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QCD phase diagram and magnetic fields

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POQH

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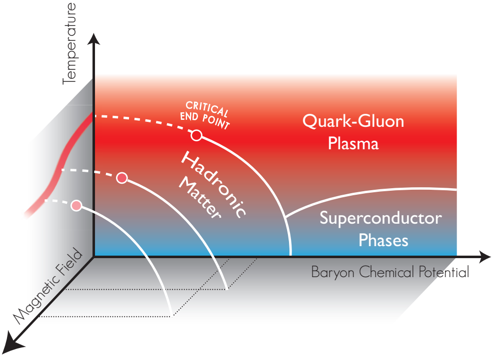
The aim of this work

Analyze the impact of an external magnetic field on the QCD phase diagram



- Do NJL-type models agree with LQCD ($\mu_B = 0,\ B \neq 0$)?
- What is the phase diagram structure ($\mu_B \neq 0,\ B \neq 0$)?
  - The impact of B on 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):** broad 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 fundamental goal of HIC experiments
is mapping the QCD phase diagram

- A considerable effort is being devoted in finding experimental signatures for the presence of a Critical-End-Point

The PNJL model

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

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

where

$$\begin{aligned}\mathcal{L}_{\text{sym}} &= G_s \sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (\bar{q}i\gamma_5\lambda_a q)^2\right]\\ \mathcal{L}_{\text{det}} &= -K\left\{\det\left[\bar{q}(1+\gamma_5)q\right] + \det\left[\bar{q}(1-\gamma_5)q\right]\right\}\end{aligned}$$

The covariant derivative is given by

$$D^\mu = \partial^\mu - iq_f A^\mu_{EM} - iA^\mu$$

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

The PNJL model

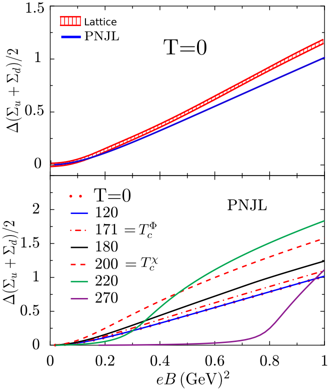
For the Polyakov loop potential we use

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

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

Quark condensate: PNJL model and LQCD



[M. Ferreira et al. PRD89(2014)116011]

- The Magnetic Catalysis effect is present at any temperature (PNJL model)
- A qualitatively agreement is obtained with LQCD at low temperatures ($T \ll T_\chi$)

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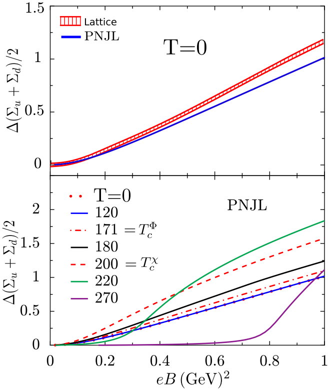

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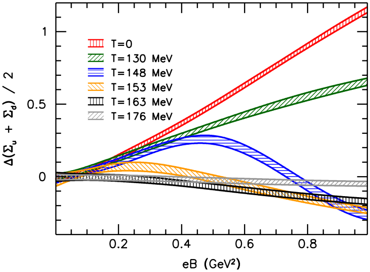

[G. Bali, et al. PRD86(2012)071502]

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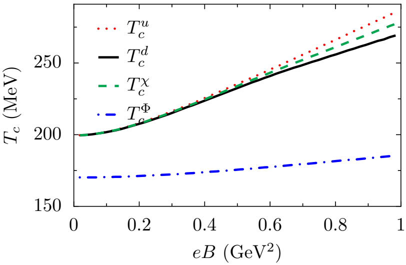
On the transition region ($T \sim T_\chi$) occurs Inverse Magnetic Catalysis: the magnetic field weakens the quark condensate

Transition temperatures: PNJL model



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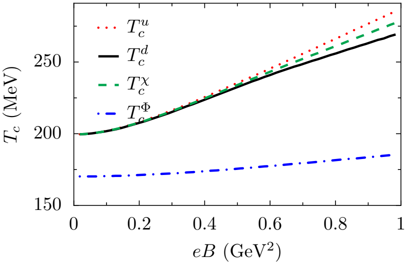
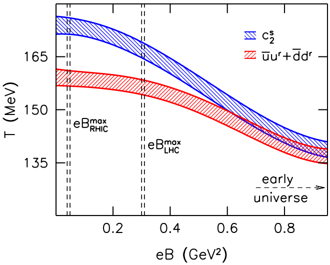
- Both the deconfinement and the chiral (pseudo) transition temperatures increase with B
- The deconfinement temperature is quite insensitive to B

Transition temperatures: PNJL model and LQCD





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

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In LQCD, both (pseudo) critical temperatures decrease with B

Quark interaction with a magnetic field dependence

The discrepancy between low energy QCD models and LQCD must emerge from the full dynamics of QCD

- IMC arises from the quarks back-reaction 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 NJL-type models and LQCD be obtained by assuming a magnetic field dependence on the scalar coupling G_s?

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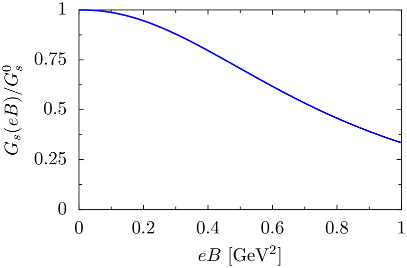
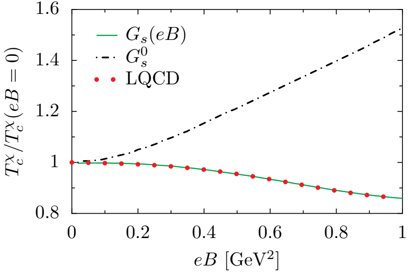
The magnetic field dependence of G_s

- The $T_c^\chi(B)/T_c^\chi(eB=0)$ (given by LQCD [G. Bali, et al. JHEP 1202 (2012) 044]) is obtained by the following $G_s(eB)$ dependence

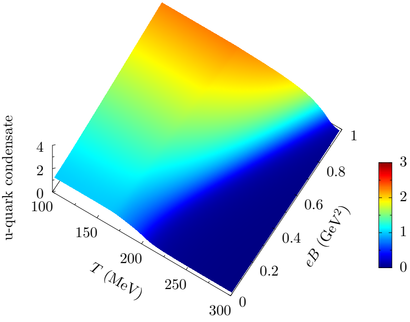
$$G_s(\zeta) = G_s^0\left(\frac{1+a\,\zeta^2+b\,\zeta^3}{1+c\,\zeta^2+d\,\zeta^4}\right), \quad \text{where} \quad \zeta = eB/\Lambda_{QCD}^2$$



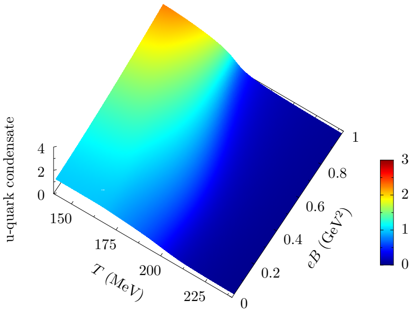


- The critical temperature decrease ratio is possible via the $G_s(eB)$
- Furthermore, the crossover nature of the transitions is preserved

Quark condensate: G_s vs. $G_s(eB)$



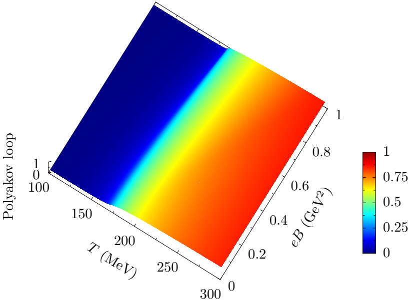
$$G_s = G_s^0$$



$$G_s(eB)$$

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

Polyakov loop: G_s vs. $G_s(eB)$



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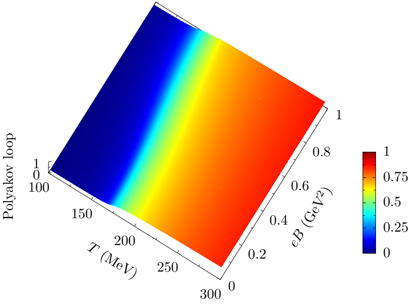
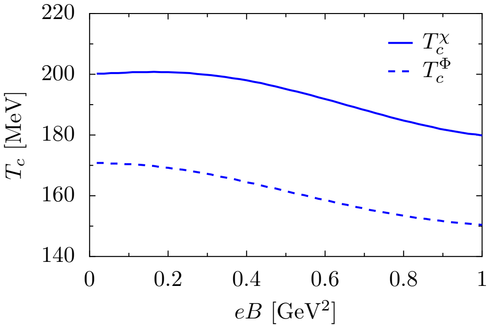


$$G_s(eB)$$

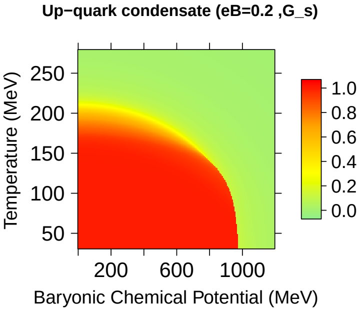
- The Polyakov loop shows the following trends (as in LQCD):
  - for a given temperature, it increases with B and changes strongly on the transition region
  - The inflection point moves to smaller temperatures with increasing B

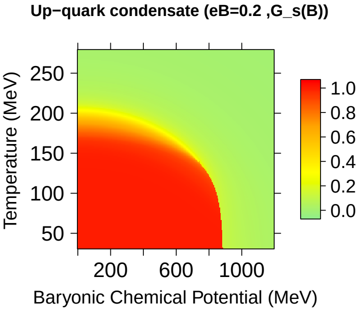
Pseudocritical temperatures with $G_s(eB)$



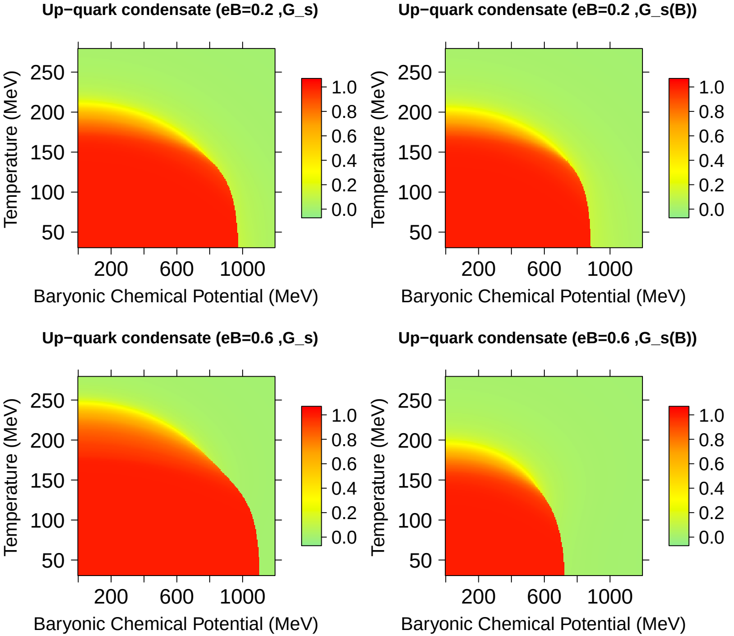
- Both chiral and deconfinement pseudocritical temperatures decrease with B
- They have a very similar dependence on B
- $T_c^\chi - T_c^\Phi$ can be reduced by adjusting the T_0 (Polyakov potential)

Chiral phase diagram


Up−quark condensate (eB=0.2 ,G_s)


Up−quark condensate (eB=0.2 ,G_s(B))

Chiral phase diagram



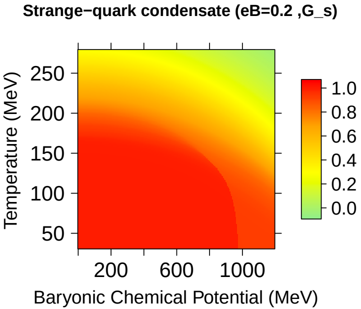
Up−quark condensate (eB=0.2 ,G_s)

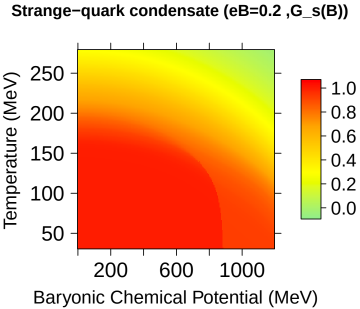
Up−quark condensate (eB=0.2 ,G_s(B))

Up−quark condensate (eB=0.6 ,G_s)

Up−quark condensate (eB=0.6 ,G_s(B))

Strange quark phase diagram


Strange−quark condensate (eB=0.2 ,G_s)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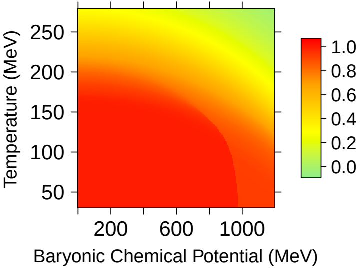
Strange quark phase diagram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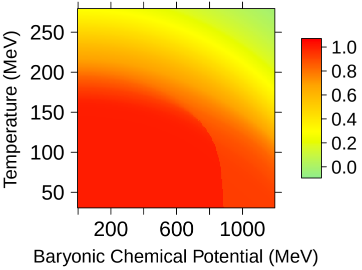
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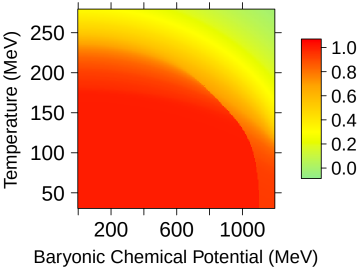
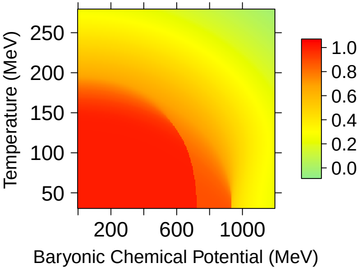
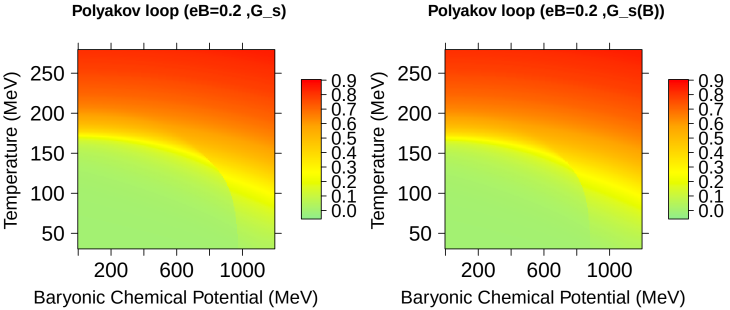

Strange−quark condensate (eB=0.6 ,G_s)


Strange−quark condensate (eB=0.6 ,G_s(B))

Deconfinement phase diagram



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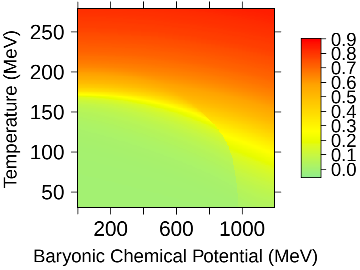
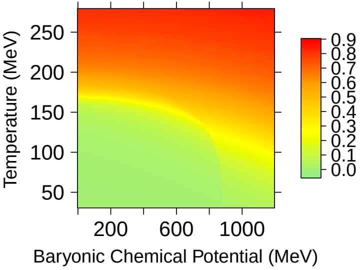
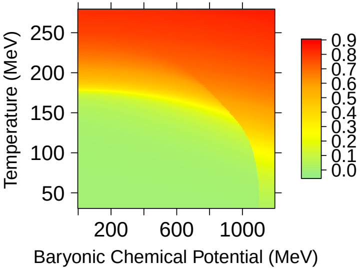

Polyakov loop (eB=0.2 ,G_s)


Polyakov loop (eB=0.2 ,G_s(B))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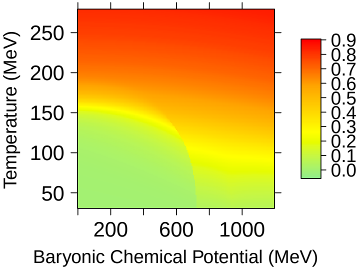
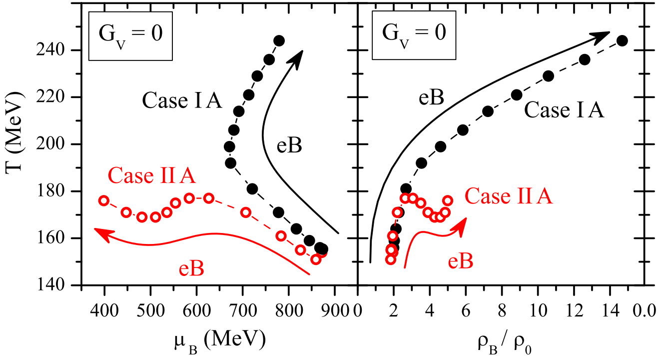

Polyakov loop (eB=0.6 ,G_s(B))

The Critical-End-Point (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

Conclusions

- An agreement of effective models with LQCD results at $\mu_B = 0$ is crucial in order to have predictive power on 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 taken into account
- As the magnetic field increases, the CEP moves towards $\mu_B = 0$, indicating that the transition might change from a crossover to a first-order phase transition for strong enough magnetic fields