Taste symmetry and QCD thermodynamics with improved staggered fermions

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HotQCD results

Previous:

- 2+1 flavor asqtad and p4 at $N_t = 8$, $m_l/m_s = 0.1$[1].

New:

- 2+1 flavor asqtad at $N_t = 8$ and 12, $m_l/m_s = 0.05$[2],
- 2+1 flavor HISQ at $N_t = 6$, $m_l/m_s = 0.2$ and at $N_t = 6, 8$, $m_l/m_s = 0.05$[3]. (For more details on HISQ see D. Toussaint's talk "Simulations with dynamics HISQ quarks". However, note what is different there: dynamical charm and the gauge action is tadpole improved.)

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[1] A. Bazavov et al. [HotQCD], Phys. Rev. D 80, 014504 (2009)

[2] HotQCD, work in progress

[3] HotQCD, work in progress and A. Bazavov and P. Petreczky [HotQCD], arXiv:1005.1131 [hep-lat]

Taste symmetry

- Staggered fermion discretization describes a theory with four flavors (called tastes to distinguish from physical flavor). The rooting procedure (reducing four flavors to one by taking the fourth root of the fermion determinant) amounts to averaging between staggered tastes.
- Four tastes are not equivalent at non-zero lattice spacing because the taste symmetry is broken.
- As a result, only one of the pseudo-scalar mesons is massless in the chiral limit and the other 15 pseudo-scalar mesons have masses of order a^2.
- Violations of the taste symmetry have been identified as the dominant source of the cutoff effects at $O(a^2)$ in the asqtad action. They lead to distortion of the hadron spectrum at non-zero lattice spacing.
- In thermodynamics calculations deviations from the physical hadron spectrum show up at low temperatures, where agreement with the Hadron Resonance Gas (HRG) model is expected.
- The cutoff effects can be reduced either by going to finer lattices (e.g., asqtad $N_t = 8$ to $N_t = 12$) or by using an action with higher degree of improvement (e.g. HISQ).

New HISQ data: $m_l = 0.05 m_s$

β	a, fm	am_s	32^4	$32^3 \times 8$	$24^3 \times 6$
6.195	0.1899	0.0880	2,365	6,110	11,100
6.285	0.1712	0.0790	2,300	6,190	6,750
6.341	0.1612	0.0740	580	7,020	6,590
6.354	0.1595	0.0728	2,295	5,990	5,990
6.423	0.1475	0.0670	2,295	5,990	5,990
6.488	0.1388	0.0620	2,295	5,990	8,790
6.515	0.1352	0.0604	2,045	10,100	10,430
6.550	0.1317	0.0582	2,295	5,990	7,270
6,575	0.1278	0.0564	2,295	14,500	7,330
6.608	0.1241	0.0542	2,295	5,990	6,560
6.664	0.1173	0.0514	2,295	5,990	8,230
6.800	0.1047	0.0448	2,295	5,990	7,000
6.950	0.0921	0.0386	2,295	5,990	7,480
7.150	0.0770	0.0320	2,295	5,990	4,770

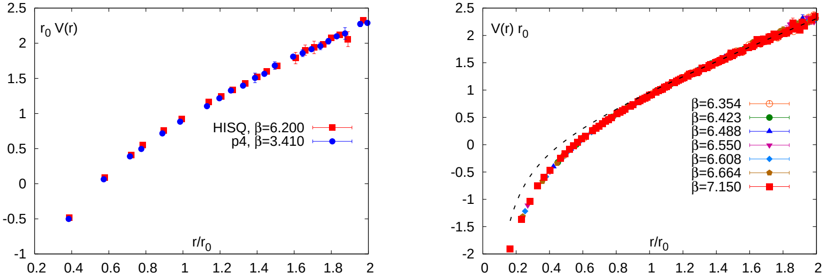
Overview of HISQ ensembles

- Two lines of constant physics (LCP):

$$m_\pi = 159.9(1.7)\ \text{MeV}\ , \qquad m_K = 528.0(6.3)\ \text{MeV},$$

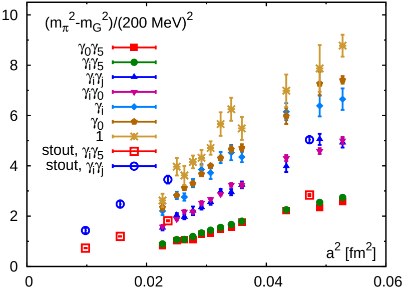
$$m_\pi = 309.6(3.4)\ \text{MeV}\ , \qquad m_K = 497.0(4.2)\ \text{MeV}.$$

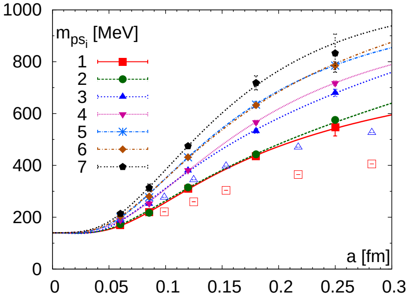
- Sommer scale $r_0 = 0.469$ fm is used to convert to physical units.
- The lattice spacing is determined from the static quark anti-quark potential, which does not show any noticeable cutoff dependence (e.g. compare p4 and HISQ on the left panel).



Taste symmetry for HISQ

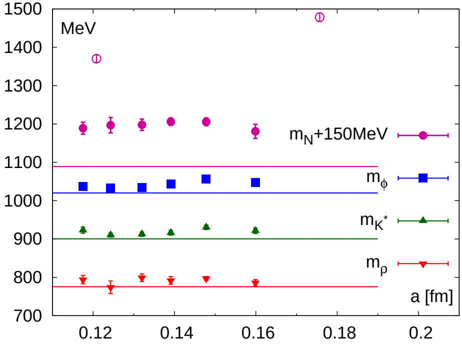
- Taste violations affect the pseudo-scalar meson sector most.
- The quadratic mass splitting of non-Goldstone mesons and the Goldstone meson is of order αa^2.
- These splittings are to a good approximation mass independent.
- For HISQ we calculated the mass splittings along $m_l/m_s = 0.2$ LCP.
- Left panel: splittings for HISQ and stout.
- Right panel: non-Goldstone pseudo-scalar meson masses in units of MeV assuming that the lightest pion mass is tuned to the physical value for asqtad and stout.



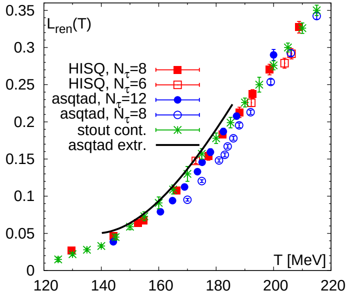


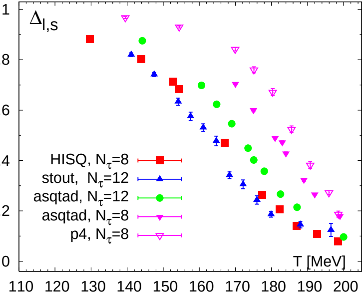
Taste symmetry for HISQ

- Effects of taste symmetry breaking are also seen in other channels, increasing masses of hadrons at non-zero lattice spacing comparing to their continuum values.
- For HISQ the cutoff effects are significantly reduced, e.g. vector meson masses are close to the experimental values and the nucleon mass is about 10% higher (but the agreement is significantly improved comparing to the asqtad calculation, open symbols).



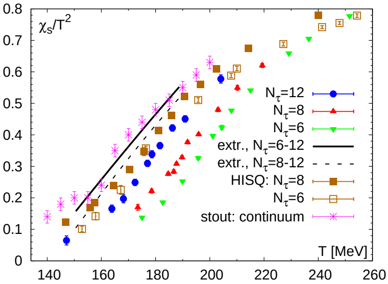
Polyakov loop and chiral condensate





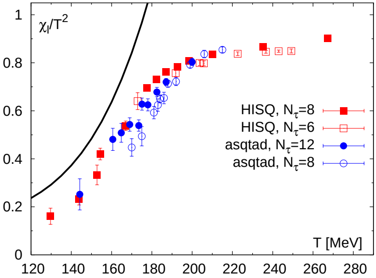
- Renormalized Polyakov loop: comparison of astqtad and HISQ at different N_t and continuum asqtad (solid line) and stout (green points) results.
- Asqtad continuum extrapolation: polynomial in $T^{1/4}$ with a^2-dependent coefficients.
- Renormalized chiral condensate: sensitive to the taste symmetry violation, reducing cutoff effects shifts the transition region to lower temperatures.

Fluctuations of conserved charges: strangeness



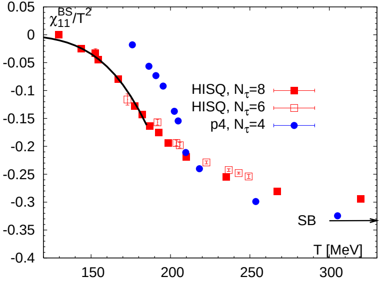
- At low T strangeness is carried by massive hadrons and its fluctuations are suppressed. At high T it is carried by quarks.
- In the transition region the strangeness fluctuation rises and eventually reaches the ideal quark gas value.
- Reducing taste symmetry violations shifts the transition region to lower temperatures, compare asqtad and HISQ results at different N_t and also asqtad and stout continuum extrapolated results.

Fluctuations of conserved charges: light q. n. s.



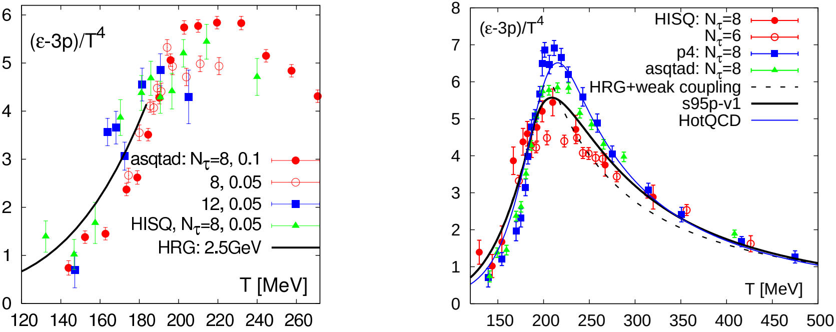
- The light quark number susceptibility – at low temperatures is dominated by lightest states and thus is very sensitive to the taste-breaking effects.
- Large cutoff effects are present even for HISQ, but the agreement with the Hadron Resonance Gas improves.

Correlations of conserved charges



- Baryon number strangeness correlation with HISQ
- At low temperatures is due to the presence of strange baryons. At high temperatures is carried by strange quarks, thus, approaches $-1/3$ in the Stefan-Boltzmann limit.
- Reducing the taste-breaking effects improves the agreement with HRG.

Trace anomaly



- Taste symmetry violation is substantial at low temperatures and in the transition region (left panel). Reducing it improves agreement with HRG (asqtad at $N_t = 12$, HISQ at $N_t = 8$).
- At high temperatures the taste symmetry is not expected to play a role, thus, we expect agreement of p4, asqtad and HISQ.
- Lines represent different parametrizations based on HRG and lattice data.

Conclusions

- We have generated HISQ ensembles at $N_t = 6$ and 8 along $m_l/m_s = 0.05$ LCP and compared with the previous p4 and asqtad studies, and in some cases with the stout results.
- Taste symmetry breaking effects are identified as the largest source of the cut-off effects in the low-temperature region for staggered actions.
- Thus, higher degree of improvement (e.g. the HISQ action) substantially reduces cut-off effects in many thermodynamic quantities at lattice spacings comparable to previously used.
- To control the systematic errors we compare different staggered actions, and also perform the continuum extrapolations on asqtad ensembles (work in progress).