Chiral restoration and deconfinement in two-color QCD with two flavors of staggered quarks

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- Introduction
- Observables
- Setting the temperature scale
- Magnetic scaling
- Summary and outlook
Motivation

- two-color QCD as QCD-like theory where finite density is accessible
- preparations for finite density

**chiral properties**

- scale setting
- scaling behavior

**effective Polyakov loop potential**

- influence of quarks
- compare to effective model descriptions

→ next talk by Philipp Scior
Simulation setup

- $N_c = 2$ Wilson gauge action
- $N_f = 2$ staggered quarks via RHMC
- $N_t = 4, 6, 8$ with aspect ratio $N_s/N_t = 4$
- finite temperature: vary coupling $\beta$
- several masses

symmetry breaking

- continuum: $\text{SU}(2N_f) \to \text{Sp}(N_f)$
- staggered: $\text{SU}(2N_f) \to \text{O}(2N_f)$, here: $\text{SU}(4) \simeq \text{O}(6) \to \text{O}(4)$
Order parameters

![Graph showing order parameters for chiral condensate and Polyakov loop](image)

- **Chiral condensate**
  - **Coupling $\beta$**:
    - Values: $0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 1.6, 1.8, 2, 2.2, 2.4$
  - **System size**: $4 \times 16^3$

- **Polyakov loop**
  - **Coupling $\beta$**:
    - Values: $0.004, 0.012, 0.02, 0.04, 0.08, 0.4$
  - **System size**: $4 \times 16^3$

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Order parameters

- Chiral condensate
  - Coupling $\beta$
  - Values: 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4

- Polyakov loop
  - Coupling $\beta$
  - Values: 1.6, 1.8, 2, 2.2, 2.4

Heat capacity

$C = \frac{2}{3} m^2 \frac{d^2}{dT^2} \left( \frac{1}{\beta} \right)$

- Values: m/T = 0.006, 0.018, 0.03, 0.06, 0.12, 0.6

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Order parameters

![Graph of chiral condensate](image)

![Graph of Polyakov loop](image)

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Chiral susceptibilities

4x16$^3$

- m/T=0.004
- m/T=0.012
- m/T=0.02
- m/T=0.04
- m/T=0.08
- m/T=0.4

6x24$^3$

- m/T=0.006
- m/T=0.018
- m/T=0.03
- m/T=0.06
- m/T=0.12

8x32$^3$

- m/T=0.04
- m/T=0.16
- m/T=0.6
- m/T=0.8
Runtime

\[ N_t = 8, \quad N_s = 32, \quad m/T = 0.04 \] data:

- approx. runtime: 80 GPU months
- using NVIDIA Tesla K20X
- Lichtenberg-Cluster @ TU Darmstadt
Ferrenberg-Swendsen reweighting

Example: $N_t = 4$
Ferrenberg-Swendsen reweighting

Example: $N_t = 4$

$\begin{array}{cccccccc}
N_t & N_s & m/T & 0.02 \\
\hline
4 & 16 & 3.5 & 1.855 \\
4 & 16 & 4 & 1.860 \\
4 & 16 & 4.5 & 1.865 \\
4 & 16 & 5 & 1.870 \\
4 & 16 & 5.5 & 1.875 \\
4 & 16 & 6 & 1.880 \\
4 & 16 & 6.5 & 1.885 \\
4 & 16 & 7 & 1.890 \\
4 & 16 & 7.5 & 1.895 \\
4 & 16 & 8 & 1.900 \\
\end{array}$

chiral susceptibility

coupling $\beta$

$N_t=4 \ N_s=16 \ m/T=0.02$

data

from F-S reweighting
Ferrenberg-Swendsen reweighting

Example: $N_t = 6$

![Graph showing chiral susceptibility as a function of coupling β for $N_t=6$, $N_s=24$, and $m/T=0.03$.]
Ferrenberg-Swendsen reweighting

Example: $N_t = 6$
Ferrenberg-Swendsen reweighting

Example: $N_t = 8$
Ferrenberg-Swendsen reweighting

Example: $N_t = 8$

![Graph showing chiral susceptibility as a function of coupling $\beta$. The graph includes data points and a curve from F-S reweighting, with parameters $N_t=8$, $N_s=32$, $m/T=0.04$.](image-url)
Pseudo-critical line

\[ \beta_{pc} \] vs. \( m/T \) for different values of \( N_t \):
- \( N_t = 4 \)
- \( N_t = 6 \)
- \( N_t = 8 \)
chiral extrapolation

\[ \beta_{pc}(m, N_t) = \beta_c(N_t) + d \cdot \left( \frac{m}{T} \right)^c \]

with \( c = \frac{1}{\beta \delta} = 0.38 \) from Basile et al. JHEP02(2005)044
Pseudo-critical line

\[ \beta_{pc}(m, N_t) = \beta_c(N_t) + d \cdot \left( \frac{m}{T} \right)^c \]

with \( c = \frac{1}{\beta \delta} = 0.38 \) from Basile et al. JHEP02(2005)044
Temperature scale

leading scaling behavior:

\[ \frac{T}{T_c} = \exp \{ b(\beta - \beta_c) \} \]

-0.1  0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8

from linear fit:

\[ b = 2.54 \pm 0.02 \]

\( N_t = 4 \)  
\( N_t = 6 \)  
\( N_t = 8 \)

similar analysis using deconfinement transition in pure SU(2) (Smith et al. [1307.6339])
Critical exponents

\[ M_{h=0,t \to 0} \sim |t|^\beta \]
\[ \chi_{h=0,t \to 0} \sim |t|^{-\gamma} \]
\[ M_{t=0,h \to 0} \sim |h|^{1/\delta} \]

with reduced temperature \( t = \frac{T - T_c}{T_c} \), external symmetry breaking field \( h = \frac{H}{H_0} \)

pseudo-critical line:

\[ t_{\text{peak}} \sim h^{1/\delta \beta} \]
\[ \chi_{\text{peak}} \sim t_{\text{peak}}^{-\gamma} \sim h^{1/\delta - 1} \]
magnetic scaling

peak height: \( \chi_{\text{peak}} \sim m^{1/\delta - 1} \)
magnetic scaling

peak height: \( \chi_{\text{peak}} \sim m^{1/\delta - 1} \)
Summary and outlook

Summary

- first steps towards scale setting and determination of critical exponents
- successful use of Ferrenberg-Swendsen reweighting for $N_t = 4$ and $N_t = 6$

Outlook

- chiral properties need more work, especially at $N_t = 8$
- lines of constant physics
- finite density

see next talk

- effective Polyakov loop potentials, Polyakov loop correlators, ...
- in comparison to pure gauge simulations and effective theories