Phase diagram of QCD in (B, T, μ) space from analytical continuation

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in collaboration with

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Heavy Ion Collisions: interplay of strong and electromagnetic interactions

- Electric and Magnetic Fields $eE, eB \sim m_\pi^2$

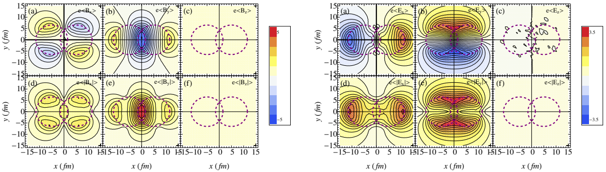
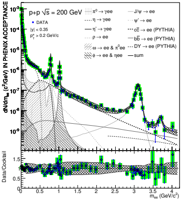


Figure from [X.-G. Huang, 2016]

- Electromagnetic probes (photon and dilepton production rates)



[PHENIX, 2010]

QCD and Magnetic Fields

- (Inverse) Magnetic Catalysis
- Chiral Magnetic Effect
- Chiral Waves, Chiral Spiral

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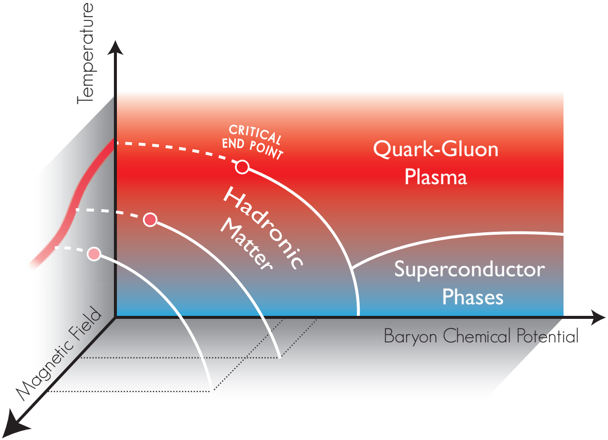

Sketch from [P.Costa, M.Ferreira, C. Providência, 2018]

Lattice setup

- Lattice size: $\underline{6 \times 24^3}$, 6×32^3
- Stout improved staggered $N_f = 2 + 1$ fermions
- Tree level Symanzik gauge action
- Physical masses of u, d, s quarks
- $q_u = 2/3e$, $q_d = q_s = -1/3e$
- Data for $eB = 0$ are taken from [C. Bonati et al., 2014]
- $\mu_s = 0$, $\mu_u = \mu_d = \mu_l \to i\mu_l$

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- $\mu_s = 0$, $\mu_u = \mu_d = \mu_I \to i\mu_I$

- Fix $\frac{\mu_I}{\pi T} \in [0.00, 0.275]$
- Fix $eB = \frac{6\pi n_B}{(N_s a)^2}$ in physical units
- β (or lattice step a) is varied
- $n_b \in \mathbb{Z} \longrightarrow$ discrete values of β (or, equivalently T)
- $O(100)$ configurations

Observables

Light quark chiral condensate:

$$\langle\bar{\psi}\psi\rangle_l = \frac{T}{V}\frac{\partial \log Z}{\partial m_l} = \langle\bar{u}u\rangle + \langle\bar{d}d\rangle$$

$$\langle\bar{\psi}\psi\rangle_r = \frac{\left[\langle\bar{\psi}\psi\rangle_l - \frac{2m_l}{m_s}\langle\bar{s}s\rangle\right](T, eB, \mu)}{\left[\langle\bar{\psi}\psi\rangle_l - \frac{2m_l}{m_s}\langle\bar{s}s\rangle\right](T=0, eB=0, \mu=0)}$$

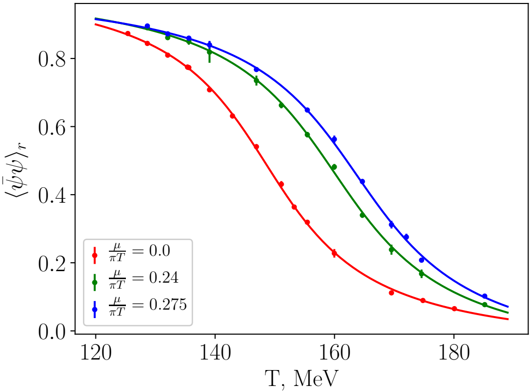
Polyakov loop:

$$L(\vec{x}) = \mathrm{tr}\prod_{\tau=1}^{N_\tau} U_4(\vec{x}, \tau)$$

Renormalized with GF [P.Petreczky and H.-P. Schadler, 2016]

$$L^r(\vec{x}) = L(\vec{x})[V_{t=f}(x, \mu)]$$

Chiral condensate. $eB = 0$



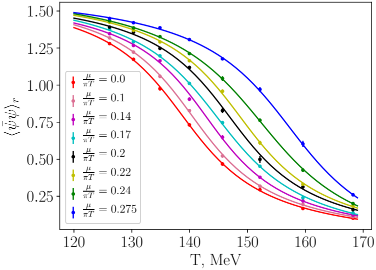
Data from [C. Bonati et al., 2014]

Inflection point:

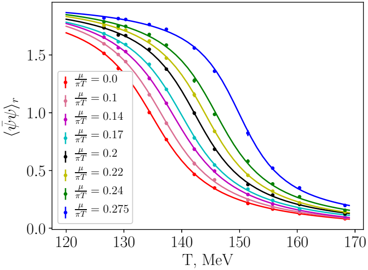
$$\langle\bar{\psi}\psi\rangle_l^r(T) = A_1 + B_1 \arctan(C_1(T - T_c))$$

Chiral condensate

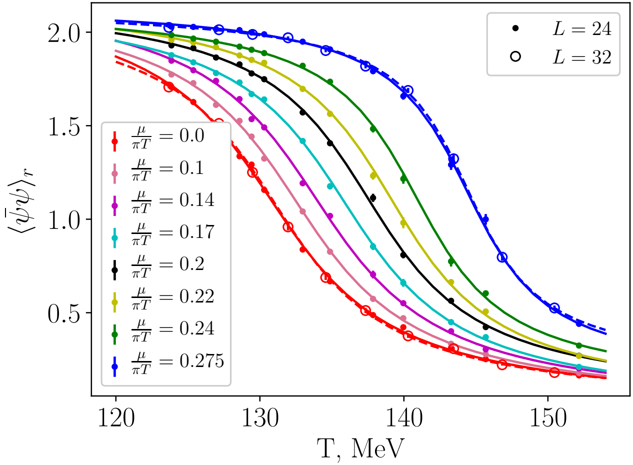
$eB = 0.6\mathrm{GeV}^2$



$eB = 1.0\mathrm{GeV}^2$



Chiral condensate

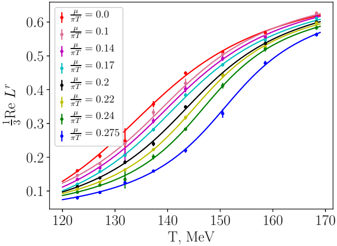


Large $eB = 1.5\mathrm{GeV}^2$: finite volume effects under control

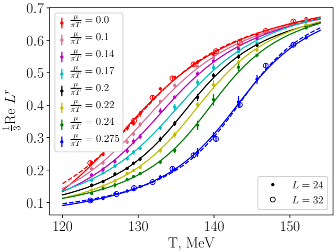
No signatures of first order phase transition

Polyakov loop

$eB = 0.8\mathrm{GeV}^2$



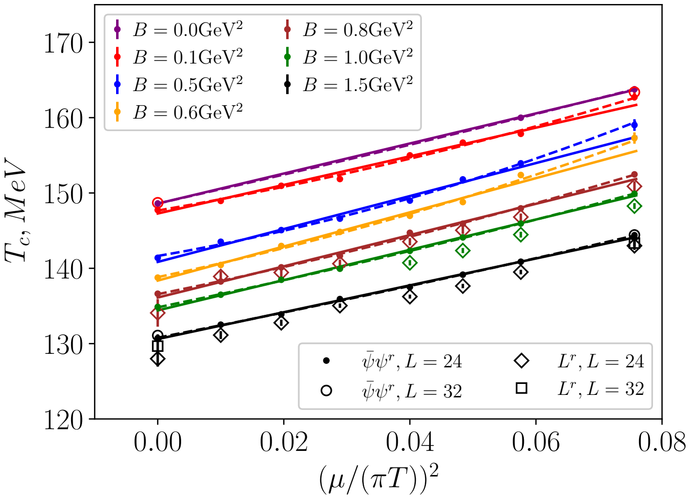
$eB = 1.5\mathrm{GeV}^2$



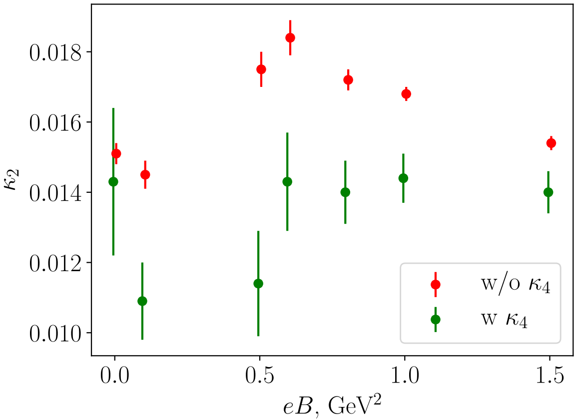
Clear inflection point only for large magnetic fields $eB \geq 0.8 GeV^2$ [G.Endrodi, 2015]:

$$\langle L \rangle^r(T) = A_2 - B_2 \arctan(C_2(T - T_c))$$

Pseudo-critical temperature



Curvature of (chiral) pseudocritical line

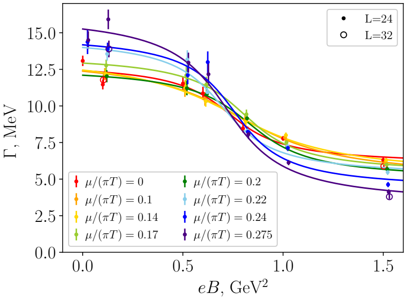


$$T_c(\mu) = T_c(\mu = 0)\left(1 + 9\kappa_2\left(\frac{\mu}{T_c}\right)^2 + 81\kappa_4\left(\frac{\mu}{T_c}\right)^4 + \dots\right)$$

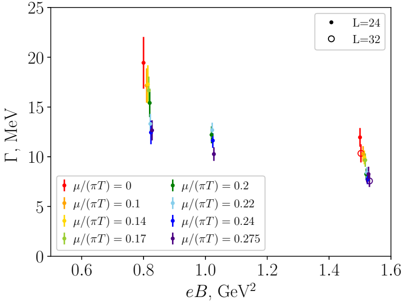
Width of the transition (C^{-1})

$$O = A + B \arctan(C(T - T_c))$$

$\bar{\psi}\psi^r$



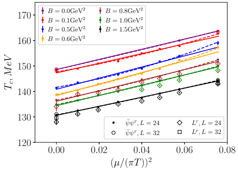
L^r



Lines correspond to simple arctan-fit
Change of behaviour at $eB \sim 0.7\text{GeV}^2$

Conclusions

- QCD phase diagram with nonzero T, eB, μ
- Simulations with imaginary $\mu_u = \mu_d = i\mu_I$, $\mu_s = 0$
- Almost no dependence of κ_2 on eB
- Magnetic field makes the transition sharper
- At small magnetic fields eB the width Γ grows with μ_I, at large values of eB Γ decreases with μ_I
- No signatures of CEP or first order transition



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Outlook:

- Finite lattice step effects (various N_t)
- Susceptibilities
- Change in behaviour of Γ ?