Flux tubes in $N_f = 2+1$ QCD in the presence of external magnetic fields

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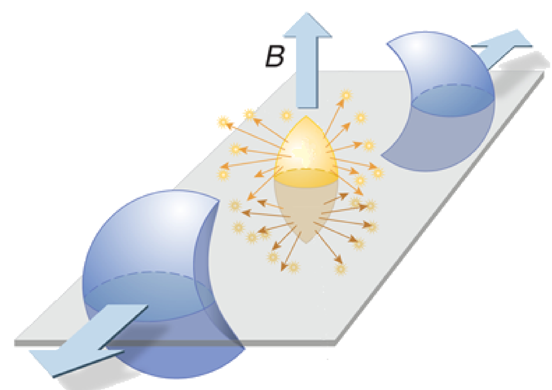
Phenomenological motivation

Magnetic fields $(\mathbf{eB})$ comparable to Λ_{QCD} are present in these contexts:

- Astrophysics - in a class of neutron stars, called **magnetars**: $eB \sim 10^{10}$ T
- Cosmology - during the **ElectroWeak phase transition**: $eB \sim 10^{16}$ T
- Heavy ion collisions - at LHC in **non-central HIC**: $eB \sim 10^{15}$ T $\sim 15 m_\pi^2$

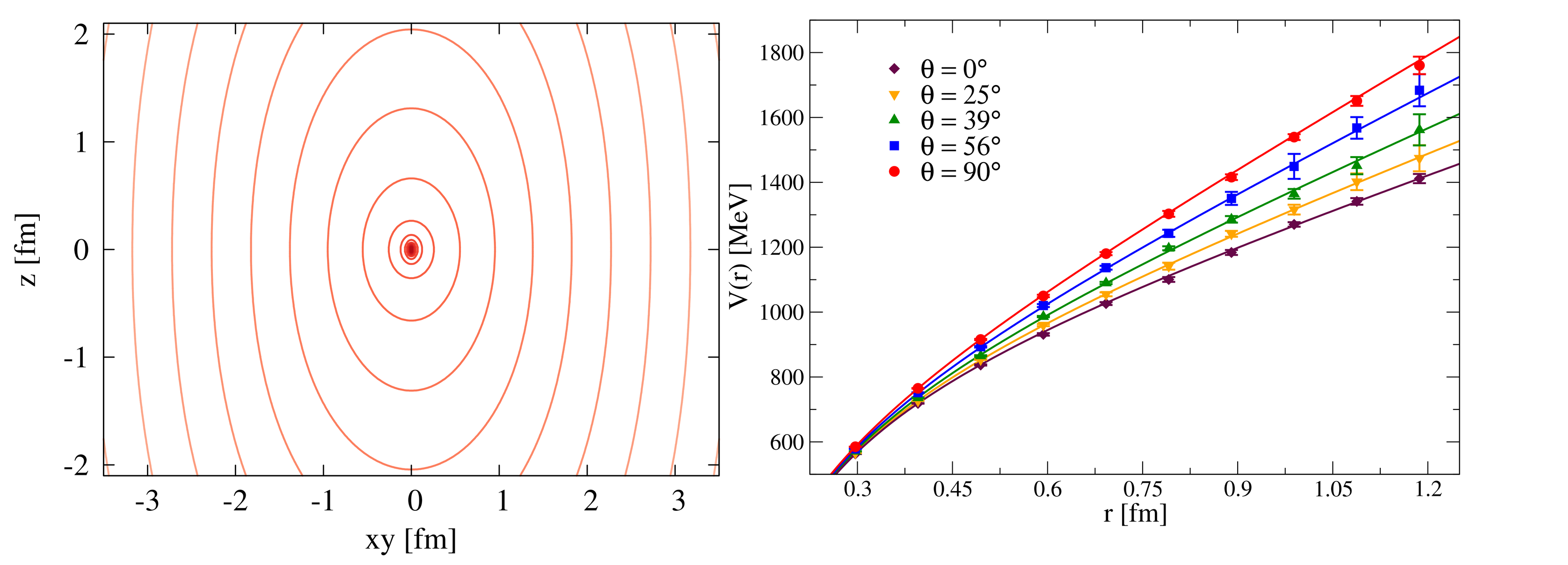
$1\ \mathrm{GeV}^2 \sim 5 \cdot 10^{15}$ T



What happens to QCD properties in such an environment?

The effect of B on the static $Q\overline{Q}$-Potential

Let θ be the angle between the $\mathbf{Z}$-oriented field and the $Q\overline{Q}$ separation. The $\mathbf{B}$-field modifies the static $Q\overline{Q}$-potential, making it anisotropic. It grows steeply along the $\mathbf{X}$ and $\mathbf{Y}$ directions and slowly along $\mathbf{Z}$.



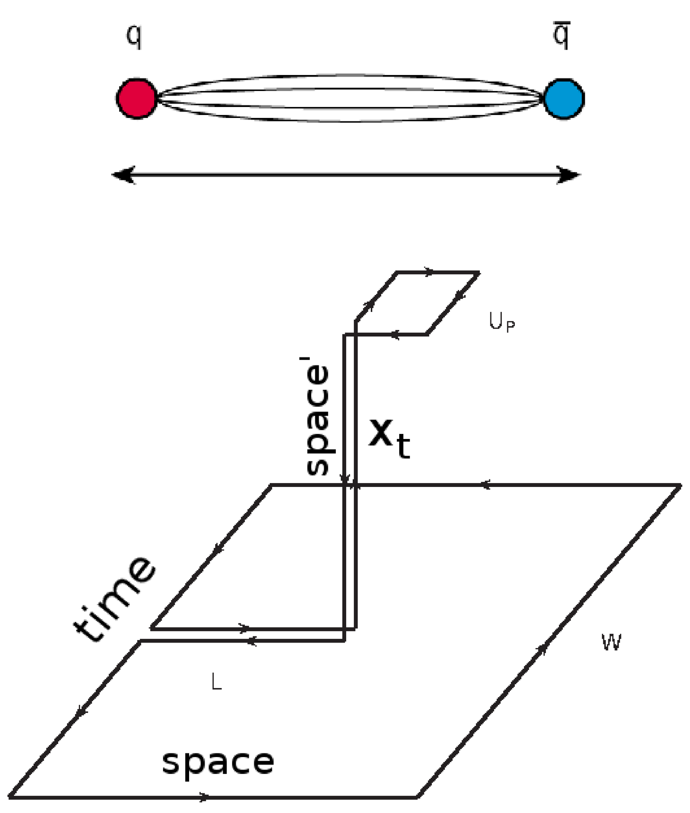
Results for $N_f = 2+1$ QCD at the physical point at $a = 0.0989$ fm on a $48^3 \times 96$ lattice. Magnetic field value: $(eB) \simeq 1\mathrm{GeV}^2$.
By fitting with the Cornell parametrization $V_{Q\overline{Q}}(\vec{r}) = C + \sigma|\vec{r}| + \alpha/|\vec{r}|$ we find[a] that both α and σ depend on θ.

Lattice observable for the flux tube

We consider a $Q\overline{Q}$ pair at relative distance $\vec{d} = d\hat{u}$ (with $\hat{u} = \hat{x},\ \hat{y},\ \hat{z}$).

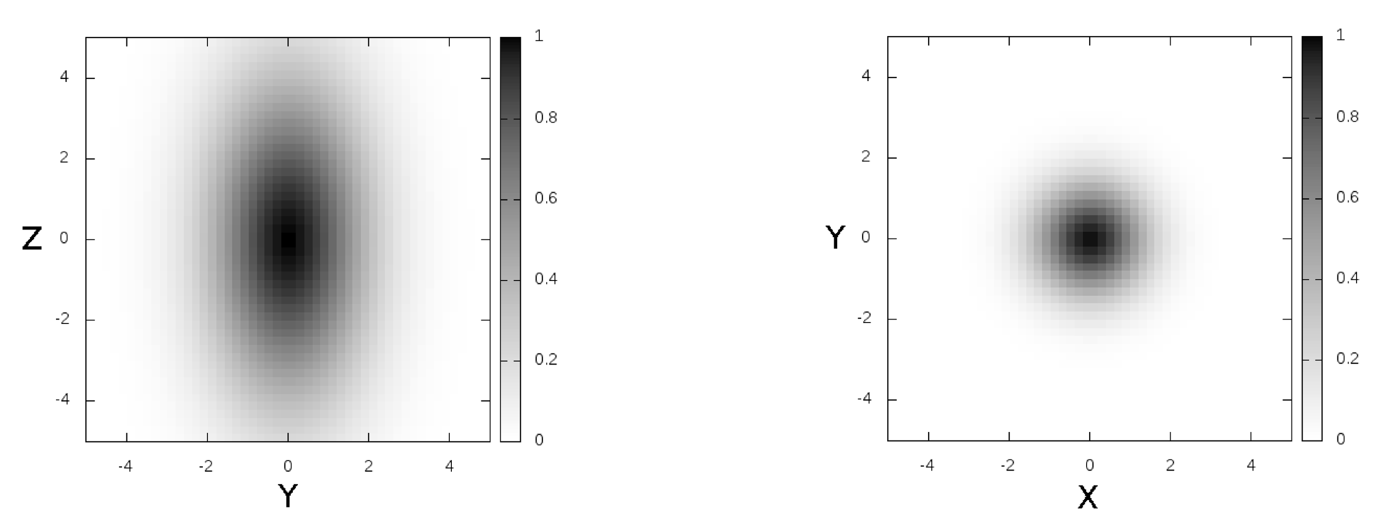
We measure the chromoelectric field E_l (longitudinal with respect to the $Q\overline{Q}$ separation) in between the pair, along a transverse direction using[b,c]

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



$\mathbf{W}$ is a squared Wilson Loop
$\mathbf{U_P}$ is a coplanar plaquette

Classes of flux tubes according to rotational symmetry breaking



[XT − Y & YT − X]
[XT − Z & YT − Z]
[ZT − X & ZT − Y]

We need to study individually these possible direction combinations.

Numerical setup and smearing

We discretize the $N_f = 2+1$ QCD action at the physical point $(m_\pi^{LAT} = m_\pi^{PHYS})$ considering the tree level improved Symanzik gauge action and stout smearing improved rooted staggered fermions.

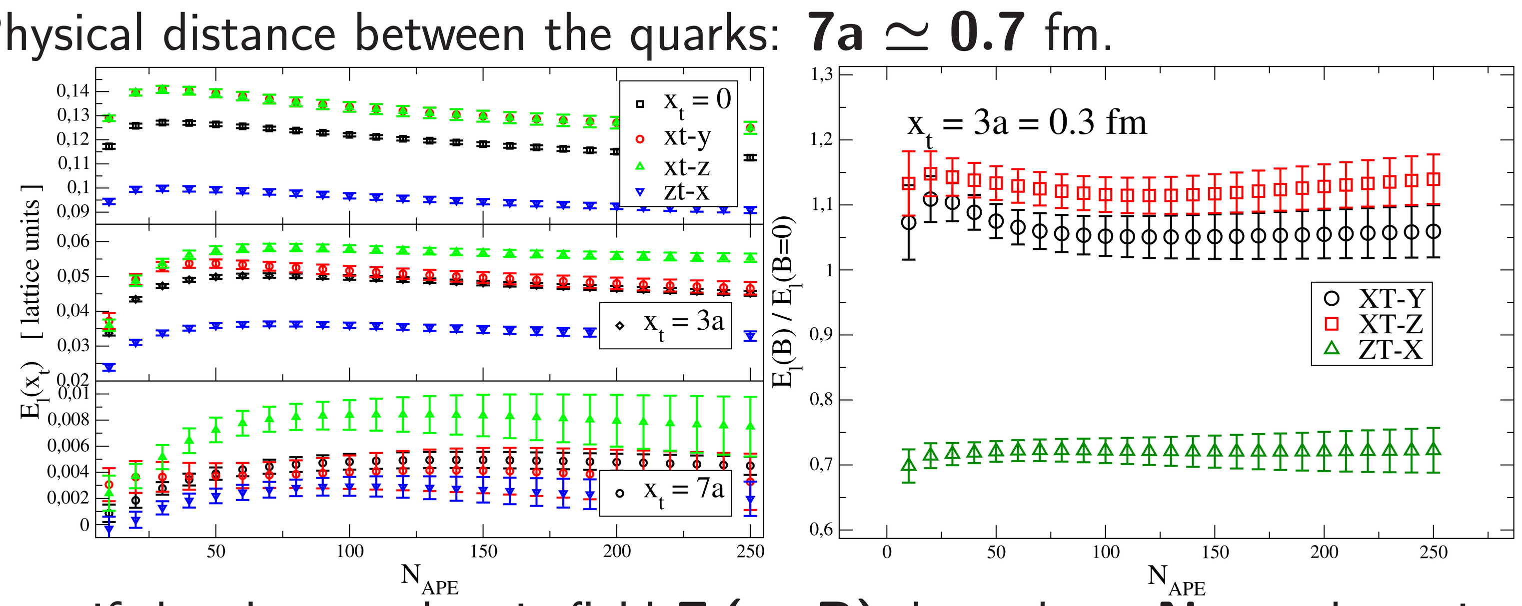
Simulations done on BG/Q-Fermi and on KNL-Marconi at CINECA, Italy.

Wilson Loop related observables are extremely noisy. To reduce the UV fluctuations, we smear the configurations:

1) 1 HYP smearing on the temporal links
2) N_{APE} spatial APE smearing steps $\alpha = 0.1666$ on spatial links

Ratios to avoid the smearing dependence of the flux tube

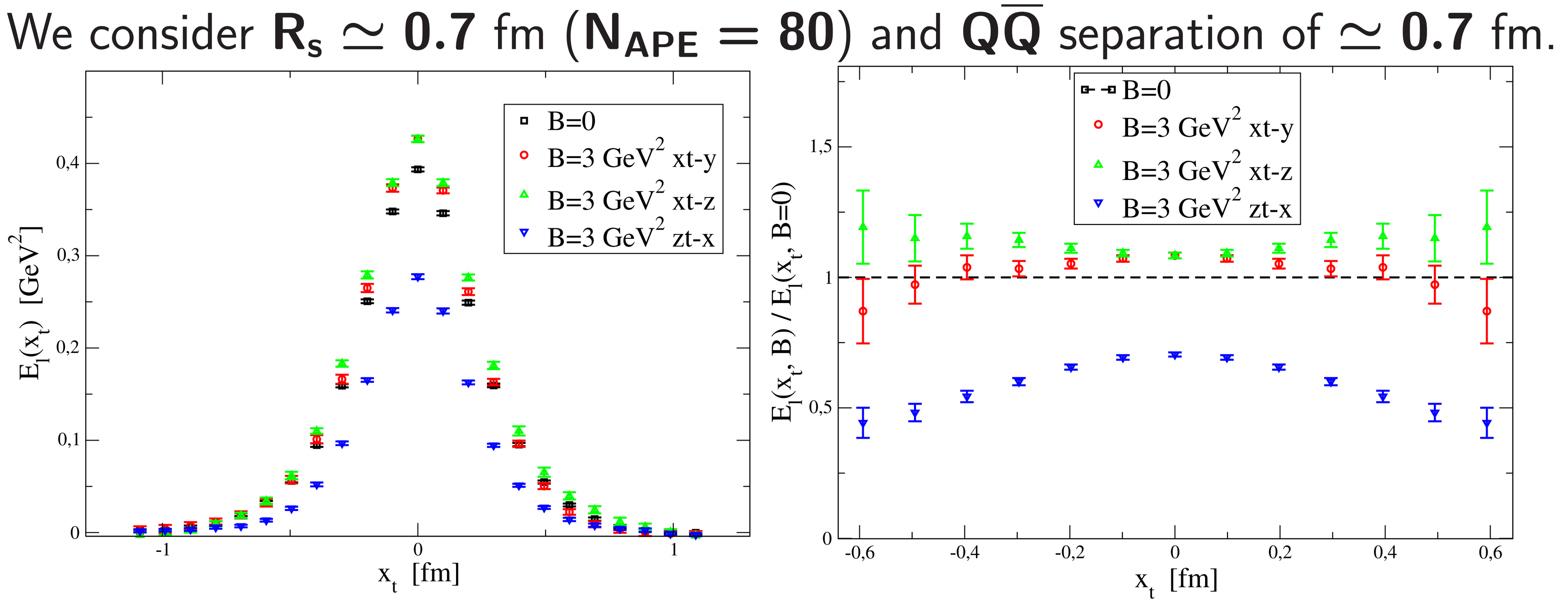
As an example, we plot the $(eB) \simeq 2\ \mathrm{GeV}^2$ case.
Physical distance between the quarks: $7a \simeq 0.7$ fm.



Even if the chromo-electric field $E_l(x_t, B)$ depends on N_{APE}, the ratios $E_l(x_t, B \neq 0)/E_l(x_t, B = 0)$ are almost smearing independent.

Flux tube profiles at $(eB) \neq 0$

Profile of the flux tube at $(eB) = 3\mathrm{GeV}^2$ compared to that at $(eB) = 0$. The ratios are also plotted.
We consider $R_s \simeq 0.7$ fm $(N_{APE} = 80)$ and $Q\overline{Q}$ separation of $\simeq 0.7$ fm.



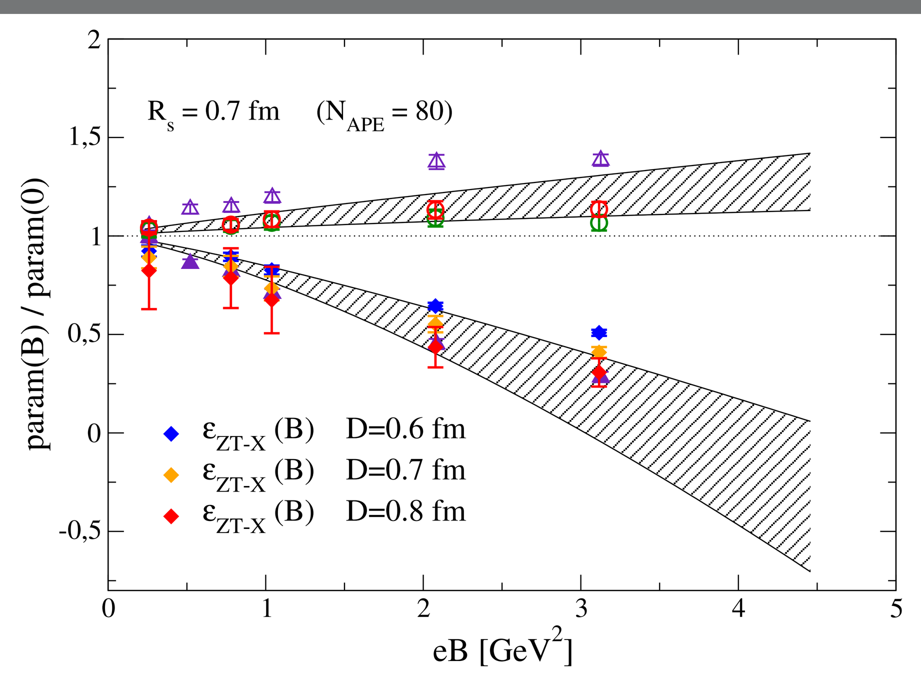
Energy per unit lenght and string tension

As observed in **(c)**, the flux tube profile is well described by[d] :

$$E_l(x_t) = \frac{\phi\mu^2}{2\pi\alpha}\frac{K_0(\sqrt{\mu^2 x_t^2 + \alpha^2})}{K_1(\alpha)}$$

The energy per unit lenght $\epsilon = \int d^2x_t E_l^2(x_t)/2$ can be extracted from $\phi,\ \mu,\ \alpha$:

$$\epsilon = \frac{\mu^2\phi^2}{8\pi}\left(1 - \left(\frac{K_0(\alpha)}{K_1(\alpha)}\right)^2\right)$$



Even if $\epsilon \neq \sigma$, their ratios appear consistent to each other.

Acknowledgements and references

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