Towards thermodynamics with $N_f = 2 + 1 + 1$ twisted mass quarks

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1. Introduction
2. First estimate of T_c, some observables
3. Towards the thermodynamic equation of state
4. Conclusions & Outlook

Outline

1. Introduction

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Motivation

- Explore finite T crossover with dynamical second quark generation
- Study role of charm quark - mass thresholds in thermodynamics
- Dynamical charm little studied, so far only with staggered quarks ([Budapest-Wuppertal & MILC, 2012])
- Goal of project: EoS with (near to) physical masses
- In this talk: some first preliminary results

Fixed scale approach

- First used by [WHOT-QCD, 2009]
- Used to compare Wilson and staggered quark results [Budapest-Wuppertal, 2012]
- Fewer $T = 0$ lattices needed for EoS
- At small T and around T_c: close to continuum (here T_χ at $N_\tau \sim 12$)
- Large T: Need several lattice spacings to check for lattice artefacts
- Temperature resolution limited - possible improvement: odd N_τ

$N_f = 2 + 1 + 1$ twisted mass action

- $N_f = 2 + 1 + 1$ lattice QCD with Wilson fermions at maximal twist.

  Degenerate light sector:

  $$S_f^l[\chi_l, \overline{\chi_l}, U] = \sum_x \overline{\chi_l}(x) \left[D_W + i\mu\gamma_5\tau^3\right] \chi_l(x)$$

  Heavy sector:

  $$S_f^h[\chi_h, \overline{\chi}_h, U] = \sum_x \overline{\chi}_h(x) \left[D_W + i\mu_\sigma\gamma_5\tau^1 + \mu_\delta\tau^3\right] \chi_h(x)$$

- Iwasaki Gauge Action:

  $$S_g[U] = \beta\Big(c_0 \sum_P [1 - \frac{1}{3}\mathrm{ReTr}\,(U_P)] + c_1 \sum_{\mathrm{R}} [1 - \frac{1}{3}\mathrm{ReTr}\,(U_R)]\Big)$$

Setup

$\mathbf{T = 0}$ ETMC results

- $\mathcal{O}(30)$ $T = 0$ gauge field ensembles
- Pion masses in the range of 220 to 500 MeV
- Strange and charm tuned to reproduce physical values of K- and D-meson masses at the level of 10 %
- Three lattice spacings:
  $a \sim 0.086, 0.078$ and 0.061 fm (preliminary) [ETMC, 2011]
- $m_\pi L > 3.3$

$\mathbf{T > 0}$:

- So far only $m_\pi \sim 400$ MeV
- Spatial sizes $N_\sigma = 24, 32$, $4 \leq N_\tau \leq 16$
- Aspect ratio ≤ 2

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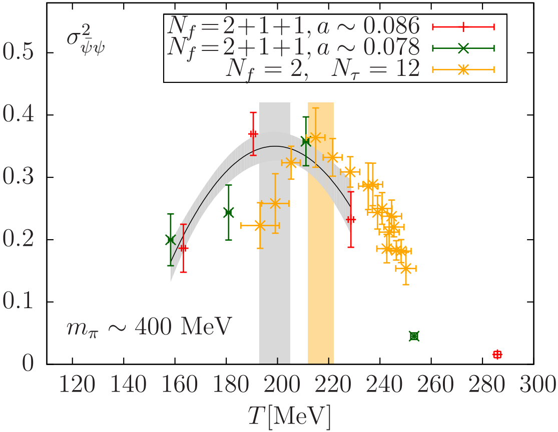
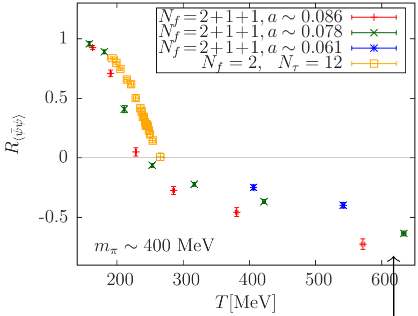
Susceptibility of $\langle\bar{\psi}\psi\rangle$



$T_\chi \sim 20$ MeV lower compared to $N_f = 2$
at same pion mass value [tmfT, 2012: FB et al. PRD 87,074508]

Renormalized Re(L), $\langle\bar{\psi}\psi\rangle$

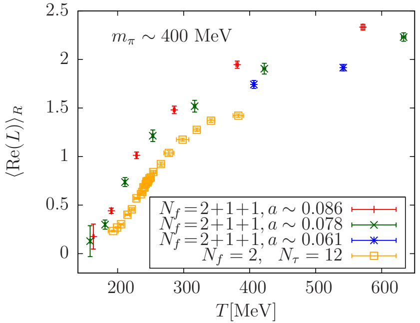
$$R_{\langle\bar{\psi}\psi\rangle} = \frac{\langle\overline{\psi}\psi\rangle(T,\mu)-\langle\overline{\psi}\psi\rangle(0,\mu)+\langle\overline{\psi}\psi\rangle(0,0)}{\langle\overline{\psi}\psi\rangle(0,0)}$$



$N_\tau = 4$

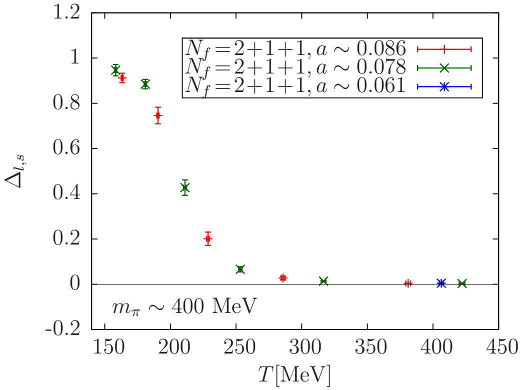
$N_f = 2$ cf. [tmfT, 2012]

$$\langle \mathrm{Re}(L)\rangle_R = \mathrm{Re}(L)\exp\left(V(r_0)/2T\right)$$



$$\Delta_{l,s} = \frac{\langle\overline{\psi}\psi\rangle_l - \frac{\mu_l}{\mu_s}\langle\overline{\psi}\psi\rangle_s}{\langle\overline{\psi}\psi\rangle_l^{T=0} - \frac{\mu_l}{\mu_s}\langle\overline{\psi}\psi\rangle_s^{T=0}}$$

[M. Cheng et al., 2008]



OS strange quark mass value by courtesy of A. Ammon

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Trace anomaly

- Trace anomaly

$$I = \epsilon - 3p = -\frac{T}{V}\frac{d\ln Z}{d\ln a}\ .$$

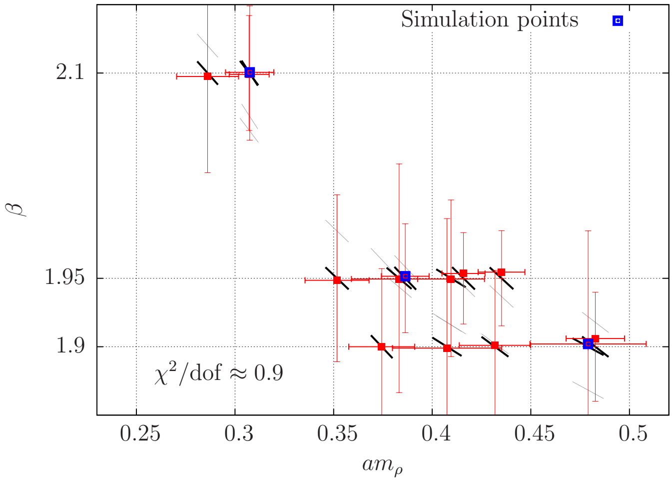
- Starting point for $p(T)$ and $\epsilon(T)$ by integral method

$$\frac{I}{T^4} = T\frac{\partial}{\partial T}\left(\frac{p}{T^4}\right)\ .$$

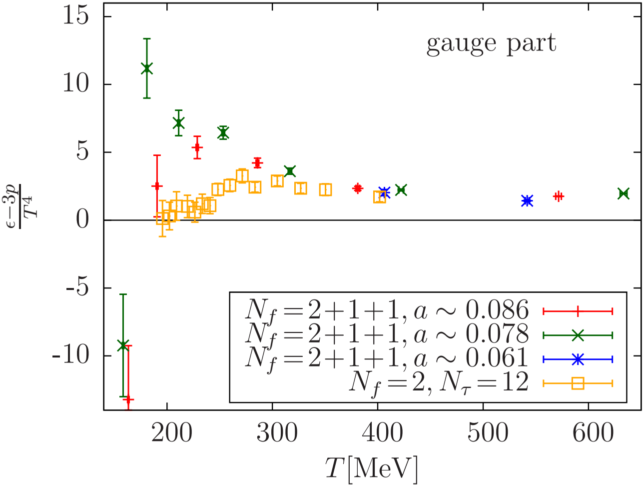
- Subtracted expectation values $\leftrightarrow$ fixed scale advantageous
- Very preliminary results for gauge part:

$$\frac{\epsilon - 3p}{T^4} = a\frac{d\beta}{da}\left\langle S_g\right\rangle_{\mathrm{sub}}\ .$$

$$\beta = c_0 \log\left(c_1\left(am_\rho\right)\right) + c_3\left(am_\pi\right) + c_4 \frac{\left(am_\rho\right)^2}{\left(am_\pi\right)^2}$$



A preliminary result



$N_f = 2$ cf. [tmfT, 2012]

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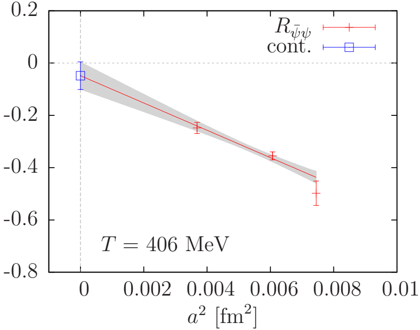
Conclusions & Outlook

- Conclusions:
  - First Wilson quark results for $N_f = 2 + 1 + 1$
  - Crossover shifted to smaller T
- Outlook:
  - Improvement necessary on β-function and statistics
  - In progress: light and heavy fermion contrib. to trace anomaly
  - Extension of code to odd N_τ
  - Decrease light mass

Thank you

Continuum limit of $R_{\langle\bar{\psi}\psi\rangle}$

$T = 406$ MeV



$T = 541$ MeV