Properties of strongly interacting matter in extreme conditions

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In collaboration with: (NPQCD)
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Outline

- Introduction: QCD properties, phase diagram and lattice methods
- QCD and ElectroMagnetic Fields
- QCD Phase diagram in the $T - \mu$ plane
- Conclusions and perspectives

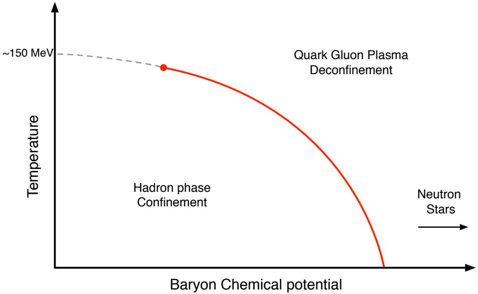
Introduction: Quantum ChromoDynamics (QCD)

QCD is the Gauge QFT describing quarks and gluons interactions

- Coupling constant $\alpha_s \sim \mathcal{O}(1)$: perturbation theory is hindered; need for a fully non-perturbative (NP) approach.
- The theory displays several NP properties, such as:
  - confinement
  - spontaneous breaking of chiral symmetry
  - topological activity
- These properties change according to external parameter:
  - Temperature
  - Baryon chemical potential / density
  - Electro-Magnetic fields
  - Topological θ term
- By changing these parameters phase transitions may originate, as well as new effects and properties.

Introduction: QCD phase diagram

When the energy scale identified by these external parameters is comparable to $\Lambda_{QCD} \sim 200$ MeV we expect something new to happen.



- Crossover transition to the QGP phase ($\mu = 0$).
- Sign problem at $\mu = 0$: simulations are hindered.
- Presence of a critical endpoint (??)

Prediction for the QCD phase diagram, not only in the $T - \mu$ plane, are of utmost importance for HIC experiments.

For example, in the early stages of non-central collisions magnetic fields of the order of $|e|B \sim 0.1$ GeV^2 are present.

Lattice QCD

Expectation values of observables $\langle \mathcal{O} \rangle$ can be expressed, via the Feynman path integral, as:

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}\phi \; \mathcal{O}[\phi, param] \; e^{-S_{QCD}[\phi, param]}$$

The integral $\mathcal{D}\phi$ is performed over all the possible fields configurations.

This infinite dimensional integral can be computed by
1) discretizing the theory on a finite lattice
2) adopting a Monte Carlo integration technique

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}U \; \mathcal{O} e^{-S^D_{QCD}[U, param]} = \int \mathcal{D}U \; \mathcal{O} \frac{P[U, param]}{Z}$$

where now U are the field variables of the discretized theory S^D_{QCD}.

Discretizations and Computing Resources

Lattice QCD is computationally very expensive, in particular if we have small masses and large lattices.

Anyhow, algorithms are naturally parallelizable.

One of the most time consuming task is the inversion of huge sparse matrices, which we perform adopting proper CG algorithms.
For example, on a $48^3 \times 96$ lattice we have $3 \cdot 10^7 \times 3 \cdot 10^7$ matrices.

QCD discretizations, codes and computing resources:

- Wilson gauge action $\oplus$ staggered fermions
  $\rightarrow$ serial and GPU codes for local resources
- Tree level improved Symanzik gauge action $\oplus$ stout smearing improved staggered fermions
  $\rightarrow$ parallel code for Zefiro and optimized for BG/Q, where we are investing $\sim$ 100 M $core-hours$ from 3 IscrB, 1 Prace and the INFN-Cineca agreement.

Work in progress: development of a multi-GPU code, implemented using the OpenAcc framework. More during E. Calore's talk on Friday.

Magnetic Fields research program

Recently, motivated by HIC, many groups started to investigate the physics of QCD in the presence of large magnetic fields.
Our contributions to the literature of this field:

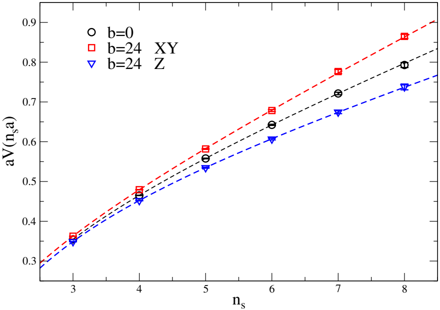
- Dependence of T_c on B
  [D'Elia, Mukherjee, Sanfilippo, PRD 82 (2010) 051501]
- Magnetic Catalysis at $T = 0$
  [D'Elia and N, PRD 83 (2011) 114028]
- Anisotropic static $Q\overline{Q}$ potential ✓
  [Bonati, D'Elia, Mariti, Mesiti, N and Sanfilippo, PRD 89 (2014) 11, 114502]
  $\oplus$ [Ongoing Work]
- Effective pseudo-scalar QED-QCD interactions
  [D'Elia, Mariti and N, PRL 110 (2013) 8, 082002]
  $\oplus$ [Ongoing Work]
- Magnetic Susceptibility at finite temperature ✓
  [Bonati, D'Elia, Mariti, N and Sanfilippo, PRL 111 (2013) 182001]
  [Bonati, D'Elia, Mariti, N and Sanfilippo, PRD 89 (2014) 5, 054506]
  $\oplus$ [Ongoing Work]

QCD Phase Diagram research program

- Curvature of the pseudocritical line in the $T-\mu$ plane ✓
  [Bonati, D'Elia, Mariti, Mesiti, N and Sanfilippo, PRD 90 (2014) 11, 114025]
  ⊕ [Ongoing Work]
- Phase diagram in the $T-\theta$ plane
  [D'Elia and N, PRL 109 (2012) 072001]
  [D'Elia and N, PRD 88 (2013) 3, 034503]
- Change of $\theta-$dependence across deconfinement
  [Bonati, D'Elia and Vicari, PRL 110 (2013) 25, 252003]
- Critical properties in the QCD phase diagram
  [Bonati, De Forcrand, D'Elia, Philipsen, Sanfilippo, PRD 90 (2014) 7, 074030]
  ⊕ [Ongoing Work]

Anisotropic $Q\overline{Q}$ potential: 1/2

Can the magnetic field affect a non perturbative property of the gauge fields, such as the confining potential? Surprisingly, yes!
Yes, even if the B field is directly coupled only to the quark field.



We simulated $N_f = 2 + 1$ QCD at physical quark masses, and we set a magnetic field oriented along the Z axis.
The potential becomes anisotropic, and more (less) steep in the XY (Z) direction.

We adopted 3 lattice spacings and we kept the volume constant in physical units $V \simeq (5 \text{ fm})^4$. In lattice units we had 24^4, 32^4 and 40^4.

Improvements: a finer lattice spacing on a $48^3 \times 96$ lattice, meson masses and finite temperature (Prace 34 Mh).

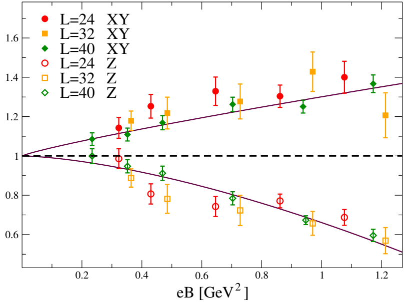
Anisotropic $Q\overline{Q}$ potential: 2/2

We parametrize the anisotropic static $Q\overline{Q}$ potential with the Cornell form

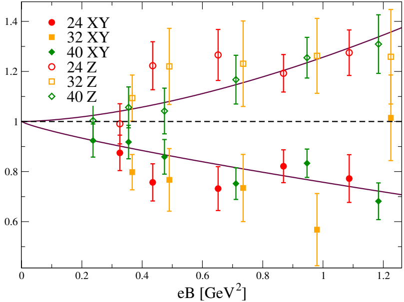
$$V(r\hat{d}) = C_d + \frac{\alpha_d}{r} + \sigma_d r$$

where the index d can be either XY or Z.

This induced anisotropy may considerably change the bound states of heavy quarks: possible effects on meson masses, and hence on their production and decay rates in HIC experiments.



String tension ratio



Coulomb parameter ratio

Magnetic susceptibility of the QCD medium: 1/3

How does strongly interacting matter responds to B?

Is the QCD medium a paramagnet or a diamagnet?

Is $\chi(T)$ positive or negative? Does it depends on T?

We should compute the magnetization (or higher derivatives):

$$\langle M(B) \rangle = \frac{\partial}{\partial B} \log Z$$

On the lattice only quantized values of B are physical.

$\longrightarrow$ Hence derivatives with respect to B are not well-defined!

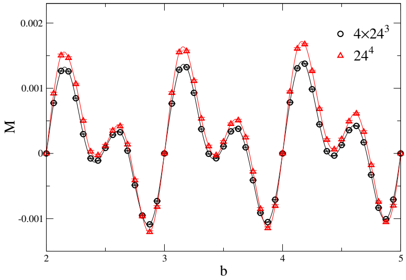
Then, we adopted a thermodynamic integration-like approach.
We get finite free energy differences between physical values of B from

$$\Delta F(B_1, B_2) = - \int_{B_1}^{B_2} db \, \frac{\partial \log Z}{\partial b}$$

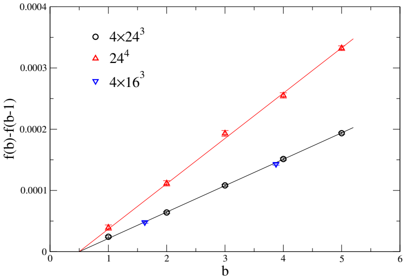
Finally, we determine $\chi(T)$ by performing a best fit ($F \propto B^2$).

Magnetic susceptibility of the QCD Medium: 2/3

Pseudo-Magnetization



Finite Differences of Free Energy

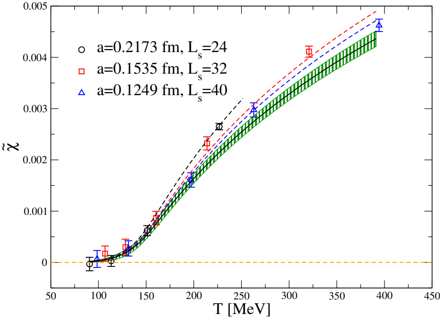


We have proposed the new method and performed a preliminary study adopting a standard discretization. [PRL (2013)]
GPU code on devices in Pisa and Genoa

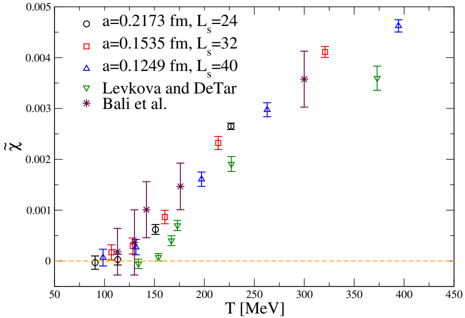
$\Longrightarrow$ We improved the results adopting a state-of-art discretization, physical quark masses and three lattice spacings. [PRD (2014)]
Parallel code on Zefiro and BG/Q

Magnetic susceptibility of the QCD Medium: 3/3

$\chi(T)$ and Continuum Limit



Various Comparisons



- QCD thermal medium is paramagnetic!
- The response is linear up to $eB \sim 0.1\text{GeV}^2$, a relevant field for HIC.
- χ sharply increases around T_c.

The magnetic contribution to the free energy (i.e. to the pressure) is large and can be relevant for the early stages of the Universe.

Improvement: computation of higher order derivatives (IscrB 10 Mh).

Curvature of the critical line: 1/3

An interesting topic, also from a phenomenological point of view (mainly for HIC experiments), is the QCD phase diagram in the $T - \mu_B$ plane.

The expected dependence of T_{pc} on μ_B can be parametrized as:

$$\frac{T_{pc}(\mu)}{T_{pc}(0)} = 1 - \kappa \left(\frac{\mu_B}{T_{pc}(0)} \right)^2 + \mathcal{O}(\mu_B^4)$$

There is not a general consensus about the value of the curvature κ: a severe sign problem hinders simulation at $\mu \neq 0$.

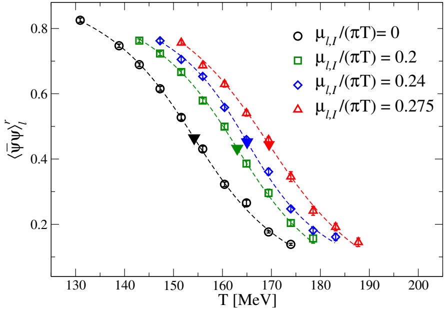
Adopting analytic continuation, we computed κ for $N_f = 2 + 1$ QCD at the physical point, using 2 different lattice spacings ($N_t = 6, 8$).
[Bonati, D'Elia, Mariti, Mesiti, N and Sanfilippo, PRD 90 (2014) 11, 114025]

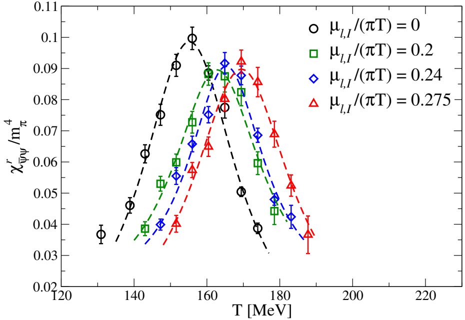
We are taking particular care into understanding the systematic effects due to finite volume, possible μ setups, ...

Curvature of the critical line: 2/3

We identify the transition temperature by computing the renormalized chiral condensate $\langle\bar{\psi}\psi\rangle_r$ and its susceptibility χ_r.

We repeat the simulations for some imaginary chemical potential:

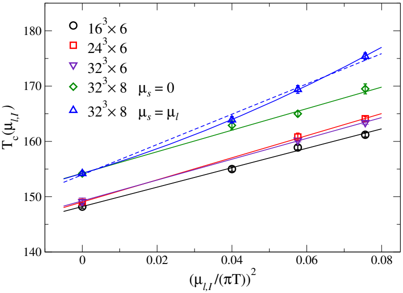




We extract T_{pc} for ~ 4 values of $\mu_{I,l}$, the light quark chemical potential.

- We have performed simualtions on $24^3 \times 6$ and $32^3 \times 8$ lattices.
- We studied the $16^3 \times 6$ and $32^3 \times 6$ lattice to check for volume effects.
- We adopted also the $\mu_{I,s} = \mu_{I,l}$ setup to check for systematics.

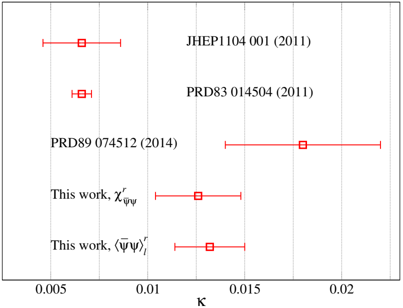
Curvature of the critical line: 3/3



- By fitting with a quadratic ansatz and trying a continuum limit we get:

$$\kappa = 0.013(2)(1)$$

- In the $\mu_s = \mu_l$ setup we observe the emergence of higher powers.



Comparison with other works:

- topmost two → Taylor expansion.
- middle → analytic continuation, different action; Cea, Cosmai and Papa (previous talk)
- last two → our results.

Improvements: refining the continuum limit ($N_t = 10$ at least) and study possible critcal behaviours (1 IscrB 7 Mh + INFN-Cineca agreement).

Conclusions

▶ Thanks to large scale computing resources we can now perform full QCD simulations at the physical point and extrapolate towards the continuum limit.

▶ QCD and strong Magnetic Fields:

- Anisotropic $Q\overline{Q}$ static potential
- Paramagnetic response of the QCD thermal medium

▶ Determination of the curvature of critical line in the $T - \mu$ plane (full $N_f = 2 + 1$ QCD at the physical point)

Future Perspectives:

- Improve previous computations, as discussed.
- Development of a multi-GPU code with OpenAcc.

Example:

the largest lattice we are adopting is a $48^3 \times 96$ lattice which requires about 20 GB of memory.

Because of cache memory reasons it best fits on 1024 BG/Q nodes (16 Kcores).

On this lattice, we reach $\sim\ 25 - 30$ % during the CG inversion of the fermion matrix.