STRONG INTERACTION IN EXTREME CONDITIONS

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Introduction
QCD

Quantum Chromodynamics (QCD) is the theory we use to describe strong interactions between color charges

Properties:

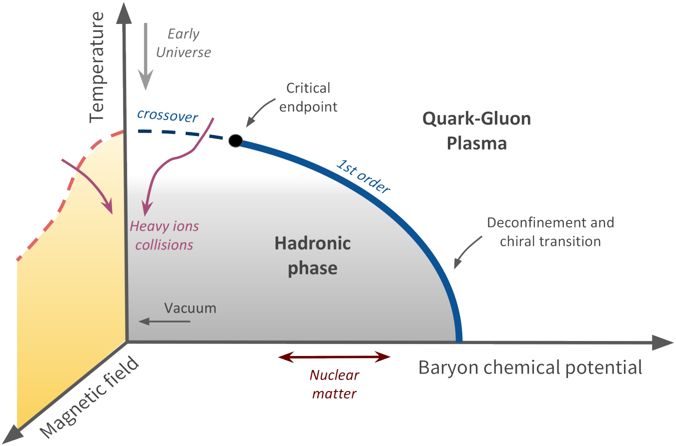
- **SU(3) gauge theory** with quarks fermionic matter while gluons are the gauge fields

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + \sum_f \bar{\psi}^f (i\not{D} - m_f)\psi^f$$

- **Confinement**: colored states cannot be observed
- **Asymptotic freedom**: coupling constant $g \to 0$ for high energies
- Almost exact **chiral symmetry** $\mathrm{SU}(N_f)_R \times \mathrm{SU}(N_f)_L$ which is spontaneously broken by $\langle \bar{\psi}\psi \rangle$

Introduction

(A POSSIBLE) QCD PHASE DIAGRAM

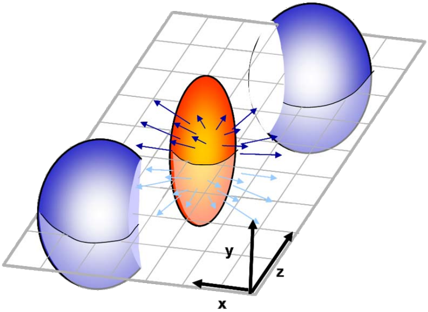


- **Chiral restauration** and **deconfinement** expected at high temperatures and/or baryon densities
- Magnetic field reduces the critical temperature [Bali et al. '11]

Introduction
QCD AND MAGNETIC FIELDS

QCD with strong magnetic fields $eB \simeq m_\pi^2 \sim 10^{15-16}$ T

- **Non-central heavy ion collisions** [Skokov et al. '09]
- Possible production in early universe [Vachaspati '91]



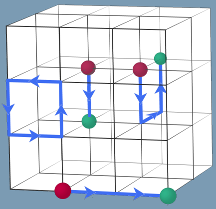
In **heavy ion collisions**:

- Expected $eB \simeq 0.3$ GeV^2 at LHC in Pb+Pb at $\sqrt{s_{NN}} = 4.5$ TeV
- Spatial distribution of the fields and lifetime are still debated

Introduction
LATTICE QCD

QCD +
path integral +
euclidean +
discretization +
finite volume +
Monte-Carlo =

Lattice QCD



LQCD formulation allows to study non-perturbative regime of QCD

Quark fields $\psi(n)$ and gluon links $U_\mu(n)$ (SU(3) parallel transports) discretized in a $N \times N_t$ volume with spacing a and temperature given by $T = 1/(aN_t)$.

Monte-Carlo: system configurations are sampled according to the desired probability distribution, then physical observables are computed over the sample

An external **magnetic field on the lattice** can be introduced through abelian parallel transports $u_\mu(n)$

$$U_\mu(n) \rightarrow U_\mu(n) u_\mu(n)$$

PROJECT OUTLINE

Aim: Study of the heavy quark $Q\bar{Q}$ interaction in the presence of an external strong magnetic field

Confined phase:
in-depth study of the static potential

- anisotropy
- large B limit
- finite T

Phys. Rev. D**94**, 094007 (2016)

Deconfined phase:
influence of the magnetic field on the screened potential

- extraction of the screening masses

Phys. Rev. D**95**, 074515 (2017)

The Anisotropic Potential
STATIC POTENTIAL

The $Q\bar{Q}$ potential is well described by the Cornell formula

$$V(r) = -\frac{\alpha}{r} + \sigma r + \mathcal{O}\left(\frac{1}{m^2}\right)$$

where α is the Coulomb term and σ is the **string tension**.

On the lattice the potential has been largely investigated and it is extracted from the behaviour of some observables

- At **T=0** from Wilson loops

  $$V(R) = \lim_{t\to\infty} \log \frac{W(R,t+1)}{W(R,t)}$$

  with $W(R,t)$ a rectangular $R \times t$ loop made up by gauge links $U_\mu(n)$.

- At **T>0** from Polyakov correlators

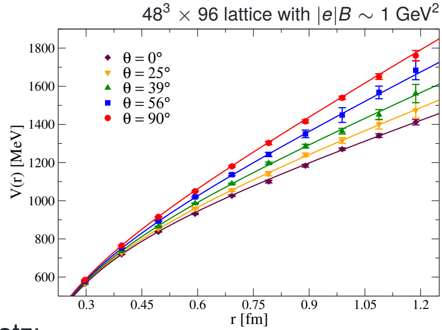
  $$V(R) \simeq -\frac{1}{\beta} \log\langle \mathrm{Tr}L^\dagger(R)\mathrm{Tr}L(0)\rangle$$

  where $L(R)$ is a loop winding over the compact imaginary direction.

The Anisotropic Potential
STUDY AND RESULTS T=0

Using a constant and uniform B:

- Wilson loop averaged over different spatial directions
- Access to 8 angles using three $\vec{B}$ orientations



V(R) is anisotropic. Ansatz:

$$V(R,\theta,B) = -\frac{\alpha(\theta,B)}{R} + \sigma(\theta,B)R + V_0(\theta,B)$$

$$\mathcal{O}(\theta,B) = \bar{\mathcal{O}}(B)\left(1 - \sum_n c_{2n}^{\mathcal{O}}(B)cos(2n\theta)\right)$$

where $\mathcal{O} = \alpha, \sigma, V_0$ and θ angle between quarks and $\vec{B}$.

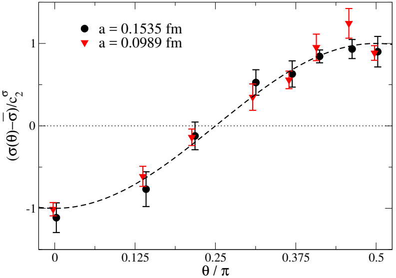
The Anisotropic Potential
STUDY AND RESULTS T=0

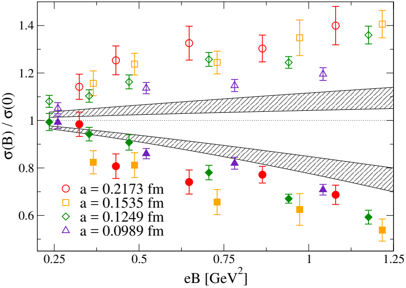
Results:

- Good description in terms of c_2s only
- $\bar{\mathcal{O}}(B)$s compatible with values at $B = 0$

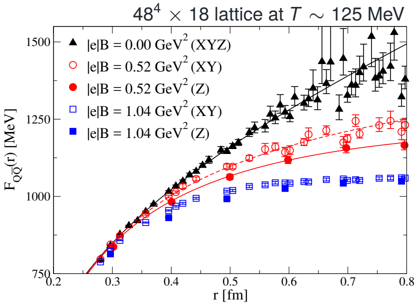
Continuum limit:

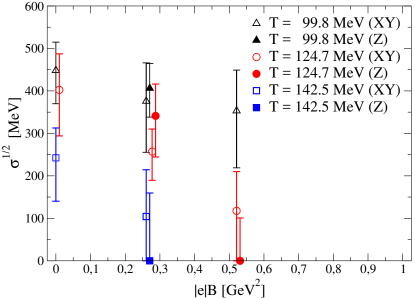
- Anisotropy c_2^σ of the string tension survives the limit $a \to 0$
- c_2^α and $c_2^{V_0}$ compatible with zero
- Large field limit: string tension seems to vanish for $|e|B \sim 4\text{GeV}^2$





The Anisotropic Potential
STUDY AND RESULTS T>0





Results:

- Anisotropy still visible but disappears at large *r*
- String tension decreases with *T*
- Cornell form fits only at small *B*
- Magnetic field effects enhanced near T_c

Data compatible with a decrease of T_c due to B [Bali et al. '12]

Screening masses in magnetic Field
DEBYE SCREENING

In the deconfined phase the color interaction is screened

Screening mass(es) can be defined non-perturbatively by studying the large distance behaviour of suitable gauge-invariant correlators

[Nadkarni ’86, Arnold and Yaffe ’95, Braaten and Nieto ’94]

Looking at the Polyakov correlator $C_{LL^\dagger}(r,T)$ we expect it to decay

- with correlation length $1/m_E$ dominant at small distances

$$C_{LL^\dagger}(\mathbf{r}) \sim \frac{1}{r} e^{-m_E(T)r}$$

- with length $1/m_M$ dominant at larger distances

$$C_{LL^\dagger}(\mathbf{r}) \sim \frac{1}{r} e^{-m_M(T)r}$$

Using symmetries it is possible to separate the electric and magnetic contributions and **define correlators decaying with the desired screening masses**. [Arnold and Yaffe ’95, Maezawa et al. ’10, Borsanyi et al. ’15]

Screening masses in magnetic Field
STUDY AND RESULTS

Some results:

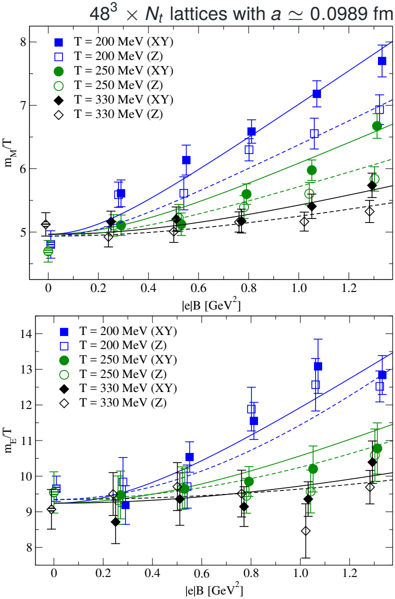
- $m_E > m_M$ and $m_E/m_M \sim 1.5 - 2$
- masses grow linearly with T

[Maezawa et al. '10, Borsanyi et al. '15 (lattice)
Hart et al. '00 (EFT)]

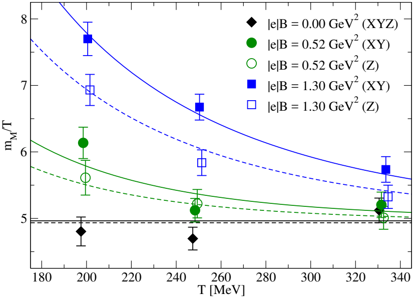
Turning on the magnetic field

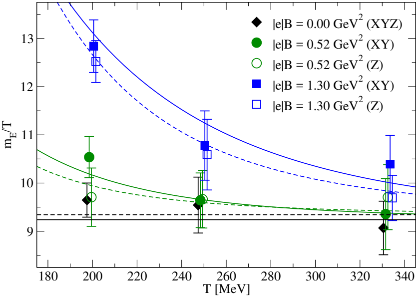
we studied the screening masses behaviour along the directions parallel and orthogonal to **B**

- Values at $B = 0$ agree previous results
- Masses increase with B
- Magnetic mass m_M show a clear anisotropic effect



Screening masses in magnetic Field
STUDY AND RESULTS





Results:

- Magnetic effects vanish when T increase
- A simple ansatz describing our data

$$\frac{m^d}{T} = a^d \left[1 + c_1^d \frac{eB}{T^2} \operatorname{atan}\left(\frac{c_2^d}{c_1^d}\frac{eB}{T^2}\right)\right]$$

Data compatible with a decrease of T_c due to B [Bali et al. '12]

The results we obtained about the effects of magnetic fields on $Q\bar{Q}$ interaction show that

- The potential is deeply influenced by B
- Also the screening properties get modified
- All the results agree the picture of a decreasing T_c due to the external field

Possible implications:

- On the heavy quarkonia spectrum: mass variations, mixings and Zeeman-like splitting effects
  [Alford and Strickland ’13, Bonati et al. ’15]
- On heavy meson production rates in non-central ion collisions [Guo et al. ’15, Matsui and Satz ’86]

PROJECT OUTLINE
FUTURE PROSPECTIVES

2015 | 2016 | 2017 | 2018 |

Anisotropic static potential + non-zero temperature + large B

Screening effects in magnetic field

TODO: Screening at finite density

OTHER TODO:
- ?
- write thesis

TODO: Flux tube in magnetic field