STRONG INTERACTIONS IN BACKGROUND MAGNETIC FIELDS

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INTRODUCTION

THE ANISOTROPIC STATIC POTENTIAL

SCREENING MASSES IN MAGNETIC FIELD

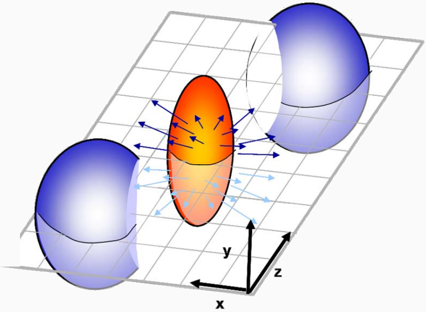
CONCLUSIONS

INTRODUCTION

QCD and magnetic fields

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

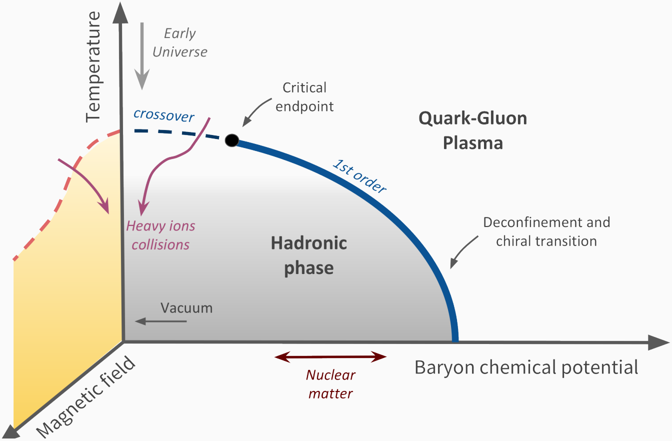
- **Non-central heavy ion collisions** (Skokov et al. '09)
- Possible production in early universe (Vachaspati '91)



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

Phase diagram of QCD

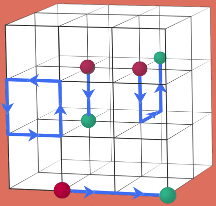


- **Chiral restauration** and **deconfinement** expected at high temperatures and/or baryon densities
- Magnetic field reduces the critical temperature (Bali et al. '11)

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

What about **magnetic fields?**

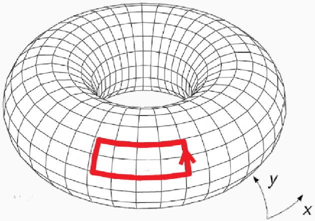
Background field on the lattice

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

- Abelian phases enter the Lagrangian by modifying the covariant derivative

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

- External magnetic field: non-propagating fields, no kinetic term



- Periodic boundary conditions lead to the quantization condition

$$|q_{\mathrm{min}}| B = \frac{2\pi b}{a^2 N_x N_y} \quad b \in \mathbb{Z}$$

THE ANISOTROPIC STATIC 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

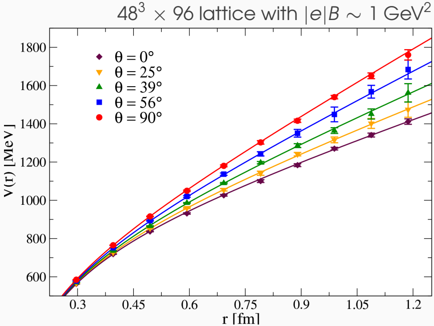
$$V(R) \simeq -\frac{1}{\beta} \log\langle \mathrm{Tr}L^\dagger(R)\mathrm{Tr}L(0)\rangle$$

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

Study and results zero temperature

Using a constant and uniform B: (Bonati et al. '16)

- 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 $\vec{B}$.

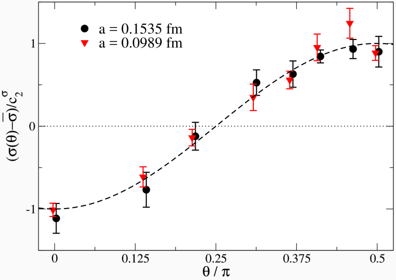
Study and results zero temperature

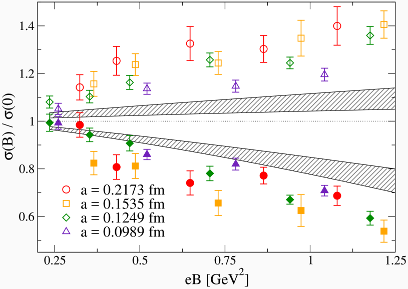
Results:

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

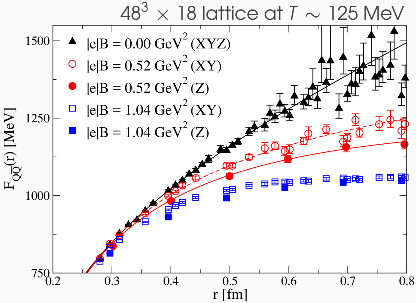
Continuum limit:

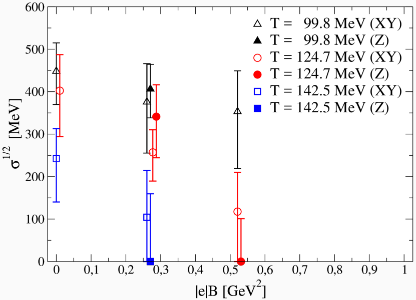
- Anisotropy c_2^σ of the string tension survives the limit $a \to 0$
- c_2^α and $c_2^{V_0}$ compatible with zero
- Large field limit: string tension seems to vanish for $|e|B \sim 4\text{GeV}^2$





Study and results at (not so) high T





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 decrease of T_c due to B (Bali et al. '12)

SCREENING MASSES IN MAGNETIC FIELD

Screening masses definition

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**.

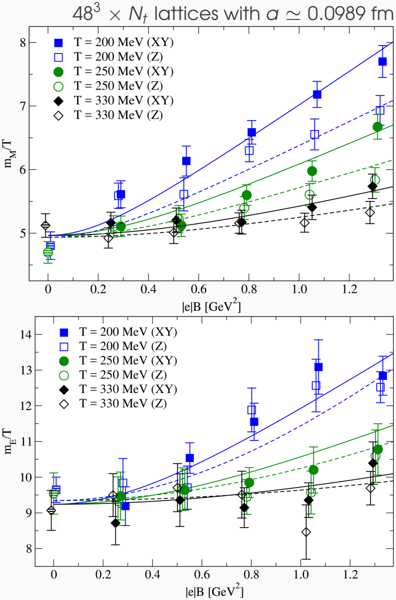
(Arnold and Yaffe '95, Maezawa et al. '10, Borsanyi et al. '15)

Study and results

Some results:

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

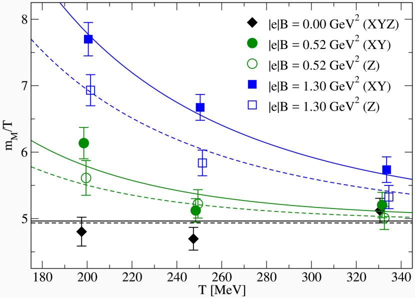
(Maezawa et al. '10, Borsanyi et al. '15 (lattice) Hart et al. '00 (EFT))

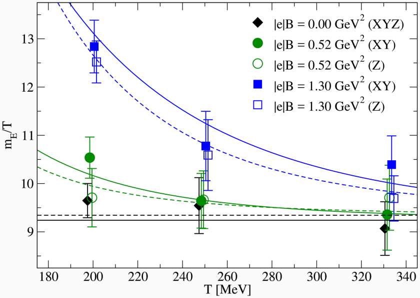


Turning on the magnetic field we studied the screening masses behaviour along the directions parallel and orthogonal to **B** (Bonati et al. '17)

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

Study and results





Results:

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

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

Data compatible with decrease of T_c due to B (Bali et al. ’12)

CONCLUSIONS AND RECAP

CONCLUSIONS

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)

Todo with magnetic fields:

- Effects on flux tube / color-electric field