QCD phase diagram in a magnetic background

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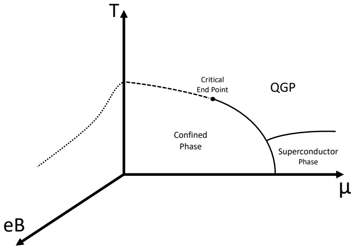


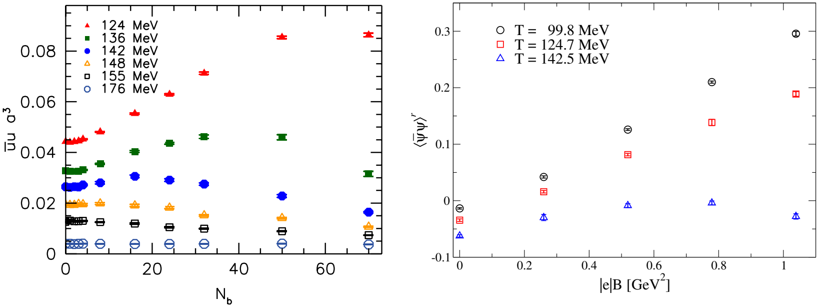
When a magnetic field is present, it is able to interact with the matter fields, which carry electric charge (i.e. quarks).

The vacuum properties are affected by the external field. Its effects are relevant even in the pure gauge sector of the theory, because of vacuum polarization effects.

Strong interacting matter can be found under such extreme conditions in the first stages of the Early Universe, in Magnetars and in heavy ion collisions.

The magnetic field, as well as the chemical potential, has effects on the thermodynamics of the theory. A drop in the critical temperature is the first signature of its presence.

Different predictions suggest that at extremely strong magnetic field intensities, the thermal crossover is expected to turn in a discontinuous phase transition.



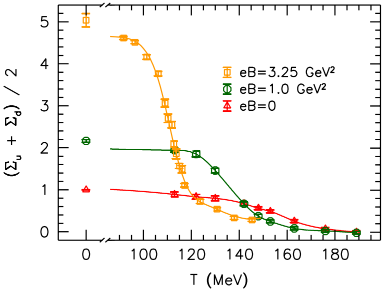
The magnetic catalysis is known to revert when the temperature approaches the pseudo critical region in which the crossover transition to the QGP phase takes place.

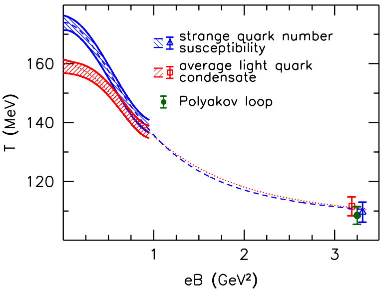
The stronger the magnetic field is, the more relevant the *"reverse chiral catalysis"* is. This effect combined with the chiral catalysis observed at low temperatures, results in a "strengthening" of the transition with the magnetic field.

G. S. Bali, F. Bruckmann, G. Endrodi, Z. Fodor, S. D. Katz, S. Krieg, A. Schafer and K. K. Szabo, JHEP **1202**, 044 (2012) [arXiv:1111.4956 [hep-lat]].

C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo Phys. Rev. D **94**, 094007 (2016) [arXiv:1607.08160 [hep-lat]].

Transition temperature

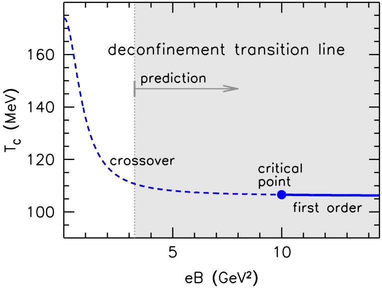




In this picture the strengthening of the transition is even clearer and another effect is highlighted: a strong background magnetic field causes a drop in the (pseudo) critical temperature.

The critical temperatures looking at different order parameters are closer, meaning that the crossover transition is slowly going to become a real and discontinuous phase transition.

G. Endrodi, JHEP **1507**, 173 (2015) [arXiv:1504.08280 [hep-lat]].



A speculative proposal for the position of the critical point in the QCD phase diagram in the (eB, T) plane was proposed by Endrődi in the same work.

The existence of a first order transition in a strong field regime is deduced from a model of anisotropic pure gauge theory, which is expected to approximate the $eB \gg \Lambda^2_{QCD}$ limit of QCD.

The localization of the critical point is based on an extrapolation to zero of the width of the susceptibility peak at the transition. No direct observations were performed.

G. Endrodi, JHEP **1507**, 173 (2015) [arXiv:1504.08280 [hep-lat]].

Magnetic field on the lattice

Continuum Dirac Operator in the presence of Abelian and non-Abelian gauge fields:

$$\overline{\psi}^f(x) D^f_\mu(x) \psi^f(x) = \overline{\psi}^f(x) \left(\partial_\mu + igG^a_\mu(x) T^a + iq^f A_\mu(x) + m^f \right) \psi^f(x)$$

The discretization can be performed through the following substitution in the usual LQCD quark action

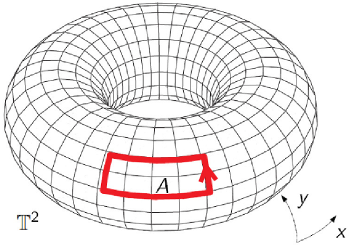
$$U_{i;\mu} \to u^f_{i;\mu} U_{i;\mu}$$

Where the Abelian phases $u^f_{i;\mu}$ are defined as follows

$$u^f_{i;y} = e^{ia^2 q_f B_z \, i_x}, \qquad u^f_{i;x}|_{i_x = L_x} = e^{-ia^2 q_f L_x B_z i_y}$$

And are quantized in order to avoid ambiguities in the definition:

$$eB = \frac{6\pi b_z}{a^2 L_x L_y}, \quad \text{with} \quad b_z \in \mathbb{Z} \quad \text{and} \quad b_z < \frac{L_x L_y}{6}.$$



Exploiting the equivalence between the path integral formulation of the QFTs and the statistical mechanics, we can perform simulations at finite temperature.

It can be done through the imposition of periodic boundary conditions on the Euclidean time direction of the lattice.

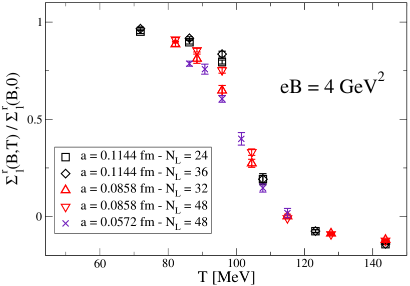
Then the temperature is linked to the physical extent of the time axis according to

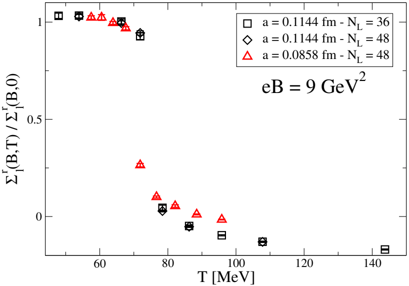
$$T(\beta, m_l, m_s, N_t) = \frac{1}{a(\beta, m_l, m_s)N_t} \qquad (\text{with} \quad K_B = 1).$$

Different temperatures can be probed both changing the lattice spacing a (suitably tuning the parameters) and changing the lattice sites number in the temporal axis N_t.

We simulated three different lattice spacings: $a = 0.114$, 0.0858 and 0.057 fm; and two different magnetic field values: $eB = 4$ and 9 GeV^2.

Chiral Transition





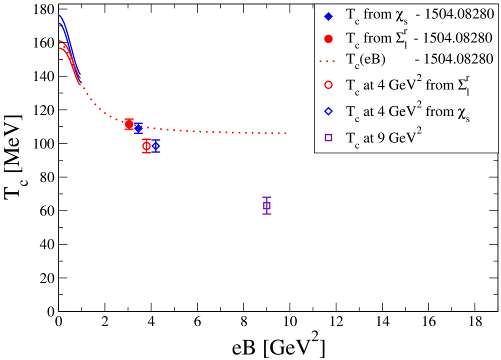
We performed simulations at higher values of the magnetic field, the same of the $T = 0$ section, bringing up to $eB = 9$ GeV^2 the limit of the direct observations.

The critical temperature for the transition is still dropping down to lower values as the magnetic field is increased.

The step in the chiral condensate across the transition looks steeper as the field grows, signaling that the phase transition could actually be a first order.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].

Critical temperature drop

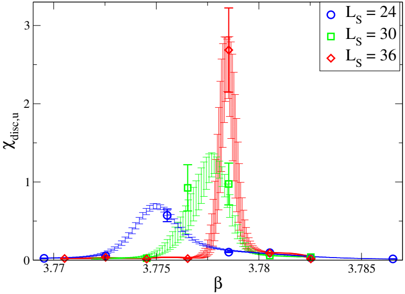


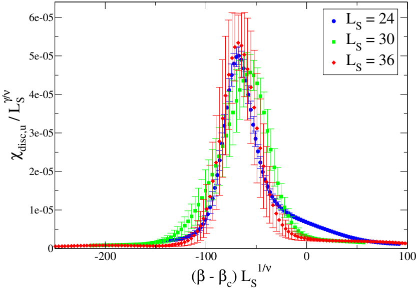
The drop in T_c that we observe is much higher than the predicted one.

An extrapolation on these data to $T_c = 0$ would return the deconfining magnetic field intensity $eB \simeq 18$ GeV^2.

There is no a ~ 4 GeV energy scale in QCD which would explain such a value for a deconfining magnetic field.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].





Because of the fixed scale prescription, a study of the nature of the transition at $eB = 9$ GeV^2 on the same constant physics line was not affordable with the available computational resources.

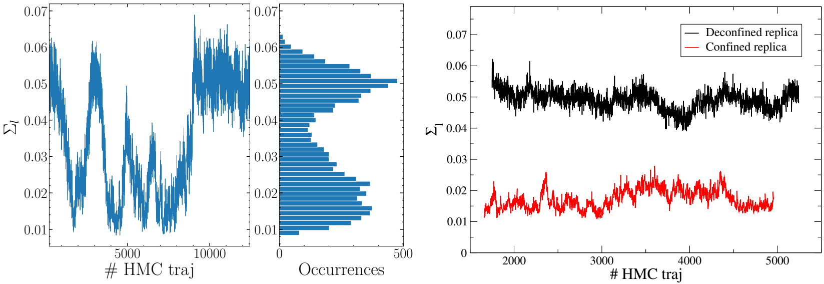
Since the presence of a first order transition is stable under small variations of the parameters, we performed a fine tuning in order to cross the critical line.

Using as starting point a simulation performed at a temperature and magnetic field close to the transition, we slightly changed β until the transition occurred.

Using this prescription, a finite size scaling was now affordable without lack in reliability, and it clearly shows a first order transition.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].

Transition nature



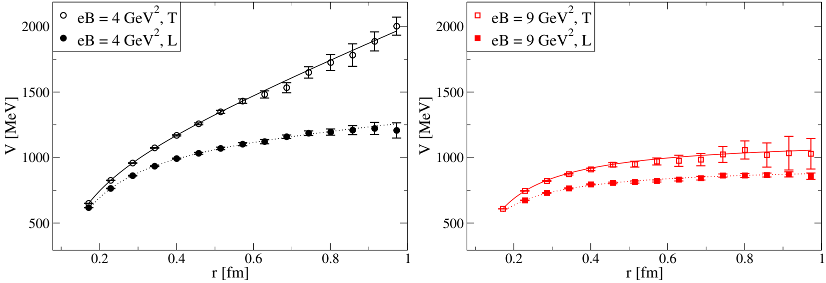
Other smoking guns of a first order transition are found on these samples.

A simulation running on the pseudo critical value of β shows indeed a bi-stable history of the chiral condensate.

At a larger volume the tunneling probability becomes small and simulations with the same parameters but different starting points show parallel histories.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].

Static potential across the critical line

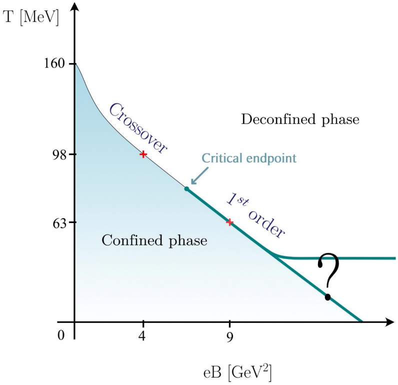


Looking again at the static potential, we found that it is compatible with a Coulomb description across the transition temperature.

An asymmetry is still present, but both in the longitudinal and transverse directions, this picture is compatible with deconfinement at $eB = 9\ \mathrm{GeV}^2$.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].

Phase diagram update



We propose a new hint for the phase diagram of the QCD in the (eB, T) plane, based upon our results.

Since the nature of the transition appears to be a crossover at $eB = 4$ GeV^2 and a first order transition at $eB = 9$ GeV^2, the critical endpoint should be located somewhere in that interval.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **105** (2022) no.3, 034511 [arXiv:2111.11237 [hep-lat]].

Summary & Outlooks

Summary

- The drop in T_c for $|e|B = 9$ GeV^2 is larger than expected;
- We found an analytical crossover transition at $eB = 4$ GeV^2, and a first order transition at $eB = 9$ GeV^2;
- A critical endpoint is expected to lie between this two magnetic fields at a temperature in the range $T_{CEP} \in (63, 98)$ MeV.

Outlooks

- Refining the prediction for the critical endpoint position;
- Studying phase properties across the critical line, in order to better classify the different phases (in his talk on Monday, Manuel Naviglio showed results on transport properties. Go back in time to hear him, if you missed it.)

Thanks for your attention.

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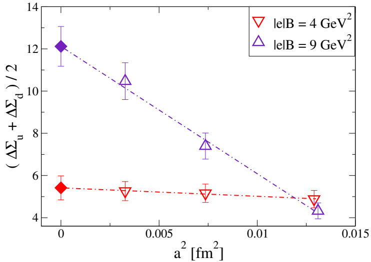
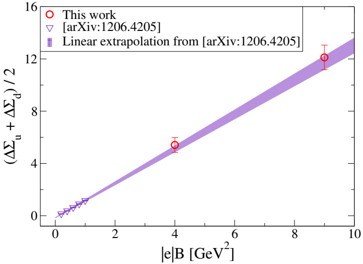
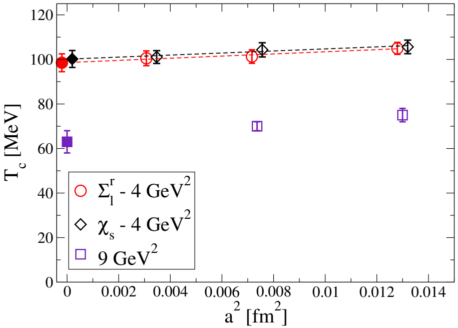




Finite UV cutoff effects on the system are well under control, as can be seen studying chiral condensate at vanishing temperature.

Finite lattice spacing effects are visible in coarsest lattices, but continuum limit extrapolates on values compatible with the Lowest Landau Level approximation predictions.

M. D'Elia, LM, F. Sanfilippo and A. Stanzione, Phys. Rev. D **104** (2021) no.11, 114512 [arXiv:2109.07456 [hep-lat]].



Finite cutoff effects on the transition temperature are under control: it slightly decreases toward continuum limit.

The low value it reaches at $eB = 9$ GeV^2 is such that it was unfeasible, given our computational resources, to observe a transition at the finest lattice spacing.

Our continuum extrapolation for the transition temperature, in such a strong background, is a guess, relying on the two finite lattice spacing measured critical temperatures, and on the well behaving scaling observed this far.