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Magnetized QCD phase diagram

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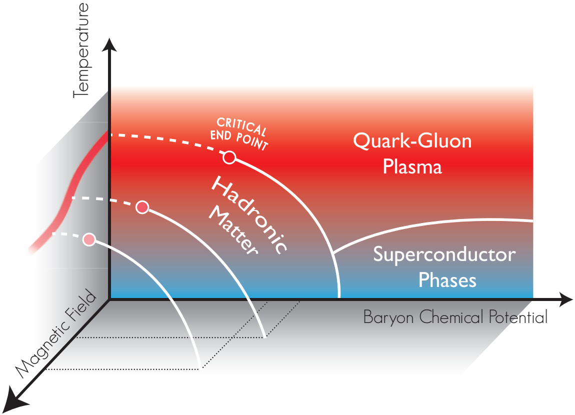
Motivation

How does a magnetic field affect the QCD phase diagram?



- Impact on chiral symmetry breaking and confinement
- What happens to the Critical End Point (CEP)?

Framework: the PNJL model

Nambu-Jona–Lasinio model coupled to the Polyakov loop

$$\mathcal{L} = \bar{q}\left[i\gamma_\mu D^\mu - \hat{m}_c\right]q + \mathcal{L}_{\mathsf{sym}} + \mathcal{L}_{\mathsf{det}} + \mathcal{U}\left(\Phi, \bar{\Phi}; T\right) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where

$$\mathcal{L}_{\mathsf{sym}} = G_s \sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (\bar{q}i\gamma_5\lambda_a q)^2\right]$$
$$\mathcal{L}_{\mathsf{det}} = -K\left\{\det\left[\bar{q}(1+\gamma_5)q\right] + \det\left[\bar{q}(1-\gamma_5)q\right]\right\}$$

- Minimal coupling: $D^\mu = \partial^\mu - iq_f A^\mu_{EM} - iA^\mu$
- Constant B field in the z direction: $A^{EM}_\mu = \delta_{\mu 2}x_1 B$
- For the Polyakov loop potential we use

$$\frac{\mathcal{U}\left(\Phi, \bar{\Phi}; T\right)}{T^4} = -\frac{a\left(T\right)}{2}\bar{\Phi}\Phi + b(T)\ln\left[1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2\right]$$

Framework: the PNJL model

- Regularization: 3-momentum cutoff Λ
- NJL parametrization: [P. Rehberg, et al. PRC53, 410]

$$m_u = m_d = 5.5 \text{ MeV}, \quad m_s = 140.7 \text{ MeV}$$

$$G_s \Lambda^2 = 3.67, \quad K\Lambda^5 = -12.36, \quad \Lambda = 602.3 \text{ MeV}$$

$\Rightarrow$ Fixed to reproduce several physical vacuum properties (f_π, M_π, M_K, and $M_{\eta'}$)

- $\mathcal{U}\left(\Phi, \bar{\Phi}; T\right)$ parametrization: [S. Roessner, et al. PRD75, 034007]

$$a_0 = 3.51, \quad a_1 = -2.47, \quad a_2 = 15.2, \quad b_3 = -1.75$$

$$T_0 = 210 \text{ MeV}$$

$\Rightarrow$ Chosen to reproduce lattice results

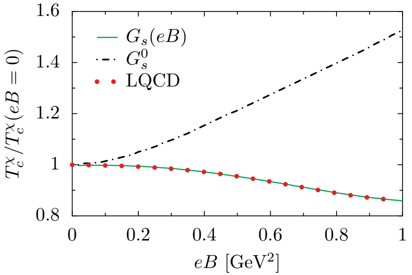
- Transition temperatures (pseudocritical):

$$T_\chi(\mu_B = 0) = 200 \text{ MeV}$$

$$T_\Phi(\mu_B = 0) = 171 \text{ MeV}$$

Two models: different scalar couplings

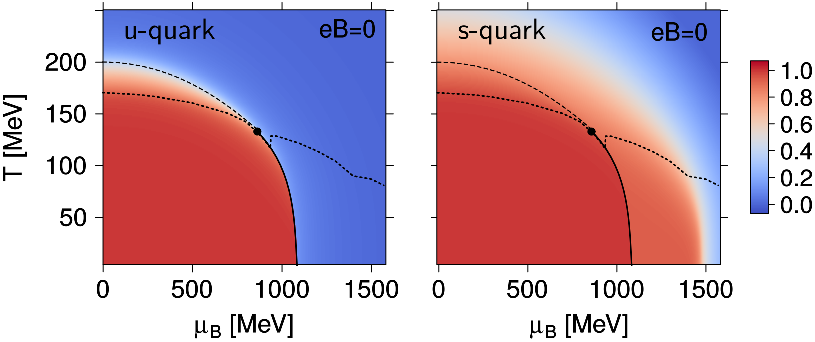
- Constant coupling: $G_s = G_s^0 = 3.67/\Lambda^2$
- Magnetic field dependent coupling: $G_s = G_s(eB)$



- Same vacuum properties for both models:
  - $G_s(eB) \to G_s^0$ as $B \to 0$

Phase diagram for $B = 0$: chiral transition

- Symmetric quark matter: $\mu_q = \mu_B/3$
- Isospin symmetry: $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$ for $B = 0$
- **Quark condensates**: $\langle \bar{q}q \rangle (T, \mu_B)/ \langle \bar{q}q \rangle (0, 0)$



- Critical point at $(T^{CEP}, \mu_B^{CEP}) = (133\ \text{MeV}, 862\ \text{MeV})$
- Crossover transition for the strange quark

Net-baryon fluctuations

- They provide vital information on critical phenomena:
  - possible experimental signatures for the presence of a CEP and the onset of deconfinement
- The nth-order **net-baryon fluctuations** (susceptibility):

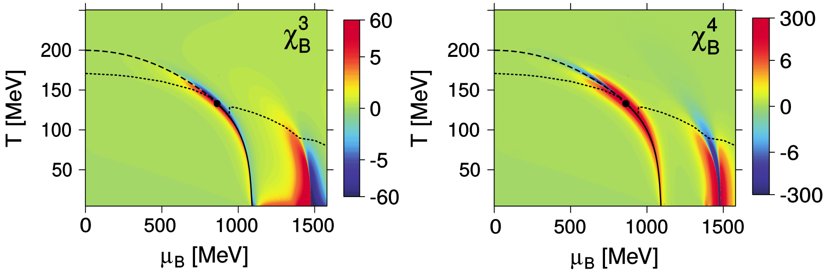
$$\chi_B^n(T,\mu_B) = \frac{\partial^n \left(P(T,\mu_B)/T^4\right)}{\partial(\mu_B/T)^n}$$

- Susceptibilities ratios have no volume dependence:

$$\chi_B^4/\chi_B^2 = \kappa\sigma^2 \qquad \chi_B^3/\chi_B^1 = S\sigma^3/M$$

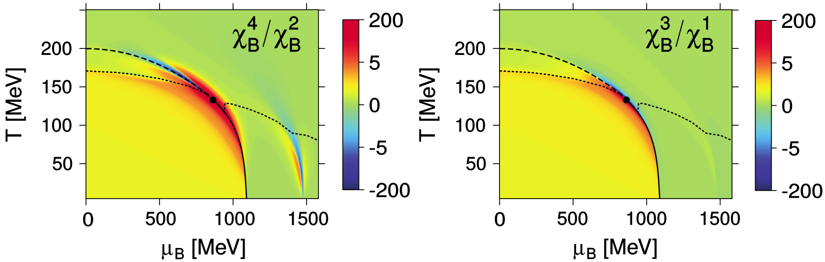
- They measure the kurtosis and skewness of the net-baryon distribution.

χ_B^3 and χ_B^4 fluctuations ($B = 0$)



- Non-monotonic dependences around the CEP
- Positive fluctuations of χ_B^3 on the chiral restored phase
- The χ_B^4 fluctuations are symmetric with respect to the chiral transition
- A similar non-monotonic dependence occurs at high μ_B (strange quark transition)
  - A stronger G_s would give rise to a first-order phase transition

χ_B^4/χ_B^2 and χ_B^3/χ_B^1 fluctuations ratios ($B = 0$)

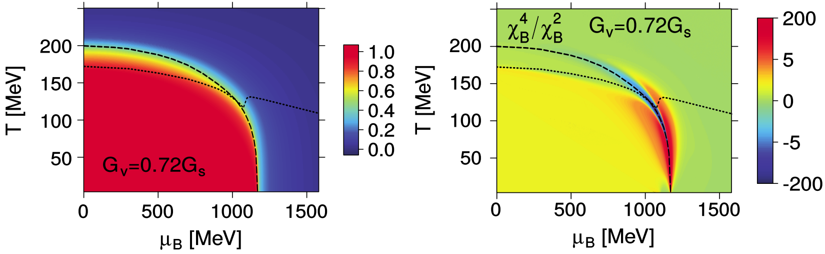


- Clear distinction between the broken/restored chiral symmetry region.
- There is a pronounced variation around deconfinement
- The non-monotonic dependence at higher μ_B is still visible

Can the non-monotonic (critical) region still persist in the absence of a CEP?

Strong vector interaction: $G_V = 0.72 G_s$ ($B = 0$)

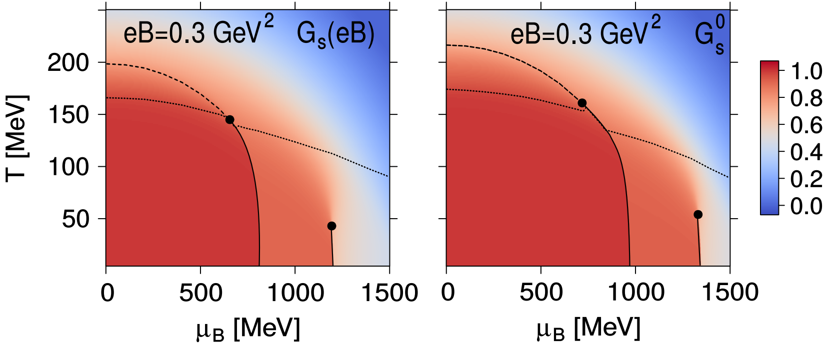
- Adding the vector interaction $G_V(\rho_u^2 + \rho_d^2 + \rho_s^2)$
- The CEP disappears for a strong enough G_V



- The non-monotonic dependence remains and still covers a wide region of the phase diagram.
- Even in the absence of a CEP, high net-baryon fluctuations still might be present in low T region.

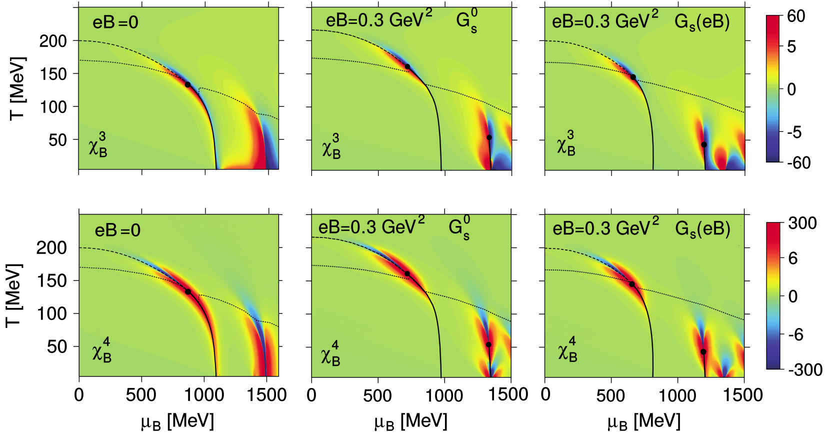
Strange quark condensate in a strong B

- A strong magnetic field induces a (multiple) first-order phase transition.



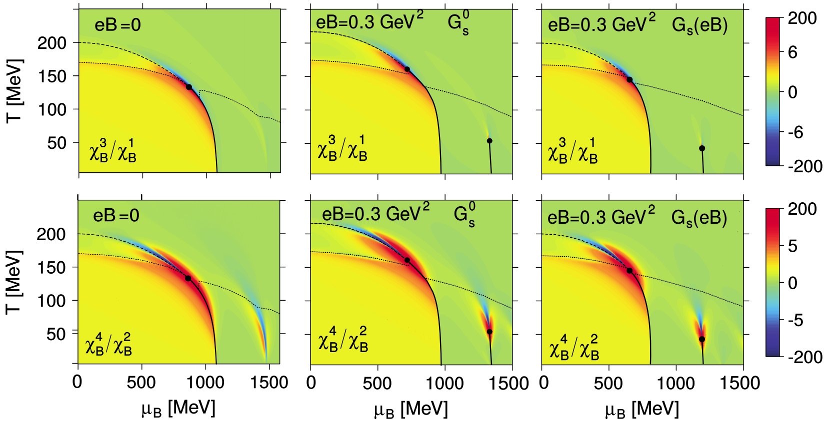
- The $G_s(eB)$ model predicts a smaller region for the chiral broken phase

χ_B^3 and χ_B^4 fluctuations in a strong B



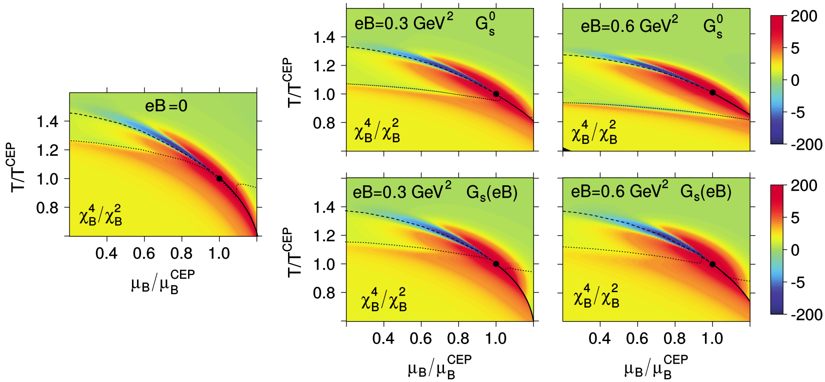
- Three CEP like structures at high μ_B:
  - 1^{st}: s-quark first-order phase transition
  - 2^{nd}: population of a new LL for the d-quark
  - 3^{rd}: s-quark first-order phase transition at higher μ_B

χ_B^4/χ_B^2 and χ_B^3/χ_B^1 fluctuations ratios in a strong B



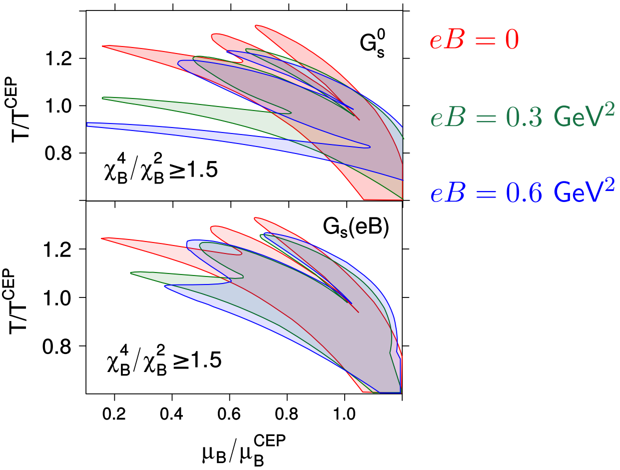
- Only the non-monotonic behavior around the CEPs remains
- B concentrates the high fluctuation region around de CEP

χ_B^4/χ_B^2 around the (light) CEP in a strong B



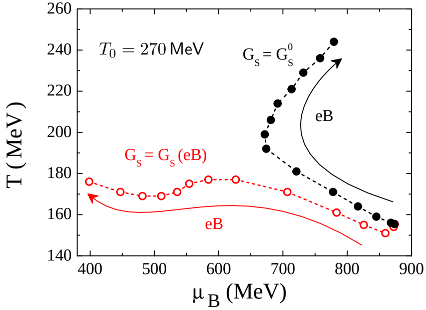
- A gap appears for the G_s^0 model ($T_\chi^{ps} - T_\Phi^{ps}$ increases with B)
- $G_s(eB)$ predicts smother fluctuations in a larger region

Fluctuation region: $\chi_B^4/\chi_B^2 \geq 1.5$



- The relative size of the large fluctuation region is quite insensitive to B, except for the deconfinement crossover in G_s^0 model

CEP's location as a function of B



- However, the B dependence of the large fluctuation region at low μ_B reflects the CEP location:
  - Decrease of fluctuations at low μ_B with B (> 0.3 GeV^2) for G_s^0
  - Increase of fluctuations at low μ_B with B for $G_s(eB)$
- LQCD calculations might distinguish both scenarios.

Conclusions

- External magnetic fields induce a complex pattern of multiple phase transitions
- B induces multiple first-order phase transitions for the strange quark
- Fluctuations do not necessarily indicate the existence of a CEP
- The relative size of the large fluctuation region close to CEP is quite insensitive to B
- The $G_s(eB)$ predicts that μ_B^{CEP} decreases with B
  - Enhancement of fluctuations at low μ_B
- The G_s^0 predicts that μ_B^{CEP} increases with B ($eB > 0.3$ GeV^2)
  - Suppression of fluctuations at low μ_B

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