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グラディエント・フローによる量子色力学の状態方程式

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To understand the state of matter at very high temperature/density such as in the early universe, the inside of the neutron star, and the heavy ion collision etc., it is crucial to know the Equation of State (EoS) in the Quantum Chromo Dynamics (QCD), the fundamental theory of the strong interaction. The ultimate goal of our project is to compute the EoS by employing the lattice QCD on the basis of the Wilson-type quark action. For this aim, we are now employing the energy-momentum tensor (EMT) defined through the gradient flow. In this poster, we summarize achievements we made so far to set up the starting point in this JHPCN exploratory project.

1. Gradient Flow (GF) (Narayanan-Neuberger (’06), Lüscher (’09~)) is the evolution of the gauge field A_μ along a fictitious time $t\geq 0$:

$(d/dt)B=D_\nu G_{\nu\mu}$, $B_\mu|_{t=0}=A_\mu$.

This may be regarded as the smearing of A_μ over the region $|x|=\surd(8t)$.

Any local product of the flowed fields is a renormalized finite operator (Lüscher-Weisz (’11)).

2. The above property of GF can be used to construct a universal expression for EMT: H.S., PTEP 2013, 083B03 (’13).

(1) EMT with the dimensional regularization satisfies Ward-Takahashi relations associated with the translational invariance.

(2) We can construct an operator of flowed fields that coincides with the above EMT for t->0. This expression is universal.

(3) This provides a method to define EMT on the lattice. This method was shown to work quite well in the quenched QCD: FlowQCD, PRD90, 011501 (’14), PRD94, 114512 (’16).

(4) We apply this method to N_f=2+1 QCD. Formulation: Makino-H.S., PTEP 2014, 063B02 (’14). This enable us to determine EoS without additional input as the beta function.

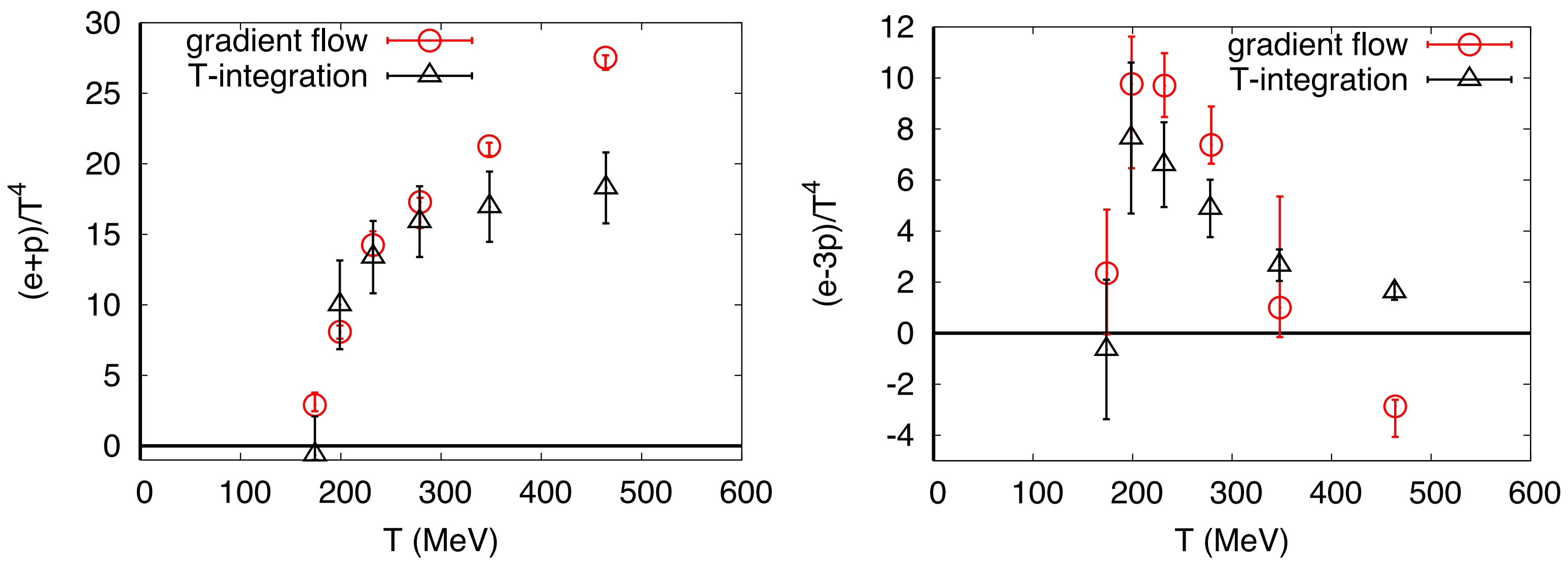
(5) Similar idea can be applied to scalar/current operators: Hieda-H.S., Mod. Phys. Lett. A31, 1650214 (’16) , and the topological charge, etc.

3. QCD with heavy ud quarks: WHOT-QCD, PRD96, 014509 (’17); D95, 054502 (’17) .

N_f=2+1 QCD, Iwasaki gauge action+NP improved clover action. Fine lattice (a≈0.07fm), but ud quarks are heavy ($m_{\mathrm{PS}}/m_{\mathrm{V}}$≈0.63) , physical s quark mass

CP-PACS+JLQCD T=0 configurations (β=2.05, $28^3\times 56$). WHOT-QCD T>0 fixed-scale configurations ($32^3\times N_t$, N_t=4 ,6, ⋯, 16) WHOT−QCD, PRD85, 094508 (’12).

- EoS:

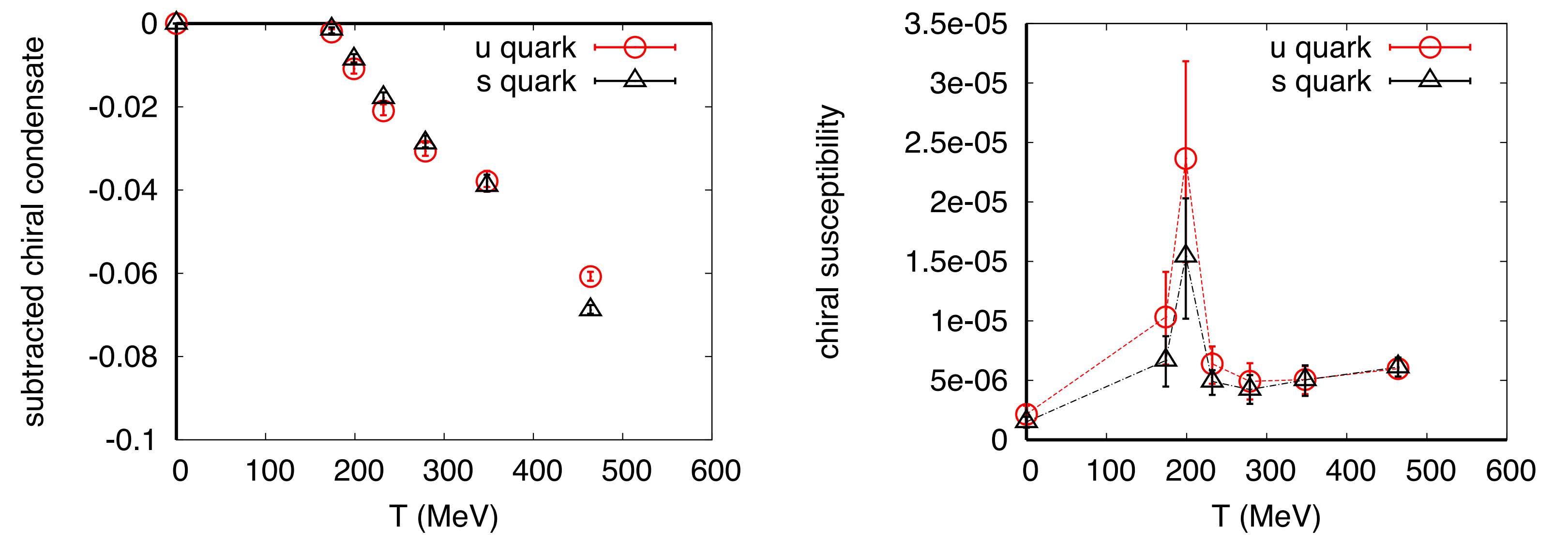


EoS by GF well agrees with the conventional method for T≤300MeV (N_t≥10).

Suggests a≈0.07fm is rather close to the continuum.

Disagreement at T≥350MeV may be attributed to $O((aT)^2=1/N_t^2)$ artifacts at N_t≤8

- Chiral condensate/disconnected susceptibility:

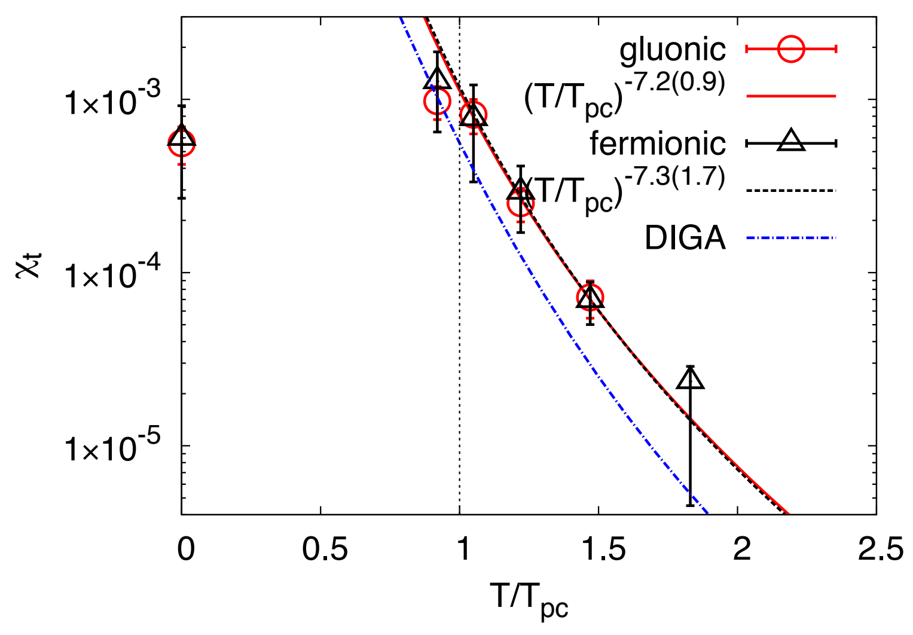


Crossover around T_{pc}≈190MeV.

Peak higher with decreasing m_q as expected.

Physically expected results even with the Wilson-type quarks.

- Topological susceptibility



Gluonic and fermionic definitions of χ_t agree even with the Wilson-type quarks.

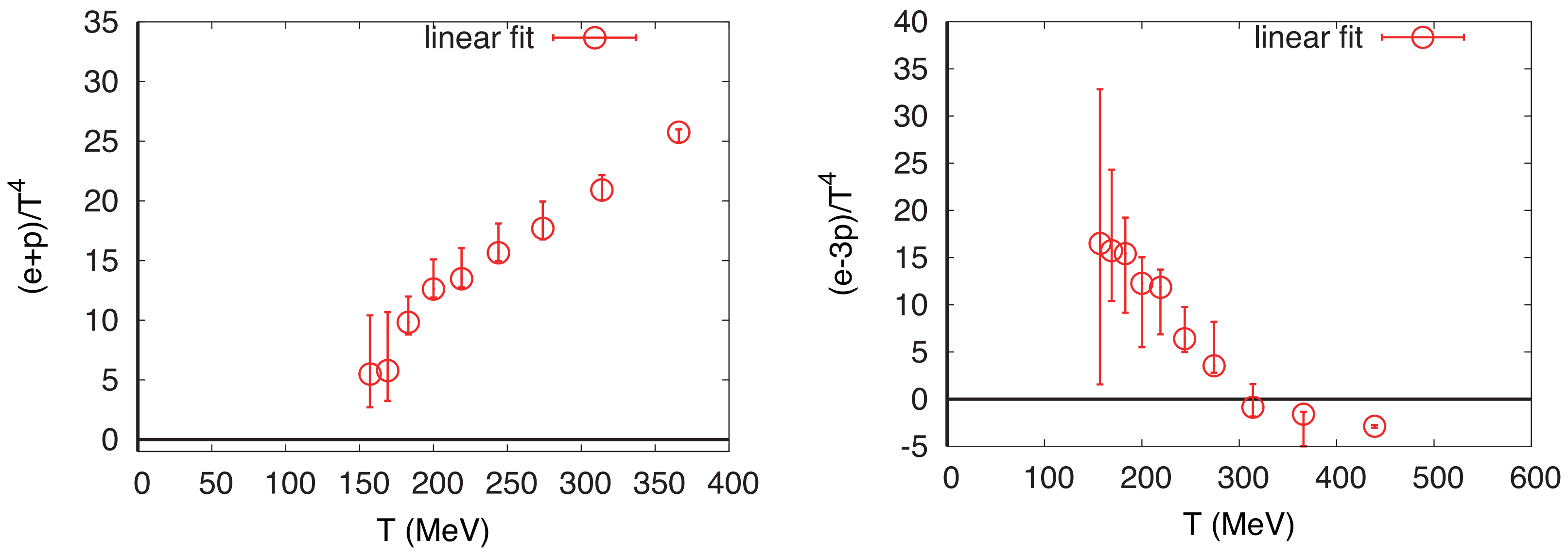
Power-low behavior Is consistent with the dilute instanton gas approximation (DIGA) which predicts the exponent -8.

4. QCD at physical point

N_f=2+1 QCD, Iwasaki gauge action+NP improved clover action. a≈0.09fm, physical point

PACS-CS T=0 configurations (β=1.90, $32^3\times 64$). WHOT-QCD T>0 fixed-scale configurations ($32^3\times N_t$, N_t=4, 5, ⋯, 14).

- EoS (preliminary):



Similar to the heavy quark case.

The method seems to be working. $e+p$≈staggered, but $e-3p$≈3×staggered with large errors.

5. Within the scope of this JHPCN exploratory study, we are planning,

☐ Heavy ud quark with a coarse lattice a≈0.1fm. Configuration generation and the thermodynamic measurement (in progress).

☐ Physical point, a≈0.09fm with N_t=16 and 15. Configuration generation and the thermodynamic measurement.

☐ Heavy ud quark with a finer lattice a≈0.05fm. Thermalization.

☐ We want to obtain solid results which can be continued to a full scale JHPCN project.

JHPCN　学際大規模情報基盤共同利用・共同研究拠点 第10回シンポジウム
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2018年　7月12日, 13日
THE GRAND HALL（品川）