Critical endpoints in (2+1)- and 4-flavor QCD with Wilson-Clover fermions

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in collaboration with

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Introduction

- Order of finite temperature phase transitions in $N_f = 2+1$ QCD
 - Depending on quark masses
- Phase transition of $N_{\rm f}$ = 3 QCD
 - Expected to be first order at m = 0
 - Second order critical endpoint $m = m_E$
 - Crossover $m > m_{\rm E}$

R. D. Pisarski and F. Wilczek, PRD 29 (1984) 338

- Lattice studies so far
 - $m_{\rm E}$ keeps decreasing for more improved actions and as $a \rightarrow 0$
 - Different scaling btw. Wilson and staggered
 - $-m_{\rm E}$ in $a \rightarrow 0$ is still not conclusive



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Our approach

• Iwasaki gauge + Wilson clover fermion actions



Previous results

 $N_{\rm f} = 2 + 1$



Continuum extrapolation is needed.

Continuum extrapolation is still not precise enough.

 $N_{\rm f}=4$

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Simulation setup for $N_{\rm f} = 2 + 1$

- Iwasaki gauge action
- Non-perturbatively O(a)-improved Wilson clover fermion action
- *N*_t = 8
- $N_{\rm s}$ = 12, 16, 20, 24, 28 for finite size scaling studies
- β = 1.75
- κ_{s} = 0.1330 \rightarrow 0.1327 and 0.1333 by reweighting
- Varying κ_l to search for transition points

$N_{\rm f}$ = 2+1 result at β = 1.75, $\kappa_{\rm s}$ = 0.1327



Chiral susceptibility

There might be a first order phase transition around $\kappa_1 = 0.14218$.

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$N_{\rm f}$ = 2+1 result at β = 1.75, $\kappa_{\rm s}$ = 0.1330



Chiral condensate

There might be a first order phase transition around $\kappa_1 = 0.14214$.

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$N_{\rm f}$ = 2+1 result at β = 1.75, $\kappa_{\rm s}$ = 0.1333



Chiral susceptibility

There might be a first order phase transition around $\kappa_1 = 0.14210$.

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Simulation setup for $N_{\rm f} = 4$

- A good analogue to understand $N_f = 3$ QCD
 - Also expected to have a first order phase transition at m = 0
 - No issue of rooting for staggered quarks \rightarrow better comparison btw. Wilson and staggered
- Iwasaki gauge action
- Non-perturbatively O(a)-improved Wilson clover fermion action
- *N*_t = 10
- $N_s = 20, 24, 32$ for finite size scaling studies
- $\beta = 1.645$, 1.65 and 1.655
- Varying к to search for transition points

$N_{\rm f}$ = 4 result at β = 1.645





N_f = 4 result: susceptibility peak



Results for $N_t = 6$ and 8 are consistent with Z_2 . $N_t = 10$ is also close to Z_2 .

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Kurtosis intersection method



Critical endpoint : No volume dependence ↓ Searching for an intersection

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N_f = 4 result: kurtosis intersection





Results for $N_t = 6$ and 8 are consistent with Z_2 . $N_t = 10$ is also close to Z_2 but still not conclusive.

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*N*_f = 4 result: critical endpoint



Non-monotonic behavior. β_E becomes smaller for the finer lattice.

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Summary & Outlook

- Finite temperature phase transitions were studied for $N_f = 2+1$ and 4 QCD.
- For $N_{\rm f} = 2 + 1$
 - First order phase transitions were found in the parameter region we have studied.
 - Parameters for crossover will be studied.
- For $N_{\rm f} = 4$
 - A critical endpoint was found around β = 1.65 for $N_{\rm t}$ = 10.
 - Zero temperature simulations are needed to translate bare parameters to physical ones
 - Continuum extrapolations will be studied.

$N_{\rm f}$ = 4 result at β = 1.65



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$N_{\rm f}$ = 4 result at β = 1.655



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