Heavy quark interactions in magnetic backgrounds

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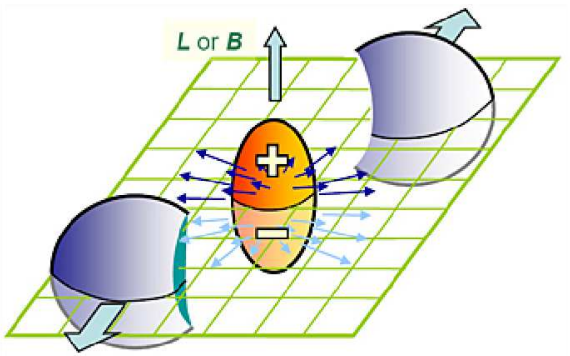
Bound states in strongly coupled systems - GGI - Arcetri - 14 March 2018

OUTLINE

- **QCD in a magnetic background: why it is interesting and main features**
- **Heavy-quark potential in a magnetic background**
- **Above T_c: gauge invariant electric and magnetic screening masses**

Electroweak interactions in general induce small corrections to strong interaction dynamics, but exceptions are expected in the presence of strong e.m. backgrounds, a situations which is relevant to many contexts:

- Large magnetic fields ($B \sim 10^{10}$ Tesla) are expected in a class of neutron stars known as magnetars (Duncan-Thompson, 1992).
- Large magnetic fields ($B \sim 10^{16}$ Tesla, $\sqrt{|e|B} \sim 1.5$ GeV), may have been produced at the cosmological electroweak phase transition (Vachaspati, 1991).
- 

in non-central heavy ion collisions, largest magnetic fields ever created in a laboratory (B up to 10^{15} Tesla at LHC) with a possible rich associated phenomenology: chiral magnetic effect (Vilenkin, 1980; Kharzeev, Fukushima, McLerran and Warringa, 2008).

E.m. fields affect quarks directly and gluons only at the 1-loop level.

However non-perturbative effects can be non-trivial in the gluon sector as well.

Various model computations predict a rich phenomenology:

- Effects on the QCD vacuum structure:
  - chiral symmetry breaking? Quite natural (Magnetic catalysis of χSB)
  - confinement? Less obvious (see later)
- Effects on the QCD phase diagram: $T_c(\mu)$? New phases?
- Equation of state: is strongly interacting matter paramagnetic or diamagnetic?

LQCD is the ideal tool for a non-perturbative investigation of such issues. QCD+QED studies of the e.m. properties of hadrons go back to the early days of LQCD

- G. Martinelli, G. Parisi, R. Petronzio and F. Rapuano, Phys. Lett. B 116, 434 (1982).

- C. Bernard, T. Draper, K. Olynyk and M. Rushton, Phys. Rev. Lett. 49, 1076 (1982).

A magnetic background does not pose any technical problem (such as a sign problem) to lattice QCD simulations.

An e.m. background field a_μ modifies the covariant derivative as follows:

$$D_\mu = \partial_\mu + i\, g A_\mu^a T^a \quad \rightarrow \quad \partial_\mu + i\, g A_\mu^a T^a + i\, q a_\mu$$

in the lattice formulation:

$$D_\mu \psi \rightarrow \frac{1}{2a}\left(U_\mu(n) u_\mu(n)\psi(n+\hat{\mu}) - U_\mu^\dagger(n-\hat{\mu}) u_\mu^*(n-\hat{\mu})\psi(n-\hat{\mu})\right)$$

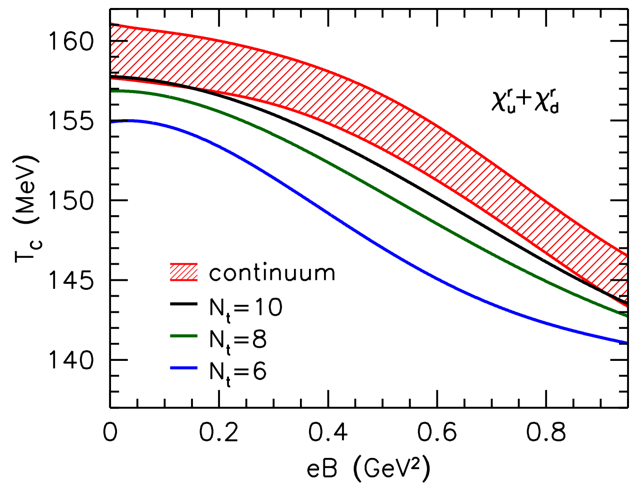
$U_\mu \in SU(3) \qquad \mathbf{u}_\mu \simeq \exp(\mathbf{i\, q\, a}_\mu(\mathbf{n})) \in \mathbf{U(1)}$

- $F_{ij}^{(em)} \neq 0 \implies$ **non-zero magnetic field (no sign problem)**
- $F_{0i}^{(em)} \neq 0 \implies$ **non-zero imaginary electric field (sign problem for real e. f.)**
- **Uniform background field are quantized in the presence of periodic boundary conditions**

Some properties of QCD in a strong magnetic field from the lattice

The magnetic field has strong effects also on QCD thermodynamics and leads to a decrease of the pseudo-critical temperature

G. S. Bali et al., arXiv:1111.4956

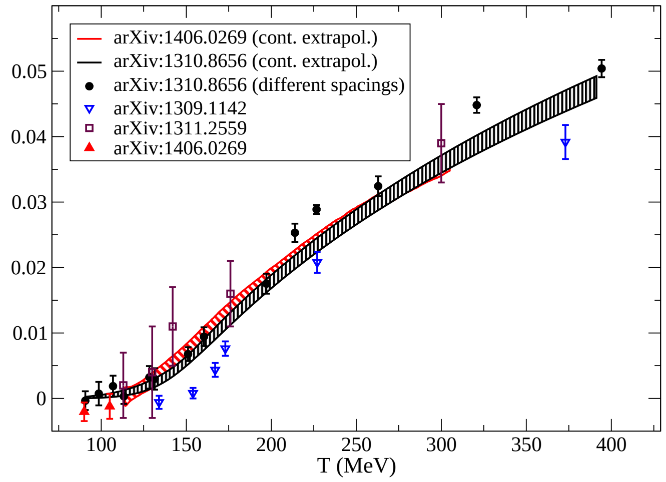


The thermal QCD medium becomes strongly paramagnetic right above T_c. On the left: magnetic susceptibility

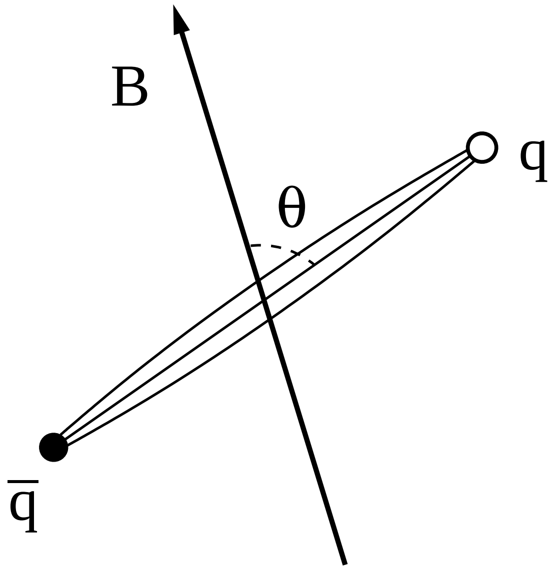
C. Bonati et al., arXiv:1307.8063, arXiv:1310.8656;

L. Levkova and C. DeTar, arXiv:1309.1142;

G. S. Bali et al., arXiv:1406.0269



The magnetic field has also shown to strongly influence the interaction between heavy quarks, introducing an anisotropy in the potential.

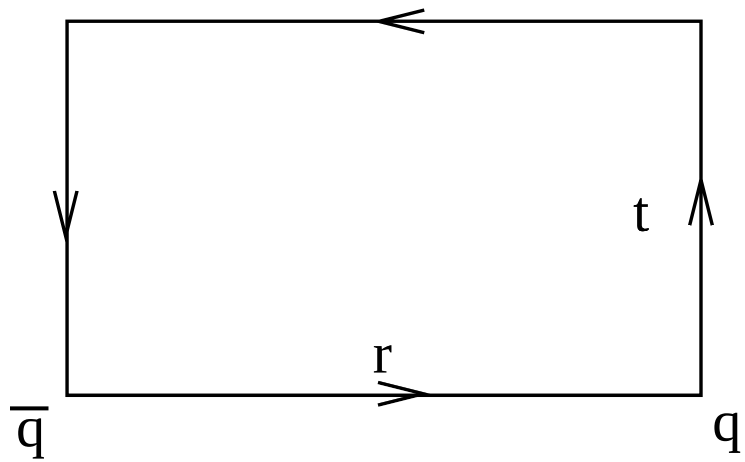


C. Bonati, MD, M. Mariti, M. Mesiti, F. Negro, A. Rucci, F. Sanfilippo, arXiv:1403.6094, arXiv:1607.08160

$N_f = 2+1$ with rooted staggered quark at the physical point

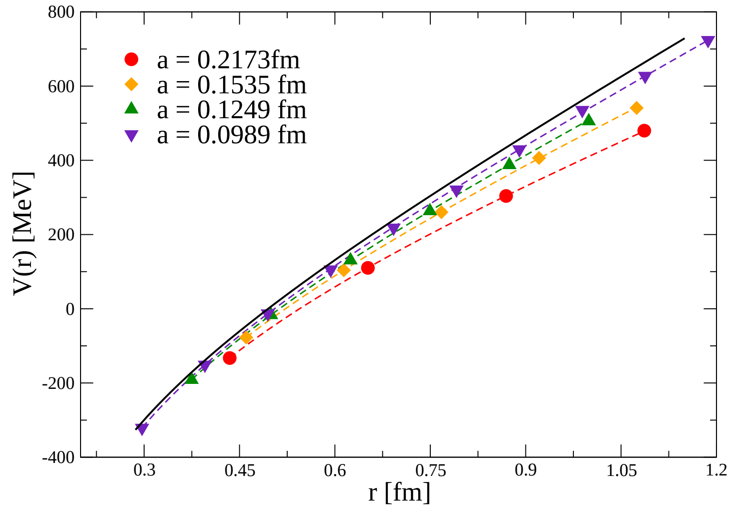
The potential is determined through Wilson loop expectation values

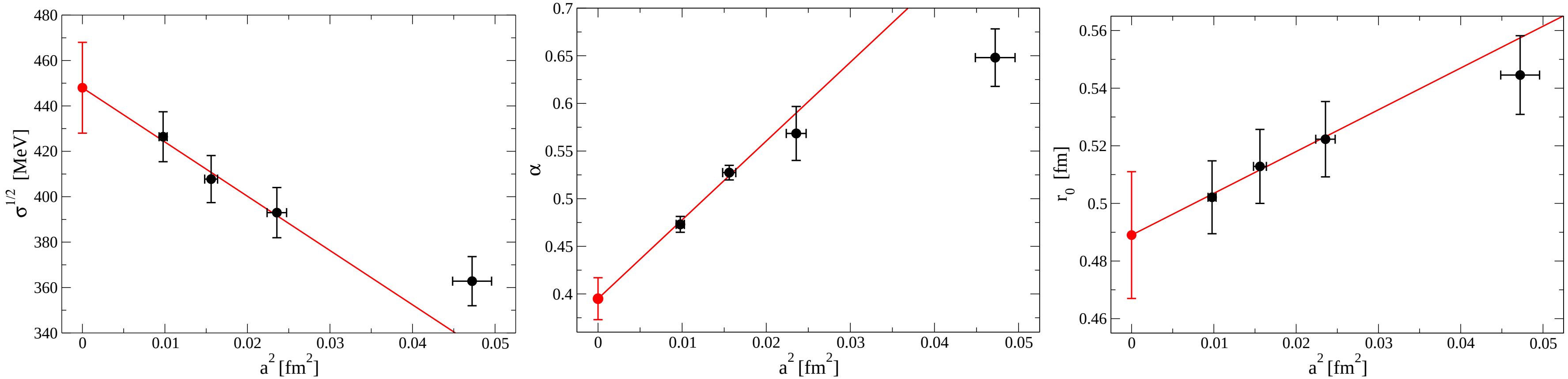
$$aV(a\vec{n}) = \lim_{n_t \to \infty} \log \left(\frac{\langle W(\vec{n}, n_t) \rangle}{\langle W(\vec{n}, n_t + 1) \rangle} \right)$$



at $B = 0$ the standard Cornell potential described data for all lattice spacings

$$V(r) = -\frac{\alpha}{r} + \sigma r + V_0 \ ,$$





Continuum extrapolated results for σ, α and for the Sommer parameter r_0

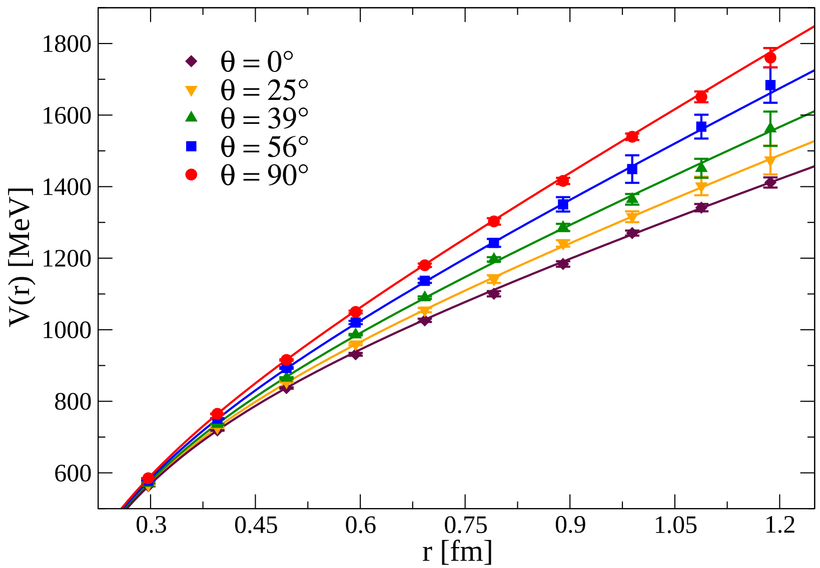
$$r_0^2 \left. \frac{dV}{dr} \right|_{r_0} = 1.65$$

α	**0.395(22)**
$\sqrt{\sigma}$	**448(20) MeV**
r_0	**0.489(20) fm**

The potential is Cornell like along each direction

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

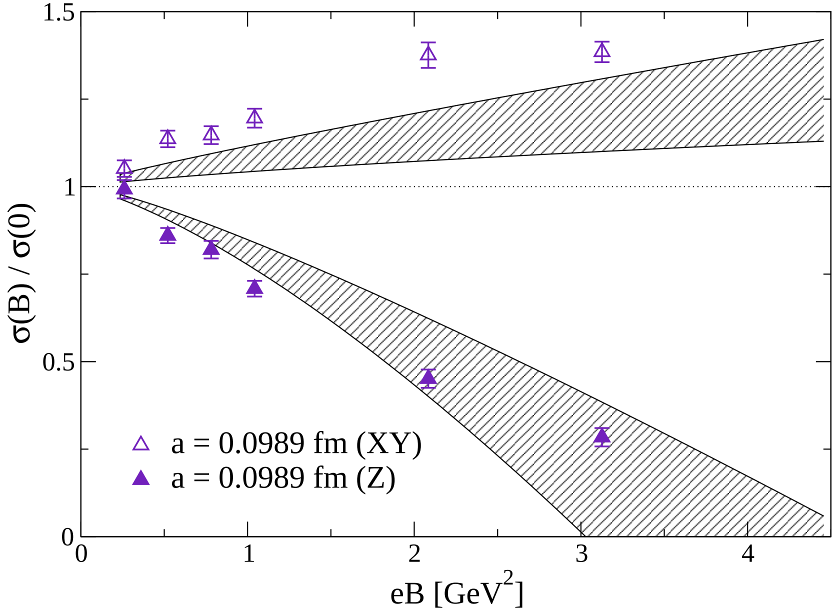
At fixed r, the potential is an increasing function of the angle and reaches a maximum for orthogonal directions



After continuum extrapolation, most of the effect seems related to an anisotropy in the string tension.

σ grows with B in the orthogonal direction

The longitudinal string tension decreases and could even vanish for $eB \sim 4$ GeV^2, but one would need $a \ll 0.1 fm$ to actually check it.



Is the deformation of the static quark-antiquark potential associated with a corresponding deformation of the color flux tube?

In principle, two different phenomena may happen:

- **The flux tube for longitudinal separation is less intense than that for transverse separation;**

- **The flux tube for transverse separation loses cilindrical symmetry and becomes anisotropic**

Lattice determinations of color flux tubes make use of correlation between Wilson loops and plaquette operators.

Connected correlators allow the determination of the field strength itself

[Di Giacomo, Maggiore, Olejnik, 1990] [Cea, Cosmai, Cuteri, Papa, 2017]

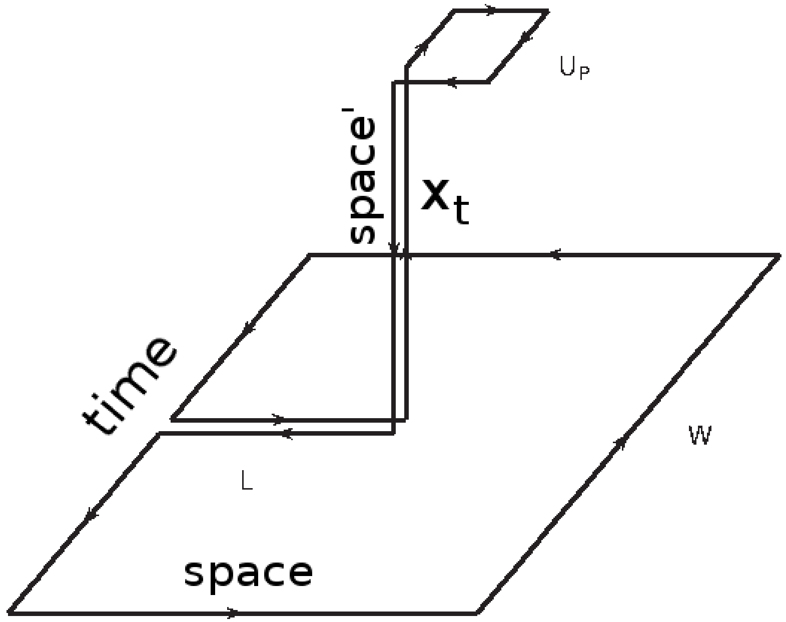
$$E_l^{chromo} = \lim_{a \to 0} \frac{1}{a^2 g} \left[\frac{\langle Tr(W L U_P L^\dagger) \rangle}{\langle Tr(W) \rangle} - \frac{\langle Tr(W) Tr(U_P) \rangle}{\langle Tr(W) \rangle} \right]$$

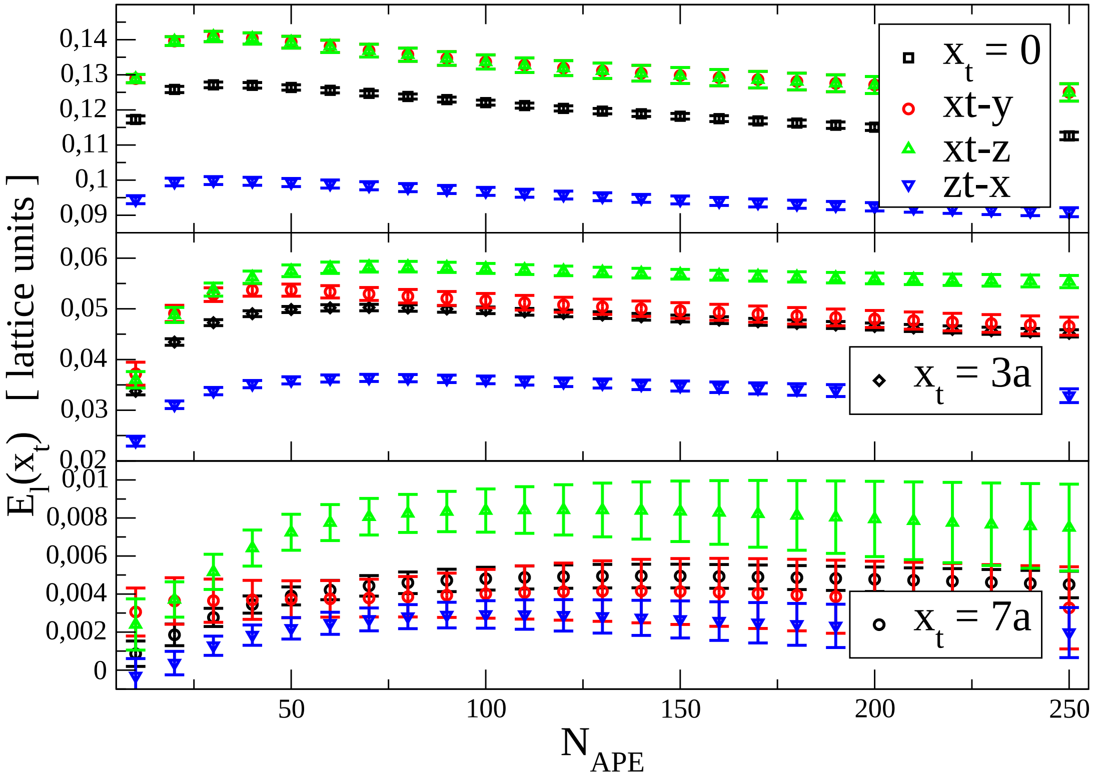
W is the open Wilson loop operator

U_P is the open plaquette operator

L is the adjoint parallel transport

A smearing procedure is adopted (1 HYP for temporal links, several APE for spatial links) as a noise reduction technique





Results at $eB = 0$ vs $eB \sim 2$ GeV^2 for $Q\bar{Q}$ separation 0.7 fm ($a \simeq 0.1$ fm), different transverse distances x_t, as a function of the APE smearing steps $\alpha_{APE=1/6}$

BLACK: $B0$

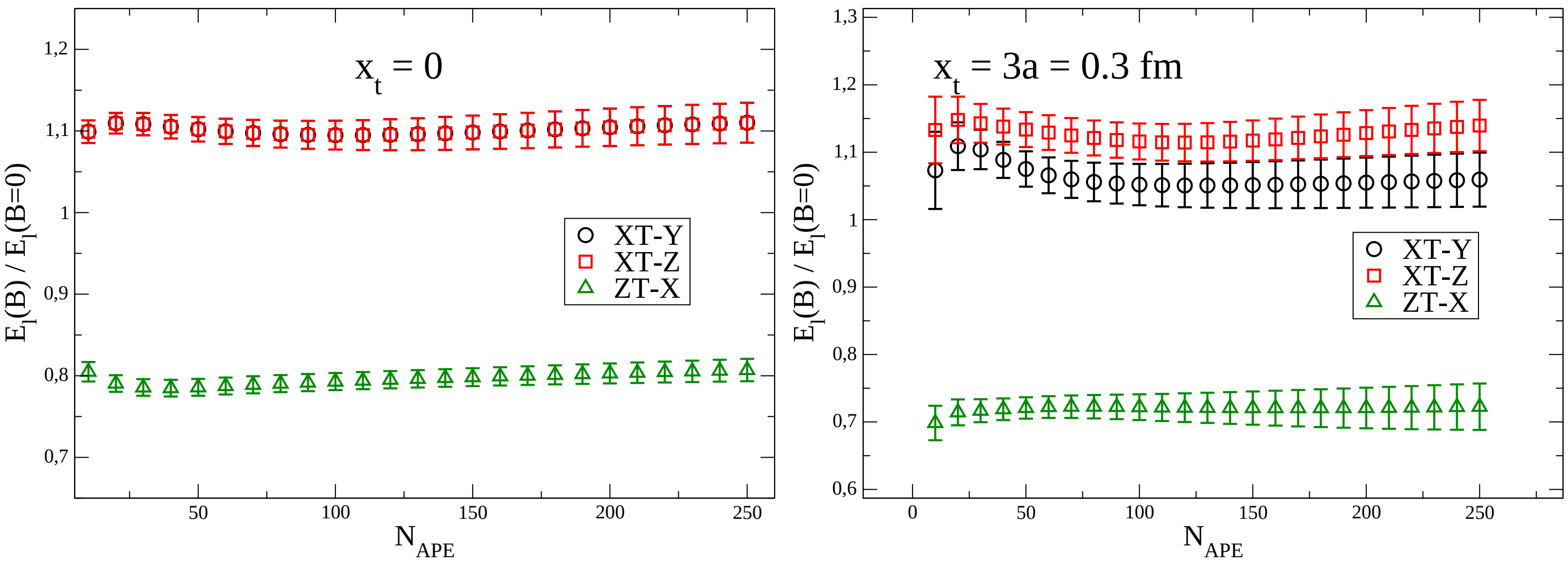
ZT-X: $Q\bar{Q}$ **separation parallel to** B

XT-Y: $Q\bar{Q}$ **separation orthogonal to** B**; transverse direction orthogonal to** B

XT-Z: $Q\bar{Q}$ **separation orthogonal to** B**; transverse direction parallel to** B

Dependence on the smearing step is non-trivial, however ...

... the dependence almost completely disappears as we consider the ratio of $B \neq 0$ to $B = 0$ quantities

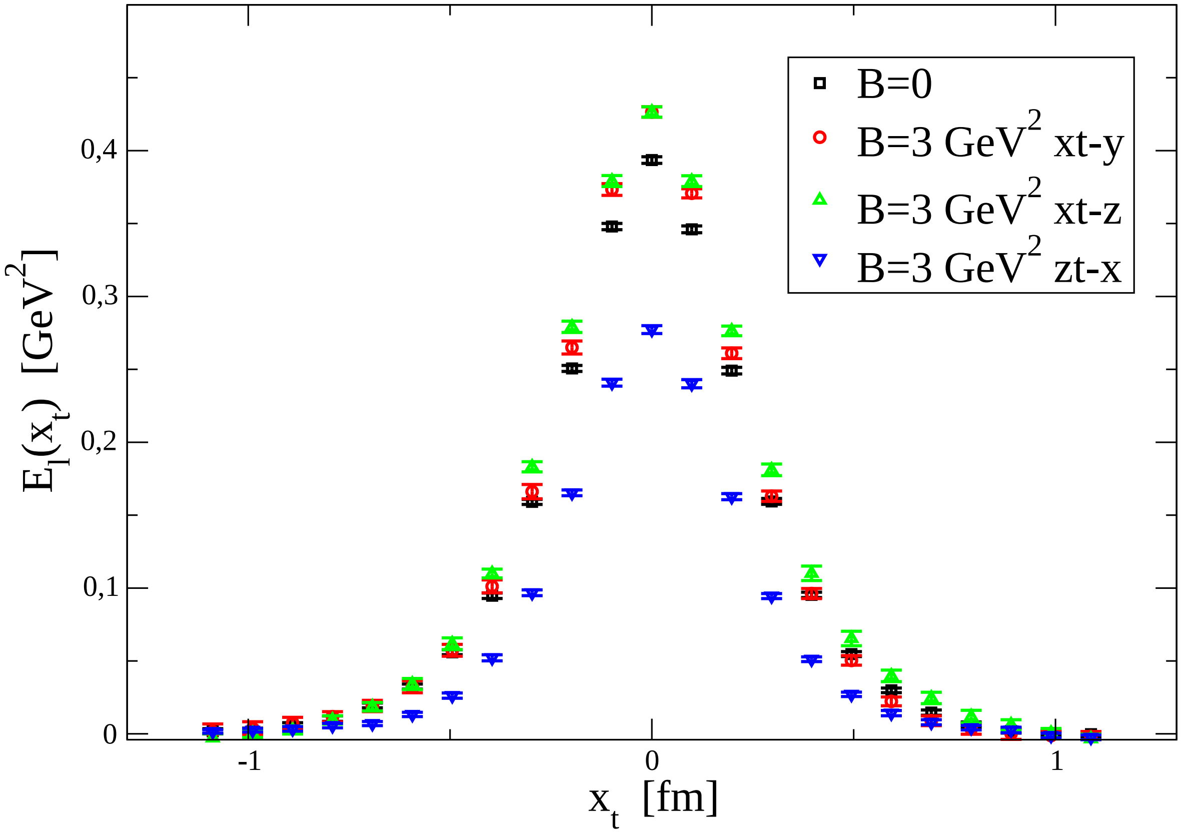


following analysis (PRELIMINARY) mostly based on such ratios

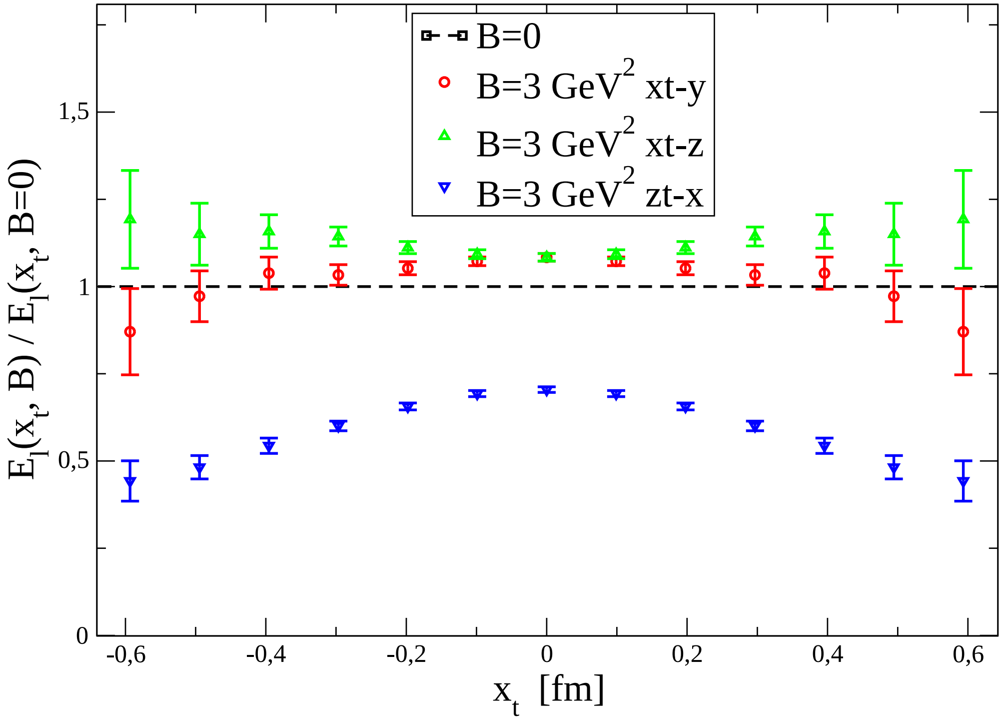
Signals of both kinds of anisotropy already visible:

- field strength for $Q\bar{Q}$ separation parallel/orthogonal to B is suppresses/enhanced

- for separation orthogonal to B, field strength keeps larger when moving along B



These are the flux tube profiles for $eB \sim 3$ GeV^2 compared to $B = 0$ at a fixed number of smearing steps $N_{APE} = 80$



These are the same data (for $eB = 3$ GeV^2) normalized to those at $B = 0$. It is not just the overall normalization of the flux tube which changes, but also the flux tube profile:

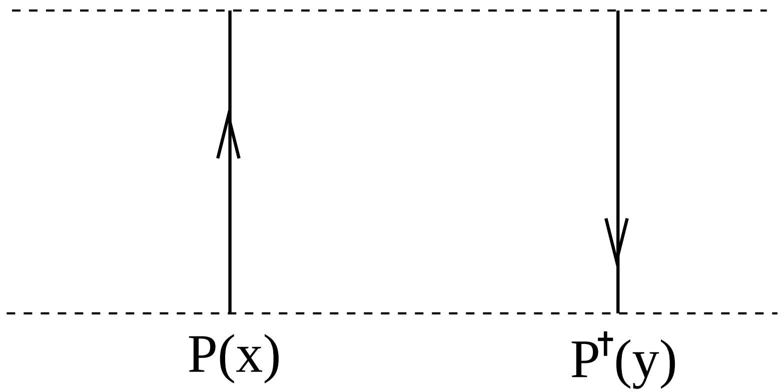
- it clearly shrinks for $Q\bar{Q}$ separation parallel to B

- it is more or less stable for orthogonal separation, with a tendency to shrink/widen in directions orthogonal/parallel to B.

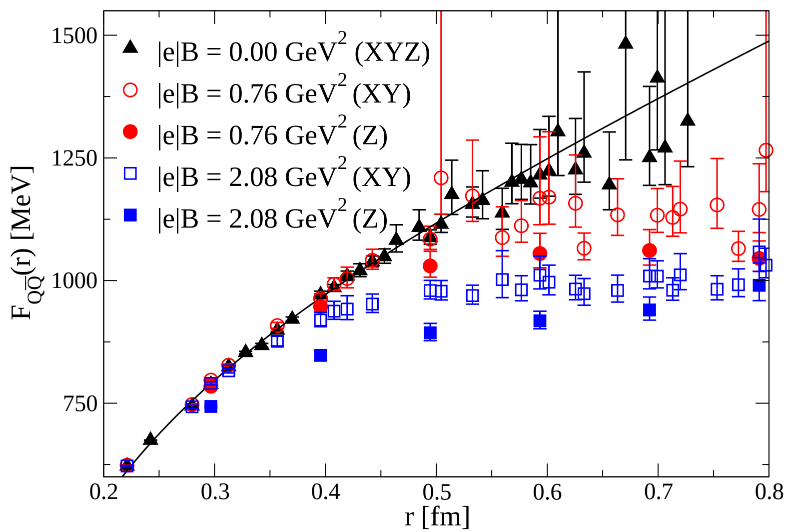
Finite T results

At finite T, the quark-antiquark potential is measured from Polyakov loop correlators

$$\langle \mathrm{Tr} P(\vec{x})\, \mathrm{Tr} P^\dagger(\vec{y}) \rangle \sim \exp\left(- \frac{F_{\bar{q}q}(r,T)}{T} \right)$$



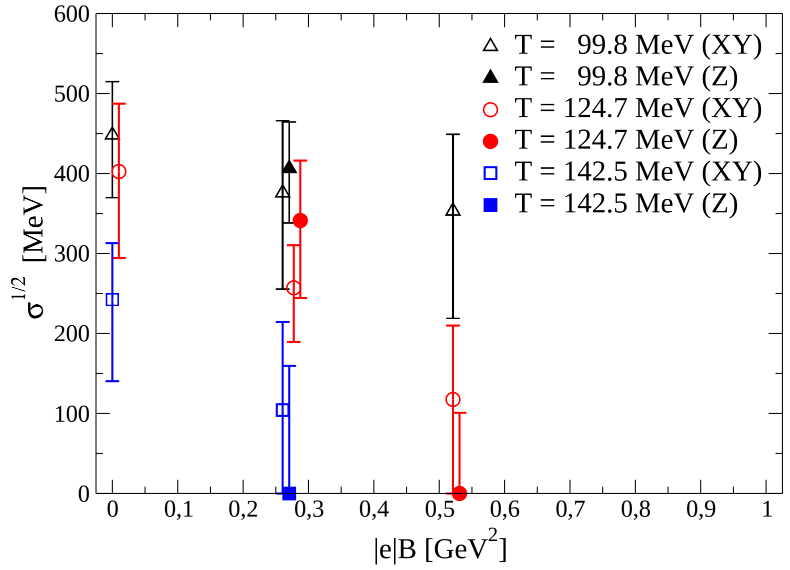
Results at $T \sim 100$ MeV on a $N_t = 20$ lattice



Although a small anisotropy is still visible, the main effect of B seems to suppress the potential in all directions

The string tension tends to disappear

A fit to the Cornell potential works in a limited range of distances and permits to obtain a determination of σ, which shows a steady decrease in all directions.



The decrease of T_c as a function of B seems related to a change in the confining properties of the medium.

Above T_c

Deep in the deconfined phase, heavy quark interactions are related to the screening properties of the Quark-Gluon plasma.

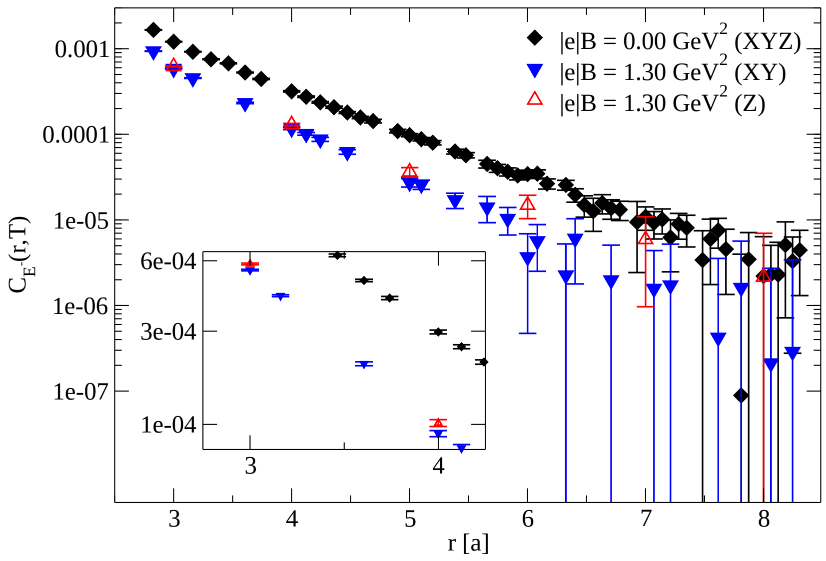
It is known that, contrary to electro-magnetic plasmas, interactions mediated by magnetostatic gluon are dominant at large distances.

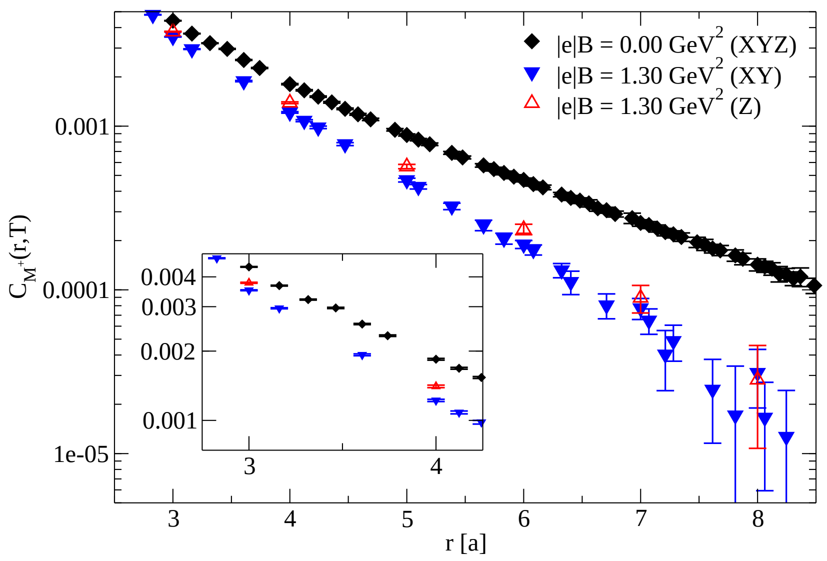
Nevertheless, it is possible to separate the electric and magnetic channels and define two different gauge invariant screening masses:

(Braaten-Nieto, 1994; Arnold-Yaffe, 1995)

$$C_{M^+} = +\frac{1}{2}\mathrm{Re}\big[C_{LL} + C_{LL^\dagger}\big] - |\langle \mathrm{Tr}L\rangle|^2 = \langle \mathrm{Tr}\mathrm{Re}L(\mathbf{0})\mathrm{Tr}\mathrm{Re}L(\mathbf{r})\rangle$$

$$C_{E^-} = -\frac{1}{2}\mathrm{Re}\big[C_{LL} - C_{LL^\dagger}\big] = \langle \mathrm{Tr}\mathrm{Im}L(\mathbf{0})\mathrm{Tr}\mathrm{Im}L(\mathbf{r})\rangle \ .$$

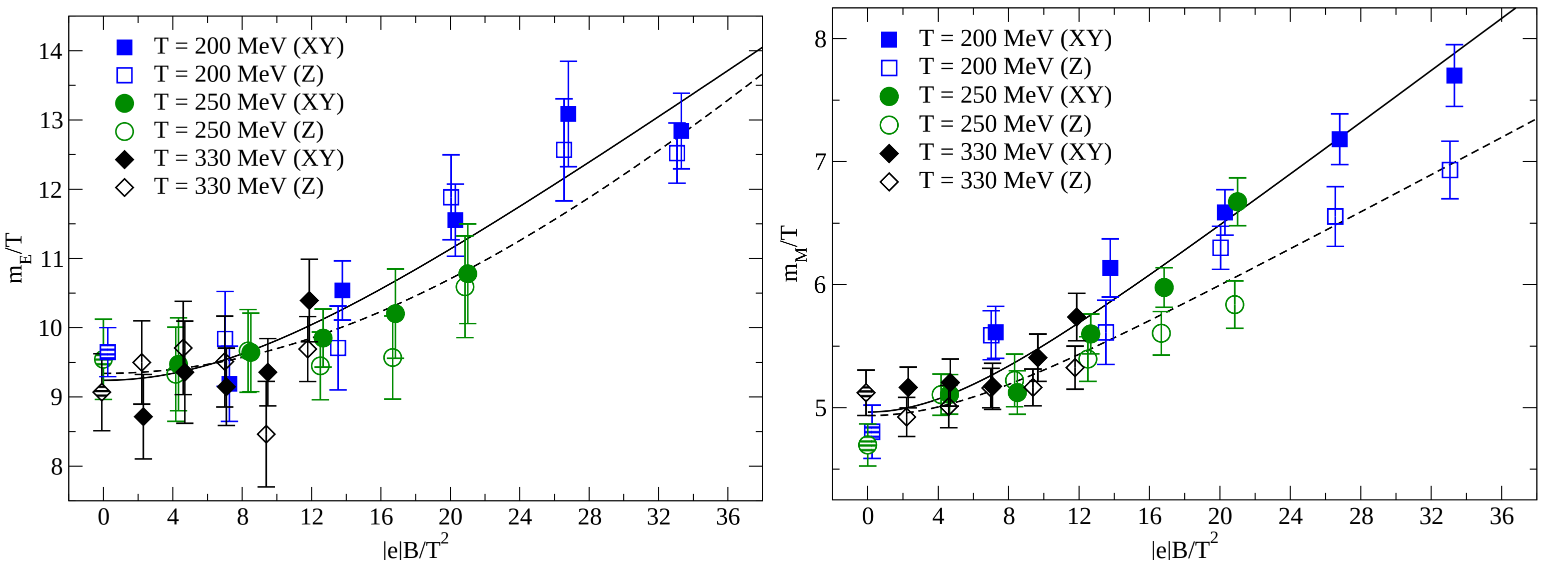




$$C_{E^-}(\mathbf{r},T)\big|_{r\to\infty} \simeq \frac{e^{-m_E(T)r}}{r}$$

$$C_{M^+}(\mathbf{r},T)\big|_{r\to\infty} \simeq \frac{e^{-m_M(T)r}}{r}$$

Electric and magnetic screening masses show a sizable dependence on the magnetic background



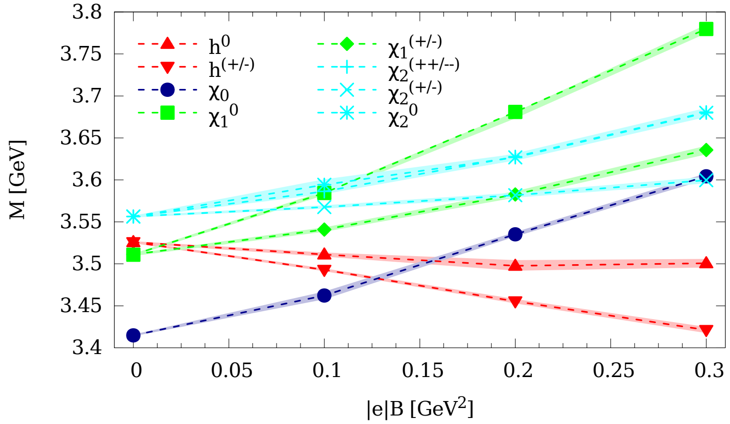
Such masses show a clear (increasing) dependence on B: the magnetic background field enhances the color screening properties of the QGP

$$\frac{m^d_{E/M}}{T} = a^d_{E/M}\left[1 + c^d_{1;E/M}\frac{|e|B}{T^2}\text{atan}\left(\frac{c^d_{2;E/M}}{c^d_{1;E/M}}\frac{|e|B}{T^2}\right)\right]\,,$$

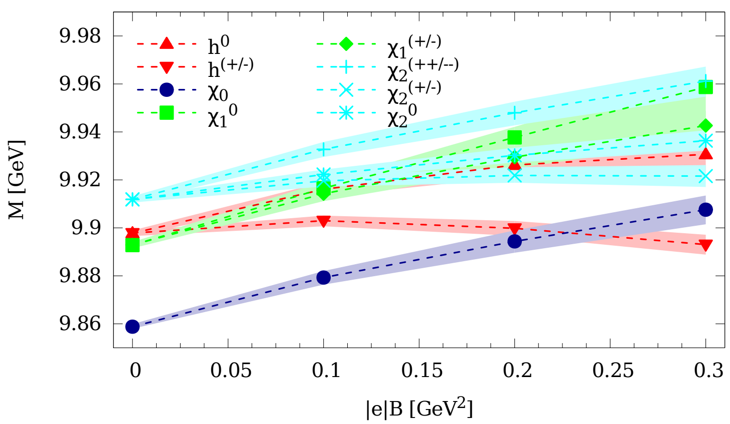
from C. Bonati, MD, M. Mariti, M. Mesiti, F. Negro, A. Rucci, F. Sanfilippo, 1703.00842

Discussion and Conclusions

Modifications of the static quark potential at $T = 0$ have consequences on quarkonia spectra which might be relevant to the early stages of heavy ion collisions



Charmonia



Bottomonia

From C. Bonati, MD, A. Rucci, 1506.07890

Screening lengths decrease as a function of B:

does B have any influence on heavy quarkonia suppression in the QGP? Not clear, provided B survives thermalization, one should also know how the quarkonia wave function is modified by B

A direct determination of quarkonia spectral functions in the presence of B would be the most direct way to check