Strongly versus weakly coupled QGP

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QGP is expected to be strongly coupled around T_c: how does this features manifest itself in terms of different quantities, how do we observe it on lattice ?

QGP: state of strongly interacting matter for weakly interacting gas of quark and gluons ? $T \gg \Lambda_{QCD}, g \ll 1$

$$2\pi T \gg m_D \sim gT \gg g^2 T$$

EFT approach: EQCD

Magnetic screening scale: non-perturnative

Perturbative series is an expansion is in g and not α_s
Loop expansion breaks down at some order (weak coupling may still work)

Problem : $g(\mu = 10^2 \mathrm{GeV}) = \sqrt{4\pi\alpha_s(\mu = 10^2 \mathrm{GeV})} \simeq 1 \qquad g(\mu = 10^{16} \mathrm{GeV}) \simeq 1/2$

In this talk :
Fluctuations of conserved charges, color screening, topological susceptibility

Winter Workshop for Nuclear Dynamics, Snowbird, Utah, January 9-14, 2017

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

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

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

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

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)

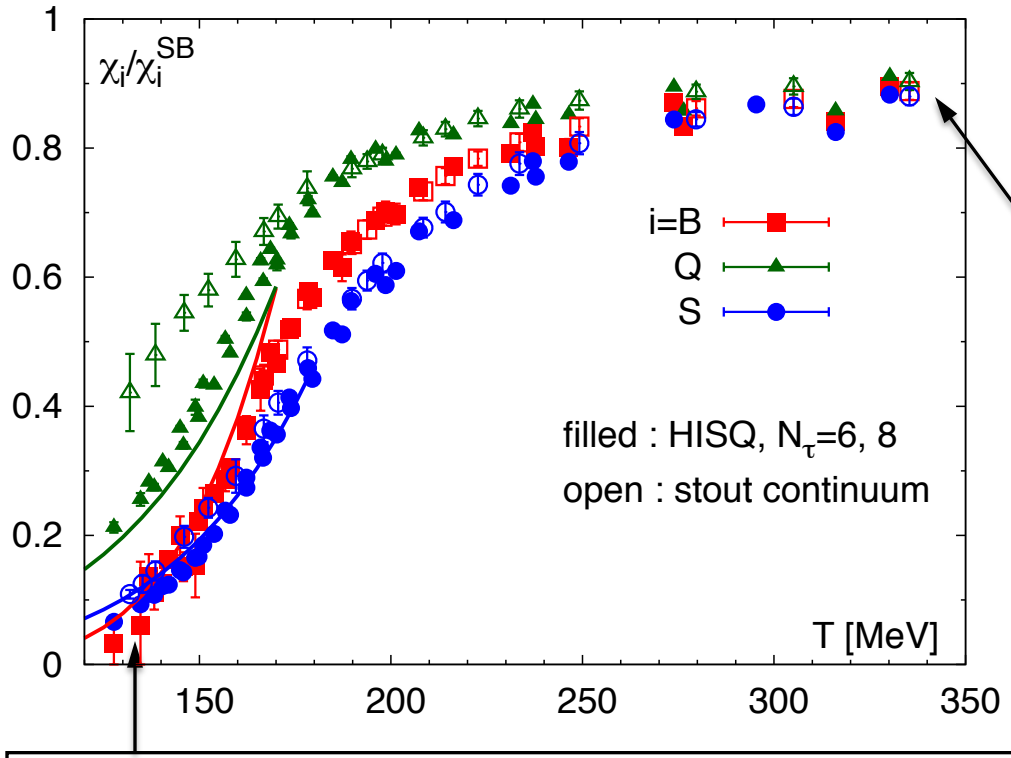
probes of deconfinement

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



conserved charges are carried by massive hadrons

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

HotQCD: PRD86 (2012) 034509

BW: 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

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

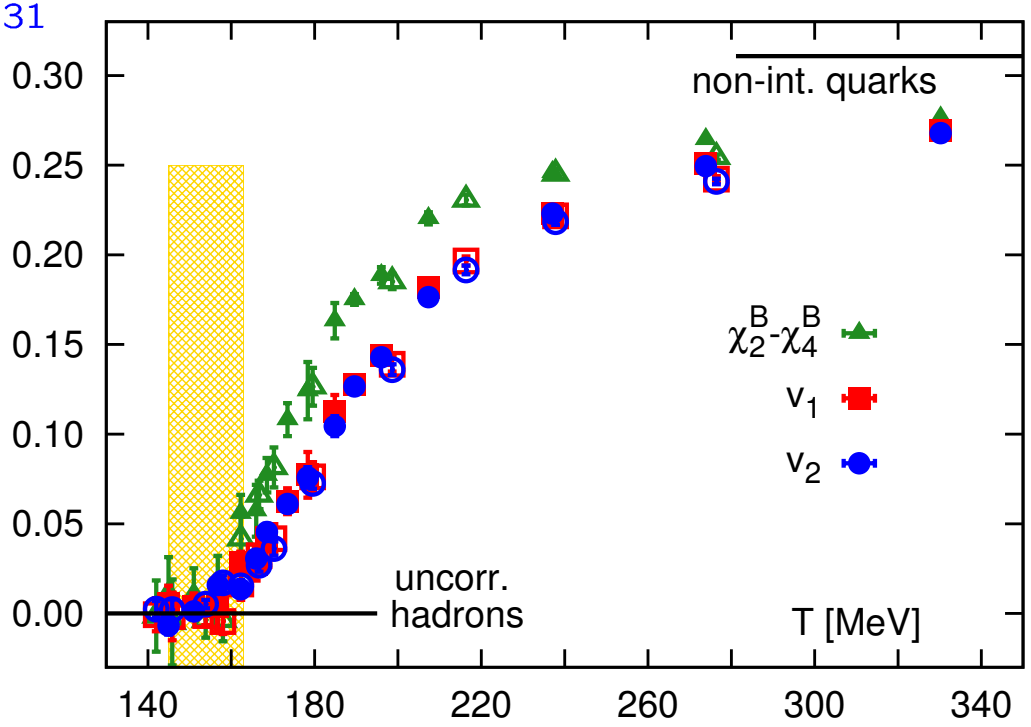
$$v_2 = \frac{1}{3}\left(\chi_4^S - \chi_2^S\right) - 2\chi_{13}^{BS} - 4\chi_{22}^{BS} - 2\chi_{31}^{BS}$$

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

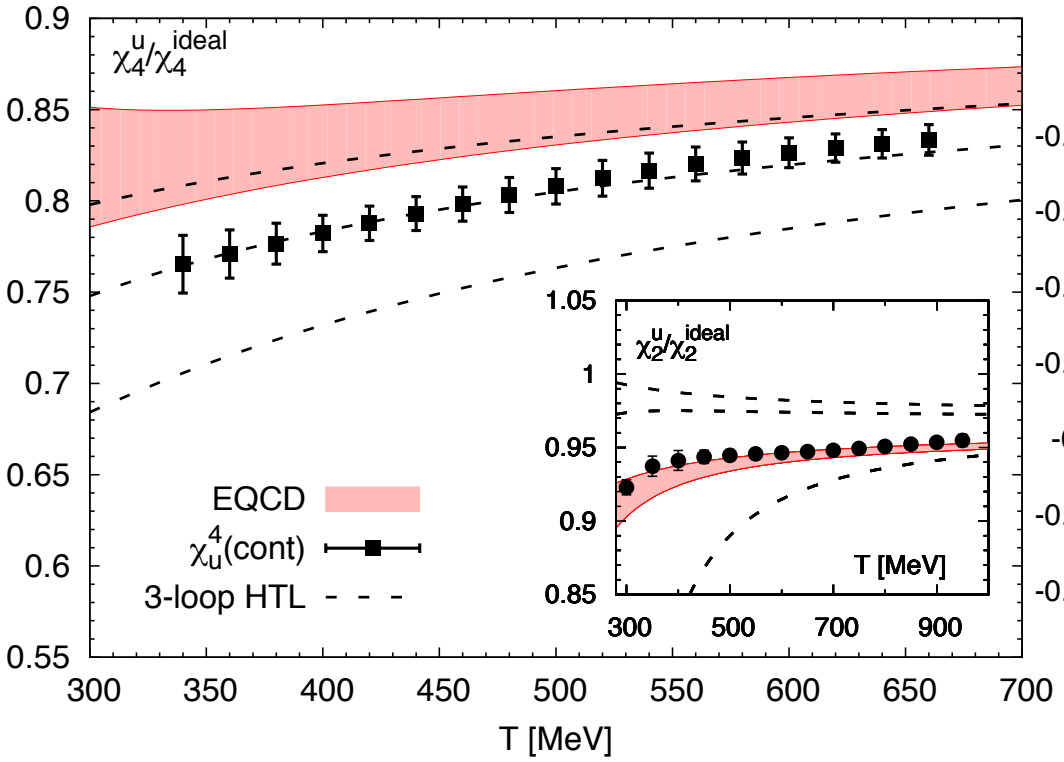
Bazavov et al, PRL 111 (2013) 082301



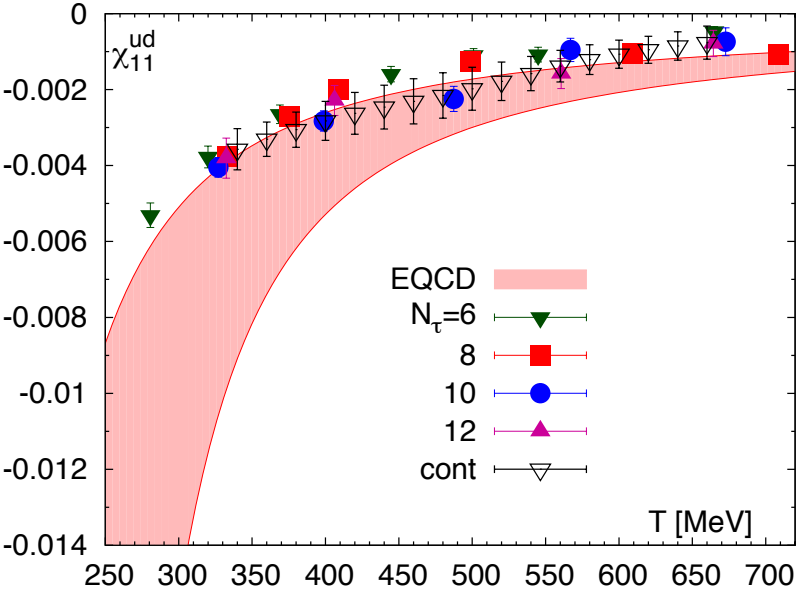
Quark number fluctuations at high T

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



- Good agreement between continuum extrapolated lattice results and the weak coupling approach
- Quark number correlations vanish at any loop order but can be calculated in EQCD and the EQCD calculations agree with the continuum extrapolated lattice results

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

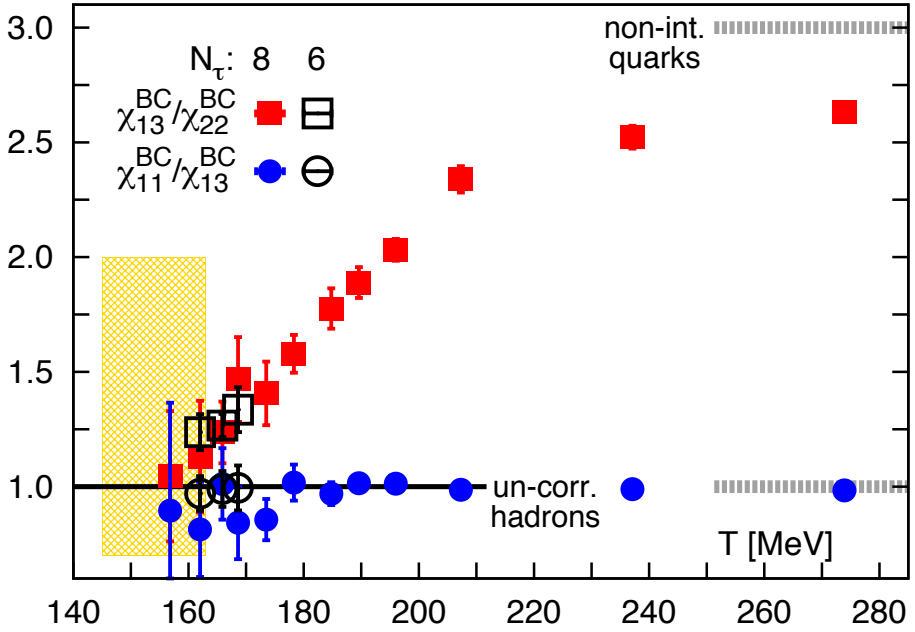
What about charm hadrons ?

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

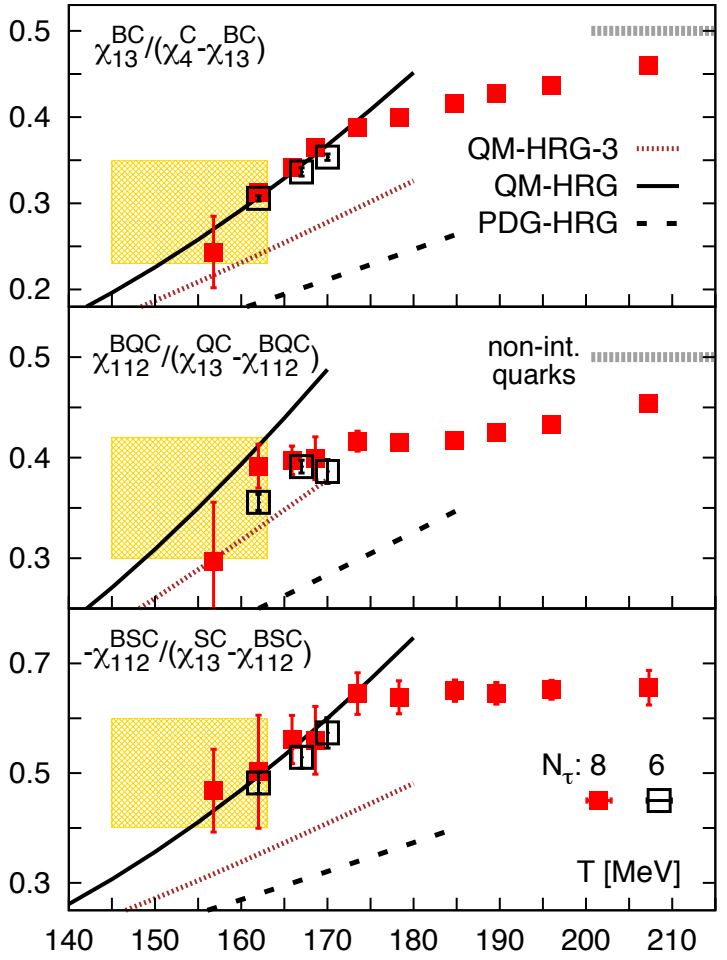
Bazavov et al, Phys.Lett. B737 (2014) 210

$m_c \gg T$ ⇨ 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

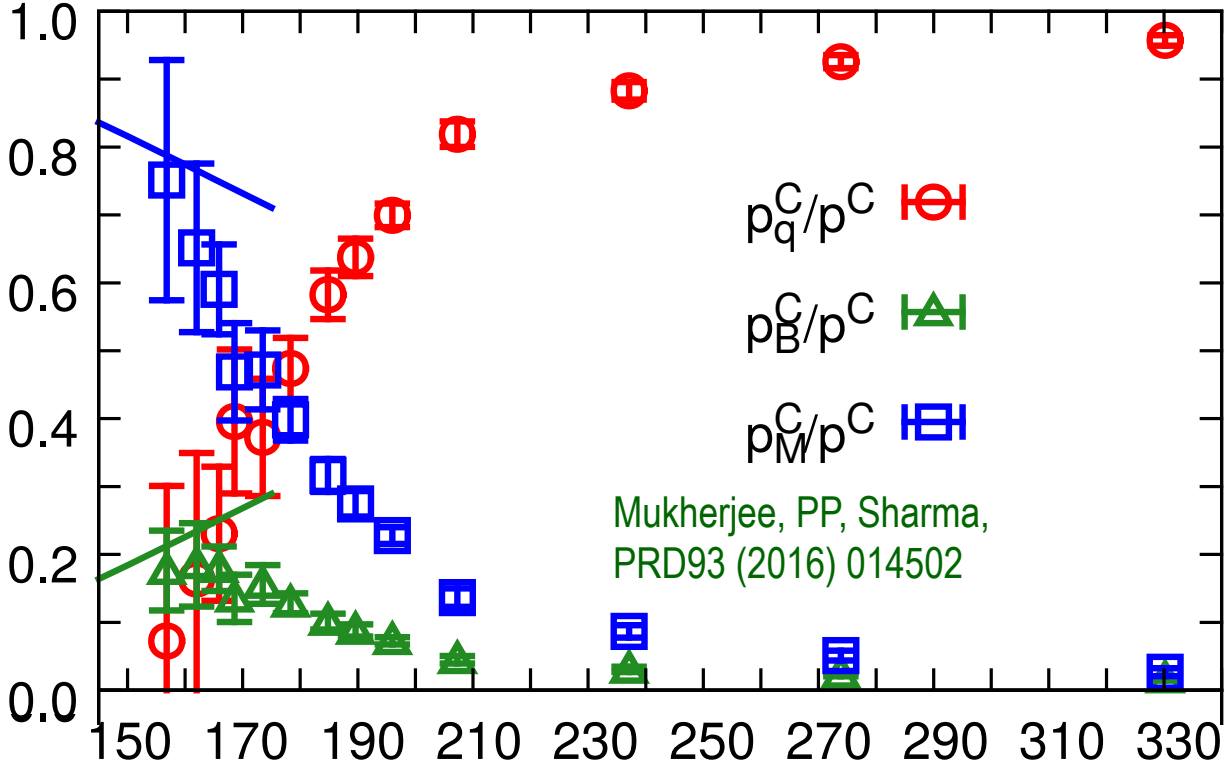
Charm dof are good quasi-particles at all *T* because $M_c >> T$ and Boltzmann approximation holds

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

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

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

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

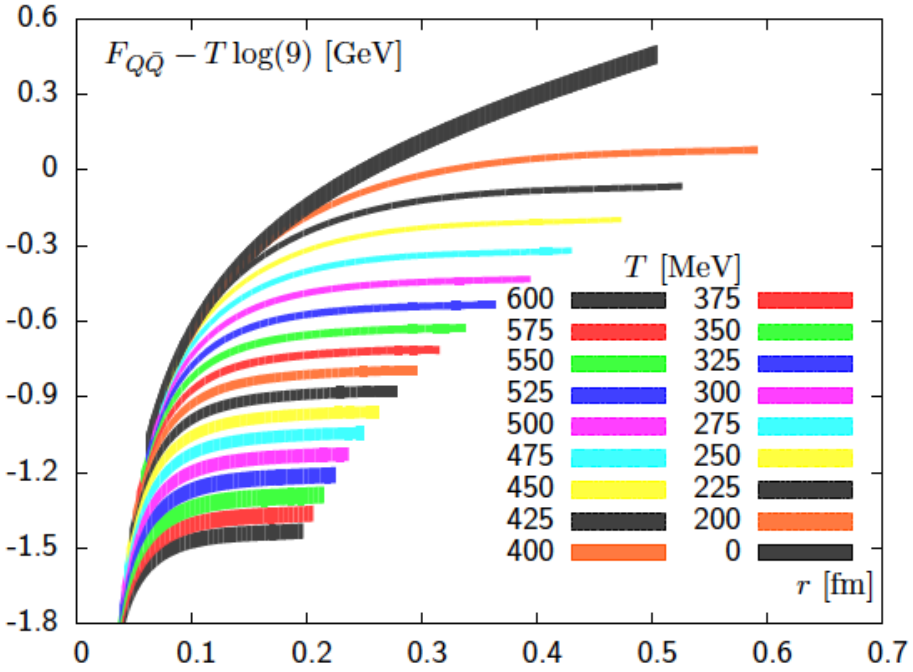
Deconfinement and color screening

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

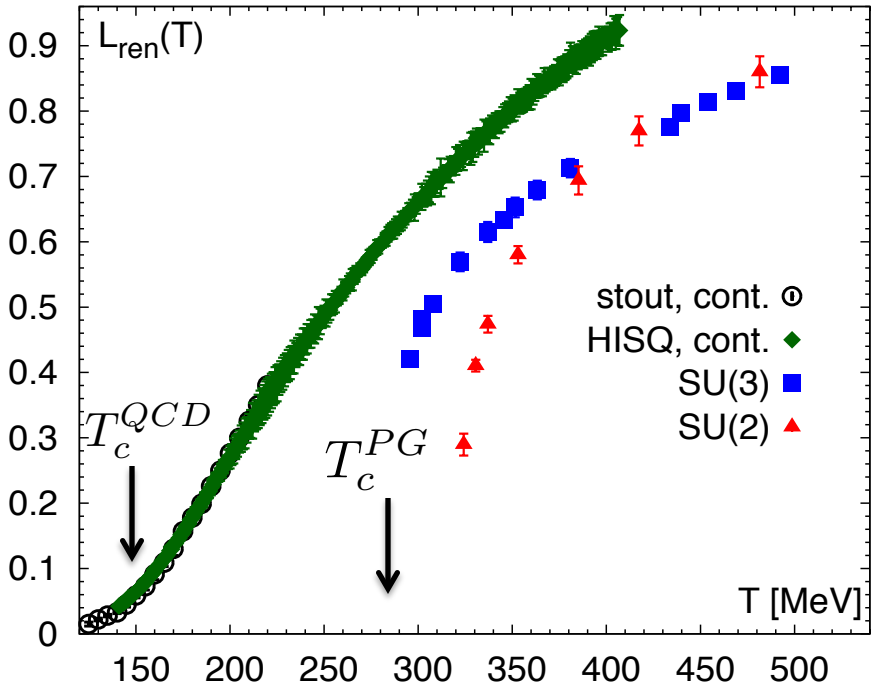
$$L = \mathrm{tr}\mathcal{P}e^{ig\int_0^{1/T} d\tau A_0(\tau,\vec{x})} \qquad \exp(-F_{Q\bar{Q}}(r,T)/T) = \frac{1}{9}\langle \mathrm{tr}L(r)\mathrm{tr}L^\dagger(0)\rangle$$

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

2+1 flavor QCD, continuum extrapolated (see talk by Johannes Weber)



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



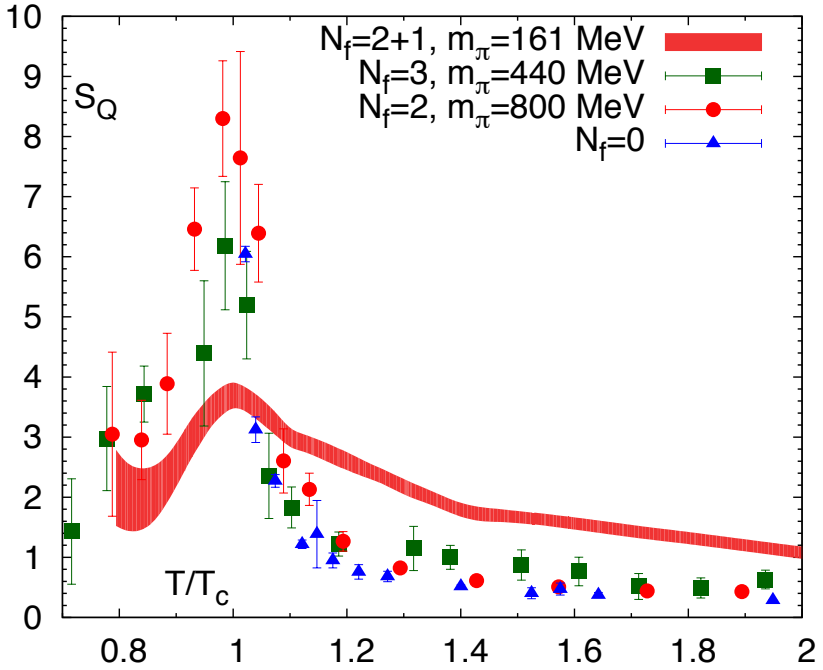
SU(N) gauge theory ≠ QCD !

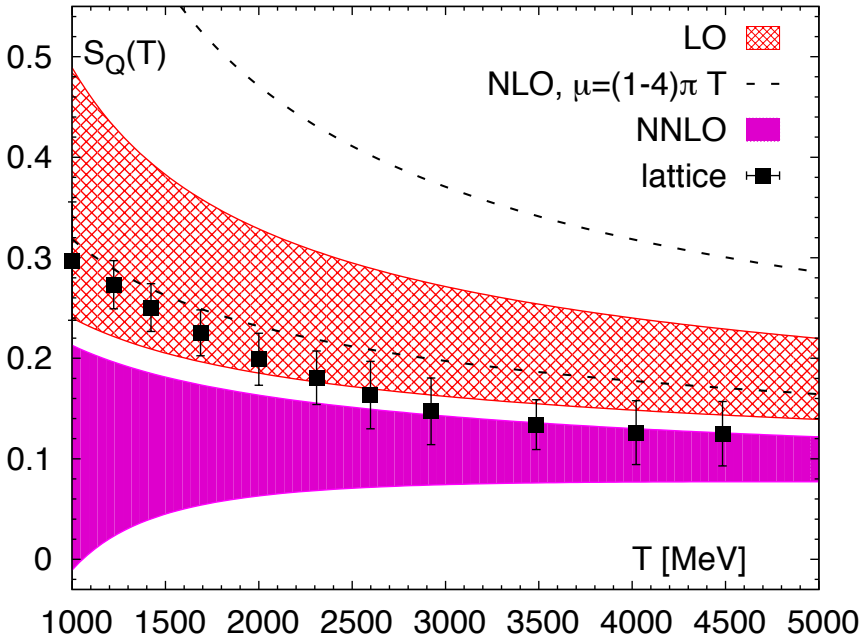
Similar results with stout action Borsanyi et al, JHEP04(2015) 138

The entropy of static quark

TUMQCD, arXiv:1606.06637

$$S_Q = -\frac{\partial F_Q}{\partial T}$$





At low *T* the entropy S_Q increases reflecting the increase of states the heavy quark can be coupled to; at high temperature the static quark only "sees" the medium within a Debye radius, as *T* increases the Debye radius decreases and S_Q also decreases

The onset of screening corresponds to peak is S_Q and its position coincides with T_c

Weak coupling (EQCD) calculations work only or *T> 1500* MeV

Casimir scaling of the Polyakov loop

Instead of fundamental representations consider Polyakov loop P_n in arbitrary representation n

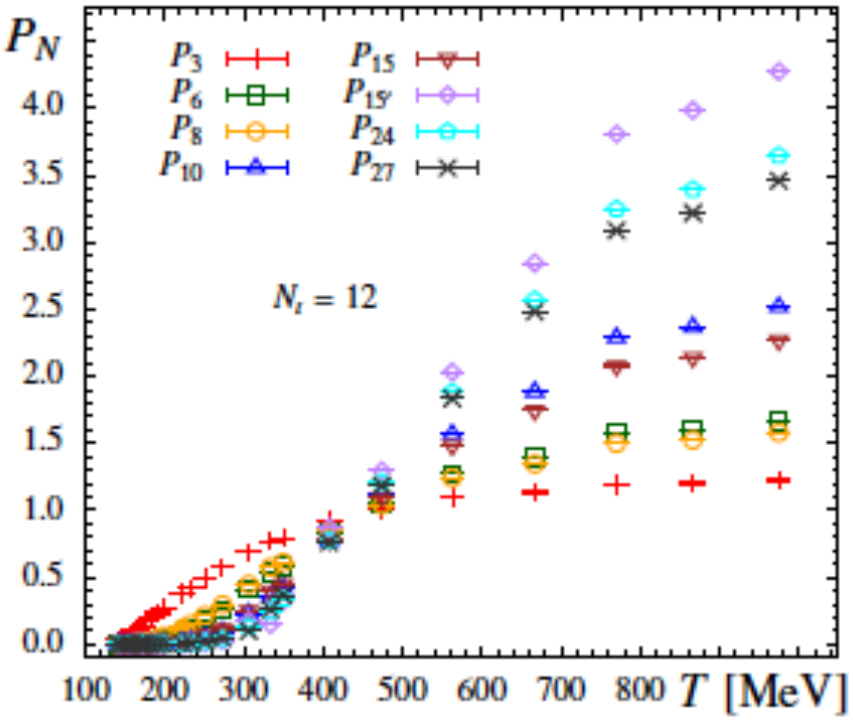
PP, Schadler, PRD92 (2015) 094517

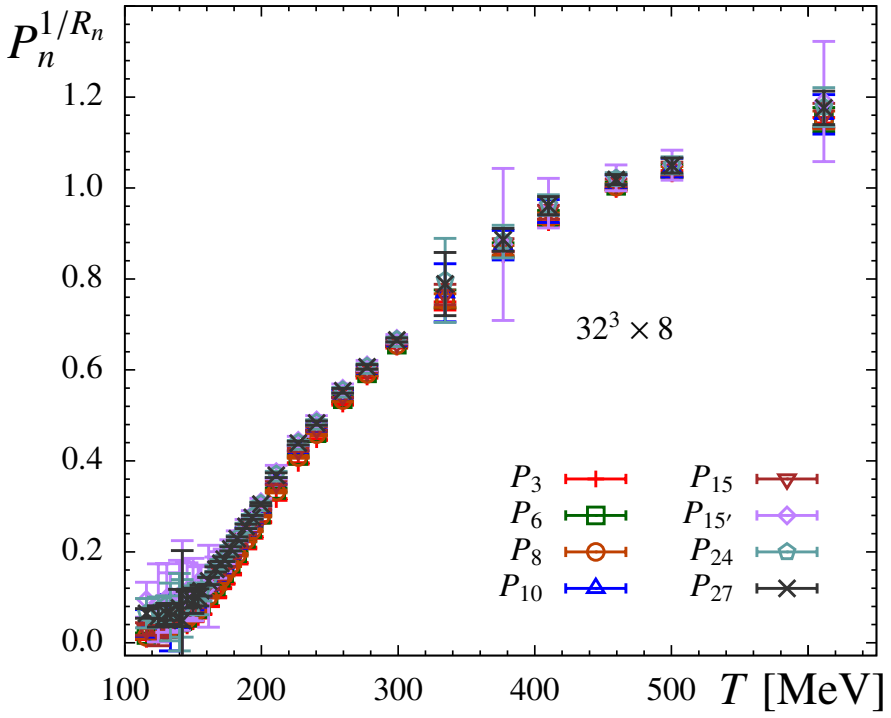
$$P_3 = L_{ren}$$

Use symanzik flow to renormalized the Polyakov loop and reduce the noise
Fodor et al, JHEP 1409 (2014) 018

Casimir scaling: free energy is proportional to qudratic
Casimir operator C_n of rep n

$$R_n = C_n/C_3$$

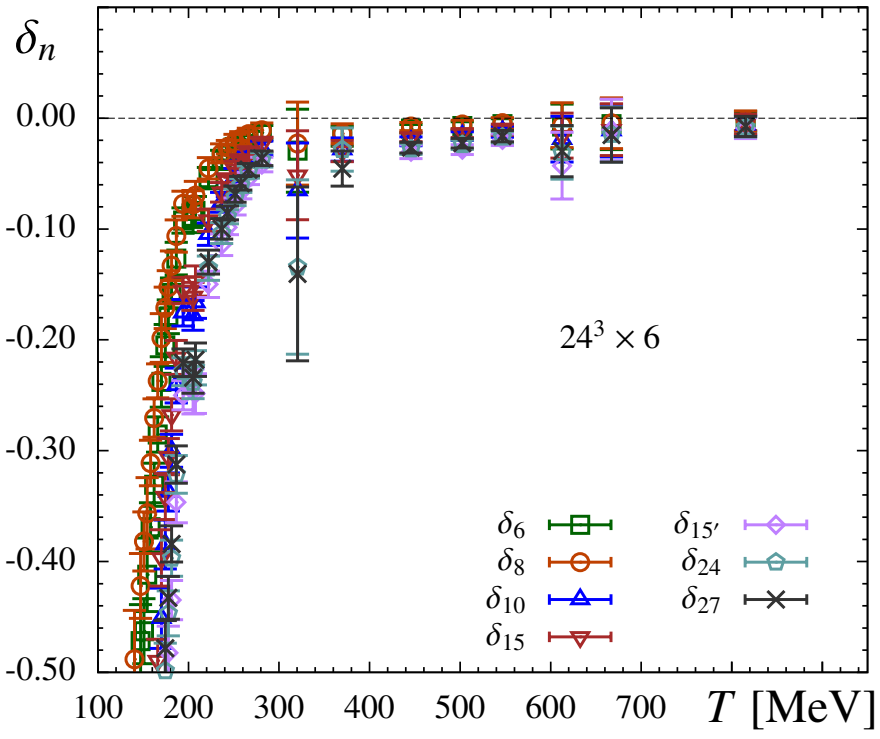


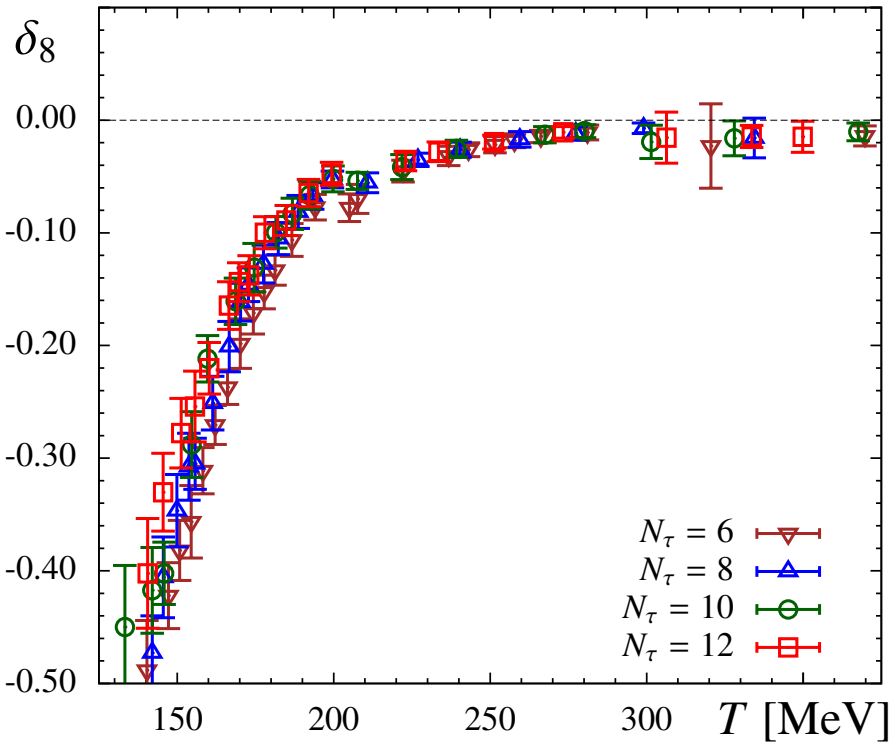


Expected in weak coupling expansion: e.g. at LO $F_Q^n = -C_n \alpha_s m_D$

Casimir scaling of the Polyakov loop (con't)

$$\delta_n = 1 - P_n^{1/R_n}/P_3$$





Casimir scaling holds for *T>300* MeV color screening like in weakly coupled QGP ?

Breaking of Casimir scaling first appear at order α_s^4 in the weak coupling expansion

Berwein et al, PRD93 (2016) 034010

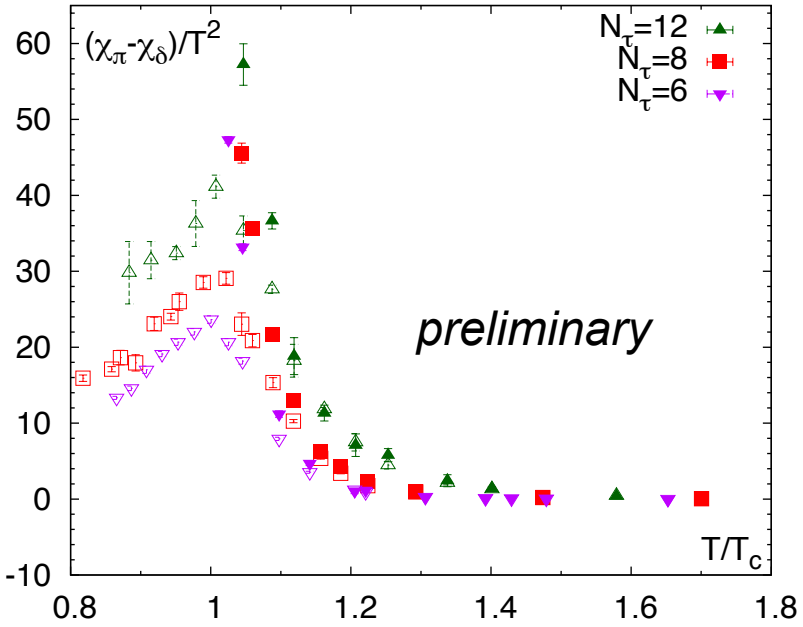
Instanton gas at work ?

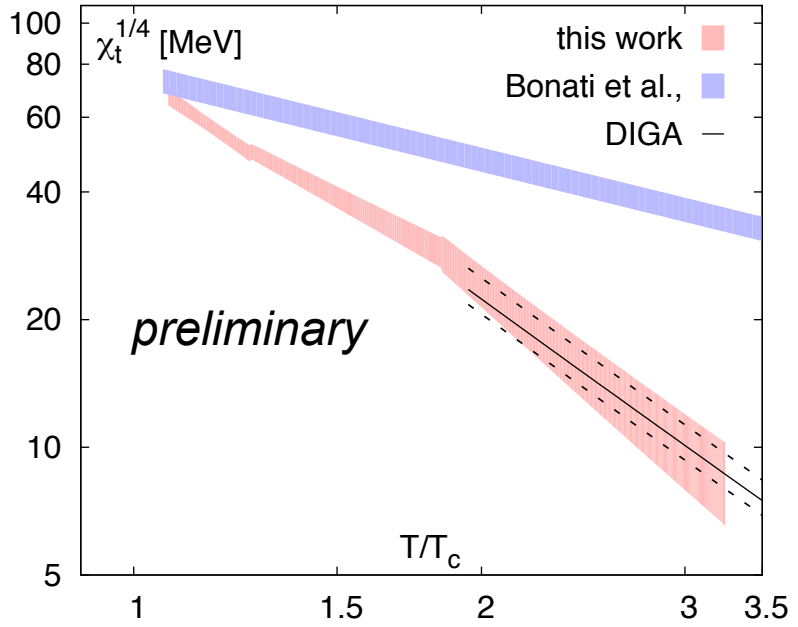
The amount of $U_A(1)$ breaking at high T is reduce because of the reduced instanton density => dilute instanton gas approximation (DIGA), Gross et al, RMP 53 (1981) 43

Topological susceptibility with HISQ action using Symanzik flow

$$\chi_{top} = \frac{1}{V}\left(\langle Q^2\rangle - \langle Q\rangle^2\right) \qquad \chi_{top}/m_l^2 = \chi_{\mathrm{disc},5} \simeq \chi_{\mathrm{disc}}$$

Schadler, Sharma, PP

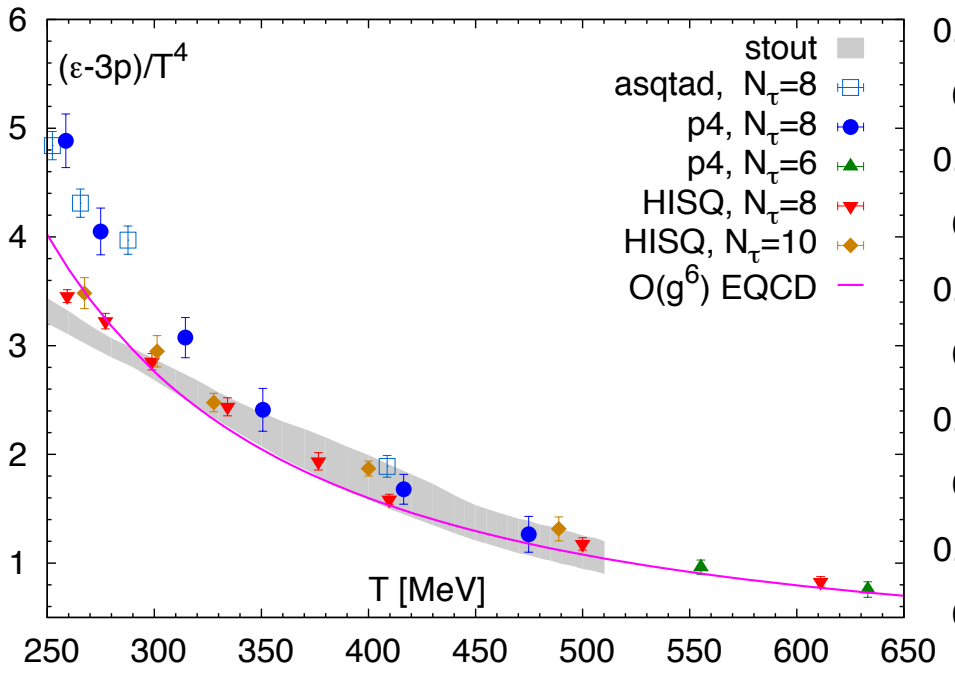


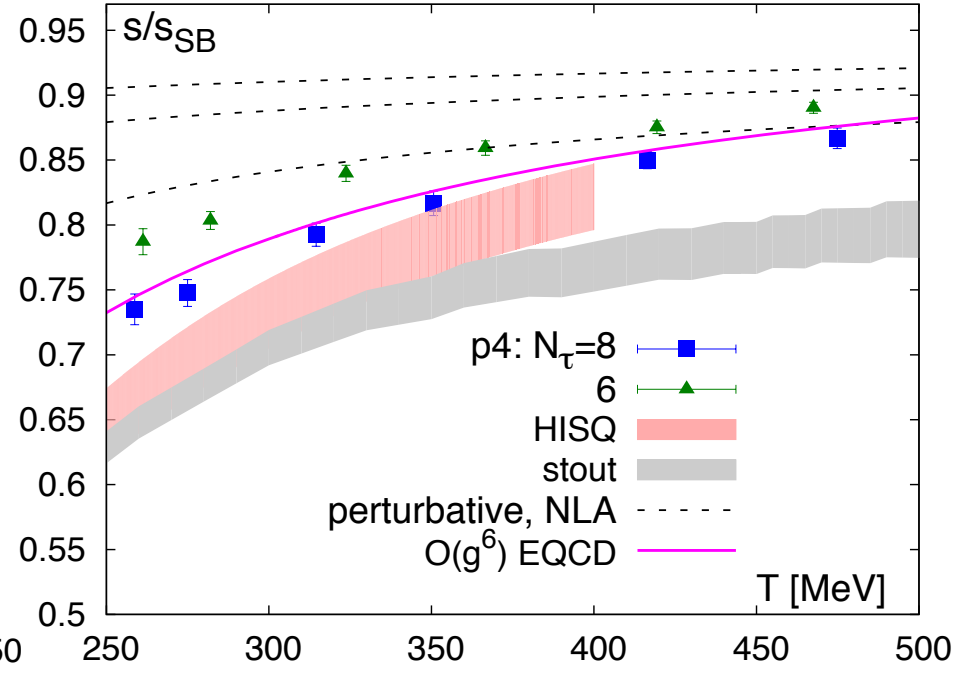


DIGA is not incompatible with the lattice results a K factor ~1.79 is included
Similar K factor was found for SU(3) gauge theory, Borsányi et al, PLB 752 (2016) 175

$U_A(1)$ is broken at any high temperatures due static chromo-magnetic magnetic fields
Laine, Vepsalainen, 2003; application to axion phenomenology ? See talk by Zoltan Fodor

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 ?

Summary

- The deconfinement transition temperature defined in terms of the free energy of static quark agrees with the chiral transition temperature for physical quark mass; $U_A(1)$ symmetry remains broken t high T

- 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.

- 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

- Charm hadrons can exist above T_c and are dominant dof for *T<180* MeV

- For *T > (300-400)* MeV weak coupling expansion works well for certain quantities but more work is needed to establish the validity of weak coupling methods

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