Deconfinement and chiral transition in finite temperature lattice QCD

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Deconfinement and chiral symmetry restoration are expected to happen at some temperature

At what temperatures these transition(s) take place ?

Does the chiral and deconfinement transition happen at the same temperatures ?

Is there is an interplay between these too transitions?

How wide are these transitions if they are not true phase transitions ?

Goal : answer these questions using 1st principle LQCD with controlled discretization errors

Continuum limit : $a \to 0, \quad N_\tau \to \infty \quad a = 1/(TN_\tau)$ Computational costs: $\sim a^{-8}, \quad \sim N_\tau^8$

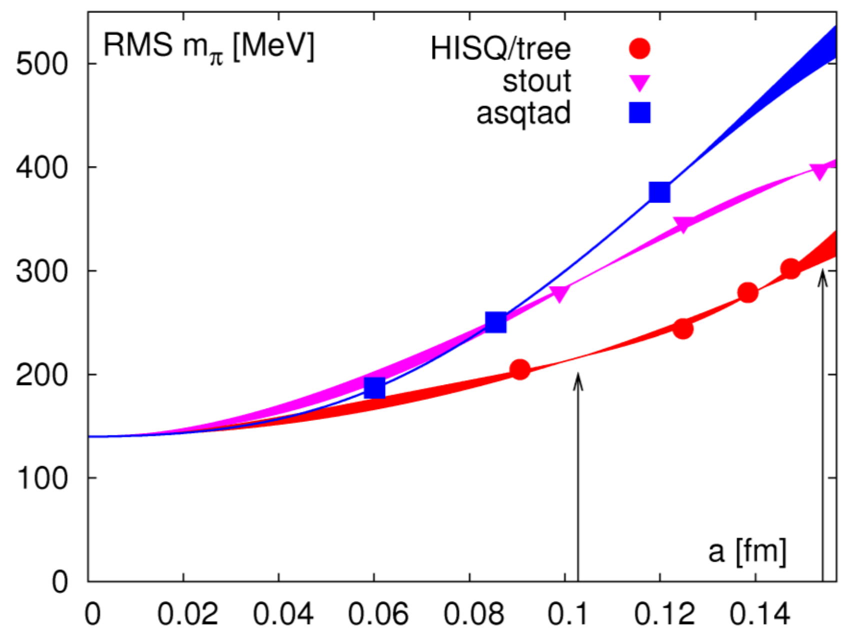
reduce discretization effects by using improved action => Highly Improved Staggered Quark (HISQ) action

Bazavov and P.P., arXiv:1005.1131, arXiv:1009.4914, arXiv:1012.1257,

Improved staggered fermion actions

Calculations with Highly Improved Staggered Quark (HISQ) action using N_τ=6, 8 and 12 lattices for, $m_l=m_s/20 \Rightarrow m_\pi \approx 160$ MeV + tree level improved gauge action => HISQ/tree

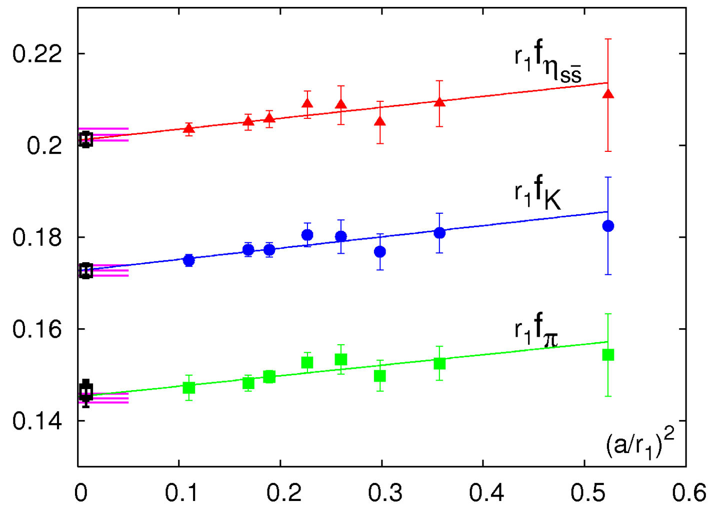
HISQ/tree action removes a^2 discretization effects as well as suppresses lattice artifact related to breaking of the flavor symmetry of the staggered fermions causing non-degenerate pion spectrum.

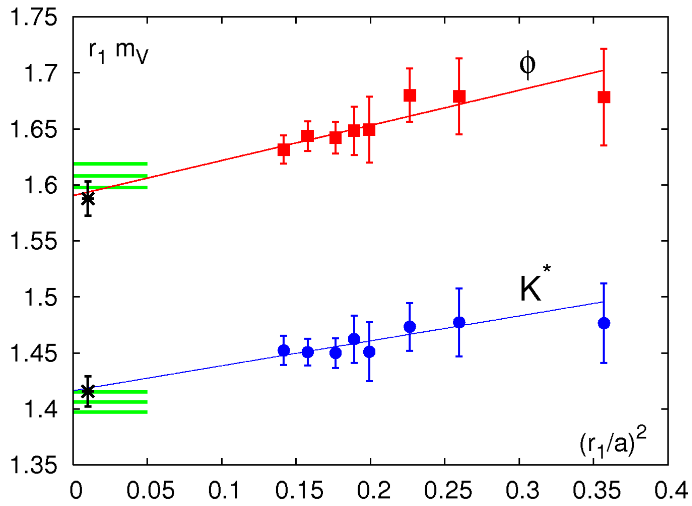


calculation with asqtad : N_τ=6, 8 and 12, $m_\pi \approx 160$ MeV

lattice spacing from r_1=0.3106(20) fm

$$\left(\frac{dV_{q\bar{q}}(r)}{dr}\right)_{r=r_1} = 1.0$$

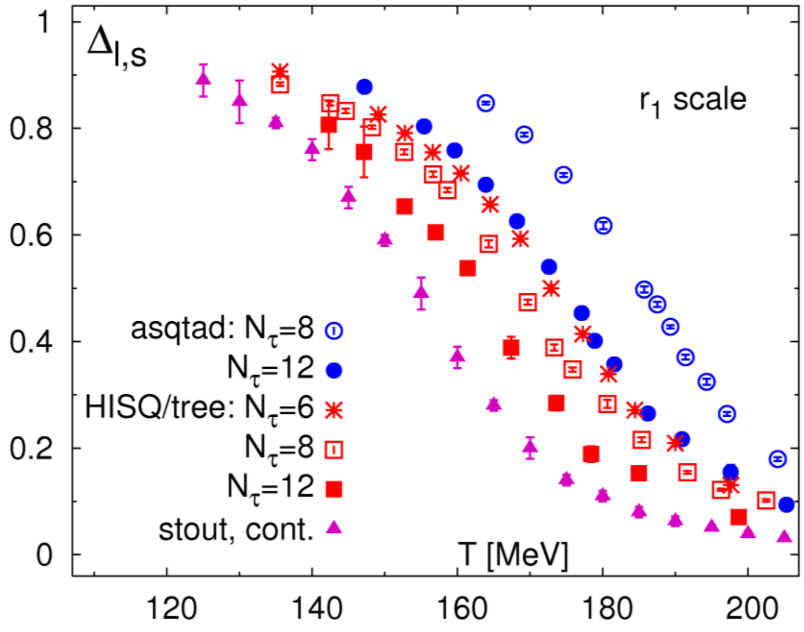


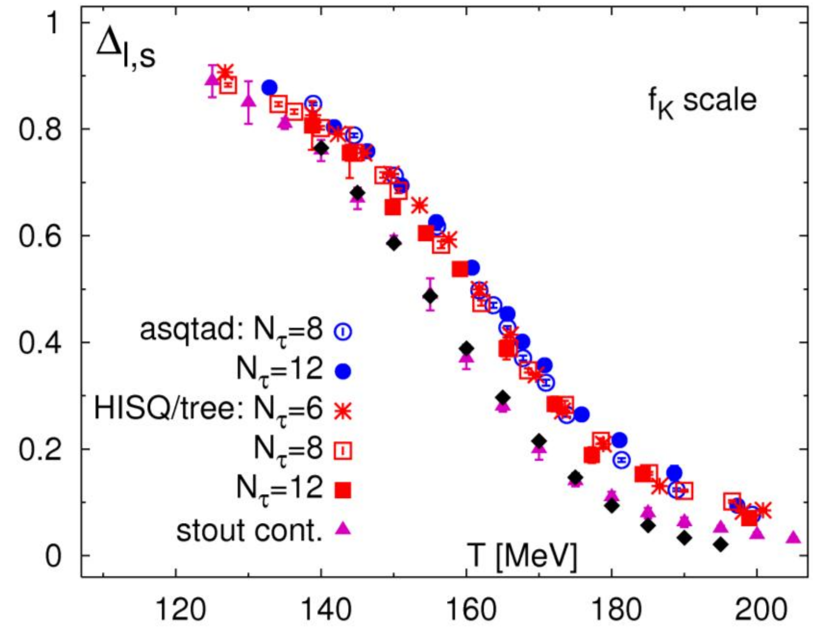


The temperature dependence of chiral condensate

Chiral condensate needs multiplicative and additive renormalization for non-zero quark mass

$$\langle\bar{\psi}\psi\rangle_l \Rightarrow \Delta_{s,l}(T) = \frac{\langle\bar{\psi}\psi\rangle_{l,T} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,T}}{\langle\bar{\psi}\psi\rangle_{l,T=0} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,T=0}}$$





- Cut-off effects are significantly reduced when f_K is used to set the scale

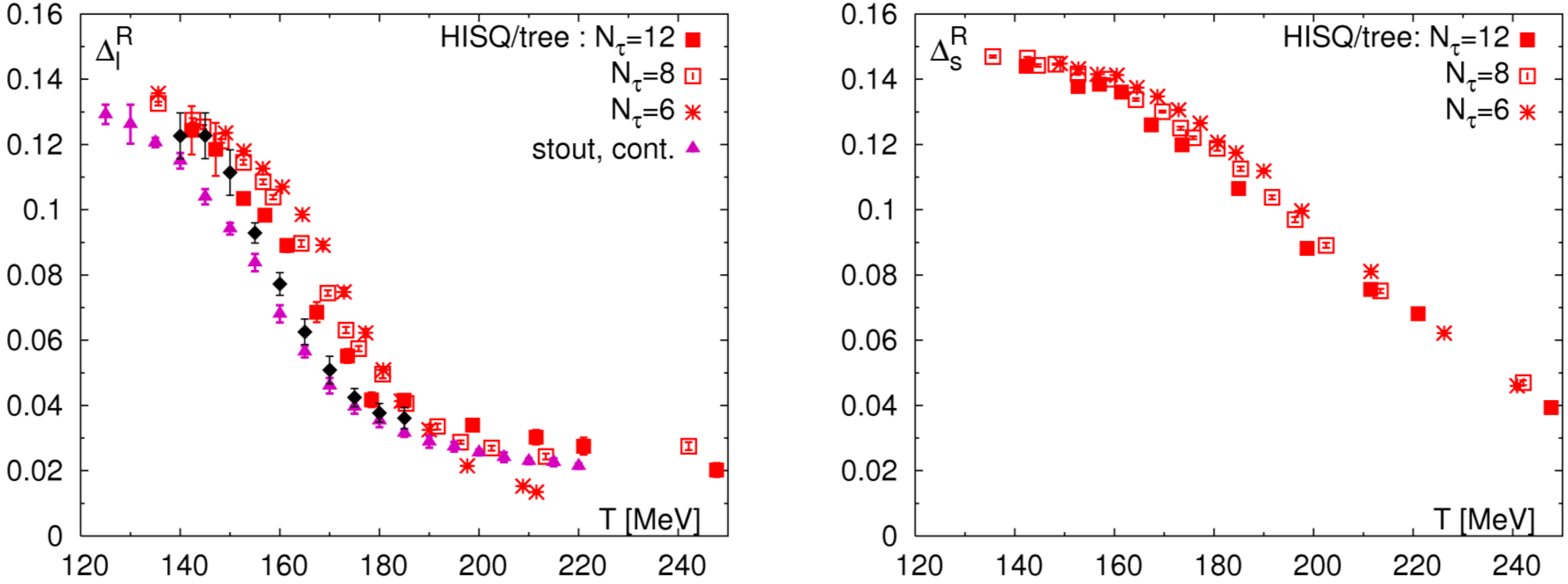
- After quark mass interpolation based on *O(N)* scaling the HISQ/tree results agree with the stout continuum result !

The temperature dependence of chiral condensate (cont'd)

Renormalized chiral condensate introduced by Budapest-Wuppertal collaboration

$$\langle\bar{\psi}\psi\rangle_q \Rightarrow \Delta_q^R(T) = m_s r_0^4 \left(\langle\bar{\psi}\psi\rangle_{q,T} - \langle\bar{\psi}\psi\rangle_{q,T=0}\right) + d, \quad q = l, s$$

with our choice *d=0.15:*



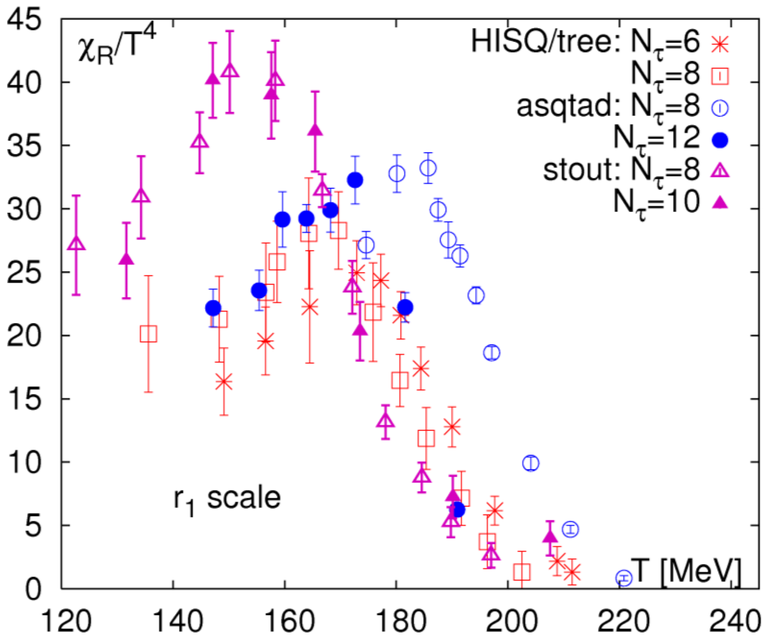
• after extrapolation to the continuum limit and physical quark mass HISQ/tree calculation agree with stout results !

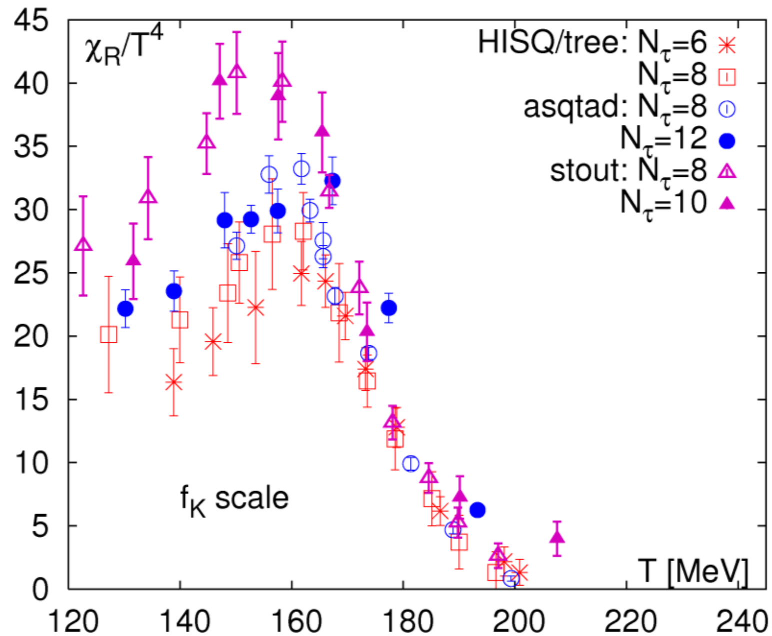
• strange quark condensate does not show a rapid change at the chiral crossover => strange quark do not play a role in the chiral transition

The temperature dependence of chiral susceptibility

The renormalized 2 light flavor chiral susceptibility:

$$\chi_R(T) = \frac{m_l^2}{T^4}\left(\chi_{m,l}^{(n_f=2)}(T) - \chi_{m,l}^{(n_f=2)}(T=0)\right) \qquad \chi_{m,l}^{(n_f=2)} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m_l^2}$$





- Cut-off effects are significantly reduced when f_K is used to set the scale

- Differences in the peak region and at low temperatures between HISQ/tree and stout results (Aoki et al, arXiv:hep-lat/0609068v2) are due to difference in the quark mass

O(N) scaling and the chiral transition temperature

For sufficiently small m_l and in the vicinity of the transition temperature:

$$f(T,m_l) = -\frac{T}{V}\ln Z = f_{reg}(T,m_l)+f_s(t,h),\ t=\frac{1}{t_0}\left(\frac{T-T_c^0}{T_c^0}+\kappa\frac{\mu_q^2}{T^2}\right),\ H=\frac{m_l}{m_s}, h=\frac{H}{h_0}$$

governed by universal *O(4)* scaling $\quad M = -\frac{\partial f_s(t,h)}{\partial H} = h^{1/\delta} f_G(z),\ \ z=t/h^{1/\beta\delta}$

T_c^0 is critical temperature in the mass-less limit, h_0 and t_0 are scale parameters

Pseudo-critical temperatures for non-zero quark mass are defined as peaks in the response functions (susceptibilities) :

$$\chi_{m,l} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m_l^2} \sim m_l^{1/\delta-1} \qquad \chi_{t,l} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial m_l \partial t} \sim m_l^{\frac{\beta-1}{\beta\delta}} \qquad \chi_{t,t} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial t^2} \sim |t|^{-\alpha}$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$T_{m,l} \quad = \quad T_{t,l} \quad = \quad T_{t,t} \quad = \quad T_c^0$$

in the zero quark mass limit

$$\frac{\chi_{l,m}}{T^2} = \frac{T^2}{m_s^2}\left(\frac{1}{h_0}h^{1/\delta-1} f_\chi(z) + reg.\right)$$

universal scaling function has a peak at $z=z_p$

$$T_c(H) = T_{m,l} = T_c^0 + T_c^0\frac{z_p}{z_0}H^{1/(\beta\delta)} + \ldots$$

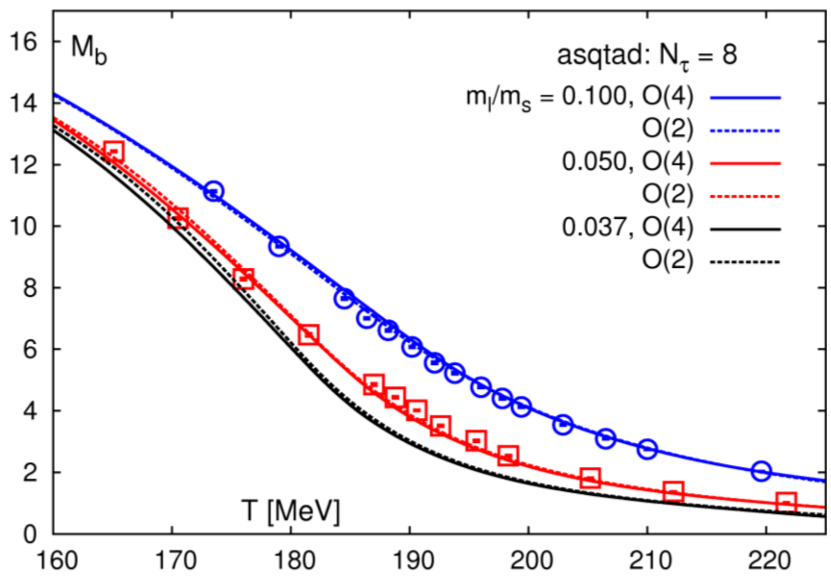
Caveat : staggered fermions O(2)
$m_l \to 0,\ a > 0,$
proper limit $a \to 0$, before $m_l \to 0$

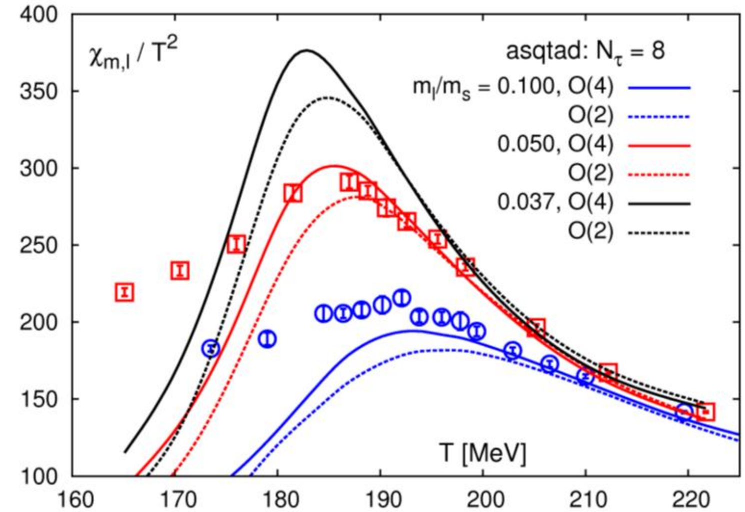
O(N) scaling and the lattice results : asqtad action

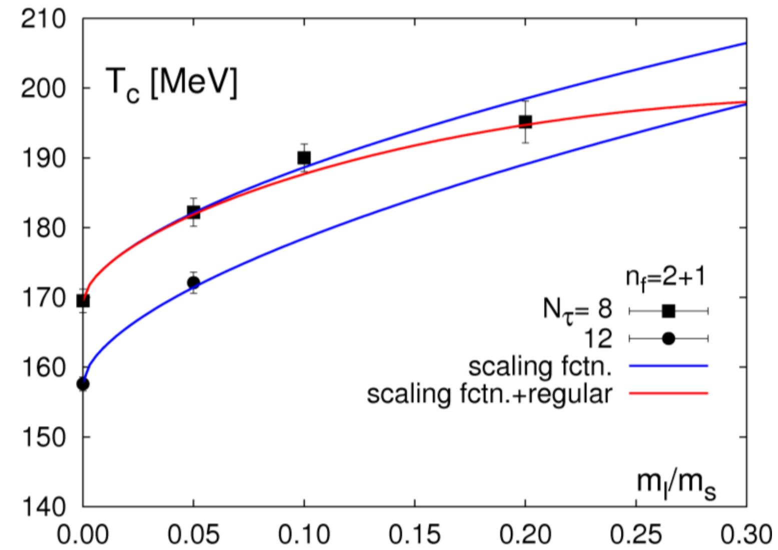
The notion of the transition temperature is only useful if it can be related to the critical temperature in the chiral limit : fit the lattice data on the chiral condensate with scaling form + simple Ansatz for the regular part

$$f_{reg}(T,H) = (a_t(T - T_c^0) + b_1)H$$

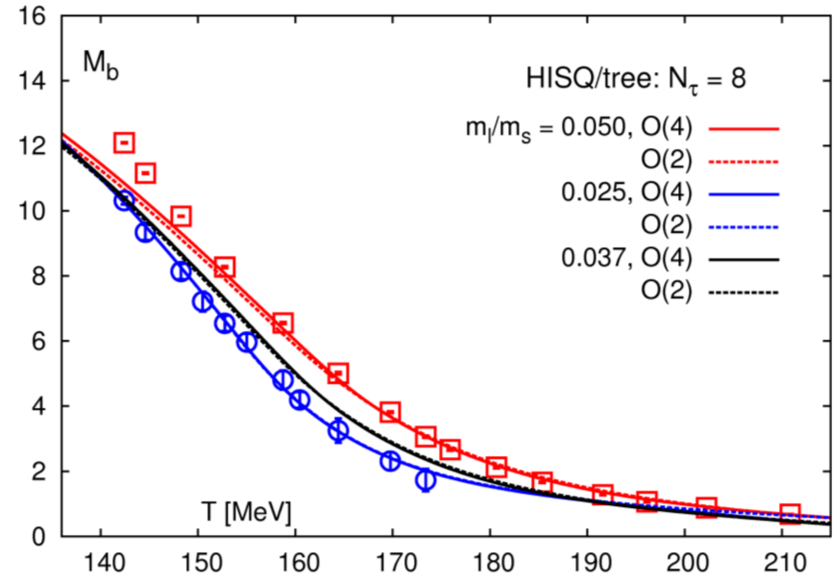
5 parameter fit : T_c^0, t_0, h_0, a_t, b_1

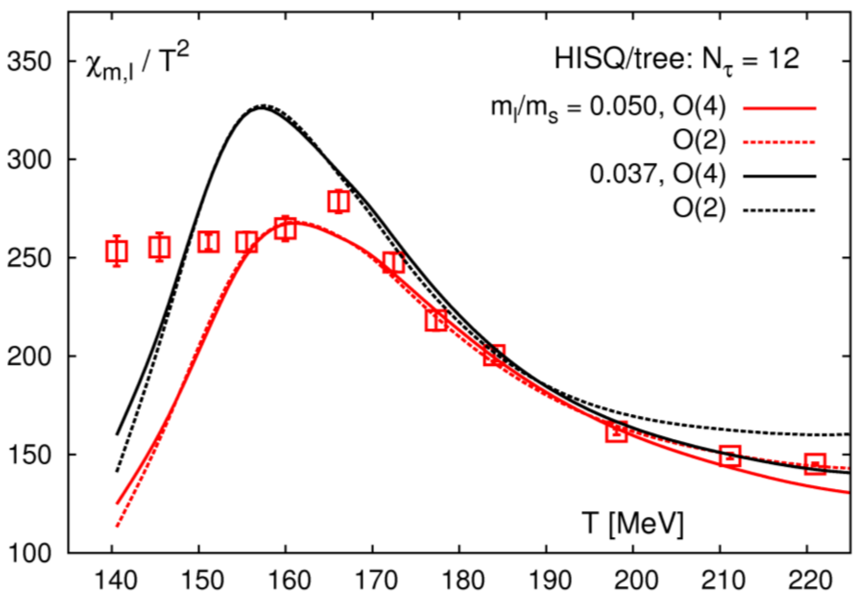






O(N) scaling and the lattice results : HISQ/tree action

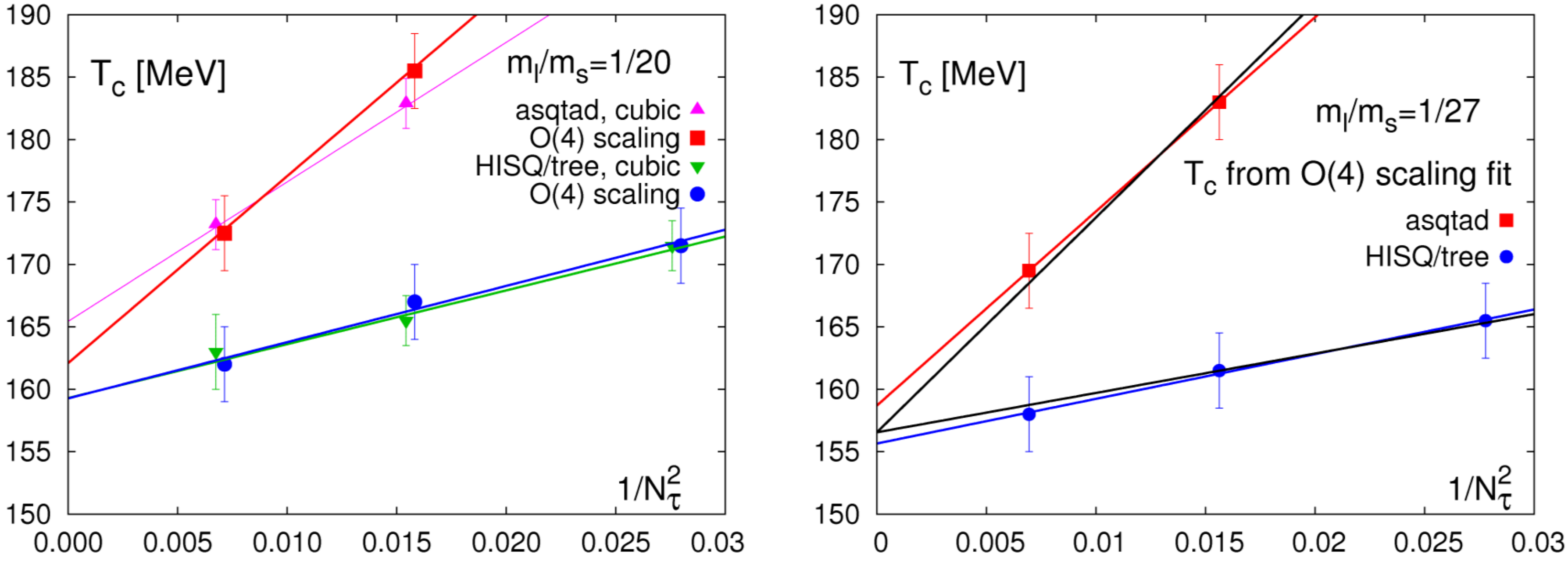




the analysis uses preliminary RBC-Bielefeld data at $m_l = m_s/40$ for $N_\tau = 6$ and 8 lattices

The chiral transition temperature in the continuum limit

Separate and joint $1/N_\tau^2$ extrapolations for asqtad and HISQ/tree have been performed



$$T_c = (157 \pm 4(stat) \pm 3(ext) \pm 1(scale))\text{MeV}$$

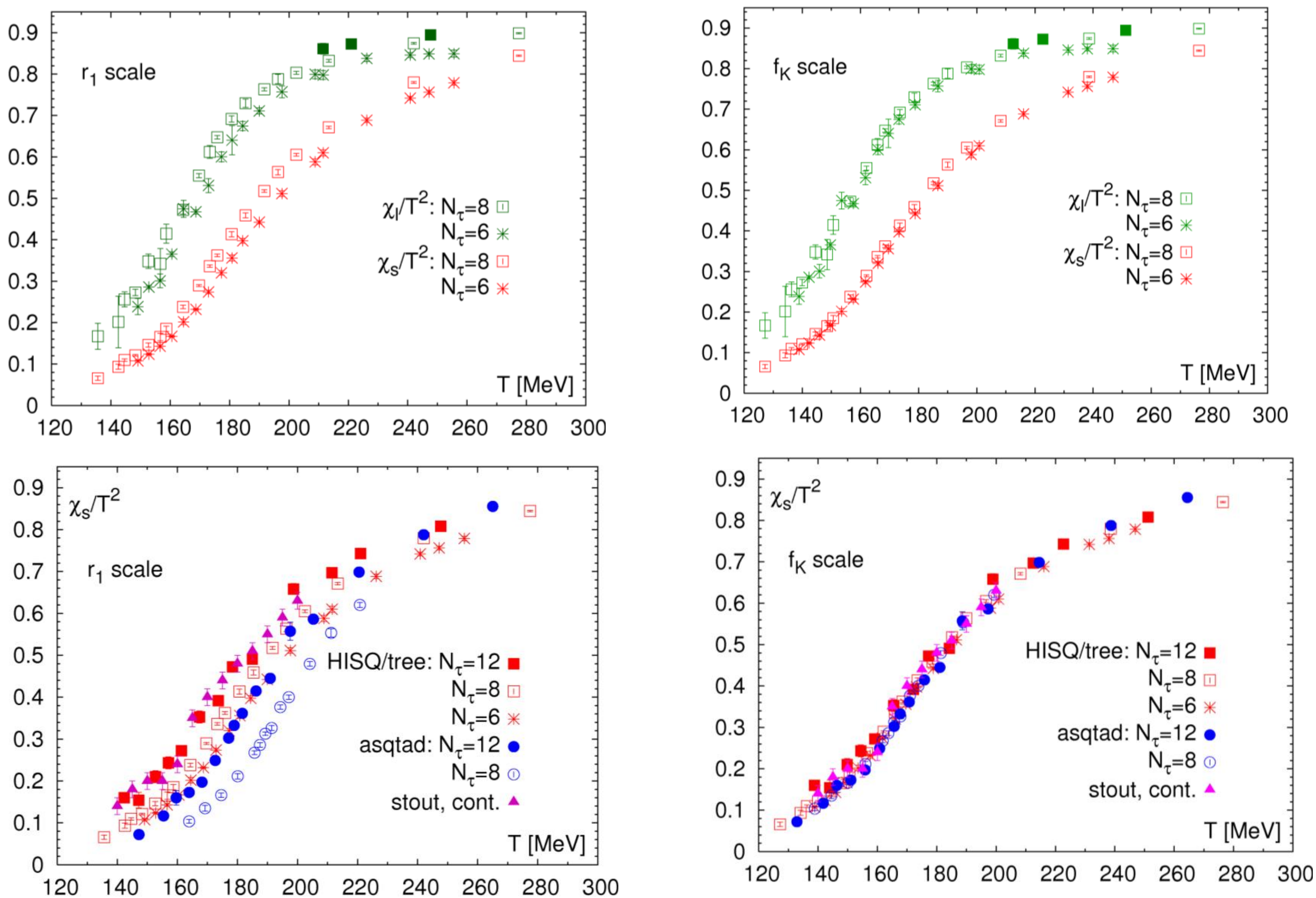
the error budget includes difference between asqtad and HISQ/tree, *O(2)* vs. *O(4)*, possible a^4 corrections

in good agreement with the values obtained with stout action from chiral observables: T_c=147(2)(3)MeV, 157(3)(3)MeV, 155(3)(3)MeV, Borsányi et al, arXiv:1005.3508

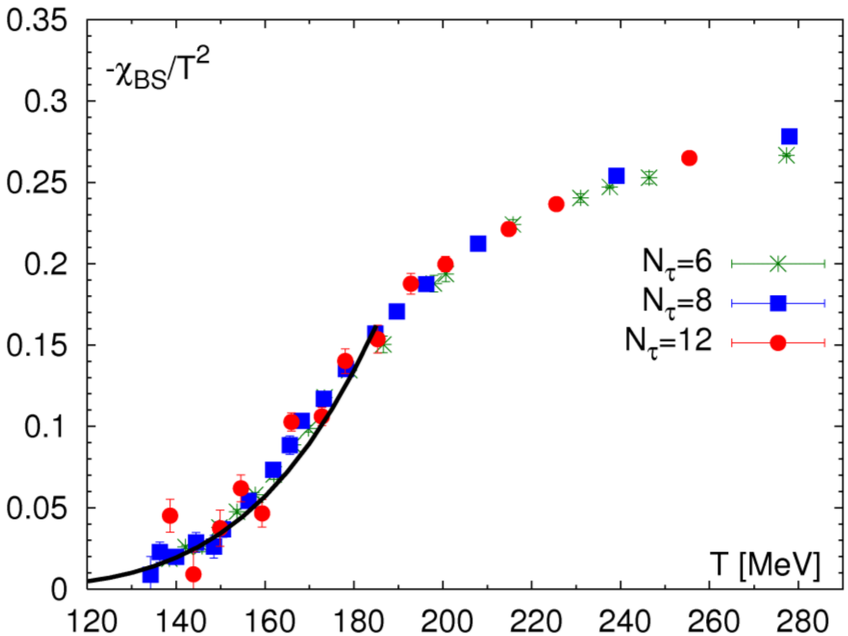
RBC-Bielefeld result $T_c=192(7)(4)$MeV (Cheng et al, arXiv:hep-lat/0608013) is overestimated due to large a^4 corrections that have been neglected in the extrapolations

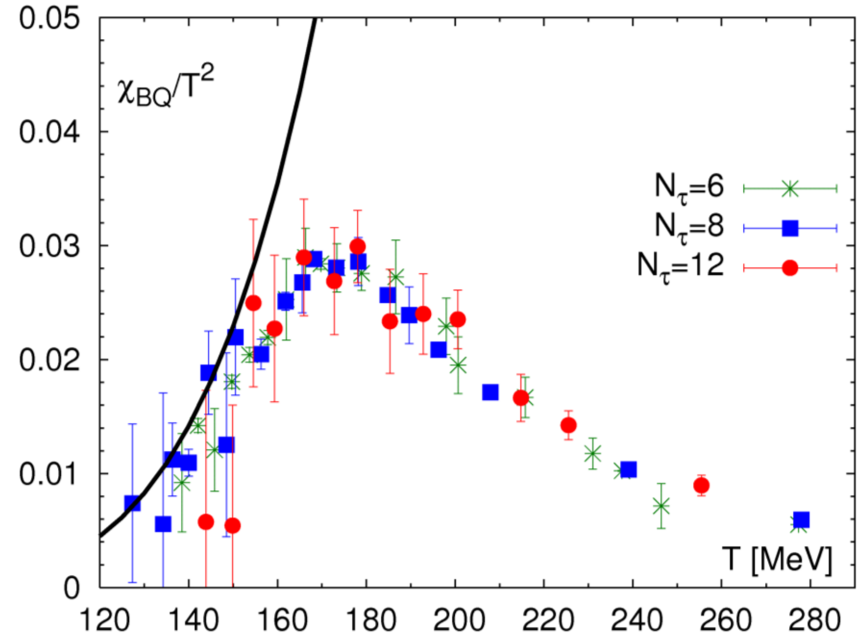
Quark number susceptibility and deconfinement

$$\chi_q(T) = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_q^2}, q = l, s \qquad t = \frac{1}{t_0}\left(\frac{T - T_c}{T_c} + \kappa\left(\frac{\mu_q}{T}\right)^2\right), \ \frac{\chi_q}{T^2} \sim A_\pm |t|^{1-\alpha} + reg.$$



Correlation of conserved charges and deconfinement





- At low temperatures correlations are well described by hadron resonance gas (HRG)

- At high *T (>280* MeV) strangeness is carried by s-quarks => strangeness-baryon number correlation approaches -1/3

- All quarks (u,d and s) contribute to baryon-electric charge correlations at high *T (>280*MeV*)* but the net charge is zero => $\chi_{BQ}=0$

- What are the carriers the quantum numbers for *190* MeV < *T* < *280* MeV

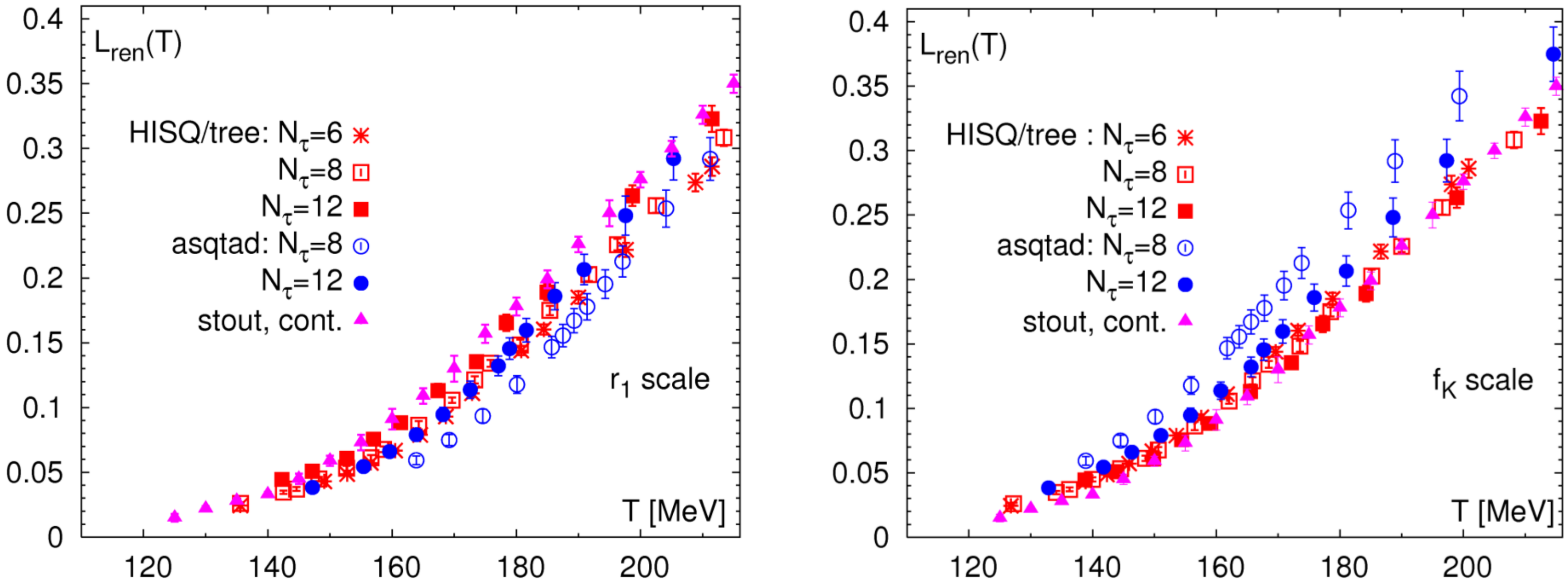
Polyakov loop and deconfinement

The Polyakov loop describes screening properties of the medium but is not related to critical behaviour in the chiral limit

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

$F_Q(T) \simeq \Lambda_{QCD}$ low T

$F_Q(T) \simeq -C_F \alpha_s m_D$ high T



cutoff effects are smaller for HISQ/tree than for asqtad and further reduced when f_K is use to set the scale for HISQ/tree (but not asqtad)

and agree with stout continuum result Borsányi et al, arXiv:1005.3508

Lattice results on the trace of energy momentum tensor

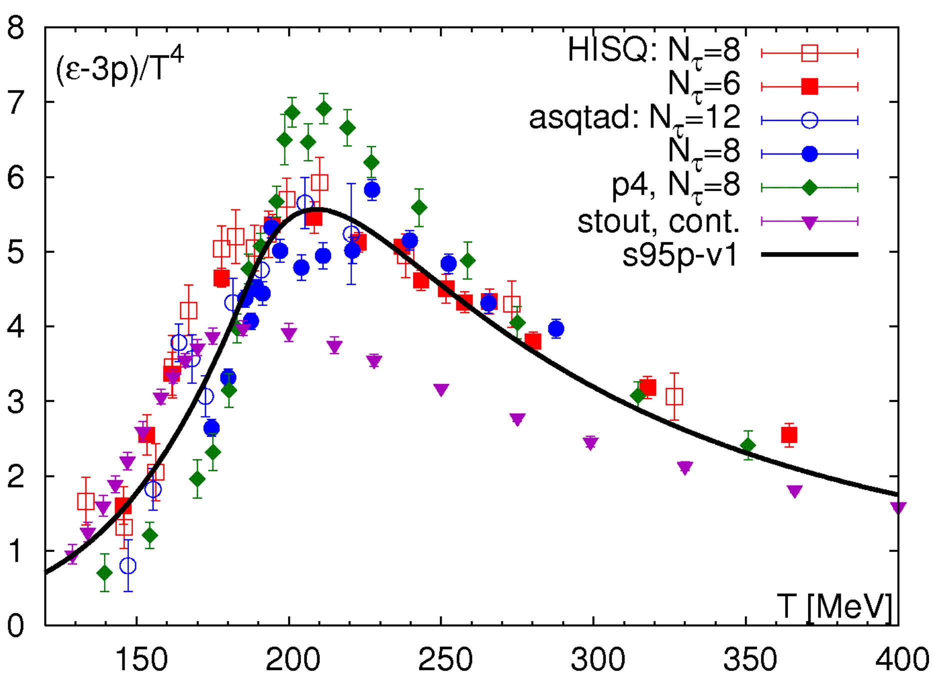
EoS is calculated from the trace anomaly $\Theta^{\mu\mu}(T) = \epsilon - 3p$ (integral method)

$$\frac{p(T)}{T^4} - \frac{p(T_0)}{T_0^4} = \int_{T_0}^{T} dT' \frac{\Theta^{\mu\mu}(T')}{T'^5},$$

For weakly interacting quarks and gluons:

$$\epsilon - 3p \sim \alpha_s^2(T) T^4 \ll T^4$$

Bazavov, P.P., arXiv:1005.1131
Bazavov, P.P., arXiv:1012.1257



- HISQ results on the trace anomaly agree with previous HotQCD results for *T>250* MeV
- A better agreement is achieved with HRG in the low *T* region with the HISQ action
- The HISQ results are compatible with asqtad calculations in the peak region
- HISQ results agree quite well with s95p-v1 parametrization of EoS that is based on HRG+LQCD and used in hydro models

Huovinen, P.P., NPA 837 (10) 26

Summary

• Lattice calculations with HISQ/tree action largely reduce cutoff effects in thermodynamic quantities and make possible to get close to the continuum limit with currently available computational resources.

• The chiral transition can be described in terms of universal *O(N)* scaling as scaling violations are small

• The chiral transition defined through the chiral susceptibility is

$$T_c = (157 \pm 4(stat) \pm 3(ext) \pm 1(scale))\text{MeV}$$

• It is necessary to define the pseudo-critical temperature in terms mixed susceptibility and specific heat to establish the width of the chiral crossover

• Possible problems with T_c determination are due to lack of full chiral symmetry, e.g. *O(2)* vs. *O(4)* scaling, calculations chiral (e.g. DWF) will be necessary to crosscheck the above result.

• Deconfinement appears to be a rather smooth process with no well defined transition temperature. Depending on the observable it may happen at the chiral transition temperature or at higher temperatures