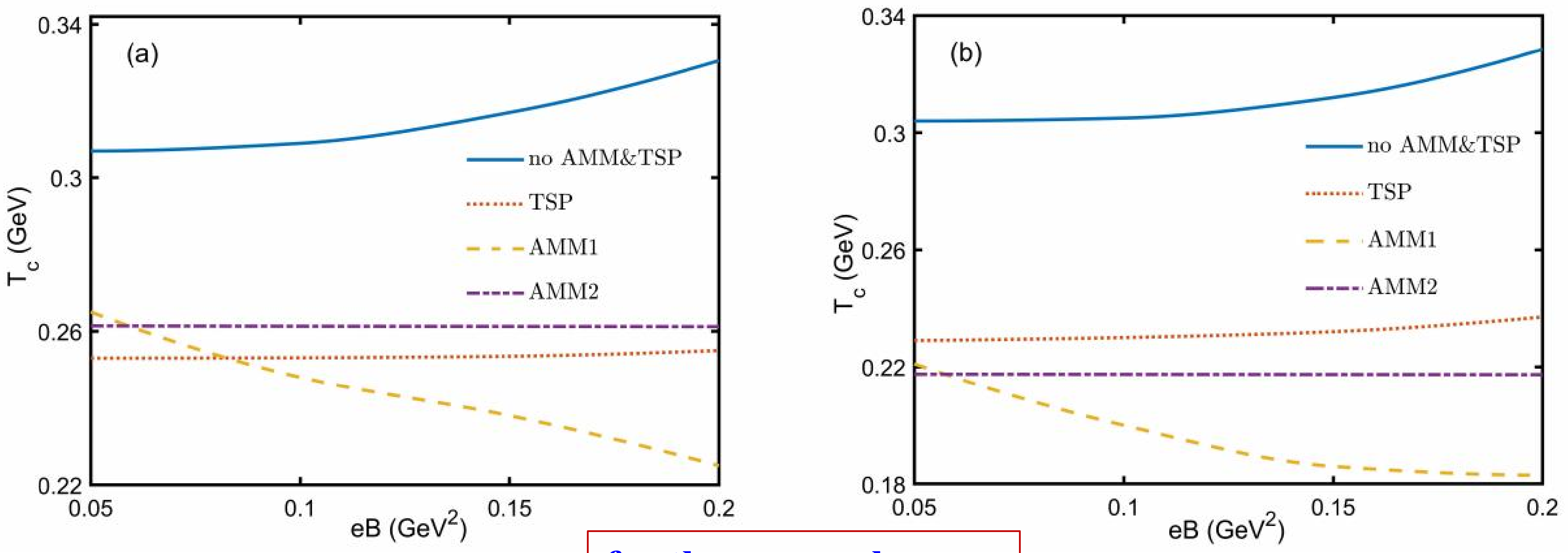
The comparison of chiral phase transition by considering the TSP and the AMM



The critical temperature of *u* and *d* quarks as a function of the magnetic field at $\mu = 0$ (a) and $\mu = 0.25$ GeV (b).

It is thus found that the critical temperature decreases with the magnetic field for the AMM1 and AMM2 sets, which indicates an inverse magnetic catalysis. On the contrary, with the TSP, T_C enhances as a function of the magnetic field, which is the extension of the magnetic catalysis effect from vacuum to finite temperature.

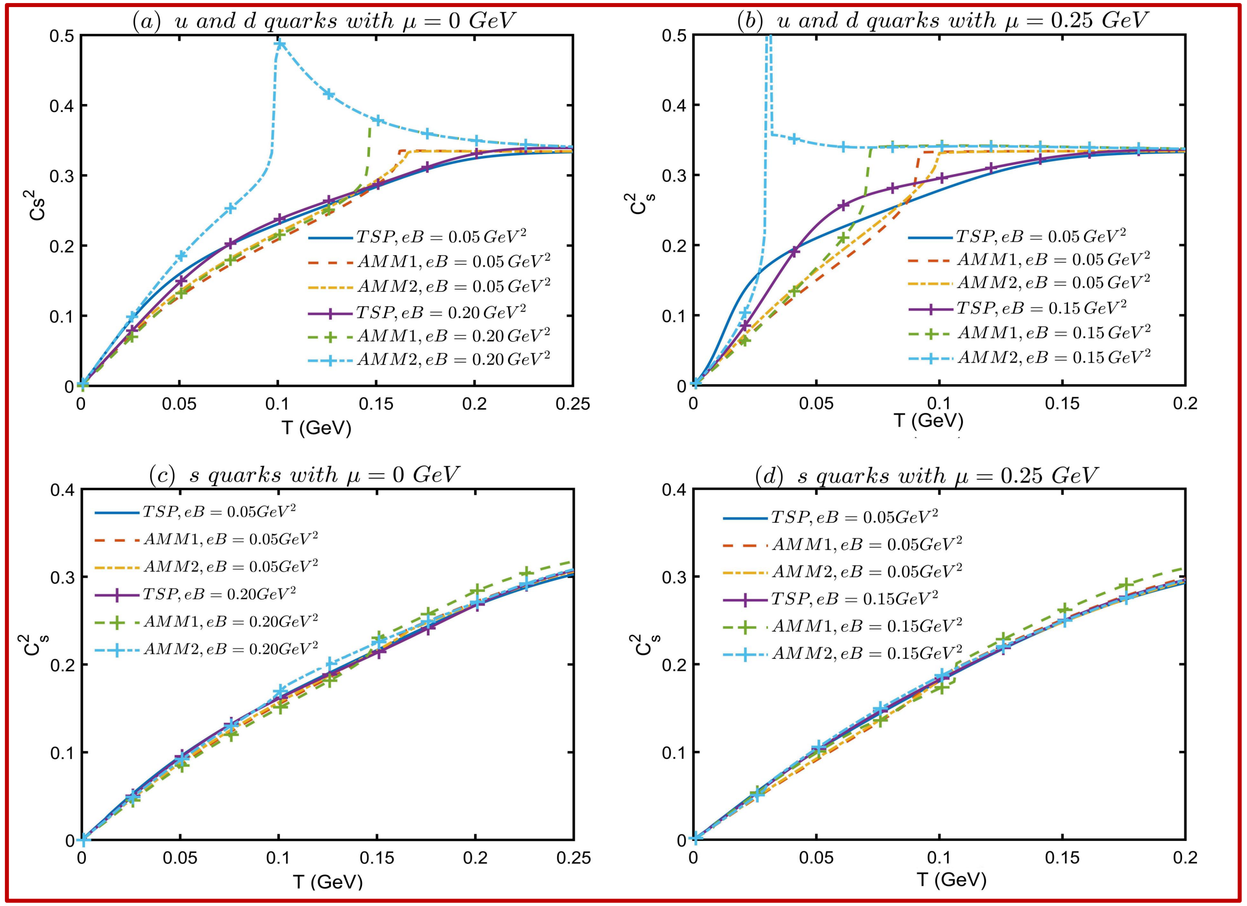
The comparison of chiral phase transition by considering the TSP and the AMM



for the s - quark.

The critical temperature of the chiral phase transition of *s* quark as a function of *eB* is manifested in the upper picture. Compared with light quarks of *u* and *d*, the phase transition temperature T_C of *s* quark with TSP increases significantly with the increase of magnetic field, which corresponds to the characteristics of magnetic catalysis. The introduction of AMM sets corresponds to inverse magnetic catalytic characteristics.

Crossover or first-order phase transition? by considering the TSP and the AMM



The sound-velocity square C_s^2 of *u* and *d* with *s* quarks as a function of the temperature T with different chemical potential. (a, b) is for *u* and *d* quarks with zero chemical potential $\mu = 0$, and $\mu = 0.25$ GeV, and (c, d) is for *s* quarks

(1) For u, d quarks, by considering AMM, the bump rises at a larger magnetic field, makes it inclines to first-order transition. The bump rises rapidly because the dynamical quark mass has a discontinuous drop at this narrow region of temperature. by considering TSP is a smooth function, crossponding to crossover phase transtion even has a larger magnetic field and chemical potential.

(2) For s quarks, by considering AMM and TSP, no bump rises are found even at a larger magnetic field, there correspond to crossover phase transition.

4. Summary and Conclusions

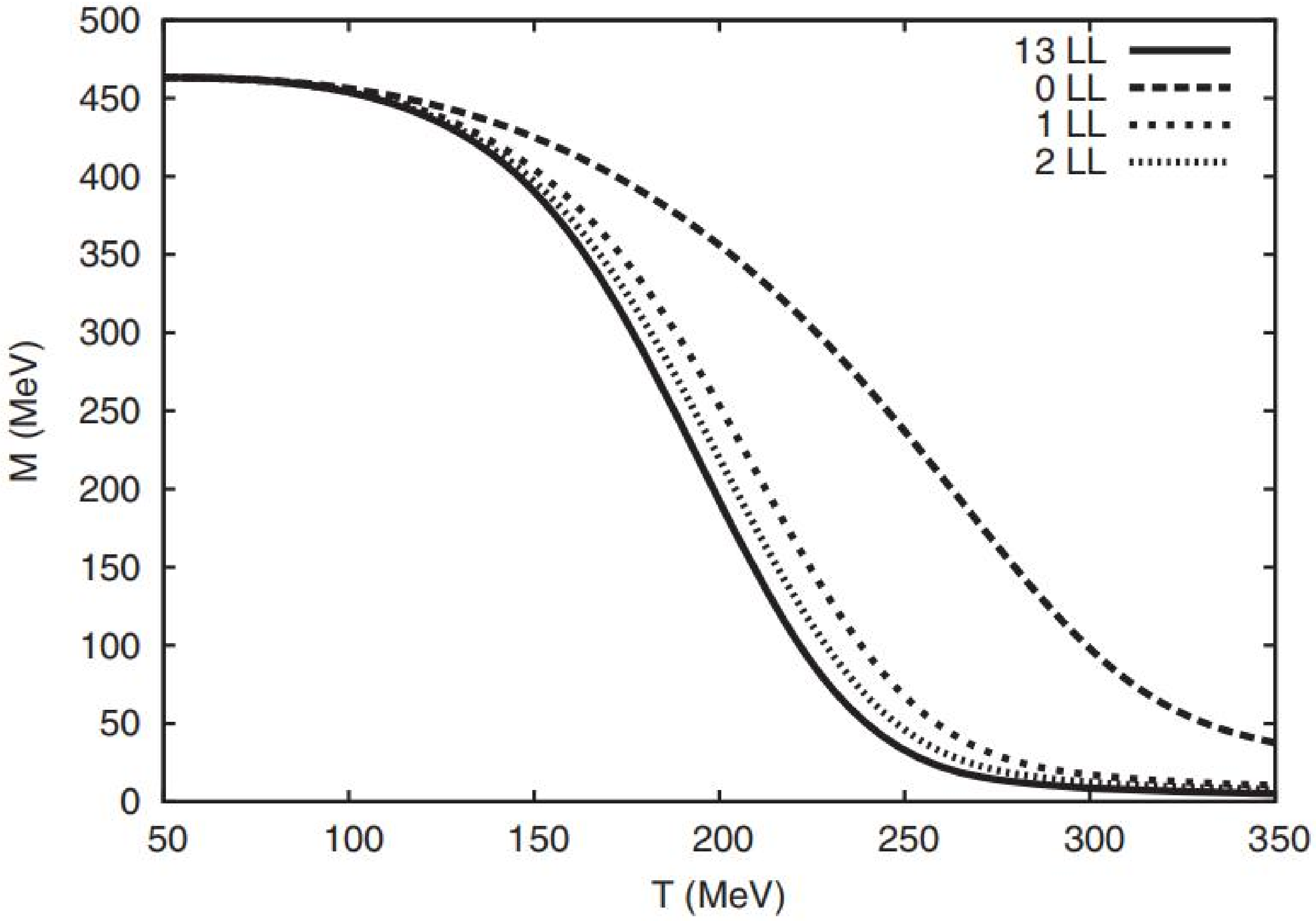
Summary and conclusions

We thoroughly study the effect from TSP and AMM on the vacuum, phase transition and thermal magnetized QCD in the (2 + 1)-flavor NJL model with nonzero current quark masses at finite temperature and chemical potential. A unified physical mechanism to illustrate the novel consequences from recent lattice QCD as magnetic catalysis and inverse magnetic catalysis effect.

1. In the TSP case, since the dynamical quark mass is increased by the spin condensate, which is generated by an extra tensor channel independently as well as enhanced by the magnetic field, the pseudocritical temperature is increased by a rising magnetic field. Quark Spin polarization is ferromagnetic, and ferromagnetic Spin polarization approaches zero at high temperature.

2. While in the AMM case, the AMM term $1/2 q_f \kappa \delta^{\mu\nu} F_{\mu\nu}$ does not directly produce a new condensate to impact the dynamical mass. Instead, it changes the energy spectrum of all Landau levels. As the result, it has been found that the AMM term will reduce the dynamical mass, once the temperature is high enough to excite much more particles to jump to higher Landau levels.

Thanks！



From Boomsma and Boer, 2010.