FCTUC FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE DE COIMBRA

CENTRO DE FÍSICA COMPUTACIONAL

Inverse Magnetic Catalysis in (P)NJL models

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New Trends in High Energy Physics and QCD
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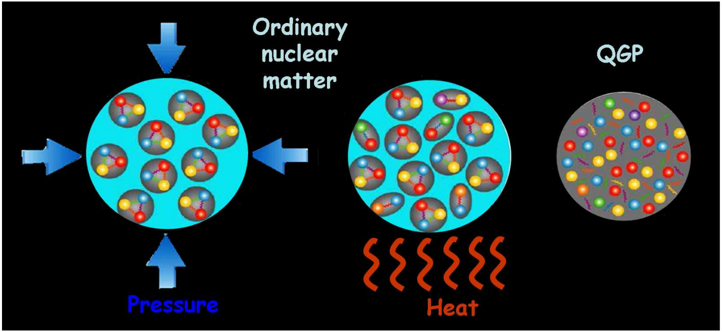
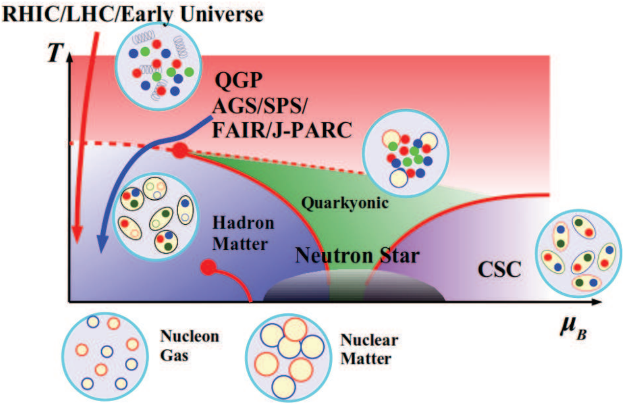
What are the different states of matter?



What happens when hadronic matter is compressed or/and heated?

QCD phase diagram

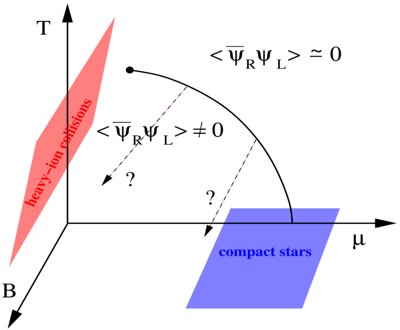
Our current picture of the phase diagram



- At zero chemical potential a smooth transition from hadronic matter to quark-gluon plasma occurs

The effect of an external magnetic field

- **How does the QCD phase diagram change with an increasing magnetic field?**



- Its effect is important in magnetars, heavy-ion collisions,...
  - RHIC $\rightarrow eB_{max} \approx 5m_\pi^2 \approx 0.09\,\mathrm{GeV}^2$
  - LHC $\rightarrow eB_{max} \approx 15m_\pi^2 \approx 0.27\,\mathrm{GeV}^2$

Phase transitions

Order parameters

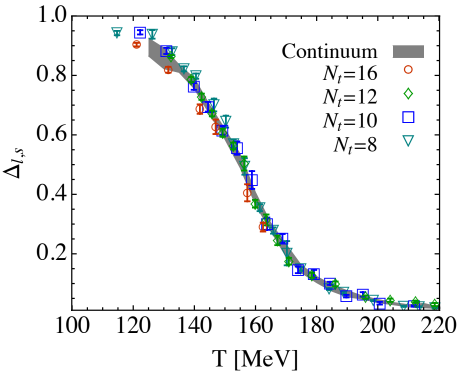
- The quark condensate $\langle \bar{q}q \rangle$ measures the chiral symmetry breaking
  - Exact order parameter for $m_q \to 0$
- The Polyakov loop Φ measures the center symmetry breaking
  - Exact order parameter for $m_q \to \infty$

- Both symmetries are explicitly broken when the physical quark masses values are used
  - In this case we have approximate order parameters

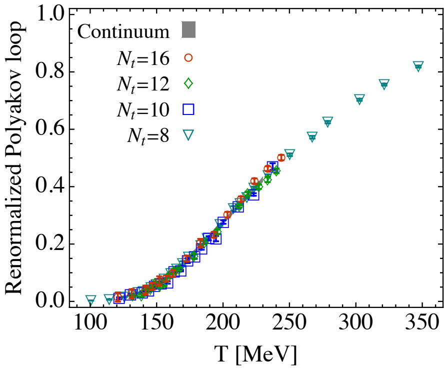
Solving QCD on a Lattice (LQCD)

Wuppertal-Budapest Collaboration JHEP 1009 (2010) 073

- We are limited to zero chemical potential
- For $N_f = 2 + 1$ both transitions are crossovers



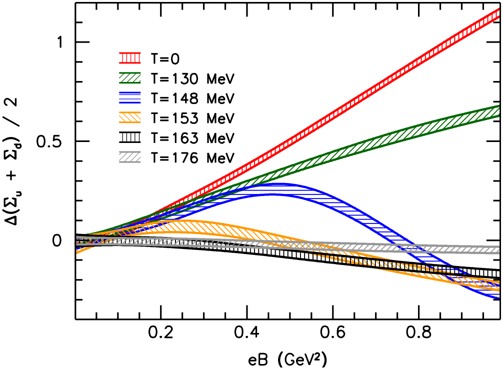
$T_c^\chi \approx 157\,\mathrm{MeV}$



$T_c^\Phi \approx 175\,\mathrm{MeV}$

LQCD in a presence of an external magnetic field

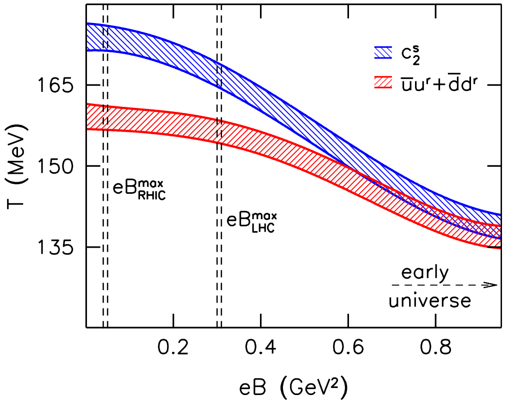
G.S. Bali, et al., JHEP 1202 (2012) 044



- At low temperatures $\Delta\Sigma$ is enhanced by the magnetic field (Magnetic Catalysis)
- A non-monotonic behavior is obtained at temperatures near the transition temperature
  - Σ_i are suppressed by the magnetic field (Inverse Magnetic Catalysis)

LQCD in a presence of an external magnetic field

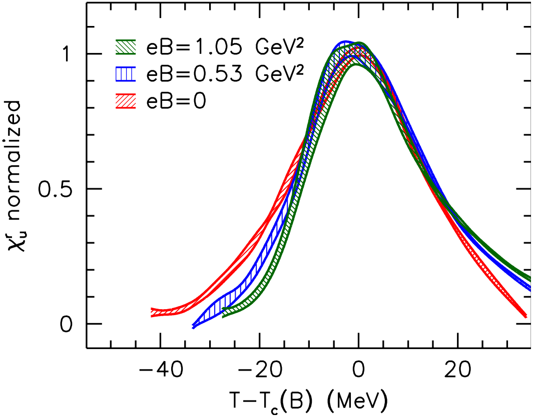
G.S. Bali, et al., JHEP 1202 (2012) 044



- The pseudo-critical temperatures $T_c(eB)$ are determined as the inflection points of the susceptibilities

The impact of B on the nature of chiral transition

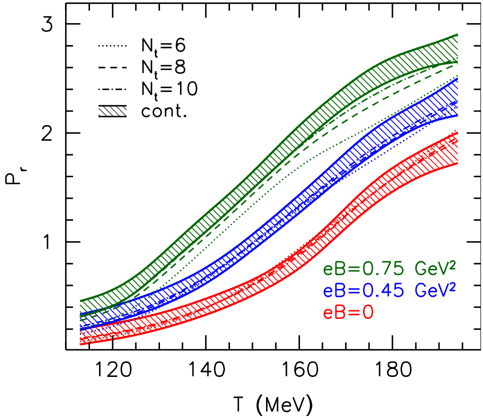
G.S. Bali, et al., JHEP 1202 (2012) 044



The transition remains an analytic crossover at least up to 1 GeV^2

The effect of B on the Polyakov loop

F. Bruckmann, et al., JHEP 1304 (2013) 112



- It increases with B for a fixed temperature
    - More pronounced near the transition temperature
- The inflection point moves towards lower temperatures with increasing B

The Nambu–Jona-Lasinio (NJL) model

$$\mathcal{L} = \bar{q}\left[i\gamma_\mu D^\mu - \hat{m}_f\right]q + G_s \sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (\bar{q}i\gamma_5\lambda_a q)^2\right] + \mathcal{L}_{det}$$

- Local 4 quark point interaction
- The 't Hooft six fermion term $\mathcal{L}_{det}$ models the axial $U_A(1)$ symmetry breaking

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

- Dynamic generation of quark masses

$$M_i = m_i - 2G_s\langle\bar{q}_i q_i\rangle - 2K\langle\bar{q}_j q_j\rangle\langle\bar{q}_k q_k\rangle$$

Adding the Polyakov potential (PNJL model)

- There is no confinement mechanism in the NJL model
- The gluonic degrees of freedom are introduced by an effective potential $\mathcal{U}(\Phi, \bar{\Phi}, T)$

$$\Phi = \frac{1}{N_c} \mathrm{Tr}_c \left\langle \left\langle \mathcal{P} exp \left[i \int_0^\beta d\tau A_0(x,\tau) \right] \right\rangle \right\rangle$$

$$\mathcal{L}_{PNJL} = \mathcal{L}_{NJL} + \mathcal{U}(\Phi, \bar{\Phi}, T)$$

- The quarks interact with the gluon fiels through the minimal coupling

$$D^\mu = \partial^\mu - igA^\mu \;\; ; \;\; A^\mu = \delta_0^\mu A^0 \;\; \text{(Polyakov Gauge)}$$

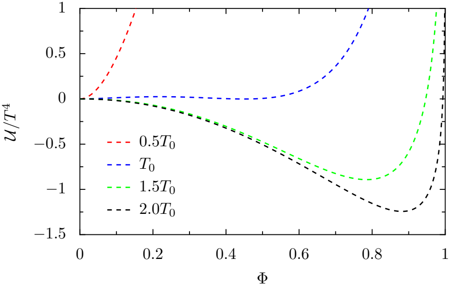
The Polyakov potential

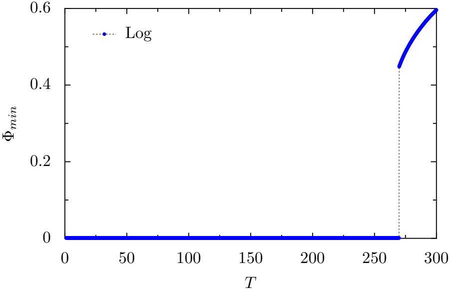
S. Roessner, et al., PRD75 (2007) 034007

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

$$a(T) = a_0 + a_1\left(\frac{T_0}{T}\right) + a_2\left(\frac{T_0}{T}\right)^2 \ , \ b(T) = \left(\frac{T_0}{T}\right)^3$$

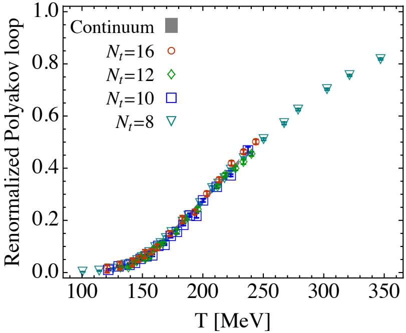
- Fitted to pure gluonic lattice results
  - $a_0 = 3.51,\ a_1 = -2.47,\ a_2 = 15.2,\ b_3 = -1.75$
- Reproduce a first order phase transition at $T_0 = 270\,\mathrm{MeV}$





Adjusting the T_0 of the Polyakov potential

- In the presence of dynamical quarks T_0 must be adjusted
- A decrease of T_0 from 270 to 210 MeV in the PNJL is needed
  - $T_c^{\Phi} = 171$ MeV *(crossover)* is obtained



$T_c^{\Phi} \approx 175\,\mathrm{MeV}$ (LQCD) *(crossover)*

Adding an external magnetic field to the model

- Static and constant magnetic field in the z direction

$$A^{\mu}_{EM} = \delta^{\mu 2} x_1 B$$

- Interaction with quarks via minimal coupling

$$D^{\mu}_{i} = \partial^{\mu}_{i} - i q_i A^{\mu}_{EM}$$

- The energy spectrum is modified by $\mathbf{B} = B\hat{z}$

$$E_i \rightarrow \sqrt{(p^i_z)^2 + 2|q_i|Bn + M_i^2}$$

  where $n = 0, 1, 2, ...$ is the Landau level.

- Dimensional reduction: $D \rightarrow D - 2 \Rightarrow p_x, p_y, p_z \rightarrow p_z$

Model vs LQCD results at zero temperature

MF, et al., PRD 89, 016002-10 (2014)

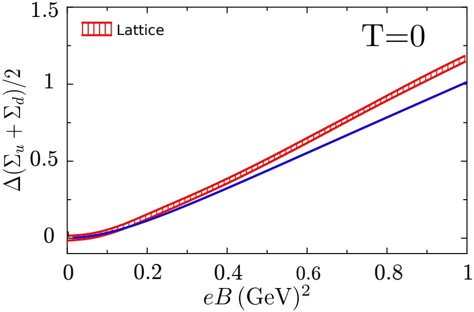
- In order to compare with LQCD results the condensates are defined as

$$\Sigma_f(B,T) = \frac{2m_f}{m_\pi^2 f_\pi^2}\left[\langle \bar{q}_f q_f\rangle (B,T) - \langle \bar{q}_f q_f\rangle (0,0)\right] + 1$$

- and the condensates change due to B as

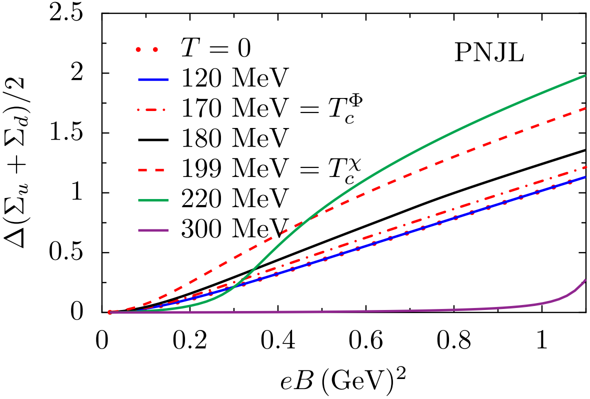
$$\Delta\Sigma_f(B,T) = \Sigma_f(B,T) - \Sigma_f(0,T)$$

- The condensate is enhanced (Magnetic Catalysis)
- Even at $eB = 1$ GeV^2 the discrepancy is lower than 18%



Model results: condensate at finite temperature

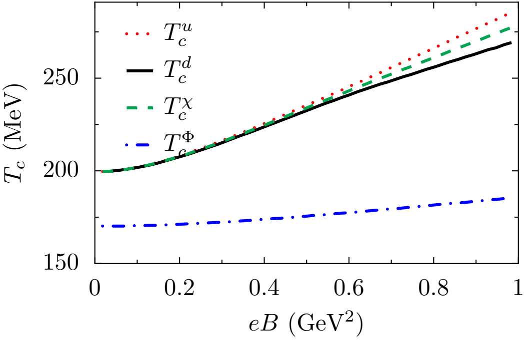
MF, et al., PRD 89, 016002-10 (2014)



- The enhancement of the condensate (MC) occurs at any T
- There is no suppression of the condensates (IMC) near the transition temperature as LQCD have shown
  - The $\Delta\Sigma_f$ have a monotonic behavior with B for any T

Model results: critical temperatures

MF, et al., PRD 89, 016002-10 (2014)



- Both critical temperatures increase with B
    - LQCD shows the opposite: both decrease with B
- The deconfinement transition is less affected
- The difference between T_c^u and T_c^d is due to their electric charge

Strong coupling weakening

- In the lower p region relevant for the chiral symmetry breaking dynamics the magnetic field screens the gluon interactions

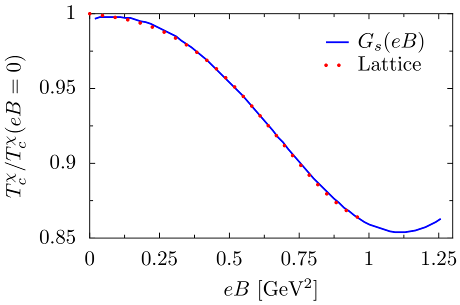
- For sufficiently strong magnetic fields $eB \gg \Lambda_{QCD}^2$, the α_s is in leading-order a decreasing funtion of eB
  [V. A. Miransky, et. al. PRD66,045006]

  - *Deconfinement and chiral restoration within the SU(3) PNJL and EPNJL models in an external magnetic field*, MF et al. Phys.Rev. D89 (2014) 016002
  - *Quark Antiscreening at Strong Magnetic Field and Inverse Magnetic Catalysis*, Ferrer, E.J. et al. arXiv:1407.3503
  - *The Importance of Asymptotic Freedom for the Pseudocritical Temperature in Magnetized Quark Matter*, Farias, R.L.S. et al. Phys. Rev. C 90, 025203 (2014)
  - *Inverse magnetic catalysis in the (2+1)-flavor NJL and PNJL models*, MF et al. Phys.Rev. D89 (2014) 116011
  - *Inverse magnetic catalysis for the chiral transition induced by thermo-magnetic effects on the coupling constant*, Ayala, Alejandro et al. Phys.Rev. D90 (2014) 03600
  - *Anticatalysis in the linear sigma model with quarks*, Ayala, Alejandro et al. arXiv:1406.7408
  - *Finite temperature quark-gluon vertex with a magnetic field in the Hard Thermal Loop approximation*, Ayala, Alejandro et al. arXiv:1410.6388

Parametrization of $G_s(eB)$

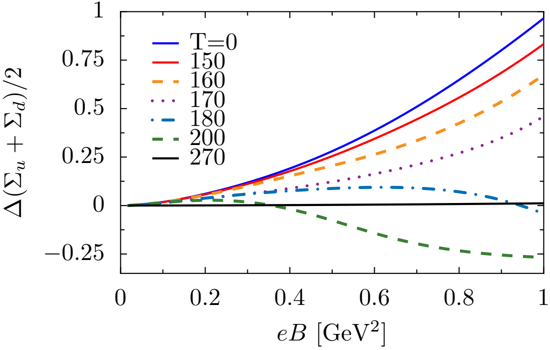
MF, et al., PRD 89, 116011-9 (2014)

- There is a weakening of quark interactions
- In the NJL model $G_s \propto \alpha_s \;\rightarrow\; G_s(eB)$
- The $G_s(eB)$ is obtained by fitting a generic function in order to obtain the relative decrease of the critical temperature given by LQCD results
    - $G_s(0) = G_s^0$ and $G_s(eB \rightarrow \infty) \rightarrow 0$



Average condensate with $G_s(eB)$

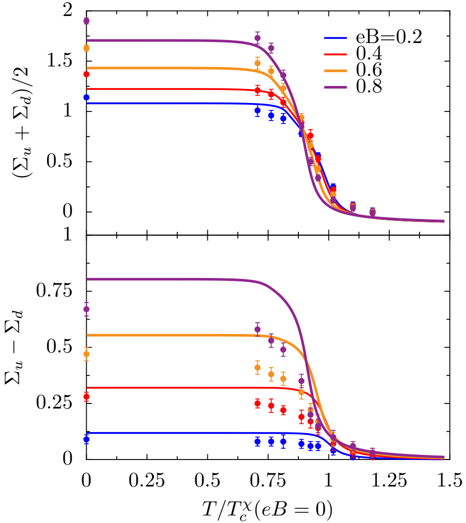
MF, et al., PRD 89, 116011-9 (2014)



- Three qualitatively features in agreement with LQCD
  - MC at lower temperatures
  - IMC (non-monotonic behavior) at temperatures near the T_c^χ
  - MC at higher temperatures (black line)

PNJL model with $G_s(eB)$ vs LQCD results

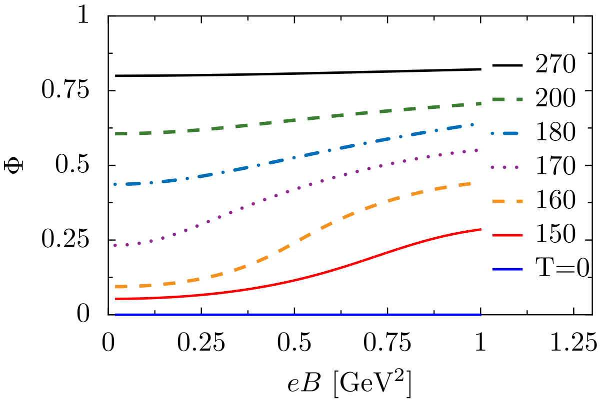
MF, et al., PRD 89, 116011-9 (2014)



- The $\Sigma_u - \Sigma_d$ deviation might suggest a magnetic SU(3) flavor breaking.

Deconfinement transition with $G_s(eB)$

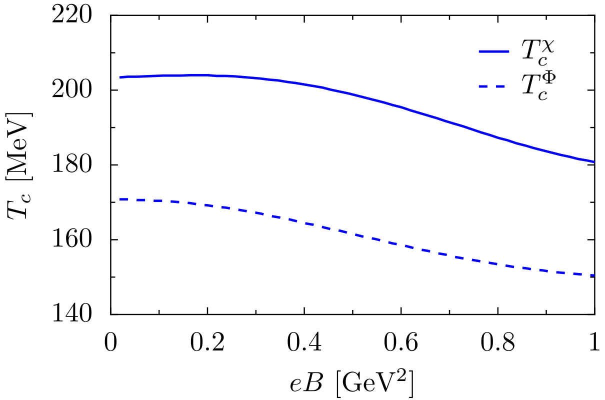
MF, et al., PRD 89, 116011-9 (2014)



- For a fixed temperature the Polyakov loop increases with B: the deconfinement transition starts earlier
- This behavior is more pronounced in the transition temperature region in agreement with LQCD results

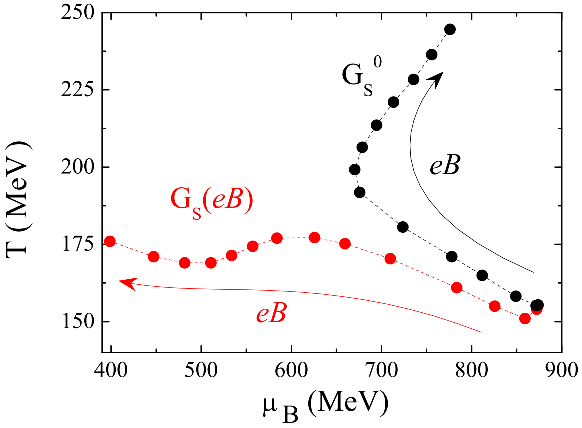
Critical temperatures with $G_s(eB)$

MF, et al., PRD 89, 116011-9 (2014)



- Both transition temperatures decrease with the magnetic field strength

The Critical-End-Point (CEP)



Conclusions

- The magnetic field weakens the interactions between quarks
- We have used a simple ansatz for the B dependence of G_s
- It was fitted in order to reproduce the critical temperature decrease ratio with B
- In agreement with LQCD, the following features are reproduced:
  - Inverse Magnetic Catalysis in the transition temperature region
  - Magnetic Catalysis at low and at high temperatures
  - Good qualitative agreement of $(\Sigma_u + \Sigma_d)/2$
  - The Polyakov loop value has a pronounced rise with B in the transition temperature region
  - Both pseudo-critical temperatures are decreasing functions of B