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Magnetized QCD phase diagram

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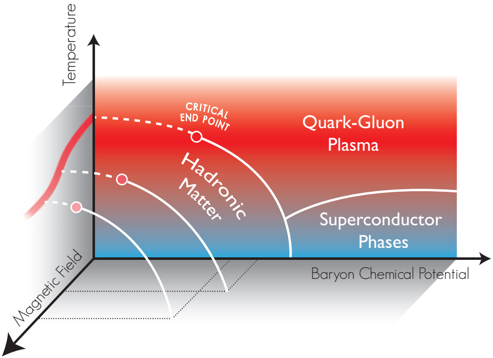
The aim of our work

Investigate how an external magnetic field affects the phase diagram of quark matter



- Do NJL-type models agree with LQCD ($\mu_B = 0$)?
- How B affects the phase diagram within NJL-type models?
  - What happens to the Critical-End-Point (CEP)?

The importance of magnetic fields

- **Magnetized neutron stars:** low T and high μ_B region
- **First phases of the Universe:** high T and low μ_B region
- **Heavy-Ion Collisions (HIC):** wider region of the phase diagram
  - **Strong magnetic fields are generated in HIC**
    - RHIC $\rightarrow eB_{max} \approx 5m_\pi^2 \approx 0.09\,\mathrm{GeV}^2$
    - LHC $\rightarrow eB_{max} \approx 15m_\pi^2 \approx 0.27\,\mathrm{GeV}^2$

One of the fundamental goals of HIC experiments
is to map the QCD phase diagram

- The search for the Critical-End-Point is the major goal of several HIC experiments
  - The increase and divergence of fluctuations is the characteristic feature of a critical point
    - Momentum distributions, ratios of observed particles, etc.

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The PNJL model

We use the Polyakov loop extended Nambu-Jona–Lasinio (PNJL) model,

$$\mathcal{L} = \bar{q}\left[i\gamma_\mu D^\mu - \hat{m}_c\right] q + \mathcal{L}_{\text{sym}} + \mathcal{L}_{\text{det}} + \mathcal{L}_{\text{vec}} + \mathcal{U}\left(\Phi, \bar{\Phi}; T\right) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu},$$

where

$$\mathcal{L}_{\text{sym}} = G_s \sum_{a=0}^{8} \left[(\bar{q}\lambda_a q)^2 + (\bar{q} i\gamma_5 \lambda_a q)^2\right]$$

$$\mathcal{L}_{\text{det}} = -K \left\{\det\left[\bar{q}(1+\gamma_5)q\right] + \det\left[\bar{q}(1-\gamma_5)q\right]\right\}$$

$$\mathcal{L}_{\text{vec}} = -G_V \sum_{a=0}^{8} \left[(\bar{q}\gamma^\mu \lambda_a q)^2 + (\bar{q}\gamma^\mu \gamma_5 \lambda_a q)^2\right]$$

The covariant derivative is given by

$$D^\mu = \partial^\mu - i q_f A^\mu_{EM} - i A^\mu$$

- A static and constant B field in the z direction $A_\mu^{EM} = \delta_{\mu 2} x_1 B$

The PNJL model

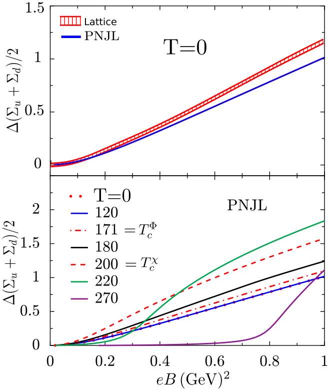
For the Polyakov loop potential we use

$$\frac{\mathcal{U}\left(\Phi,\bar{\Phi};T\right)}{T^4} = -\frac{a\left(T\right)}{2}\bar{\Phi}\Phi + b(T)\ln\left[1-6\bar{\Phi}\Phi+4(\bar{\Phi}^3+\Phi^3)-3(\bar{\Phi}\Phi)^2\right]$$

Model parametrization/regularization

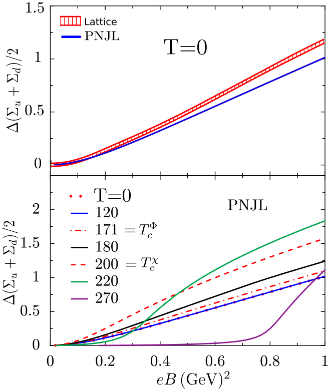
- **NJL:** P. Rehberg, et al. PRC53, 410
- **Polyakov potential:** S. Roessner, et al. PRD75, 034007
- **Magnetic field:** D. P. Menezes, et al. PRC80, 065805

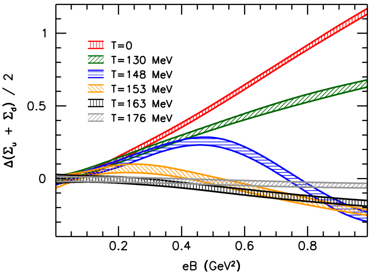
Model and LQCD quark condensates



- The Magnetic Catalysis effect is present at any temperature within the PNJL model
- A qualitatively agreement is obtained with LQCD at low temperatures

Model and LQCD quark condensates





[G. Bali, et al. PRD86(2012)071502]

- The Magnetic Catalysis effect is present at any temperature within the PNJL model
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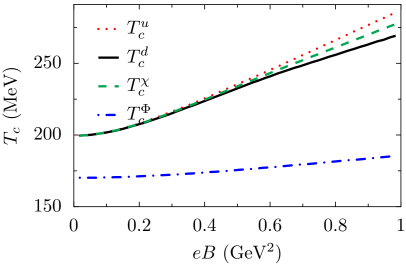
LQCD shows Inverse Magnetic Catalysis around the transition region: the magnetic field weakens the quark condensate

The pseudocritical transition temperatures



- The pseudocritical transition temperatures increase with B
- Though much more insensitive to B, the deconfinement temperature is also an increasing function

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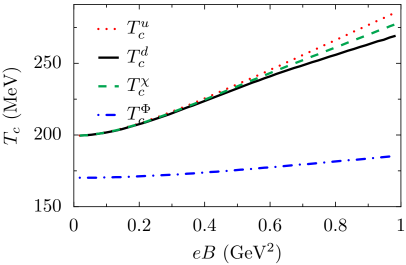

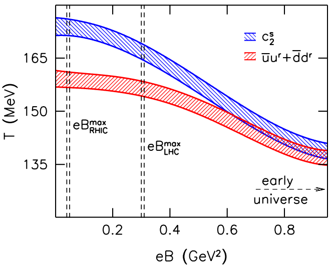

[G. Bali, et al. JHEP 1202 (2012) 044]

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In LQCD, both pseudocritical temperatures are decreasing functions of B

Magnetic field dependent quark interaction

The divergence of low energy QCD models from LQCD must emerge from the full dynamics of QCD

- IMC arises from the back-reaction of the quarks to nontrivial rearrangement of the gluonic configurations (LQCD)
  F. Bruckmann, et al. JHEP04 (2013) 112

Even though there is no full knowledge of the IMC underlying dynamics, there are several theoretical arguments for its existence

- Screening effects of the gauge sector: the gluon self-energy and strong coupling are affected by B
  - N. Mueller and Jan M. Pawlowski PRD91 (2015) 116010
  - A. Ayala, et al. PLB 759 (2016) 99–103
  - ...

Can an agreement between the model and LQCD be obtained by assuming a magnetic field dependence on the scalar coupling G_s?

M. Ferreira et al. PRD89(2014)016002, D89(2014)116011

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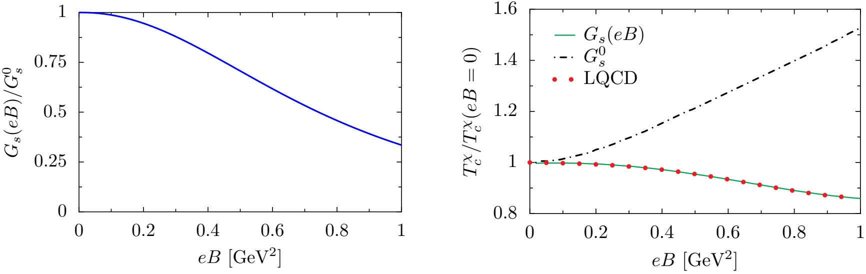
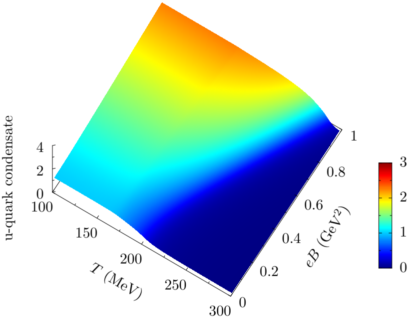
The magnetic field dependence of G_s

- The $G_s(eB)$ was fitted to reproduce $T_c^\chi(B)/T_c^\chi(eB=0)$ obtained in LQCD
  - We are reproducing the pseudocritical temperature decrease ratio

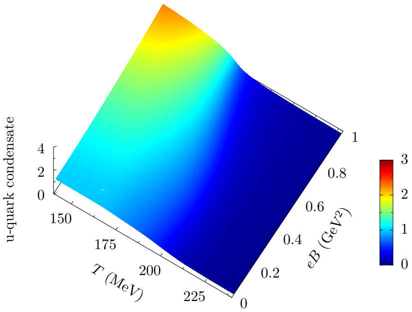
$$G_s(\zeta) = G_s^0 \left(\frac{1 + a\,\zeta^2 + b\,\zeta^3}{1 + c\,\zeta^2 + d\,\zeta^4} \right) \quad \text{with} \quad \zeta = eB/\Lambda_{QCD}^2$$



Quark condensate with $G_s(eB)$



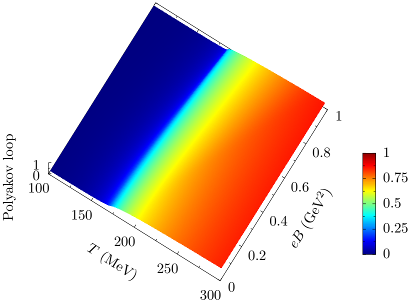
$G_s = G_s^0$



$G_s(eB)$

- $G_s(eB)$ still leads to MC at low temperatures
  - B enhances the quark condensate
- And it generates IMC on the transition temperature region
  - B weakens the quark condensate

Polyakov loop value with $G_s(eB)$



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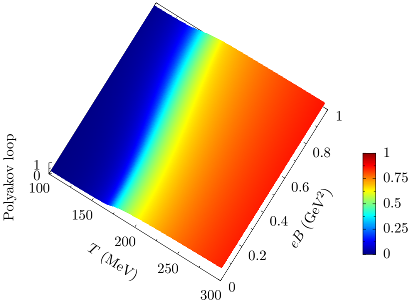
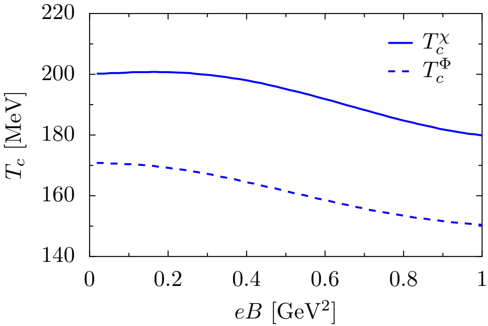


$G_s(eB)$

- As in LQCD results, the Polyakov loop shows the following trends:
  - for a given temperature, it increases with B and changes strongly on the transition region
  - The inflexion point moves to smaller temperatures with increasing B

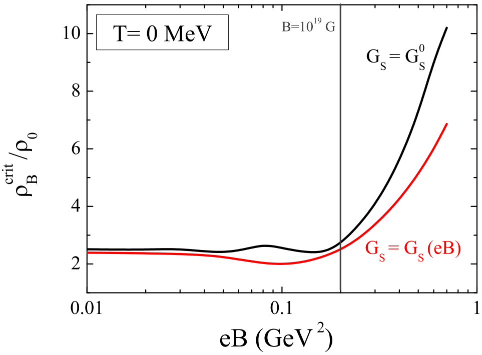
Pseudocritical temperatures with $G_s(eB)$



- Both chiral and deconfinement pseudocritical temperatures decrease with B
- They have a very similar dependence on B
- $T_c^\chi - T_c^\Phi$ can be reduced by adjusting the T_0 (Polyakov potential)

Chiral phase transition at zero temperature

- **The effect of $G_s(eB)$ on the chiral transition at $T = 0$ without vector interaction ($G_V = 0$)**



- Up to $B = 10^{19}$ Gauss, the ρ_B^{crit} remains close in both cases

Phase diagram at finite chemical potential: the CEP

If a Critical-End-Point (CEP) exists and its location is determined the general structure of the phase diagram can be outlined

- To study the impact of the magnetic field on the CEP's location, the following scenarios are analyzed:
  - With a constant scalar coupling $G_s = G_s^0$ (no IMC)
    - No vector interaction $G_V = 0$
    - Constant vector interaction $G_V = \alpha G_s^0$
  - With a magnetic dependent scalar coupling $G_s(eB)$ (with IMC)
    - No vector interaction $G_V = 0$
    - Constant vector interaction $G_V = \alpha G_s^0$
    - Magnetic dependent vector interaction $G_V = \alpha G_S(eB)$

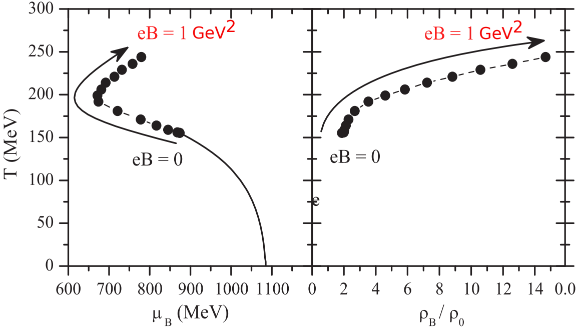
[P. Costa, et al. PRD92(2015)036012]

Magnetized QCD phase diagram

- Constant scalar coupling $G_s = G_s^0$
    - **No vector interaction** $G_V = 0$

Phase diagram for $G_s = G_s^0$ and $G_V = 0$

- The location of the CEP as a function of the magnetic field



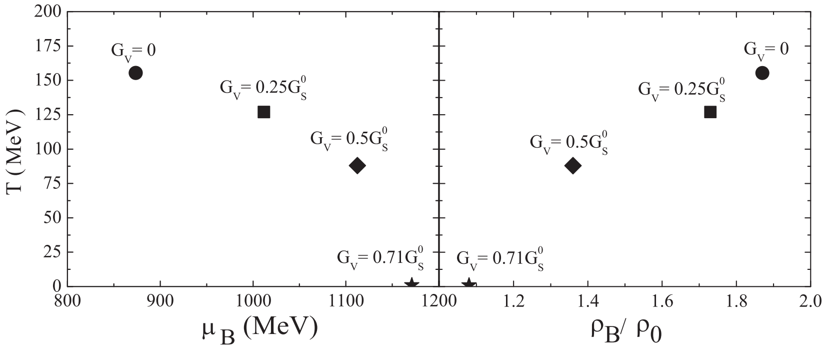
- The μ^{CEP} decreases up to $eB \approx 0.4$ GeV^2 and then increases for higher B
- The temperature and baryonic density of the CEP is an increasing function of B

Magnetized QCD phase diagram

- Constant scalar coupling $G_s = G_s^0$
  - No vector interaction $G_V = 0$
  - **Constant vector interaction** $G_V = \alpha G_s^0$

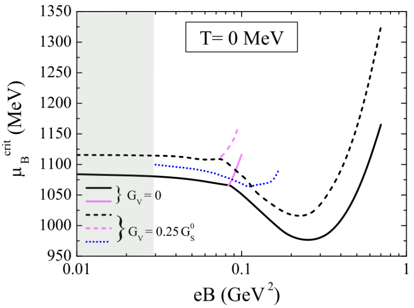
Vector interaction

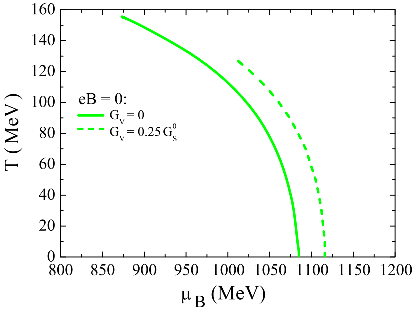
- **Phase diagram for zero magnetic field**



- The CEP's location depends on the G_V value
  - As it increases, the CEP moves to lower T and higher μ (lower ρ_B)
  - The CEP disappears for the critical value $G_V^{crit} = 0.71 G_s^0$

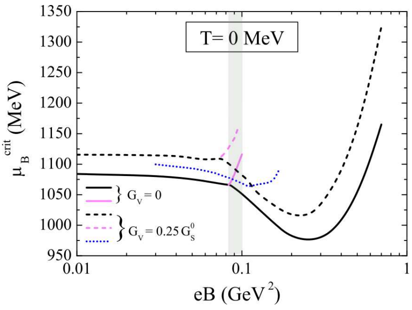
Multiple phase transitions at low temperatures

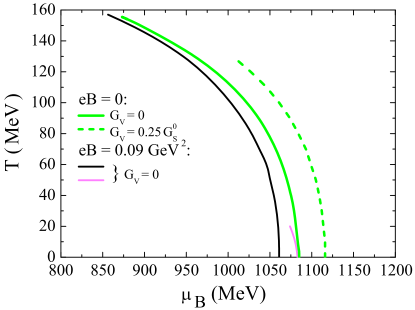




- For $eB \lesssim 0.03$, there is only one phase transition for both $G_V = 0$ and $G_V = 0.25 G_s^0$
  - There is only one CEP at finite temperature

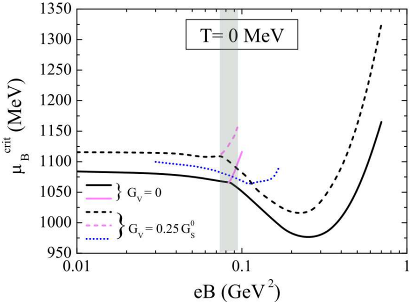
Multiple phase transitions with vector interaction

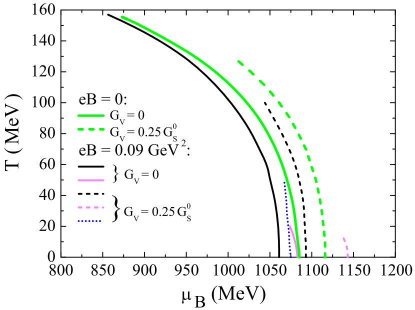




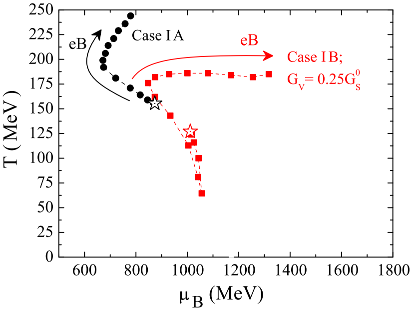
- For $eB \lesssim 0.03$, there is only one phase transition for both $G_V = 0$ and $0.25 G_s^0$
  - There is only one CEP at finite temperature
- For $eB \sim 0.09$, two phase transitions occur for $G_V = 0$
  - Two CEPs at finite temperature

Multiple phase transitions with vector interaction





- For $eB \lesssim 0.03$, there is only one phase transition for both $G_V = 0$ and $0.25 G_s^0$
  - There is only one CEP at finite temperature
- For $eB \sim 0.09$, two phase transitions occur for $G_V = 0$
  - Two CEPs at finite temperature
- For $eB \sim 0.09$, three phase transitions are present for $G_V = 0.25 G_s^0$
  - Three CEPs



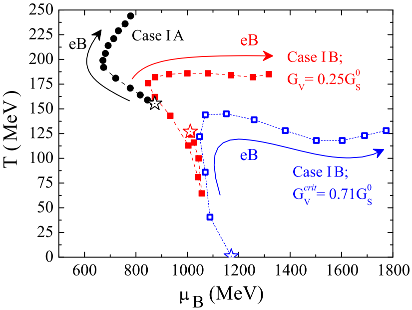
- $eB < 0.1$ GeV^2:
  $T^{CEP} \downarrow$ and $\mu^{CEP} \uparrow$
- $0.1 < eB \lesssim 0.4$ GeV^2:
  $T^{CEP} \uparrow$ and $\mu^{CEP} \downarrow$
- $eB > 0.4$ GeV^2:
  $T^{CEP} \sim$ and $\mu^{CEP} \uparrow$

$\Rightarrow$ $G_s = G_s^0$ (no IMC)

Case IA: $G_V = 0$

Case IB: $G_V = 0.25 G_s^0$

CEP's location as a function of B with $G_V = 0.71G_s^0$



$\Rightarrow$ $G_s = G_s^0$ (no IMC)

Case IA: $G_V = 0$

Case IB: $G_V = 0.25G_s^0$

Case IB: $G_V = 0.71G_s^0$

- $eB < 0.1$ GeV^2:
  $T^{CEP} \downarrow$ and $\mu^{CEP} \uparrow$
- $0.1 < eB \lesssim 0.4$ GeV^2:
  $T^{CEP} \uparrow$ and $\mu^{CEP} \downarrow$
- $eB > 0.4$ GeV^2:
  $T^{CEP} \sim$ and $\mu^{CEP} \uparrow$

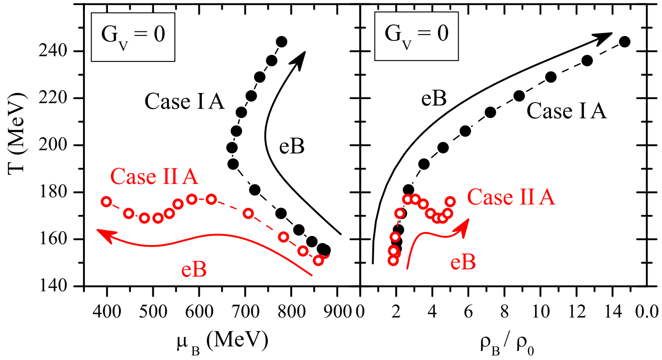
- For $0.01 \lesssim eB \lesssim 0.1$ GeV^2 a structure of multiple CEPs appears at low T.

- For $eB > 0.1$ GeV^2 just one CEP remains

Magnetized QCD phase diagram

- Constant scalar coupling $G_s = G_s^0$
  - No vector interaction $G_V = 0$
  - Constant vector interaction $G_V = \alpha G_s^0$
- **Magnetic dependent scalar coupling** $G_s(eB)$
  - **No vector interaction** $G_V = 0$

Impact of $G_s(eB)$ on CEP



The effect of IMC (Case IIA) on CEP:

- For $eB \gtrsim 0.3$ GeV^2, it leads to a lower T^{CEP} and ρ_B^{CEP}.
- The μ_B^{CEP} is a decreasing function of B.
  - For higher B, the crossover at $\mu_B = 0$ might change to a first-order phase transition

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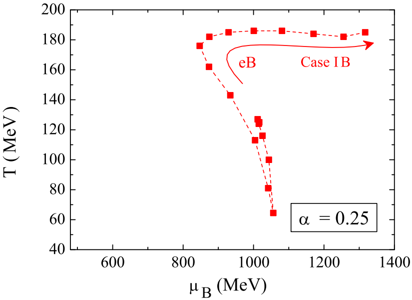
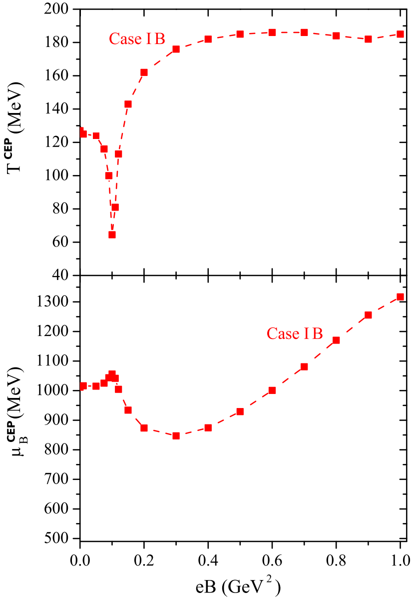
  - **Magnetic dependent vector interaction** $G_V = \alpha G_S(eB)$

Role of the vector interaction

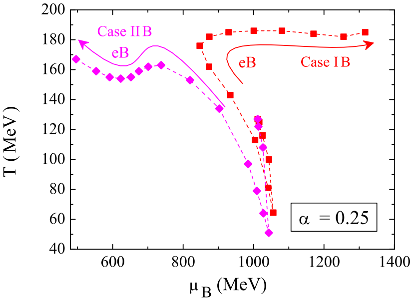


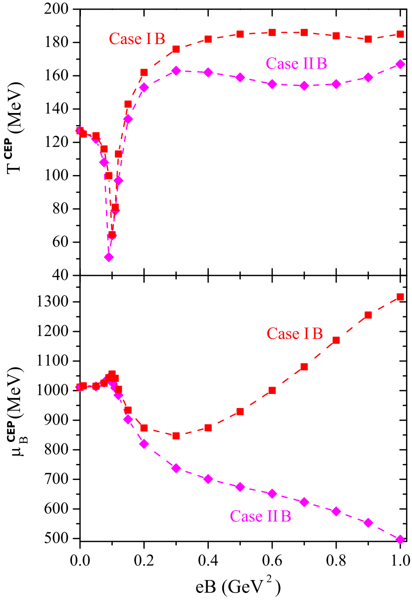
Case I $\Rightarrow G_s = G_s^0$

I B: $G_V = 0.25 G_s^0$



Role of the vector interaction (with IMC)





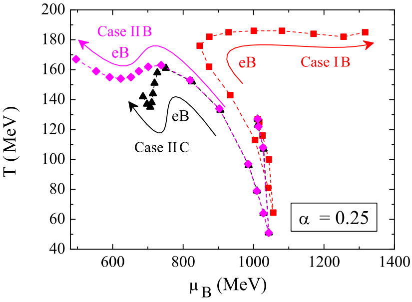
Case I $\Rightarrow G_s = G_s^0$

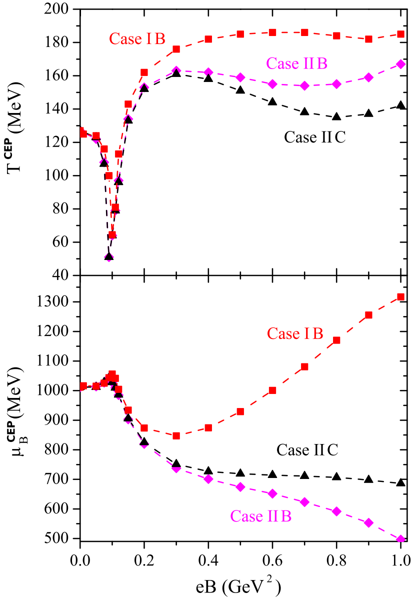
I B: $G_V = 0.25 G_s^0$

Case II $\Rightarrow G_s = G_s(eB)$

II B: $G_V = 0.25 G_s(eB)$

Role of the vector interaction (with IMC)





Case I $\Rightarrow G_s = G_s^0$

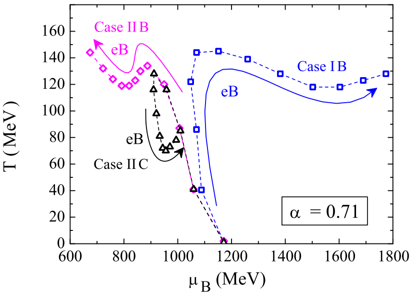
I B: $G_V = 0.25 G_s^0$

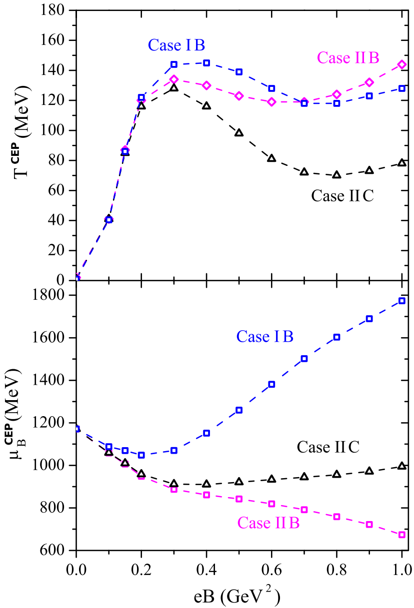
Case II $\Rightarrow G_s = G_s(eB)$

II B: $G_V = 0.25 G_s(eB)$

II C: $G_V = 0.25 G_s^0$

Role of the vector interaction (with IMC)





Case I $\Rightarrow G_s = G_s^0$

I B: $G_V = 0.71 G_s^0$

Case II $\Rightarrow G_s = G_s(eB)$

II B: $G_V = 0.71 G_s(eB)$

II C: $G_V = 0.71 G_s^0$

Conclusions

- An agreement of effective models with LQCD results is crucial for an accurate prediction of the magnetized QCD phase diagram
- Using the $G_S(eB)$, we were able to conclude that the IMC effect affects the QCD phase structure
- The CEP's location strongly depends on whether the IMC is taked into account
- For high magnetic fields the CEP moves towards $\mu_B = 0$, indicating that the transition might change from a crossover to a first-order phase transition
- The vector interaction strength plays an important role on the CEP's location in a magnetized medium