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Net-baryon fluctuations in magnetized QCD matter

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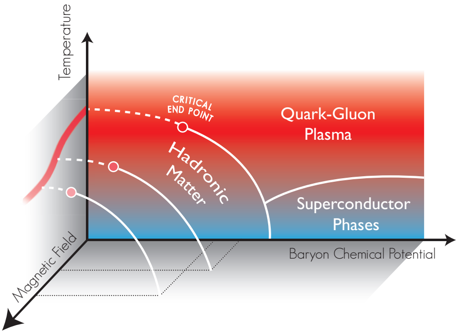
Motivation

The magnetic field effect on the QCD phase diagram



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

The importance of magnetic fields

- **Magnetized neutron stars** (low T and high μ_B)
- **First phases of the Universe** (high T and low μ_B)
- **Heavy-Ion Collisions (HIC)** (a broader (T, μ_B) region)
  - **Strong magnetic fields are generated in HIC**
    - ⋆ RHIC $\rightarrow eB_{max} \approx 5m_\pi^2 \approx 0.09\,\mathrm{GeV}^2$
    - ⋆ LHC $\rightarrow eB_{max} \approx 15m_\pi^2 \approx 0.27\,\mathrm{GeV}^2$

Mapping the QCD phase diagram
is one fundamental goal of HIC experiments

Framework: the Polyakov–Nambu-Jona–Lasinio model

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

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: $A^{EM}_\mu = \delta_{\mu 2}x_1 B$
- Polyakov loop value: $\Phi = \frac{1}{N_c}\langle\langle\mathcal{P}\exp\{i\int_0^\beta d\tau\, A^4\left(\vec{x},\tau\right)\}\rangle\rangle_\beta$ (order parameter for the Z_3 symmetry in pure gauge)
- Polyakov loop potential:

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

Framework: the PNJL model

- Regularization: 3D-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 physical vacuum properties:

$$(f_\pi, M_\pi, M_K, \text{ and } M_{\eta'})$$

- $\mathcal{U}\left(\Phi, \bar{\Phi}; T\right)$ 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

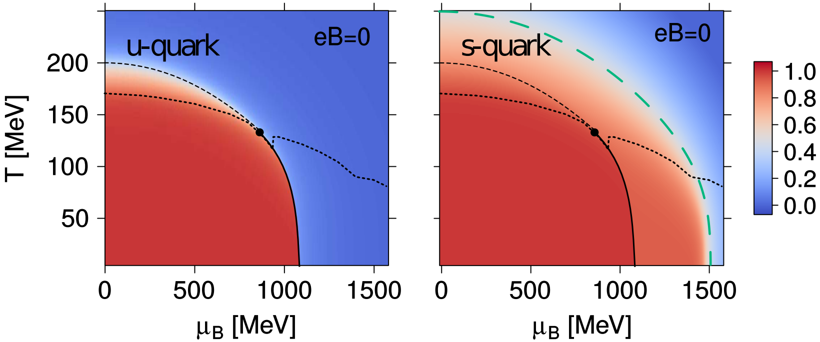
- (Pseudo-critical) Transition temperatures:

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

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

Phase diagram: chiral transition $[B = 0]$

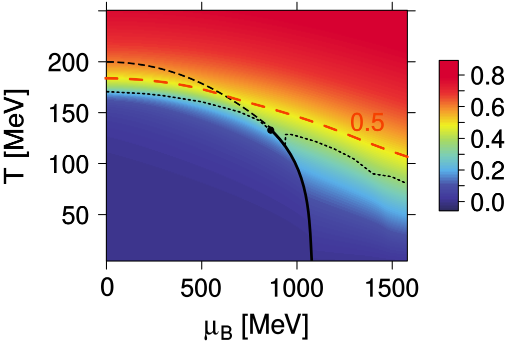
- **Symmetric quark matter:** $\mu_q = \mu_B/3$
- **Isospin symmetry:** $\langle \bar{u}u \rangle = \left\langle \bar{d}d \right\rangle$ (for $B = 0$)
- **Quark condensates:** $\langle \bar{q}q \rangle (T, \mu_B) / \langle \bar{q}q \rangle (0, 0)$



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

Phase diagram: Polyakov loop $\Phi(T, \mu_B)$ $[B = 0]$

- $\Phi \to 0$: *(statistically)* confined phase (low temperatures)
- $\Phi \to 1$: *(statistically)* deconfined phase (high temperatures)



- Small variation at the chiral phase transition
- The deconfinement transition is a crossover

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 fluctuation** (susceptibility):

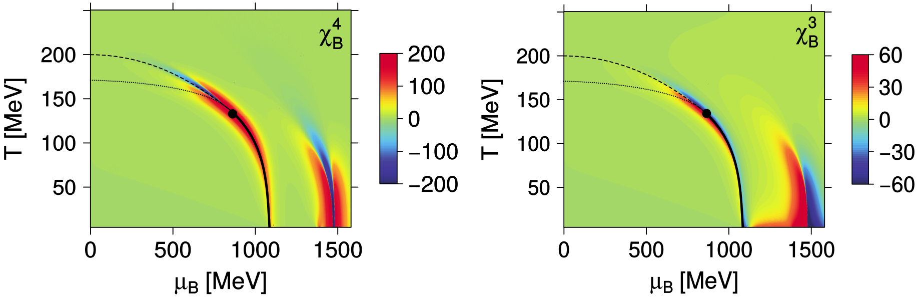
$$\chi_B^n(T,\mu_B) = \frac{\partial^n\left(P(T,\mu_B)/T^4\right)}{\partial(\mu_B/T)^n}$$

- Susceptibilities ratios have no volume dependence:

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

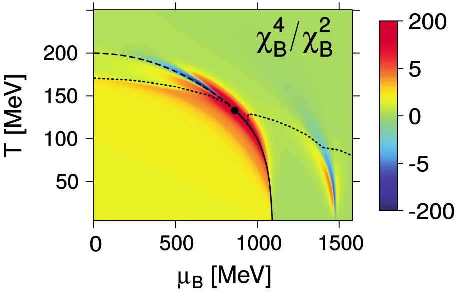
- They measure the kurtosis and skewness of the net-baryon distribution.

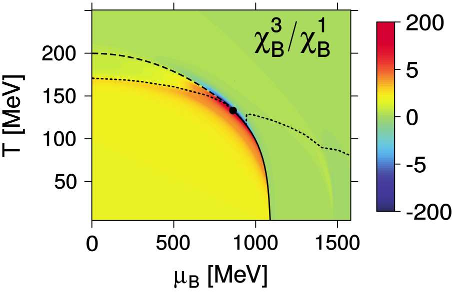
χ_B^3 and χ_B^4 fluctuations $[B = 0]$



- Non-monotonic dependence around the CEP
- Positive χ_B^3 fluctuations on the chiral restored phase
- χ_B^4 is almost symmetric with respect to the chiral transition
- A similar non-monotonic dependence occurs at high μ_B
  - A stronger G_s would generate a first-order phase transition

χ_B^4/χ_B^2 and χ_B^3/χ_B^1 fluctuations $[B = 0]$



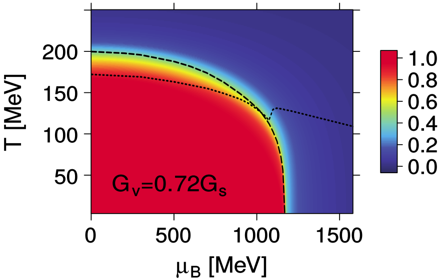


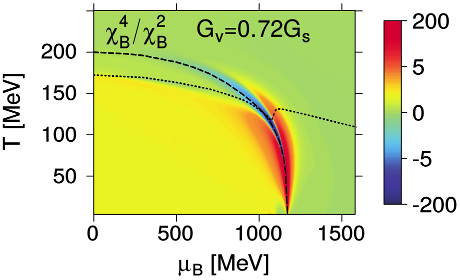
- Clear distinction between the broken/restored chiral symmetry region
- There is a pronounced variation around deconfinement
- A non-monotonic dependence persists at higher μ_B

Can a non-monotonic (critical) region be present even in the absence of a CEP?

Strong vector interaction $[B = 0]$

- **Vector interaction:** $G_V(\rho_u^2 + \rho_u^2 + \rho_s^2)$
- The CEP disappears for a $G_V \geq 0.72 G_s$.





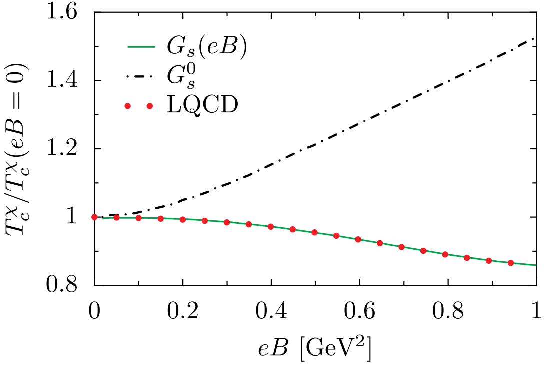
- The non-monotonic region is still present
- High net-baryon fluctuations might still be present at low temperatures

Including an external magnetic field

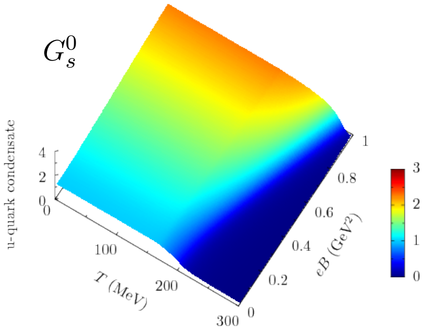
Two models: different scalar coupling

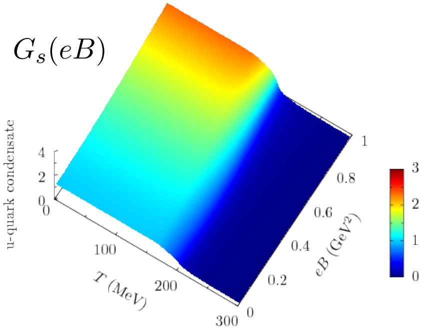
- Constant coupling: $G_s = G_s^0 = 3.67/\Lambda^2$
- Magnetic field dependent coupling: $G_s = G_s(eB)$

Same vacuum properties for both models.



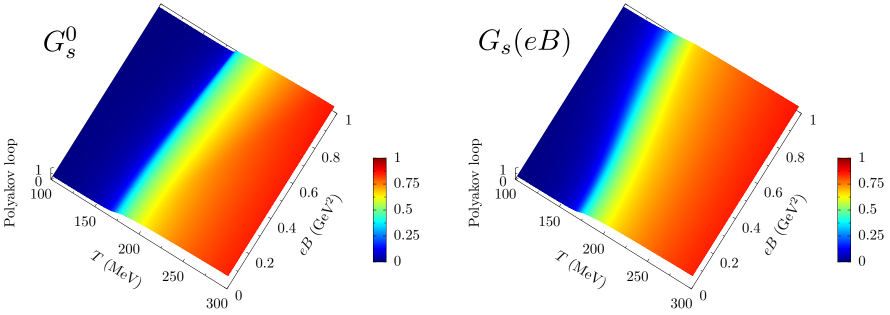
Quark condensate for $B \neq 0$ and $\mu_B = 0$





- G_s^0 predicts Magnetic Catalysis at any temperature
- $G_s(B)$ predicts both Magnetic and Inverse Magnetic Catalysis
  - Agrees with LQCD

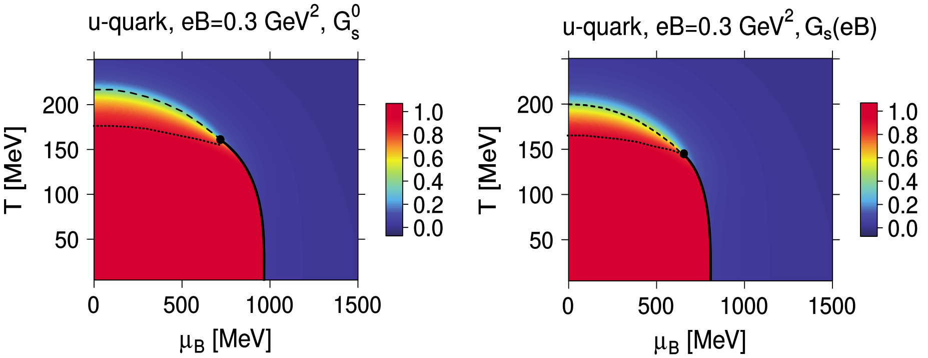
Polyakov loop value for $B \neq 0$ and $\mu_B = 0$



- T_c^Φ increases with B for G_s^0
- T_c^Φ decreases with B for $G_s(eB)$
  - Agrees with LQCD

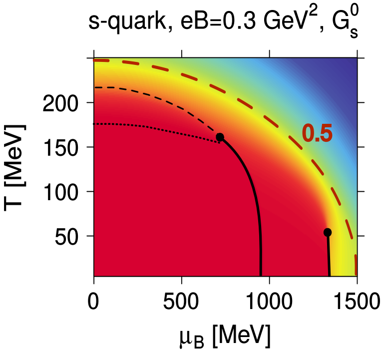
Phase diagram at finite B: up quark

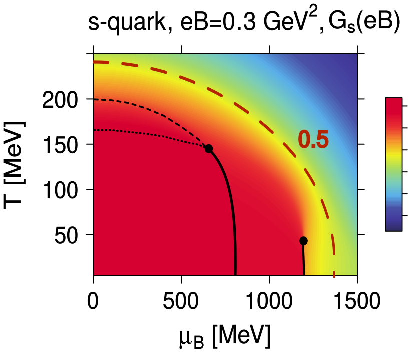
- External magnetic field: $eB = 0.3$ GeV^2



- $G_s(eB)$ model shows **Inverse Magnetic Catalysis**
  - Both T_{pc}^{χ} and T_{pc}^{Φ} decrease with B
- $\mu_B^{\text{crit}}(T = 0)$ also decreases with B for the $G_s(eB)$ model

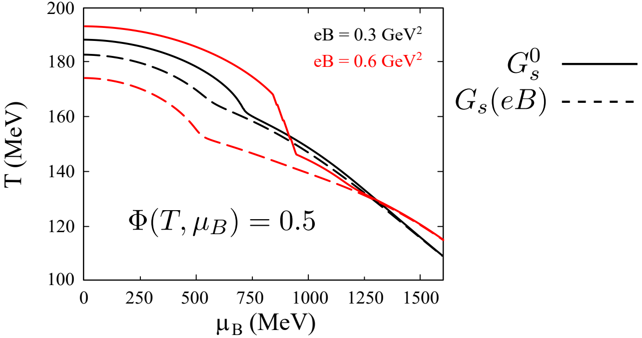
Phase diagram at finite B: Strange quark





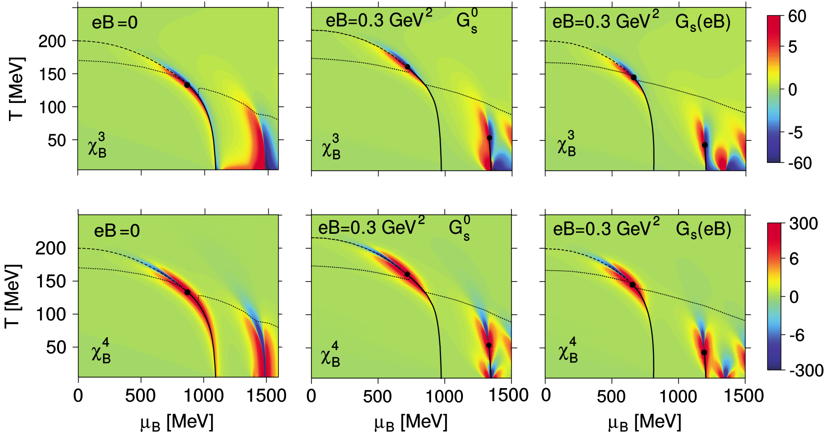
- There is a small variation at the chiral phase transition
- A first-order phase transition happens at higher μ_B
- A CEP related with the strange quark appears
- The strange quark is far from being *"(approximately) chirally restored"*, and several phase transitions take place at higher μ_B

Phase diagram at finite B: Polyakov loop



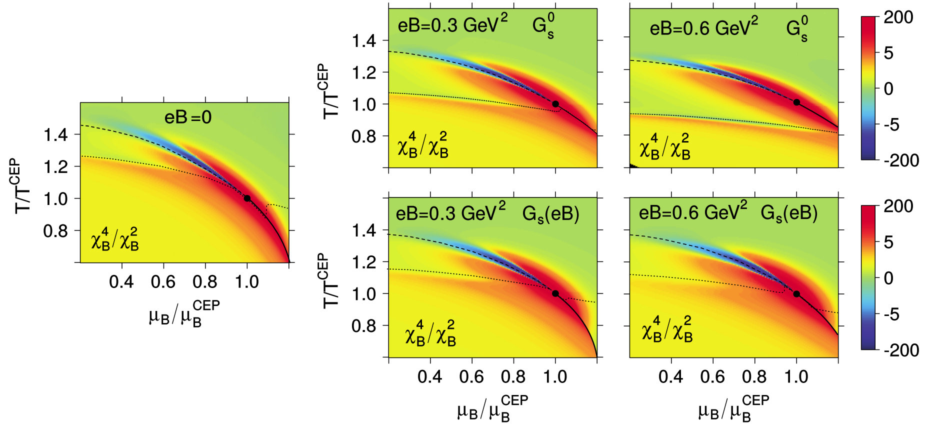
- The T_{ps}^{Φ} decreases with B for the $G_s(eB)$ model.
- Both models converge at higher μ_B
- The *"confined region"* decreases with growing B for $G_s(eB)$

χ_B^3 and χ_B^4 fluctuations in strong B



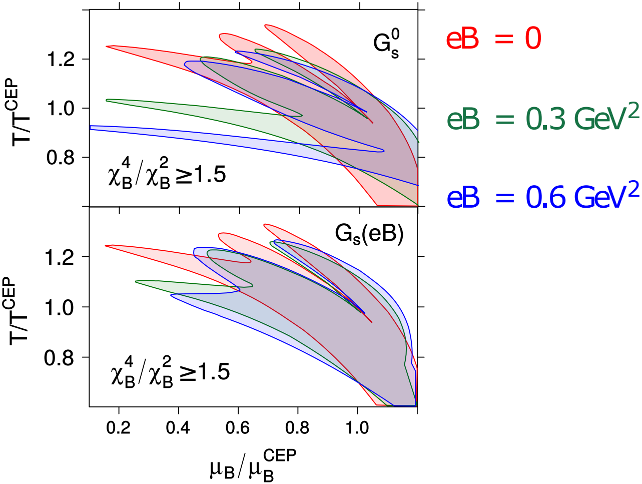
- Three CEP like structures at $\mu_B > 1000$ MeV:
  - 1^{st}: s-quark first-order phase transition
  - 2^{nd}: population of a new LL for the d-quark
  - 3^{rd}: s-quark first order-phase transition at higher μ_B

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



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

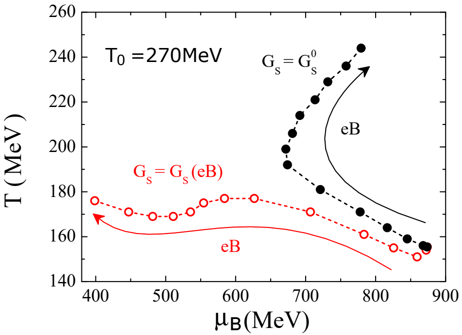
Fluctuation region with $\chi_B^4/\chi_B^3 \geq 1.5$



The relative size of the strong fluctuations regions

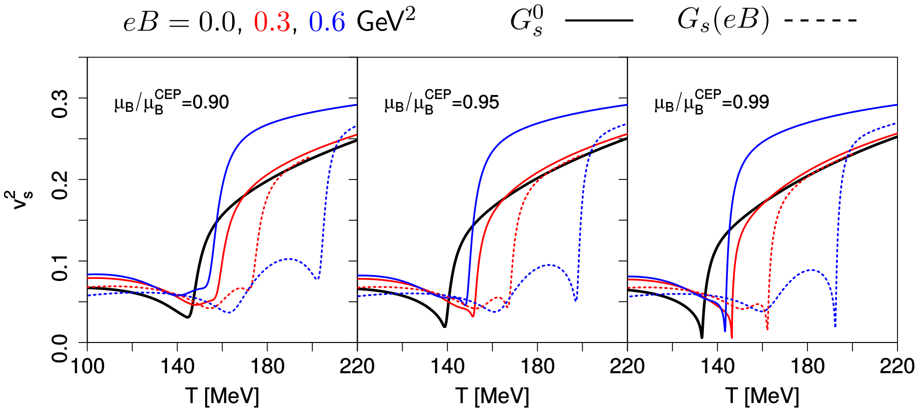
- is quite insensitive to B
- reflects the gap between T^{Φ} and T^{χ}

CEP location as a function of B



- Fluctuations at low μ_B reflect the location of the CEP for strong B
  - Decrease of fluctuations for G_s^0
  - Increase of fluctuations for $G_s(eB)$
- LQCD calculations might be able to distinguish both scenarios

Sound velocity near the CEP



- Both transitions are clear at finite B (increasing gap for G_s^0)
- The minimum occurs at T^Φ for $\mu_B/\mu_B^{CEP} \leq 0.95$ $(B \neq 0)$

Conclusions

- External magnetic fields induce multiple phase transitions
- The strange quark undergoes multiple first-order phase transitions
- Fluctuations at low T might occur even in the absence of a CEP
- The relative size of the large fluctuation region close to the 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