QCD thermodynamics with HISQ action

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for HotQCD Collaboration

For further details see
A. Bazavov, P.P, PoS LAT2009 (2009) 163 ; e-Print: arXiv:0912.5421 [hep-lat]

• Introduction : cutoff effects and thermodynamics in the low-T region, lattice vs. HRG

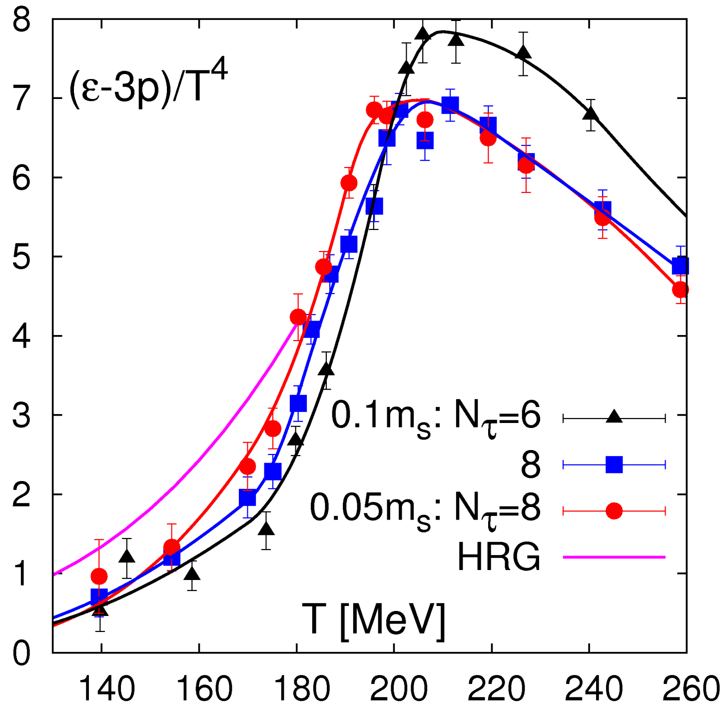
• HISQ action and *T=0* physics

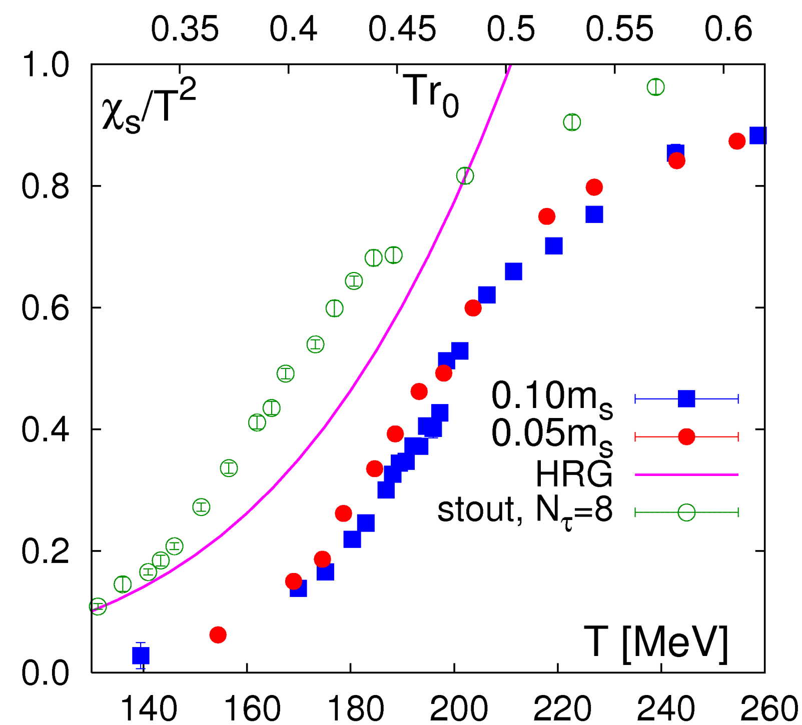
• QCD thermodynamics with HISQ action and comparsion with other improved action calculations : p4, asqtad (RBC-BI, HotQCD) and stout (Budapest-Wuppertal)
Cheng et al, arXiv:0911.2215 [hep-lat]

Bazavov et al, PRD 80 (2009) 014504 [arXiv:0903.4379 [hep-lat]]
Aoki et al, JHEP 0906 (2009) 088 [arXiv:0903.4155 [hep-lat]]

Lattice results for "physical" quark masses

Lattice calculations at the physical quark mass and $N_\tau=8$, Cheng et al, arXiv:0911.2215





- Thermodynamics quantities are quark mass independent for $T>200$MeV
- The quark mass effect is also small at low temperature and is similar to cutoff effects
- Lattice results are significantly below the Hadron Resonance Gas

Improved staggered calculations at finite temperature

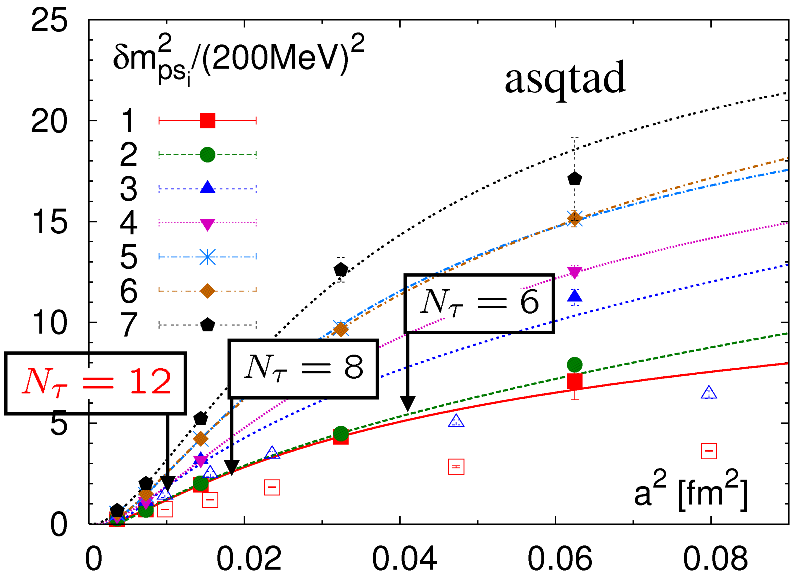
cutoff effects are different in :

low T region		high-T region
T<200 MeV		T>200MeV
$\mathcal{O}(\alpha_s^n (a\Lambda_{QCD})^2)$ errors	$a = 1/(TN_\tau)$	$\mathcal{O}((aT)^2)$ errors
a>0.125fm	$N_\tau = 8$	a<0.125fm

hadronic degrees of freedom

improvement of the flavor symmetry is important $\rightarrow$ fat links

$$\delta m^2_{ps_i} = m^2_{ps_i} - m^2_{ps_G} \sim \alpha_s a^2$$



stout

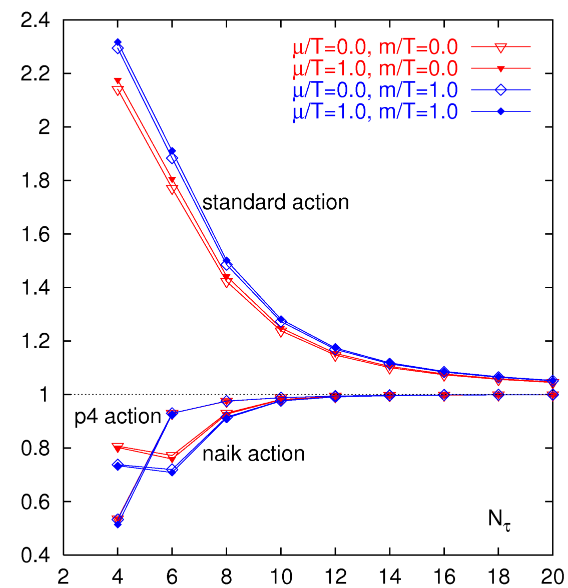
quark degrees of freedom

quark dispersion relation

for #flavors < 4

rooting trick

$$detD \rightarrow (detD)^{\frac{n_f}{4}}$$



p4*, *asqtad*, *HISQ

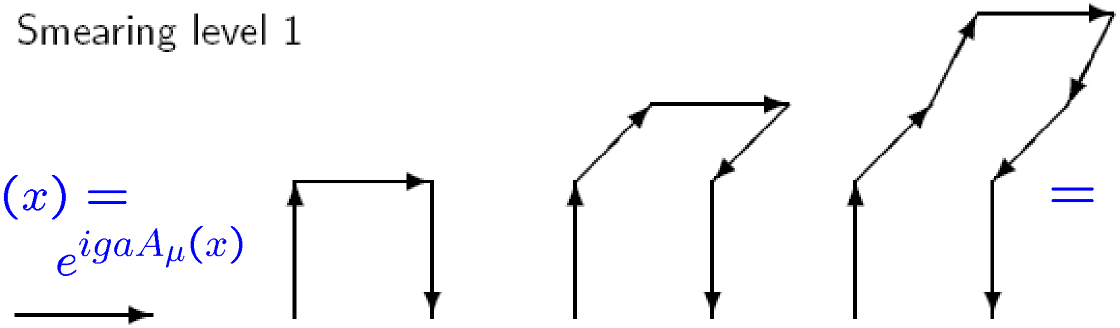
The Highly Improved Staggered Quark (HISQ) Action

HISQ action two levels of gauge field smearing with re-unitarization

Follana et al, PRD75 (07) 054502

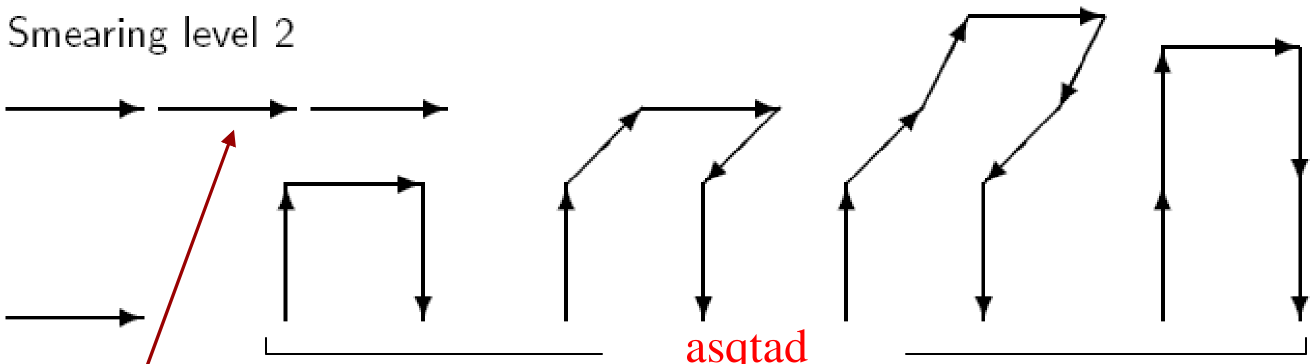
Smearing level 1

$$U_\mu(x) = e^{igaA_\mu(x)}$$



$$= U_\mu^{fat7} \rightarrow \tilde{U}_\mu = \frac{U_\mu^{fat7}}{\sqrt{U_\mu^{fat7} U_\mu^{fat7\dagger}}}$$

Smearing level 2



projection onto U(3) improves flavor symmetry

Hasefratz, arXiv:hep-lat/0211007

3-link (Naik) term to improve the quark dispersion relation + asqtad smearing

T=0 calculations with HISQ action

0.2m$_s$, N$_\tau$=6

$m_\pi = 306 - 312$ MeV

$m_K = 522 - 532$ MeV

$m_\rho = 850 - 883$ MeV

$m_N = 1130 - 1183$ MeV

0.05m$_s$, N$_\tau$=8

$m_\pi = 156 - 161$ MeV

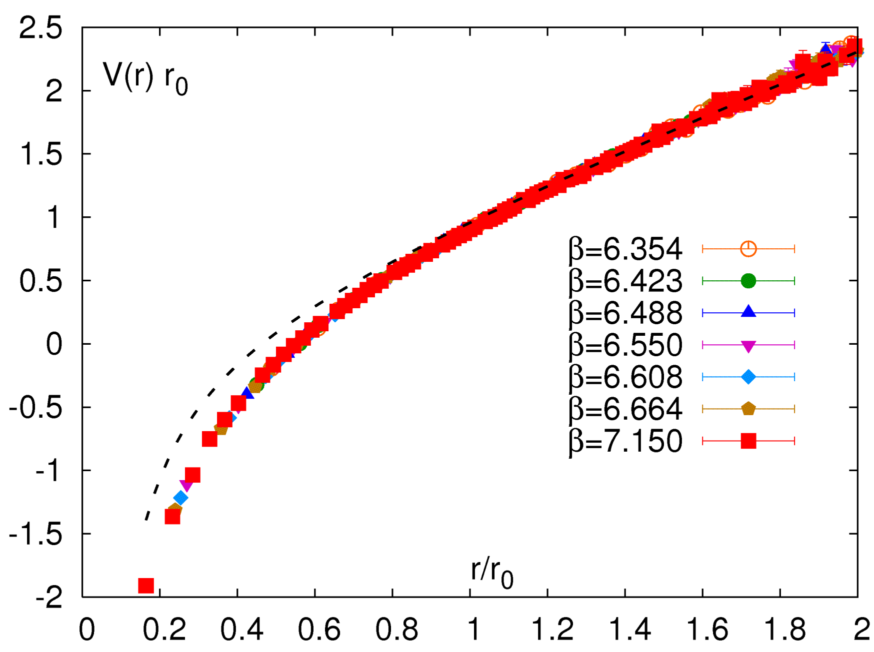
$m_K = 493 - 501$ MeV

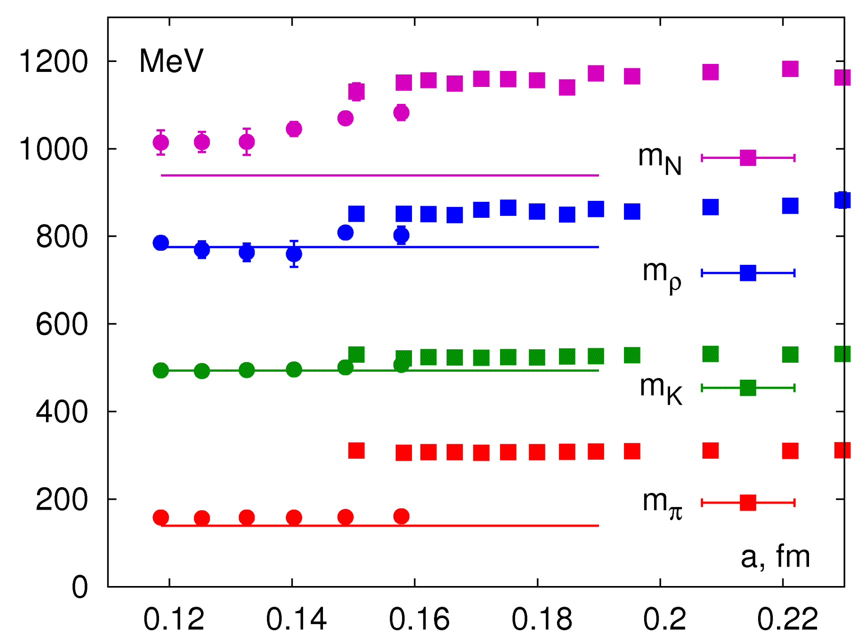
$m_\rho = 760 - 808$ MeV

$m_N = 1014 - 1083$ MeV

The lattice spacing is set through the calculation of static potential

$$\left(\frac{dV_{q\bar{q}}(r)}{dr}\right)_{r=r_0} = 1.65, \; r_0 = 0.469(7) fm$$

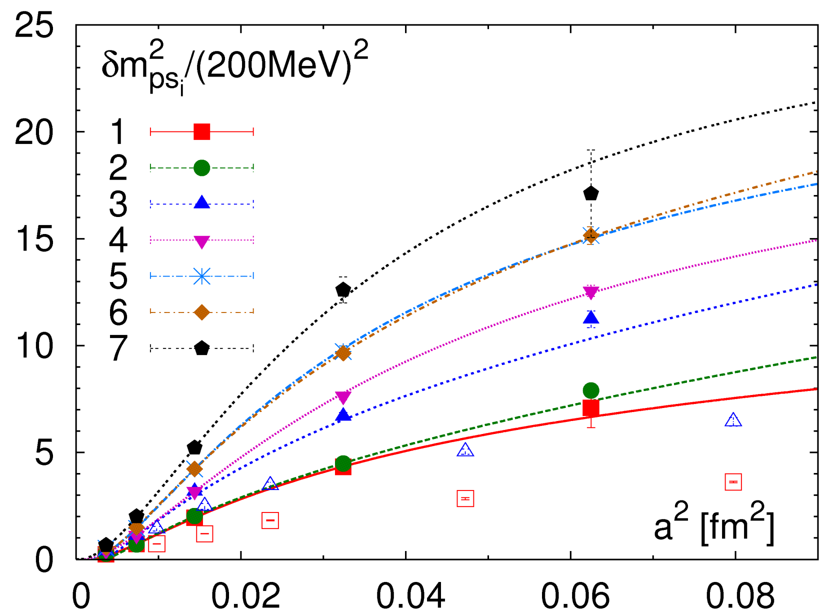




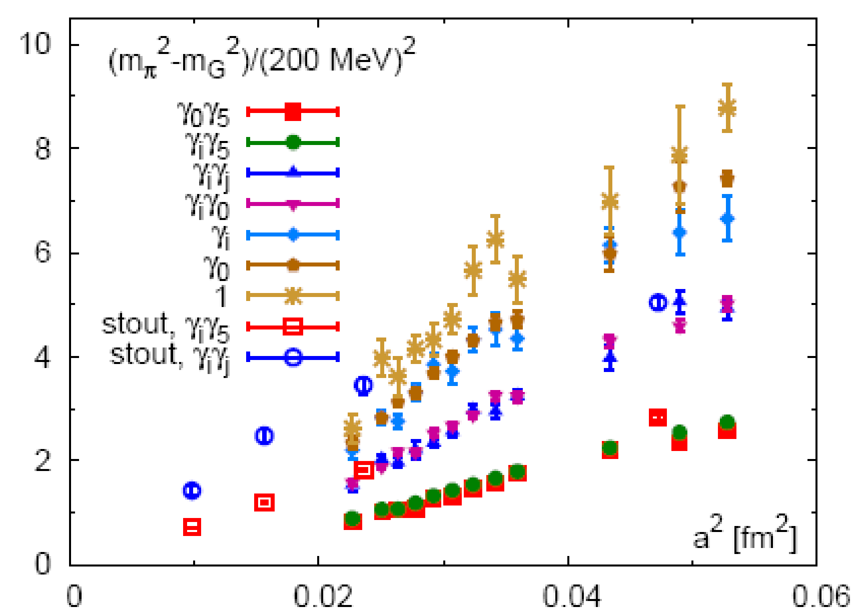
Mass splitting of pseudo-scalar mesons

Only one out of 16 PS mesons has zero mass in the chiral limit, the quadratic mass splitting is the measure of flavor symmetry breaking

asqtad



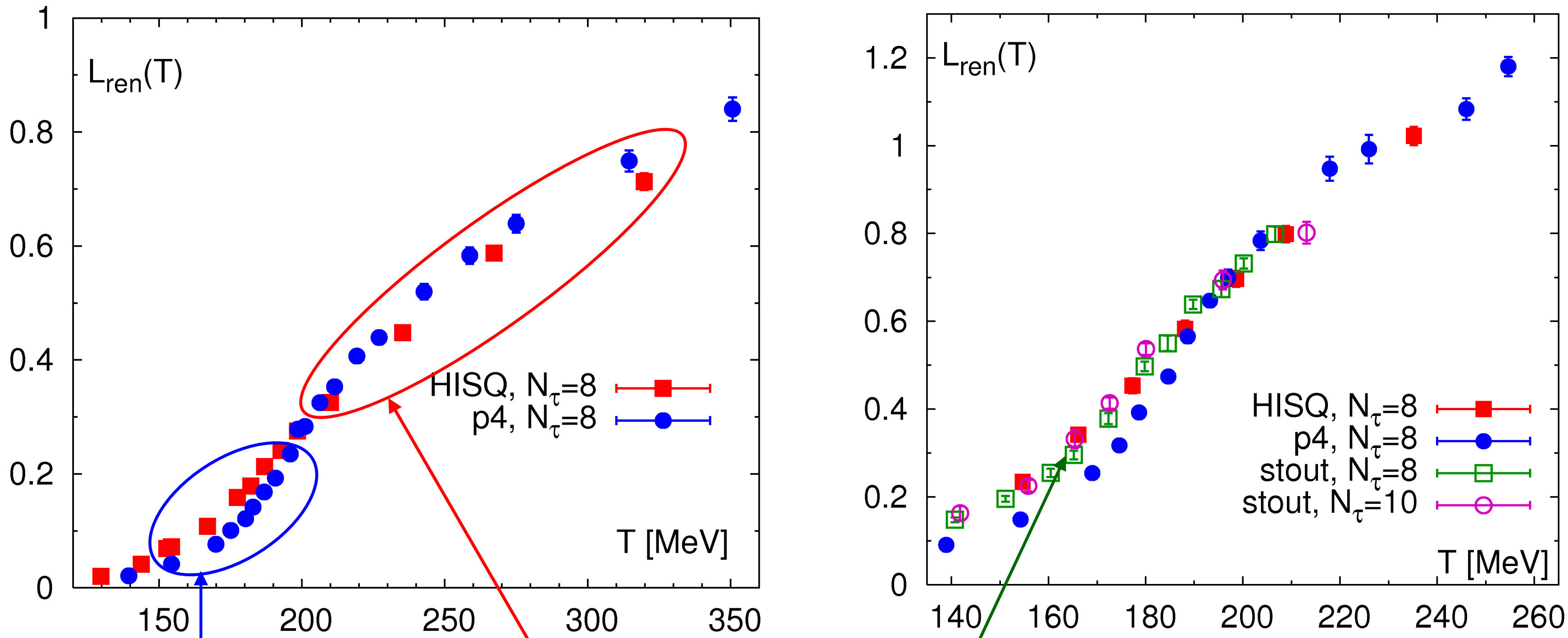
HISQ



PS meson splittings in HISQ calculations are reduced by factor ~ 2.5 compared to asqtad at the same lattice spacing and are even smaller than for stout action => discretizations effects for N_τ=*8* HISQ calculations are similar to those in N_τ=*12* asqtad calculations

Deconfinement transition : the Polyakov loop

$$L_{ren} = \exp(-F_Q(T)/T)$$



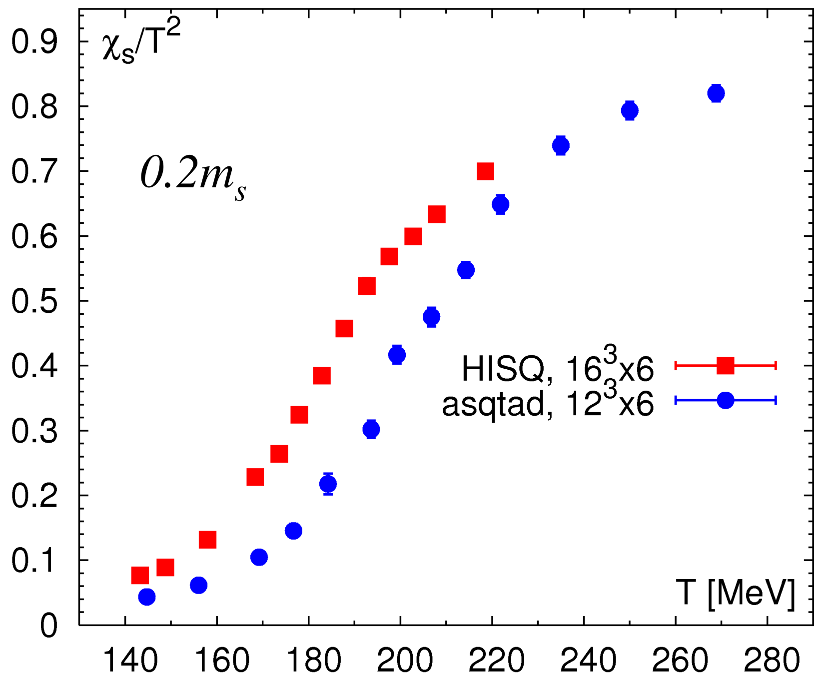
- Polyakov loops in HISQ and p4 calculations agree reasonably well at high T

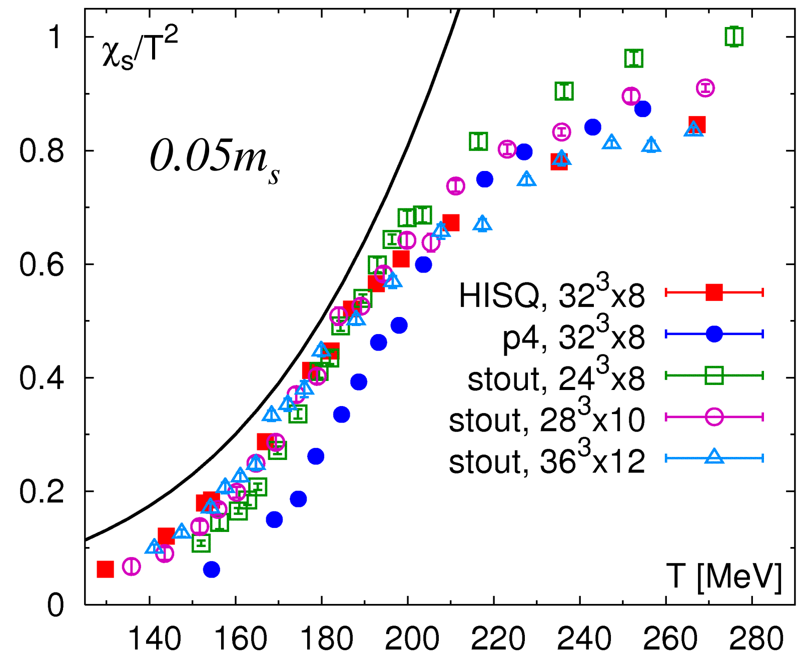
- HISQ results are consistently larger than p4 results at low temperatures and transition

- If the same procedure for fixing the lattice spacing is used (r_0) the HISQ and stout calculation agree for the raw data of $L_{ren}(T)$

Deconfinement transition : strangeness susceptibility

$$\chi_s = \frac{1}{VT^3}\frac{\partial^2 \ln Z(T,\mu_s)}{\partial \mu_s^2}$$





• At high T HISQ results agree reasonably well with p4 and asqtad results

• Significant enhancement in strangeness fluctuations at low T compared to asqtad and p4

• HISQ calculations agree with the stout results on the raw data on χ_s when r_0 scale is used

• HISQ results are closer to the HRG than p4 and asqtad results but still smaller than HRG

Deconfinement transition : strangeness susceptibility

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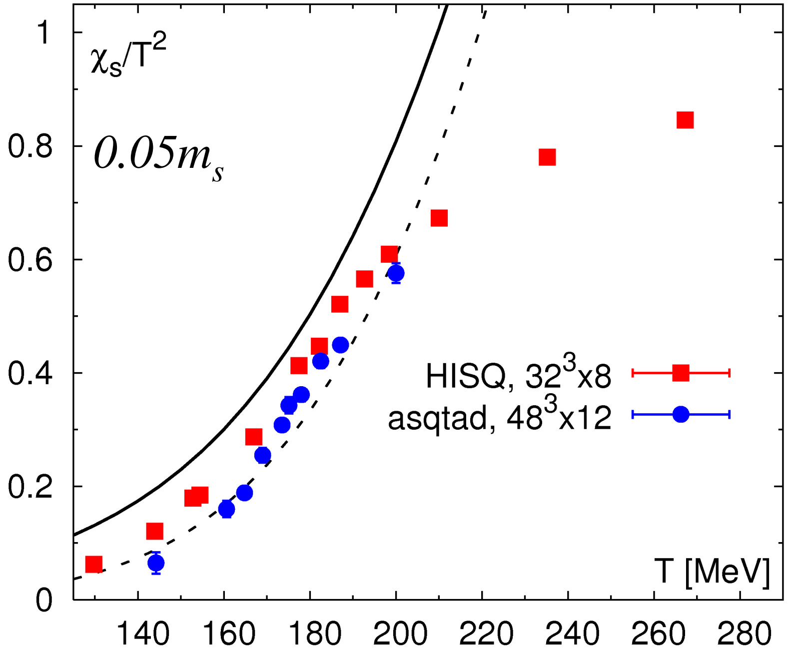
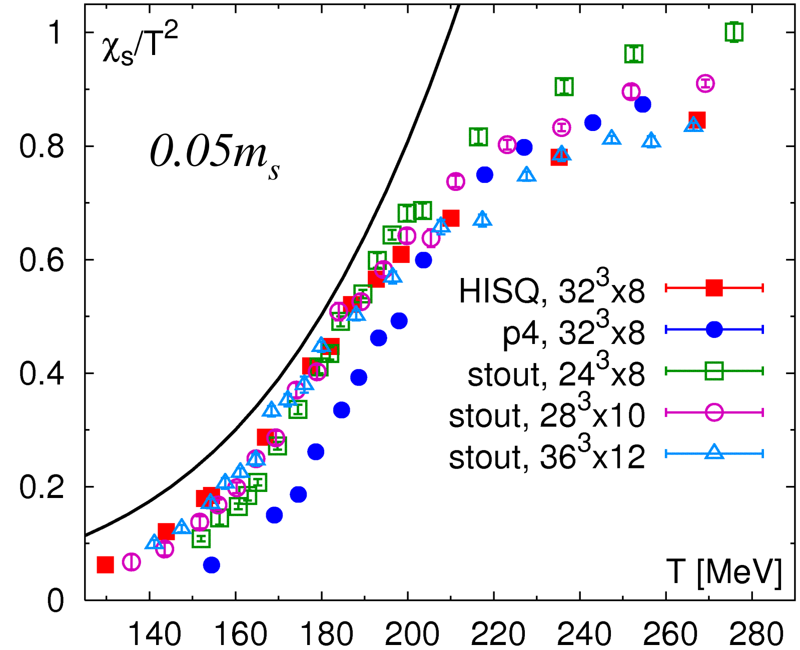




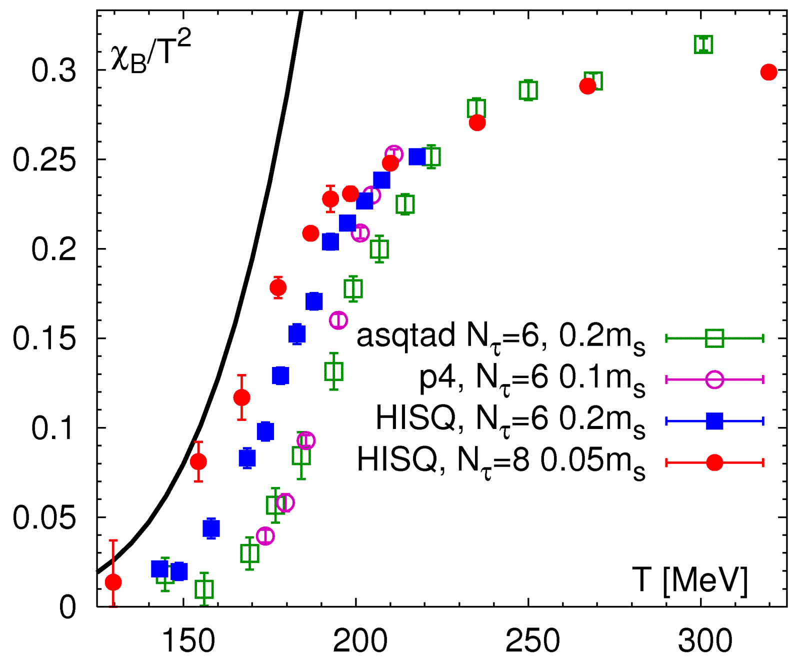
• HISQ calculations on N_τ=8 agree resonably well with asqtad calculations on N_τ=12

• Lattice results agree with the HRG model results, where hadron masses have been corrected for finite lattice spacing effects, Huovinen, P.P., arXiv:0912.2541 [hep-ph]
=> cutoff effects are similar to quark mass effect

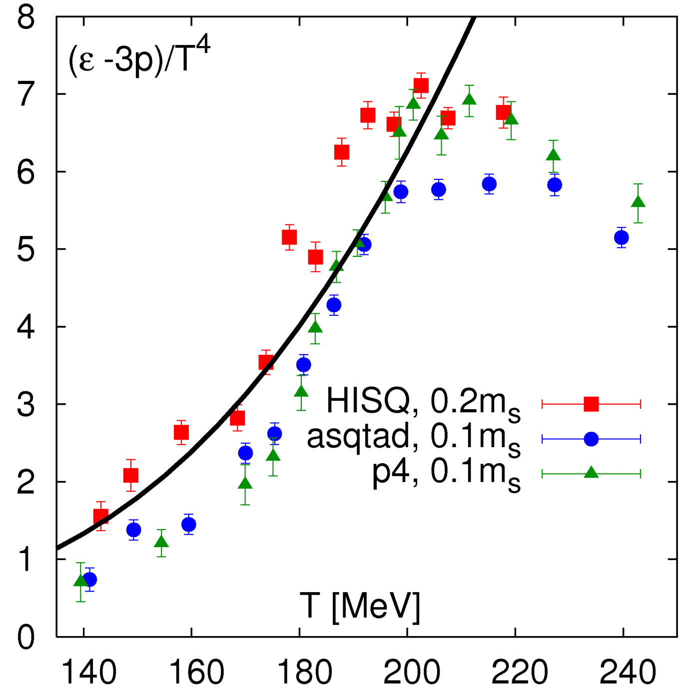
• HISQ results are closer to the HRG than p4 and asqtad results but still smaller than HRG

Further comparison with HRG model

$$\chi_B = \frac{1}{VT^3}\frac{\partial^2 \ln Z(T,\mu_B)}{\partial \mu_B^2}$$



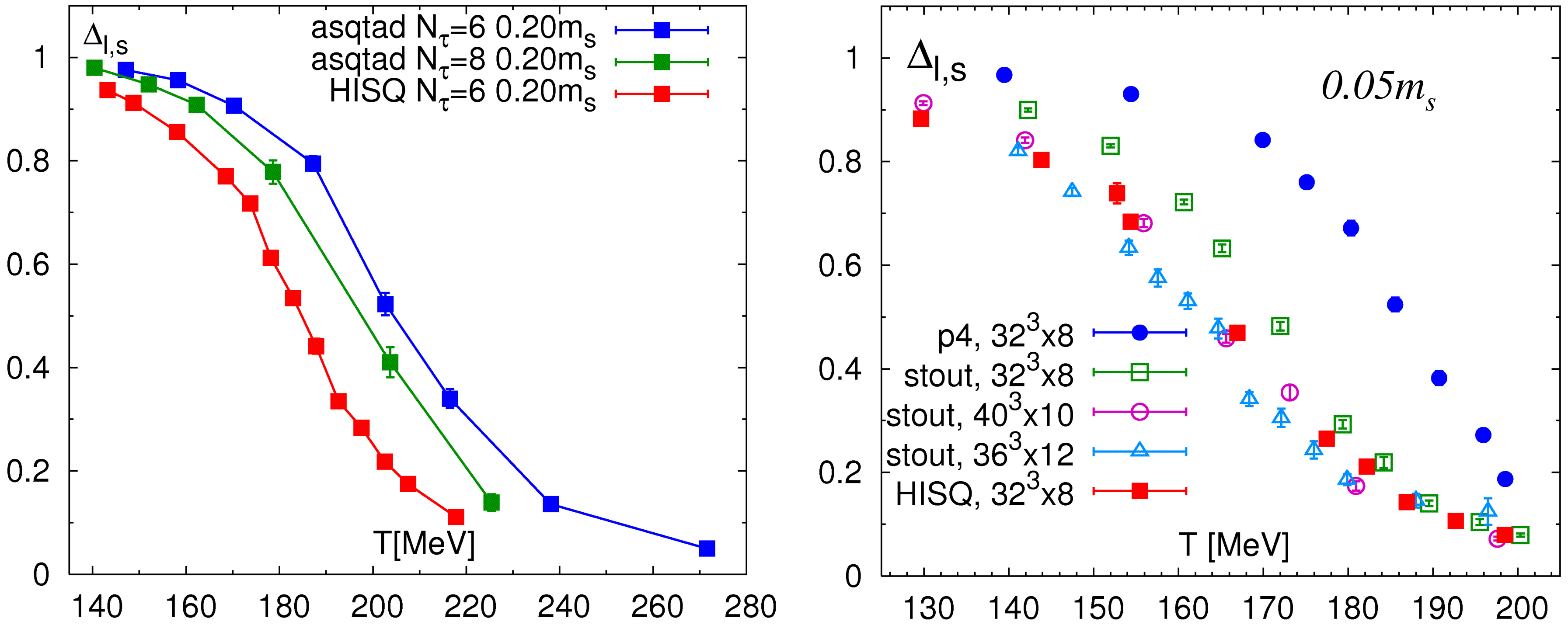
Trace anomaly



• significant enhancement of baryon number fluctuations and trace anomaly at low T compared to asqtad and p4 obtained using N_τ=8 and N_τ=6 lattices

The subtracted chiral condensate

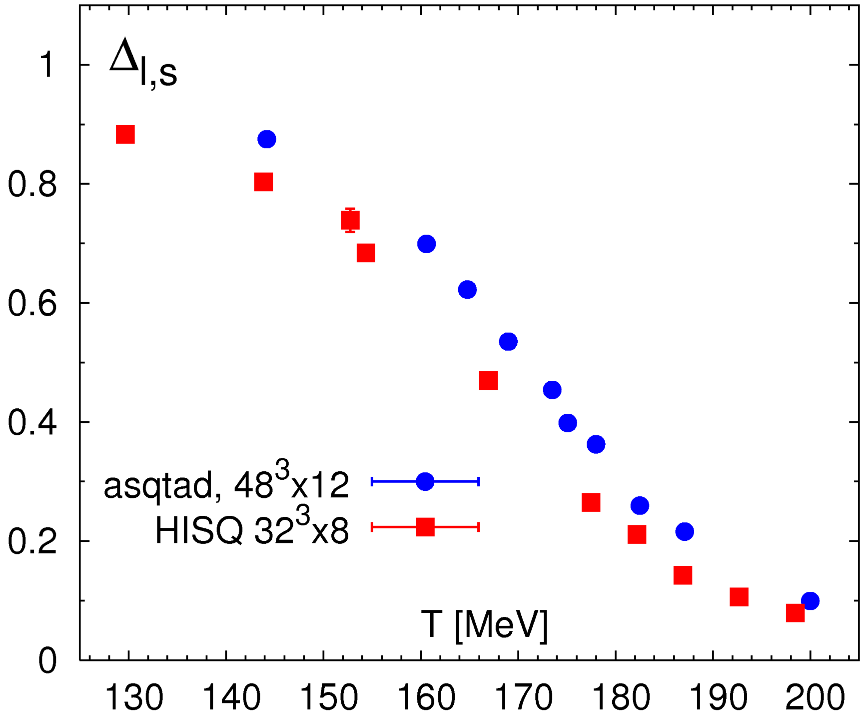
$$\Delta_{s,l}(T) = \frac{\langle \bar{q}q \rangle_T - \frac{m_q}{m_s}\langle \bar{s}s \rangle_T}{\langle \bar{q}q \rangle_{T=0} - \frac{m_q}{m_s}\langle \bar{s}s \rangle_{T=0}}$$

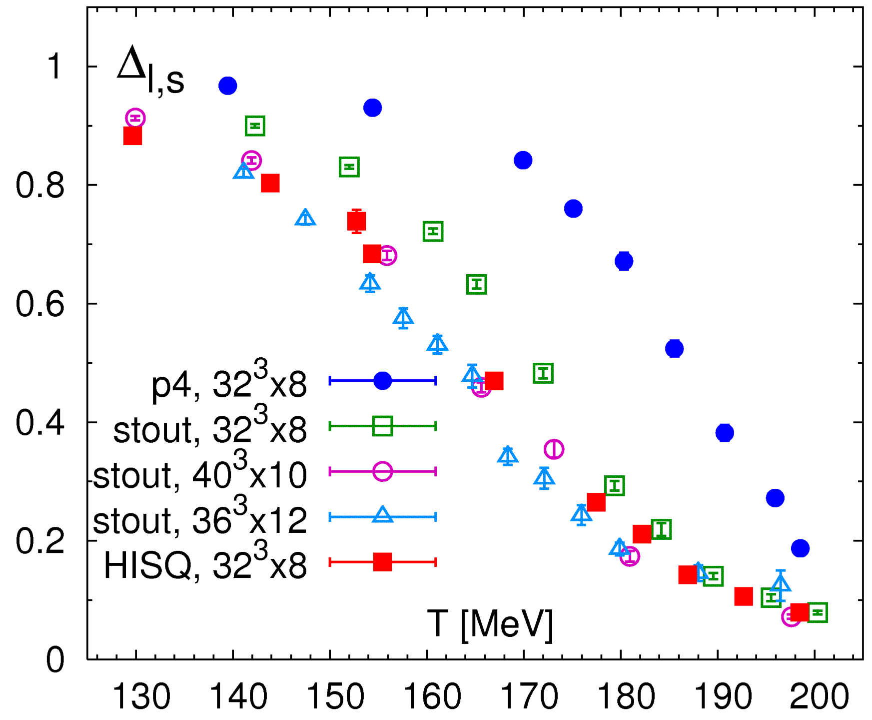


- The transition region defined by the rapid change in the chiral condensate is shifted to smaller temperature compared to asqtad and p4 action
- HISQ results on the $\Delta_{l,s}$ raw data agree with stout results if the scale is set by r_0

The subtracted chiral condensate

$$\Delta_{s,l}(T) = \frac{\langle \bar{q}q \rangle_T - \frac{m_q}{m_s} \langle \bar{s}s \rangle_T}{\langle \bar{q}q \rangle_{T=0} - \frac{m_q}{m_s} \langle \bar{s}s \rangle_{T=0}}$$

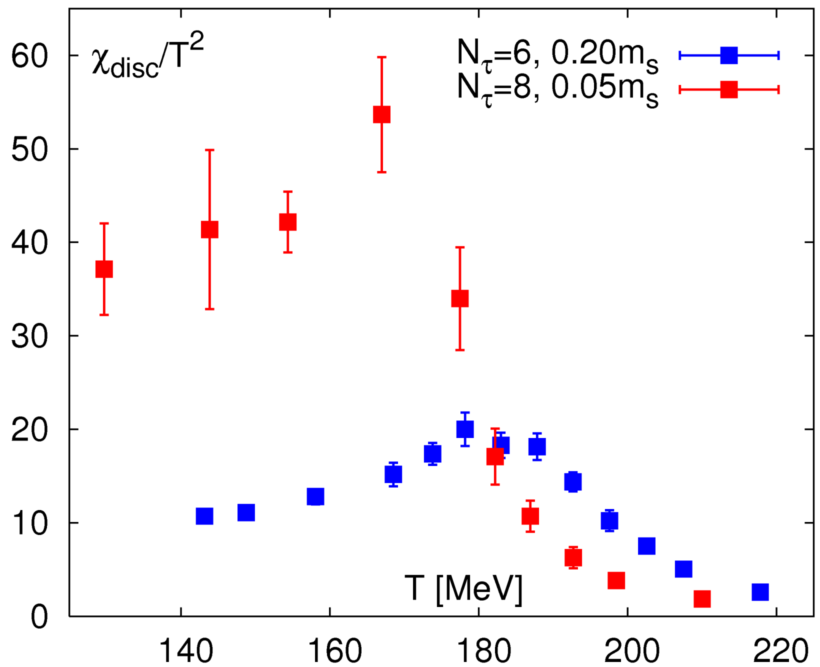


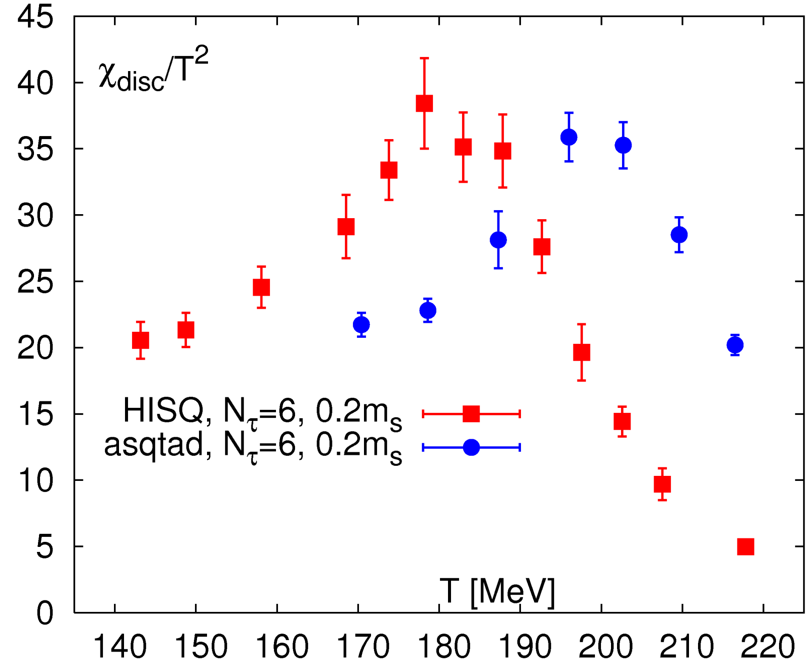


- The transition region defined by the rapid change in the chiral condensate is shifted to smaller temperature compared to asqtad and p4 action
- HISQ results on the $\Delta_{l,s}$ raw data agree with $N_\tau=10$ stout results if the scale is set by r_0
- HISQ calculations on $N_\tau=8$ agree resonably well with asqtad calculations on $N_\tau=12$

Disconnected chiral susceptibility

$$\chi_{disc} = N_\sigma^3 N_\tau (\langle (\bar{q}q)^2 \rangle - \langle \bar{q}q \rangle^2)$$





- The disconnected chiral susceptibility in HISQ calculations shows broad plateau at low temperatures due to Goldstone effect similar to the p4 action

  => difficult to extract T_c

- The transition region is shifted to smaller temperature compared to asqtad at the same lattice spacing

- finite lattice spacing effects act like finite mass effect

Summary and outlook

- The use of the HISQ action reduces discretization effects in the hadron spectrum, especially in the pseudo-scalar sector

- Thermodynamic quantities are enhanced in the low T region compared to calculations with p4 and asqtad action at the same lattice spacing, while consistent with the previous calculations in high temperature region => cutoff effects act like quark mass effect

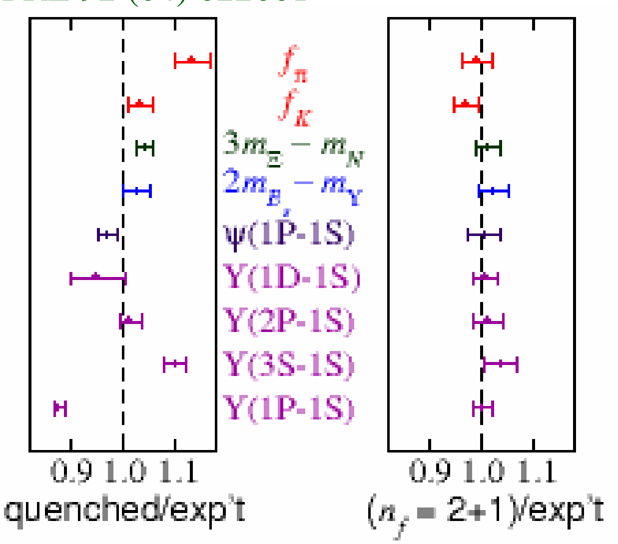
- A consistent picture emerges in the low T region : due to reduced flavor symmetry breaking calculations with HISQ action on $N_\tau=8$ lattices agree well with the raw stout results on L_{ren}, χ_s and subracted chiral condensate if r_0 is used to set the lattice spacing; There is also resonably good agreement with the $N_\tau=12$ asqtad calculations

- Future : detailed calculations of EoS, Taylor expansion coefficients, quark mass dependence of the transition and verification of the $O(N)$ scaling with HISQ action on $N_\tau=8$ and $N_\tau=12$ lattices

Back-up: Results from improved staggered calculations at *T=0*

a=0.125fm, 0.09fm, 0.06fm, chiral and continuum extrapolations

HPQCD, UKQCD, MILC and Fermilab,
PRL 92 (04) 022001



also N, Ω and ϕ masses

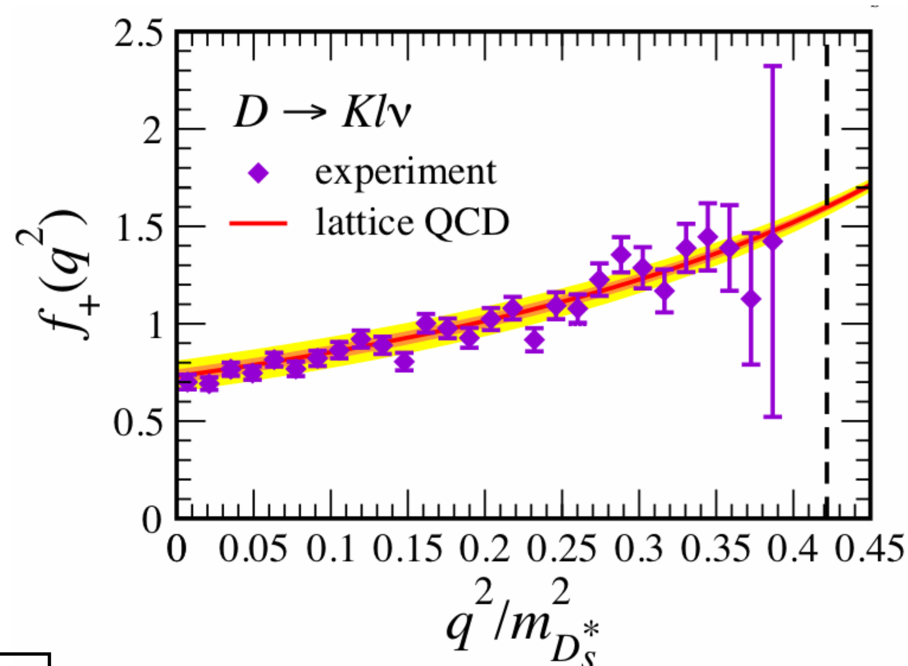
Bernard et al (MILC), PoSLAT2007 (07) 137;
Aoki et al, arXiv:0903.4155v1 [hep-lat]

To obtain these results it was necessary to implement :

1) $\mathcal{O}(a^2)$ improvement of quark dispersion relation

2) reduce the flavor symmetry breaking in the staggered fermion formulation

Fermilab, HPQCD, MILC
PRL 94 (05) 011601 (hep-ph/0408306)
Exp.: Belle, hep-ex/0510003



LQCD : $M_{B_c} = (6304 \pm 12 + 18)$MeV
Fermilab, HPQCD, UKQCD
PRL 94 (05) 172001 [hep-lat/0411027]
Exp: $M_{B_c} = (6285.7 \pm 5.3 \pm 1.2)$MeV
CDF, PRL 96 (06) 082002 [hep-exp/0505076]