# Quantum Chromodynamics phase transition with strong magnetic fields

Falk Bruckmann
(Univ. Regensburg)

Workshop QGHMEC II, St. Goar, March 2013

with G. Bali, G. Endrődi, Z. Fodor, F. Gruber, S. Katz, S. Krieg, T. Kovács, A. Schäfer, K. Szabó

JHEP 1202 (2012) 044, PRD 86 (2012) 071502 , 1303.1328, 1303.3972

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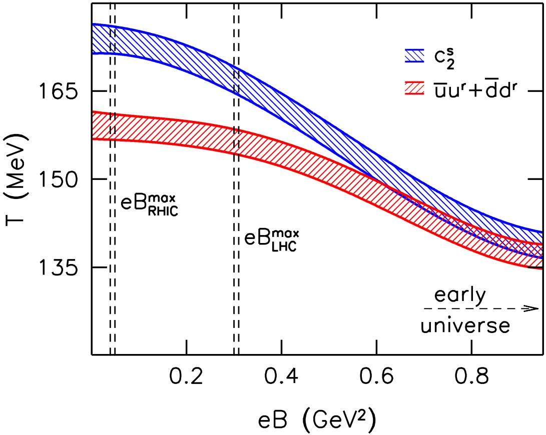
# QCD phase diagram with magn. field

- (pseudo-) $T_c$ as a function of magnetic field:



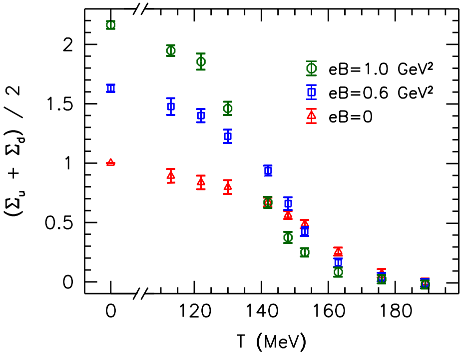

strange number susceptibility
light quark condensate
both renormalized

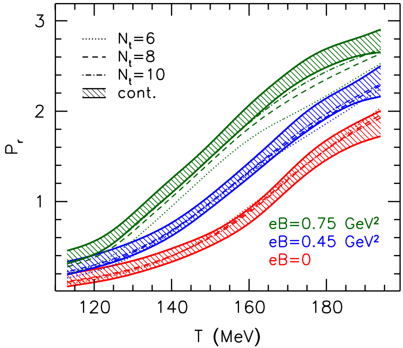
$\Rightarrow$ $T_c$ decreases by O(10) MeV for $eB \lesssim 0.5$ GeV$^2$ Bali, FB, Endrődi et al. 11

transition not becoming stronger

cont. limit of $N_f = 1 + 1 + 1$ (staggered) quarks at physical masses

- (light) condensate and Polyakov loop as a function of $T$ at fixed $B$'s:




$T = 0$: Magnetic Catalysis

- Model Conjecture
- Monte Carlo ✓ D'Elia et al. 10

Inverse Magnetic Catalysis $\overset{!?}{\rightleftharpoons}$ $T_c \searrow$

- Important: Masses of Current quarks
- Investigate Monte Carlo configurations!

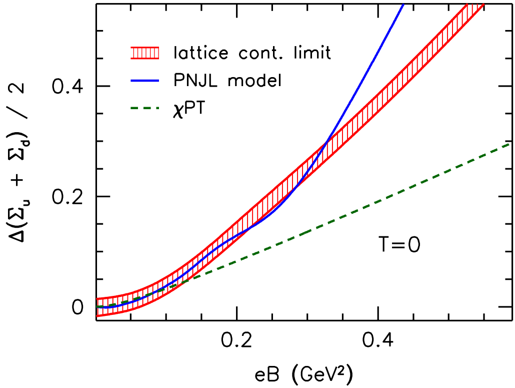
$\Rightarrow$ sea and valence effects vs. P-loop

plus: MC and IMC in the gluon sector

# Magnetic catalysis

Müller, Schramm[2] 92; Gusynin, Miransky, Shovkovy 96

- change of condensate $\left[\langle\bar{\psi}\psi_{u,d}\rangle(B) - \langle\bar{\psi}\psi_{u,d}\rangle(0)\right] m_{u=d}$ at $T = 0$:




with $\chi$PT, NJL    Cohen, McGady, Werbos 07, Andersen 12; Gatto, Ruggieri 10

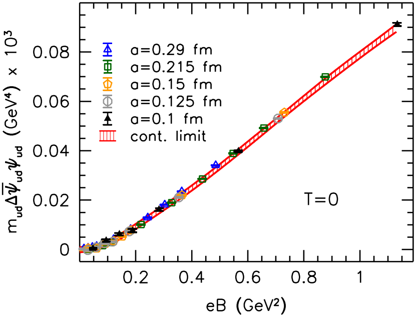
$\Rightarrow$ well approximated unless $eB > 0.1, 0.3$ GeV$^2$

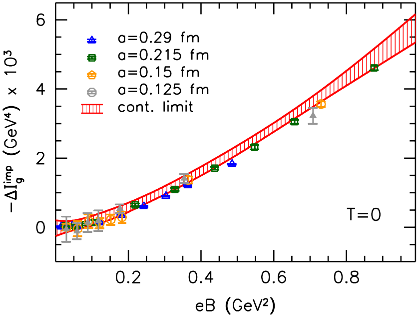
note that : $\Delta ... = ...(B) - ...(0)$ removes additive divergences (as $T$)

$m \cdot ...$ removes multiplicative divergences

# Magnetic catalysis

- change of condensate and gluonic action: Bali, FB, Endrődi et al. 13




very similar shape

$\Rightarrow$ gluons inherit magnetic catalysis from quarks via strong coupling

magnitude $\mathcal{O}(100)$ larger for gluons, but $B = 0$ scale (= gluon condensate) already $\mathcal{O}(200)$ larger: relative effect larger on quarks

# Intermezzo: Trace anomaly

$$I = \epsilon - 3p \qquad \ldots\text{interaction measure, since free gas: } \epsilon = 3p$$

$$\stackrel{\text{lattice}}{=} -\frac{T}{V}\frac{d\log Z}{d\log a} \qquad \ldots\text{scale anomaly}$$

$$= -\frac{T}{V}\left(\frac{\partial \log Z}{\partial\beta}\frac{\partial\beta}{\partial\log a} + \frac{\partial\log Z}{\partial\log am}\frac{\partial\log am}{\partial\log a}\right) \qquad \beta = \frac{6}{g^2}$$

$$= -\left(\langle s_g\rangle\frac{-\partial\beta}{\partial\log a} + m\langle\bar\psi\psi\rangle\frac{\partial\log am}{\partial\log a}\right)$$

$$\Delta I = -\left(\Delta\langle s_g\rangle\frac{-\partial\beta}{\partial\log a} + m\,\Delta\langle\bar\psi\psi\rangle\frac{\partial\log am}{\partial\log a}\right)$$

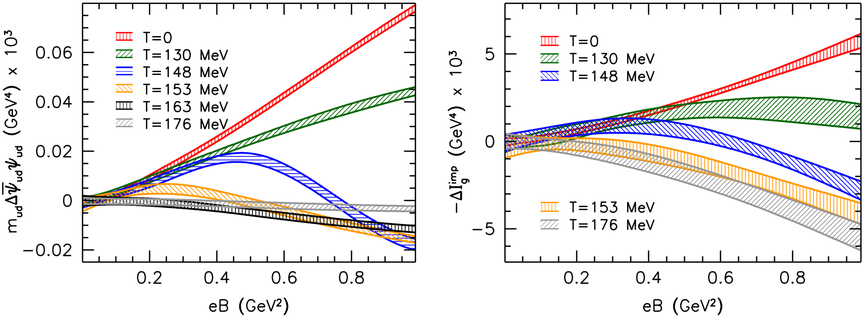
$\Rightarrow$ change of gluonic action density and condensate go together
(with beta and gamma function [line of constant physics])

$\stackrel{!?}{\Rightarrow}$ similarity in $B$-dependence
(used to improve convergence of gluonic contribution)

# Inverse magnetic catalysis

- again change of condensate and gluonic action, now finite $T$:

Bali, FB, Endrődi et al. 12, 13




non-monotonic behaviour, again similar shape

⇒ magnetic catalysis turns into inverse magnetic catalysis around $T_c$

⇒ again for both quarks and gluons

physical quark masses essential — higher $m$ in D'Elia et al. 10, Ilgenfritz et al. 12

very high $T$: condensate vanishes

# Inverse magnetic catalysis: mechanism

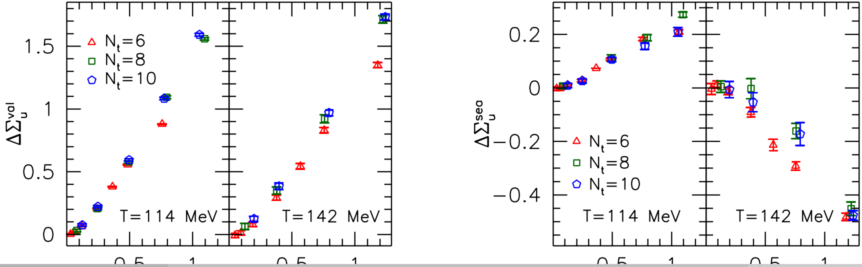
$$\langle\bar\psi\psi\rangle^{\rm full} = \frac{\int e^{-S_g}\det(\not{D}[B]+m)\,\mathrm{tr}(\not{D}[B]+m)^{-1}}{\int e^{-S_g}\det(\not{D}[B]+m)}$$

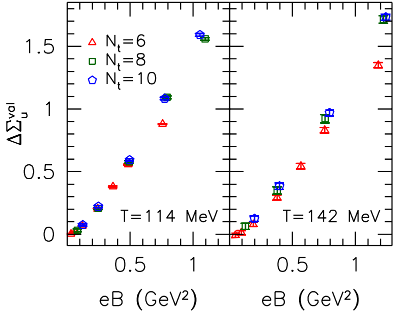
$$\langle\bar\psi\psi\rangle^{\rm val} = \frac{\int e^{-S_g}\det(\not{D}[0]+m)\,\mathrm{tr}(\not{D}[B]+m)^{-1}}{\int e^{-S_g}\det(\not{D}[0]+m)}$$ $B$ in observable

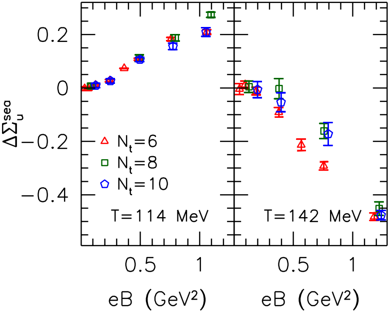
$$\langle\bar\psi\psi\rangle^{\rm sea} = \frac{\int e^{-S_g}\det(\not{D}[B]+m)\,\mathrm{tr}(\not{D}[0]+m)^{-1}}{\int e^{-S_g}\det(\not{D}[B]+m)}$$ $B$ in config. generation

to lowest order approx. : $\langle\bar\psi\psi\rangle^{\rm full} \simeq \langle\bar\psi\psi\rangle^{\rm val} + \langle\bar\psi\psi\rangle^{\rm sea}$ D'Elia, Negro 11

- $\Delta\langle\bar\psi\psi\rangle$ at low $T$ and around $T_c$: FB, Endrődi, Kovács 13






$\not{D}$ has more small eigenvalues with $B$

| | |
|---|---|
| in <u>valence</u> trace $\Downarrow$ | $\Downarrow$ in <u>sea</u> determinant |
| generates condensate | leads to a $B$-dep. probability |
| = statement about the change of the spectrum | = statement about the typical gauge field |
| (even quenched) | = feedback of quarks |

sea effect is particularly effective near $T_c$! why increasing at low $T$?

washed out for heavy quarks

# Inverse magnetic catalysis from reweighting

$$\langle O \rangle_B \sim \int e^{-S_g} \det(\not{D}[0]+m) \cdot \frac{\det(\not{D}[B]+m)}{\det(\not{D}[0]+m)} O(B)$$

change weight, put difference into observable

$\Rightarrow$ measure observable with $B$ on $B=0$ configurations and correlation with effective fermion action $-\Delta S^{\text{eff}}(B) = \log \frac{\det(\not{D}[B]+m)}{\det(\not{D}[0]+m)}$

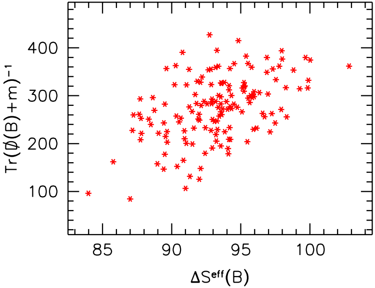
# Inverse magnetic catalysis from reweighting

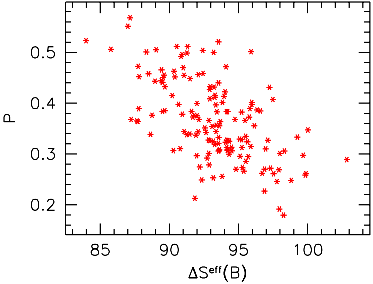
$$\langle\bar{\psi}\psi\rangle^{\text{full}} \sim \int e^{-S_g} \det(\not{D}[0]+m) \cdot e^{-\Delta S^{\text{eff}}(B)} \operatorname{tr}(\not{D}[B]+m)^{-1}$$

$$\langle P\rangle \sim \int e^{-S_g} \det(\not{D}[0]+m) \cdot e^{-\Delta S^{\text{eff}}(B)} P$$

full condensate: $S^{\text{eff}}$-weighted average

similar for Polyakov loop




(near $T_c$)

valence condensate and P at $B=0$: $e^{-\Delta S^{\text{eff}}(B)} \to 1$, simple average

$\Rightarrow$ small action prefers small condensate and large Polyakov loop ▸ PD

# Inverse magnetic catalysis: role of Polyakov loop

- Matsubara picture in free massless case:

$$(\lambda^2_{\not{D}})_{\min} = (\pi T)^2 + E^2$$

- with Polyakov loop: say real, $P = \exp \operatorname{diag}(2\pi i\varphi, -2\pi i\varphi, 0)$

$$(\lambda^2_{\not{D}})_{\min} = ((\pi + \left\{ \begin{array}{c} 2\pi\varphi \\ -2\pi\varphi \\ 0 \end{array} \right\})T)^2 + E^2$$

$(\lambda^2_{\not{D}})_{\min}$ minimal for $\varphi \neq 0$, $P \neq 1_3$ (deconfined) and so is $\det \not{D}$

$\Rightarrow$ quarks prefer deconfinement and decrease $T_c$ ✓

(in quark determinant: Schwinger's proper time formalism)

- with magn. field: Landau levels, lowest LL has $E = 0$

Landau levels degeneracy $\sim$ magn. flux $|qB| \times$ area

$\Rightarrow$ deconfinement prefered even more, $B$ reduces $T_c$

washed out for heavy quarks

# Summary

- magnetic catalysis: $\langle\bar{\psi}\psi\rangle(B) \nearrow$ at $T = 0$
  - also for gluons (trace anomaly)
- inv. magnetic catalysis: $\langle\bar{\psi}\psi\rangle(B) \searrow$ at $T \simeq T_c$
  - also for gluons
  - quark back reaction: $\langle\bar{\psi}\psi\rangle^{\text{sea}}(B) \searrow$ dominates $\leftarrow$ phys. masses
  - Polyakov loop: $\langle P\rangle(B) \nearrow$

    indicator for the change of gauge fields

    Matsubara picture with $P$ and $B$: deconfinement prefered
- QCD crossover: $T_c(B)$ decreases slightly

# Backup: Strong Magnetic fields

| | | |
|---|---|---|
| early universe | $\sqrt{eB} \simeq 2$ GeV | |
| RHIC/LHC<br>non-central collisions<br>charged spectators<br>$B$ perp. to reaction plane | 0.1..0.5 GeV | QCD scale! |
| neutron stars, magnetars | 1 MeV | $B \simeq 10^{14}$ G |
| cf. strongest field in lab | | $10^5$ G<br>($10^7$ G unstable) |
| refrigerator magnet | | 100 G |
| earths magn. field | | 0.6 G |

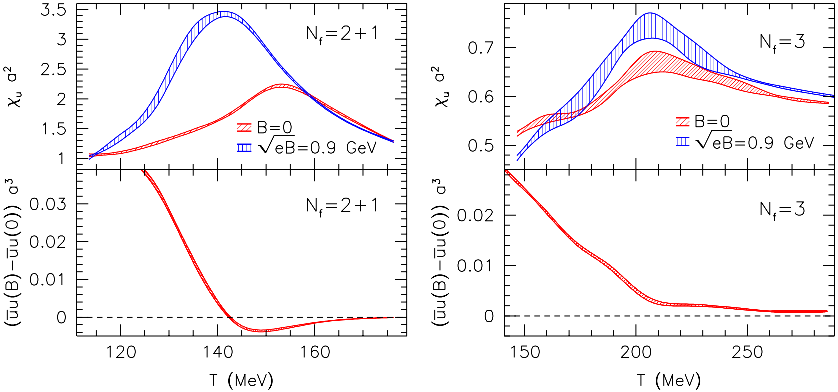
# Backup: Simulation details

as for transition studies at $B = 0$ Budapest-Wuppertal

- tree-level improved gauge action
- stout smeared staggered fermions (rooting trick)
- 2 light quarks + strange quark, charges $(q_u, q_d, q_s) = (\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})e$
- lattice spacing set at $T = 0, B = 0$
  physical pion masses
  set by $f_K$, $f_K/m_\pi$ and $f_K/m_K$
- $T = 0$: $24^3 \times 32$, $32^3 \times 48$ and $40^3 \times 48$ lattices
- $T > 0$: $N_t = 6, 8, 10$ meaning $a = 0.2, 0.15, 0.12$ fm
  $N_s = 16, 24, 32$ for finite volumes
- condensates from stochastic estimator method with 40 vectors
- magn. flux quanta: $N_B \leq 70 < \frac{N_x N_y}{4} = 144$

# Backup: Mass sensitivity

- what if we put $(m_{\text{light}}, m_{\text{light}}, m_{\text{strange}}) \to (m_{\text{strange}}, m_{\text{strange}}, m_{\text{strange}})$?




*T*-dep. of *u*-susceptibility (top) and change of *u*-condensate (bottom)

$\Rightarrow$ effects of decreasing $T_c$ & inverse magn. catalysis disappear

light quark masses are important