



UNIVERSIDADE DE COIMBRA

# Magnetized QCD phase diagram within the PNJL model

Márcio Ferreira,

Pedro Costa, and Constança Providência

*CFisUC, University of Coimbra, Portugal*

**Zimányi School 2017**

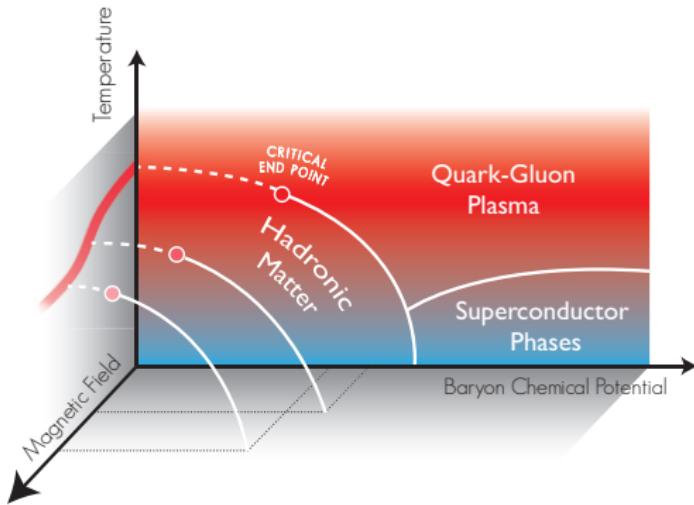
Winter school on Heavy Ion Physics

Dec. 4. - Dec. 8.

Budapest, Hungary

# Objective

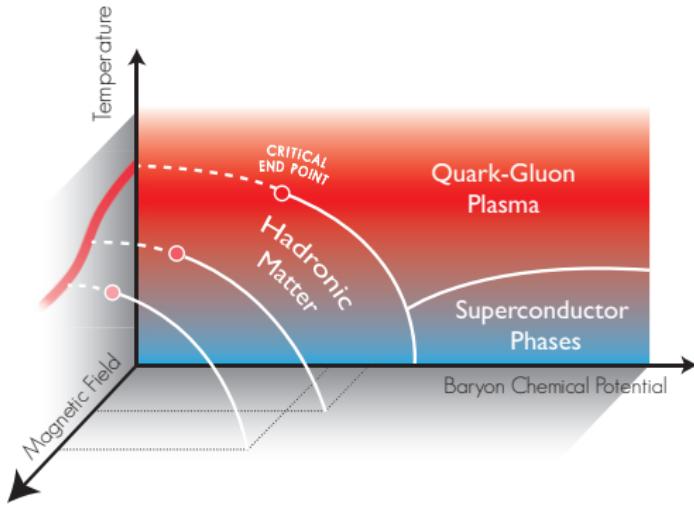
Analyze the effect of an external magnetic field on the QCD phase diagram



- Do NJL-type models agree with LQCD ( $\mu_B = 0$ )?
- What is the phase diagram structure ( $\mu_B \neq 0$ )?
  - What is the impact of  $B$  on the critical end point (CEP)?

# Objective

Analyze the effect of an external magnetic field on the QCD phase diagram



- Do NJL-type models agree with LQCD ( $\mu_B = 0$ )?
- What is the phase diagram structure ( $\mu_B \neq 0$ )?
  - What is the impact of  $B$  on the critical end point (CEP)?

# The importance of magnetic fields

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

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

# The PNJL model

Polyakov loop extended  $SU(3)$  Nambu–Jona–Lasinio model

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

where

$$\mathcal{L}_{\text{sym}} = G_s \sum_{a=0}^8 [(\bar{q}\lambda_a q)^2 + (\bar{q}i\gamma_5\lambda_a q)^2]$$

$$\mathcal{L}_{\text{det}} = -K \{\det [\bar{q}(1 + \gamma_5)q] + \det [\bar{q}(1 - \gamma_5)q]\}$$

- Covariant derivative:  $D^\mu = \partial^\mu - iq_f A_{EM}^\mu - iA^\mu$
- Constant  $B$  field in the  $z$  direction:  $A_\mu^{EM} = \delta_{\mu 2} x_1 B$
- For the Polyakov loop potential we use

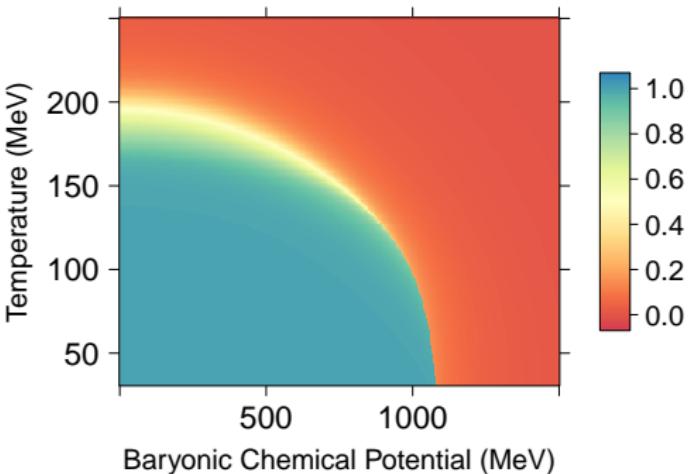
$$\frac{\mathcal{U}(\Phi, \bar{\Phi}; T)}{T^4} = -\frac{a(T)}{2} \bar{\Phi}\Phi + b(T) \ln [1 - 6\bar{\Phi}\Phi + 4(\bar{\Phi}^3 + \Phi^3) - 3(\bar{\Phi}\Phi)^2]$$

Model parametrization/regularization

- P. Rehberg, et al. PRC53, 410
- S. Roessner, et al. PRD75, 034007
- D. P. Menezes, et al. PRC80, 065805

# Phase diagram for $B = 0$

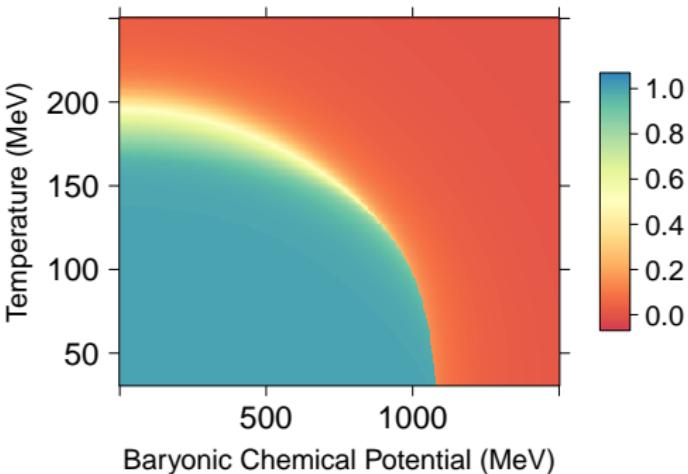
- **Chiral phase transition**
- **Order parameter:**  $\langle \bar{u}u \rangle$
- $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$  (isospin symmetry)
- $(T^{cep}, \mu_B^{cep}) = (155, 890)$



- $T < T^{cep}$ :  $\langle \bar{u}u \rangle$  ( $\rho_B = \frac{\partial \Omega}{\partial \mu_B}$ ) discontinuous
  - 1<sup>st</sup> order phase transition
- $T = T^{cep}$ :  $\langle \bar{u}u \rangle$  ( $\rho_B = \frac{\partial \Omega}{\partial \mu_B}$ ) continuous but  $\chi_B = \frac{\partial^2 \Omega}{\partial \mu_B^2}$  diverges
  - 2<sup>nd</sup> order phase transition
- $T > T^{cep}$ :  $\langle \bar{u}u \rangle$  (all thermodynamic quantities) continuous
  - crossover (analytic) transition

# Phase diagram for $B = 0$

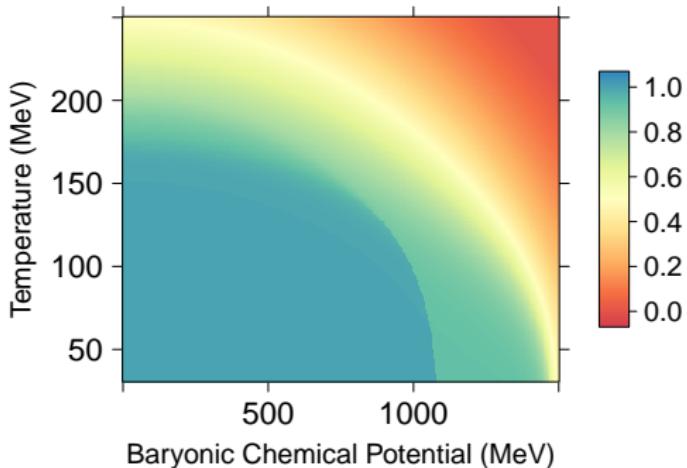
- **Chiral phase transition**
- **Order parameter:**  $\langle \bar{u}u \rangle$
- $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$  (isospin symmetry)
- $(T^{cep}, \mu_B^{cep}) = (155, 890)$



- $T < T^{cep}$ :  $\langle \bar{u}u \rangle$  ( $\rho_B = \frac{\partial \Omega}{\partial \mu_B}$ ) discontinuous
  - 1<sup>st</sup> order phase transition
- $T = T^{cep}$ :  $\langle \bar{u}u \rangle$  ( $\rho_B = \frac{\partial \Omega}{\partial \mu_B}$ ) continuous but  $\chi_B = \frac{\partial^2 \Omega}{\partial \mu_B^2}$  diverges
  - 2<sup>nd</sup> order phase transition
- $T > T^{cep}$ :  $\langle \bar{u}u \rangle$  (all thermodynamic quantities) continuous
  - crossover (analytic) transition

# Phase diagram for $B = 0$

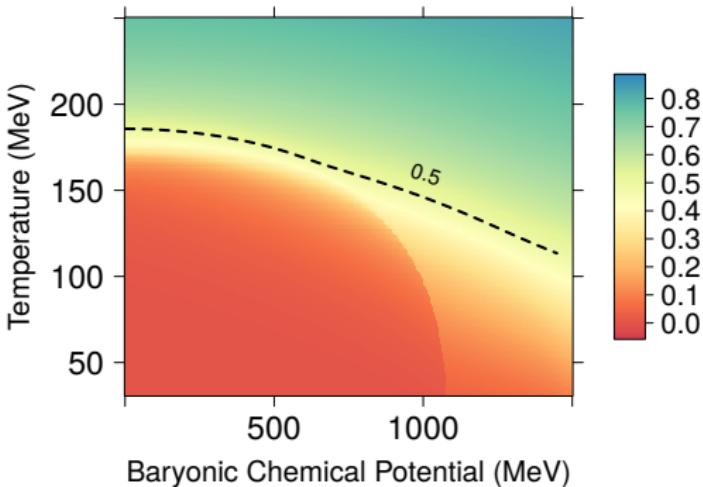
- Phase diagram for the strange quark:  $\langle \bar{s}s \rangle$



- The 1<sup>st</sup> order chiral phase transition induces a discontinuity in  $\langle \bar{s}s \rangle$
- The strange quark undergoes a crossover transition

# Phase diagram for $B = 0$

- Phase diagram for the confinement - deconfinement transition
  - Order parameter:  $\Phi(T, \mu_B)$  (Polyakov loop value)
    - $\Phi(T, \mu_B) \rightarrow 0$  : confined phase
    - $\Phi(T, \mu_B) \rightarrow 1$  : deconfined phase



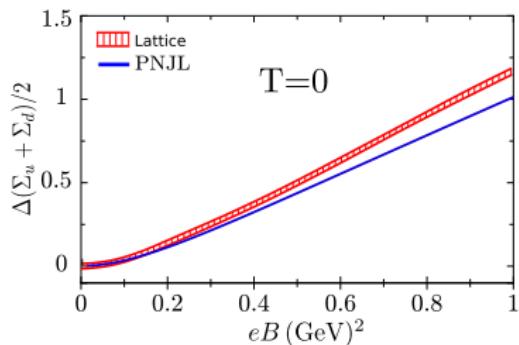
- Crossover transition
- (Pseudo-critical) transition line:  $\Phi(T, \mu_B) = 0.5$  (e.g.)

# Adding an external magnetic field $B$

Zero chemical potential ( $\mu_B = 0$ )

- Magnetic Catalysis

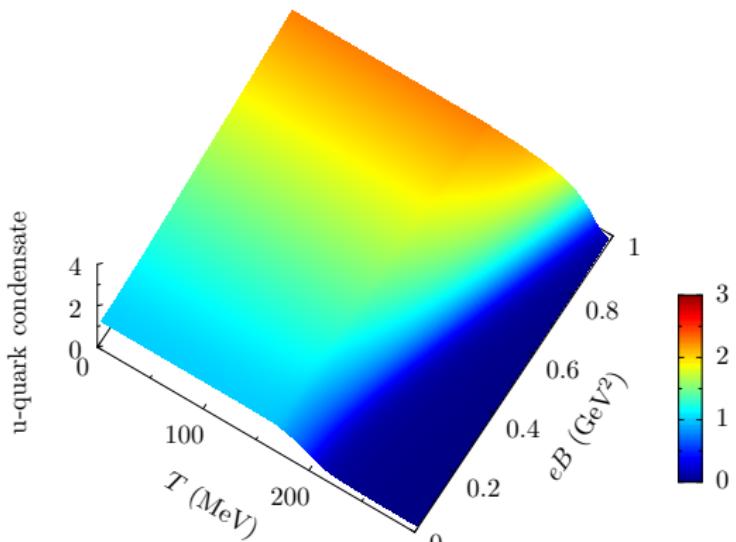
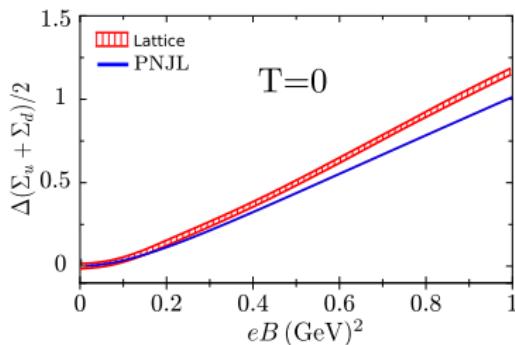
$B$  enhances chiral symmetry breaking



# Adding an external magnetic field $B$

Zero chemical potential ( $\mu_B = 0$ )

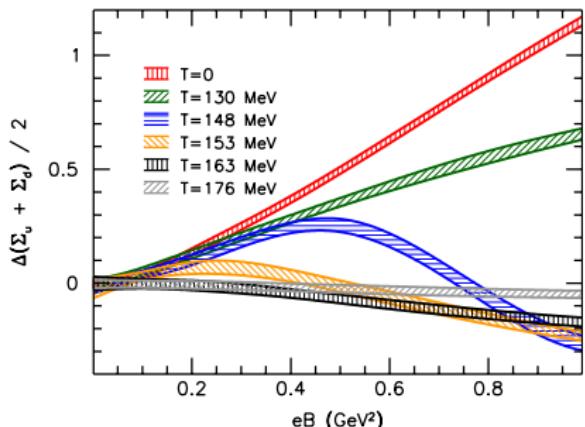
- Magnetic Catalysis  
 $B$  enhances chiral symmetry breaking



- The PNJL gives MC at any  $T$
- Both  $T_c^\chi$  and  $T_c^\Phi$  increase with  $B$

# LQCD results at finite $B$

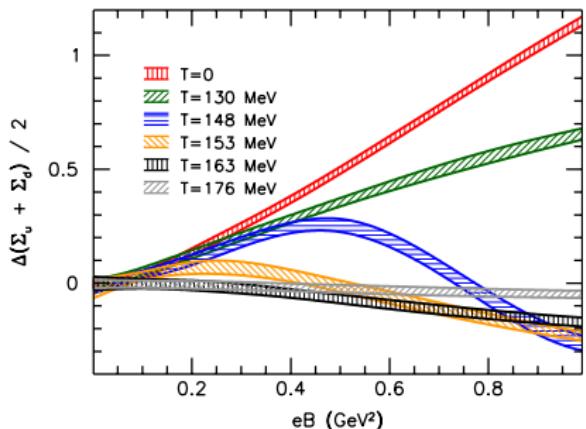
[G. Bali, et al. PRD86 (2012) 071502]



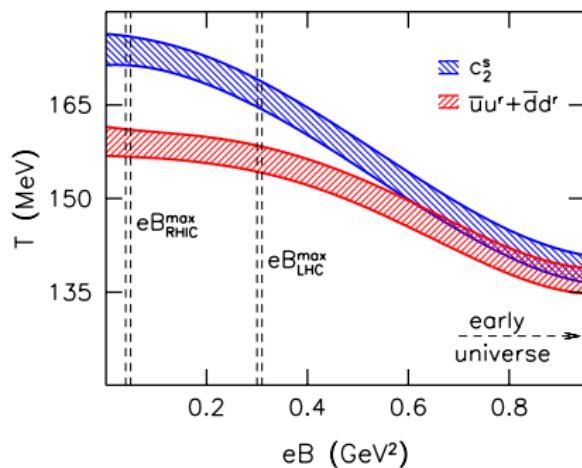
- MC at low temperatures  
(0, 130)
- Weakening of chiral symmetry breaking in the crossover region  
(Inverse Magnetic Catalysis)

# LQCD results at finite $B$

[G. Bali, et al. PRD86 (2012) 071502]



[G. Bali, et al., JHEP 1202 (2012) 044]



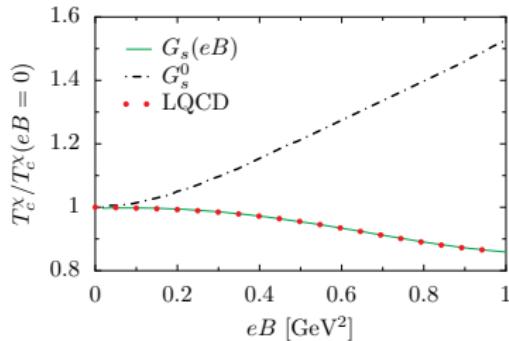
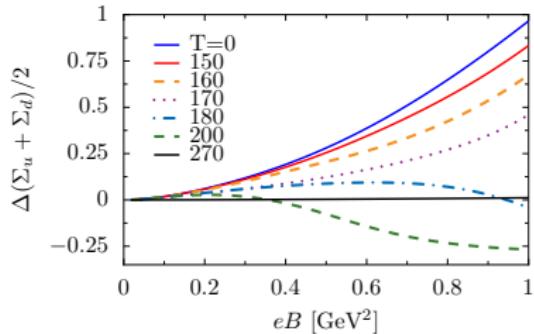
- MC at low temperatures ( $0, 130$ )
- Weakening of chiral symmetry breaking in the crossover region  
(Inverse Magnetic Catalysis)

- IMC leads to a decreasing pseudo-critical temperature with  $B$ .

# Magnetic field dependent coupling

- The PNJL can support IMC via  $G_s(eB)$

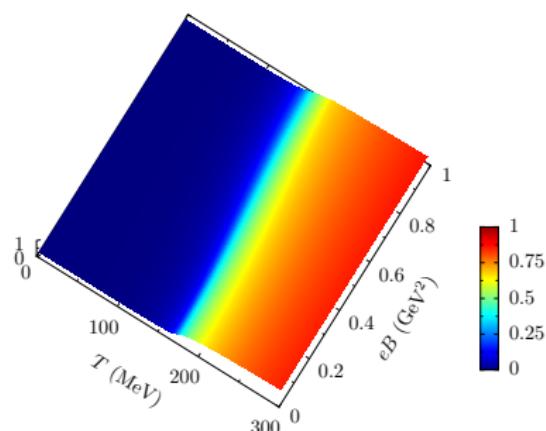
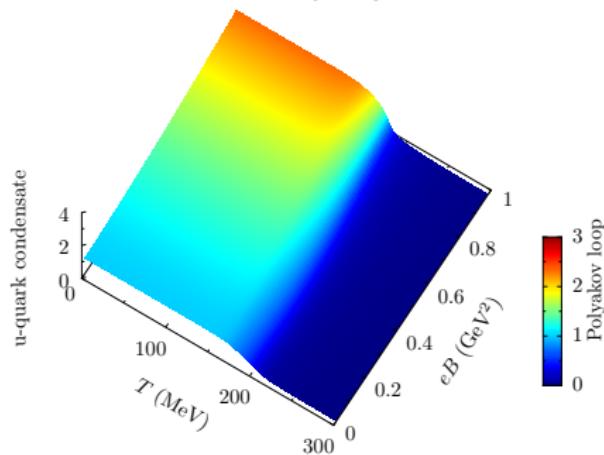
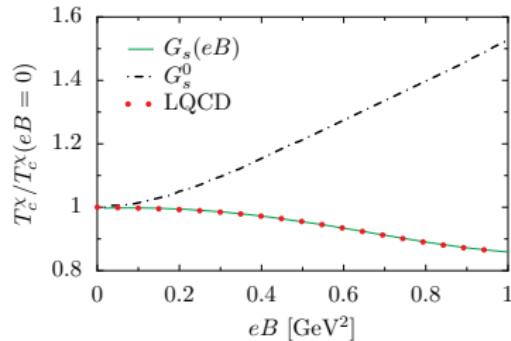
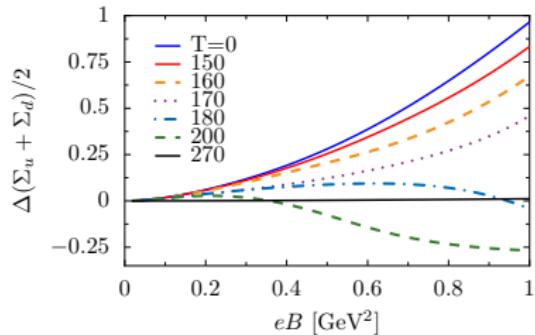
[M. Ferreira et al. PRD89(2014)116011]



# Magnetic field dependent coupling

- The PNJL can support IMC via  $G_s(eB)$

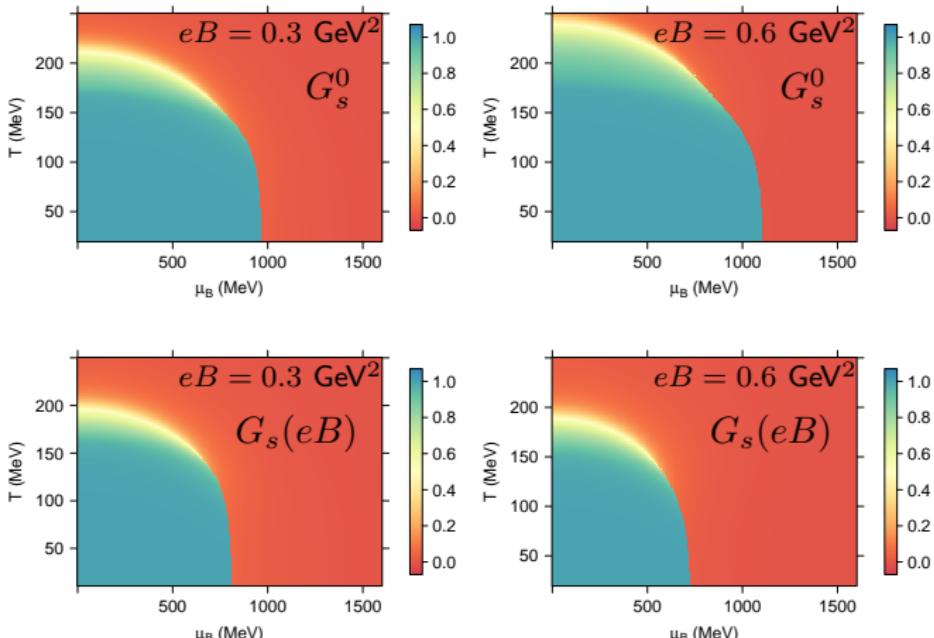
[M. Ferreira et al. PRD89(2014)116011]



# Phase diagram at finite $\mu_B$ and $B$

- **u-quark phase diagram**

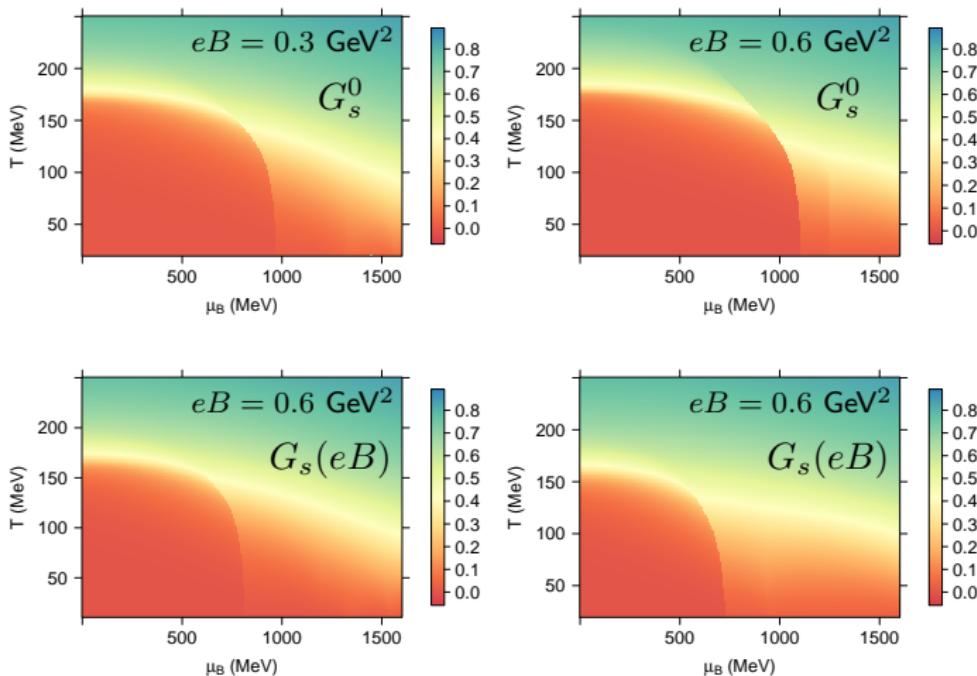
- Two values of  $B$ : 0.3 and 0.6  $\text{GeV}^2$
- Normalized condensate:  $\langle q\bar{q} \rangle_0 = \langle q\bar{q} \rangle(T, \mu_B, eB) / \langle q\bar{q} \rangle(0, 0, eB)$



- The chiral broken phase region shrinks for  $G_s(eB)$ : both  $\mu_B^c(T=0)$  and  $T^{pc}(\mu_B=0)$  decrease with  $B$

# Phase diagram at finite $\mu_B$ and $B$

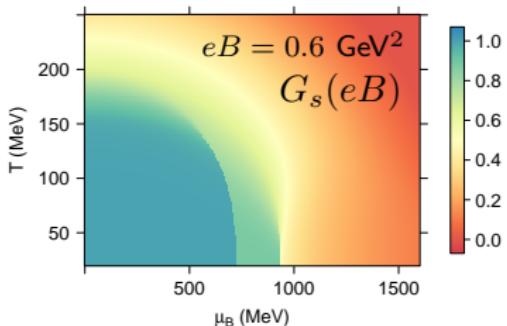
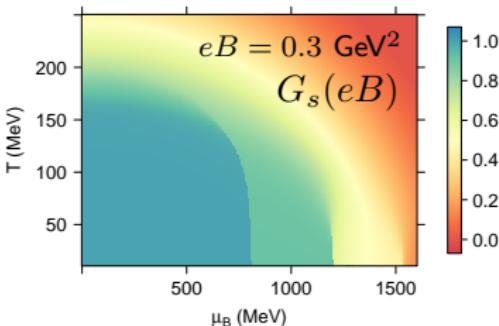
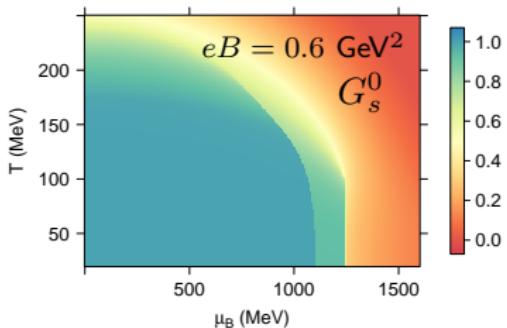
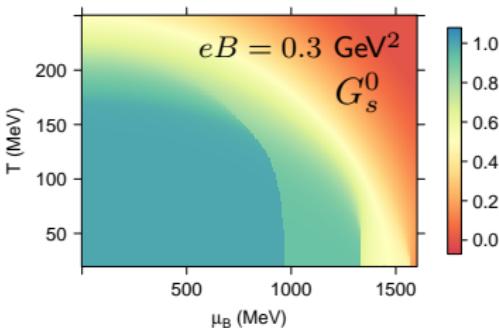
- **Confinement-deconfinement phase diagram ( $\Phi(T, \mu_B)$ )**



- The chiral phase transition induces a discontinuity in  $\Phi$
- The deconfinement transition remains a crossover at finite  $B$

# Phase diagram at finite $\mu_B$ and $B$

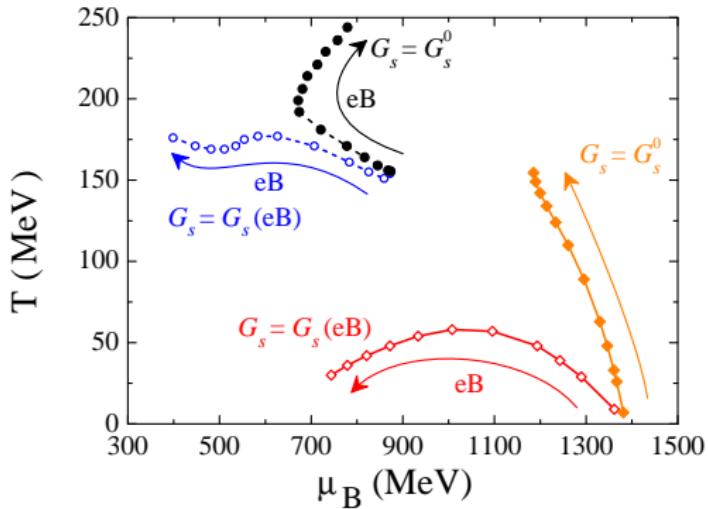
- **Strange-quark phase diagram**



- The  $B$  field induces several 1<sup>st</sup>-order phase transitions at low  $T$
- The (approx.) chiral restored phase is accomplished through several steps
- Multiple CEPs related with the *strange sector* appear.

# Location of the CEPs

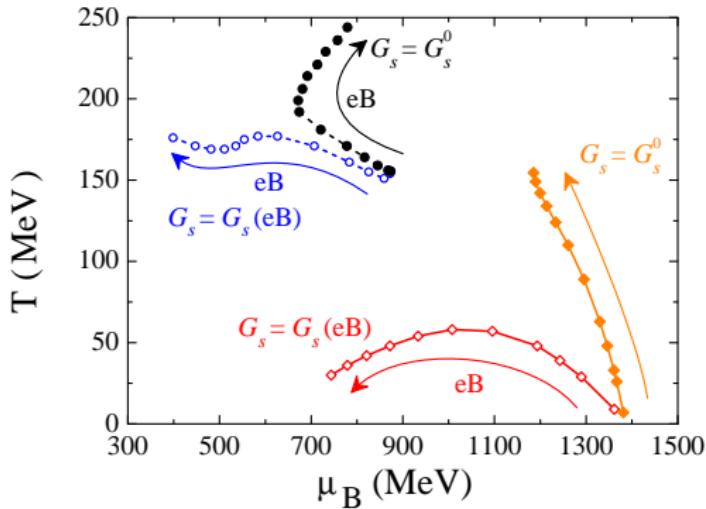
- Light/strange CEPs (those that appear at lower  $\mu_B$ )



- $G_s^0$  : both CEPs move to higher  $T$  with increasing  $B$
- $G_s(eB)$  : the light CEP occurs at smaller  $\mu_B$  and  $\approx T$
- $G_s(eB)$  : the strange CEP also occurs at smaller  $\mu_B$

# Location of the CEPs

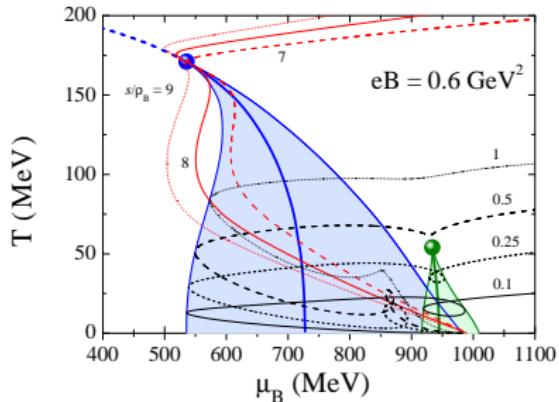
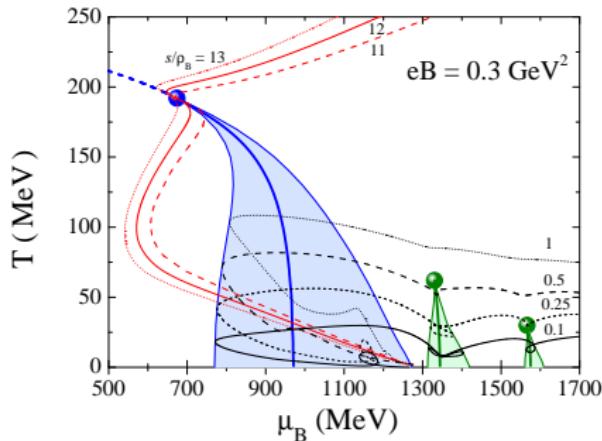
- Light/strange CEPs (those that appear at lower  $\mu_B$ )



- $G_s^0$  : both CEPs move to higher  $T$  with increasing  $B$
- $G_s(eB)$  : the light CEP occurs at smaller  $\mu_B$  and  $\approx T$
- $G_s(eB)$  : the strange CEP also occurs at smaller  $\mu_B$

# Isentropic trajectories in the presence of a magnetic field

- The hydrodynamic expansion (ideal fluid) follows isentropic trajectories: constant  $s/\rho_B$  (entropy per baryon)



- The isentropic trajectories seem to be attracted by the CEP

# Conclusions

- The IMC affects the QCD phase diagram;
- The CEP's location strongly depends on whether the IMC is taken into account;
- The presence of an external magnetic field induces multiple phase transitions, and thus the emergence of several CEPs;
- The CEP moves towards  $\mu_B = 0$  as  $B$  increases, indicating that the transition in the light sector might change from a crossover to a 1st order phase transition;
- The CEPs related with the strange quark seem to attract nearby isentropic trajectories.