# Charm degrees of freedom above deconfinement

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Charm quarks show strong collectivity in heavy ion collisions
⇒ Formation of sQGP

What is the nature of charm degrees of freedom in sQGP, are there charm hadrons above the transition temperature ?

⇒ Use correlations of charm and other quantum numbers (e.g. baryon number and strangeness to answer this question

Based on work with S. Mukherjee and S. Sharma

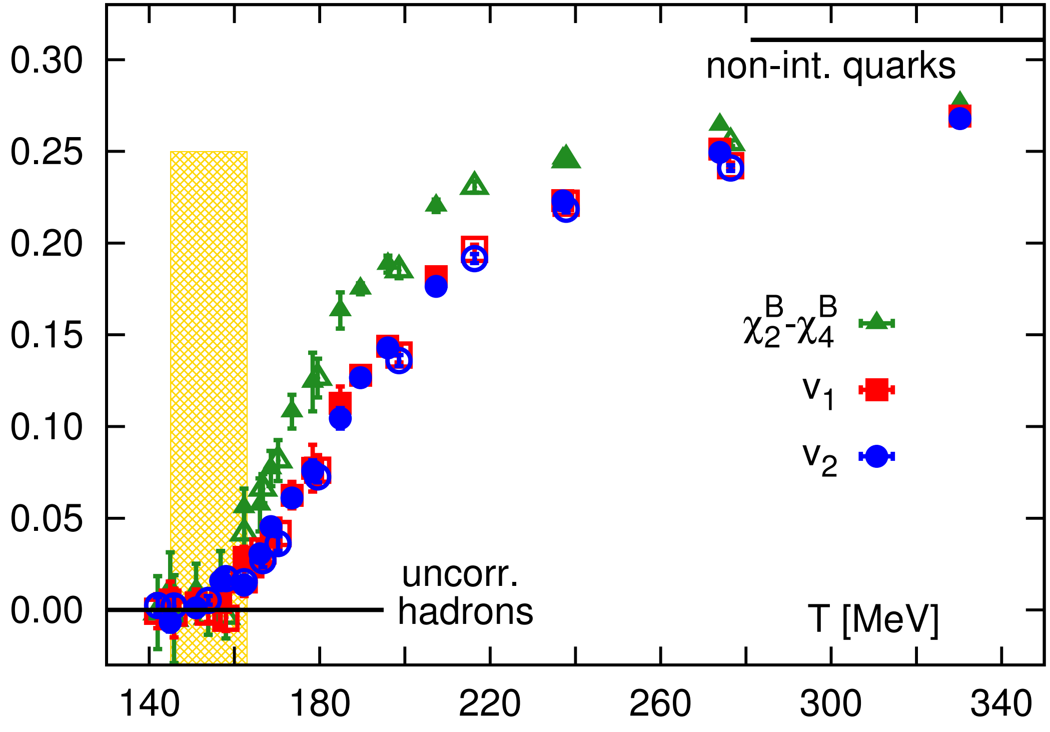
# Deconfinement of strangeness

Fluctuations

$$\chi_n^X = T^n \frac{\partial^n p(T,\mu_X,\mu_Y)/T^4}{\partial \mu_X^n} \qquad \chi_{nm}^{XY} = T^{m+n} \frac{\partial^{n+m} p(T,\mu_X,\mu_Y)/T^4}{\partial \mu_X^n \partial \mu_Y^m}$$

Deconfinement: abrupt breakdown of hadron gas description

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



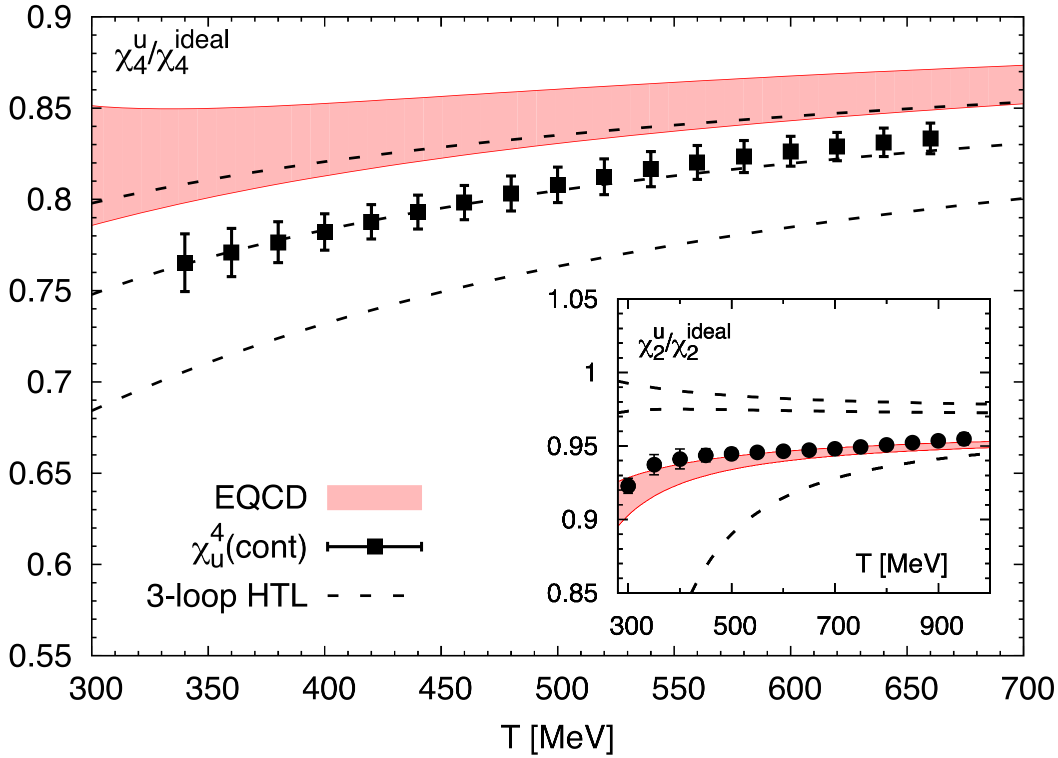

$$v_1 = \chi_{31}^{BS} - \chi_{11}^{BS}$$

Bazavov et al,
PRL 111 (2013) 082301

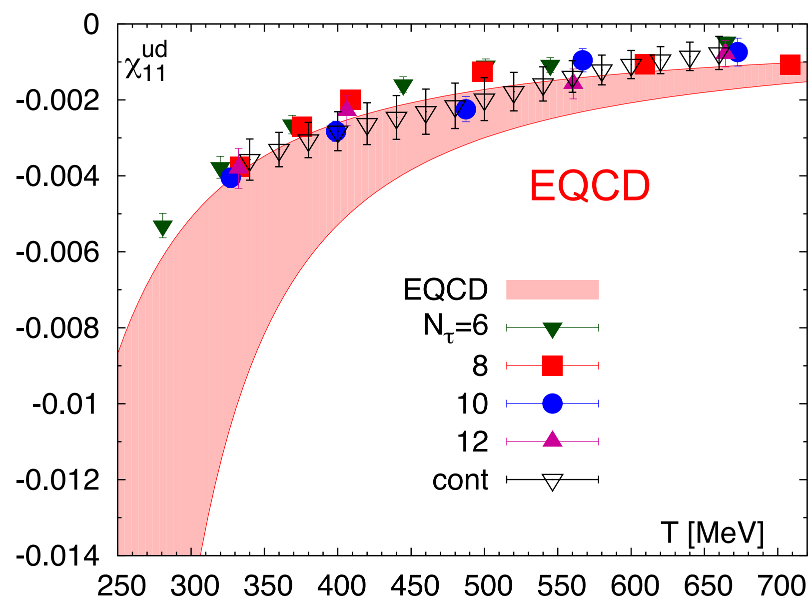
# Quark number fluctuations at high T

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 2[nd] and 4[th] order quark number fluctuations as well as for correlations

Bazavov et al, PRD88 (2013) 094021, Ding et at, **arXiv:1507.06637**

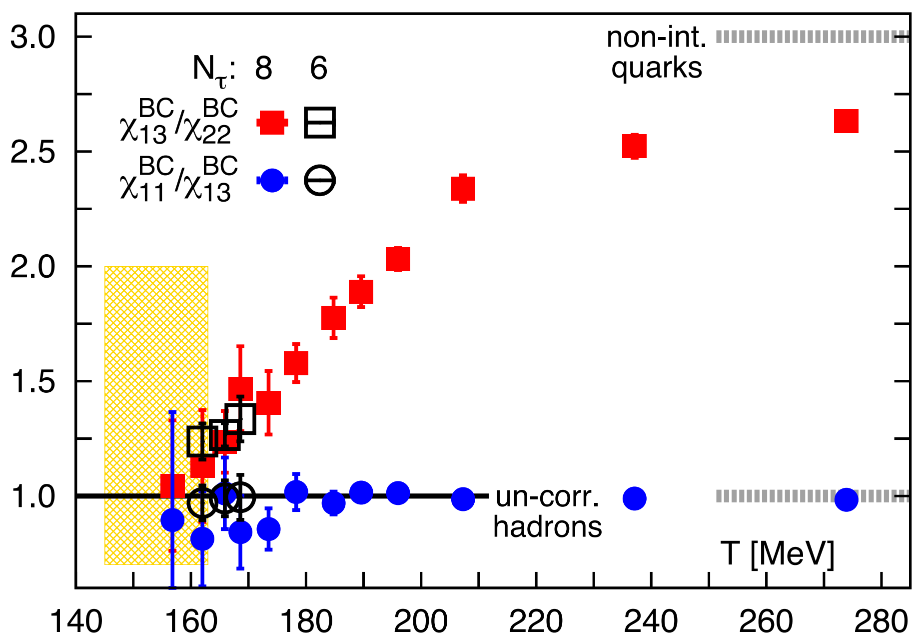
# What about charm hadrons ?

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

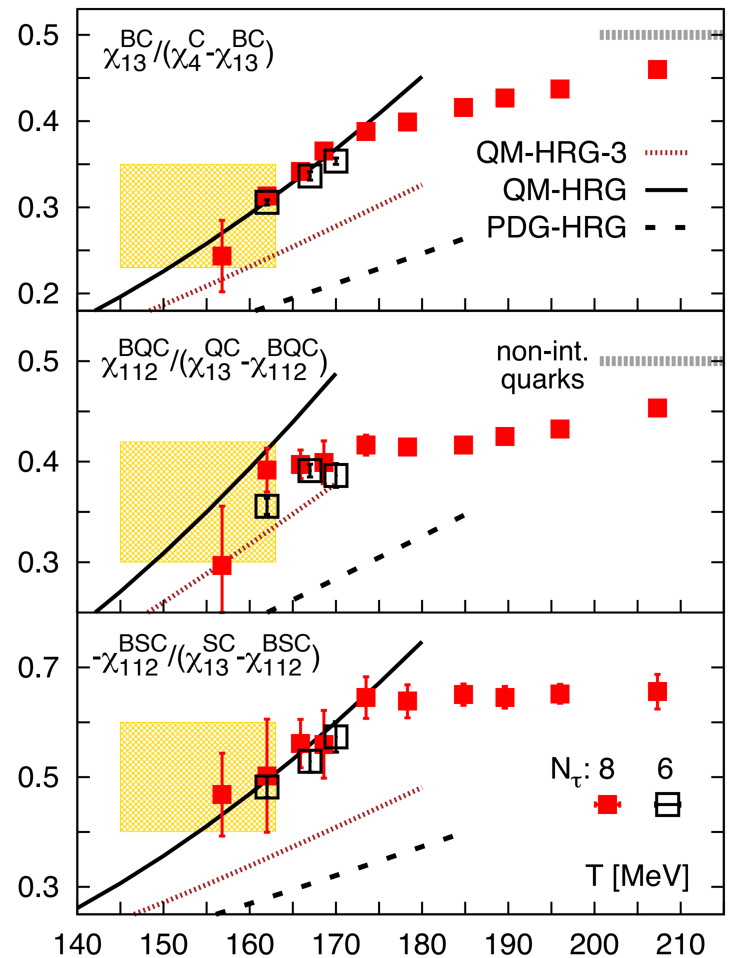
Bazavov et al, Phys.Lett. B737 (2014) 210

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

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



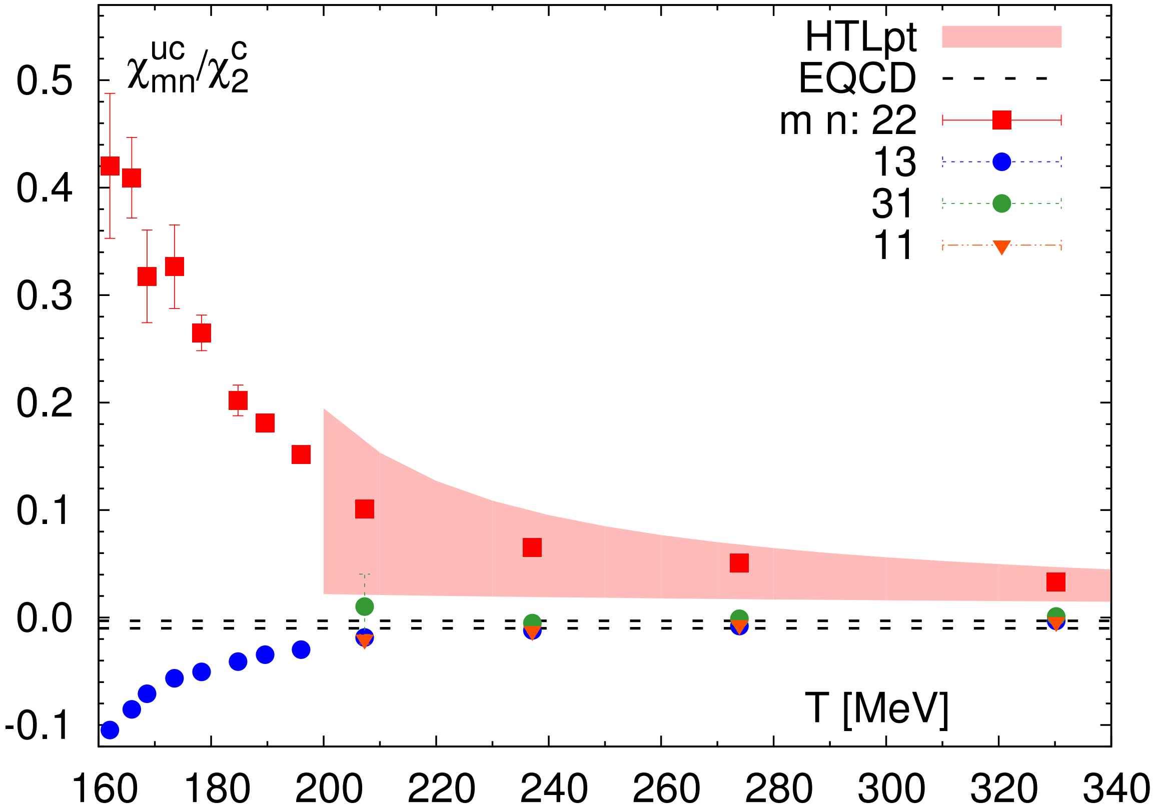

*Charm baryon to meson pressure*




Hadronic description breaks down just above $T_c$
⇒ open charm 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

# Charm quark number correlations




Quark mass effects cancel in the ratio

High T (*T>250* MeV) : $\chi^{uc}_{22} \gg \chi^{uc}_{13} \sim \chi^{uc}_{31} \sim \chi^{uc}_{11}$

Low T: correlations are large ( bound states ?)

# Quasi-particle model for charm degrees of freedom

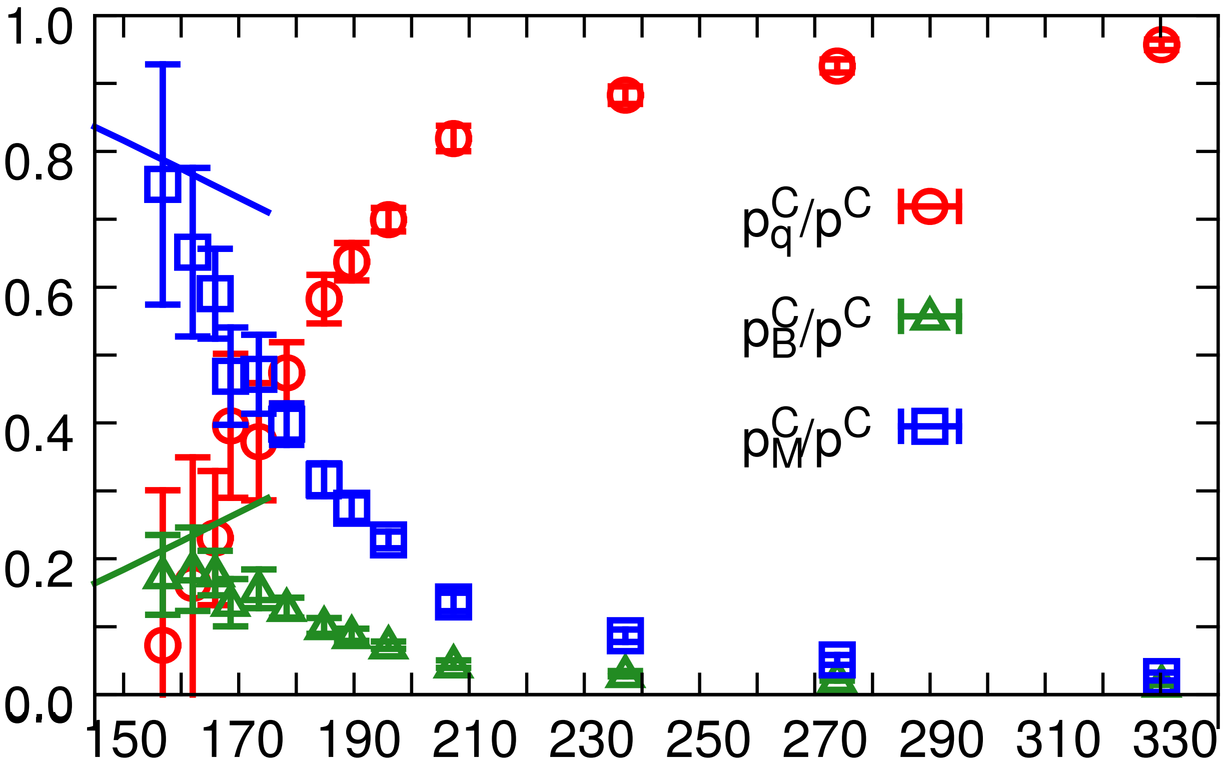
Charm dof are good quasi-particles at all *T* because $M_c >> T$ and Boltzmann approximation holds

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

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

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

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
Jakovac, PRD88 ('13), 065012
Biro, Jakovac, PRD('14)065012

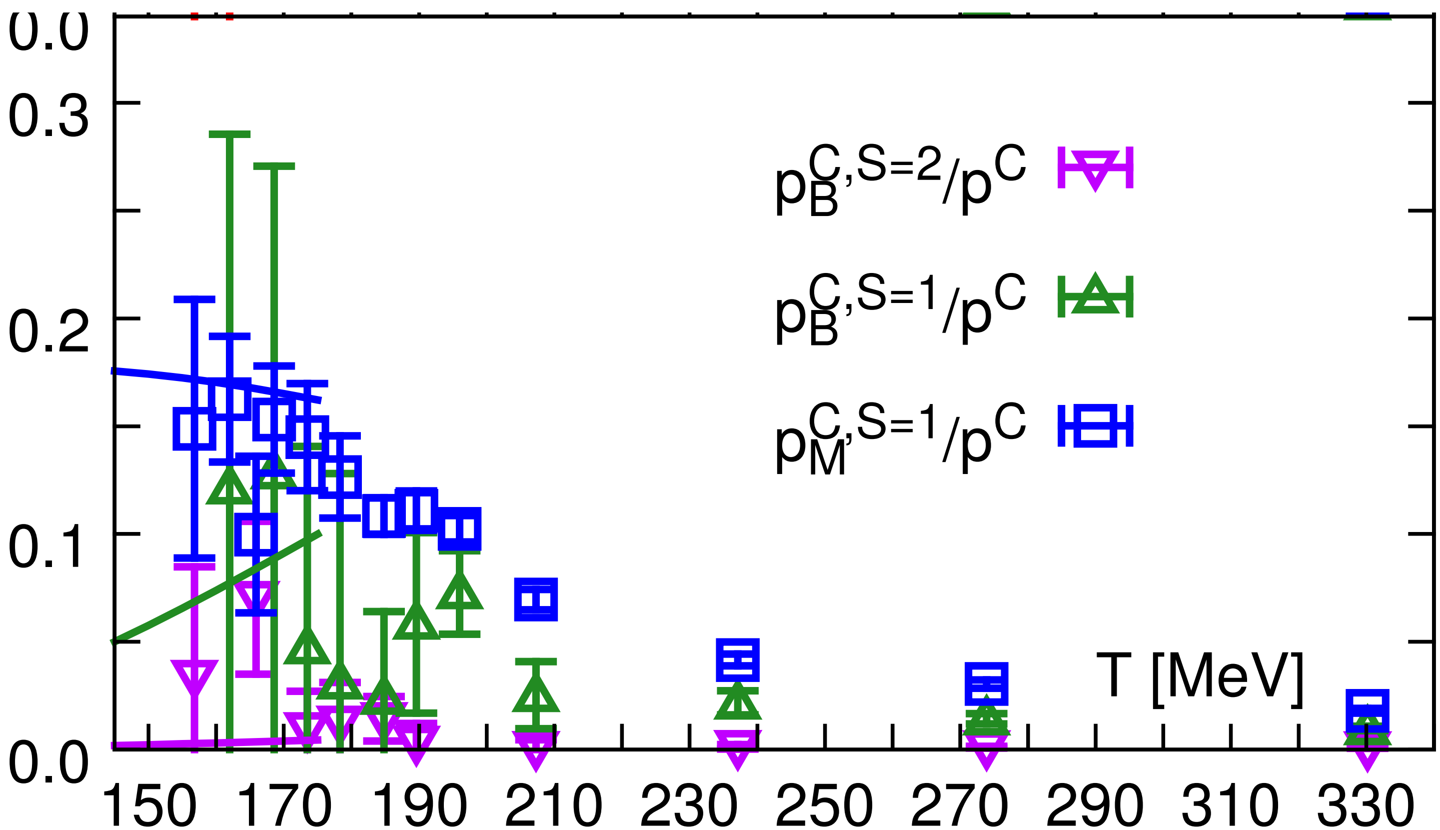
Vice versa for quarks

# Strange charm subsector

No quarks carrying both strangeness and charm
⇒ non-zero pressures in this sector implies bound charm strange bound states

Charm-strange meson and baryon pressures are consisten with HRG at $T_c$

$$p^{C,S}(T,\mu_B,\mu_S,\mu_C) = p_M^{C,S=1}(T)\cosh(\hat{\mu}_S+\hat{\mu}_C) + \sum_{j=1}^{2} p_B^{C,S=j}(T)\cosh(\mu_B - j\mu_S + \mu_C)\,.$$

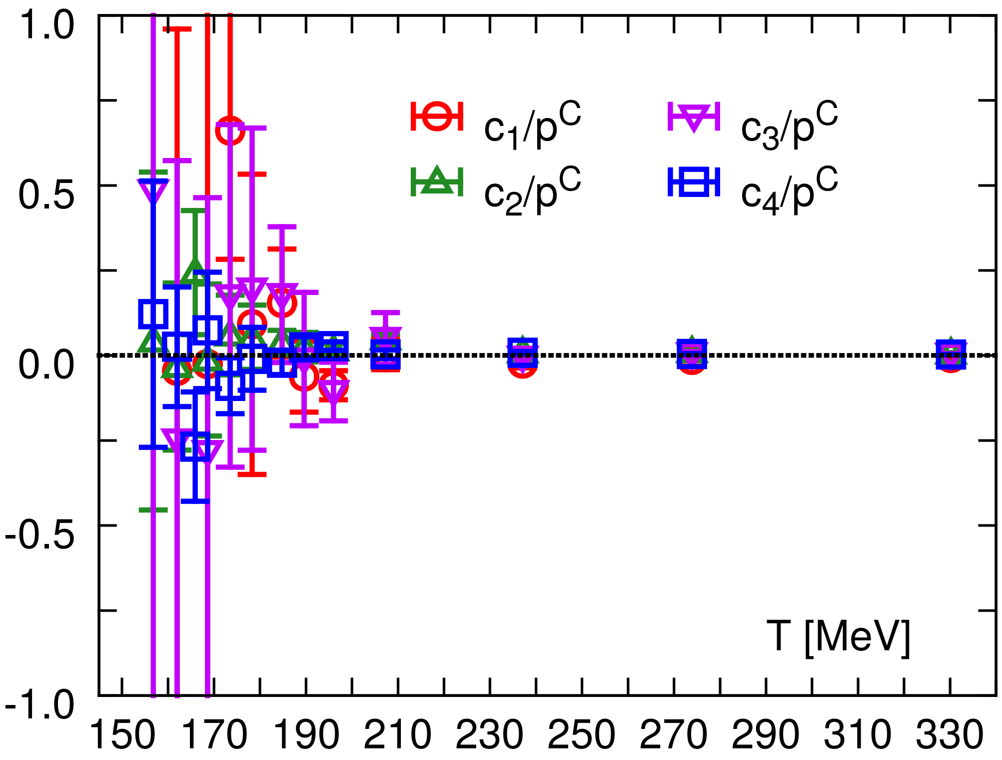


# Does the quasi-particle model makes sense ?

4 non-trivial constraints on the model provided by : $\chi_{31}^{BC}, \chi_{31}^{SC}, \chi_{121}^{BSC}, \chi_{211}^{BSC}$

$$c_1 \equiv \chi_{13}^{BC} - 4\chi_{22}^{BC} + 3\chi_{31}^{BC} = 0,$$
$$c_2 \equiv 2\chi_{121}^{BSC} + 4\chi_{112}^{BSC} + \chi_{22}^{SC} + 2\chi_{13}^{SC} - \chi_{31}^{SC} = 0$$
$$c_3 \equiv 6\chi_{112}^{BSC} + 6\chi_{121}^{BSC} + \chi_{13}^{SC} - \chi_{31}^{SC},$$
$$c_4 \equiv \chi_{211}^{BSC} - \chi_{112}^{BSC}.$$

← Diquark pressure is zero !




Models with charm quark only: correlations from an effective mass

$$m_c = m_c(T, \mu_C, \mu_S, \mu_B)$$

Taylor expand the effective mass in chemical potential

$c_n$

⇒ Un-natural fine tuning of the expansion coefficients

# Summary

- Charm correlations are consistent with weak coupling expecations for *T>250* MeV
- The lattice results on charm correlations suggest the existence of charm hadrons above $T_c$ which are distinct from vacuum charm hadrons and are in fact are the dominat dof.
- Charm quarks dominate the charm pressure only for *T>200* MeV
- Quasi-particle models with only quark degrees of freedom cannot describe the lattice data on charm fluctuations and correlations