jh190063-NAJ

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物理的なクォーク質量におけるエネルギー運動量テンソルの研究
Study of Energy-Momentum Tensor at Physical Quark Mass

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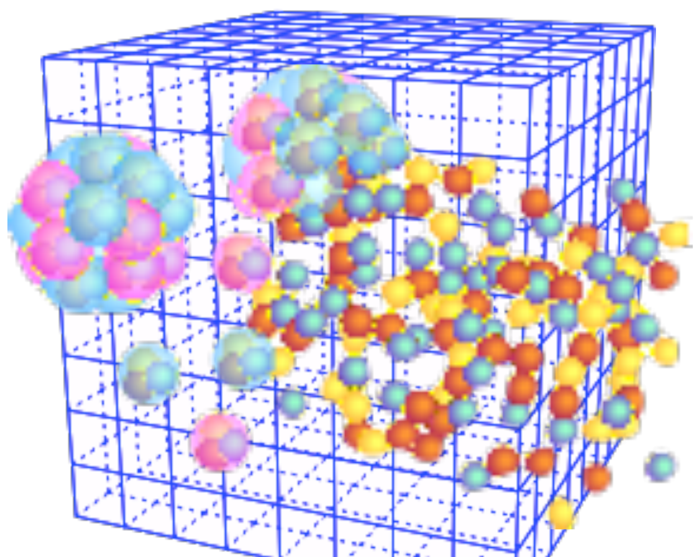
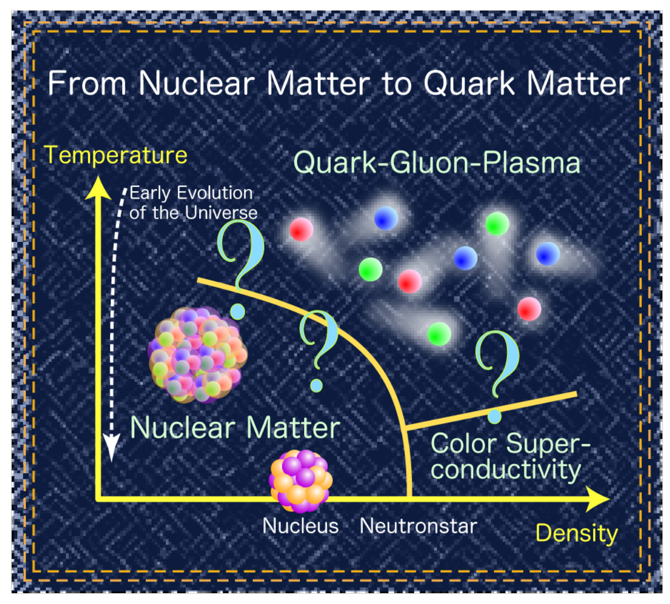


We study quark matter at high temperatures to explore early Universe by numerical simulation of 2+1 flavor lattice QCD with improved Wilson quarks at the physical point. We apply the SF*t*X (Small Flow-time eXpansion) method based on the gradient flow, which is a general method to evaluate any renormalized quantities on the lattice. The method enables us to study the Energy-Momentum Tensor and chiral observables, which have been difficult on the lattice due to explicit violation of relevant symmetries.



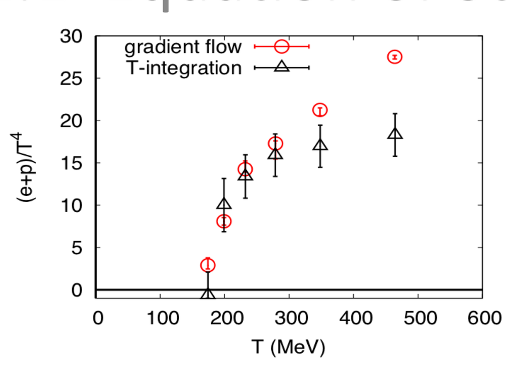
1. SF*t*X method based on the gradient flow

Gradient flow is a modification of fields in term of a fictitious time t driven by the gradient of an action [Narayanan-Neuburger 2006, Lüscher 2009-]. H. Suzuki proposed the SF*t*X method, a general method to compute any renormalized quantities on the lattice based on GF, irrespective of symmetry violations due to the lattice regularization [H.Suzuki, PTEP 083B03 (2013)]. We apply the method to evaluate EMT and chiral observables in QCD with improved Wilson quarks at high temperatures.

2. QCD with heavy u, d and physical s quarks

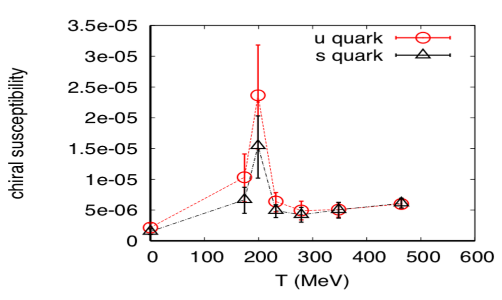
As the first systematic application of the method to QCD with dynamical quarks, we first studied the case that u and d quarks are heavier than their physical masses. [Taniguchi, Kanaya, et al., Phys. Rev. D 95, 054502 (2017); ibid. 96, 014509 (2017); 99, 059904(E) (2019)]

2.1 Equation of State (diagonal elements of EMT)



- consistent with conventional T-integration method
- disagreement at T≥350MeV due to $O((aT)^2=1/Nt^2)$ lattice artifacts at Nt≤8

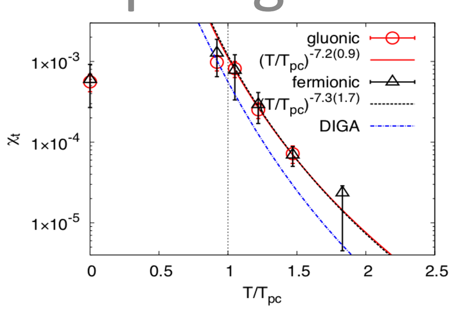
2.2 Chiral Susceptibility (disconnected)



- clear peak at Tpc≈190MeV as expected from other obs.,

  in spite of explicit chiral violation due to the Wilson quark action

2.3 Topological Susceptibility



- gluonic and fermionic definitions agree with each other, for the 1st time already on finite lattices
- T-dep. consistent with DIGA

Consistency among different methods suggests that our lattice is fine enough. We found that the SF*t*X method is quite powerful.

3. Improvement of the SF*t*X method

In the application of the SF*t*X method to QCD at physical u, d, s quark masses (physical point QCD) and other more complicated observables, we found that we need to improve the method.

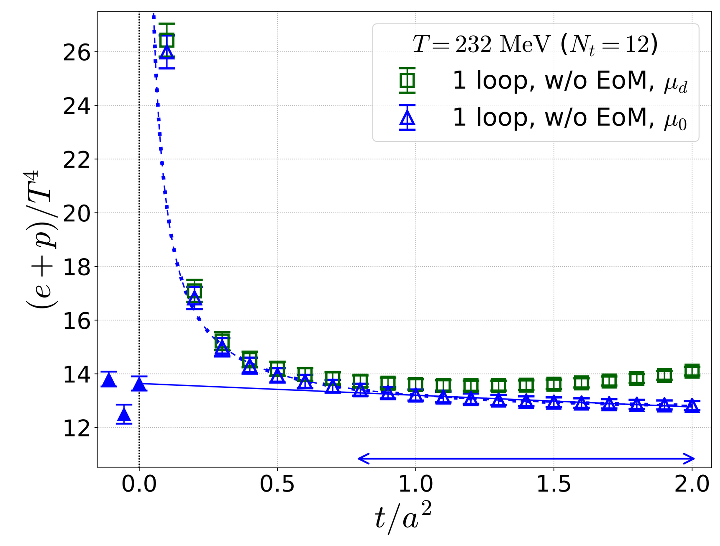
In FY 2019, besides generating finite-temperature configurations at the physical point, we carried out tests of the renormalization scale and 2-loop matching coefficients in the SF*t*X method, using the heavy u, d configurations. We found that a proper choice of the renormalization scale does extend the stability and applicability of the SF*t*X method much. [Taniguchi, Kanaya, et al., arXiv: 2005.00251]

3.1 Renormalization scale

The renormalization scale of the matching coefficients in the SF*t*X method has a freedom to choose its vale μ within a range. Besides the conventional $\mu_d = 1/\sqrt{8t}$, we test a new scale $\mu_0 = 1/\sqrt{2e^{\gamma}t}$, which may improve data at large t.

We found that the μ_0-scale

- improves the signal at large t,
- extends the stability and applicability of the SF*t*X method.

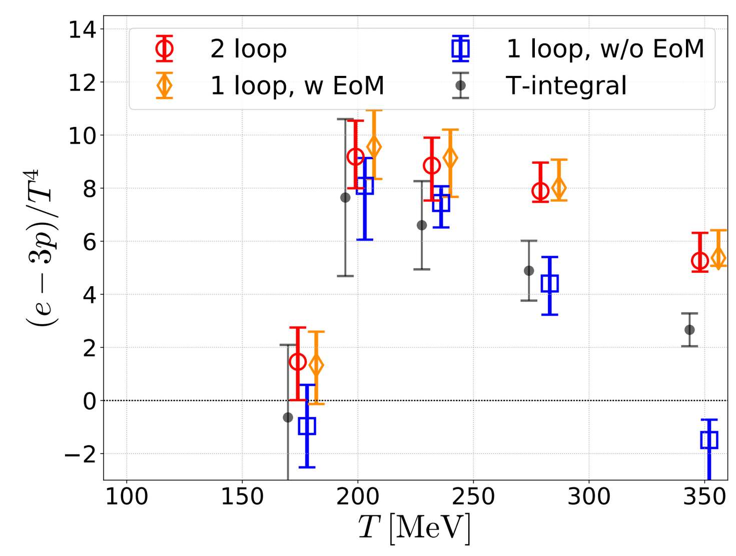


3.2 2-loop matching coefficients

We have been using 1-loop matching coefficients of Makino and Suzuki (2014). Recently, Harlander et al. calculated 2-loop coeff.'s for EMT, using equation of motion (EoM) for quarks (2018). Use of 2-loop coeff.'s may improve data at small intermediate t.

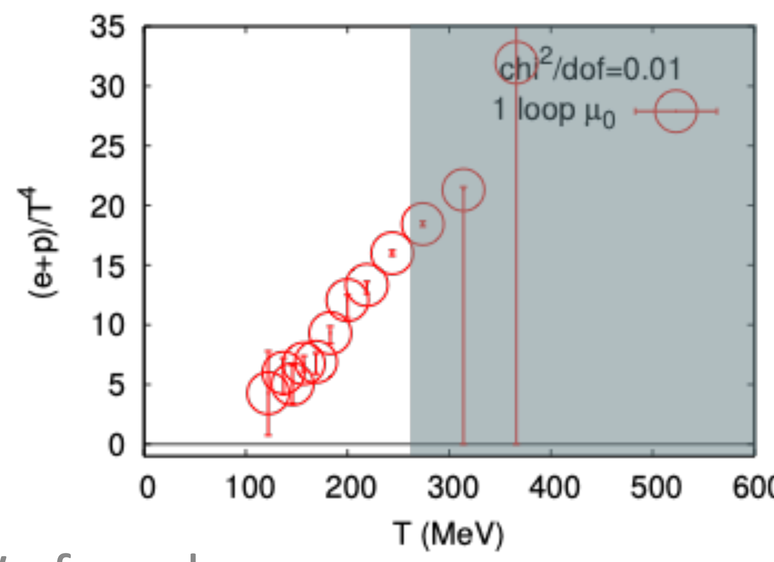
In our test, we found

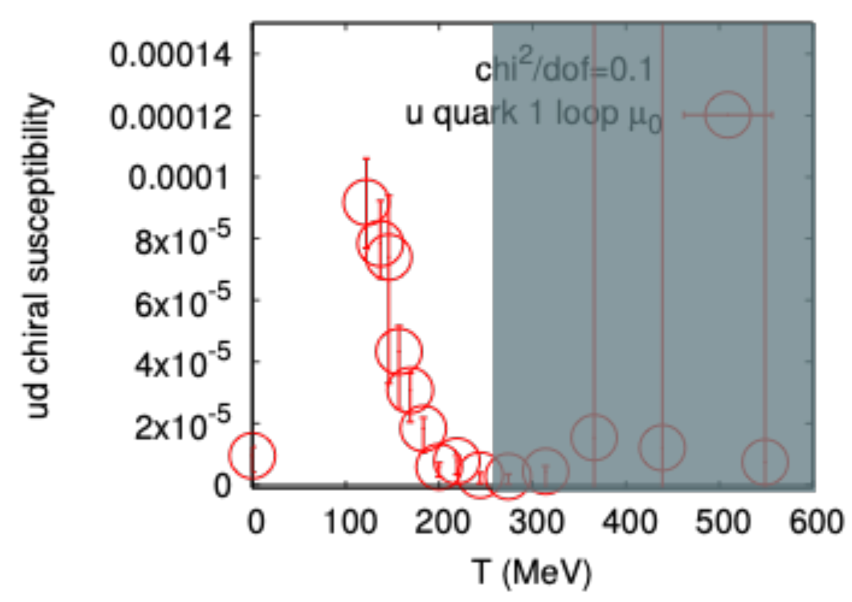
- no apparent improvement with 2-loop coeff.'s on our fine lattice,
- EoM gets $O(1/Nt^2)$ artifacts at Nt ≤ 10.



4. QCD with physical u, d, s quarks (preliminary)

We now extend the study to 2+1 flavor QCD with all quarks with physical mass with the μ_0-scale. Our preliminary results have been presented at conferences. [Kanaya, Taniguchi, et al., Lattice 2019, 088 (2020)]





We found

- big improvement of the signal with the μ_0-scale.
- signals similar to the heavy u, d case,

  but s quark shows milder transition than u, d, as expected.
- suggest T_{pc} < 157MeV (T ≈ 122-146 MeV may be critical).

Need more statistics at low T's.

=> simulations on-going with JHPCN etc.