Lattice study of the QCD phase diagram in (B, T, μ) space

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in collaboration with

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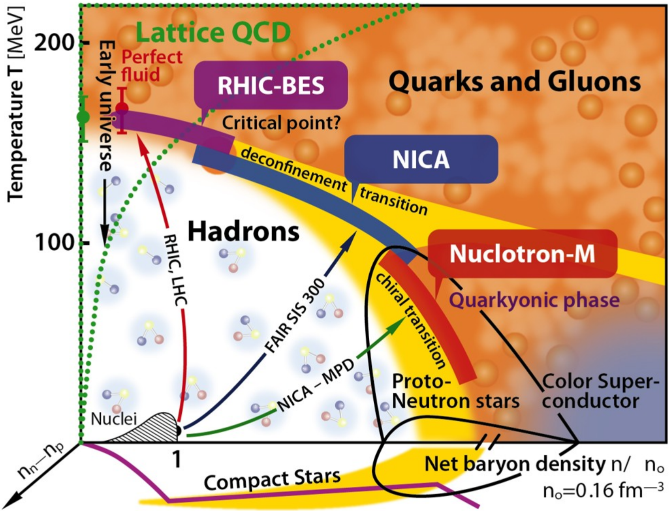
Excited QCD 2020

QCD phase diagram



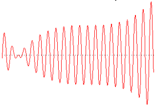
Chiral phase transition Deconfining phase transition

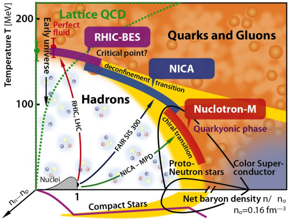
$T - \mu$ plane

Sign problem!

$Z = \int DA_\mu D\bar{\psi} D\psi e^{-S[\bar{\psi},\psi,A_\mu]}$

$\mu_B \Rightarrow S \notin \mathbb{R}$



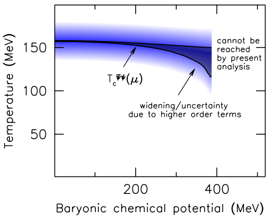


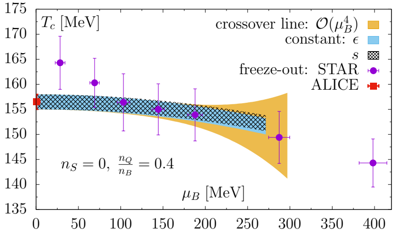
Analytical continuation: $\mu_B \to i\mu_I$ - no sign problem!

$$M(\mu_I) = A + B\mu_I^2 + \ldots \Rightarrow M(\mu_B) = A - B\mu_B^2 + \ldots$$

$T - \mu$ plane

- Curvature of pseudocritical line
  $T_c(\mu_B) = T_c(0) - A_2\mu_B^2 + O(\mu_B^4)$





[R. Bellwied et al., 2015]

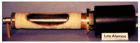
[HotQCD, 2018]

Magnetic fields in nature

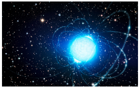
Souvenir magnet — 5×10^{-3} T

Max permanent magnet — 1.25 T

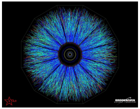
Magnetic field to levitate a frog — 16 T



Human produced pulsed magnetic field — 2.8×10^{3} T



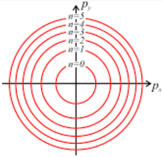
Magnetars — $10^{8} - 10^{11}$ T

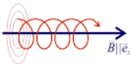


Heavy ion collisions — $10^{14}\text{T} \sim m_\pi^2$

Wikipedia

Lattice QCD in $T - B$ plane. (Inverse) Magnetic Catalysis



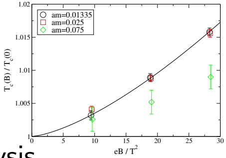


- Magnetic Catalysis

  [V. Gusynin, V. Miransky, I. Shovkovy, 1994]

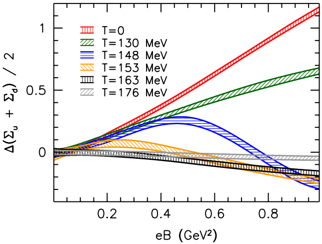
- Lattice + heavy pions: Direct Magnetic catalysis

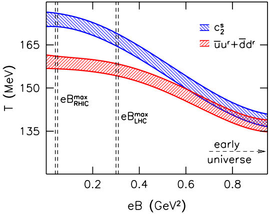
  [E.-M. Ilgenfritz et al., 2012] [M. D'Elia et al., 2010]



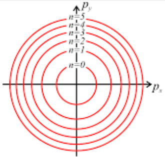
- Lattice + physical pions: Inverse Magnetic Catalysis

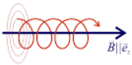
  [G. Bali et al., 2012] [F.Bruckmann et al., 2013]





Lattice QCD in $T - B$ plane. (Inverse) Magnetic Catalysis





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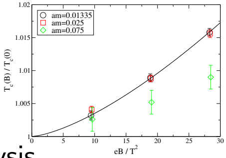


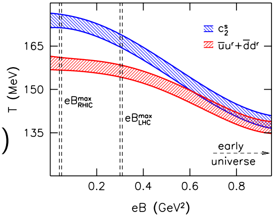
- Lattice + physical pions: Inverse Magnetic Catalysis

  [G. Bali et al., 2012] [F.Bruckmann et al., 2013]

- Recent studies with heavy pions

  [M. D'Elia et al., 2018] [G.Endrodi et al., 2019]

  - Inverse magnetic catalysis for T_c
  - Direct magnetic catalysis for $\bar{\psi}\psi$ (near T_c)



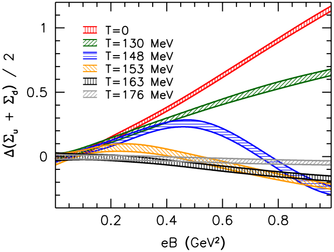
Not yet fully understood!

Lattice QCD in $T - B$ plane

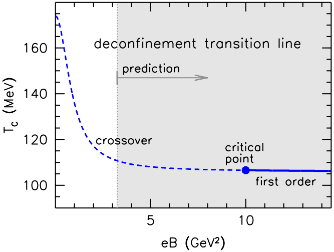
- (Inverse) Magnetic Catalysis
- CEP at very large magnetic fields?

  [G.Endrodi, 2015]
- Exotic (nonhomogenuous) phases?

  [G. Basar et al., 2010]



[F.Bruckmann et al., 2013]

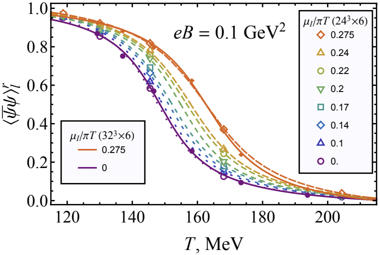


Phase diagram at nonzero T, eB, μ?

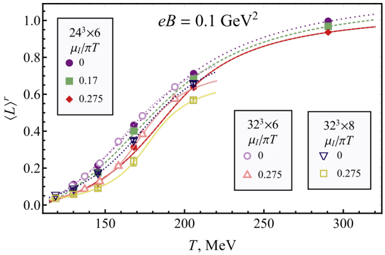
Present results at $\mu_I = i\mu$, analytical continuation $\mu_I^2 \to -\mu^2$

Observables

Chiral consensate

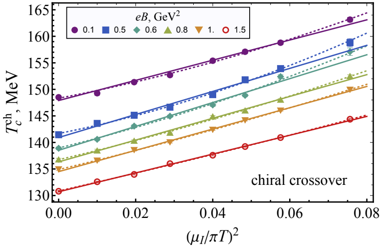


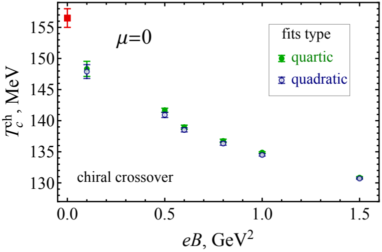
Polyakov loop

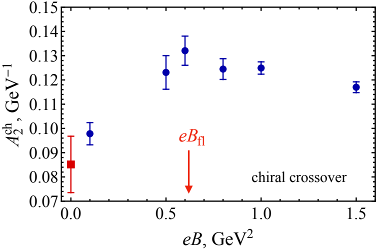


$$O(T) = A + B \arctan\left(\frac{T - T_c}{\delta T_c}\right)$$

Chiral phase transition vs $\mu_I/\pi T$

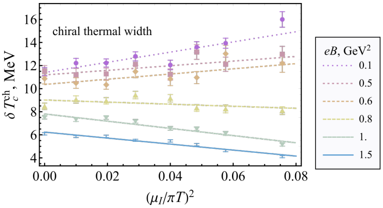






$$T_c(\mu_B, B) = T_c(0, B) - A_2(B)\mu_B^2 + O(\mu_B^4)$$

Width of the chiral phase transition



CEP(?) at $eB = 0$

$(T, \mu_B) \sim$

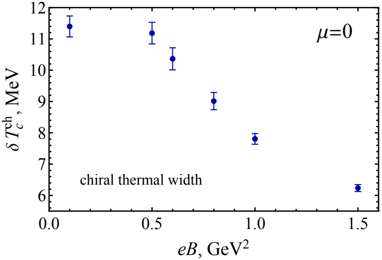
$(100(25), 800(140))$ MeV

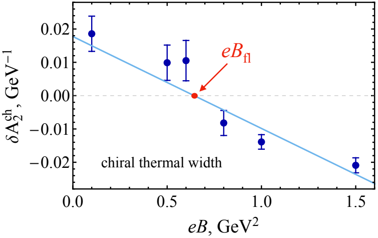
FRG: $(107, 635)$ MeV

[W. Fu, J. Pawlowski, F. Rennecke, 2019]

Holography: $(89, 724)$ MeV

[R.Critelli et al., 2017]

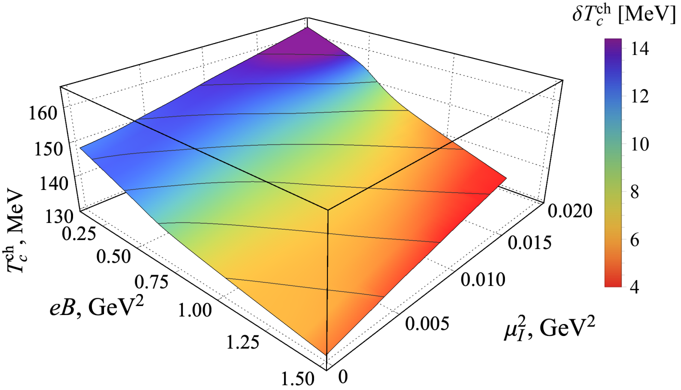




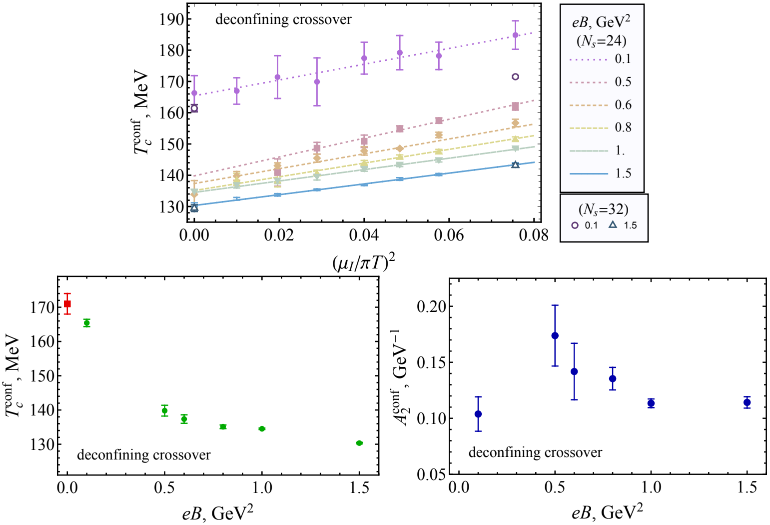
$$\delta T_c^{ch}(\mu_B, B) = \delta T_c^{ch}(0, B) - \delta A_2^{ch}(B)\mu_B^2 + O(\mu_B^4)$$

Flipping point $eB_{fl} \approx 0.6$GeV^2

Critical temperature and width (chiral crossover)

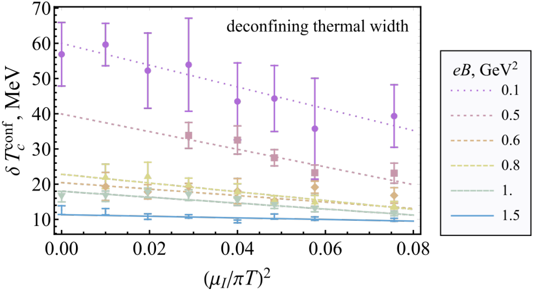


Confining crossover, critical temperature T_c

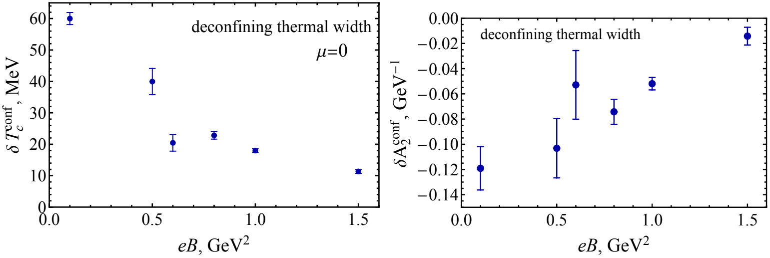


$$T_c(\mu_B, B) = T_c(0, B) - A_2(B)\mu_B^2 + O(\mu_B^4)$$

Confining crossover, width δT_c

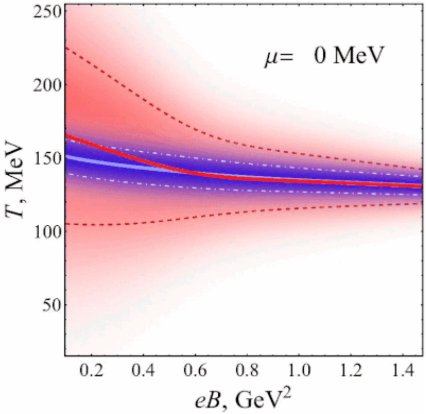


No flipping!



$$\delta T_c^{\rm conf}(\mu_B, B) = \delta T_c^{\rm conf}(0, B) - \delta A_2^{\rm conf}(B)\mu_B^2 + O(\mu_B^4)$$

$T - B - \mu_B$ space (analytical continuation)



- Blue - Chiral phase transition
- Red - Deconfining phase transition

Results and conclusions

- QCD at nonzero T, eB, μ is very interesting and nontrivial
- Can be studied by means of supercomputer simulations
- Critical temperature: mild interplay between eB and μ_B:
  - Inverse Magnetic Catalysis
- Width of the transition:
  - CEP at $eB = 0$: $(T, \mu_B) \sim (100(25), 800(140))$ MeV
  - Chiral thermal width (Behaviour changes at $eB_c \approx 0.6\text{GeV}^2$):
    - $eB < eB_c$: δT_c^{ch} slightly decreases with μ_B
    - $eB > eB_c$: δT_c^{ch} increases with μ_B