Possible formation of high temperature superconductor at early stage of heavy-ion collisions

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Outline

- **Introduction & Motivation**
- **Charge ρ condensation with MC**
  - **NJL model and Formalism**
  - **Numerical Results and Discussion**
- **Charged ρ condensation with IMC**
  - **Three different approaches to introduce IMC**
  - **Numerical results and Discussion**
- **Summary**

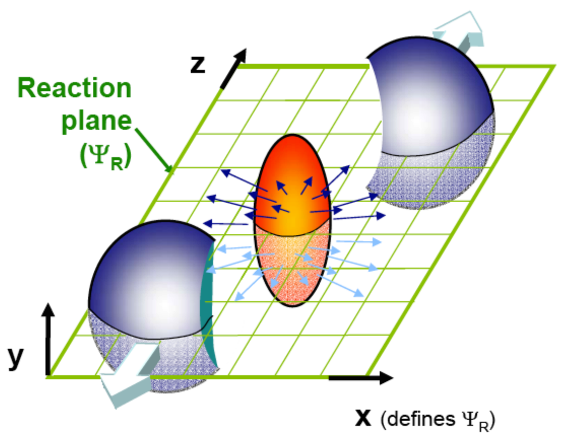
Strong Magnetic Fields in QCD

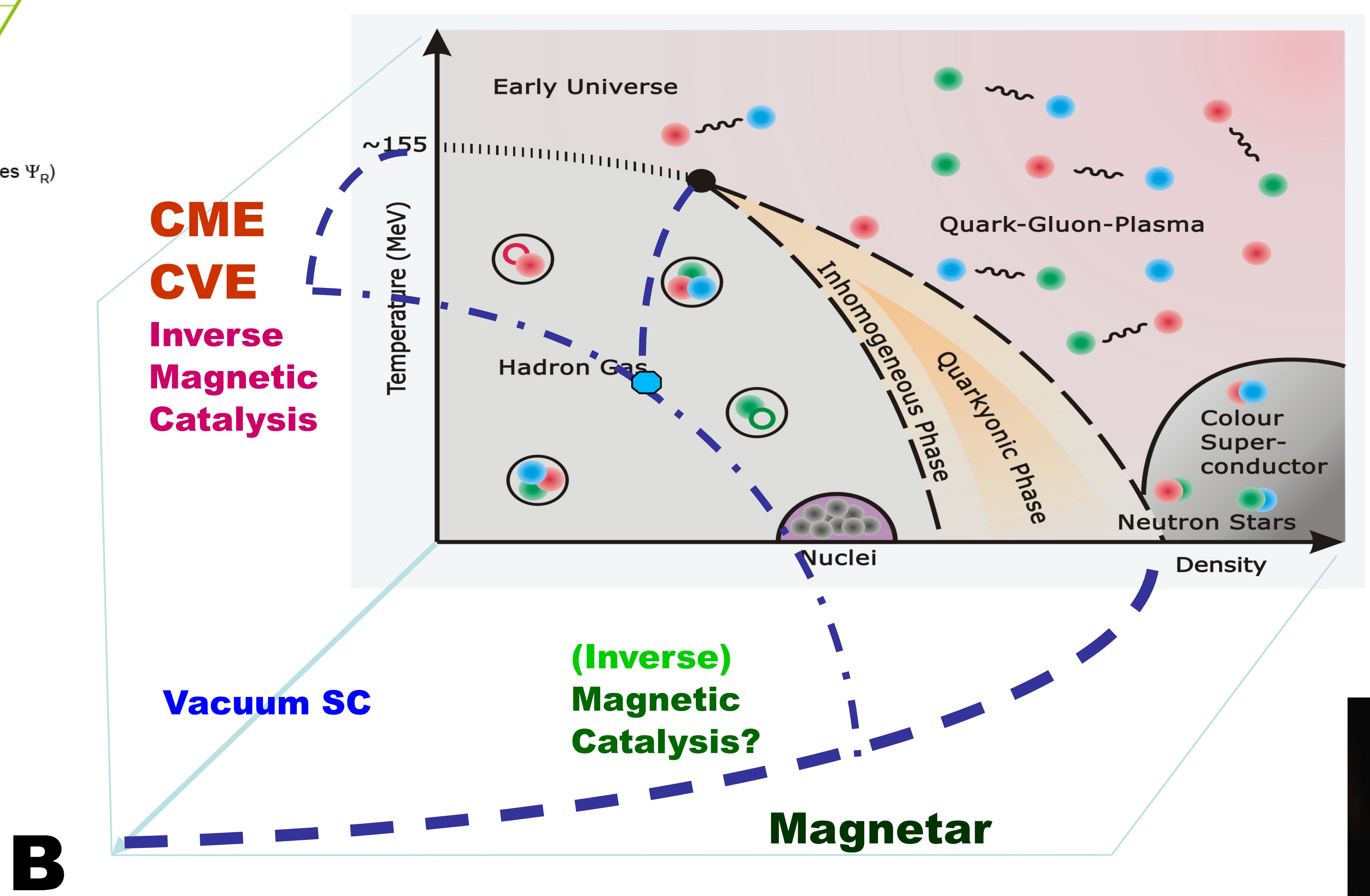
- **Early Universe: up to** 10^{24} Gauss

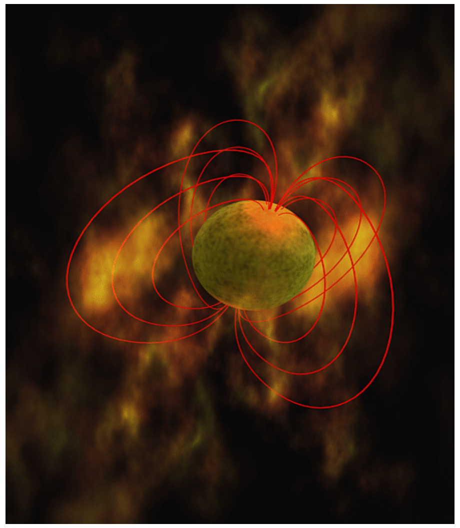
- **Magnetars: about** 10^{14} Gauss

- **Heavy ion collisions:** 10^{18} to 10^{20} Gauss

QCD Phase Diagram under Strong Magnetic Field







Vacuum Superconductor

M. N. Chernodub, Phys. Rev. Lett. 106 (2011) 142003 [arXiv:1101.0117 [hep-ph]]

-Energy of relativistic particle in the external magnetic field B:

$$E^2_{n,s_z}(p_z) = p_z^2 + (2n - 2sgn(q)s_z + 1)eB + m^2$$

p_z: the momentum along the external magnetic field

n: nonnegative integer number

s_z: projection of spin on the direction of magnetic field

-Masses of ρ mesons and π in magnetic field:

$$\mathrm{m}^2_{\pi^\pm}(\mathrm{B}) = \mathrm{m}^2_{\pi^\pm} + \mathrm{eB}$$ **becomes larger**

$$\mathrm{m}^2_{\rho^\pm}(\mathrm{B}) = \mathrm{m}^2_{\rho^\pm} - \mathrm{eB}$$ **becomes lighter**

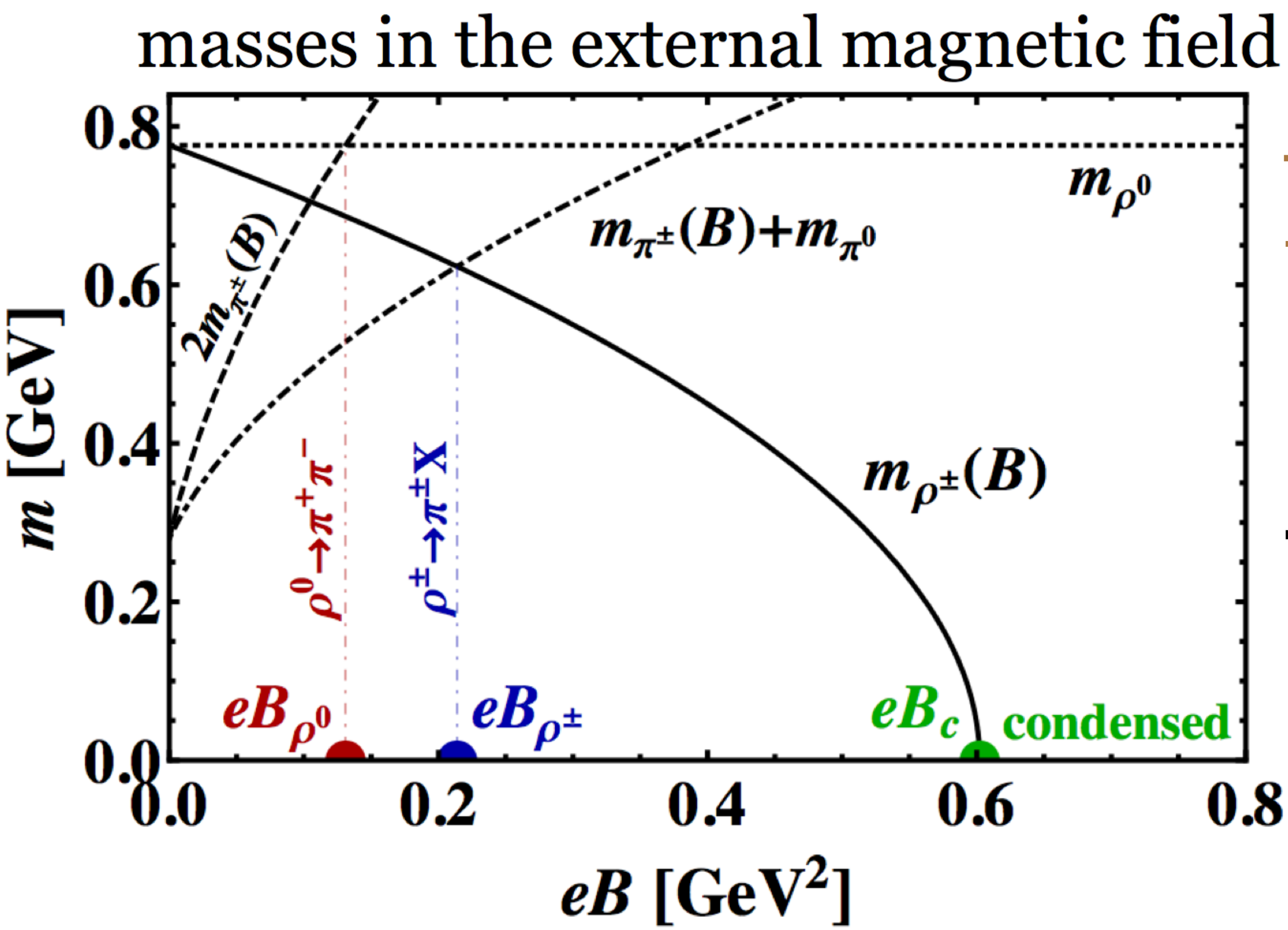
where

$\mathrm{m}_{\rho_\pm} = 768\mathrm{MeV}$, $\mathrm{m}_{\pi_\pm} = 140\ \mathrm{MeV}$

Vacuum Superconductor

The charged rho becomes massless and condensates at a critical magnetic field : $\mathrm{eB}_c = \mathrm{m}^2_{\rho^\pm}$

M. N. Chernodub, Phys. Rev. Lett. 106 (2011) 142003 [arXiv:1101.0117 [hep-ph]]



The pions become heavier while the charged vector mesons become lighter in the external magnetic field.

The $\rho^\pm \to \pi^\pm \pi^0$ decay stops at a critical eB.

Vacuum Superconductor?

- **A point particle model for the charged rho :**

$$\mathrm{eB}_c = \mathrm{m}^2_{\rho^\pm}$$

- **NJL Model (LLL):** $\mathrm{eB}_c > 1\ \mathrm{GeV}^2$

M. N. Chernodub, Phys. Rev. Lett. 106 (2011) 142003 [arXiv:1101.0117 [hep-ph]]

- **NJL Model:** $\mathrm{eB}_c = 0.978\ m_q^2$

M. Frasca, JHEP 1311, 099 (2013) [arXiv:1309.3966 [hep-ph]]

- **Holographic approach:** $eB_c \approx 1.08 m^2_\rho (B = 0)$

N. Callebaut, D. Dudal and H. Verschelde, PoS FACESQCD , 046 (2010) [arXiv:1102.3103 [hep-ph]]

Vacuum Superconductor?

- DSE and BSE:

  Kunlun Wang PhD thesis

- Quark-antiquark Green Function and effective Hamiltonian (LLL)

  M. A. Andreichikov, B. O. Kerbikov, V. D. Orlovsky and Y. . A. Simonov, Phys. Rev. D 87, no. 9, 094029 (2013) [arXiv:1304.2533 [hep-ph]]

- NJL model and the Roy equation formalism of π-π scattering

  R. Zhang, W. j. Fu and Y. x. Liu, Eur. Phys. J. C 76, no. 6, 307 (2016) [arXiv:1604.08888 [hep-ph]]

Our work

H. Liu, L. Yu and M. Huang, Phys. Rev. D 91 (2015) 1, 014017 [arXiv:1408.1318 [hep-ph]]

- We explore the character of rho meson in magnetic field in NJL Model

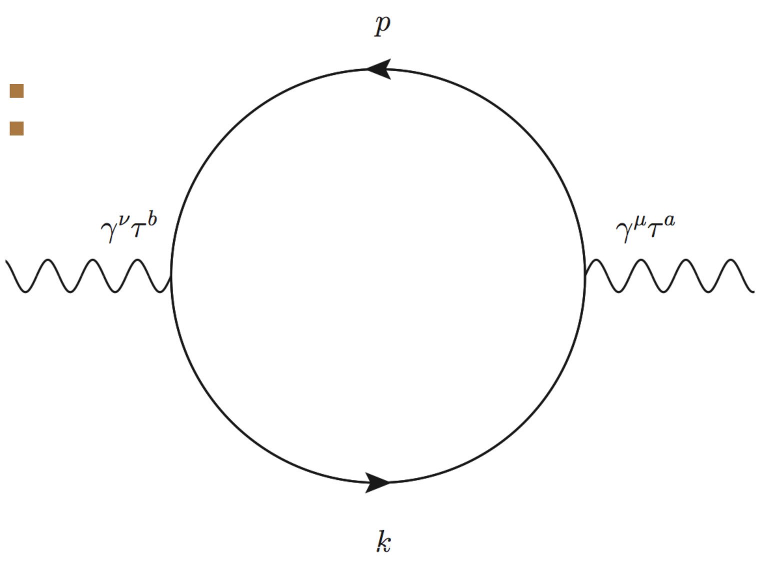
NJL Model and Analysis Result

$$\mathcal{L} = \bar{\Psi}(i \not{D} - m_0)\Psi + G_1 \left[(\bar{\Psi}\Psi)^2 + (\bar{\Psi} i\gamma^5 \tau \Psi)^2 \right]$$

$$-G_2 \left[(\bar{\Psi}\gamma^\mu \tau \Psi)^2 + (\bar{\Psi}\gamma^\mu \gamma^5 \Psi)^2 \right]$$

$\sigma = -2G_1 < \bar{\Psi}\Psi >$ **and** $M = m_0 + \sigma$

One quark-loop polarization function:



$$\Pi^{\mu\nu,ab}(x,x') = -iTr[\gamma^\mu \tau^a S_Q(x,x')\gamma^\nu \tau^b S_Q(x',x)]$$

NJL Model and Analysis Result

-In the rest frame of charged ρ meson:

$$\Pi^{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Pi^{11} & \Pi^{12} & 0 \\ 0 & \Pi^{21} & \Pi^{22} & 0 \\ 0 & 0 & 0 & \Pi^{33} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & ib & 0 \\ 0 & -ib & a & 0 \\ 0 & 0 & 0 & c \end{pmatrix}$$

-In the rest frame of neutral ρ meson:

$$\Pi^{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Pi^{11} & 0 & 0 \\ 0 & 0 & \Pi^{22} & 0 \\ 0 & 0 & 0 & \Pi^{33} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & d & 0 \\ 0 & 0 & 0 & e \end{pmatrix}$$

NJL Model and Analysis Result

$$\Pi_{ab}^{\mu\nu} = \left[\Pi_1 P_{-}^{\mu\nu} + \Pi_2 P_{+}^{\mu\nu} + \Pi_3 L^{\mu\nu} + \Pi_4 u^\mu u^\nu\right] \delta_{ab}$$

$$P_{+}^{\mu\nu} = -\epsilon_1^{\mu *}\epsilon_1^{\nu}, P_{-}^{\mu\nu} = -\epsilon_2^{\mu *}\epsilon_2^{\nu}, L^{\mu\nu} = -b^\mu b^\nu$$

$$b^\mu = (0,0,0,1), u^\mu = (1,0,0,0)$$

with $\epsilon_1^\mu, \epsilon_2^\mu$ are right-and left-handed helicities.

Π_1 **: the projection of spin is -1**

Π_2 **: the projection of spin is 1**

Π_3 **: the projection of spin is 0**

The Gap equation for vector meson: $1 + 2\mathrm{G}_2\Pi_i = 0$

NJL Model and Analysis Result

-For charged rho :

- **Condensation:** $1 + 2G_2\Pi_2 = 0$, $\quad 1 + 2G_2\Pi_1 = 0$

where $\Pi_1 = -(a+b), \Pi_2 = b - a$

Mass square of ρ^+ decrease with eB

Mass square of ρ^- decrease with eB

-For neutral rho :

$$\Pi_1 = \Pi_2 = -d, \Pi_3 = -e$$

Parameters

$$f_\pi = 95MeV, m_\pi = 140MeV, M_\rho = 768MeV$$

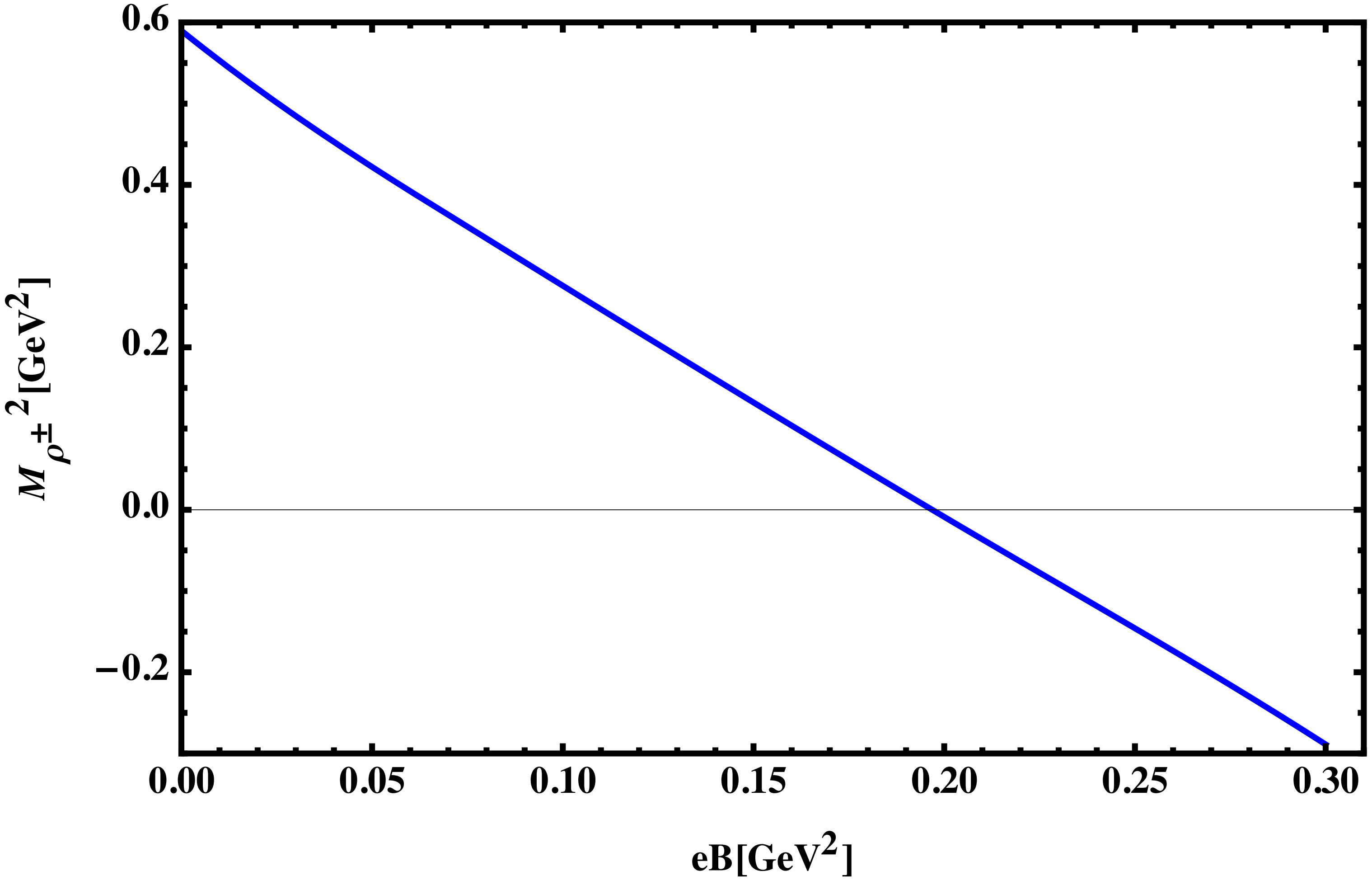
$$m = 458MeV, m_0 = 5MeV$$

Soft cut off

$$\Lambda = 582MeV, G_1\Lambda^2 = 2.388, G_2\Lambda^2 = 1.73$$

Vacuum Superconductor

H. Liu, L. Yu and M. Huang, Phys. Rev. D 91 (2015) 1, 014017 [arXiv:1408.1318 [hep-ph]]

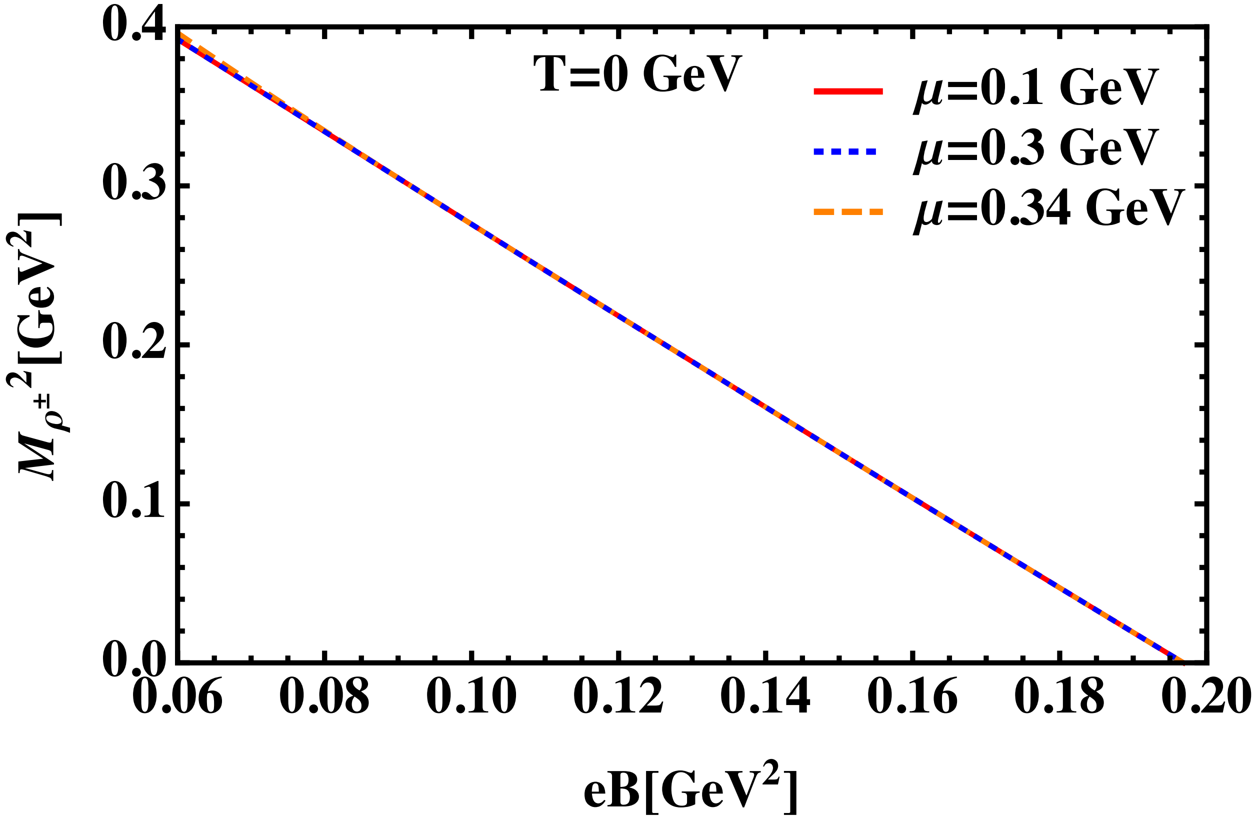


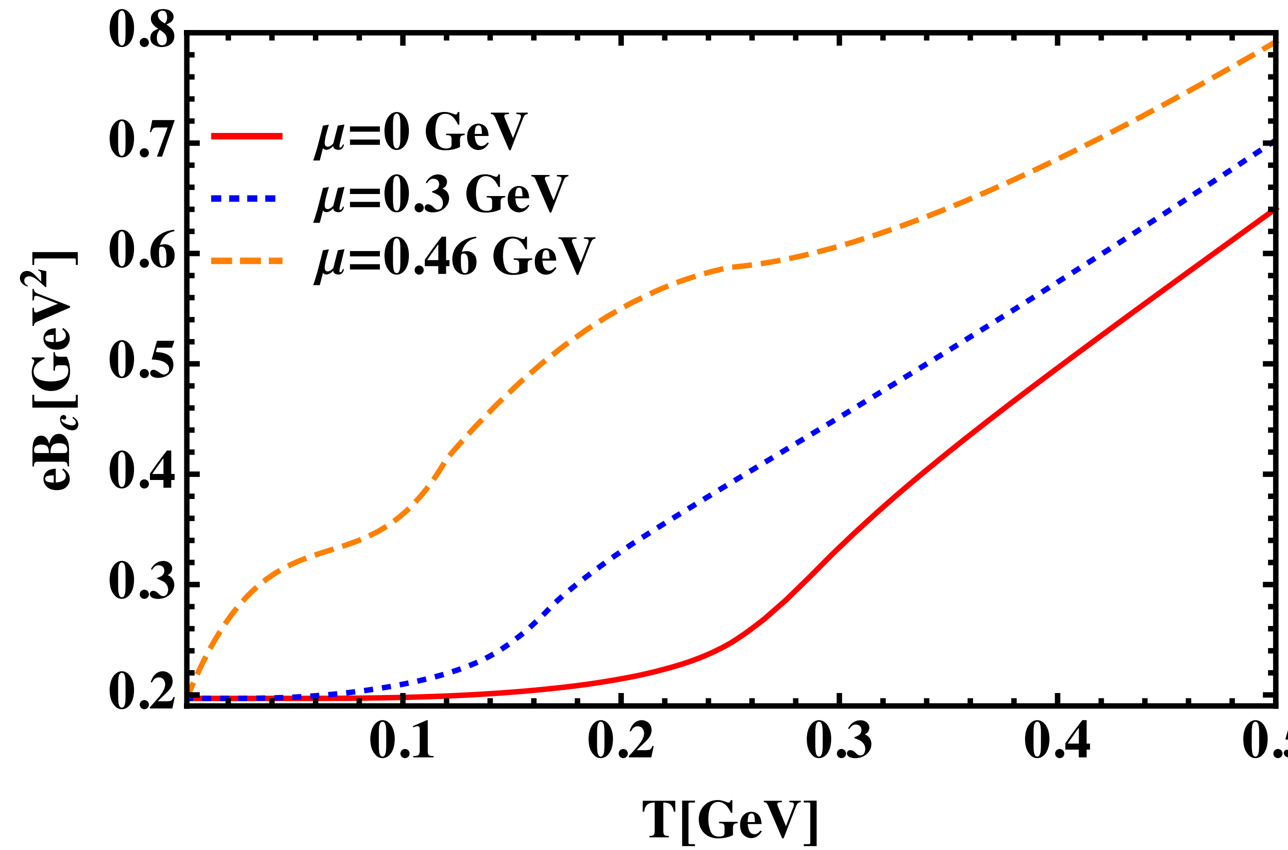
The masses of $\rho^\pm$ decrease and become massless at $\mathrm{eB}_c \approx 0.2\ \mathrm{GeV}^2$!

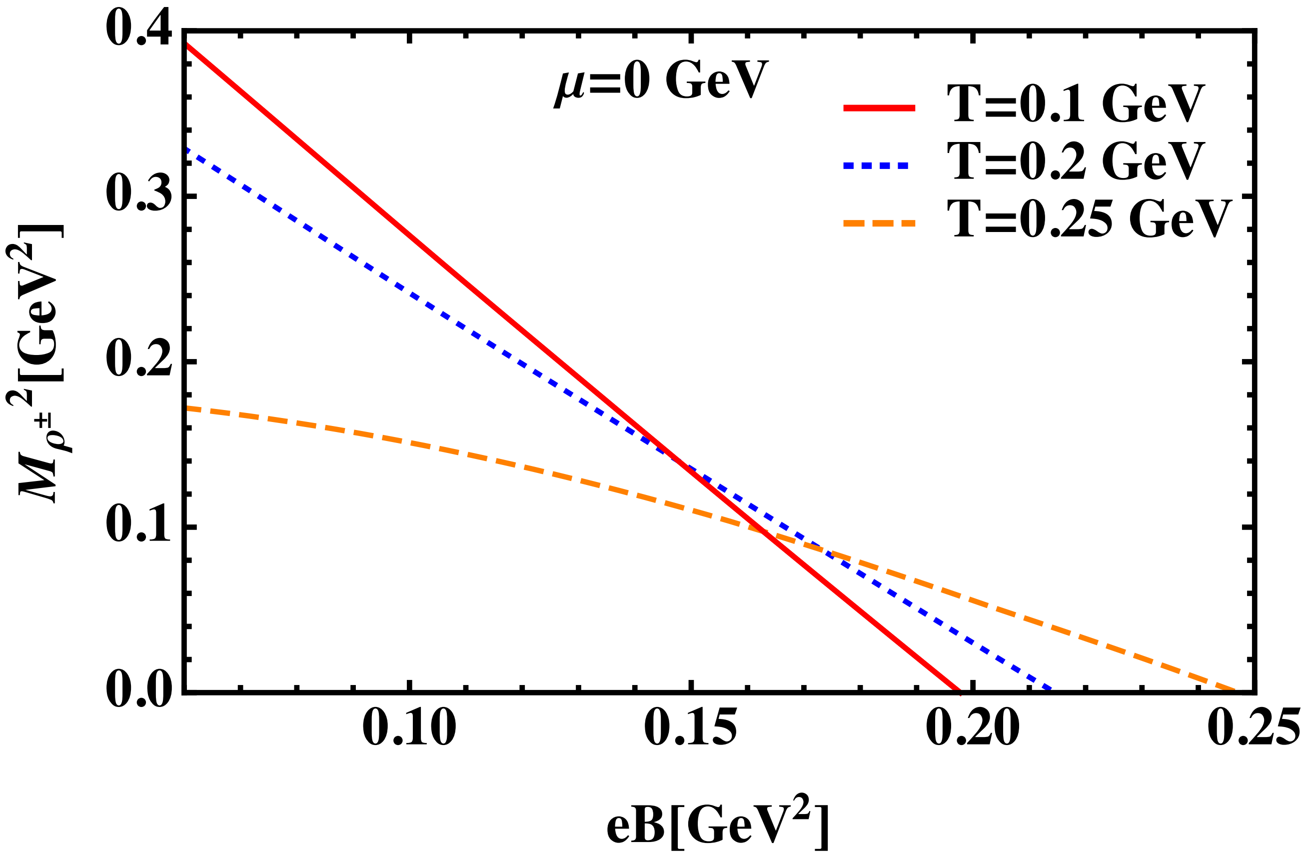
Nonzero temperature and nonzero density

H. Liu, L. Yu and M. Huang, Chin. Phys. C 40, no. 2, 023102 (2016) [arXiv:1507.05809 [hep-ph]]

Numerical Results and Discussion







Both temperature and chemical potential suppress ρ condensation.

ρ condensation can survive at very high temperature!

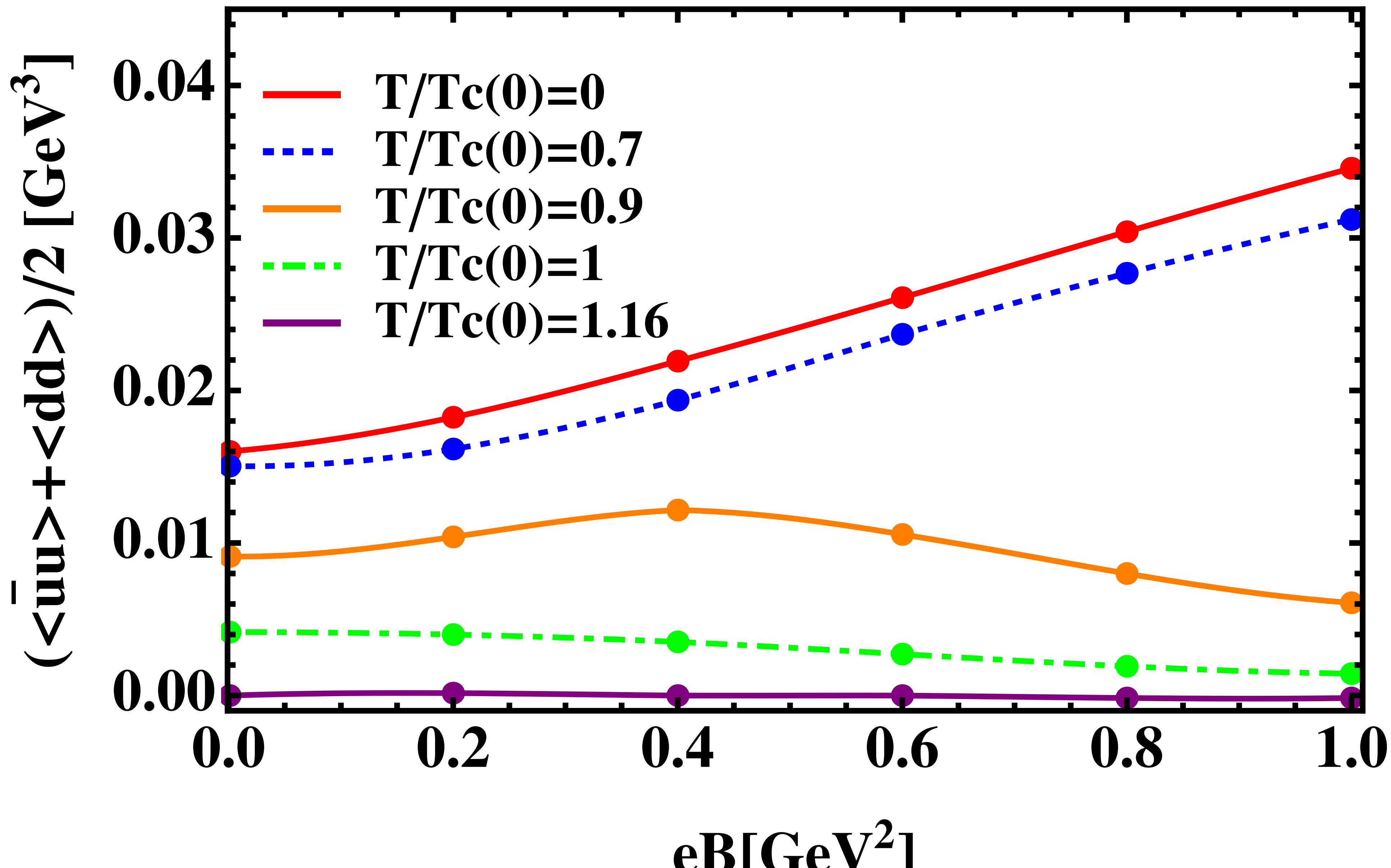
Introduce the IMC

(arxiv:1604.06662)

Fitting the Lattice data

G. S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. D. Katz, S. Krieg, A. Schafer and K. K. Szabo, JHEP 1202, 044 (2012);

G. S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. D. Katz and A. Schafer, Phys. Rev. D 86, 071502 (2012);



Running coupling constant $\mathbf{G_S(eB)}$

$$\Omega = \frac{\sigma^2}{4G_S(eB)} + \frac{B^2}{2} - 3 \sum_{q_f \in \{\frac{2}{3}, -\frac{1}{3}\}} \frac{|q_f eB|}{\beta} \sum_{p=0}^{+\infty} \alpha_p \int_{-\infty}^{+\infty} \frac{dp_3}{4\pi^2}$$

$$\left\{ \beta E_q + \ln\left(1 + e^{-\beta(E_q+\mu)}\right) + \ln\left(1 + e^{-\beta(E_q-\mu)}\right) \right\},$$

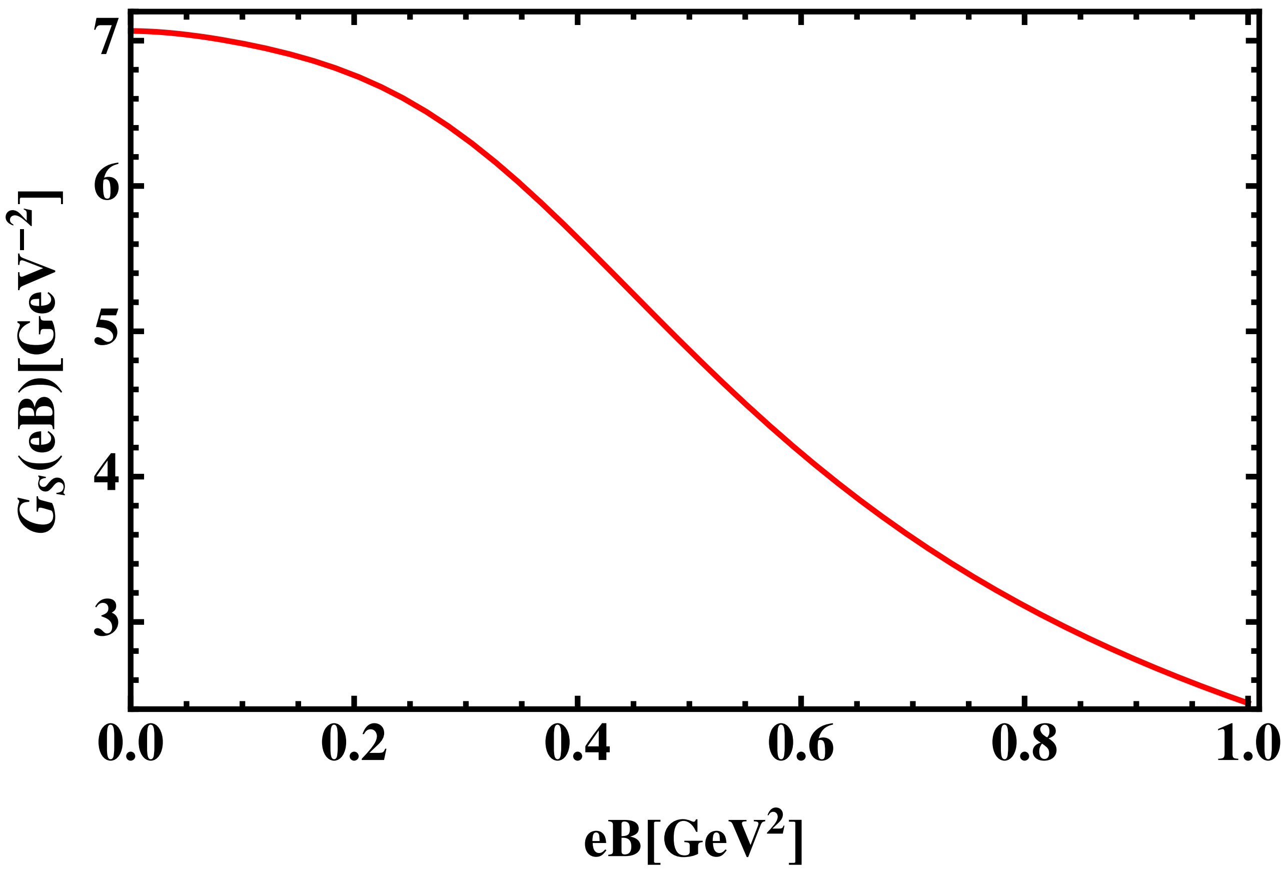
$$\frac{G_S(\xi)}{G_S(0)} = \frac{1 + a\xi^2 + b\xi^3}{1 + c\xi^2 + d\xi^4}$$

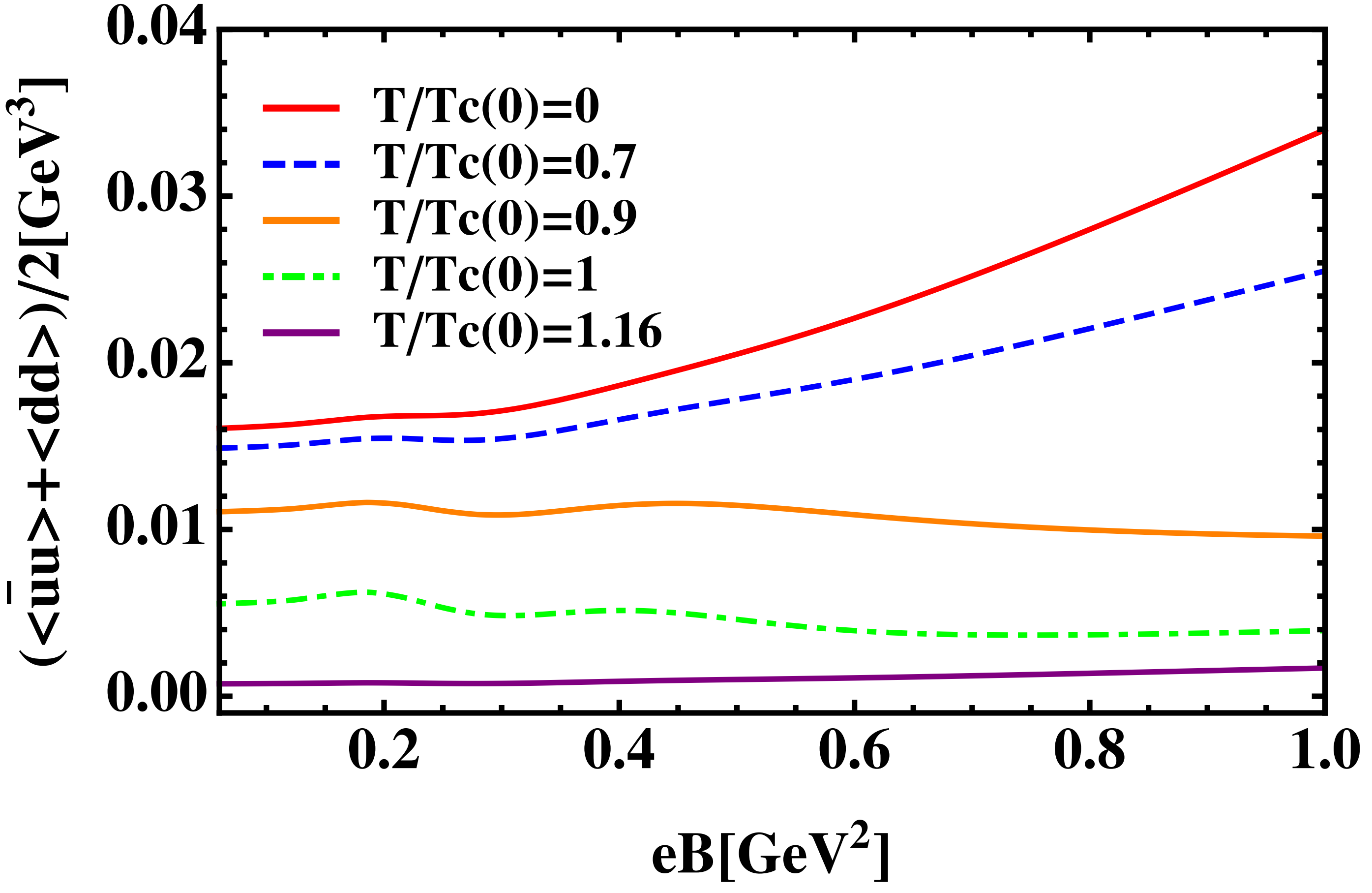
where

$$G_S(0) = G_S\,, \xi = \frac{eB}{\Lambda_{QCD}^2}\,, \Lambda_{QCD} = 300 \text{ MeV.}$$

Running coupling constant $G_S(eB)$

$$a = 0.014056, b = 0.00532074, c = 0.0281766, d = 0.00161148.$$

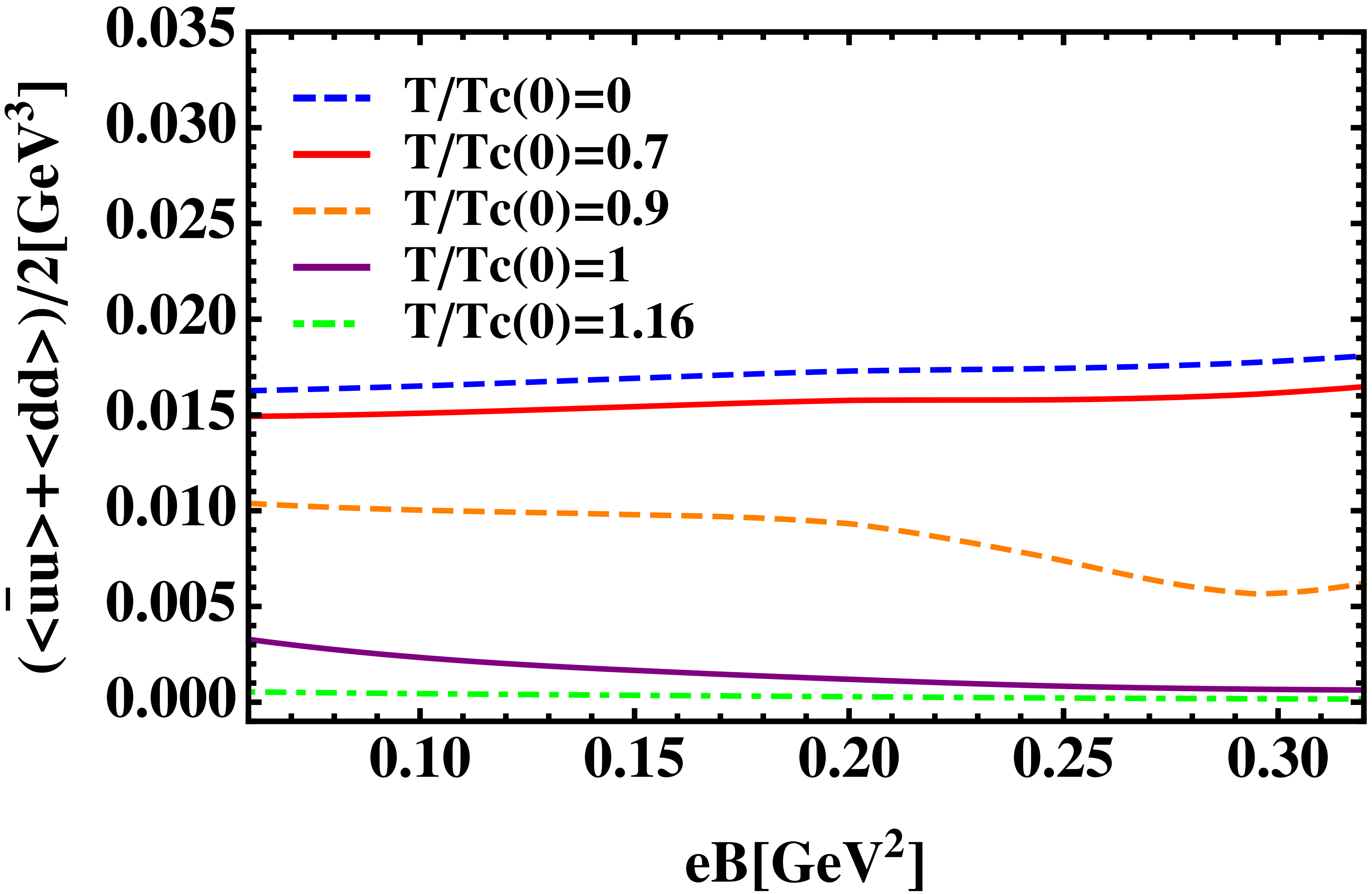




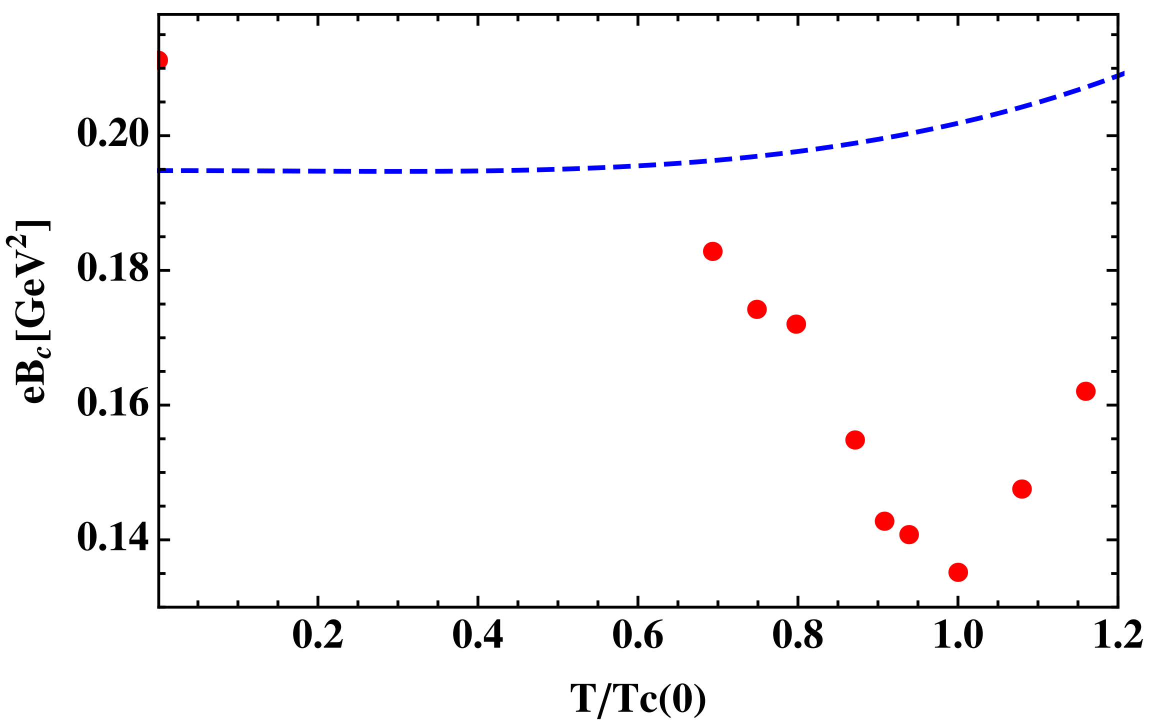
Chiral chemical potential μ_5

J. Chao, P. Chu and M. Huang, Phys. Rev. D 88, 054009 (2013) doi:10.1103/PhysRevD.88.054009 [arXiv:1305.1100 [hep-ph]].

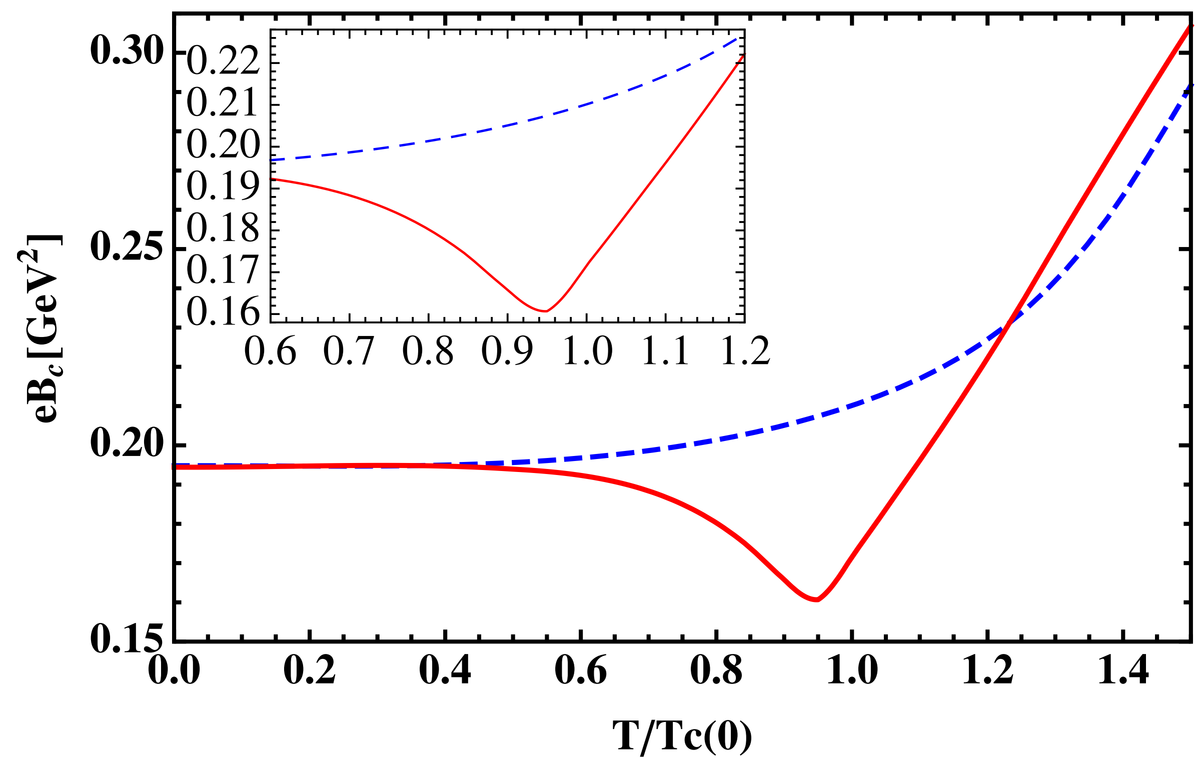
$$\mu_5(\mathrm{eB}) = 0.5\sqrt{\mathrm{eB}}$$



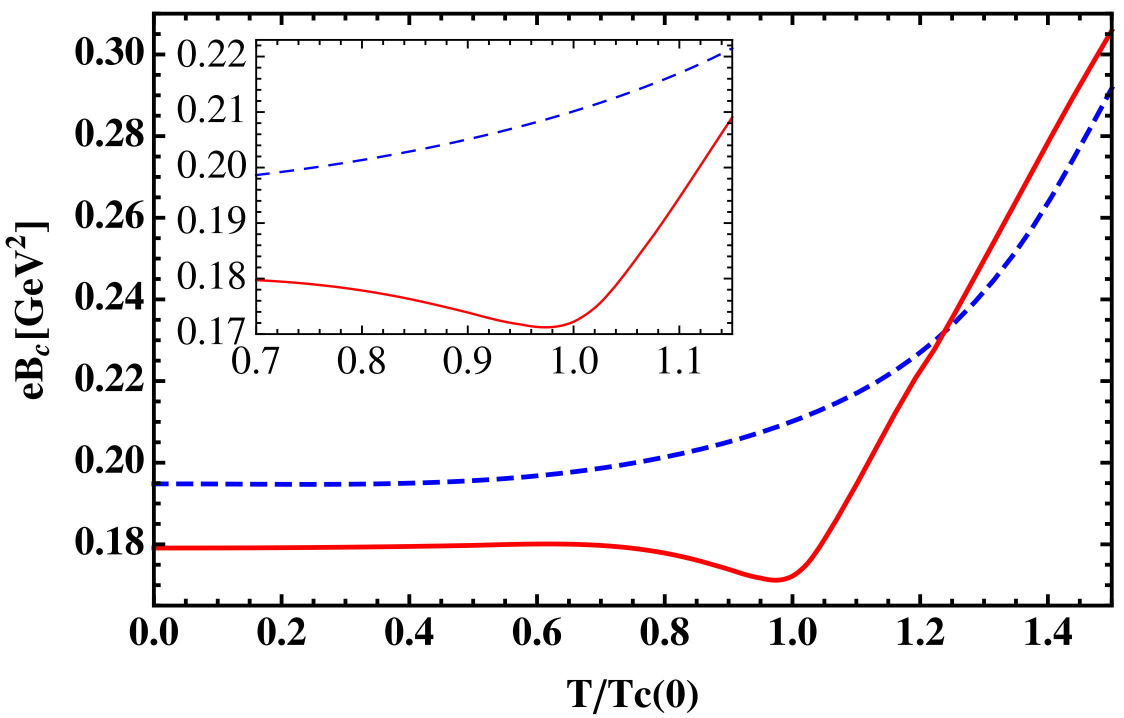
Numerical Results and Discussion



Fitting Lattice data



Chiral chemical potential

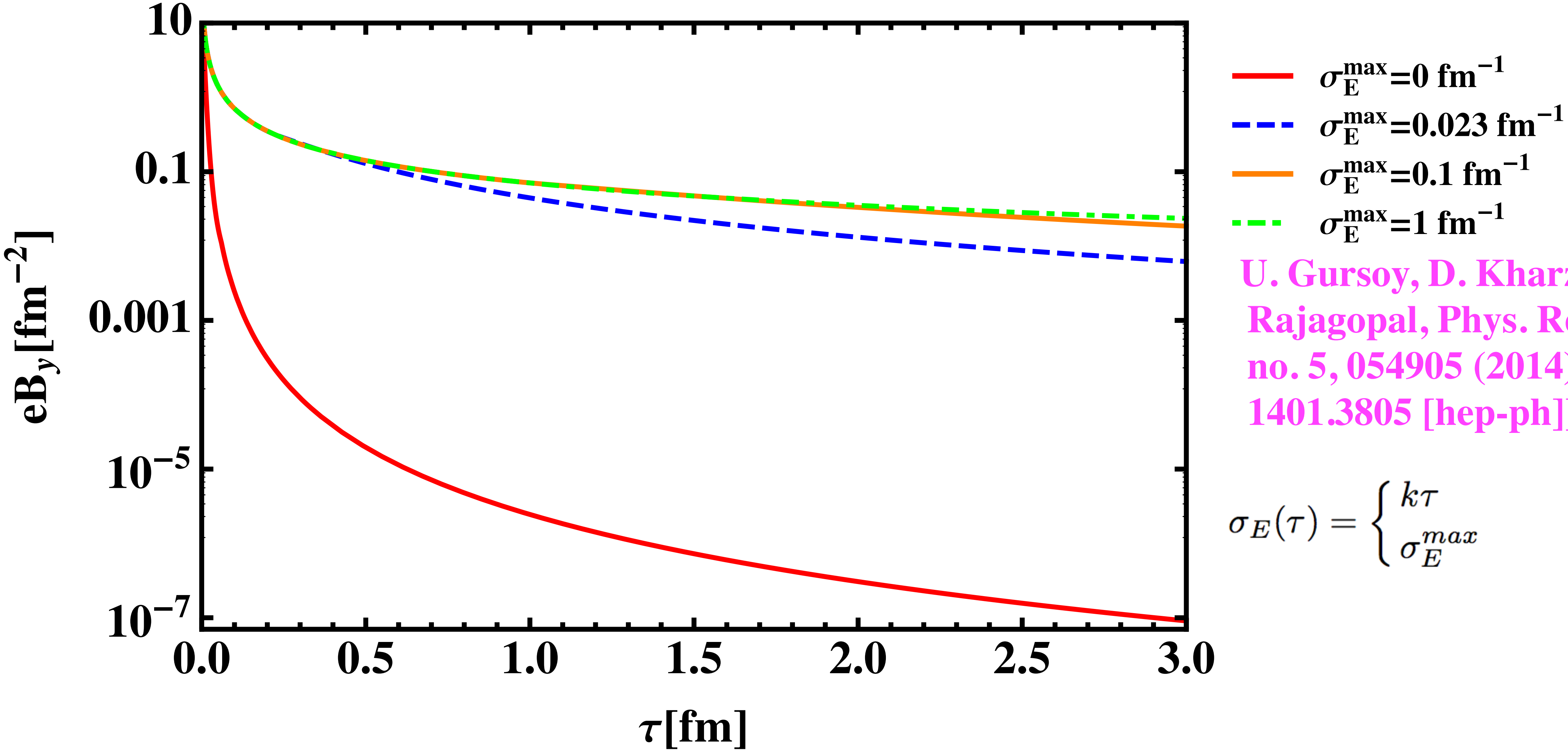


Running coupling constant

Comparing with case in MC, the IMC phenomenon affects the appearance of charged ρ condensation.

Charged ρ can condensate easier around the T_C.

Numerical Results and Discussion



U. Gursoy, D. Kharzeev and K. Rajagopal, Phys. Rev. C 89, no. 5, 054905 (2014) [arXiv: 1401.3805 [hep-ph]]

$$\sigma_E(\tau) = \begin{cases} k\tau & \sigma_E < \sigma_E^{max} \\ \sigma_E^{max} & \sigma_E \geqslant \sigma_E^{max} \end{cases}$$

- **The conducting medium delays the decay of the magnetic field.**

Summary

- **Charged rho meson condensates at** $\mathrm{eB}_c \approx 0.2\ \mathrm{GeV}^2 < 0.6\ \mathrm{GeV}^2$

- **Both temperature and chemical potential suppress the ρ condensation when we consider the MC.**

- **Comparing with case in MC, the IMC phenomenon affects the appearance of charged ρ condensation.**

- **When we consider the IMC, charged ρ can cond-ensate easier around the $\mathrm{T_C}$.**

- **The conducting medium delays the decay of the magnetic field.**

Thanks for your attention!