Deconfinement and Hadron Resonance Gas for Heavy Quarks

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1) Static quarks (Polyakov loops) and deconfinement in QCD
2) Gas of static-light hadrons and Polyakov loop
3) Charm fluctuations, charm-baryon number correlations and charm hadrons in QCD at *T>0*

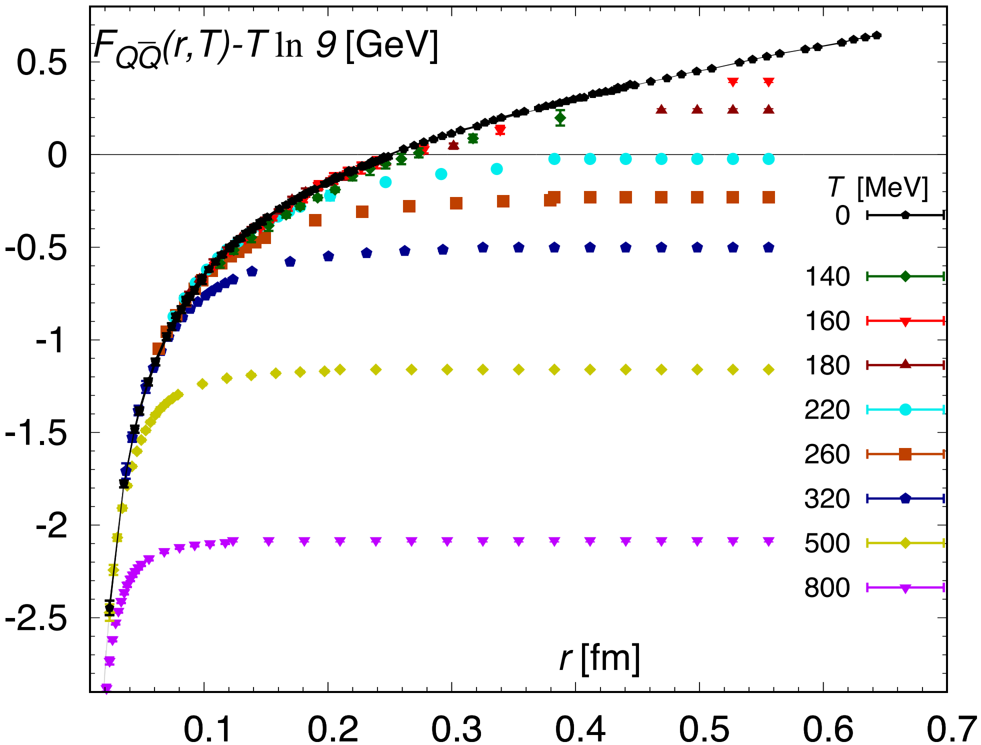
Criticality in QCD and Hadron Resonance Gas, July 29-31, 2020

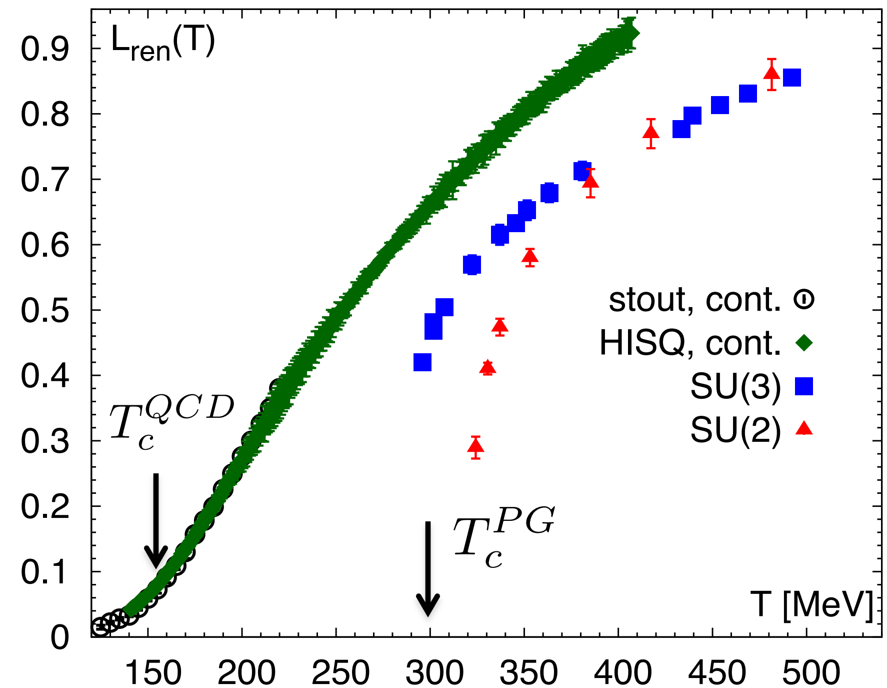
Deconfinement and color screening

Onset of color screening is described in terms of the free energy of static quark anti-quark pair

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

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





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

$F_Q < 0$ at high T ! LO: $F_Q = -C_F \alpha_s m_D$ TUMQCD, PRD 98 (2018) 054511

Renormalization of the Polyakov loop using gradient flow

$$\dot{V}_t(x,\mu) = -g_0^2(\partial_{x,\mu} S[V_t])V_t(x,\mu) \quad V_t(x,\mu)|_{t=0} = U(x,\mu)$$

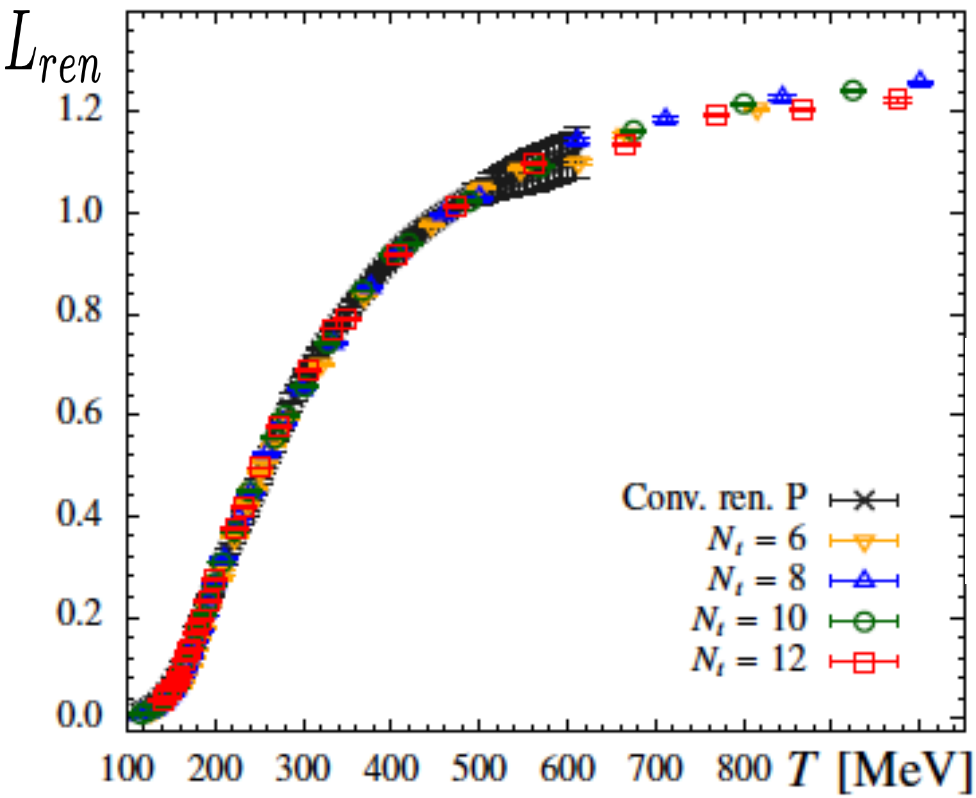
Symanzik action

Lüscher, JHEP 08 (2010) 071,
Fodor et al, JHEP 1409 (2014) 018

See talk by Kaczmarek

Use Symanzik flow to renormalize the Polyakov loop and reduce the noise

PP, Schadler, PRD92 (2015) 094517



Operators get renormalized for finite flow time $f = a\sqrt{8t} = \text{const}$

$$a \ll f \ll 1/T$$

$$f = \begin{cases} 3f_0 & \text{for } T < 200 \text{ MeV}, \\ 2f_0 & \text{for } 200 \text{ MeV} \leq T \leq 300 \text{ MeV}, \\ 0.50 f_0 & \text{for } 300 \text{ MeV} \leq T < 600 \text{ MeV}, \\ 0.25 f_0 & \text{for } T \geq 600 \text{ MeV}, \end{cases}$$

$$f_0 = 0.2129 \text{ fm}.$$

$F_Q = -T \ln L_{ren} < 0$ at high T

LO: $F_Q = -C_F \alpha_s m_D$

Agrees with the conventional renormalization procedure after x *exp(C/T)*

Casimir scaling of the Polyakov loop

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

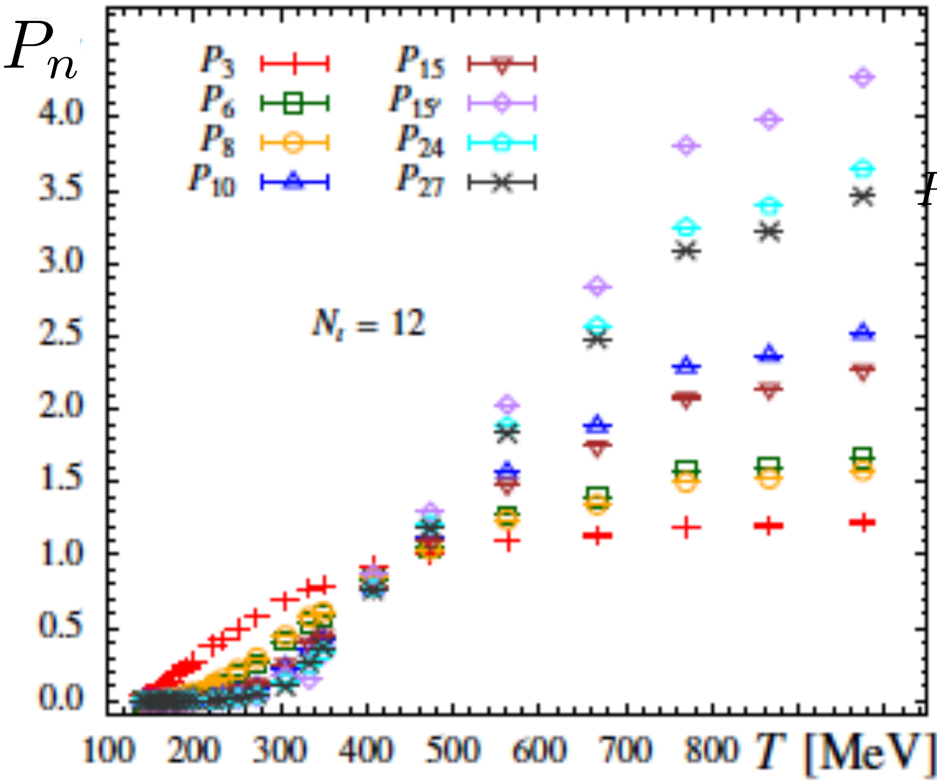
PP, Schadler, PRD92 (2015) 094517

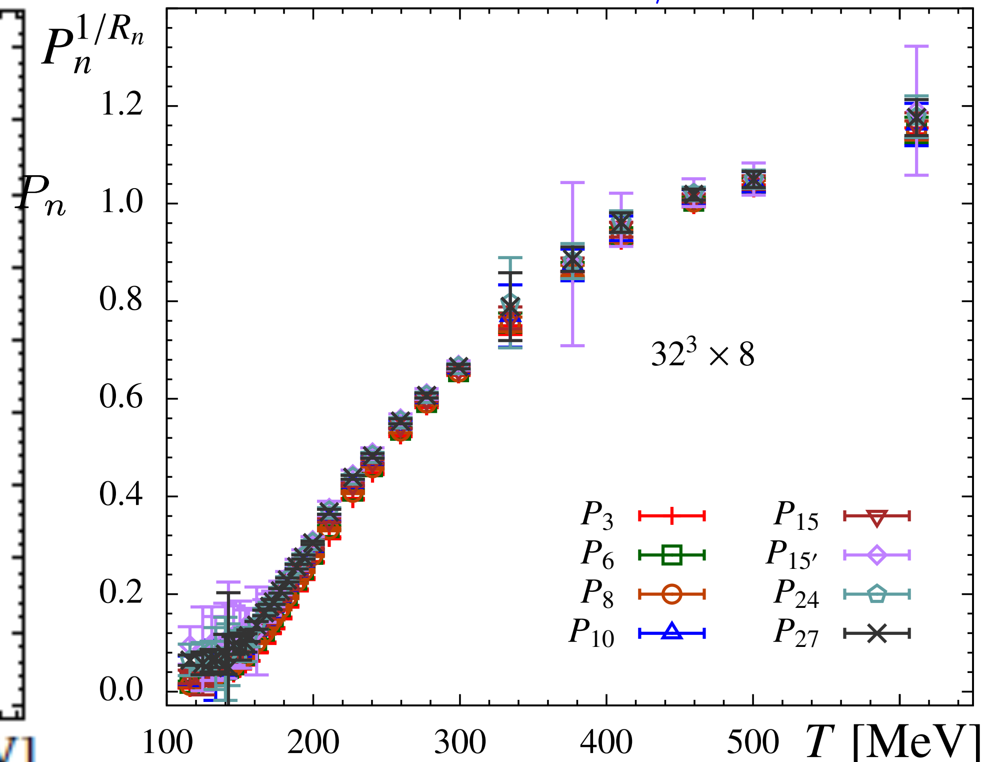
$$P_3 = L_{ren}$$

The use of the gradient flow to renormalized reduces the noise in higher representations

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

$$R_n = C_n / C_3$$

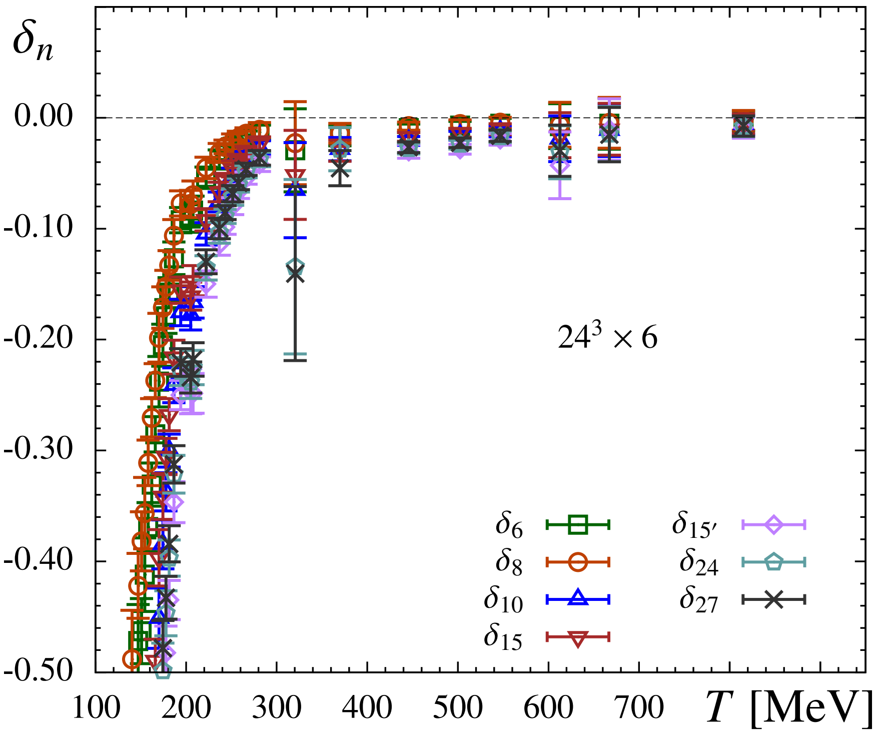


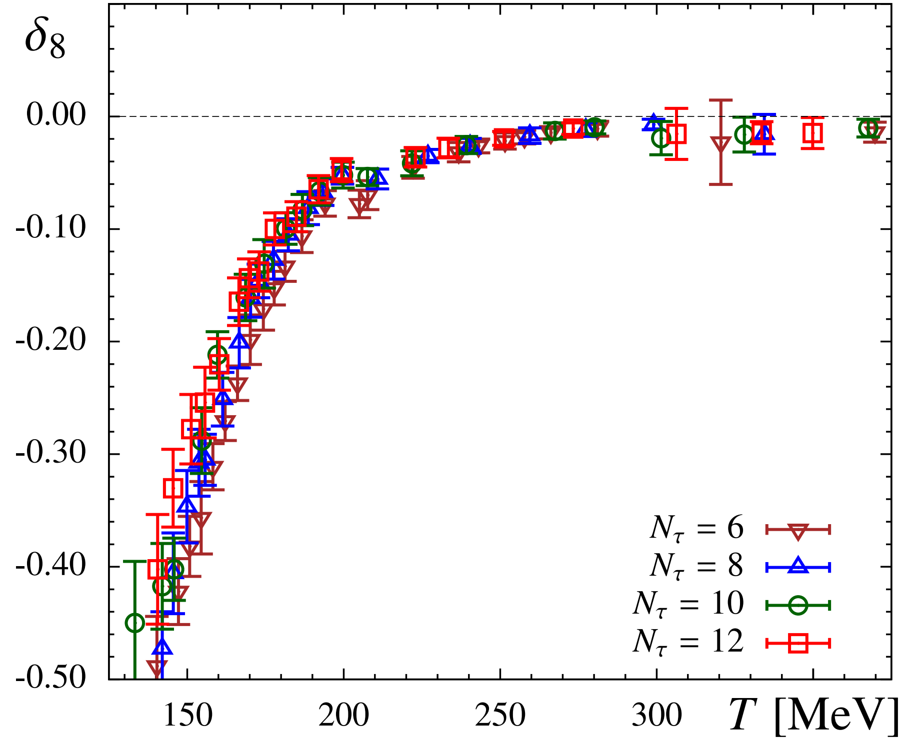


Expected in weak coupling expansion: e.g. at LO $F_Q^n = -C_n \alpha_s m_D$

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

Similar findings at high *T* in SU(N) gauge theories
Redlich, Satz, PLB 213 (1988) 191; Gupta et al, PRD 77 (2008) 034503

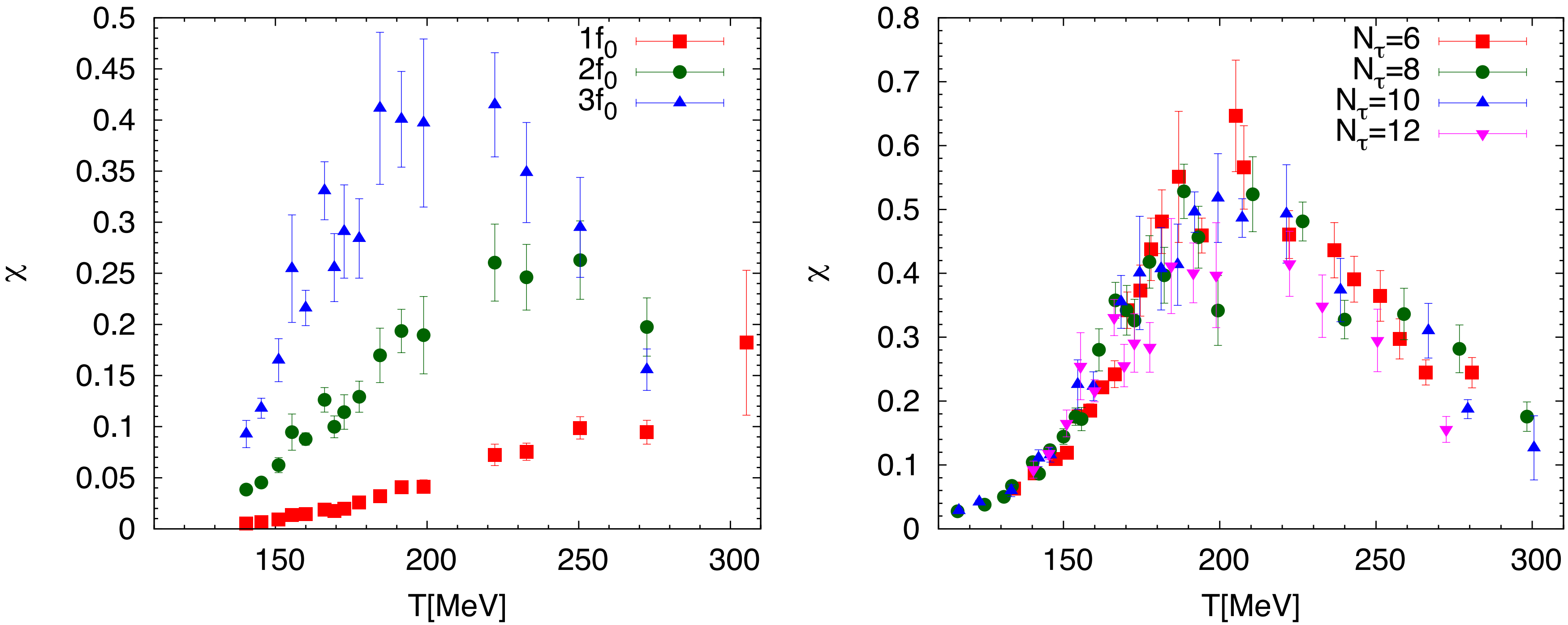
Fluctuations of the Polyakov loop

The gradient flow allows us to renormalize also the fluctuations of the Polyakov loop and study the deconfinement transition

$$\chi = VT^3 \left(\langle |L|^2 \rangle - \langle |L| \rangle^2 \right)$$

has a peak in $SU(N)$ gauge theories and diverges in the $V \to \infty$ limit

TUMQCD, PRD 93 (2016) 114502



- Polyakov loop fluctuations show only small cutoff dependence if any
- There is a significant dependence on the flow time
- Polyakov loop fluctuations show a peak at $T \approx 180\text{-}200$ MeV which is larger than T_c

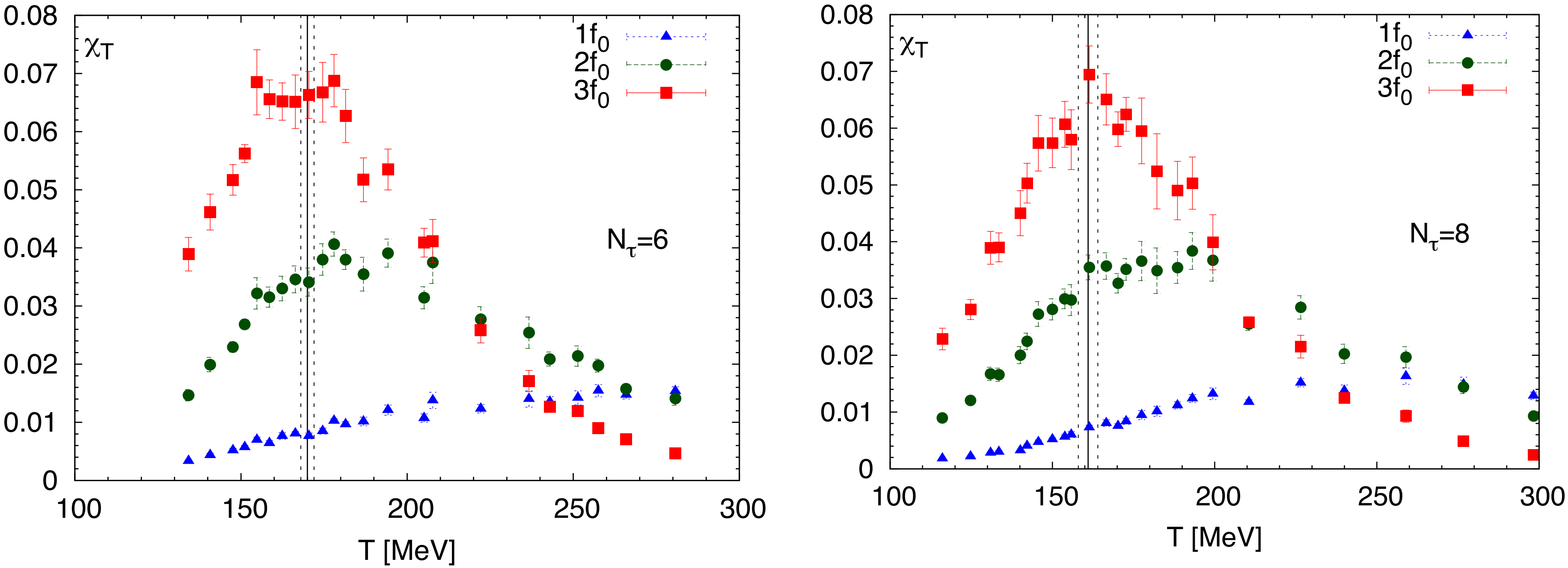
Fluctuations of the Polyakov loop (cont'd)

One can also study fluctuations of the real and imaginary part of the Polyakov loop

$$\chi_L = VT^3 \left(\langle (\mathrm{Re}L)^2 \rangle - \langle |L| \rangle^2 \right) \qquad \chi_T = VT^3 \langle (\mathrm{Im}L)^2 \rangle$$

Lo et al, PRD88 (2012) 014506

TUMQCD, PRD 93 (2016) 114502



χ_T has a peak at the chiral transition temperature T_c

χ_L is similar to χ

Polyakov loop and gas of static-light hadrons

$$Z_{Q\bar{Q}}(T)/Z(T) = \sum_n \exp(-E_n^{Q\bar{Q}}(r \to \infty)/T)$$

Energies of static-light hadrons: $E_n^{Q\bar{Q}}(r \to \infty) = 2M_n^{static-light} - 2m_Q$

Free energy of an isolated static quark: $F_Q(T) = -\frac{1}{2}(T \ln Z_{Q\bar{Q}}(T) - T \ln Z(T))$

At very low temperature F_Q or L_{ren} is determined by the lightest static-light hadrons:
6 meson and 21 baryon states if counting spin-isospin degeneracies

Megias, Arriola, Salcedo, PRL 109 (12) 151601

Number of colors

$$3L_{bare} = 4\exp(-M^0/T) + 2\exp(-M_s^0/T) + \sum_I \sum_j (2I+1)(2j+1)\exp(-M_{I,j}^{B0}/T),$$

Masses depend on the UV cutoff

At higher temperatures interactions between the static light hadrons and the medium have to be taken into account and it is assumed these are mediated by resonances
=> HRG of static-light hadrons

$$L_{ren} = \frac{1}{3}\exp(-\Delta/T)(4 + 2\exp(-E_0^s/T) + \sum_{n,I,j}(2I+1)(2j+1)\exp(-E_{n,I,j}/T))$$

$$E_0^s = M_s^0 - M^0, E_{n,I,j} = M_{n,I,j} - M^0$$

Bazavov, PP, PRD 87 (2013) 094505

Polyakov loop and gas of static-light hadrons

Need to determine E_0^s and $M_{n,j,I}$

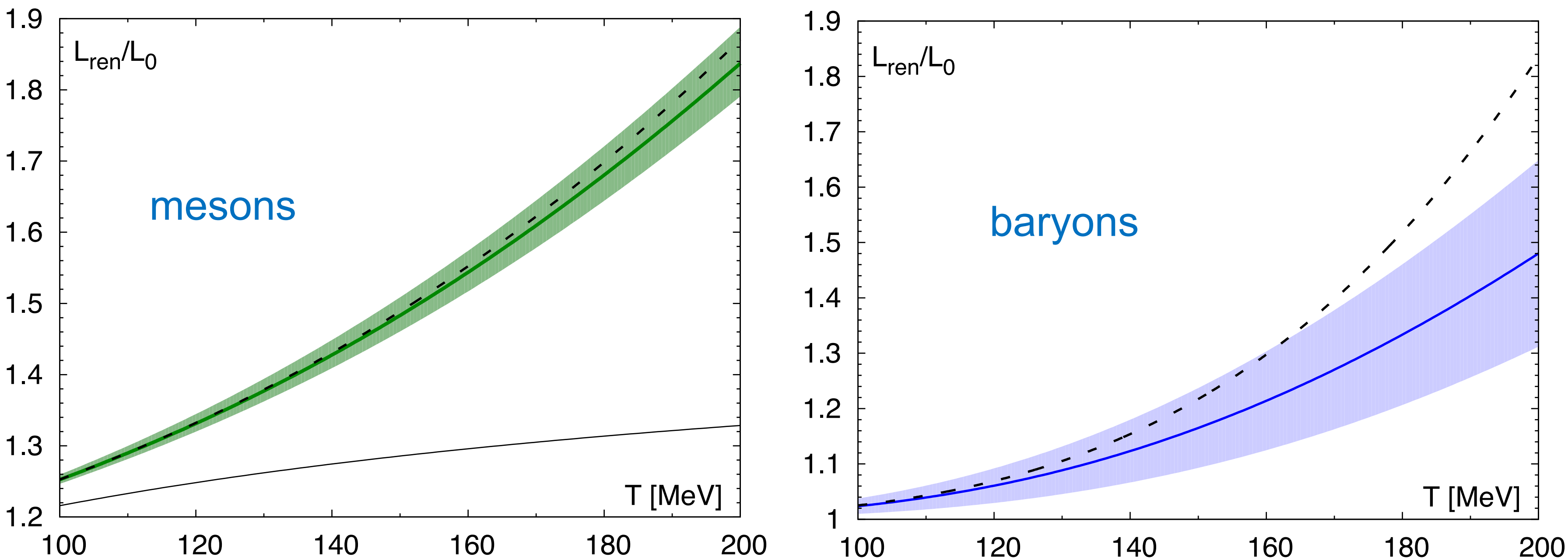
Use massed of D, D_s, B and B_s mesons from PDG to get $E_0^s \simeq 84$ MeV

$E_{n,j,I}$ from lattice QCD for ground and lower excited states

Michael, Schindler, Wagner, JHEP 1008 (2010) 009, Wagner, Wiese, JHEP 1107 (2011) 016
Bali et al, arXiv:1108 .6147

$E_{n,j,I}$ from heavy-light potential model for higher excited states

Godfrey, Isgur, PRD32 (1985) 189; Godfrey, Kokoski PRD43 (1991) 1679; Ebert et al, PRD57 (1998) 5663, PRD 84 (2011) 014025; Capstick, Isgur, PRD34 (1986) 2809

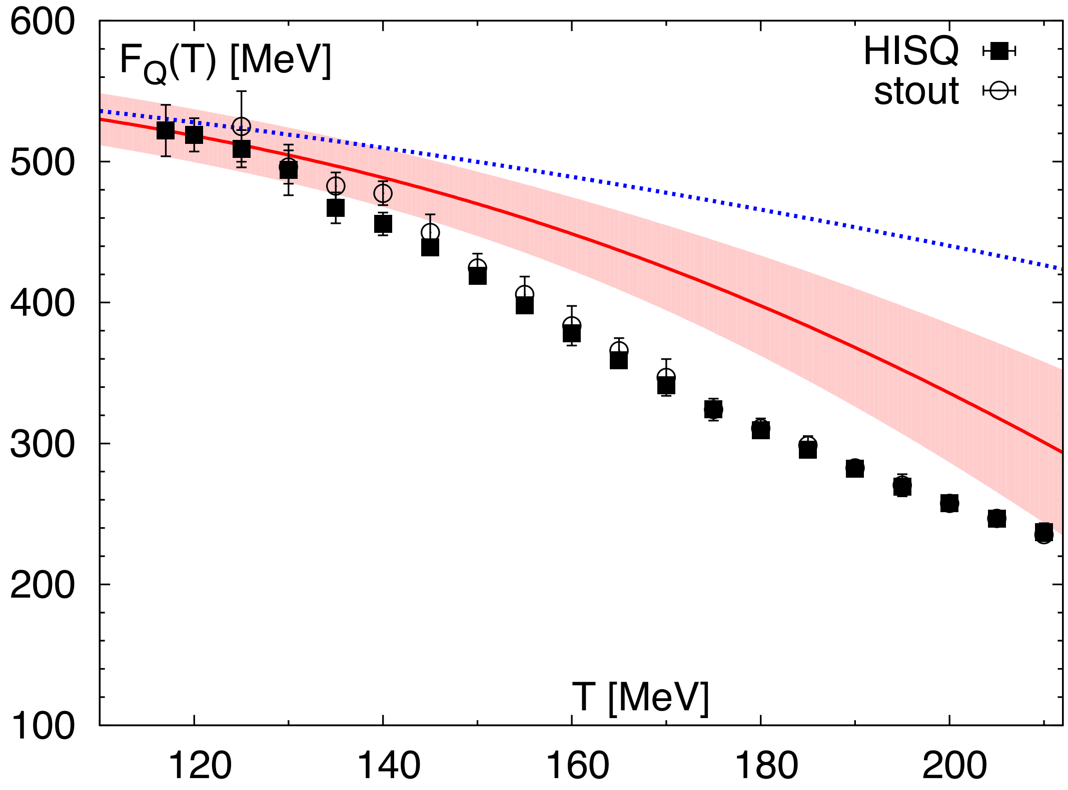


$$L_0 = 4\exp(-\Delta/T)/3$$

Polyakov and gas of static-light hadrons

Match to the continuum lattice result on $F_Q \Rightarrow \Delta = 593 \pm 18$ MeV

Bazavov, PP, PRD 87 (2013) 094505



Gas of static-light hadrons only works for *T < 145* MeV and there is a clear disagreement with the lattice data at higher temperature

Lattice data have an inflection point around T=150-160 MeV

The entropy of static quark

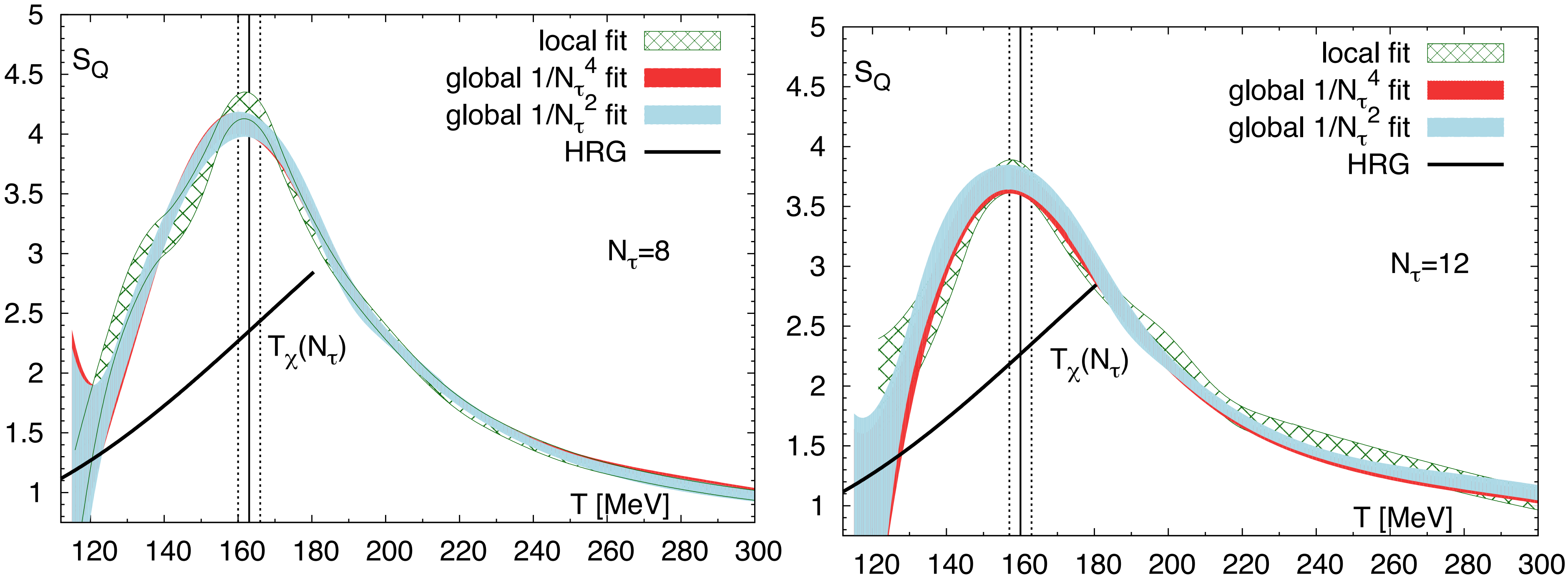
The inflection point *of $L_{ren}(T)$* can define a deconfinement transition temperature but depends on the normalization

However, the entropy

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

does not depend on normalization and carries the same information about deconfinement and color screening $\Rightarrow$ define T_{deconf} from S_Q

TUMQCD, PRD 93 (2016) 114502



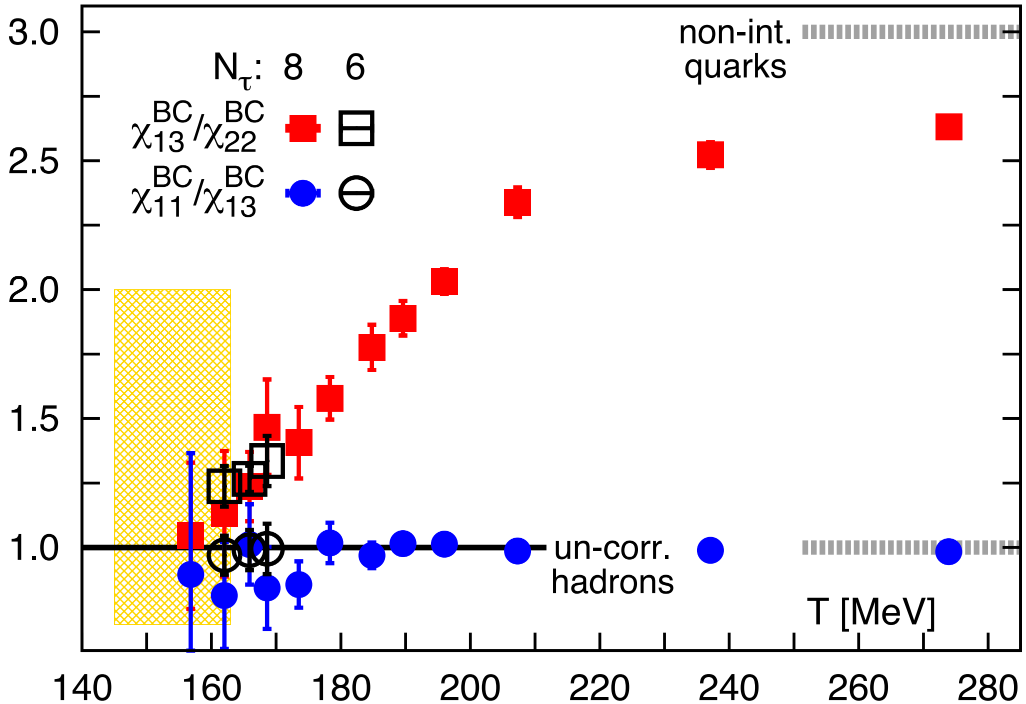
The onset of screening corresponds to peak is S_Q and its position coincides with T_c

Charm fluctuations and charm-baryon number correlations

$$\chi_{klmn}^{BQSC} = T^{k+l+m+n} \frac{\partial^{(k+l+m+n)}[P(\mu_B,\mu_Q,\mu_S,\mu_C)/T^4]}{\partial\mu_B^k \partial\mu_Q^l \mu_S^m \partial\mu_C^n}\Bigg|_{\vec{\mu}=0}$$

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

Bazavov et al, PLB737 (2014) 210



See also
Borsayi et al (B-W Coll.)
PRD92 (2015) 114505

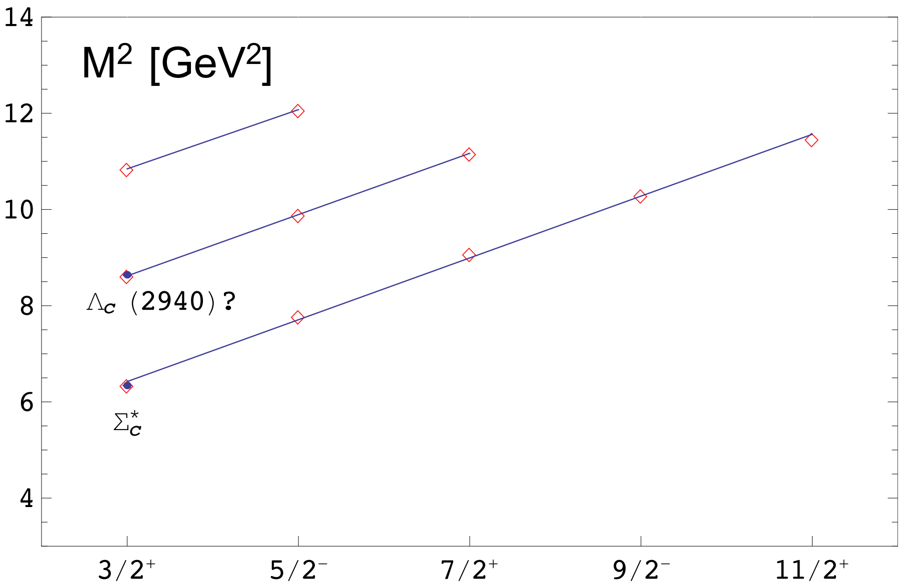
In the hadronic phase all *BC*-correlations are the same !

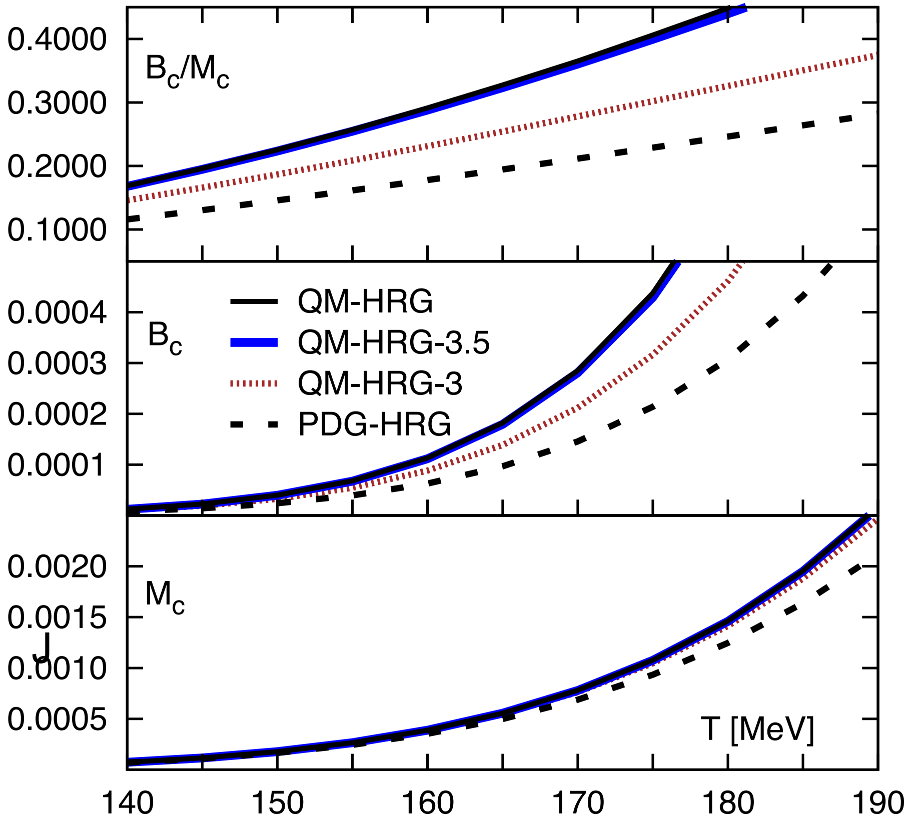
Hadronic description breaks down just above T_c
⇒ open charm deconfines above T_c ?

Baryon-charm correlations and “missing” charm baryons

Charmed baryon spectrum is poorly known

Ebert et al, PRD84 (2011) 014025



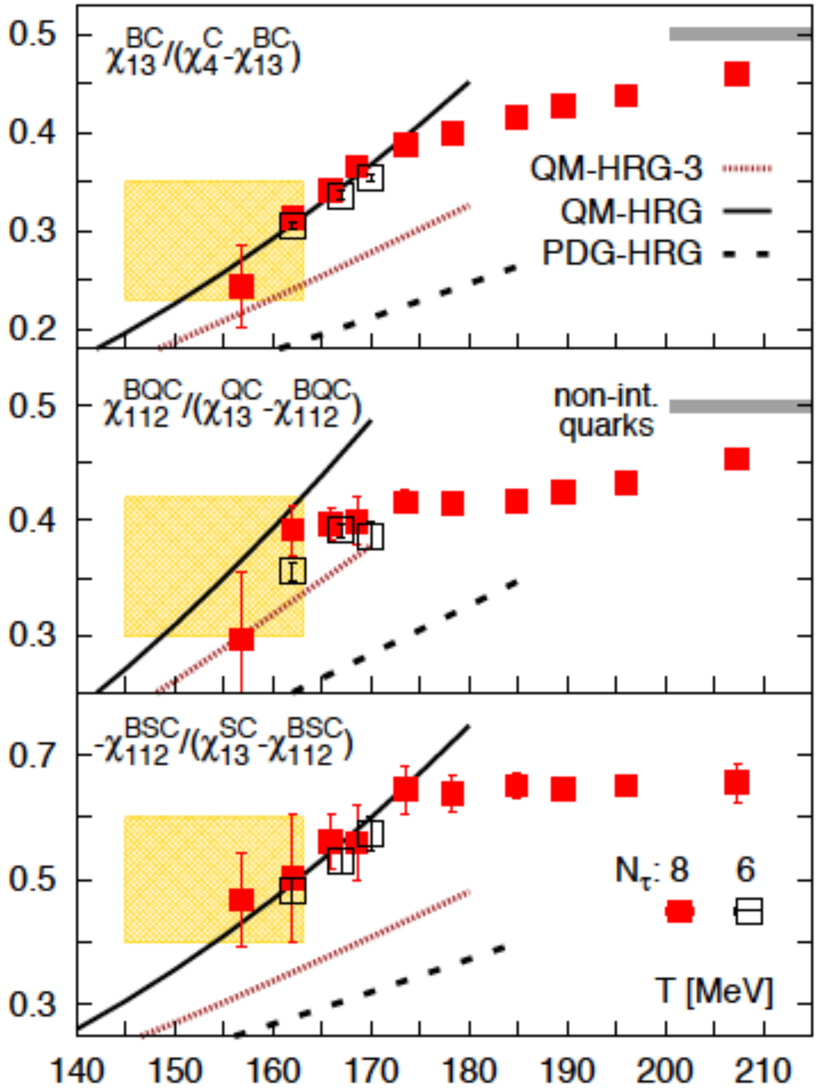


Use baryon-charm correlations and HRG to look for missing states

Bazavov et al, PLB737 (2014) 210

$$p_c(T,\mu_C,\mu_B)=\sum_M \frac{g_M}{2\pi^2}\frac{m_M^2}{T^2}K_2(m_M/T)\cosh(\mu_C/T)+\sum_B \frac{g_B}{2\pi^2}\frac{m_B^2}{T^2}K_2(m_B/T)\cosh((\mu_C+\mu_B)/T)$$

Baryon-charm correlations and "missing" charm baryons



Lattice artifacts largely cancel out in the ratios that are proxies for the charm baryon pressure to charm meson pressure

Bazavov et al, PLB737 (2014) 210

HRG works only
if the "missing" states are included

Quasi-particle model for charm degrees of freedom

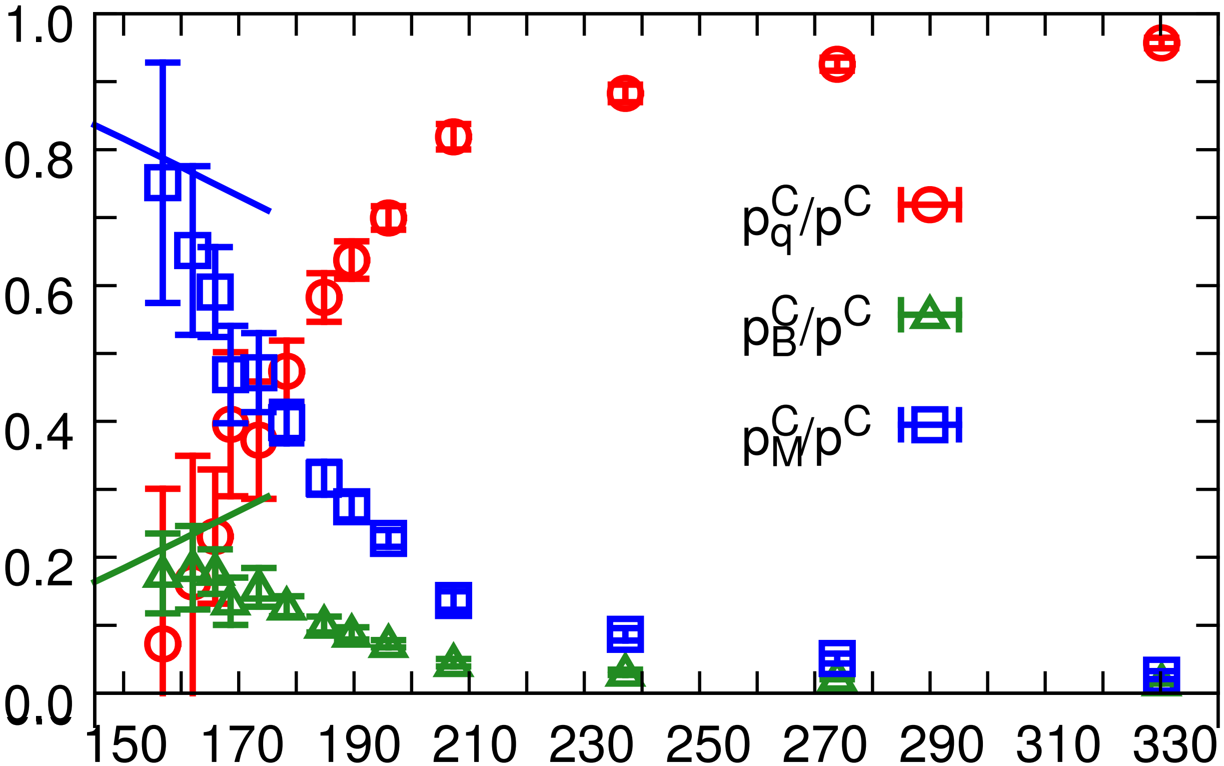
Charm dof are good quasi-particles at all *T* because $M_c >> T$ and Boltzmann approximation holds

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

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

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

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 excitations become broad at high temperatures (bound state peaks merge with the continuum)

S. Mukherjee, PP, S. Sharma, PRD93 (2016) 014502

Vice versa for quarks

Summary

- Polyakov loop in QCD behaves quite differently from the SU(N), where it is an order parameter; L_{ren} is quite small at T_c

- Gradient flow can be used to study renormalized Polyakov loop in different representations as well as the fluctuations of Polyakov loops

- Fluctuations of Polyakov loops in QCD do not show the expected characteristic behavior near T_c , though its imaginary part may

- The entropy of a static quark shows a peak at T_c, and in this sense deconfinement and chiral transitions coincide

- HRG model for static-light hadrons does not describe the Polyakov loop

- Charm-baryon number correlations are described by HRG if the missing charm baryons are included

- Charm-baryon number correlations above T_c are consistent with existence of charm hadron like excitations for $T<200$ MeV