QCD at high temperatures

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Because of finite size of hadrons hadronic matter cannot exist at high *T*

I. Ya. Pomeranchuk, Doklady Akad. Nauk. SSSR 78 (1951) 889

Do we have phase transition in QCD at high temperatures ?
What is the nature of the deconfined matter ?
What are the implications for the phenomenology of heavy ion collisions ?

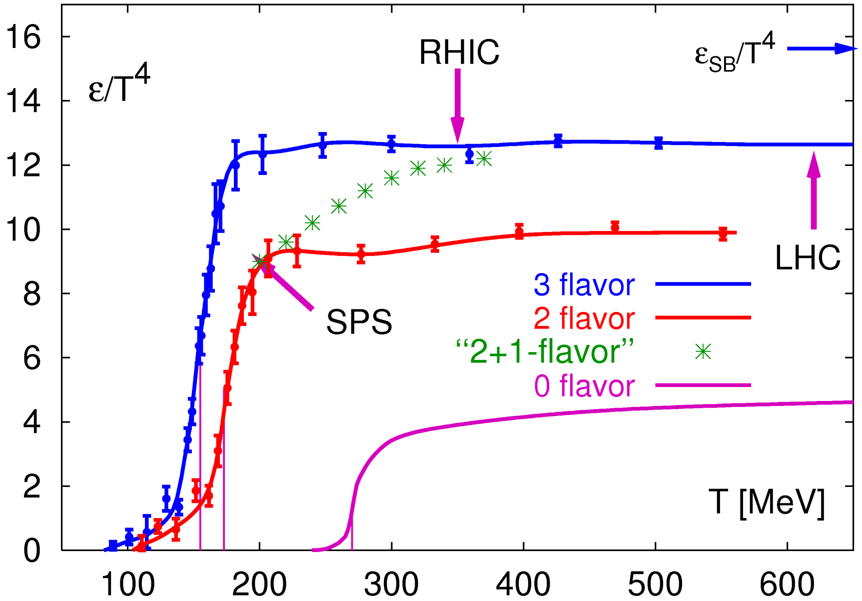
In this talk

- Chiral transition in QCD at *T>0*
- Color screening deconfinement
- Equation of state
- Fluctuations of conserved charges
- Quarkonium spectral functions at *T>0*

6th International Workshop on High Energy Physics in the LHC Era. January 6-12, Valparaiso, 2016

Lattice QCD at T>0 now and then

Lattice QCD calculations at T>0 around 2002:



$T_c \simeq 173\text{MeV}$

for both chiral transition and deconfinement transition
(in terms of Polyakov loop)

Problems:

$N_\tau = 4 : a \equiv 1/(N_\tau a) = 1/(4T)$

$m_\pi = (500 - 800)\text{MeV}$

Continuum limit and physical masses are needed

$N_\tau \to \infty$

$m_\pi = 140\text{MeV}$

$costs \sim N_\tau^{11}$

$\sim 1/m_\pi^3$

This task can be accomplished using improved staggered fermions actions:
Highly Improved Staggered Quark (HISQ) or Stout action
Some calculations are performed using chiral (Domain Wall) fermions

Fluctuations of conserved charges: new look into deconfinement and QGP properties

The temperature dependence of chiral condensate

Renormalized chiral condensate introduced by Budapest-Wuppertal collaboration

$$\langle\bar{\psi}\psi\rangle_q \Rightarrow \Delta_q^R(T) = m_s r_1^4 \left(\langle\bar{\psi}\psi\rangle_{q,T} - \langle\bar{\psi}\psi\rangle_{q,T=0}\right) + d, \quad q = l, s$$

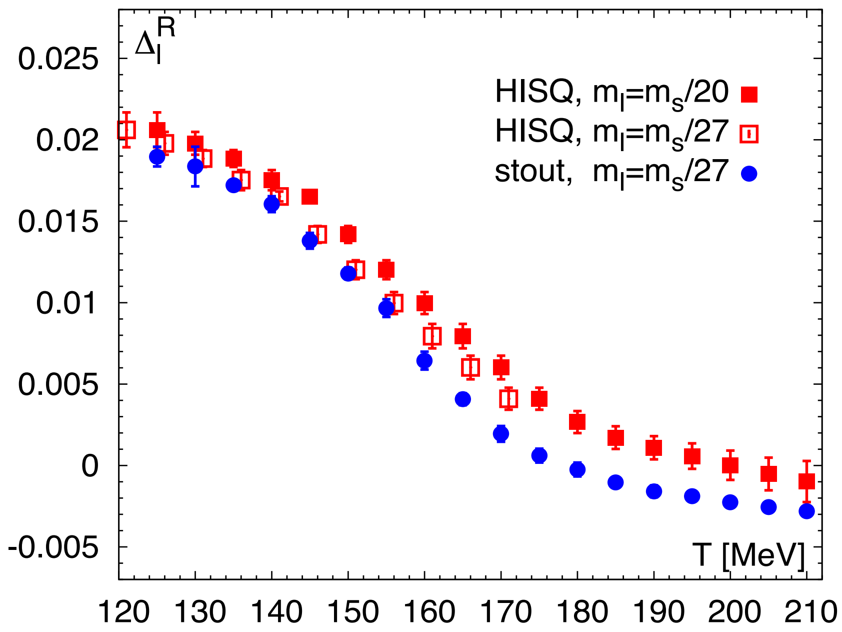
With choice : $d = \langle\bar{\psi}\psi\rangle^{T=0}_{m_q=0}$

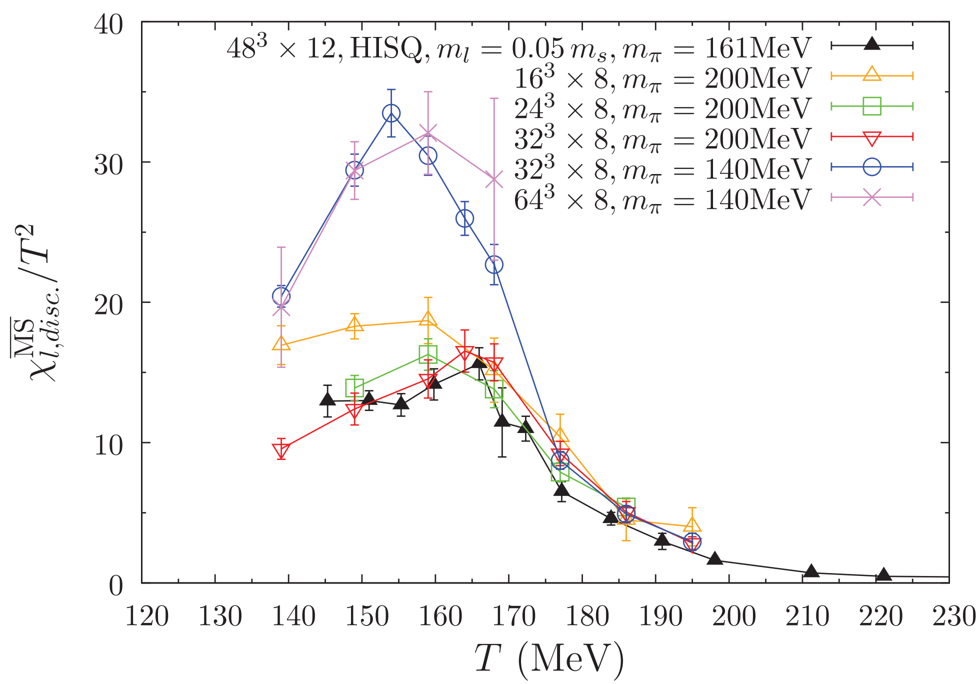
Bazavov et al (HotQCD), Phys. Rev. D85 (2012) 054503;
Bazavov et al, PRD 87(2013)094505,
Borsányi et al, JHEP 1009 (2010) 073

Calculations with chiral (Domain Wall) fermions:

$$\chi_{disc} = \frac{V}{T}\left\langle(\bar{\psi}\psi)^2\right\rangle - \left\langle\bar{\psi}\psi\right\rangle^2\Big)$$

Bhattacharya et al (HotQCD), PRL 113 (2014)082001





- O(4) scaling analysis and continuum limit:

$T_c = (154 \pm 8 \pm 1(scale))$MeV

$T_c = (155 \pm 8 \pm 1)$MeV

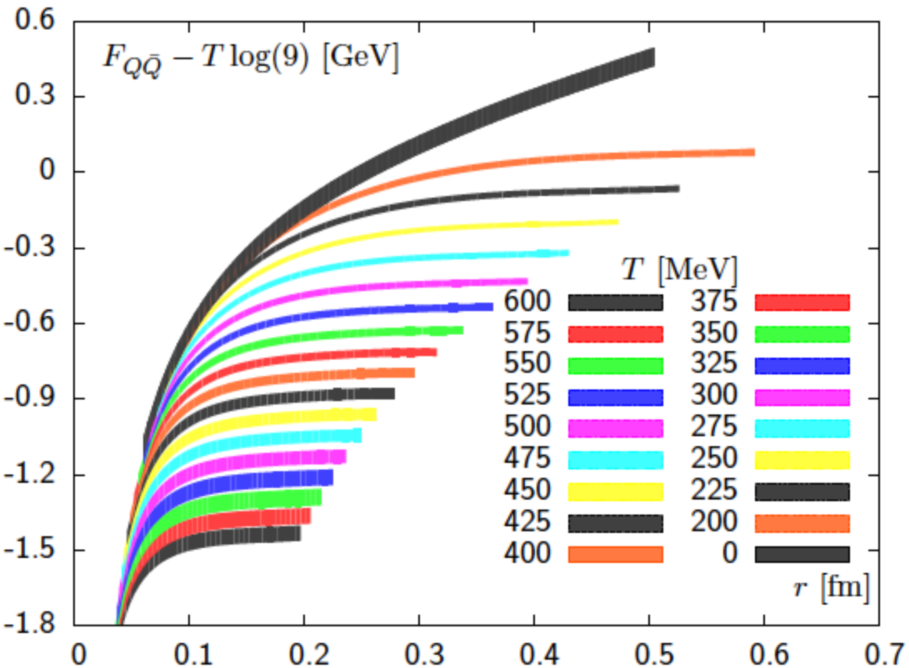
Deconfinement and color screening

Onset of color screening is described by Polyakov loop (order parameter in SU(N) gauge theory)

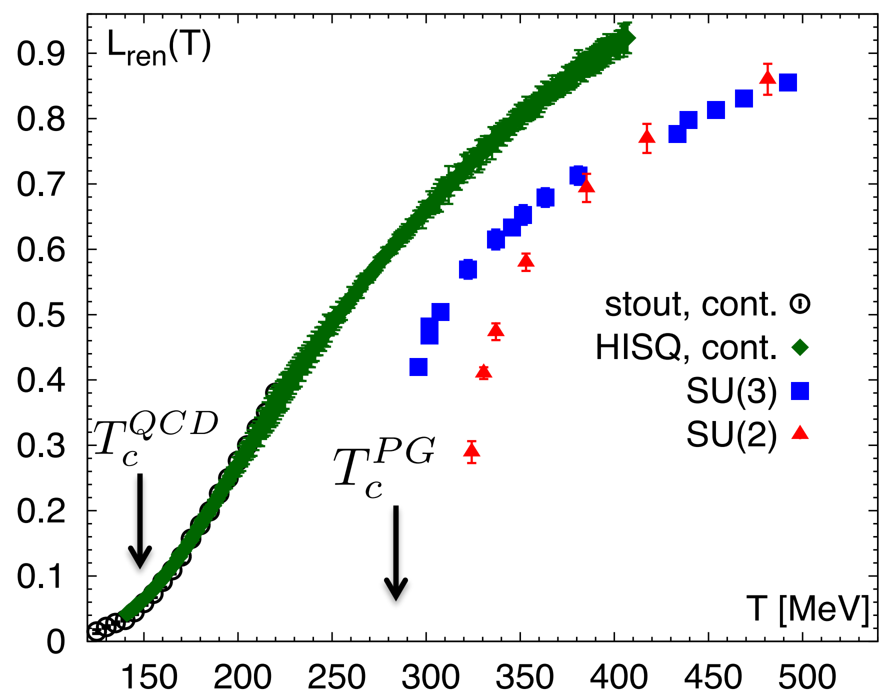
$$L = \mathrm{tr}\mathcal{P}e^{ig\int_0^{1/T} d\tau A_0(\tau,\vec{x})} \qquad \exp(-F_{Q\bar{Q}}(r,T)/T) = \frac{1}{9}\langle \mathrm{tr}L(r)\mathrm{tr}L^\dagger(0)\rangle$$

$$F_{Q\bar{Q}}(r\to\infty,T) = 2F_Q(T) \quad \Rightarrow \quad L_{ren} = \exp(-F_Q(T)/T)$$

2+1 flavor QCD, continuum extrapolated (work in progress with Bazavov, Weber …)



free energy of static quark anti-quark pair shows Debye screening at high temperatures



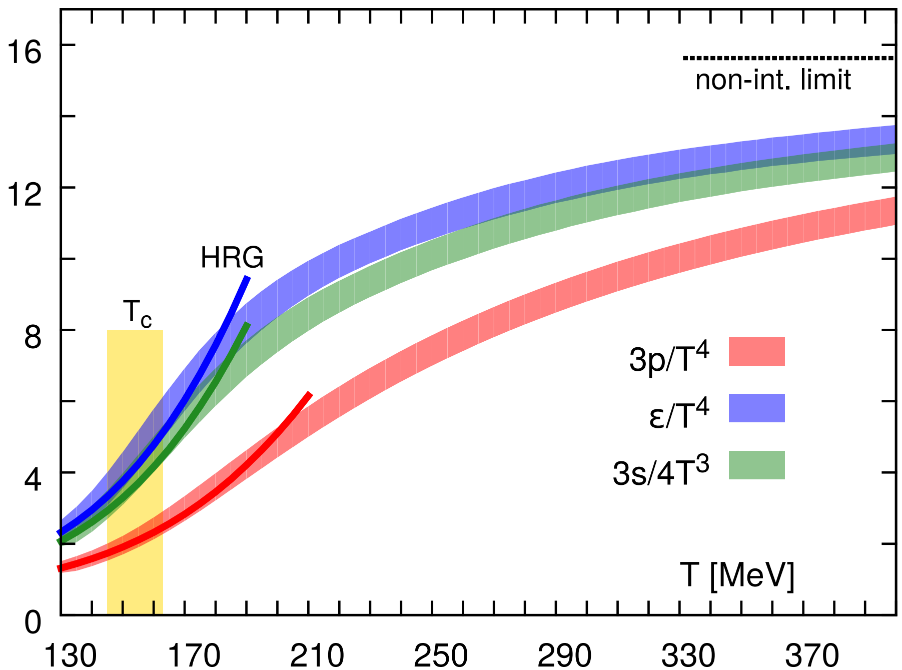
SU(N) gauge theory ≠ QCD !

Similar results with stout action Borsányi et al, JHEP04(2015) 138

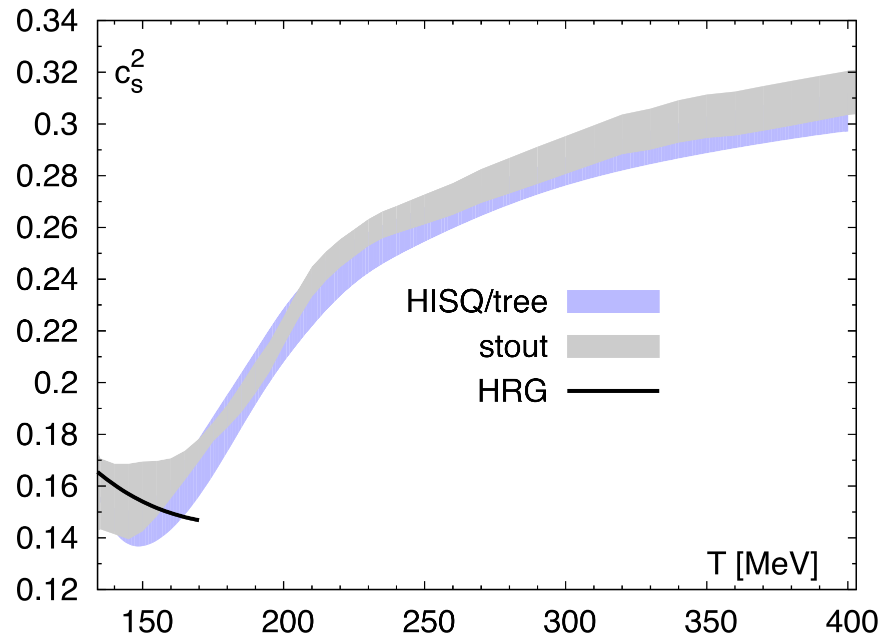
Equation of state in the continuum limit

Equation of state has be calculated in the continuum limit up to *T=400* MeV using two different quark actions and the results agree well

Bazavov et al (HotQCD), PRD 90 (2014) 094503



Borsányi et al, JHEP 1009 (2010) 073



Hadron resonance gas (HRG):
Interacting gas of hadrons = non-interacting gas of hadrons and hadron resonances
← virial expansion
Prakash,Venugopalan, NPA546 (1992) 718

HRG agrees with the lattice for *T< 155* MeV

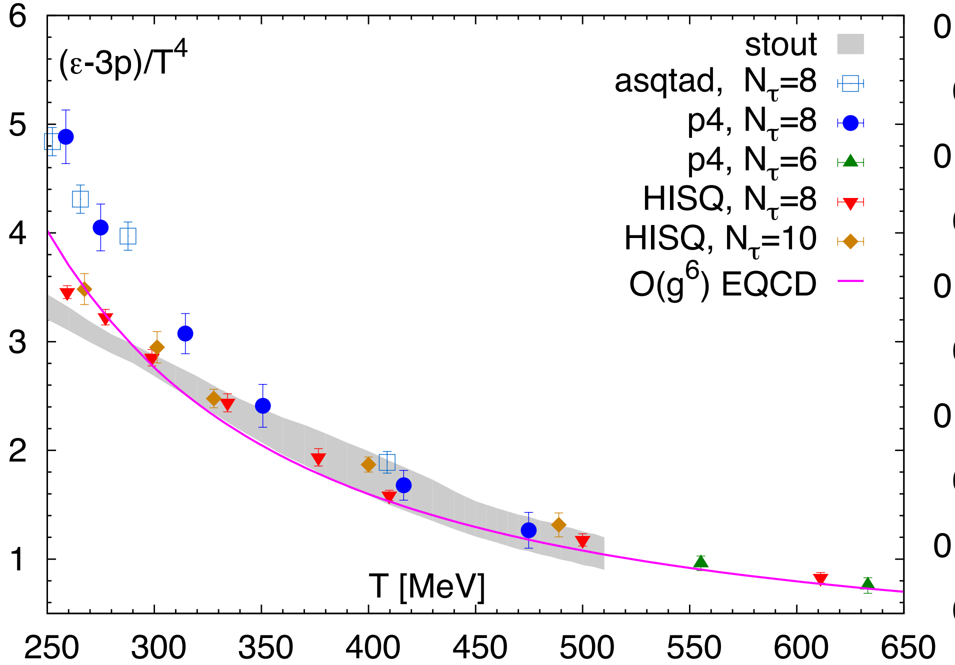
$$T_c = (154 \pm 9)\mathrm{MeV}$$

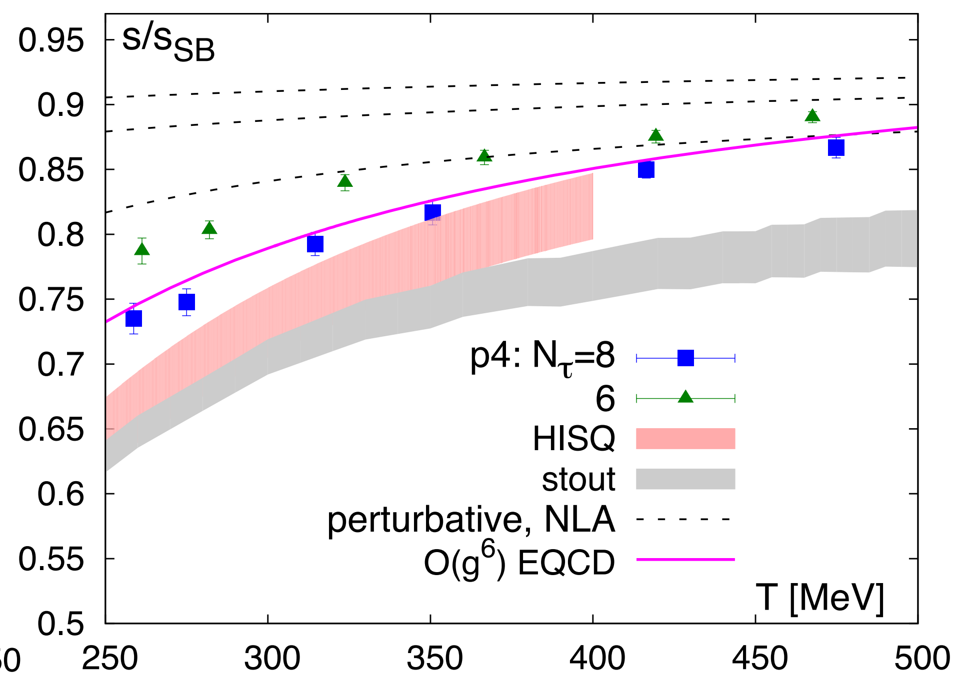
$$\epsilon_c \simeq 300\mathrm{MeV/fm^3}$$

$$\epsilon_{low} \simeq 180\mathrm{MeV/fm^3} \leftrightarrow \epsilon_{nucl} \simeq 150\mathrm{MeV/fm^3}$$

$$\epsilon_{high} \simeq 500\mathrm{MeV/fm^3} \leftrightarrow \epsilon_{proton} \simeq 450\mathrm{MeV/fm^3}$$

Equation of State on the lattice and in the weak coupling





The high temperature behavior of the trace anomaly is not inconsistent with weak coupling calculations (EQCD) for $T>300$ MeV

For the entropy density the continuum lattice results are below the weak coupling calculations For $T< 500$ MeV

At what temperature can one see good agreement between the lattice and the weak coupling results ?

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \cdot \left(\frac{\mu_B}{T}\right)^i \cdot \left(\frac{\mu_Q}{T}\right)^j \cdot \left(\frac{\mu_S}{T}\right)^k$$ hadronic

$$\frac{p(T,\mu_u,\mu_d,\mu_s)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{uds} \cdot \left(\frac{\mu_u}{T}\right)^i \cdot \left(\frac{\mu_d}{T}\right)^j \cdot \left(\frac{\mu_s}{T}\right)^k$$ quark

$$\chi_{ijk}^{abc} = T^{i+j+k} \frac{\partial^i}{\partial \mu_a^i} \frac{\partial^j}{\partial \mu_b^j} \frac{\partial^k}{\partial \mu_c^k} \frac{1}{VT^3} \ln Z(T,V,\mu_a,\mu_b,\mu_c)|_{\mu_a=\mu_b=\mu_c=0}$$

Taylor expansion coefficients give the fluctuations and correlations of conserved charges, e.g.

$$\chi_2^X = \chi_X = \frac{1}{VT^3}(\langle X^2\rangle - \langle X\rangle^2) \qquad \chi_{11}^{XY} = \frac{1}{VT^3}(\langle XY\rangle - \langle X\rangle\langle Y\rangle)$$

↓

information about carriers of the conserved charges (hadrons or quarks)

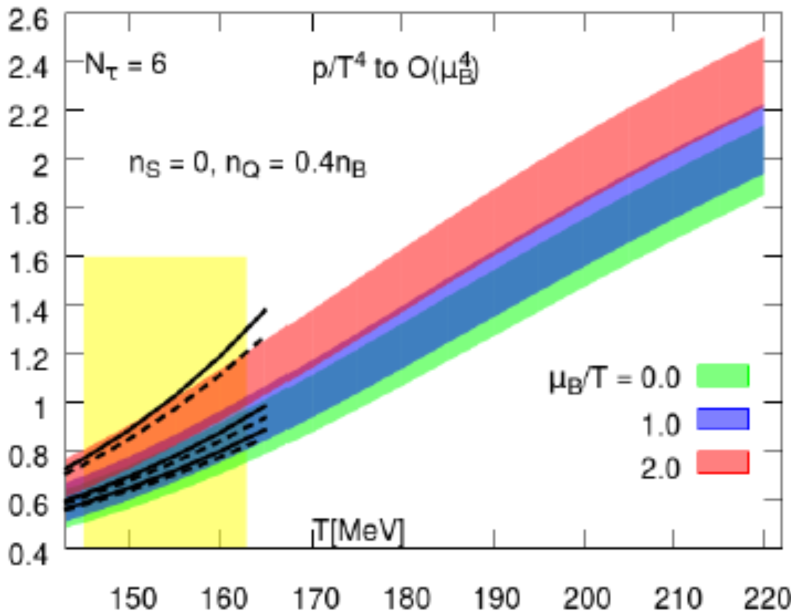
↓

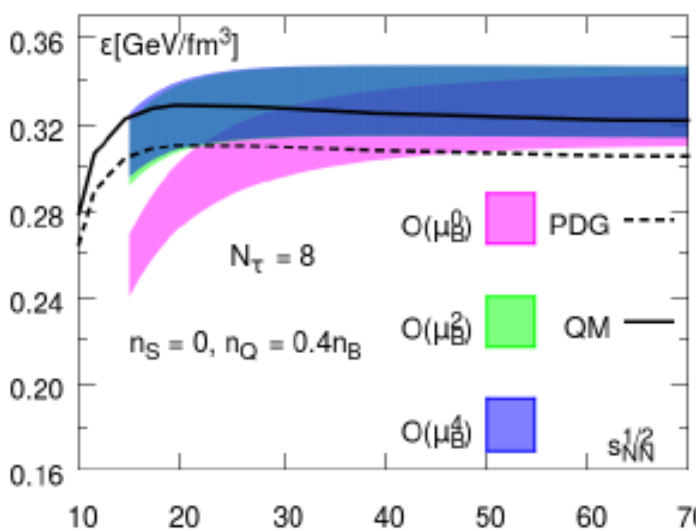
probes of deconfinement

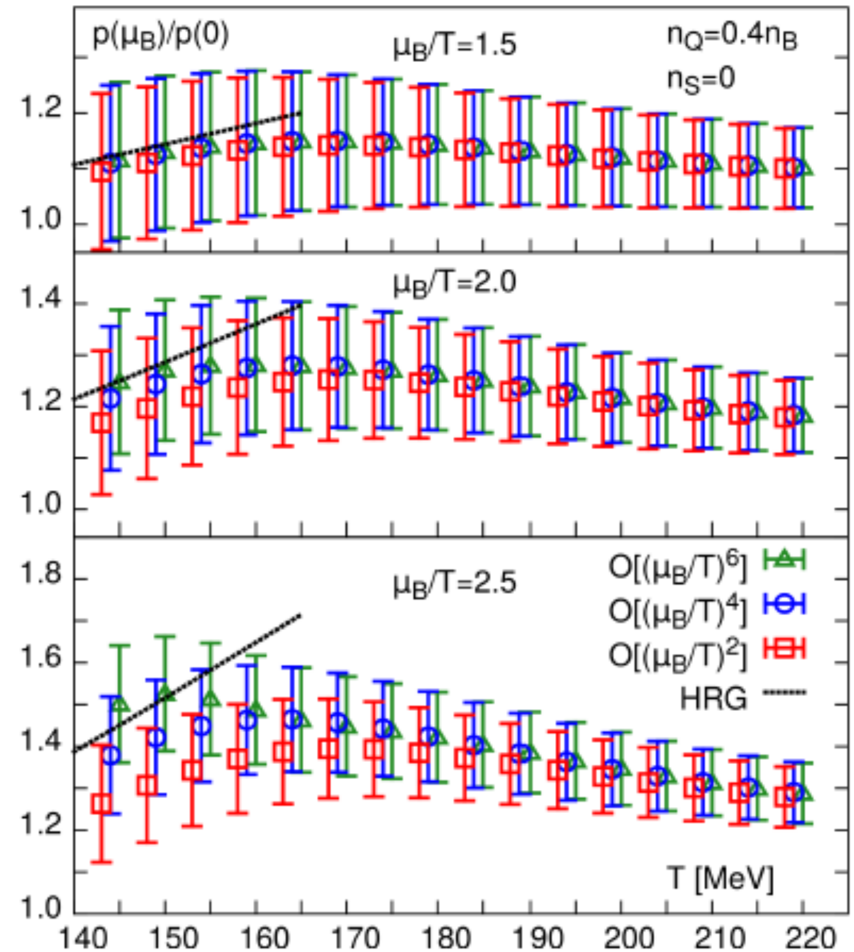
Equation of state at non-zero baryon density

Taylor expansion up to 4th order for net zero strangeness $n_S = 0$ and $r = n_Q/n_B = Z/A = 0.4$

BNL-Bielefeld-CCNU







Moderate effects due to non-zero baryon density up to $\mu_B/T = 2 \leftrightarrow \sqrt{s} \sim 20\text{GeV}$

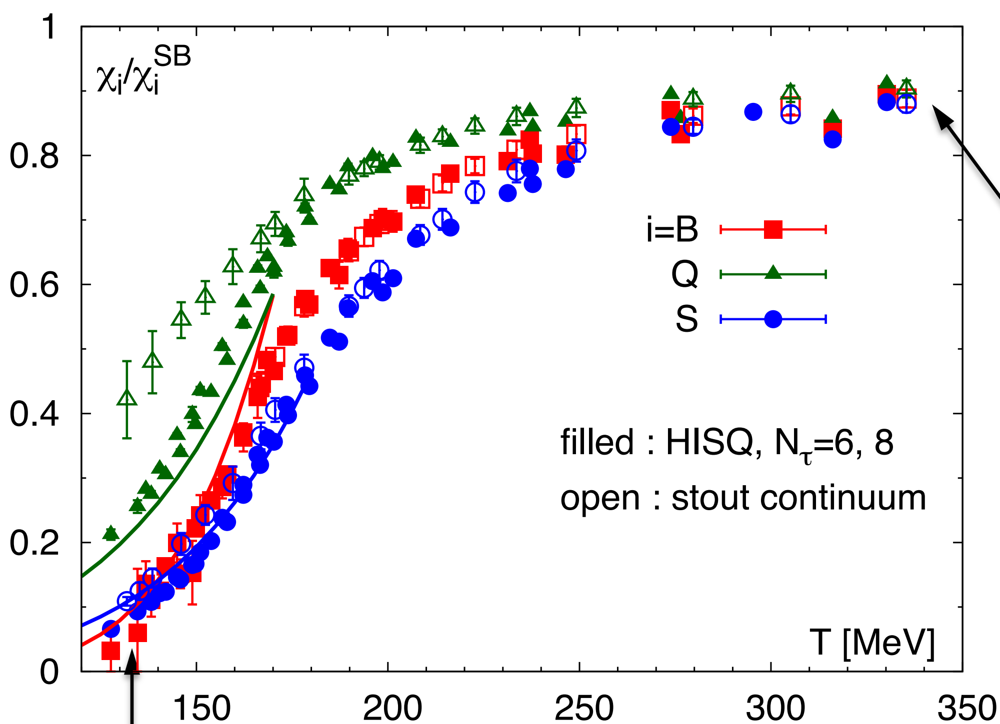
Energy density at freeze-out is independent of μ_B

Deconfinement : fluctuations of conserved charges

$$\chi_B = \frac{1}{VT^3}\left(\langle B^2\rangle - \langle B\rangle^2\right)$$ baryon number

$$\chi_Q = \frac{1}{VT^3}\left(\langle Q^2\rangle - \langle Q\rangle^2\right)$$ electric charge

$$\chi_S = \frac{1}{VT^3}\left(\langle S^2\rangle - \langle S\rangle^2\right)$$ strangeness



Ideal gas of massless quarks :

$$\chi_B^{SB} = \frac{1}{3} \qquad \chi_Q^{SB} = \frac{2}{3}$$

$$\chi_S^{SB} = 1$$

conserved charges carried by light quarks

conserved charges are carried by massive hadrons

Bazavov et al (HotQCD) PRD86 (2012) 034509
Borsányi et al, JHEP 1201 (2012) 138

Deconfinement of strangeness

Partial pressure of strange hadrons in uncorrelated hadron gas:

$$P_S = \frac{p(T) - p_{S=0}(T)}{T^4} = M(T)\cosh\left(\frac{\mu_S}{T}\right) +$$

$$B_{S=1}(T)\cosh\left(\frac{\mu_B - \mu_S}{T}\right) + B_{S=2}(T)\cosh\left(\frac{\mu_B - 2\mu_S}{T}\right) + B_{S=3}(T)\cosh\left(\frac{\mu_B - 3\mu_S}{T}\right)$$

Strange hadrons are heavy ➔ treat them as Boltzmann gas

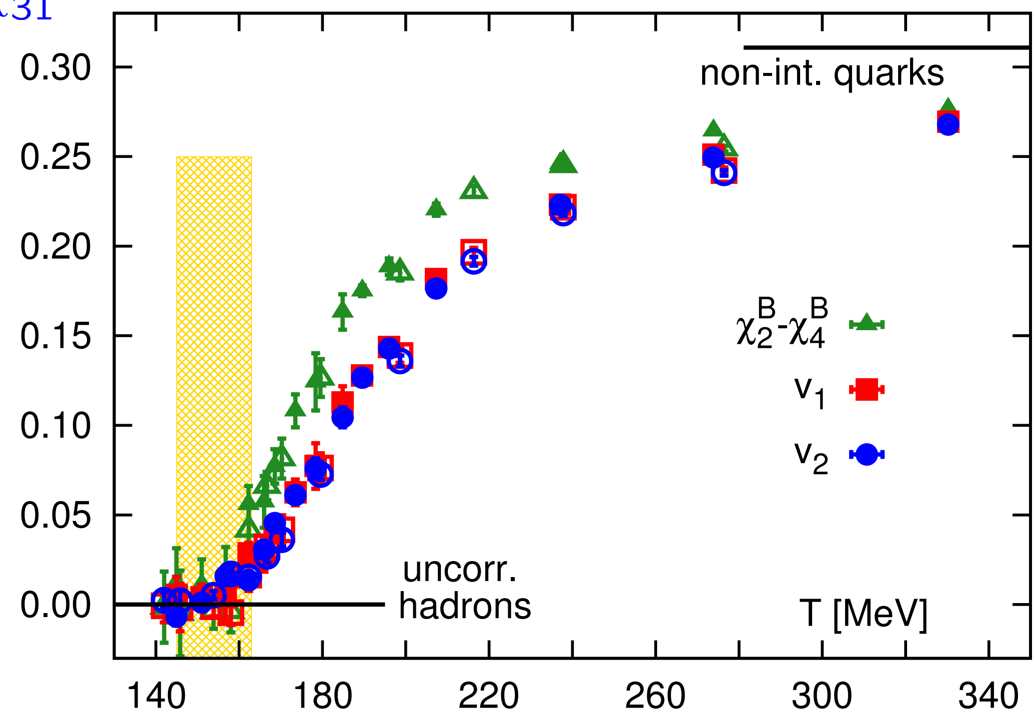
$$v_1 = \chi_{31}^{BS} - \chi_{11}^{BS}$$

$$v_2 = \frac{1}{3}\left(\chi_4^S - \chi_2^S\right) - 2\chi_{13}^{BS} - 4\chi_{22}^{BS} - 2\chi_{31}^{BS}$$

should vanish !

- v_1 and v_2 do vanish within errors at low T

- v_1 and v_2 rapidly increase above the transition region, eventually reaching non-interacting quark gas values

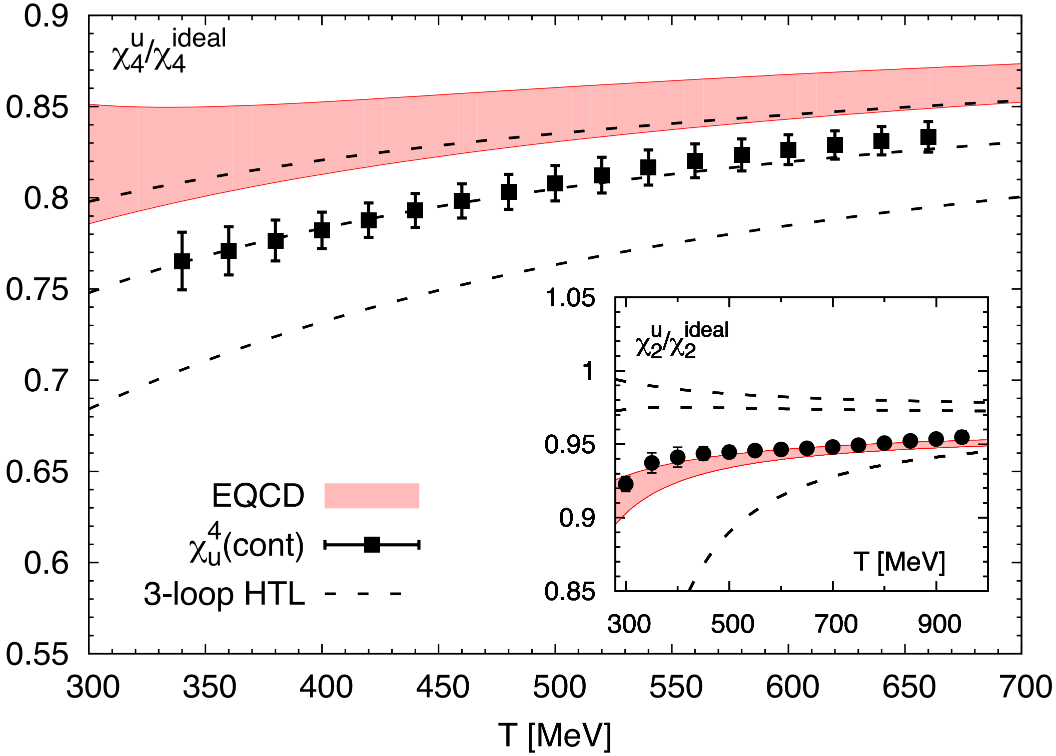


Bazavov et al, PRL 111 (2013) 082301

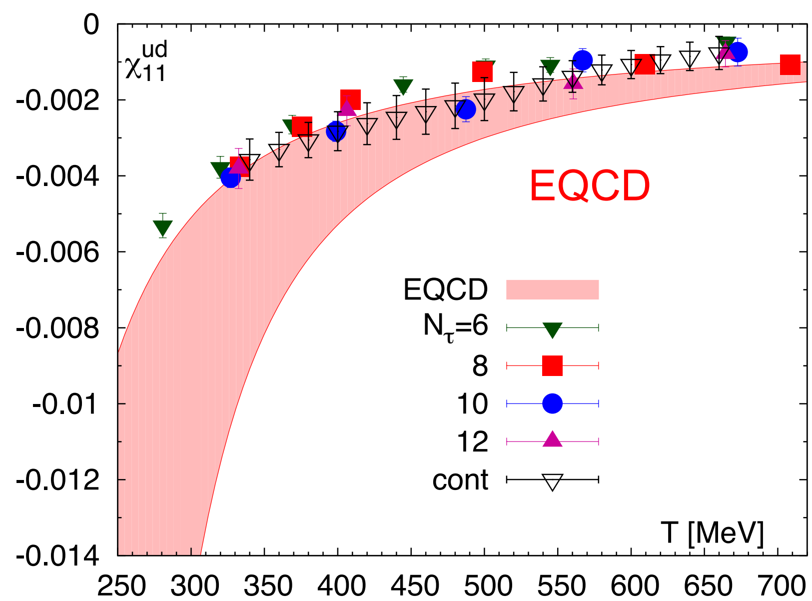
Quark number fluctuations at high T

At high temperatures quark number fluctuations can be described by weak coupling approach due to asymptotic freedom of QCD

quark number fluctuations



quark number correlations



- Lattice results converge as the continuum limit is approached
- Good agreement between lattice and the weak coupling approach for 2nd and 4th order quark number fluctuations as well as for correlations

Bazavov et al, PRD88 (2013) 094021, Ding et at, PRD92 (2015) 074043

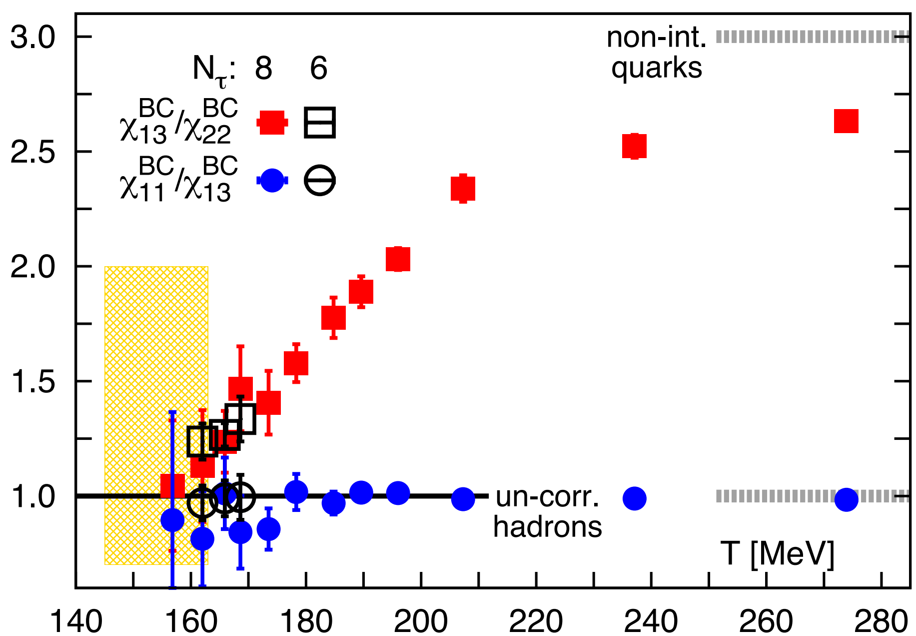
What about charm hadrons ?

$$\chi_{nml}^{XYC} = T^{m+n+l} \frac{\partial^{n+m+l} p(T, \mu_X, \mu_Y, \mu_C)/T^4}{\partial \mu_X^n \partial \mu_Y^m \partial \mu_C^l}$$

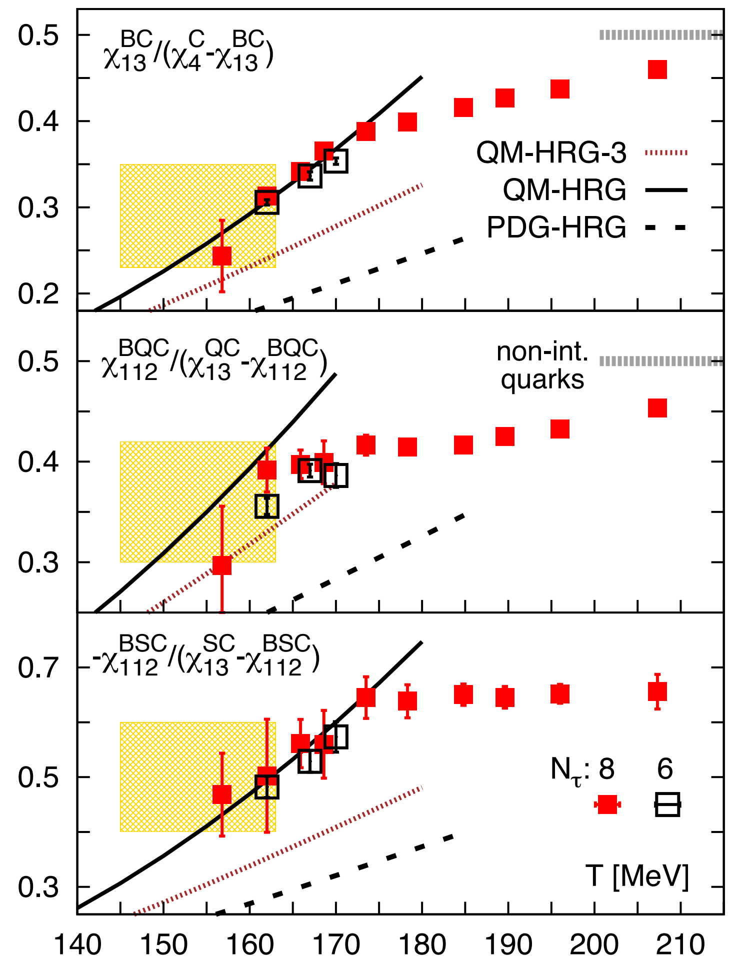
Bazavov et al, PLB 737 (2014) 210

$m_c \gg T$ ⇨ only |*C*|=*1* sector contributes

In the hadronic phase all *BC*-correlations are the same !



Charm baryon to meson pressure



Hadronic description breaks down just above T_c
⇒ open charn deconfines above T_c

The charm baryon spectrum is not well known (only few states in PDG), HRG works only if the “missing” states are included

Quasi-particle model for charm degrees of freedom

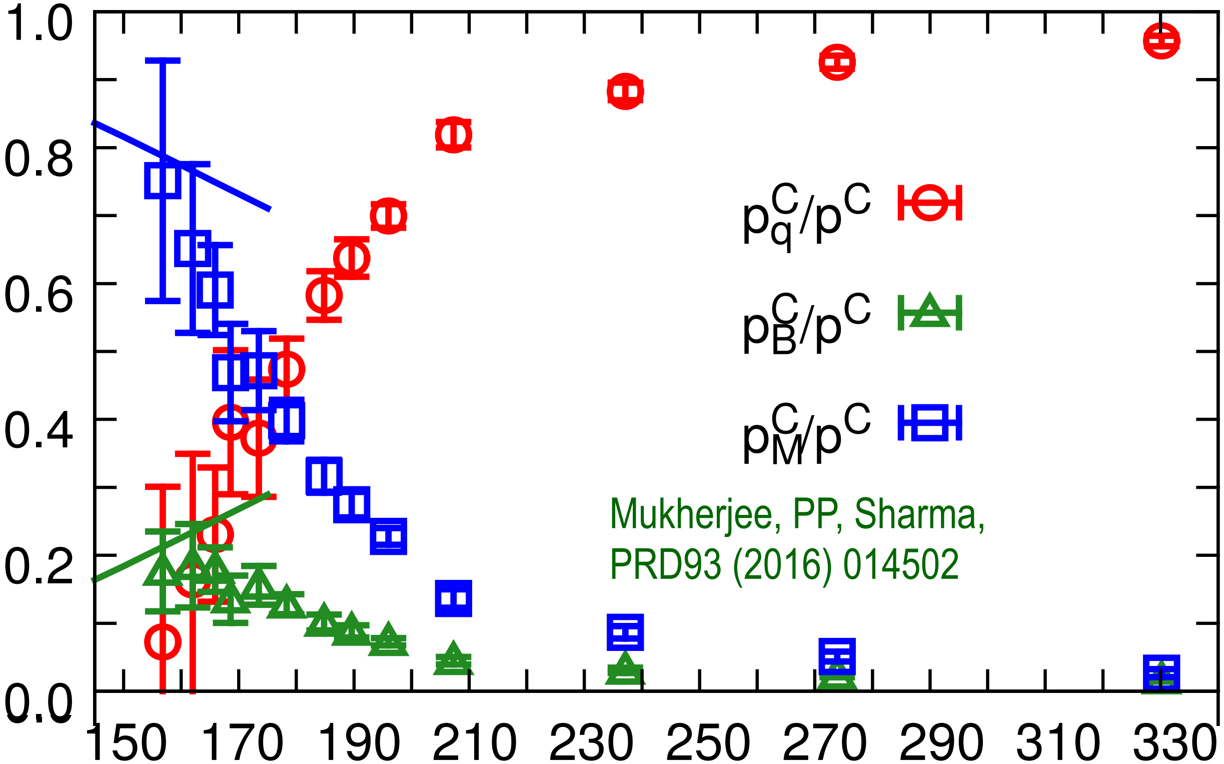
Charm dof are good quasi-particles at all T because $M_c >> T$ and Boltzmann approximation holds

$$p^C(T,\mu_B,\mu_c) = p_q^C(T)\cosh(\hat{\mu}_C + \hat{\mu}_B/3) + p_B^C(T)\cosh(\hat{\mu}_C + \hat{\mu}_B) + p_M^C(T)\cosh(\hat{\mu}_C)$$

$$\hat{\mu}_X = \mu_X/T$$

$$\chi_2^C,\ \chi_{13}^{BC},\ \chi_{22}^{BC} \Rightarrow p_q^C(T), p_M^C(T), p_B^C(T)$$

Partial meson and baryon pressures described by HRG at T_c and dominate the charm pressure then drop gradually, charm quark only dominant dof at $T>200$ MeV



Partial pressures drop because hadronic cxcitations become broad at high temperatures (bound state peaks merge with the continuum)

See
Jakovác, PRD88 (2013), 065012
Biró, Jakovác, PRD(2014)065012

Vice versa for quarks

Quarkonium Spectral Functions at T>0

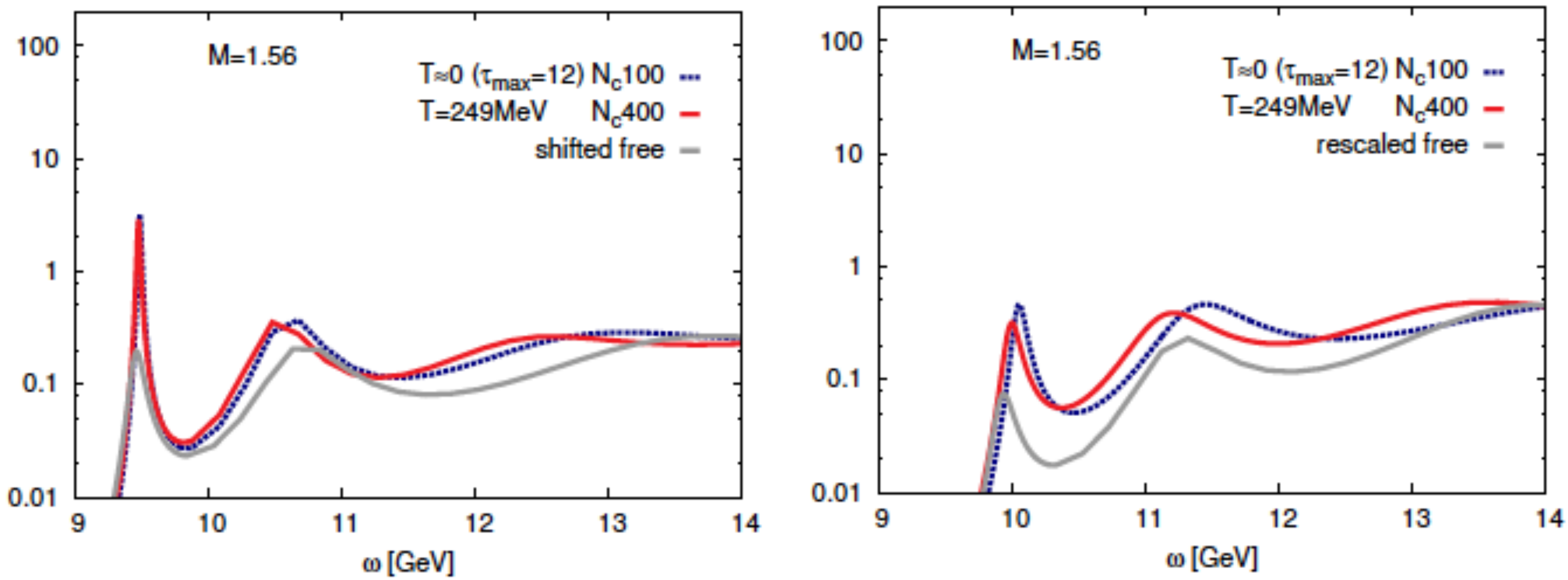
Quarkonium spectral function are related to the correlation function in Euclidean time τ:

$$D(\tau) = D(\mathbf{p}=0,\tau) = \sum_{\mathbf{x}} D(\mathbf{x},\tau) = \int_{-2M_q}^{\infty} d\omega\, e^{-\omega\tau}\, \rho(\omega)$$

The calculation of the correlation function can be performed using NRQCD

The reconstruction of the spectral functions is done using Bayesian analysis

S. Kim, PP, A. Rothkopf, PRD91 (2015) 054511



Both Υ and χ_b survive up to temperature $T \simeq 249$ MeV

Summary

- The deconfinement transition temperature coincides with the chiral transition temperature $T_c = 154(9)$ MeV

- Equation of state are known in the continuum limit up to $T=400$ MeV at zero baryon density and the effect of non vanishing baryon densities seem to be moderate; the energy density at the transition is small *300* MeV/fm^3

- Hadron resonance gas (HRG) can describe various thermodynamic quantities at low temperatures

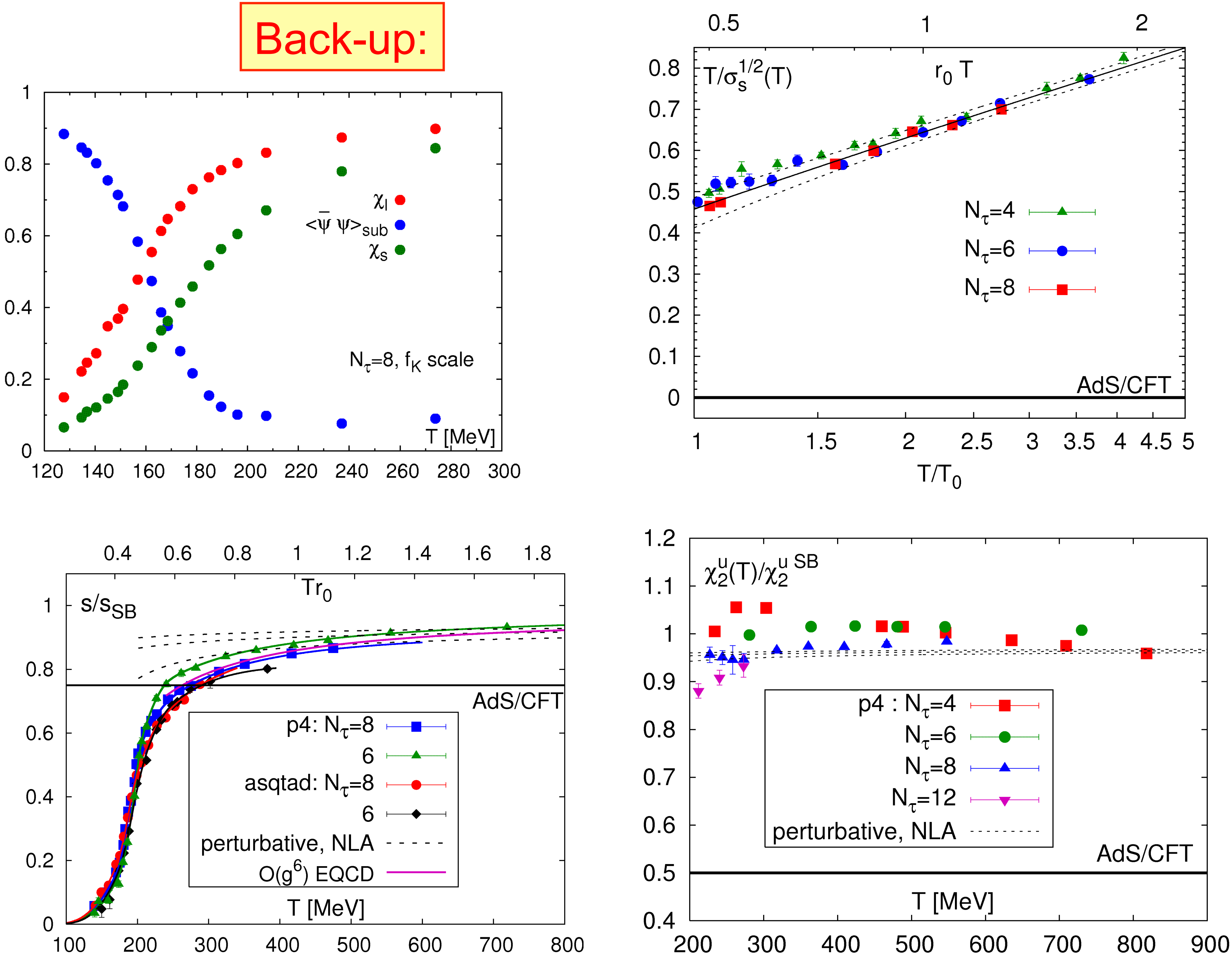
- Deconfinement transition can be studied in terms of fluctuations and correlations of conserved charges, it manifest itself as a abrupt breakdown of hadronic description that occurs around the chiral transition temperature

- Hadrons containing charm or bottom quark can exist above T_c

- For $T > (300\text{-}400)$ MeV weak coupling expansion may work for certain quantities (e.g. quark number susceptibilities)

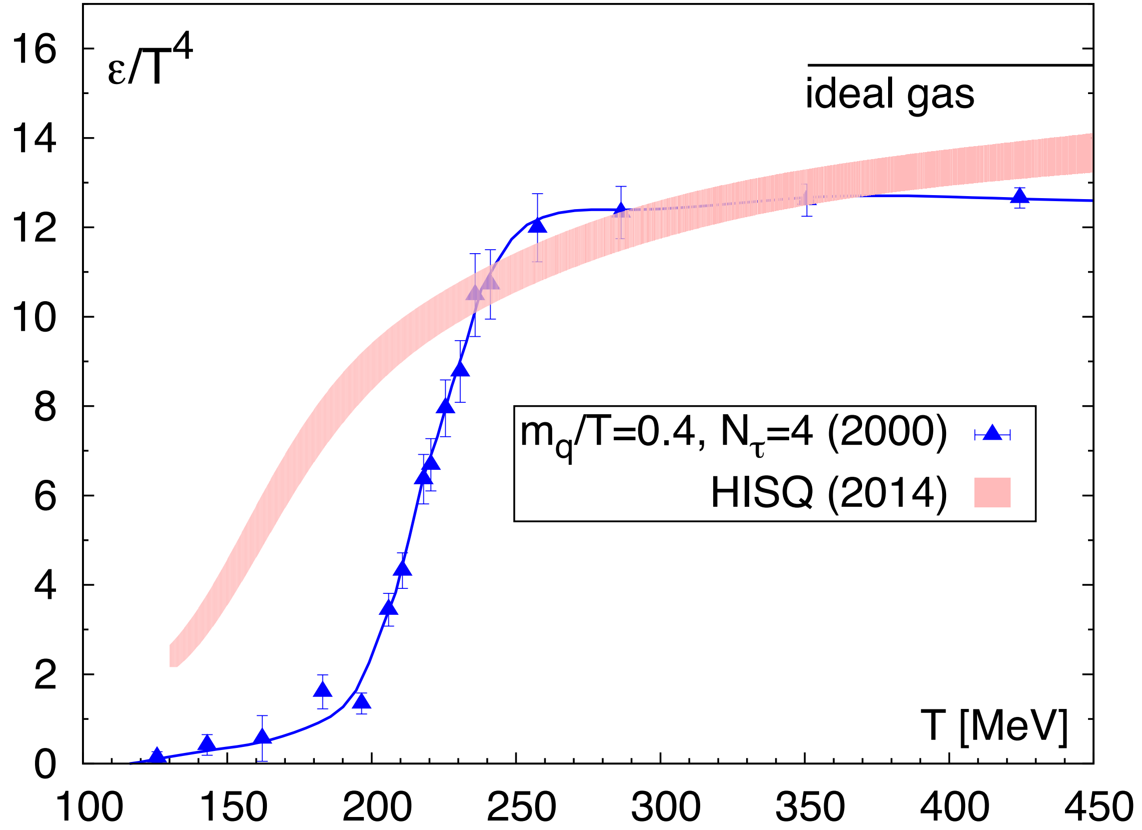
- Comparison of lattice and HRG results for certain charm correlations hints for existence of yet undiscovered excited baryons

Back-up:



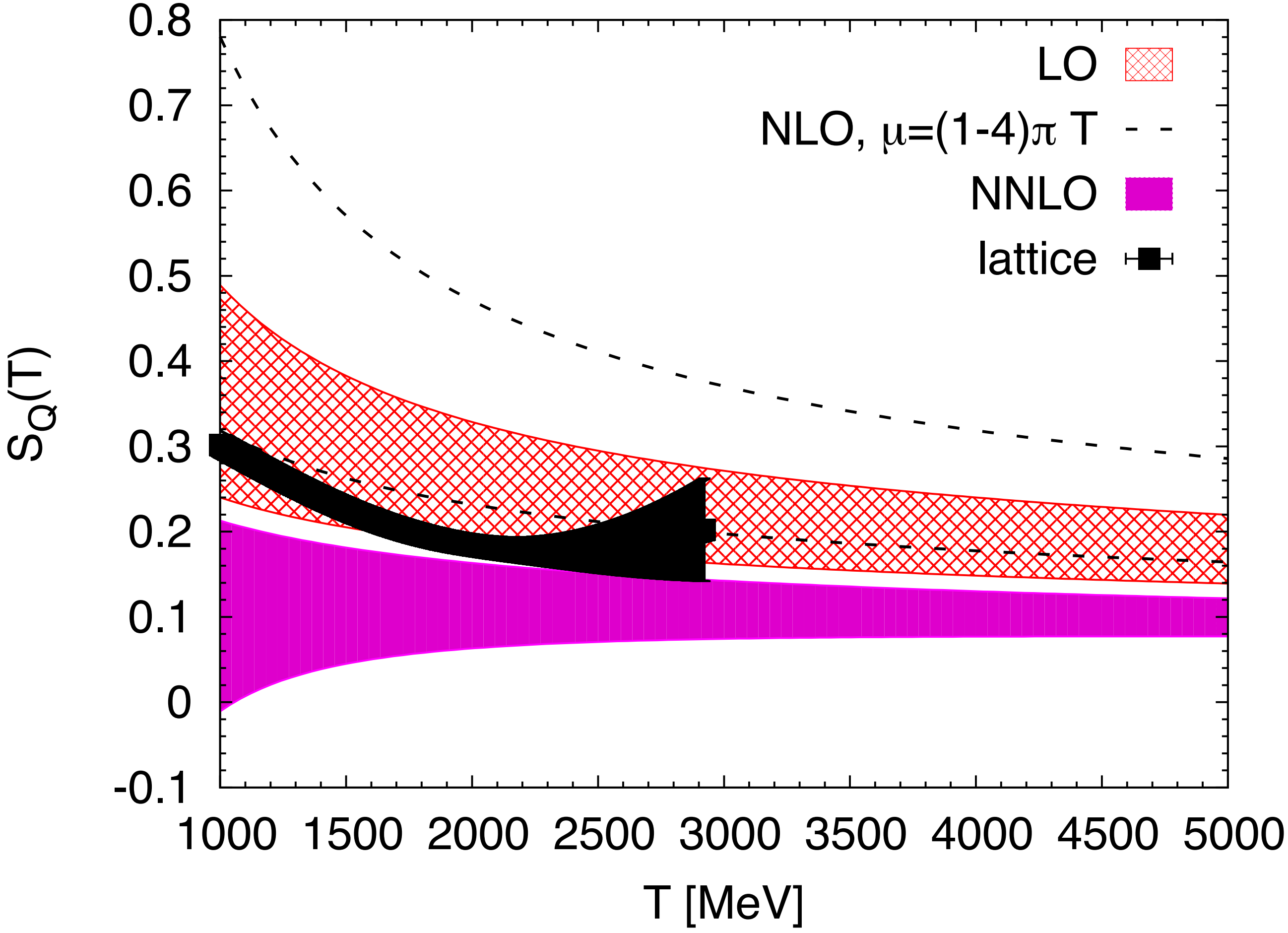
χ_l
$<\bar{\psi}\psi>_{sub}$
χ_s
N_τ=8, f_K scale
T [MeV]
$T/\sigma_s^{1/2}(T)$
r_0 T
N_τ=4
N_τ=6
N_τ=8
AdS/CFT
T/T_0
s/s_{SB}
Tr_0
p4: N_τ=8
6
asqtad: N_τ=8
6
perturbative, NLA
$O(g^6)$ EQCD
AdS/CFT
T [MeV]
$\chi_2^u(T)/\chi_2^{u\,SB}$
p4 : N_τ=4
N_τ=6
N_τ=8
N_τ=12
perturbative, NLA
AdS/CFT
T [MeV]

How Equation of state changed since 2002 ?



- Much smoother transition to QGP
- The energy density keeps increasing up to 450 MeV instead of flattening

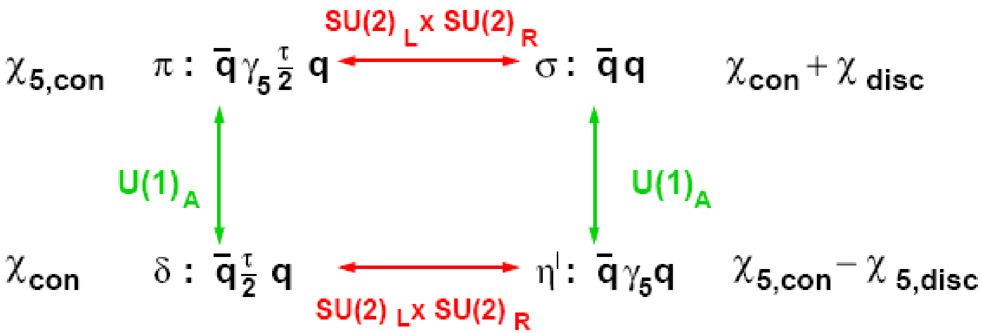
Entropy of static quark at high temperature



M. Berwein, N. Brambilla, P. Petreczky and A. Vairo, arXiv:1512.08443 [hep-ph]

Domain wall Fermions and $U_A(1)$ symmetry restoration

Domain Wall Fermions, Bazavov et al (HotQCD), PRD86 (2012) 094503



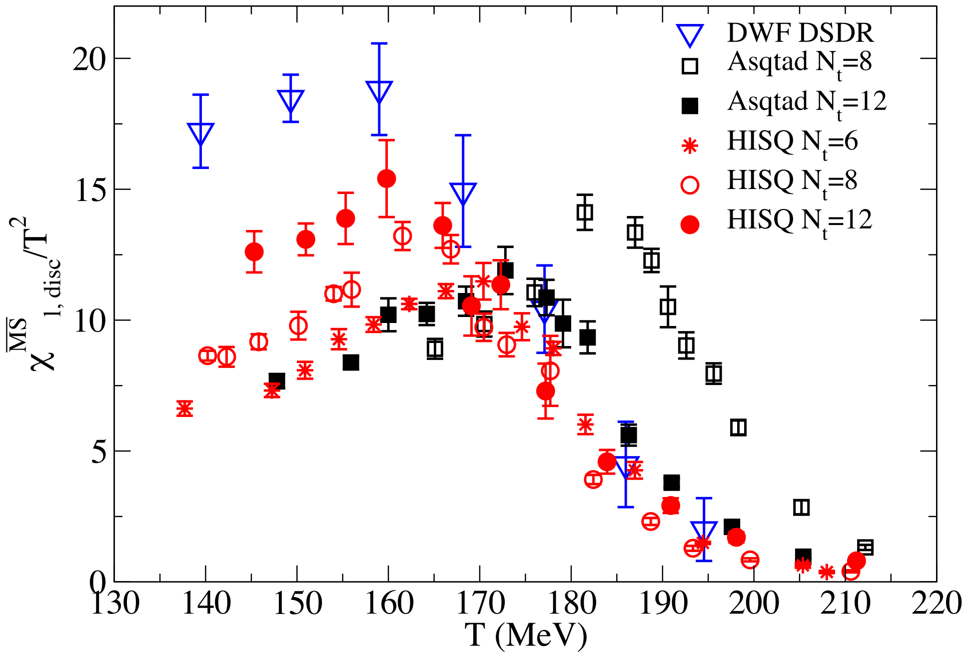
$$\chi_i = \int d^4x G_i(x)$$

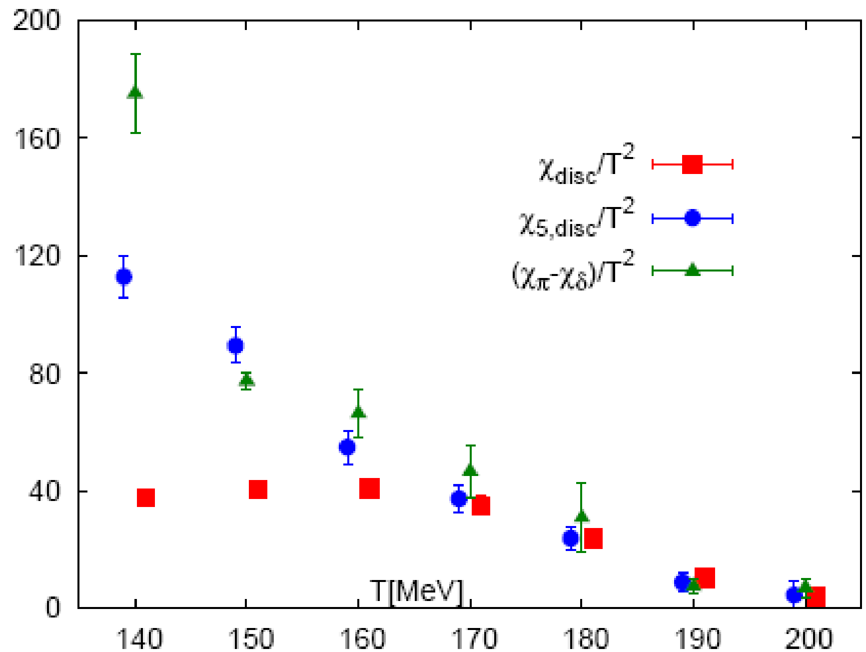
chiral:

$$\chi_\pi = \chi_\delta + \chi_{\rm disc}$$
$$\chi_\delta = \chi_\pi - \chi_{5,\rm disc}$$
$$\chi_{\rm disc} = \chi_{5,\rm disc}$$

axial:

$$\chi_\pi = \chi_\delta$$
$$\chi_\delta + \chi_{\rm disc} = \chi_\pi - \chi_{5,\rm disc}$$
$$\chi_{\rm disc} = -\chi_{5,\rm disc}$$





Peak position roughly agrees with previous staggered results

axial symmetry is effectively restored *T*>200 MeV !