Deconfinement and the explicit center symmetry breaking in the strong magnetic field

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Criticality in QCD and the Hadron Resonance Gas,
29-31.07.2020

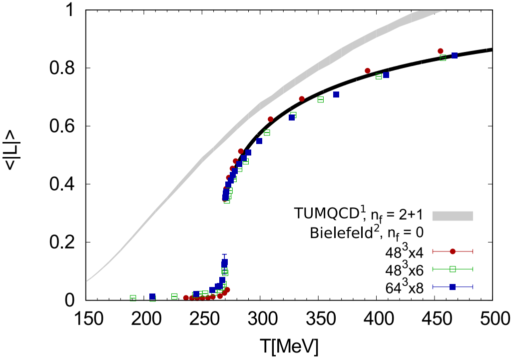
arXiv:2004.04138

Pure gauge: deconfinement → 1st order

- Spontaneous Z_3 symmetry breaking
- Order parameter → Polyakov loop

QCD:

- Z_3 symmetry → explicitly broken
- Deconfinement → crossover
- Polyakov loop → approximate order parameter



This talk:

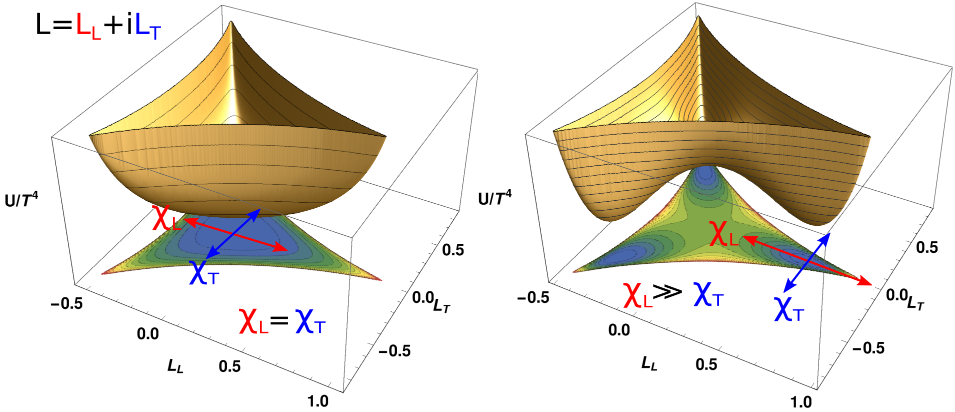
- Explicit Z_3 symmetry breaking and strong magnetic field
- Effective model
- Heavy quarks → Chiral symmetry irrelevant

[1] A. Bazavov, N. Brambilla, H.-T Ding, P. Petreczky, H. -P. Schadler, A. Vairo and J. H. Weber, Phys. Rev. D **93**, 114502 (2016).

[2] P. M. Lo, B. Friman, O. Kaczmarek, K. Redlich and C. Sasaki, Phys. Rev. D **88**, 014506 (2013)

Deconfinement & fluctuations → Polyakov loop potential[1]

$$\frac{\mathcal{U}_{PG}}{T^4} = -\frac{1}{2}a(T)L\bar{L} + b(T)\ln M_H(L,\bar{L}) + \frac{1}{2}c(T)(L^3+\bar{L}^3) + d(T)(L\bar{L})^2$$

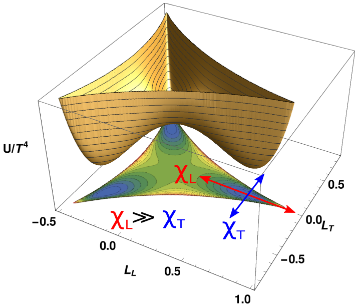


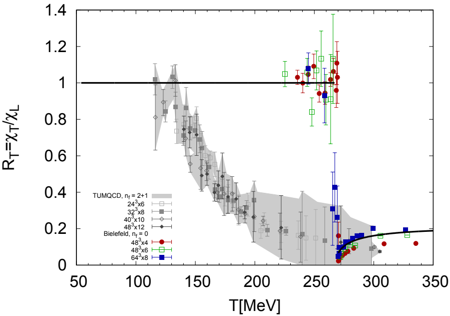
[1] P. M. Lo, B. Friman, O. Kaczmarek, K. Redlich and C. Sasaki, Phys. Rev. D **88**, 074502 (2013)

Ratio of susceptibilities → Useful probe of deconfinement[1]

$$R_T = \frac{\chi_T}{\chi_L}$$

- Sensitive to explicit center symmetry breaking strength[2]



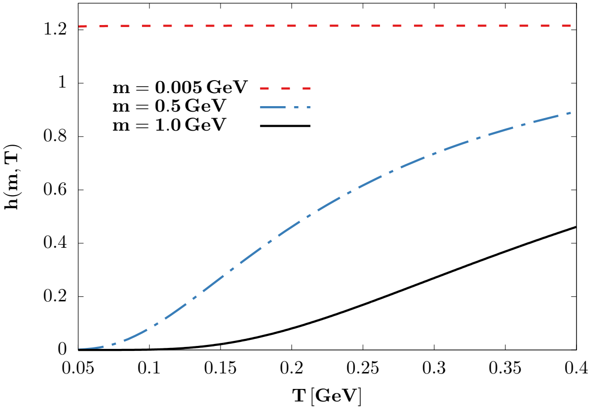


[1] *P. M. Lo, B. Friman, O. Kaczmarek, K. Redlich and C. Sasaki, Phys. Rev. D* **88**, *014506 (2013)*

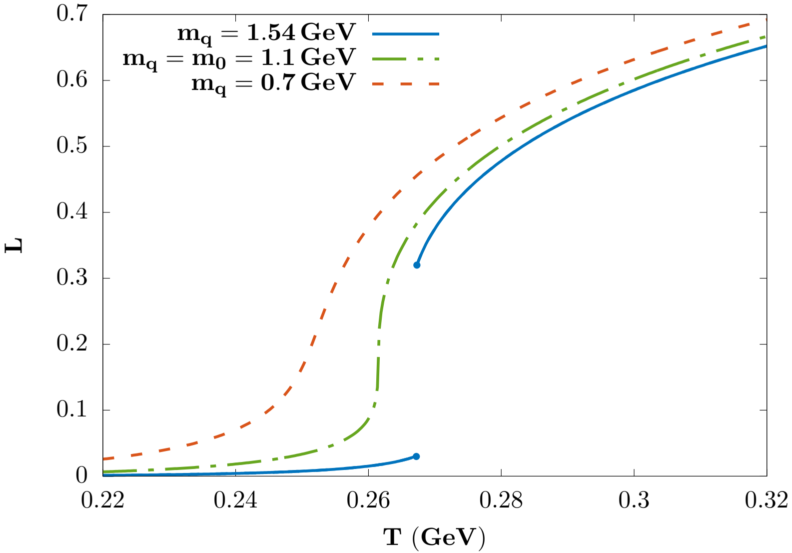
[2] *P. M. Lo, M. Szymański, K. Redlich and C. Sasaki, Phys. Rev. D* **97**, *114006 (2018)*

Dynamical quarks $\longrightarrow$ Explicit center symmetry breaking

- Heavy quarks $\rightarrow$ linear breaking, $\mathcal{U}_q = -hL_L$[1]
- 1-loop ($B = 0,\ m/T \gg 1$): $h(T,m) = \frac{6}{\pi^2}\left(\frac{m}{T}\right)^2 K_2\left(m/T\right)$



[1] F. Green, F. Karsch, Nucl. Phys. B238 (1984) 297



$m_q = 1.54\,GeV$
$m_q = m_0 = 1.1\,GeV$
$m_q = 0.7\,GeV$
L
T (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.22
0.24
0.26
0.28
0.3
0.32

External magnetic field $\rightarrow$ Landau quantization

$$2\int \frac{d^3p}{(2\pi)^3} \rightarrow \frac{|qB|}{2\pi} \sum_{\sigma=\pm1} \sum_{k=0}^{\infty} \int_{-\infty}^{\infty} \frac{dp_z}{2\pi}$$

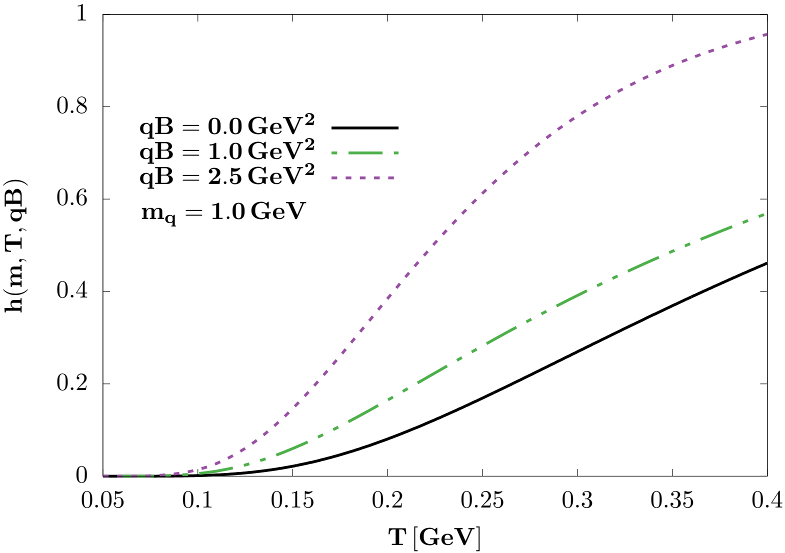
$$E_{k,\sigma}^{\,2} = m^2 + p_z^2 + (2k+1-\sigma)|q_f B| \,,$$

External breaking field for $eB \neq 0$

$$h^B(m, T, qB) = \frac{3|qB|}{\pi^2 T^3} \sum_{\sigma=\pm1} \sum_{k=0}^{\infty} M_{k,\sigma} K_1 \left(M_{k,\sigma}/T\right) \,,$$

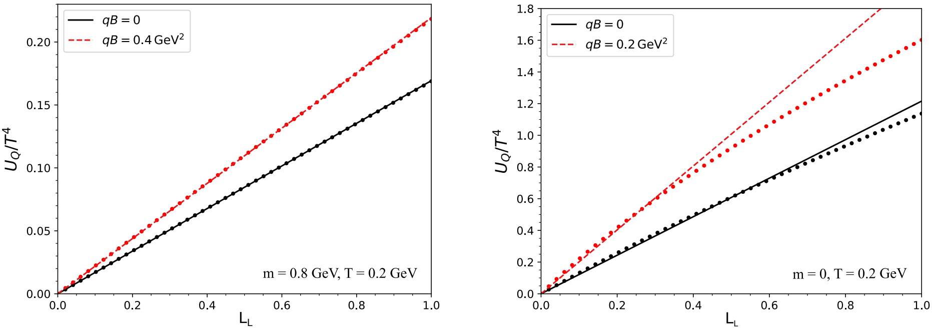
where

$$M_{k,\sigma} = \sqrt{m^2 + (2k+1-\sigma)|qB|}.$$



$\mathbf{qB = 0.0\,GeV^2}$
$\mathbf{qB = 1.0\,GeV^2}$
$\mathbf{qB = 2.5\,GeV^2}$
$\mathbf{m_q = 1.0\,GeV}$
$\mathbf{h(m, T, qB)}$
$\mathbf{T\,[GeV]}$
0
0.2
0.4
0.6
0.8
1
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

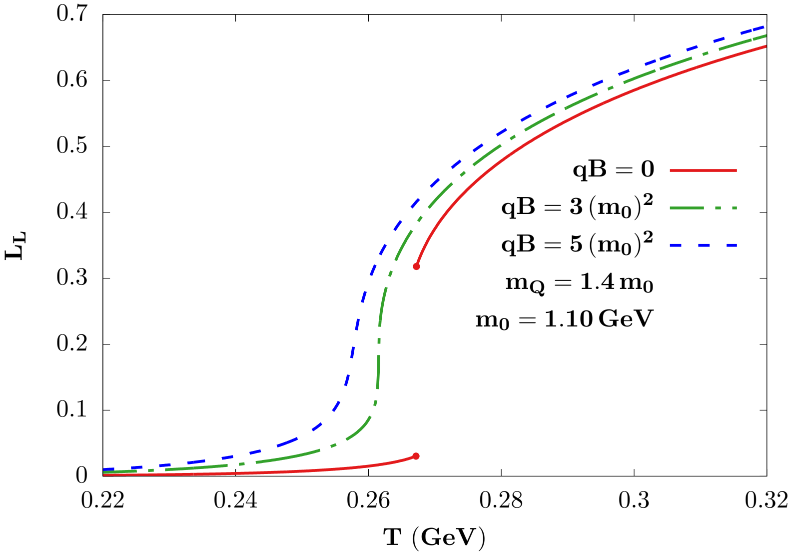
Linear potential vs. full 1-loop potential



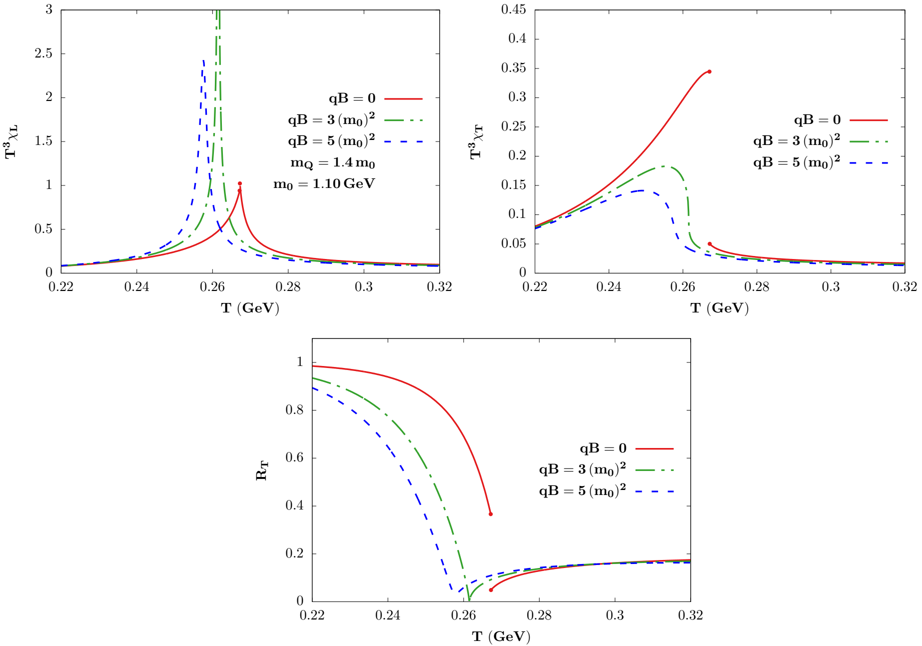
$$\mathcal{U}_Q^{Full} = -T \sum\!\!\!\!\!\!\int \left[\ln(1 + 3Le^{-\beta E} + 3\bar{L}e^{-2\beta E} + e^{-3\beta E}) + c.c\right]$$

$$\approx \mathcal{U}_0 - hL_L$$

Works well even for $m = 0$!



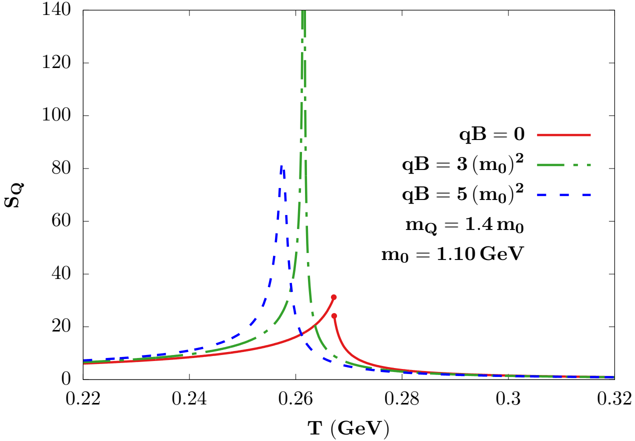
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.22
0.24
0.26
0.28
0.3
0.32
L_L
T (GeV)
qB = 0
qB = 3 $(m_0)^2$
qB = 5 $(m_0)^2$
$m_Q = 1.4\, m_0$
$m_0 = 1.10$ GeV

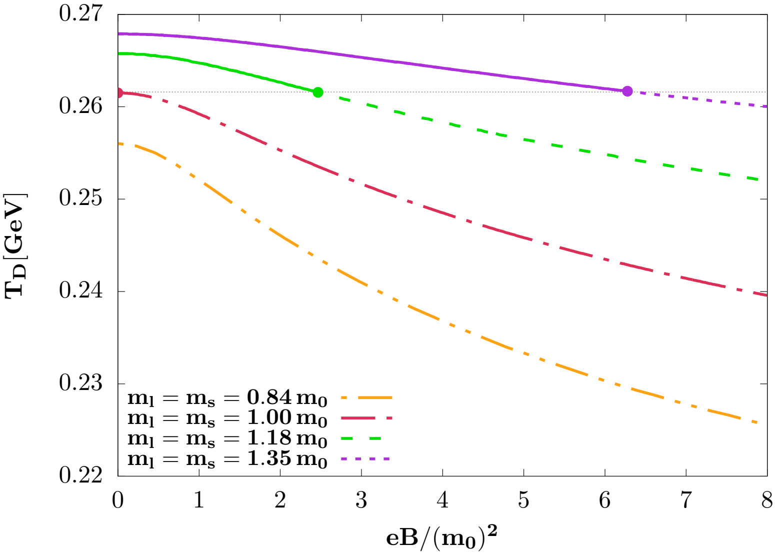


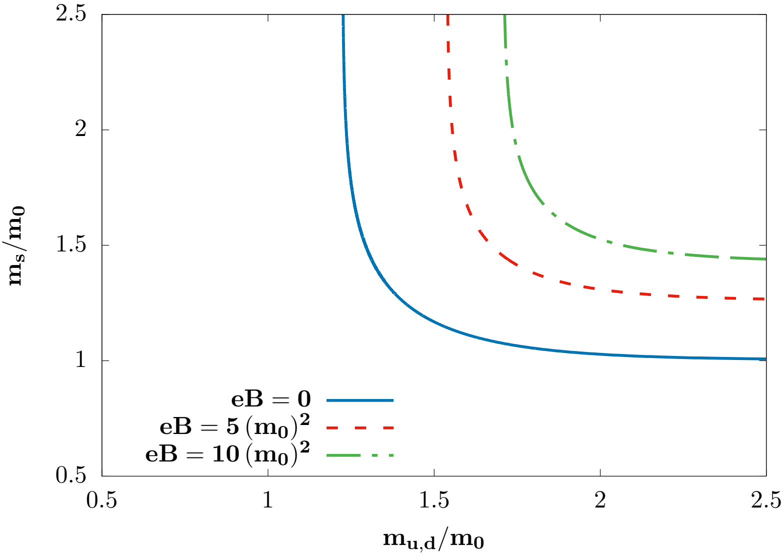
$T^3\chi_L$
T (GeV)
qB = 0
qB = 3 (m0)^2
qB = 5 (m0)^2
mQ = 1.4 m0
m0 = 1.10 GeV
$T^3\chi_T$
T (GeV)
qB = 0
qB = 3 (m0)^2
qB = 5 (m0)^2
R_T
T (GeV)
qB = 0
qB = 3 (m0)^2
qB = 5 (m0)^2

Static quark free energy and entropy

$$F_q = -T\ln(L) \qquad S_q = -\frac{\partial F_q}{\partial T}$$




0.27
0.26
0.25
0.24
0.23
0.22
T_D[GeV]
0
1
2
3
4
5
6
7
8
$eB/(m_0)^2$
$m_l = m_s = 0.84\, m_0$
$m_l = m_s = 1.00\, m_0$
$m_l = m_s = 1.18\, m_0$
$m_l = m_s = 1.35\, m_0$



2.5
2
1.5
1
0.5
0.5
1
1.5
2
2.5
m_s/m_0
$m_{u,d}/m_0$
$eB = 0$
$eB = 5\,(m_0)^2$
$eB = 10\,(m_0)^2$

Light quarks $\rightarrow$ Chiral symmetry relevant!

- Magnetic catalysis
- Inverse magnetic catalysis

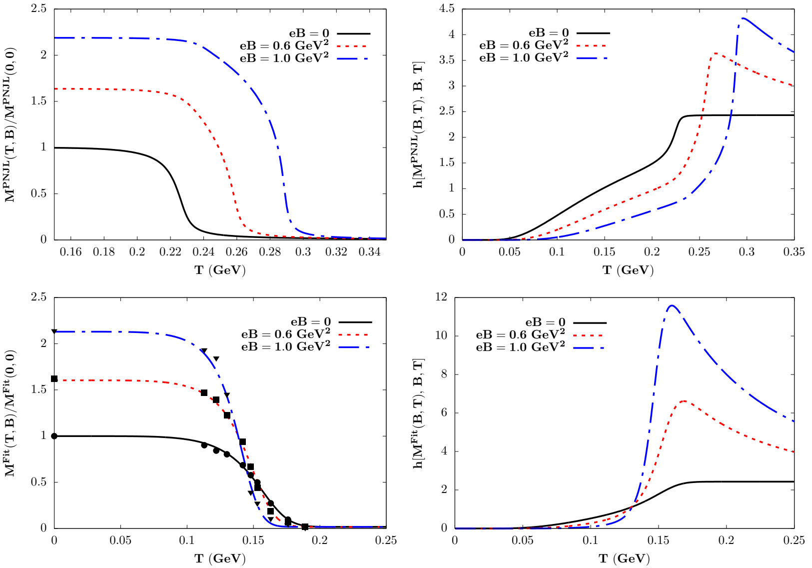
Tension between LQCD and naive PNJL models

- PNJL: $T_D(B)$ increases
- LQCD: $T_D(B)$ decreases

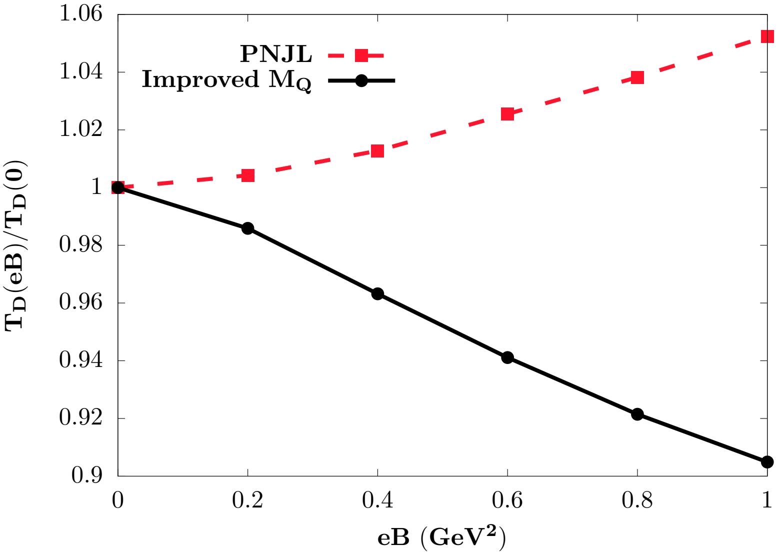
Can be understood by considering

$$h[M(T, B), T, B]$$

for PNJL and LQCD



[1] LQCD data on condensate: G. S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. D. Katz and A. Schafer, Phys. Rev. D **86**, 071502 (2012).


PNJL
Improved M_Q
$T_D(eB)/T_D(0)$
eB (GeV^2)
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
0.2
0.4
0.6
0.8
1

Conclusions

We studied impact of the strong magnetic field on deconfinement in the heavy quark approximation

- Magnetic field enhances the center symmetry breaking
- Polyakov loop and its fluctuations are sensitive to eB
- Deconfinement temperature decreases and first-order region shrinks with the magnetic field

Light-quark QCD

- Chiral dynamics important $\rightarrow$ magnetic catalysis, inverse catalysis
  - Tension between LQCD and models
- Non-trivial interplay between chiral dynamics and deconfinement
  - Can be explored in our framework

We employ the following parametrization for M_Q:

$$M_Q = m_0 - 2G\langle\bar{\psi}\psi\rangle_0\mathcal{F}(T,B)$$

with

- $m_0 = 5\,\mathrm{MeV}$
- $\langle\bar{\psi}\psi\rangle_0 = -2 \times (211\ MeV)^3$
- $G\Lambda^2 = 2.435$, $\Lambda = 515.07\,\mathrm{MeV}$
- $\mathcal{F}(T,B)$ – quark mass profile

$$\mathcal{F}(T,B) = \langle\bar{\psi}\psi\rangle(T,B)/\langle\bar{\psi}\psi\rangle_0$$

$\mathcal{F}(T,B) \rightarrow$ Quark mass profile

$$\mathcal{F}(T,B) = \mathcal{F}_0(B)/\mathcal{F}_1(T,B)$$

$$\mathcal{F}_0(B) = 1 + \frac{1}{2}\sum_{f=u,d} a_1(\sqrt{1 + a_2(q_f B)^2} - 1$$

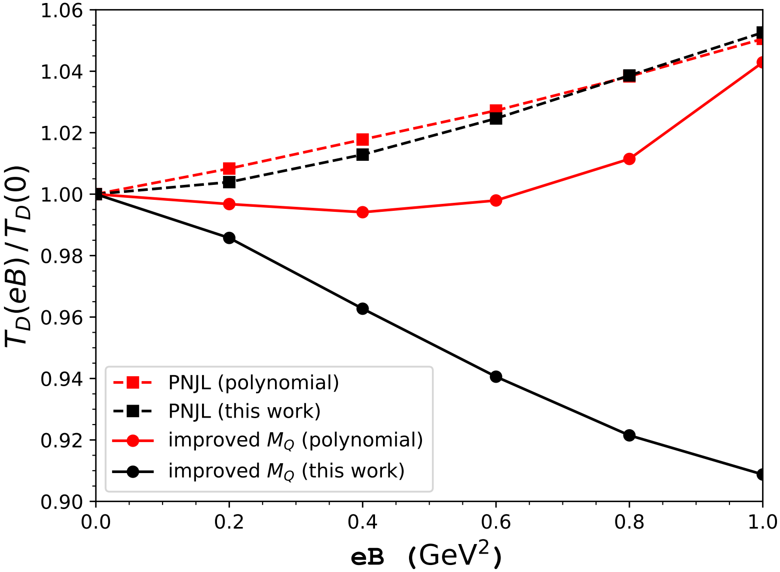
$$\mathcal{F}_1(T,B) = \frac{\alpha(B) + e^{2(T/T_\chi(B))^6}}{1 + \alpha(B)}$$

with

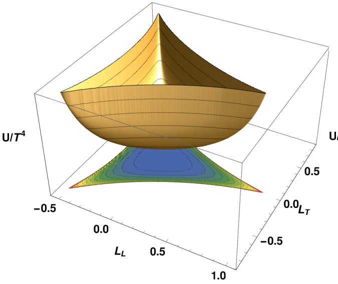
$$a_1 = 0.257,\ a_2 = 115.5$$

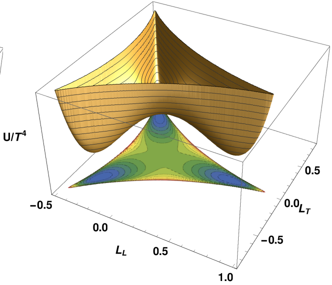
$$\alpha(B) = 2.47 + 4(eB)^2$$

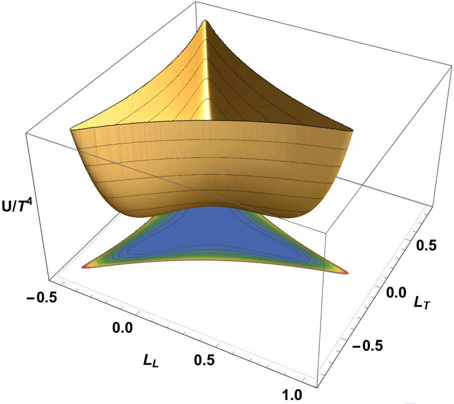
$$T_\chi(B) = 0.159 - \frac{0.0326(eB)^2}{1 + 0.4(eB)^6}$$



1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.0
0.2
0.4
0.6
0.8
1.0
$T_D(eB)/T_D(0)$
eB (GeV^2)
PNJL (polynomial)
PNJL (this work)
improved M_Q (polynomial)
improved M_Q (this work)


U/T^4
−0.5
0.0
L_L
0.5
1.0
0.5
0.0
L_T
−0.5


U/T^4
−0.5
0.0
L_L
0.5
1.0
0.5
0.0
L_T
−0.5


U/T^4
−0.5
0.0
L_L
0.5
1.0
0.5
0.0
L_T
−0.5