Confinement and Deconfinement in a Magnetic Background Field

Massimo D'Elia - University of Pisa & INFN

XXXII International (ONLINE) Workshop on High Energy Physics "Hot problems of Strong Interactions"

Moscow (online), November 9, 2020

Mostly based on:

M. D'Elia, F. Manigrasso, F. Negro and F. Sanfilippo,

"QCD phase diagram in a magnetic background for different values of the pion mass,"

Phys. Rev. D 98, no.5, 054509 (2018), arXiv:1808.07008

and

C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo,

"Magnetic field effects on the static quark potential at zero and finite temperature,"

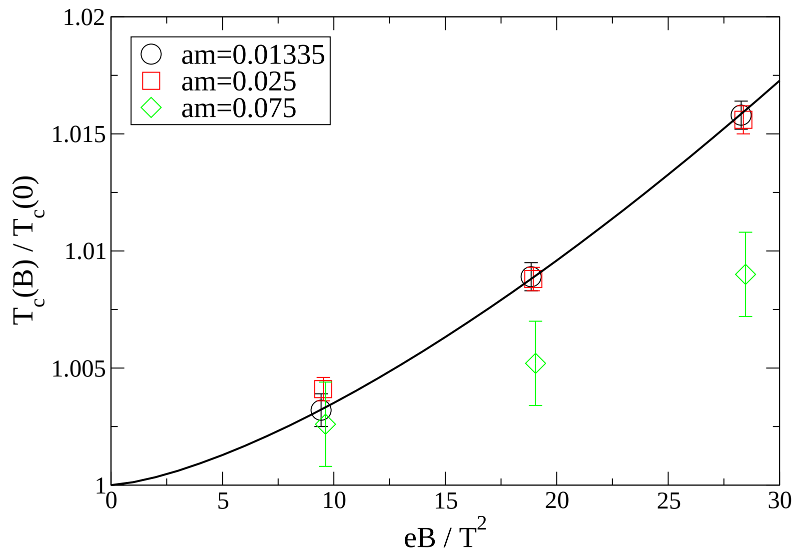
Phys. Rev. D 94, no.9, 094007 (2016), arXiv:1607.08160

C. Bonati, S. Calì, M. D'Elia, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo,

"Effects of a strong magnetic field on the QCD flux tube,"

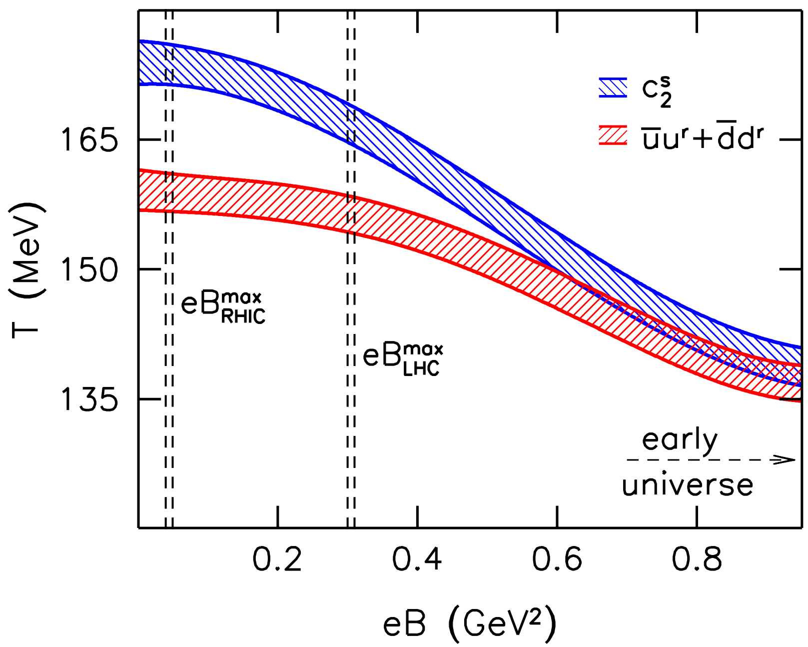
Phys. Rev. D 98, no.5, 054501 (2018), arXiv:1807.01673

Early lattice results on the QCD phase diagram in a magnetic background produced contrasting results: $T_c(B)$ increasing vs decreasing



$N_f = 2$ **standard staggered fermions, plaquette gauge action,** $m_\pi \simeq 200$ **MeV,** $a \simeq 0.3$ **fm**

M.D., S. Mukherjee and F. Sanfilippo, PRD 82, 051501 (2010), arXiv:1005.5365

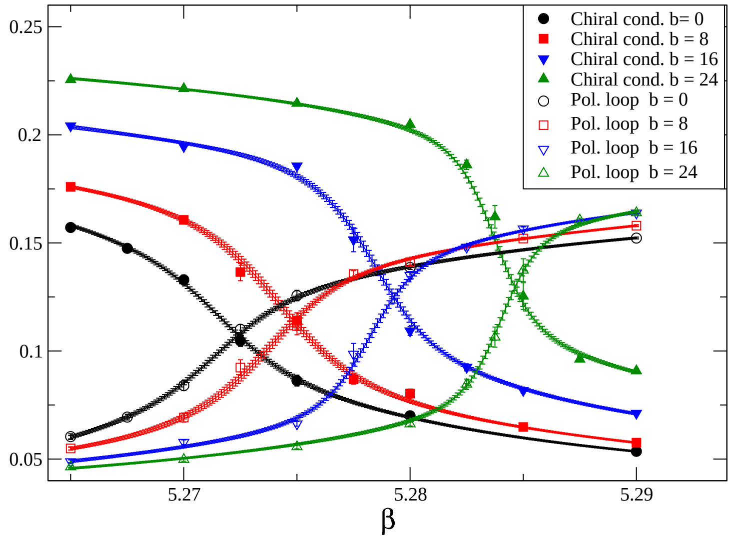


$N_f = 2+1$ **stout improved staggered fermions, Symanzik improved gauge action, physical quark masses, continuum extrap.**

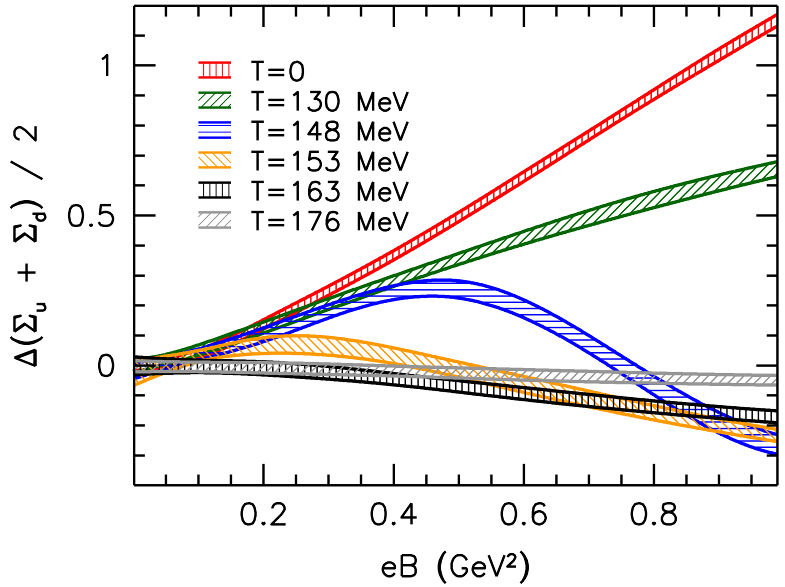
G. S. Bali *et al*, JHEP 02, 044 (2012), arXiv:1111.4956

Differences also in the behaviour of the chiral condensate around the phase transition:

magnetic catalysis vs inverse magnetic catalysis



M.D., S. Mukherjee and F. Sanfilippo, PRD 82, 051501 (2010), arXiv:1005.5365



G. S. Bali *et al*, PRD 86, 071502 (2012), arXiv:1206.4205

The unexpected decrease of T_c has been dubbed inverse magnetic catalysis

Non-monotonic behavior of the chiral condensate around T_c confirmed by later studies:

$N_f = 4$ **staggered SU(2) (E. M. Ilgenfritz, M. Muller-Preussker, B. Petersson and A. Schreiber, PRD 89, no.5, 054512 (2014), arXiv:1310.7876)**

$N_f = 2$, **dynamical overlap fermions (V. G. Bornyakov, P. V. Buividovich, N. Cundy, O. A. Kochetkov and A. Schäfer, PRD 90, no.3, 034501 (2014), arXiv:1312.5628)**

Questions

- Why the discrepancy? discretization effects or unphysical quark masses?
- Is inverse magnetic catalysis the relevant phenomenon underlying the decrease of T_c, or just a consequence?

Our study:

explore $N_f = 2 + 1$ QCD with different and increasing values of the pion mass in the range 300-660 MeV. Improved staggered fermions and gauge action, $N_t = 6$

(MD, F. Manigrasso, F. Negro and F. Sanfilippo, PRD 98, no.5, 054509 (2018), arXiv:1808.07008)

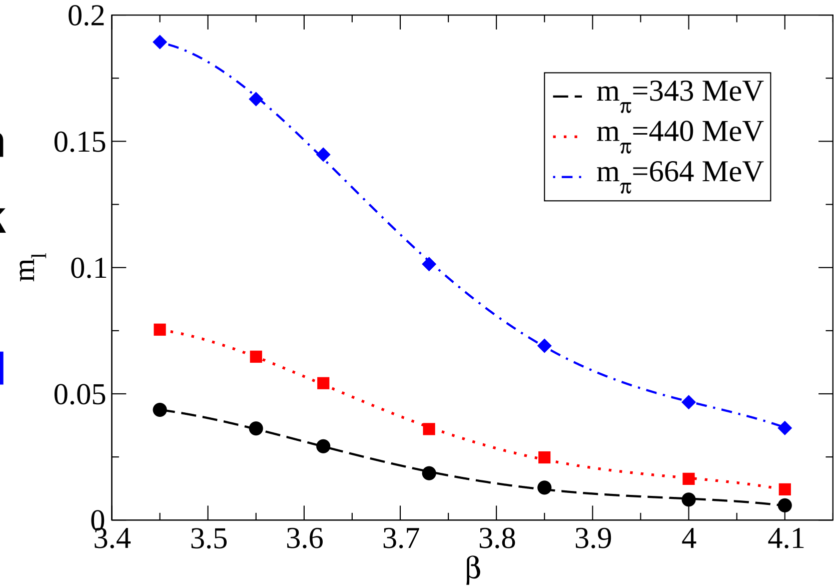
analogous investigation with consistent results:

(G. Endrodi, M. Giordano, S. D. Katz, T. G. Kovács and F. Pittler, JHEP 07, 007 (2019), arXiv:1904.10296)

SETUP

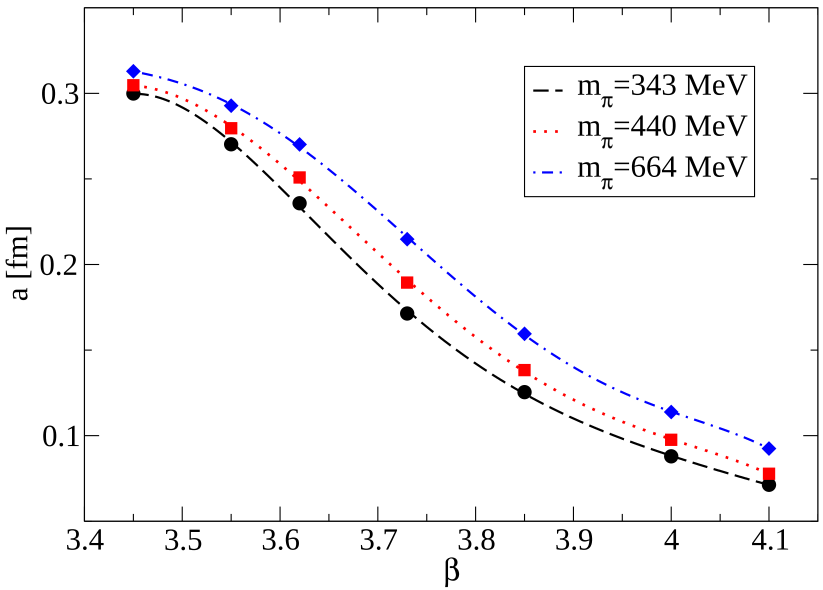
$N_f = 2 + 1$ **staggered fermions with two levels of stout smearing, Symanzik improved gauge action.**

strange/light mass ratio m_s/m_l kept fixed at its physical value



Lattice spacing fixed through the gradient flow parameter w_0

After a set of preliminary runs with variable β and m_l, we have determined the lines of constant physics in the bare parameter space



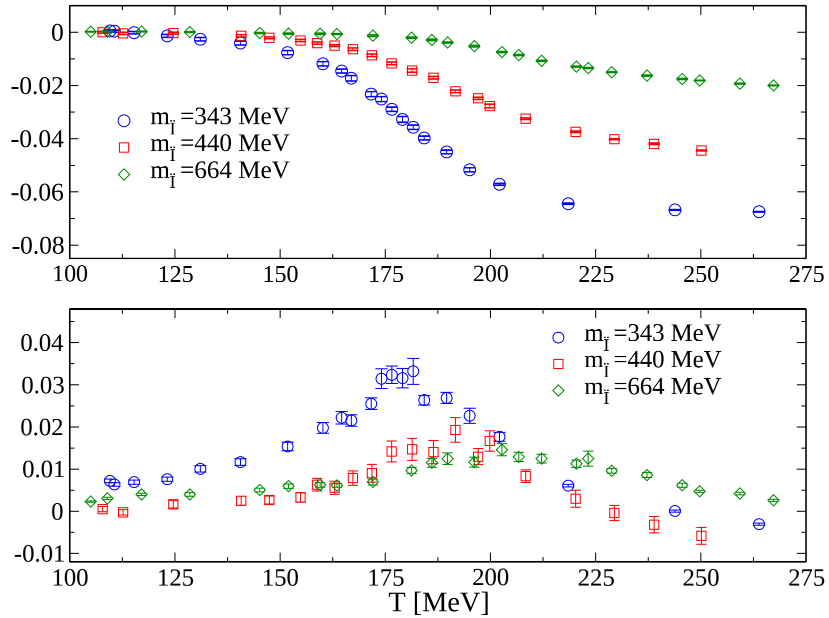
Results at $B = 0$: $T_c(m_\pi)$

Renormalized quark condensate

$$\Sigma_\ell^r(T,B) = \frac{m_\ell}{M_\pi^4}\left(\Sigma_\ell(T,B) - \Sigma_\ell(0,0)\right),$$

and its susceptibility.

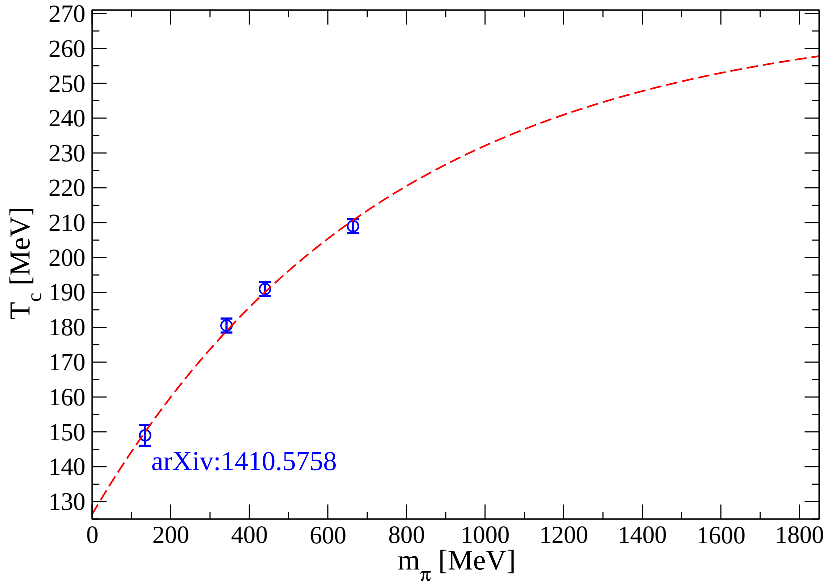
T_c determined from the inflection point of the condensate or from the peak of the susceptibility: consistent results.



Chiral-to-quenched interpolation of $T_c(m_\pi)$ (various different interpolations work well):

$$T_c(m_\pi) = T_c^{quench} - (T_c^{quench} - T_c^\chi)\, e^{-m_\pi/M}$$

$T_c^{quench} = 270$ **MeV,** $T_c^\chi = 128(4)$ **MeV**
$\tilde\chi^2 = 1.54/2$.



Chiral condensate for different values of eB

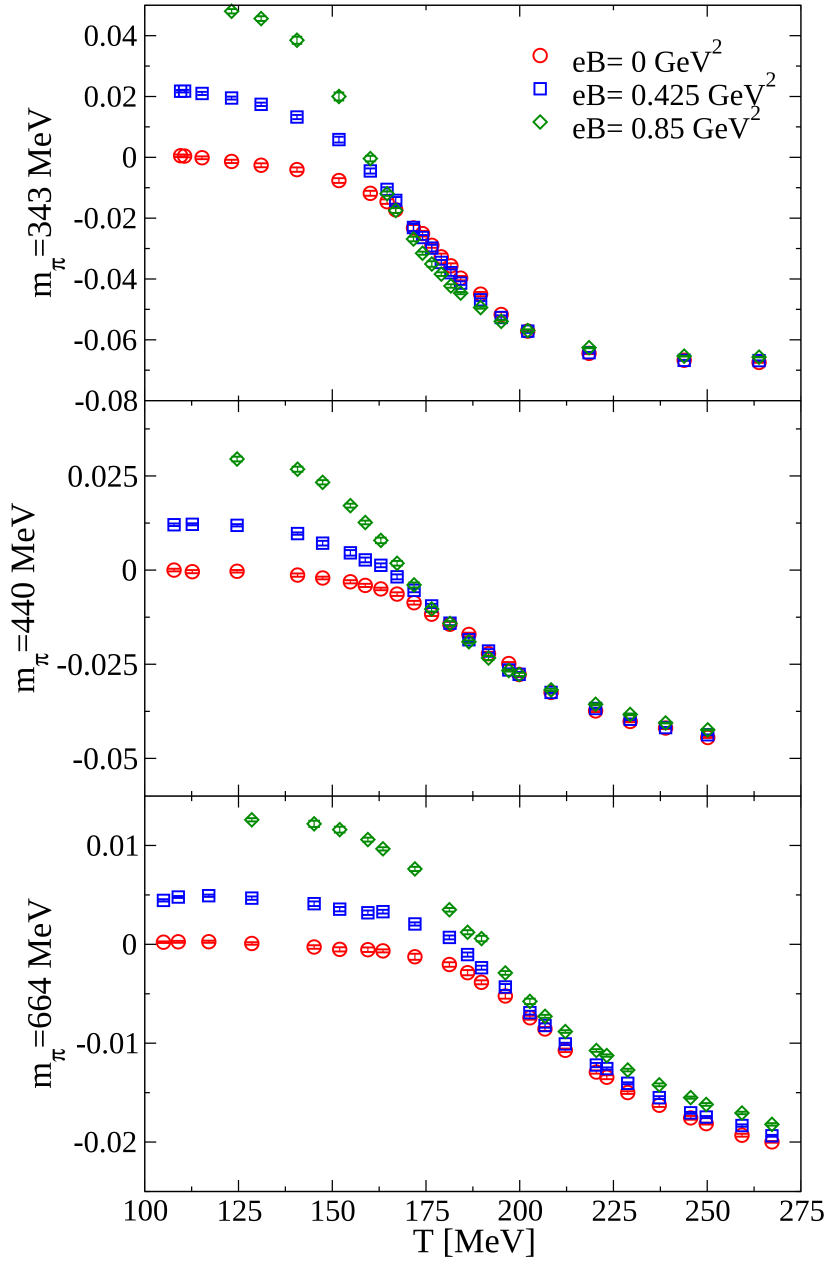
Magnetic field along $\hat{z}$. On a lattice torus B is quantized in lattice units:

$$eB_z = 6\pi b/(a^2 N_x N_y) \; ,$$

where b is integer valued.

Results for intermediate values obtained by spline interpolation.

T_c determined from the inflection point, inverse magnetic catalysis around T_c seems to disappear as m_π grows

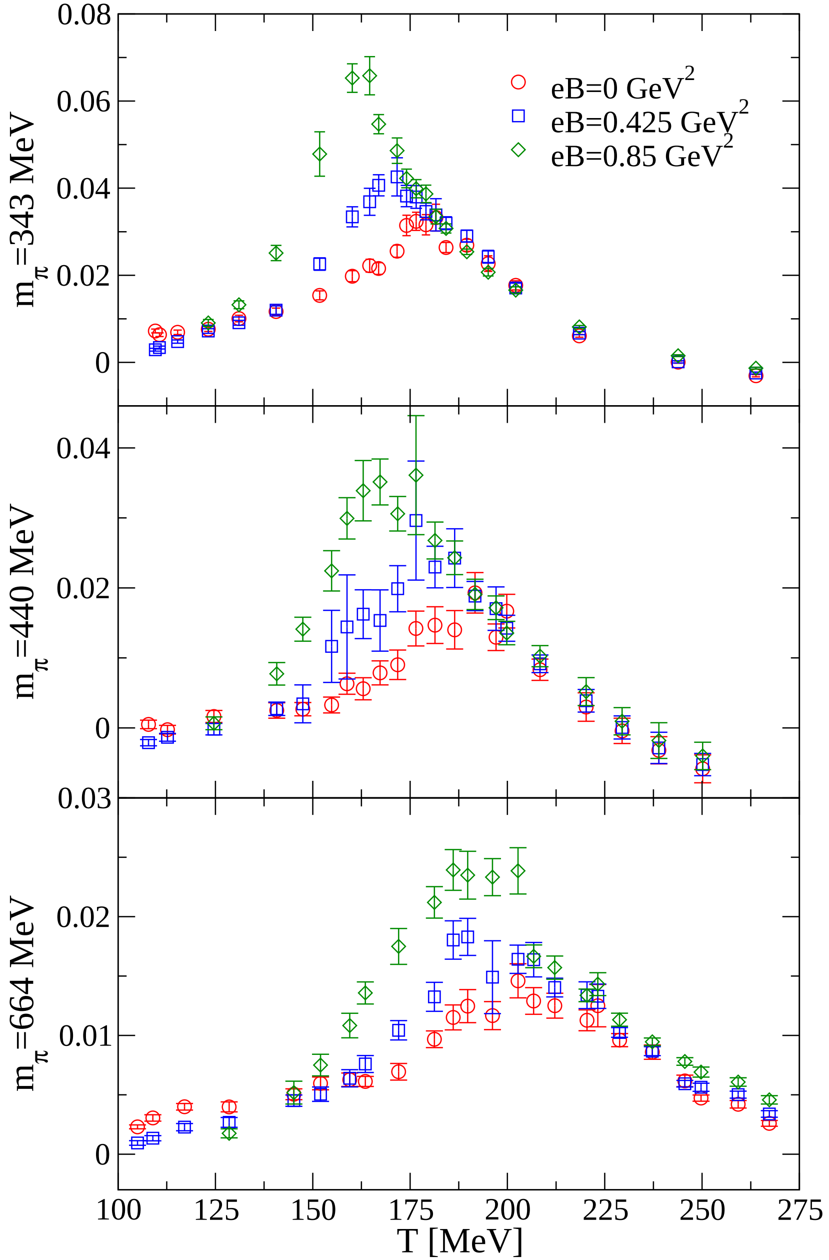


Renormalized chiral susceptibility

$$\chi_\ell^r(T,B) = m_\ell^2\left(\chi_\ell(T,B) - \chi_\ell(0,0)\right)$$

as a function of T for different values of m_π and eB.

T_c determined from the peak of the susceptibility. T_c decreases as with B in all cases and the transition strengthens

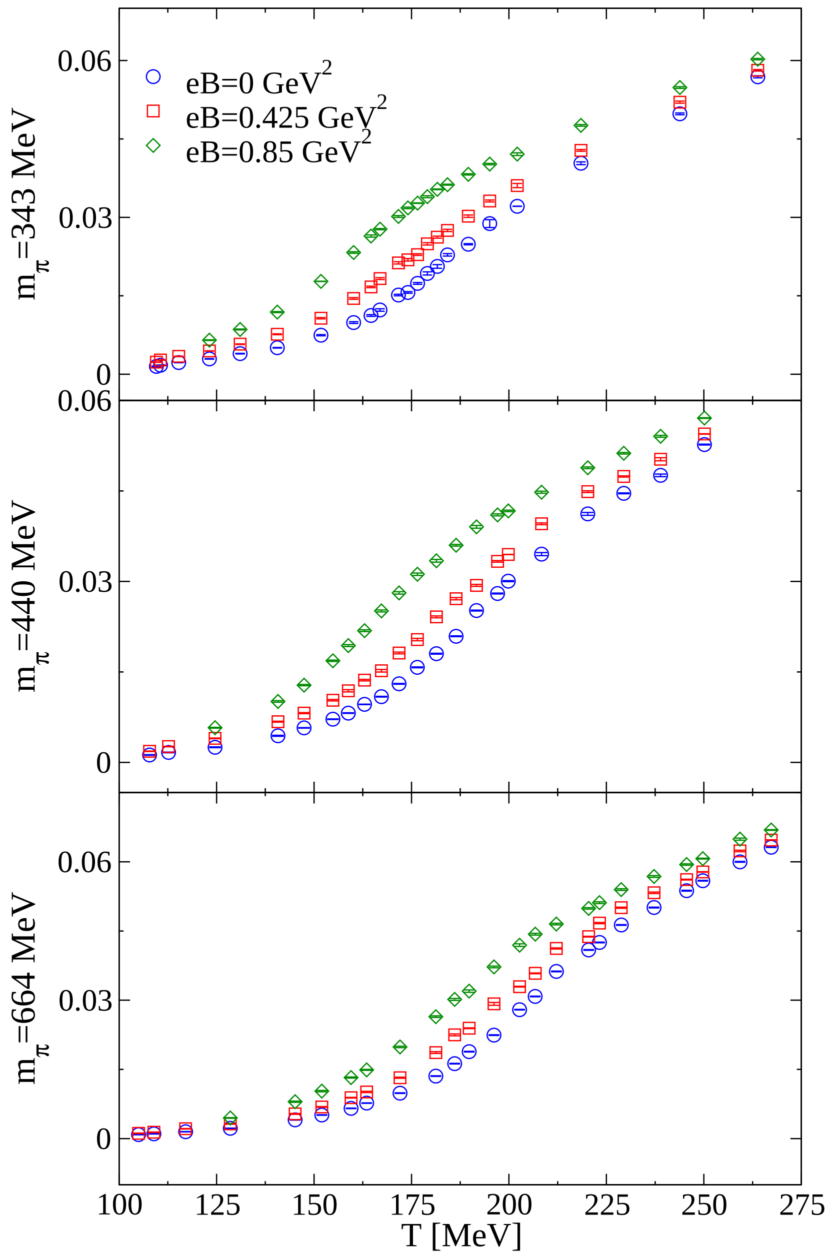


Unrenormalized Polyakov loop as a function of T for different values of m_π and eB.

The Polyakov loop is an increasing function of eB for all temperatures and pion masses, consistent with earlier results:

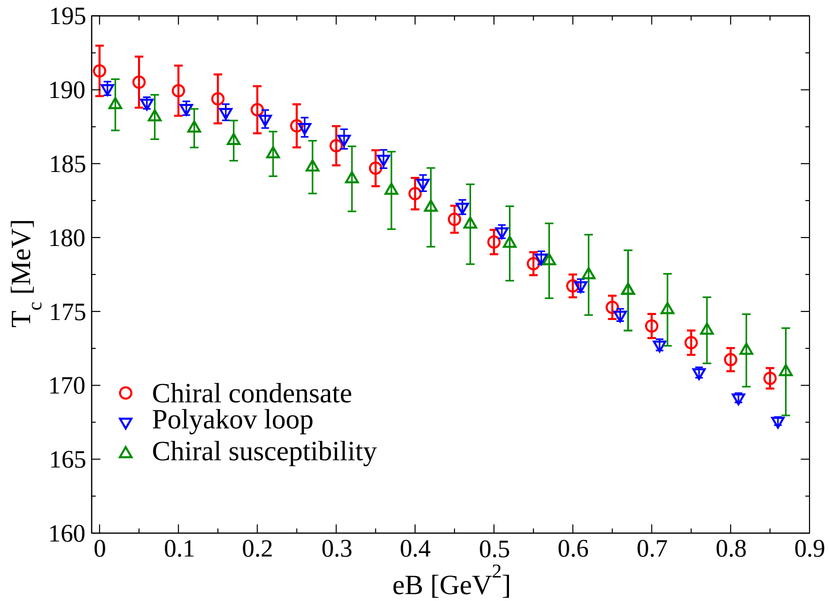
F. Bruckmann, G. Endrodi and T. G. Kovacs, JHEP 04, 112 (2013), arXiv:1303.3972

T_c from the inflection point of the Polyakov loop as a function of T

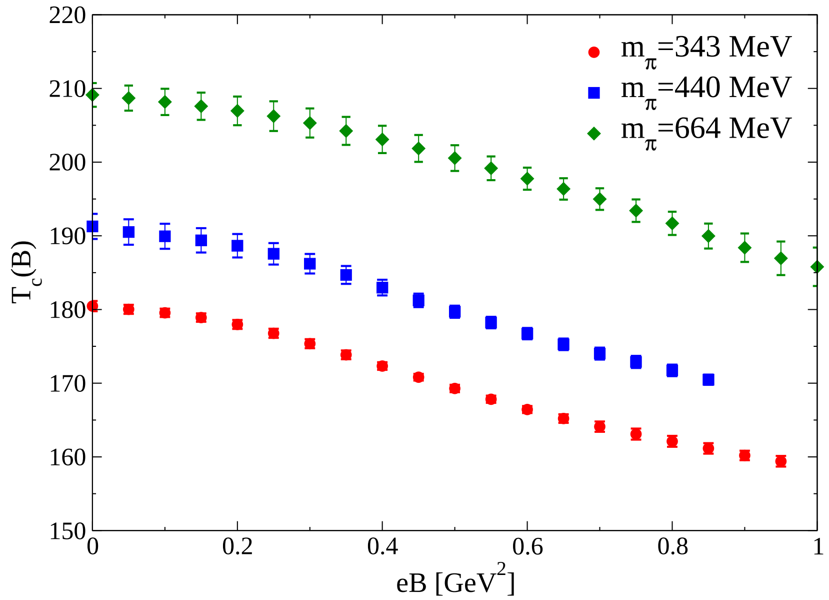


Results for T_c from the three different observables are consistent over the whole range of eB and m_π

The figure refers to $m_\pi = 440$ MeV



Main result: T_c is always a decreasing function of eB, independently of the pion mass

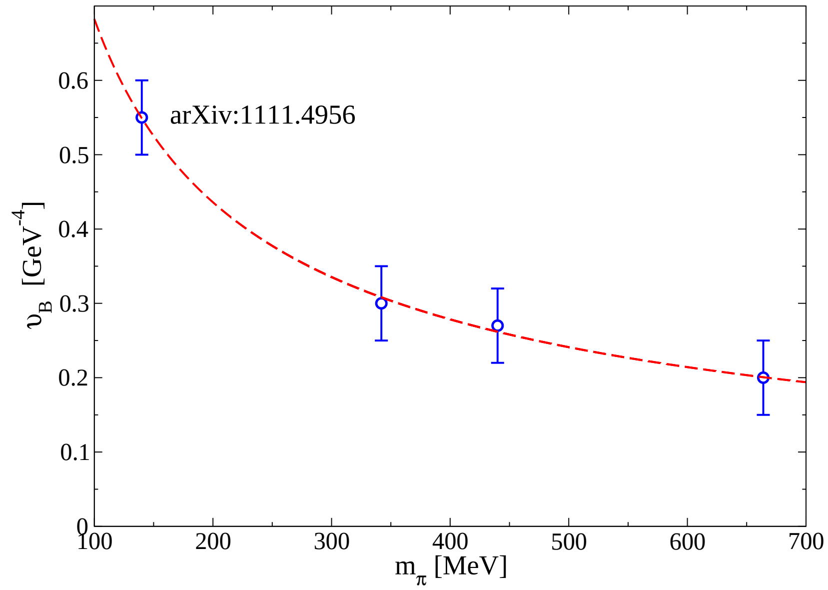


For large enough pion masses, quarks should decouple ...

From the small-eB behavior, we have determined the curvature of the pseudo-critical line:

$$\frac{T_c(eB)}{T_c0} = 1 - v_B\,(eB)^2$$

The dotted line is a best fit to a behavior $v_B = a/m_\pi^\alpha$, yielding $\alpha = 0.62(12)$



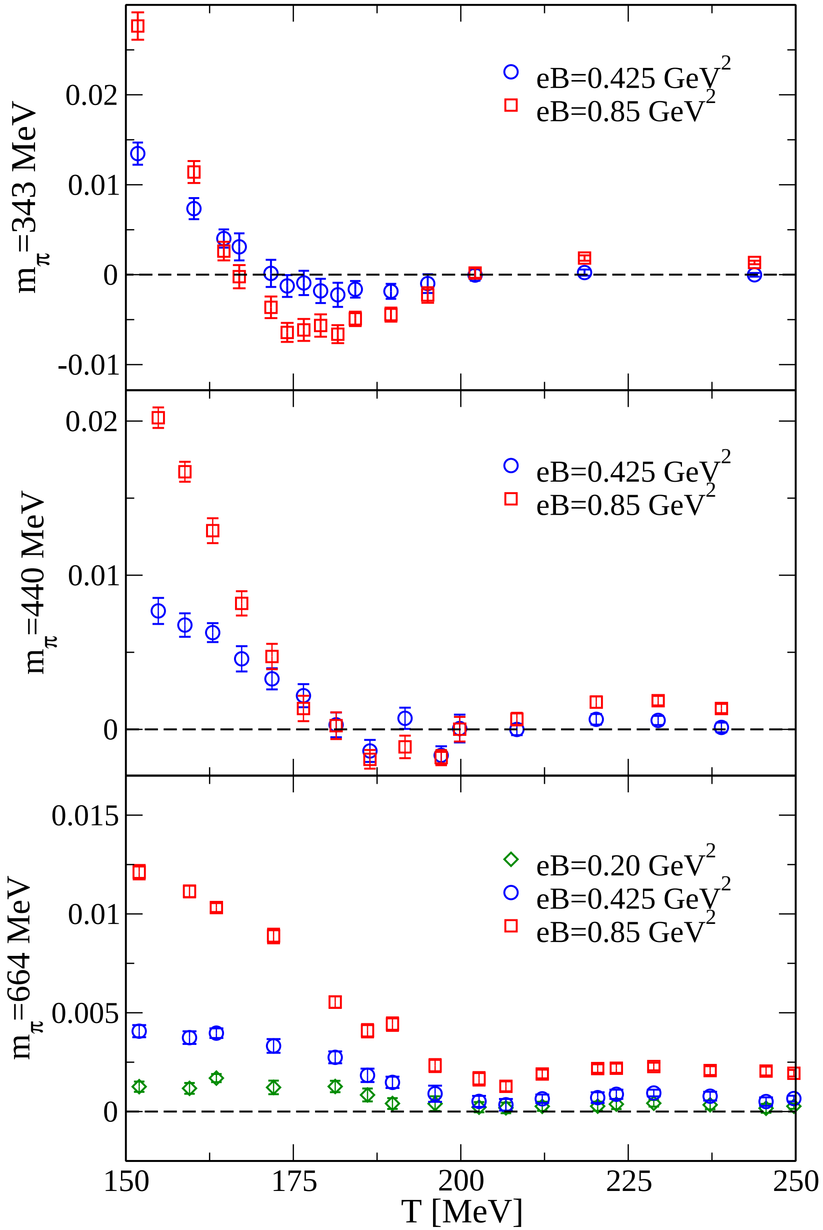
That is consistent with a vanishing curvature in the quenched limit, in agreement with the expected decoupling of quarks

Direct or inverse magnetic catalysis?

We report the difference in the chiral condensate with respect to its value at $eB = 0$

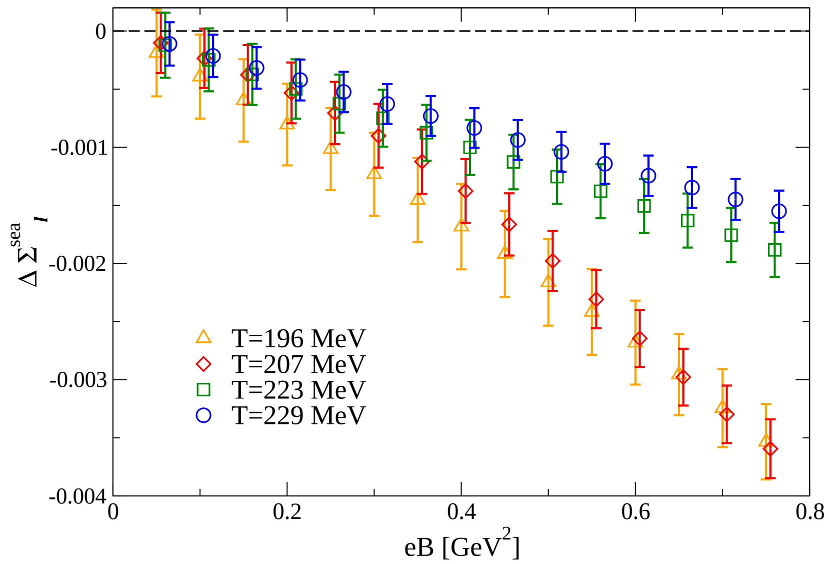
Inverse magnetic catalysis disappears between $m_\pi = 440$ MeV and $m_\pi = 664$ MeV

Consistent with results found in (G. Endrodi, M. Giordano, S. D. Katz, T. G. Kovács and F. Pittler, JHEP 07, 007 (2019), arXiv:1904.10296) where the transition pion mass is $m_\pi \sim 500$ MeV



a remnant of inverse catalysis:

decrease of the sea contribution to the quark condensate at the pion mass



$$\Sigma_f^{sea}(T,B) = \frac{T}{VZ(B)} \int \mathcal{D}U\, e^{-S_{YM}} \prod_{f'=u,\,d,\,s} \det\left(M_{\mathsf{st}}^{f'}[m_{f'},B]\right)^{1/4} \mathrm{Tr}((M_{st}^{f}[m_f,0])^{-1})$$

$$\Delta\Sigma_\ell^{sea}(T,B) = \Sigma_u^{sea}(T,B) + \Sigma_d^{sea}(T,B) - \Sigma_\ell(T,0)\,.$$

This is a direct manifestation of the decrease of T_c: the gauge field distribution moves towards the phase with confinement and chiral symmetry breaking.

Conclusions - I

- T_c is a decreasing function of eB for any value of the pion mass, likely up to the quenched limit. The dependence is milder and milder as quarks decouple in the heavy mass limit.

- The discrepancy in early results reporting an increasing $T_c(B)$ was due to discretization effects. This is also confirmed by recent results obtained with unimproved staggered fermions and $N_f = 3$ light fermions, still reporting an increasing T_c

  (H. T. Ding, C. Schmidt, A. Tomiya and X. D. Wang, PRD 102, no.5, 054505 (2020), arXiv:2006.13422)

- Inverse magnetic catalysis does not seem to be a universal phenomenon and disappears for large enough pion masses

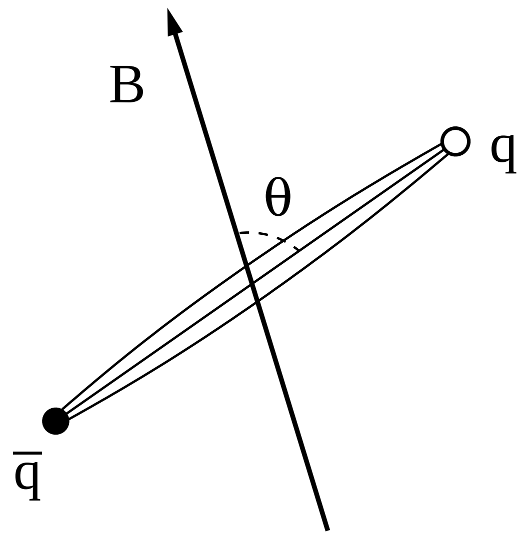
- On the other hand, the influence of B on the confining properties of QCD seems to be a universal phenomenon, regarding both $T \neq 0$ and $T = 0$ physics ...

A brief review about the effect of B on confinement

The effects of a magnetic background on the static quark-antiquark potential have been studied in a couple of recent lattice studies

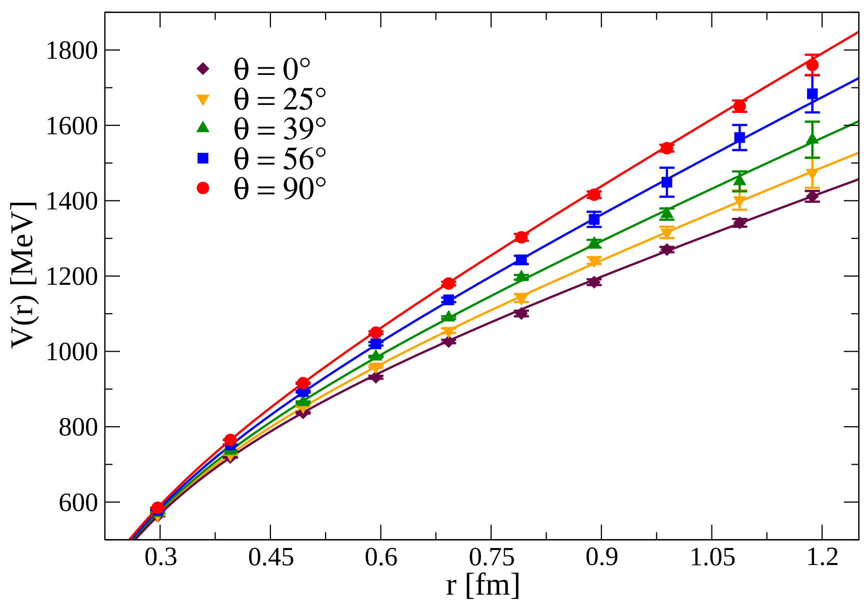
C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo, PRD 94, no.9, 094007 (2016), arXiv:1607.08160

C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro and F. Sanfilippo, PRD 89, no.11, 114502 (2014), arXiv:1403.6094



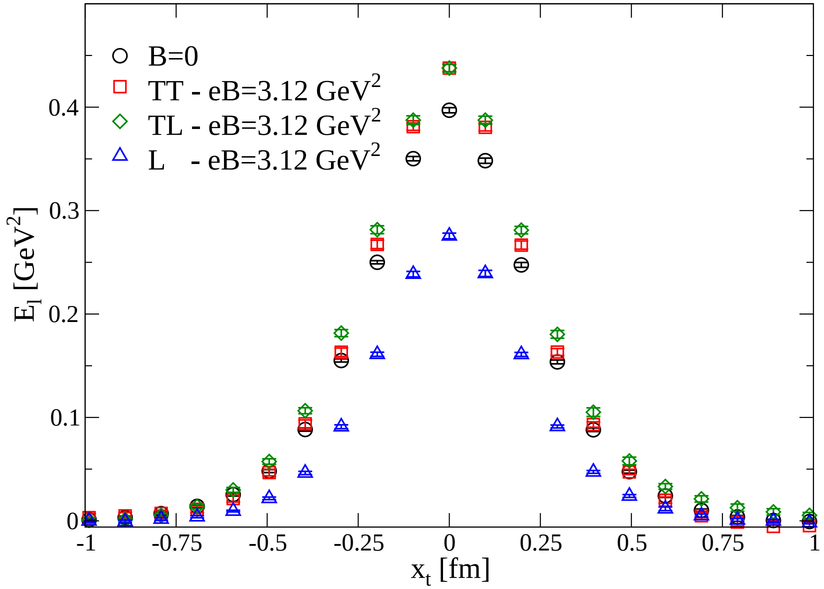
The potential turns out to be anisotropic, with a reduction of the string tension in the direction parallel to B, and an increase in the direction orthogonal to it

$eB \simeq 1$ **GeV^2** $\Longrightarrow$

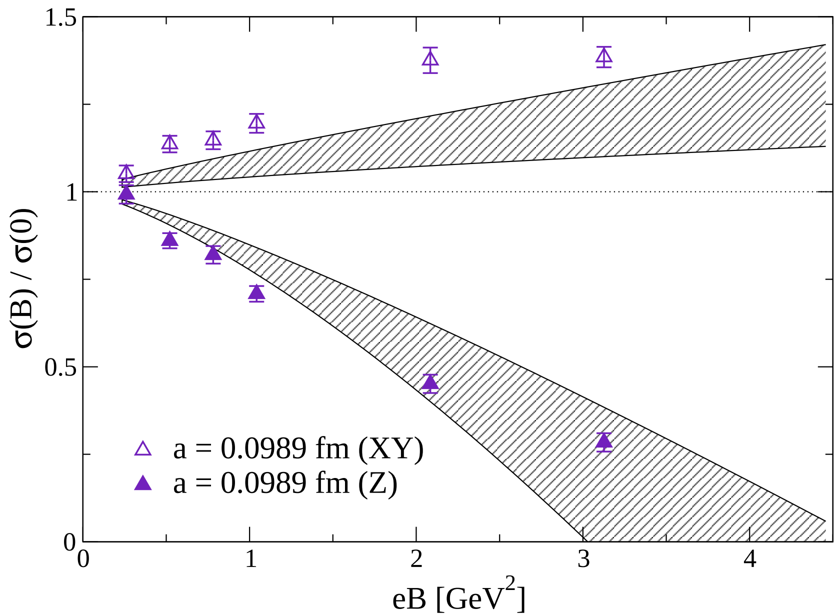


The modifications are clearly visible also at the level of the flux tube profile

C. Bonati, S. Calì, M. D'Elia, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo, PRD 98, no.5, 054501 (2018), arXiv:1807.01673



The continuum extrapolated results for σ predict a vanishing longitudinal string tension for $eB \sim 4$ GeV^2



This is however, outside the range explored for the continuum extrapolation, $eB \lesssim 1$ GeV^2, so we cannot trust the prediction, anyway it is an interesting indication for future studies

Conclusions - II

- **There is likely more to be explored in future lattice studies about the relations between the decreasing behavior of T_c and the effects of B on the confinining properties of the theory**

- **Is there any "anisotropic" deconfinement for $eB \sim O(10)$ GeV^2? Maybe this is not interesting for phenomenology (too large magnetic fields) but theoretically appealing**

- **Such strong anisotropies have been observed also in the deconfined phase at the level of the electric conductivity, which is enhanced along the magnetic field (CME) and suppressed in the orthogonal direction**

  N. Astrakhantsev, V. V. Braguta, MD, A. Y. Kotov, A. A. Nikolaev and F. Sanfilippo, PRD 102, no.5, 054516 (2020), arXiv:1910.08516

- **It is interesting that, for fields of the same order of magnitude, there is a prediction for the finite T QCD transition to become first order**

  G. Endrodi, JHEP 07, 173 (2015) arXiv:1504.08280