Influence of magnetic fields on the color screening masses

[Phys.Rev.D95,074515]

C.Bonati[2], M.D'Elia[1], M.Mesiti[1], F.Negro[1], *A.Rucci*[1], F.Sanfilippo[3]

[1] *Department of Physics of University of Pisa and INFN Pisa, Italy*
[2] *Department of Physics and Astronomy of University of Florence and INFN Florence, Italy*
[3] *INFN Roma Tre, Italy*

Lattice 2017
35th International Symposium on Lattice Field Theory

Influence of magnetic fields on the color screening masses

[Phys.Rev.D95,074515]

- Introduction
- Color screening
- Study at $B > 0$
- Conclusions

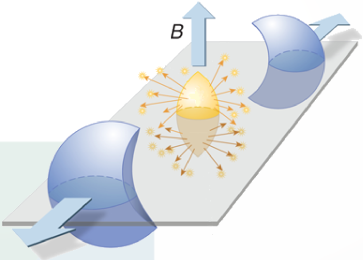
intro **physical conditions**

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

- **Non-central heavy ion collisions** with $eB \sim 10^{15}$T [Skokov et al. '09]
- Possible production in early universe $eB \sim 10^{16}$T [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 and $b = 4$fm
- Timescales depend on thermal medium properties (most pessimistic case: $0.1 - 0.5$ fm/c)
- Spatial distribution of the field and lifetime are still debated



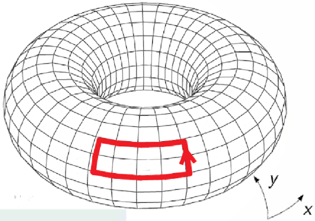
intro **turning on the B field**

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

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

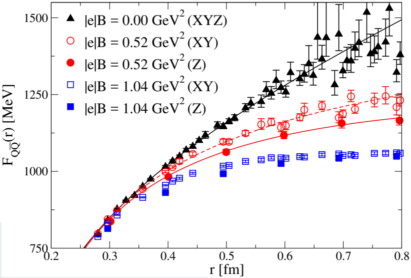
intro **to T_C and beyond!**

In the confined phase at $T < T_c$ the $Q\bar{Q}$ interaction is described by the Cornell potential

$$V_C(r) = -\frac{\alpha}{r} + \sigma r + V_0 \qquad \sigma \simeq (440\text{MeV})^2 \quad \alpha \sim 0.4$$

When $B > 0$: [Bonati et al. '16]

- Interaction becomes anisotropic (mostly due to the string tension)
- Effects larger as B grows
- Magnetic field enhances the string suppression



Picture from [Bonati et al. '16]

In the deconfined phase $T > T_c$:

- The effective color interaction is screened by the medium
- Heavy-quarks bound states suppressed in QGP [Matsui and Satz '86]
- The effect of the magnetic field... **what happens?**

color screening **Debye mass(es)**

How we define the screening masses?

Naïve approach: Debye mass (or inverse screening length) from the pole in the gluon self-energy propagator at leading order

$$m_D = \left(\frac{N_c}{3} + \frac{N_f}{6}\right)^{1/2} gT + \mathcal{O}(g^2 T)$$

where

- m_D is the "electric" mass m_E
- unscreened magnetic field (at this order) $m_B = 0$

But at higher orders **perturbation theory breaks down** due to non-perturbative contributions of magnetic gluons [Nadkarni '86]

- at small distances $r \ll (g^2 T)^{-1}$ **electric gluons** dominates
- at larger distances $r \gtrsim (g^2 T)^{-1}$ the **magnetic contribution** is no longer negligible

color screening **Debye mass(es)**

Another approach needed: **study the large distance behaviour of a suitable gauge-invariant correlator** in high temperature regime

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

One can consider the correlator between Polyakov loops

$$C_{LL^\dagger}(\mathbf{r}, T) = \langle \mathrm{Tr} L(\mathbf{0}) \mathrm{Tr} L^\dagger(\mathbf{r}) \rangle$$

with

$$L(\mathbf{r}) = \frac{1}{N_c} \mathcal{P} \exp\left(-ig \int^{1/T} A_0(\mathbf{r}, \tau) d\tau \right)$$

and look at its decay

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

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

- with length $1/m_M$ at larger distances

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

How we can discern the two contributions?

color screening **magnetic and electric sectors**

It is possible to use symmetries to separate the electric and magnetic contributions [Arnold and Yaffe '95, Maezawa et al. '10, Borsányi et al. '15]

Idea:

- Using Euclidean time-reversal: $A_i(\mathbf{r},\tau)$ and $A_0(\mathbf{r},\tau)$ are, respectively, even and odd; hence

$$L_M = (L + L^\dagger)/2 \qquad L_E = (L - L^\dagger)/2$$

  receive contributions only from magnetic and electric sectors

- Further decompose using charge conjugation $L \to L^*$, so that

$$L_{M\pm} = (L_M \pm L_M^*)/2 \qquad L_{E\pm} = (L_E \pm L_E^*)/2$$

and now we can **define magnetic and electric correlators** as

$$C_{M^+}(\mathbf{r},T) = \langle \mathrm{Tr} L_{M^+}(\mathbf{0}) \mathrm{Tr} L_{M^+}(\mathbf{r}) \rangle - |\langle \mathrm{Tr} L \rangle|^2$$
$$C_{E^-}(\mathbf{r},T) = -\langle \mathrm{Tr} L_{E^-}(\mathbf{0}) \mathrm{Tr} L_{E^-}(\mathbf{r}) \rangle$$

color screening **magnetic and electric sectors**

Fun facts: $\mathrm{Tr}L_M^+ = \mathrm{ReTr}L$, $\mathrm{Tr}L_E^- = i\mathrm{ImTr}L$ and $\mathrm{Tr}L_M^- = \mathrm{Tr}L_E^+ = 0$ and

$$C_{LL^\dagger}(\mathbf{r},T) - |\langle \mathrm{Tr}L\rangle|^2 = C_{M^+}(\mathbf{r},T) + C_{E^-}(\mathbf{r},T)$$

At this point one can expect C_M and C_E to decay as

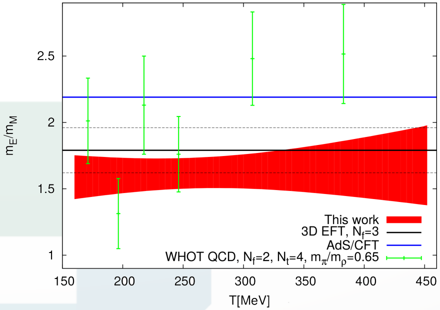
$$C_{E^-}(\mathbf{r},T) \sim \frac{1}{r}e^{-m_E(T)\mathbf{r}} \qquad C_{M^+}(\mathbf{r},T) \sim \frac{1}{r}e^{-m_M(T)\mathbf{r}}$$

Some results:

- masses grow linearly with T
- $m_E > m_M$ (expected)
- $m_E/m_M \sim 1.5 - 2$
- $m_E/T \simeq 7 - 8$,
  $m_M/T \simeq 4 - 4.5$

[Maezawa et al. '10, Borsányi et al. '15] (lattice)

[Hart et al. '00] (EFT)



Picture from [Borsányi et al. '15]

study at $B > 0$ **numerical setup and method**

Let's **see what happens if we turn on a magnetic field**

Numerical setup

- tree-level improved gauge action
- N_f=2+1 rooted staggered fermions + stout improvement
- three lattices $48^3 \times 6$, $48^3 \times 8$ and $48^3 \times 10$ corresponding to $T \simeq 330$MeV, $T \simeq 250$Mev and $T \simeq 200$MeV
- fixed spacing $a \simeq 0.0989$ fm
- simulations at physical quark masses

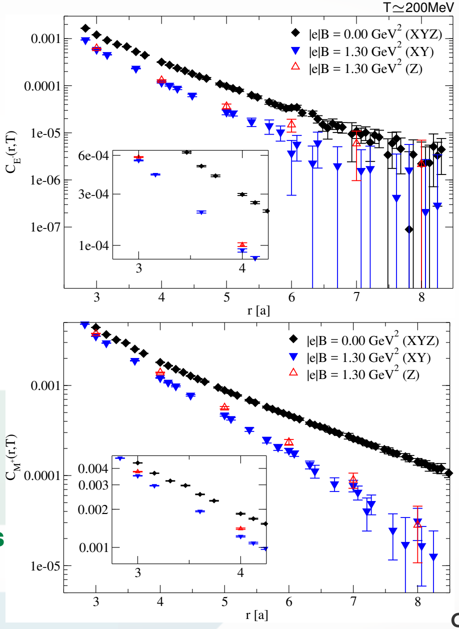
Measure of the correlators:

- Set of $\sim 5 \times 10^3$ confs for each temperature
- Extracted for generic orientations at $B = 0$
- Extracted separately along the **B** axis and in the whole orthogonal plane when $B > 0$
- Masses extracted through a fit on the ansatz e^{-mr}/r

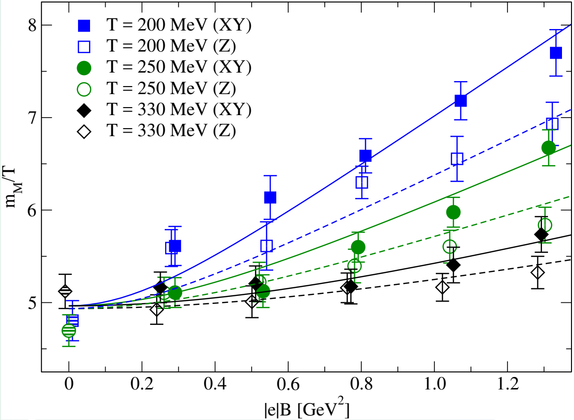
study at $B > 0$ **correlators**

Results of the correlators with magnetic field $\mathbf{B} \parallel \hat{z}$

- Both the correlators feel the magnetic field
- Correlators decay faster when $B > 0$, i.e. **masses seem to increase**
- The magnetic effect is **greater on the magnetic correlator**
- **Anisotropic effect**: different behaviour on parallel direction and orthogonal plane
- Effects seem to **reduce as temperature grows**

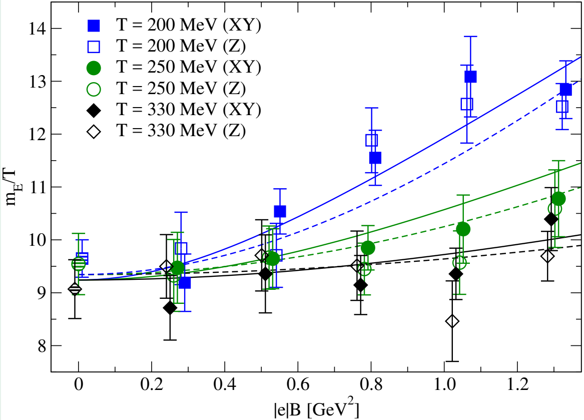


study at $B > 0$ **masses**



- Masses at $B = 0$ agree previous lattice results [Borsányi et al. '15].
- Both the masses increase with B but only m_M shows a clear anisotropic effect
- Masses are roughly linear in B for $|e|B \gtrsim 0.2 - 0.3$ MeV

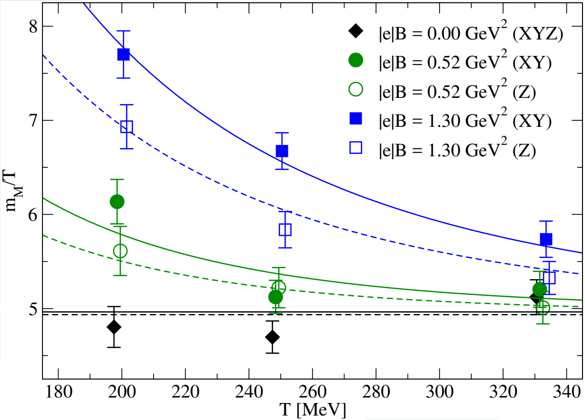
study at $B > 0$ **masses**



- Masses at $B = 0$ agree previous lattice results [Borsányi et al. '15].
- Both the masses increase with B but only m_M shows a clear anisotropic effect
- Masses are roughly linear in B for $|e|B \gtrsim 0.2 - 0.3$ MeV

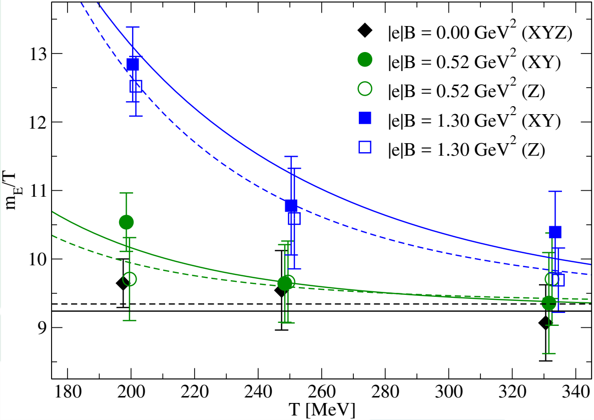
study at $B > 0$ **masses**

- Magnetic effects vanish when T increases
- Mass hierarchy does not change
- Ratio m_E/m_M turns out to be independent of both B and T



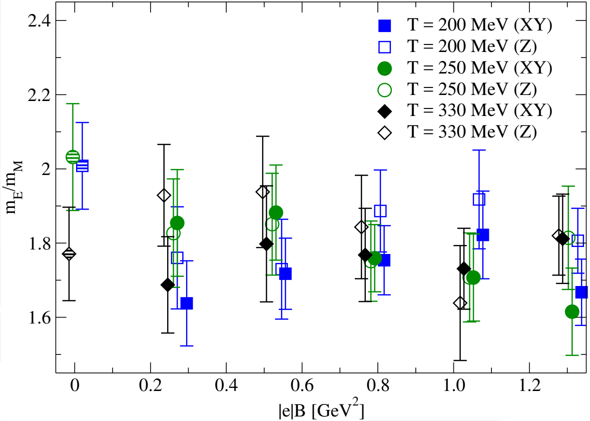
study at $B > 0$ **masses**

- Magnetic effects vanish when T increases
- Mass hierarchy does not change
- Ratio m_E/m_M turns out to be independent of both B and T



study at $B > 0$ masses

- Magnetic effects vanish when T increases
- Mass hierarchy does not change
- Ratio m_E/m_M turns out to be independent of both B and T



study at $B > 0$ **masses**

Attempt to describe the observed behaviour imposing

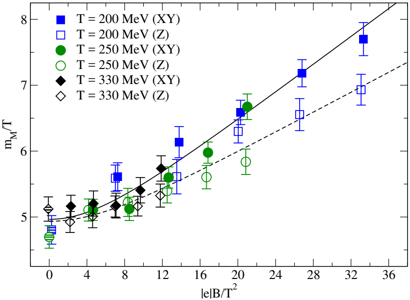
- m_E/T and m_M/T indipendent of T at $B = 0$
- linear dependence of B for large magnetic fields

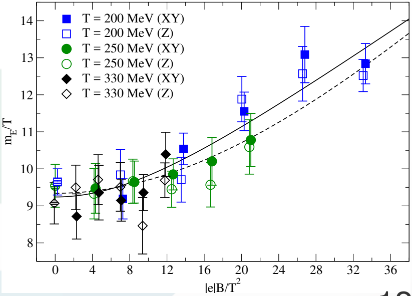
A simple ansatz is

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

for both masses and so that

- it depends only on $|e|B/T^2$
- is quadratic for small B





conclusions **and summary**

Summary:

- Screening masses increase in the presence of a B field
- Linear dependence for moderate fields ($|e|B \gtrsim 0.2\mathrm{GeV}^2$)
- Mass ratio seem to be independent to B
- Magnetic effects vanish at large T

Discussion and implications:

- Observed mass variations expected also by pertubative computations [Bandyopadhyay et al. '17]
- Results are in qualitative agreement with a decrease of T_C in strong magnetic fields [Bali et al. '11]
- Possible effects on heavy-quarks bound states caused by the shortening of the screening length? [Matsui and Satz '86]

conclusions **and summary**

Summary:

- Screening masses increase in the presence of a B field
- Linear dependence for moderate fields ($|e|B \gtrsim 0.2\text{GeV}^2$)
- Mass ratio seem to be independent to B
- Magnetic effects vanish at large T

Discussion and implications:

- Observed mass variations expected also by pertubative computations [Bandyopadhyay et al. '17]
- Results are in qualitative agreement with a decrease of T_C in strong magnetic fields [Bali et al. '11]
- Possible effects on heavy-quarks bound states caused by the shortening of the screening length? [Matsui and Satz '86]

THANK YOU!

backup **computation of C_M and C_E**

Using the relations

$$\mathrm{Tr}L_M^+ = \mathrm{Re}\mathrm{Tr}L \qquad \mathrm{Tr}L_E^- = i\mathrm{Im}\mathrm{Tr}L$$

the magnetic and electric correlators can be written as

$$C_{M^+} = +\frac{1}{2}\mathrm{Re}\left[C_{LL} + C_{LL^\dagger}\right] - |\langle \mathrm{Tr}L\rangle|^2 \qquad C_{E^-} = -\frac{1}{2}\mathrm{Re}\left[C_{LL} - C_{LL^\dagger}\right]$$

What about the C_{LL} correlator?

- For $T > T_c$ and large distances (strong deconfinement), its behaviour is similar to $C_{LL^\dagger}$
- Strongly suppressed for $T < T_c$ (in a pure gauge theory it would be zero