

# Influence of magnetic fields on the color screening masses

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C.Bonati<sup>2</sup>, M.D'Elia<sup>1</sup>, M.Mesiti<sup>1</sup>,  
F.Negro<sup>1</sup>, A.Rucci<sup>1</sup>, F.Sanfilippo<sup>3</sup>

<sup>1</sup>*Department of Physics of University of Pisa and INFN Pisa, Italy*

<sup>2</sup>*Department of Physics and Astronomy of  
University of Florence and INFN Florence, Italy*

<sup>3</sup>*INFN Roma Tre, Italy*

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

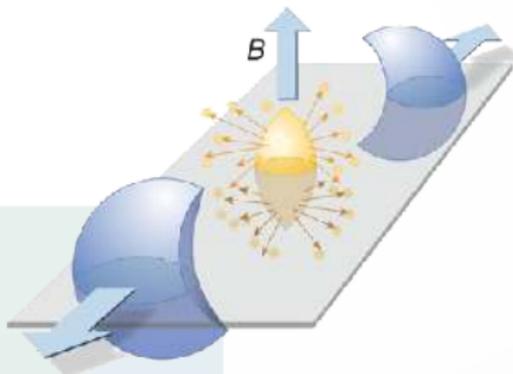
# intro physical conditions

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

- **Non-central heavy ion collisions** with  $eB \sim 10^{15} \text{ T}$  [Skokov et al. '09]
- Possible production in early universe  $eB \sim 10^{16} \text{ T}$  [Vachaspati '91]

## In heavy ion collisions

- Expected  $eB \simeq 0.3 \text{ GeV}^2$  at LHC in Pb+Pb at  $\sqrt{s_{NN}} = 4.5 \text{ TeV}$  and  $b = 4 \text{ fm}$
- Timescales depend on thermal medium properties (most pessimistic case:  $0.1 - 0.5 \text{ fm}/c$ )
- Spatial distribution of the field and lifetime are still debated



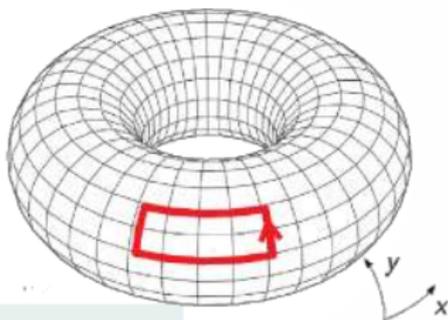
# intro turning on the B field

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

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

- External magnetic field: non-propagating fields, no kinetic term
- Periodic boundary conditions lead to the quantization condition



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

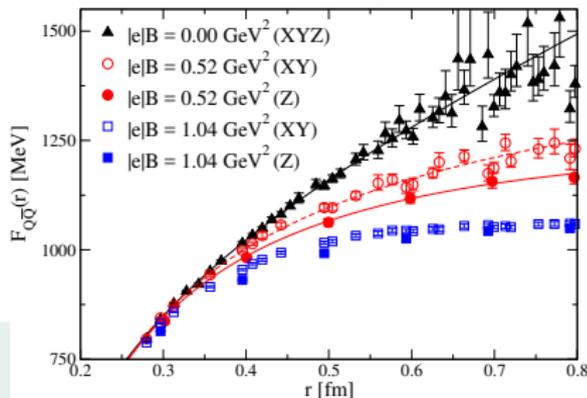
# intro to $T_C$ and beyond!

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

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

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

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

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
- with length  $1/m_M$  at larger distances

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

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

**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

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

receive contributions only from magnetic and electric sectors

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

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

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

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

$$C_{E^-}(\mathbf{r}, T) = -\langle \text{Tr} L_{E^-}(\mathbf{0}) \text{Tr} L_{E^-}(\mathbf{r}) \rangle$$

# color screening magnetic and electric sectors

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

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

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

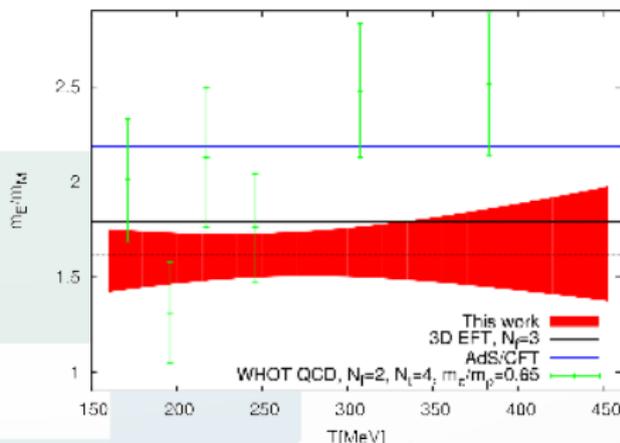
$$C_{E^-}(\mathbf{r}, T) \sim \frac{1}{r} e^{-m_E(T)r} \quad C_{M^+}(\mathbf{r}, T) \sim \frac{1}{r} e^{-m_M(T)r}$$

## 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  $T \simeq 330 \text{ MeV}$ ,  $T \simeq 250 \text{ MeV}$  and  $T \simeq 200 \text{ MeV}$
- fixed spacing  $a \simeq 0.0989 \text{ fm}$
- simulations at physical quark masses

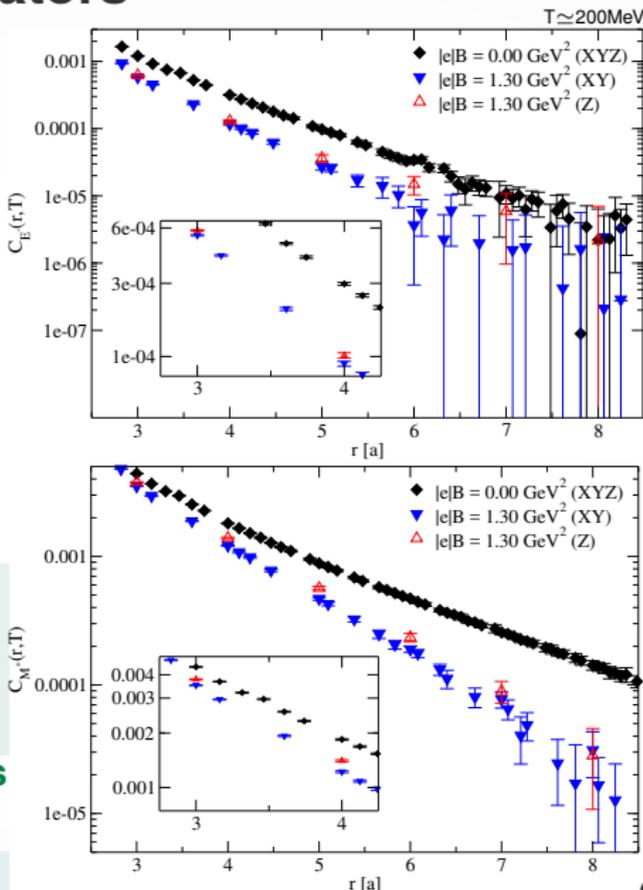
Measure of the correlators:

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

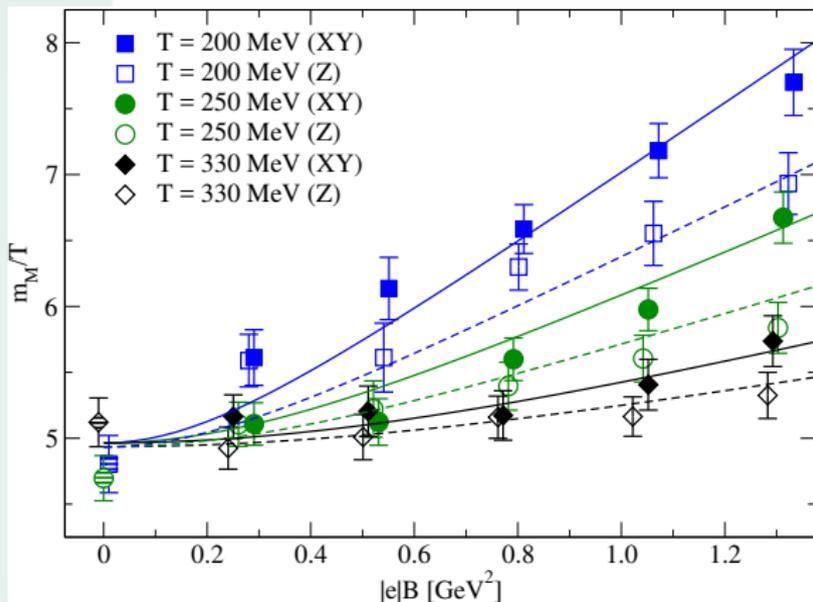
# study at $B > 0$ correlators

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**

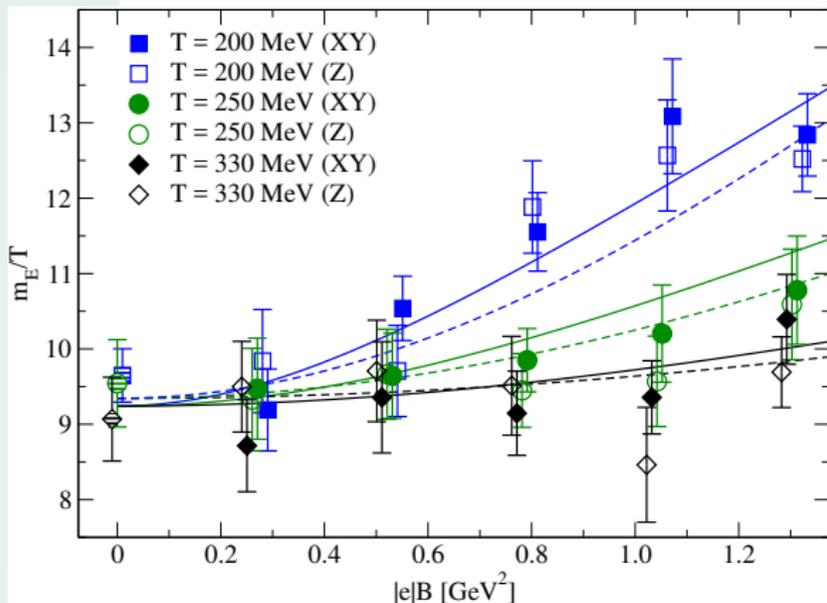


## study at $B > 0$ masses



- 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

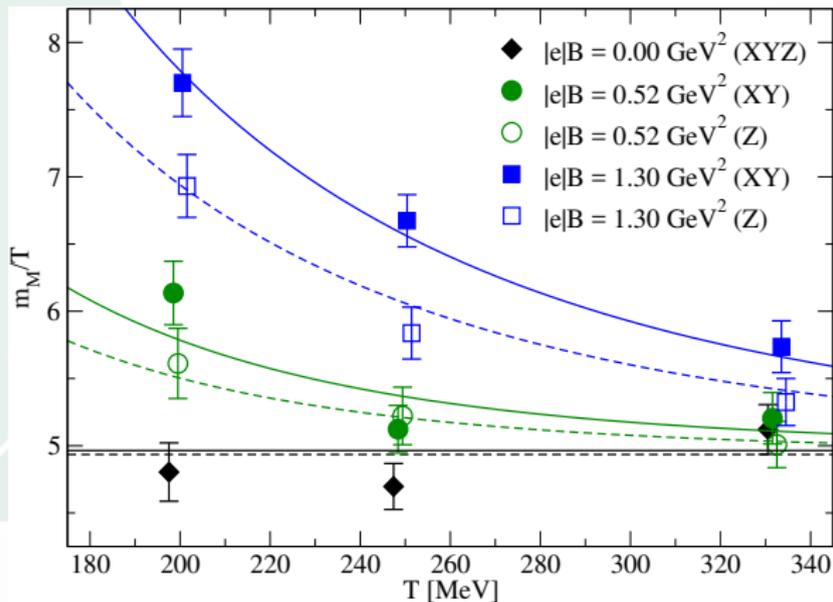
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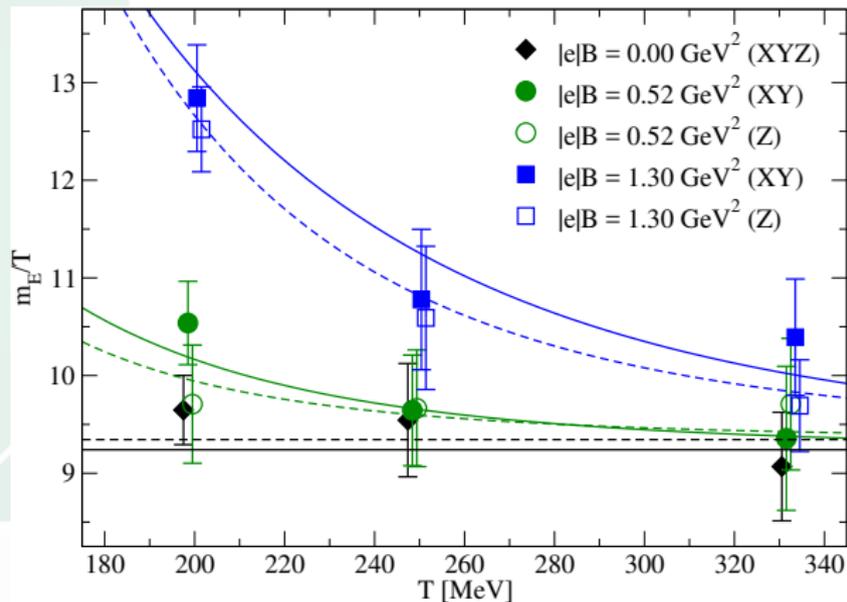
## study at $B > 0$ masses

- 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  $T$



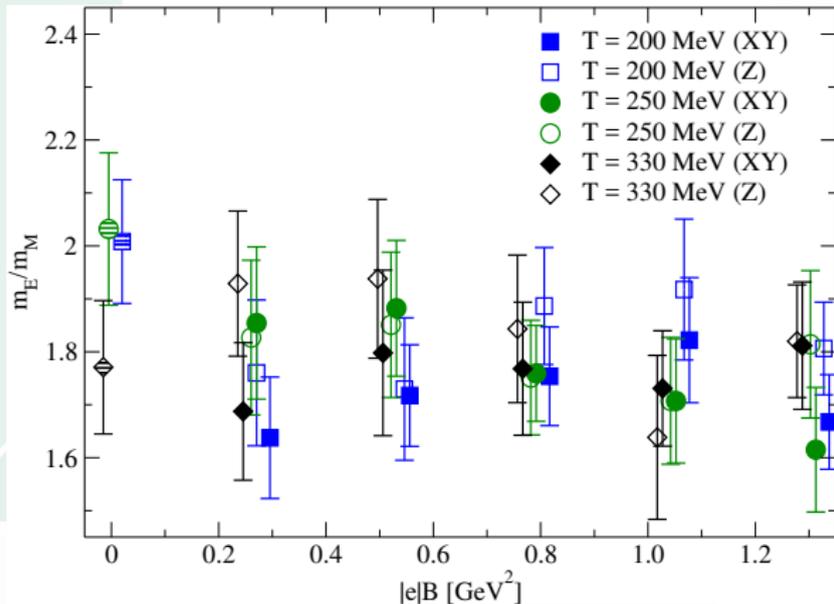
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# study at $B > 0$ masses

Attempt to describe the observed behaviour imposing

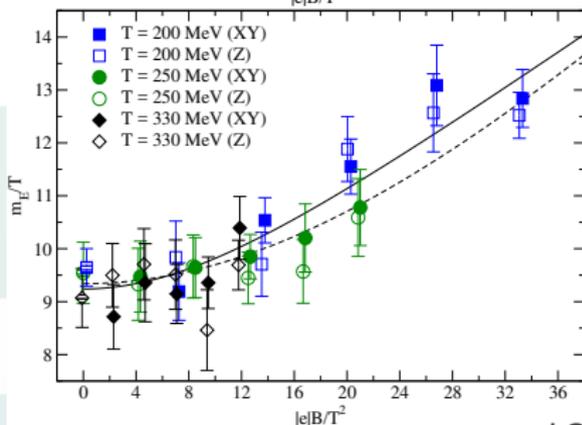
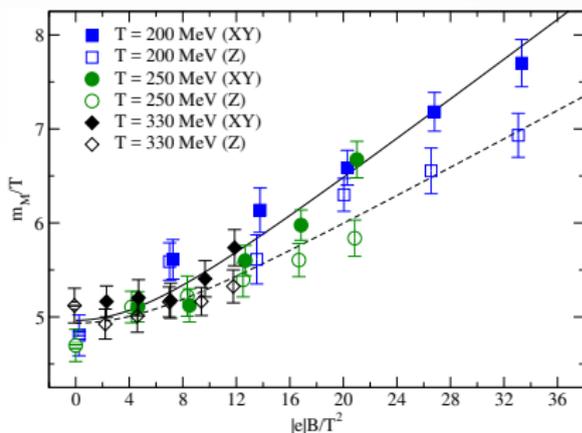
- $m_E/T$  and  $m_M/T$  independent of  $T$  at  $B = 0$
- linear dependence of  $B$  for large magnetic fields

A simple ansatz is

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

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 ( $|e|B \gtrsim 0.2\text{GeV}^2$ )
- Mass ratio seem to be independent to  $B$
- Magnetic effects vanish at large  $T$

## Discussion and implications:

- Observed mass variations expected also by perturbative 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]

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**THANK YOU!**



# backup computation of $C_M$ and $C_E$

Using the relations

$$\text{Tr}L_M^+ = \text{ReTr}L \quad \text{Tr}L_E^- = i\text{ImTr}L$$

the magnetic and electric correlators can be written as

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

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)

