Strangeness, Charm and Charmonia at High Temperatures

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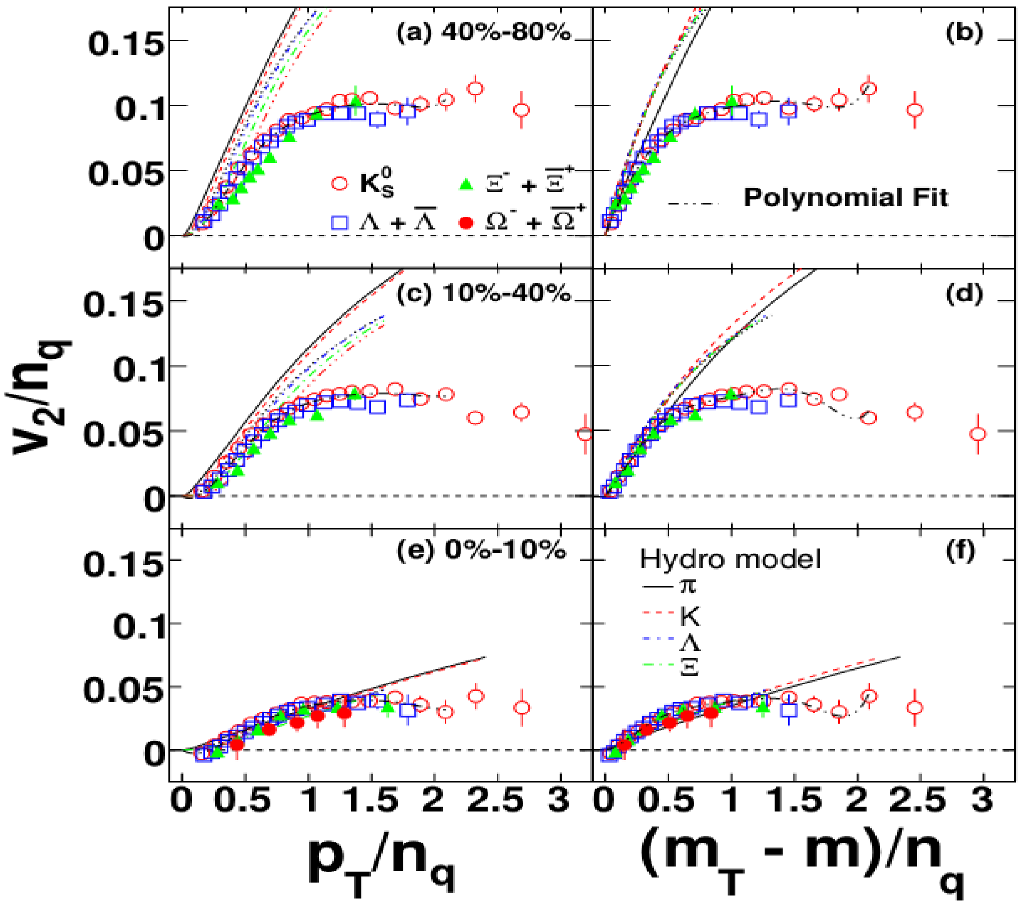
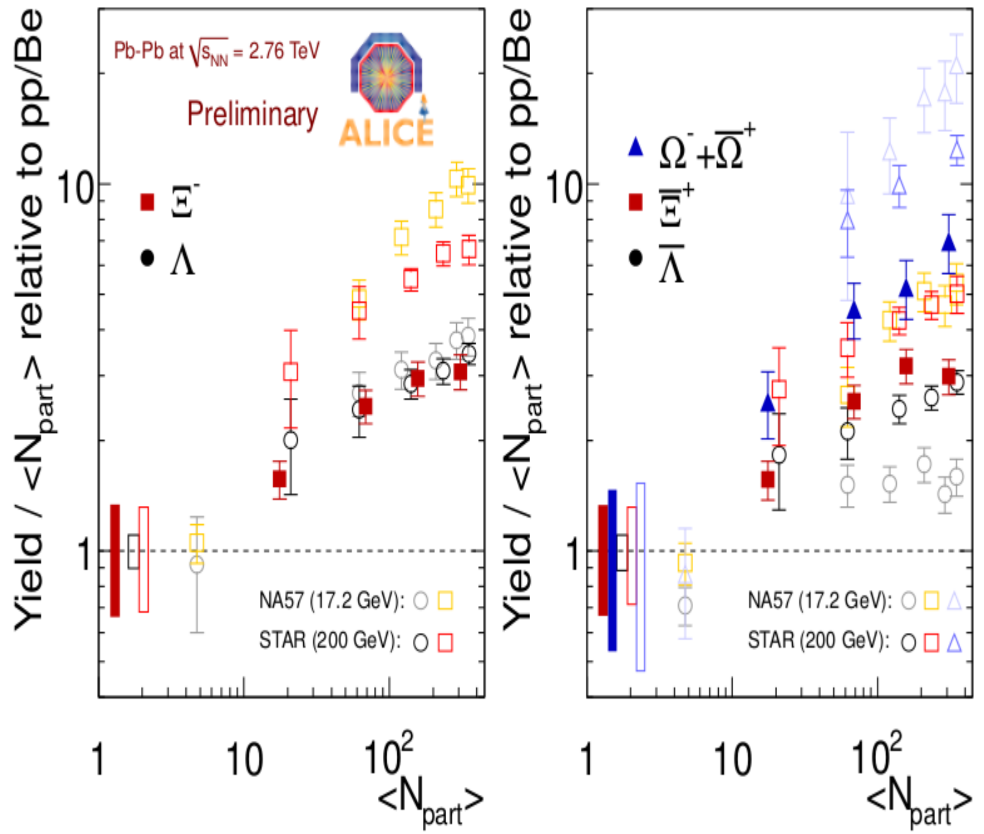
Deconfined strange and charm quarks in HIC



constituent quark number scaling of strange hadron elliptic flow

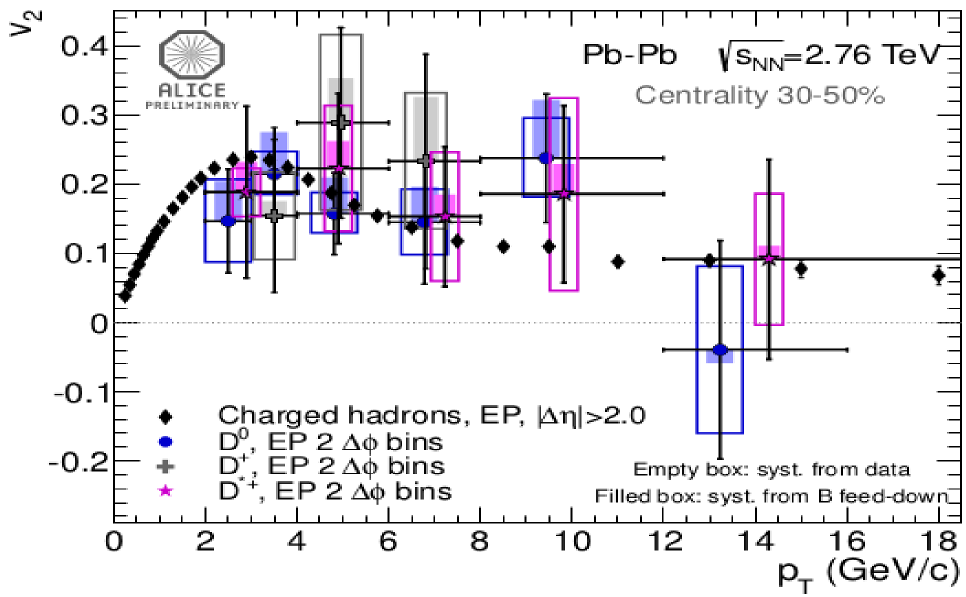
STAR: Phys.Rev. C77, 054901 (2008)



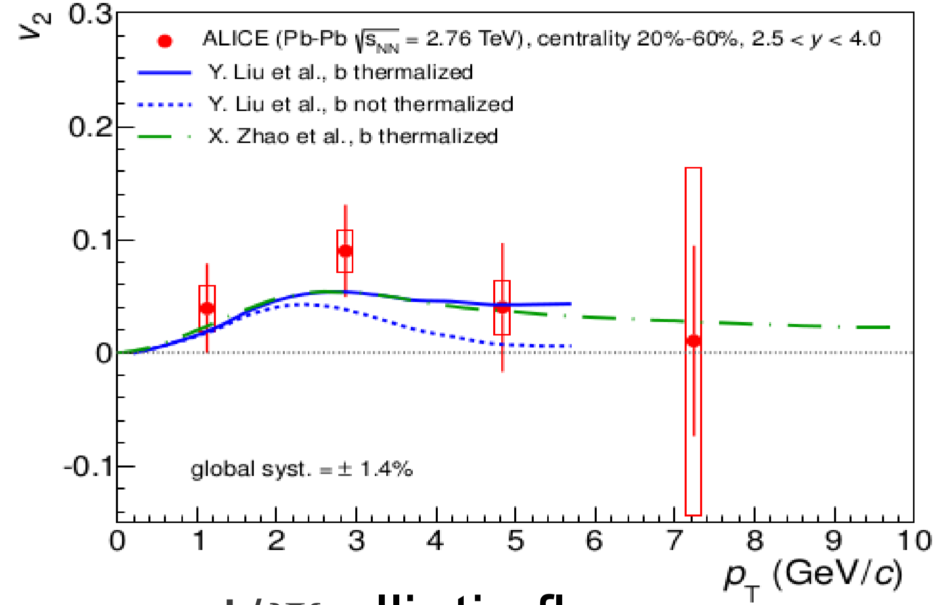
strangeness enhancement

ALICE: Acta Phys. Polon. Supp. 5, 237 (2012)

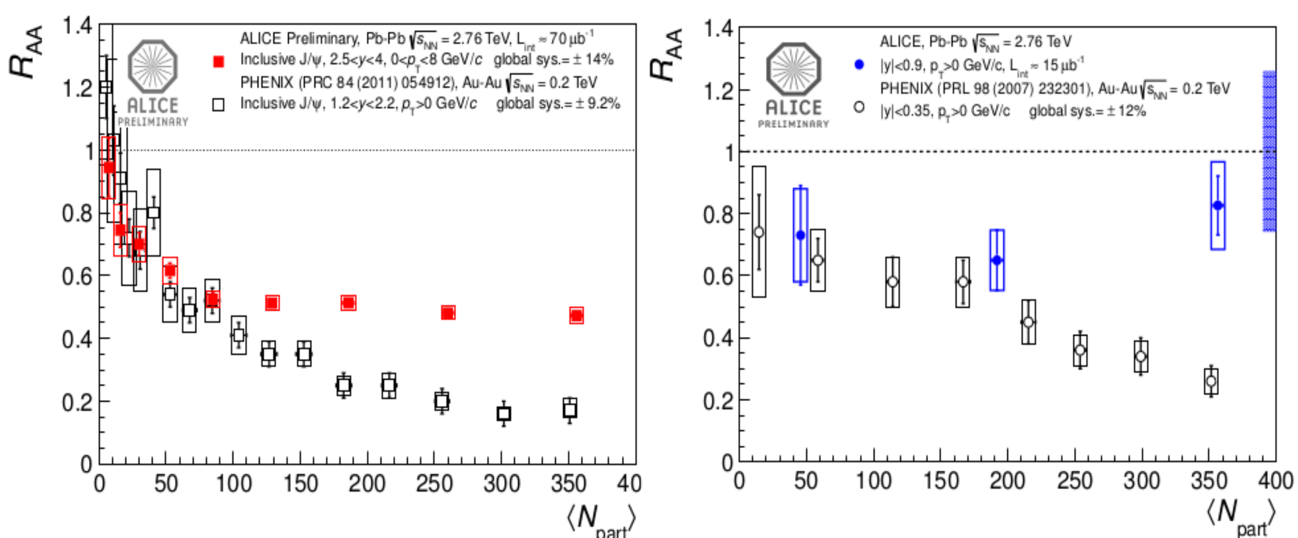
Deconfined strange and charm quarks in HIC



D meson elliptic flow



J/Ψ elliptic flow



J/Ψ suppression

partonic nature of strange & charm degrees of freedom in QGP

ALICE (A. Andronic): Journal of Physics Conference Series 455, 012002 (2013)

Influence of chiral crossover on deconfinement ?

liberation of quark DoF, $N_c^0 \rightarrow N_c \Rightarrow$ rise in quark number fluctuations

up & down, quarks deconfine around the chiral crossover

imprint of the chiral nature of the crossover

strange quark deconfines above the chiral crossover ?

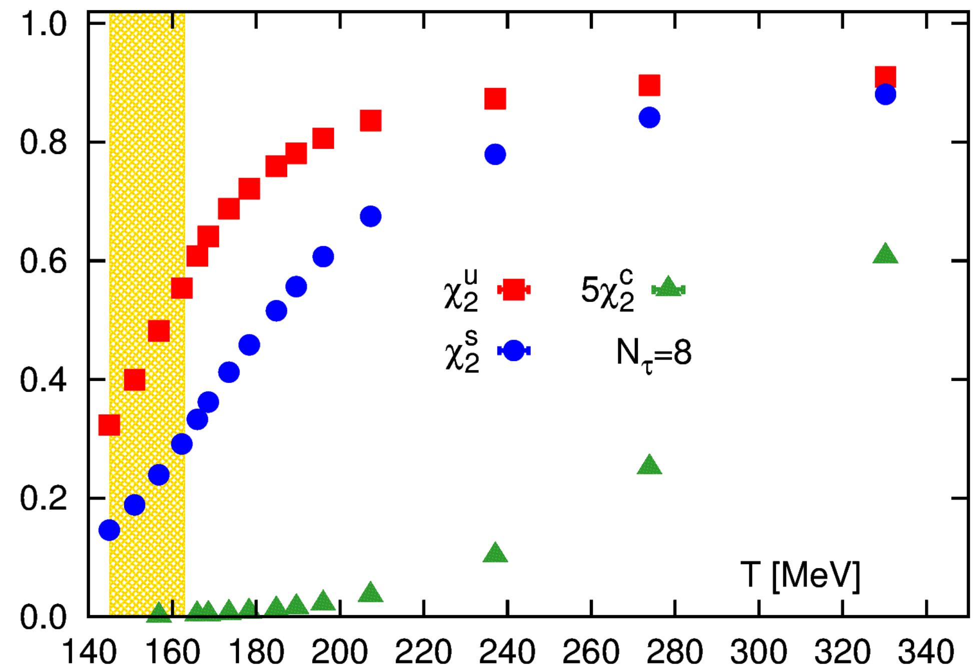
strange quark too heavy to be influenced by the chiral nature of the crossover ?

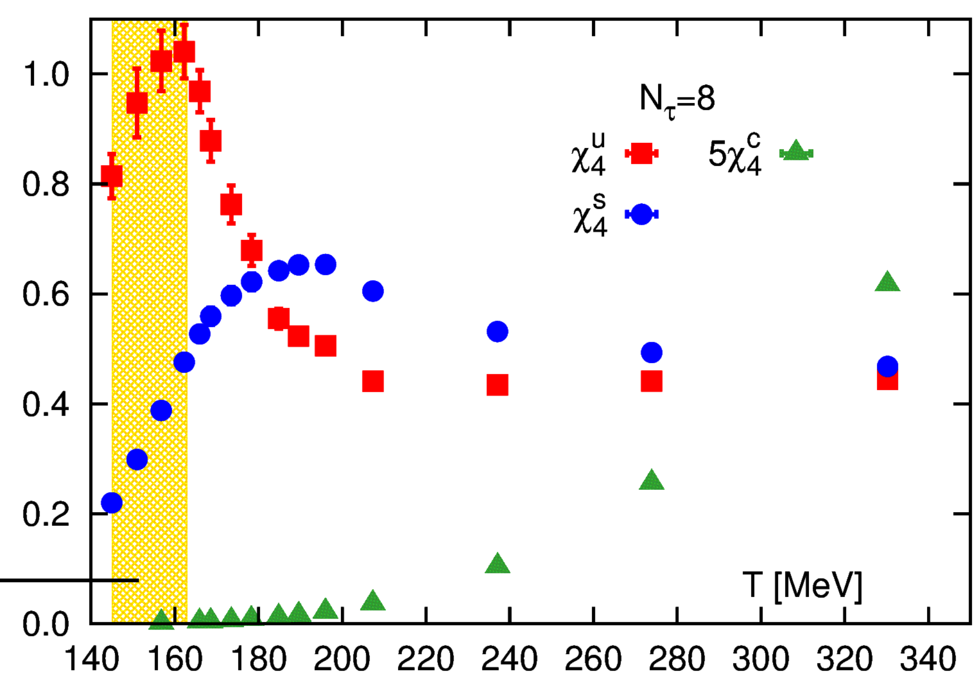
charm quarks remain confined well above the chiral crossover ?

chiral symmetry plays no role in charm quark deconfinement ?

chiral crossover: $T_c = 154(9)$ MeV

HotQCD: Phys. Rev. D85, 054503 (2012)





Need to look for proper observables

probe quantum numbers associated with sDoF & cDoF ...

higher order

baryon(B)/charge(Q)–strangeness(S) correlations

B/Q/S–charm(C) correlations

$$\chi_{mn}^{XY} = \frac{\partial^{m+n} P}{\partial^m \hat{\mu}_X \partial^n \hat{\mu}_Y} \qquad \chi_{0n}^{XY} \equiv \chi_n^Y \qquad \hat{\mu}_X = \mu_X / T \qquad P = p/T^4$$

… and construct observables from combinations of higher order S/C fluctuations, B/Q–S, B/Q/S–C correlations such that these observables are only sensitive to the quantum numbers associated with DoF irrespective of their masses

BNL-Bi: Phys. Rev. Lett. 111, 082301 (2013)

Strangeness in an uncorrelated hadron gas

$$P_S^{HRG} = P_{|S|=1,M}^{HRG} \cosh(\hat{\mu}_S) + P_{|S|=1,B}^{HRG} \cosh(\hat{\mu}_B - \hat{\mu}_S) + P_{|S|=2,B}^{HRG} \cosh(\hat{\mu}_B - 2\hat{\mu}_S) + P_{|S|=3,B}^{HRG} \cosh(\hat{\mu}_B - 3\hat{\mu}_S)$$

P_S^{HRG}: partial pressure of all |S|=/=0 hadrons

$P_{|S|=1,M}^{HRG}$: partial pressure of |S|=1 mesons

$P_{|S|=1,B}^{HRG}$: partial pressure of |S|=1 baryons

$P_{|S|=2,B}^{HRG}$: partial pressure of |S|=2 baryons

$P_{|S|=3,B}^{HRG}$: partial pressure of |S|=3 baryons

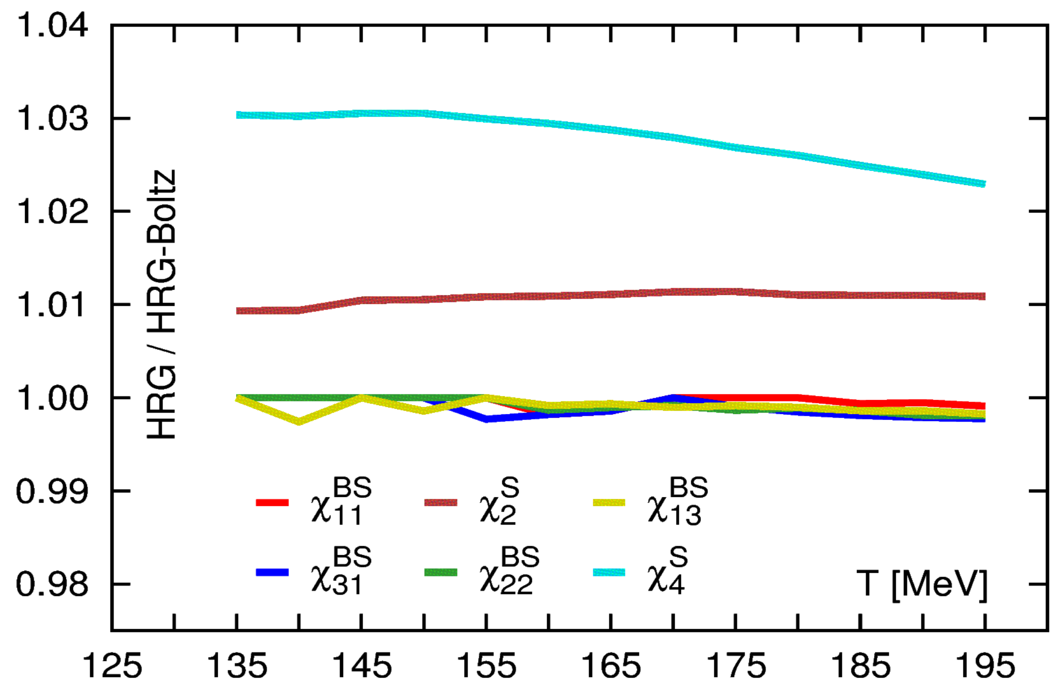
strange hadrons: $m_S^{had} \gg T$

using classical (Boltzmann) approx

up to 4th order
S fluctuations & B–S correlations

$\chi_2^S \quad \chi_4^S \quad \chi_{11}^{BS} \quad \chi_{31}^{BS} \quad \chi_{22}^{BS} \quad \chi_{13}^{BS}$

Boltzmann (classical) approx works very well for strange hadrons, deviations < 3%



Strangeness in an uncorrelated hadron gas

up to 4th order
S flucn & B–S corrln.
6 known (LQCD)

$\chi_2^S \quad \chi_{11}^{BS} \quad \chi_{13}^{BS}$

$\chi_{31}^{BS} \quad \chi_{22}^{BS} \quad \chi_4^S$

separate conrt. of strange mesons & baryons
4 unknown

$P^{HRG}_{|S|=1,M}$: partial pressure of |S|=1 mesons

$P^{HRG}_{|S|=1,B}$: partial pressure of |S|=1 baryons

$P^{HRG}_{|S|=2,B}$: partial pressure of |S|=2 baryons

$P^{HRG}_{|S|=3,B}$: partial pressure of |S|=3 baryons

$$M(s_1, s_2) = \chi_2^S - \chi_{22}^{BS} + s_1 S_1 + s_2 S_2$$

$$B_1(s_1, s_2) = \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right) + s_1 S_1 + s_2 S_2$$

$$B_2(s_1, s_2) = -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right) + s_1 S_1 + s_2 S_2$$

$$B_3(s_1, s_2) = \frac{1}{18}\left(\chi_4^S - \chi_2^S + 3\chi_{13}^{BS} + 3\chi_{22}^{BS}\right) + s_1 S_1 + s_2 S_2$$

2 constraints

$S_1 = S_2 = 0$

irrespective of hadron mass spectrum

uncorrelated hadron gas: $M(s_1, s_2) \rightarrow P^{HRG}_{|S|=1,M}$, $B_i(s_1, s_2) \rightarrow P^{HRG}_{|S|=i,B}$ for all (s_1, s_2)

Strangeness in an uncorrelated hadron gas

$$S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} \qquad S_2 = \left(\chi_S^2 - \chi_S^4\right)/3 - 2\left(\chi_{13}^{BS} + 2\chi_{22}^{BS} + \chi_{31}^{BS}\right)$$

if sDoF are (uncorrelated) hadrons
with S=1,2,3 and B=0,1
irrespective of the hadron masses

$S_1 = 0,\ S_2 = 0$

for example:

$$S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} = \left(B^3 - B\right) \times f\left(m_S^{had}\right)$$

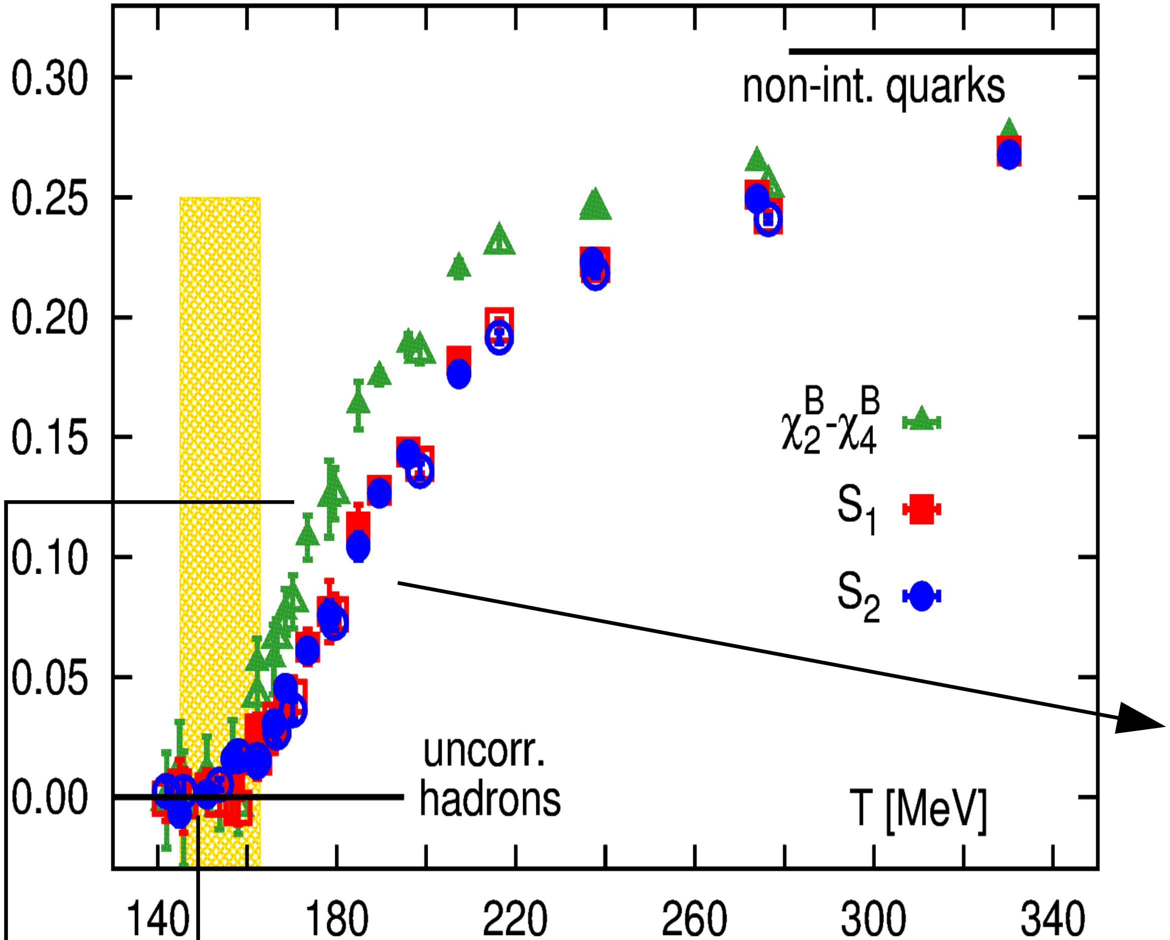
$S_1 = 0$ for $B = 0,1$

depends on the hadron mass spectrum

if sDoF are quarks then B=1/3: $S_1 \neq 0$

similarly: $\chi_4^B - \chi_2^B = \left(B^4 - B^2\right) \times f\left(m_{u,d,S}^{had}\right)$

Are there strange hadrons above the chiral crossover ?



$T \lesssim T_c$: sDoF have B=0,1

no strange hadrons for $T \gtrsim T_c$

$T \gtrsim T_c$: sDoF have fractional B

$T \lesssim T_c$: $S_1 = 0$, $S_2 = 0$

BNL-Bi:
Phys. Rev. Lett. 111, 082301 (2013)

$\chi_2^B - \chi_4^B$: light quark analog of S_1

sDoF behave similarly as the light quark DoF

Extensions to charm sector

$$C_1 = \chi_{31}^{BC} - \chi_{11}^{BC}$$

$$C_2 = \left(\chi_C^2 - \chi_C^4\right)/3 - 2\left(\chi_{13}^{BC} + 2\chi_{22}^{BC} + \chi_{31}^{BC}\right)$$

$$C_3 = 3\left(\chi_{13}^{BC} - 2\chi_{22}^{BC} + \chi_{31}^{BC}\right) + \left(\chi_{11}^{QC} - 3\chi_{13}^{QC} + 3\chi_{22}^{BC} - \chi_{31}^{BC}\right)/2$$

if sDoF are (uncorrelated) hadrons with C=1,2,3 & Q=0,1,2 and B=0,1 irrespective of the hadron masses

$C_1 = 0,\ C_2 = 0,\ C_3 = 0$

for example:

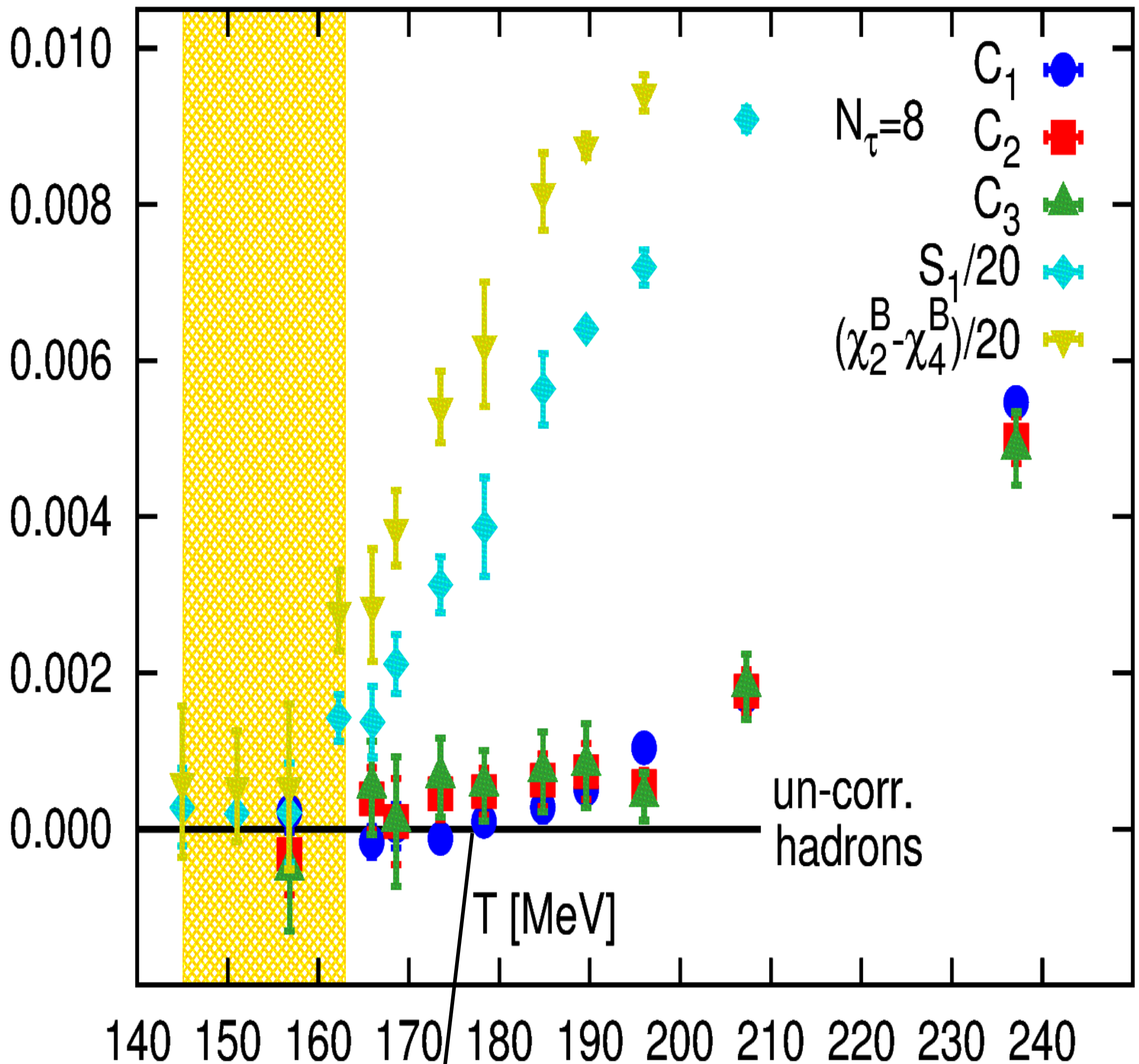
$$C_1 = \chi_{31}^{BC} - \chi_{11}^{BC} = \left(B^3 - B\right) \times f\left(m_C^{had}\right)$$

depends on the hadron mass spectrum

$$C_1 = 0 \ \text{ for } \ B = 0,1$$

if sDoF are quarks then B=1/3: $C_1 \neq 0$

Are there charmed hadrons above the chiral crossover ?



$T \lesssim 175$ MeV : $C_1 = C_2 = C_3 = 0$

$T \lesssim 175$ MeV :

cDoF have B=0,1 & Q=0,1,2

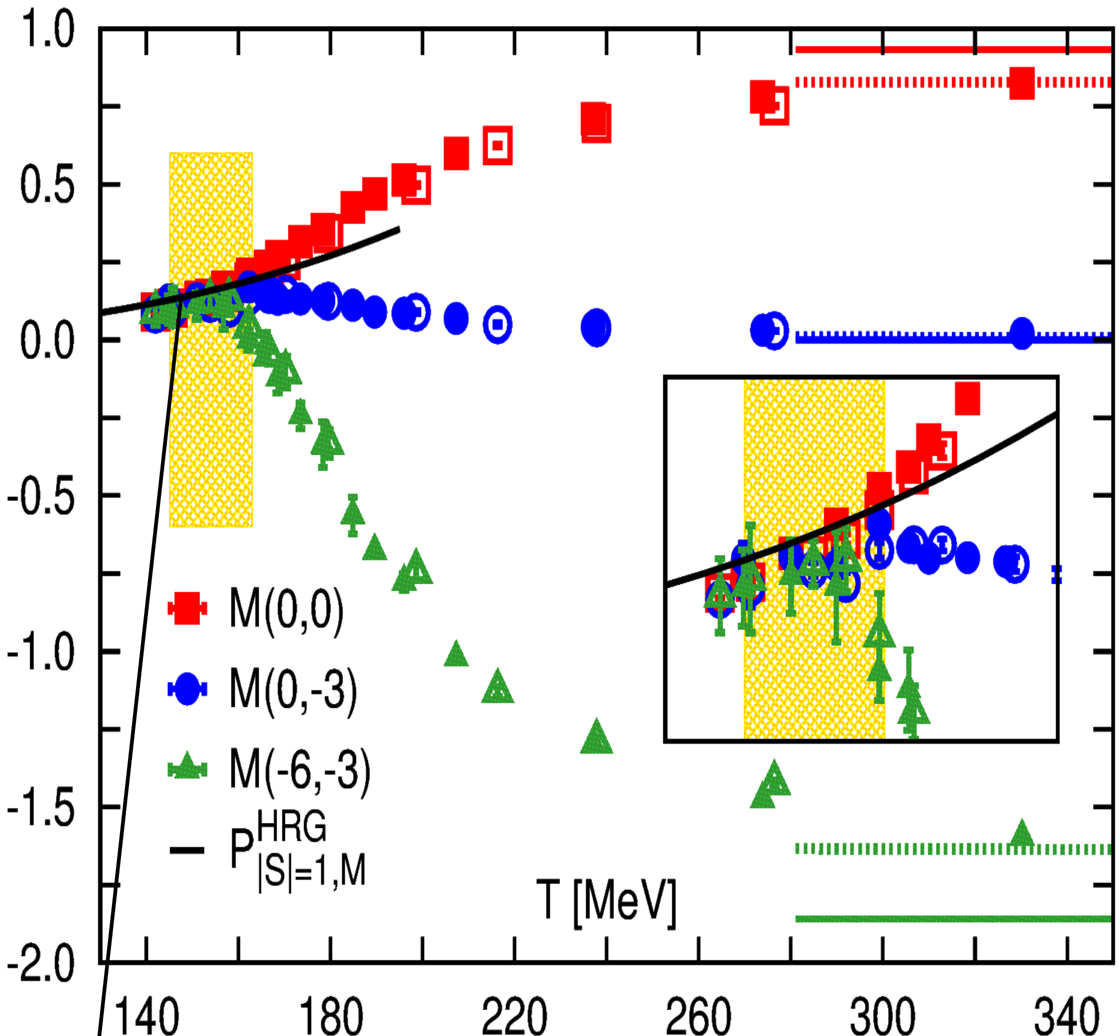
no charmed hadrons for

$T \gtrsim 1.1 T_c$

charm quarks are treated as probe particles in a bath of gluons and up, down quarks, *i.e.* partially quenched charm quarks → no contribution from charm quark loop

Confined sDoF

$$M(s_1, s_2) = \chi_2^S - \chi_{22}^{BS} + s_1 S_1 + s_2 S_2$$



$T \lesssim T_c$: $M(s_1, s_2) \rightarrow P^{HRG}_{|S|=1,M}$ for all (s_1, s_2)

if sDoF are hadrons: $S_1 = S_2 = 0$

$M(s_1, s_2) \rightarrow P^{HRG}_{|S|=1,M}$ for all (s_1, s_2)

$P^{HRG}_{|S|=1,M}$: partial pressure of strange mesons with vacuum masses

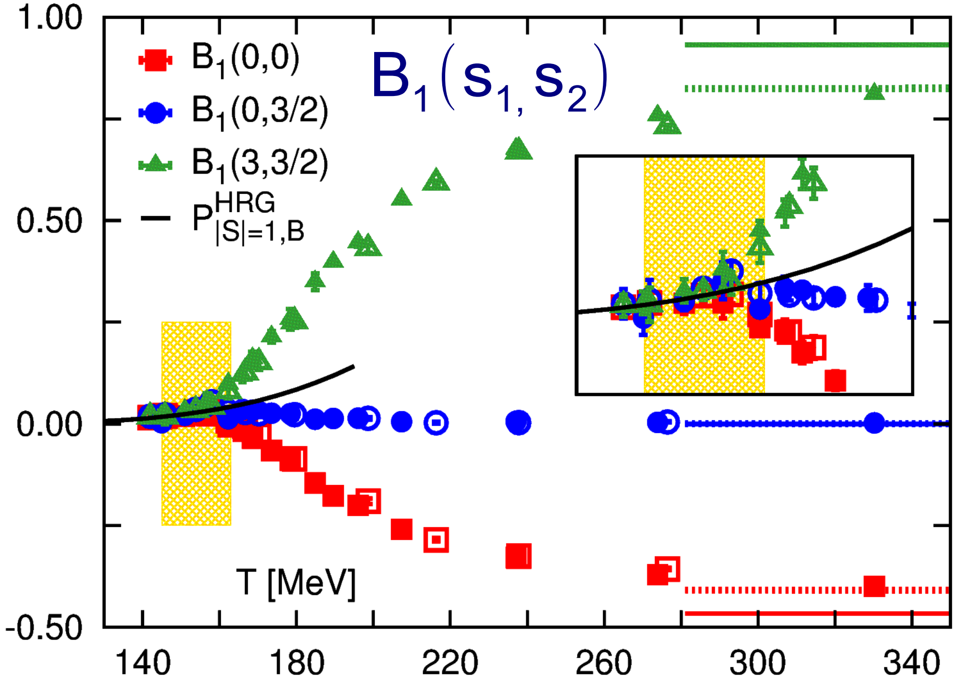
high T: $S_1 = S_2 \neq 0$

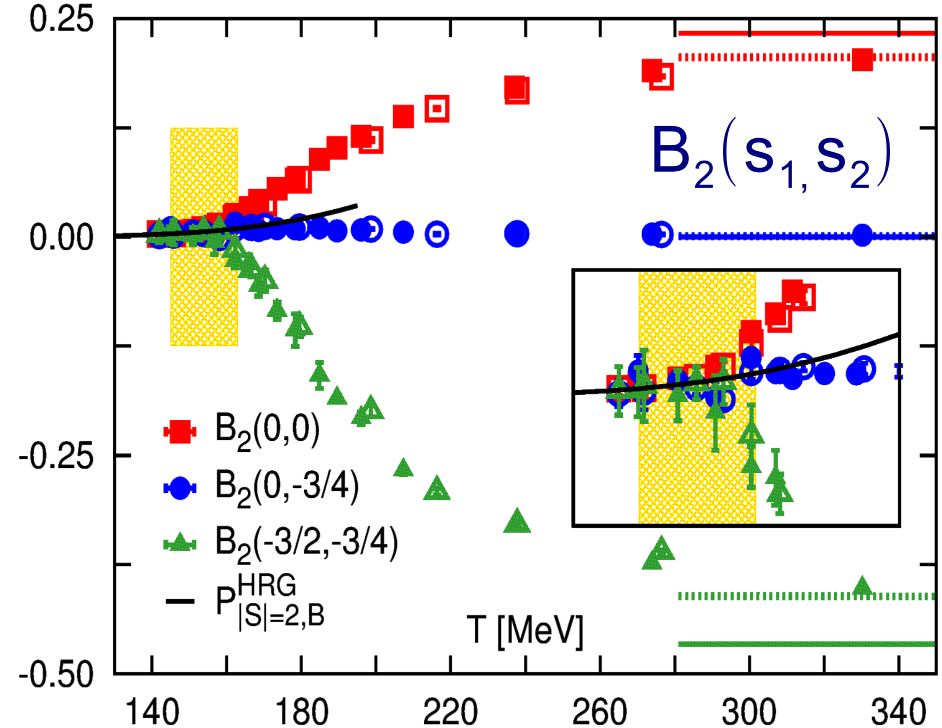
$M^{nonint}(s_1, s_2)$ depends on (s_1, s_2)

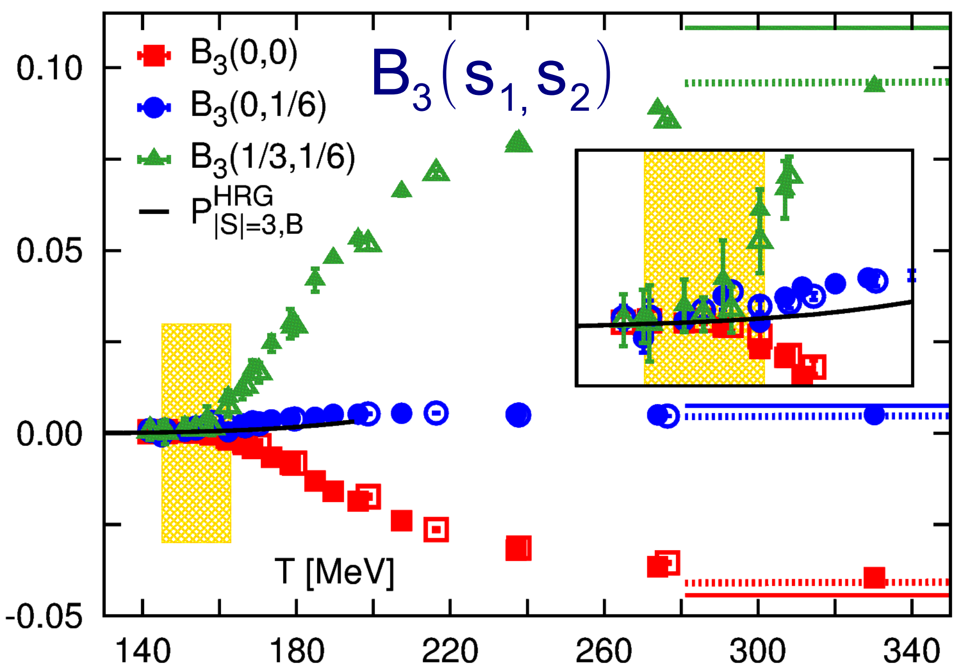
sDoF are well described by strange hadrons having vacuum masses for $T \lesssim T_c$

BNL-Bi:
Phys. Rev. Lett. 111, 082301 (2013)

Confined sDoF







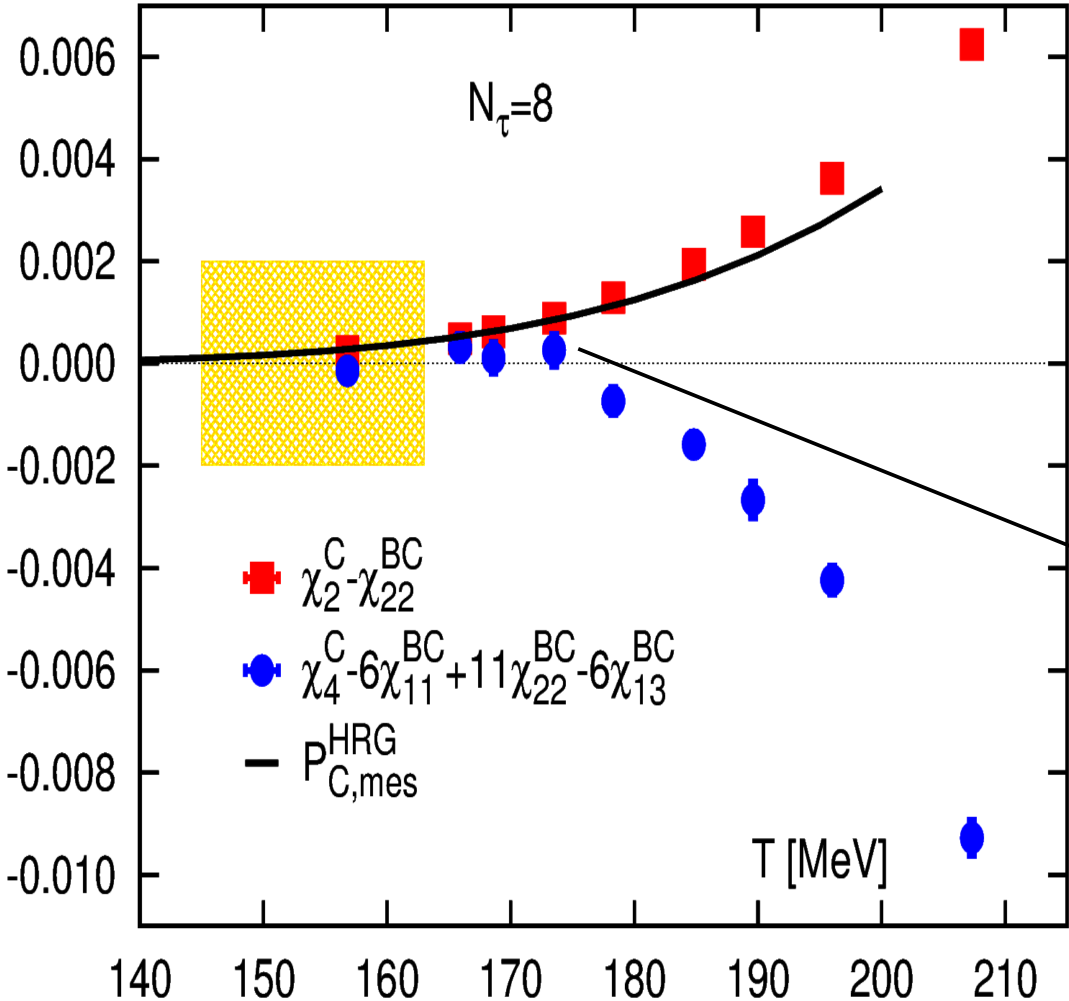
$T \lesssim T_c$: $B_n(s_1, s_2) \rightarrow P^{HRG}_{|S|=n,B}$ for all (s_1, s_2)

$P^{HRG}_{|S|=n,B}$: partial pressure of S=n baryons with vacuum masses

similar conclusion for strange baryons

BNL-Bi:
Phys. Rev. Lett. 111, 082301 (2013)

Confined cDoF



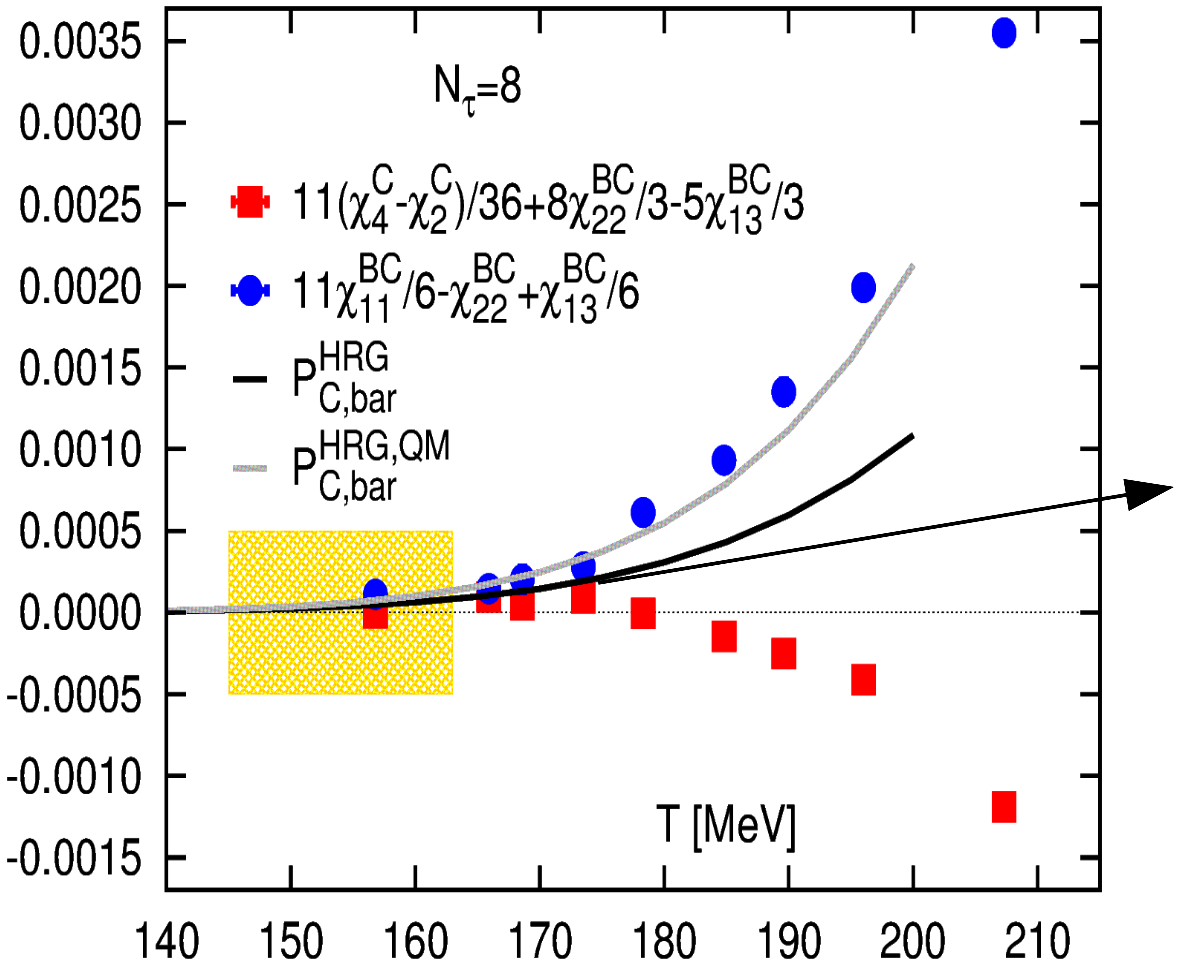
similar observables for cDoF:
both observables give the partial pressure of charmed mesons at low T, but have widely different high T limit

$T \lesssim 175$ MeV:

$P_{C,mes}^{HRG}$: partial pressure of open charm mesons with vacuum masses

cDoF are well described by charmed hadrons having vacuum masses for $T \lesssim 1.1T_c$

Confined cDoF



both observables give the partial pressure of charmed baryons at low T, but have widely different high T limit

$T \lesssim 175$ MeV :

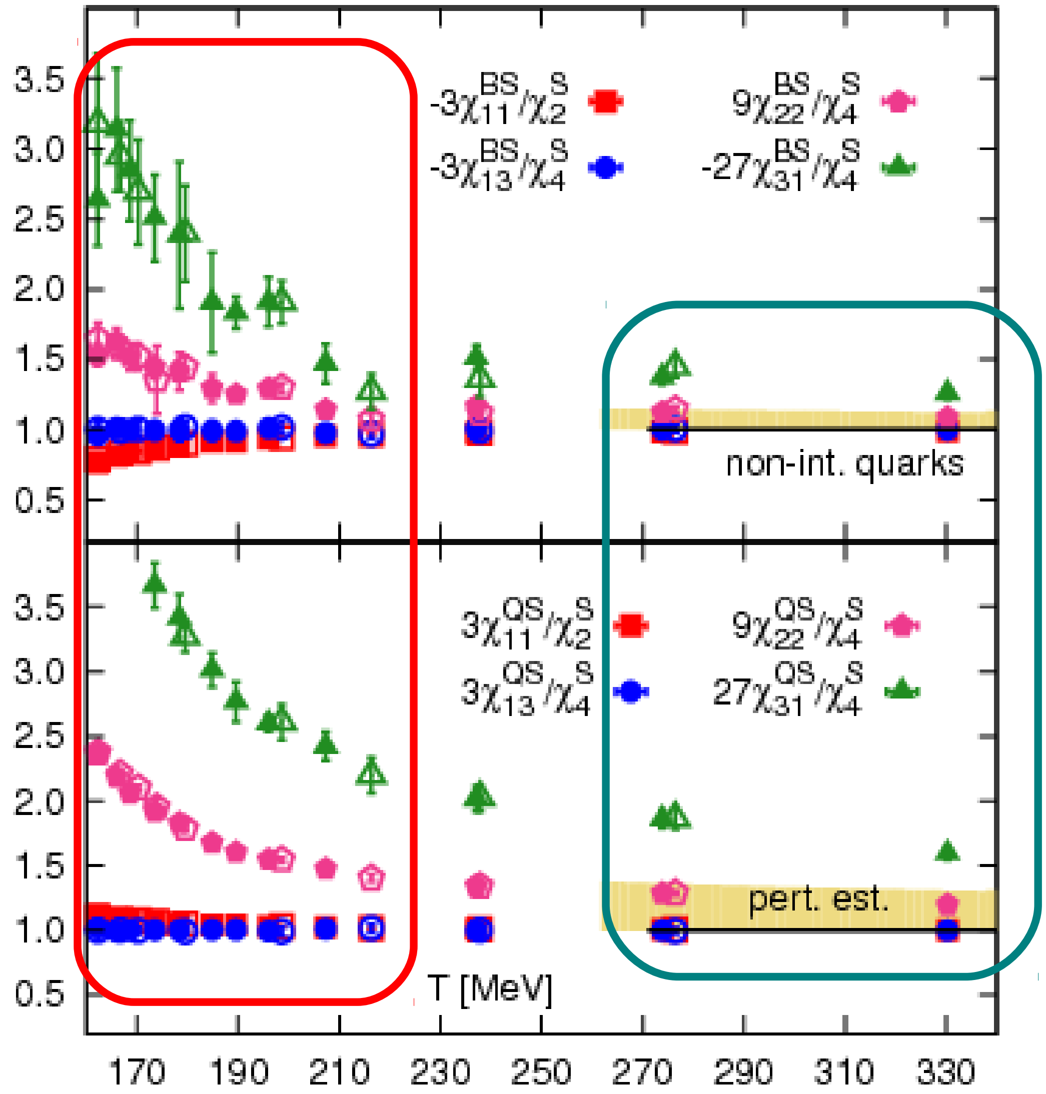
$P_{C,bar}^{HRG}$: partial pressure of charmed baryons with vacuum masses

same conclusion for charmed baryons

accidental agreement of the blue data points with $P_{C,bar}^{HRG,QM}$ up to much higher T illustrate the importance of multiple observables with widely different high T limit

$P_{C,bar}^{HRG,QM}$: partial pressure of charmed baryons including unobserved states predicted in a Quark Model [Roberts & Pervin, IJMP A23, 2817 (2008)]

Deconfined sDoF



strongly interacting sDoF
for $T_c \lesssim T \lesssim 2T_C$

weakly/non-interacting quasi-quarks

$S=-1,\ B=1/3,\ Q=-1/3$

baryon–strangeness correlation

$$\chi_{mn}^{BS}/\chi_n^S = B^m S^n = (-1)^n/3^m$$

charge–strangeness correlation

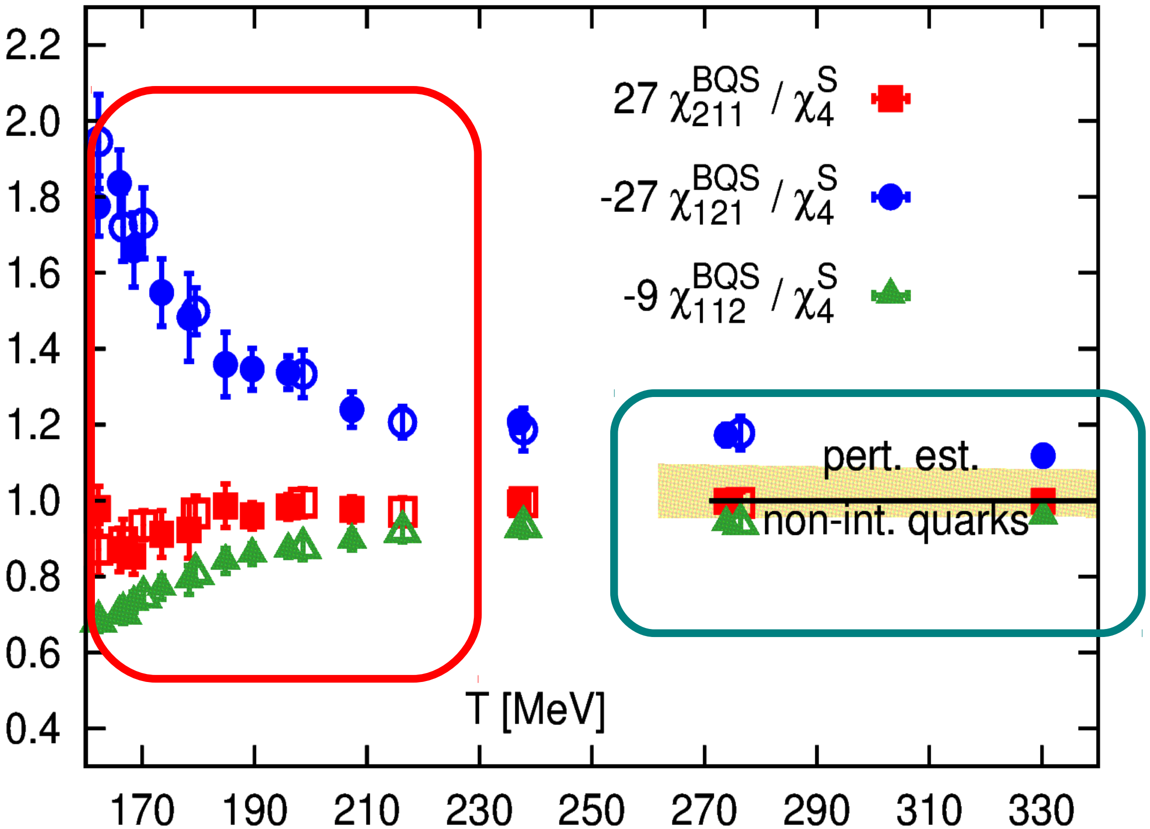
$$\chi_{mn}^{QS}/\chi_n^S = Q^m S^n = (-1)^{m+n}/3^m$$

weakly interacting strange quasi-quarks for $T \gtrsim 2T_C$

higher order B–S & Q–S corrl. show stronger deviations from the weakly interacting quasi-quark picture

BNL-Bi: Phys. Rev. Lett. 111, 082301 (2013)

Deconfined sDoF



weakly/non-interacting quasi-quarks

$S=-1,\ B=1/3,\ Q=-1/3$

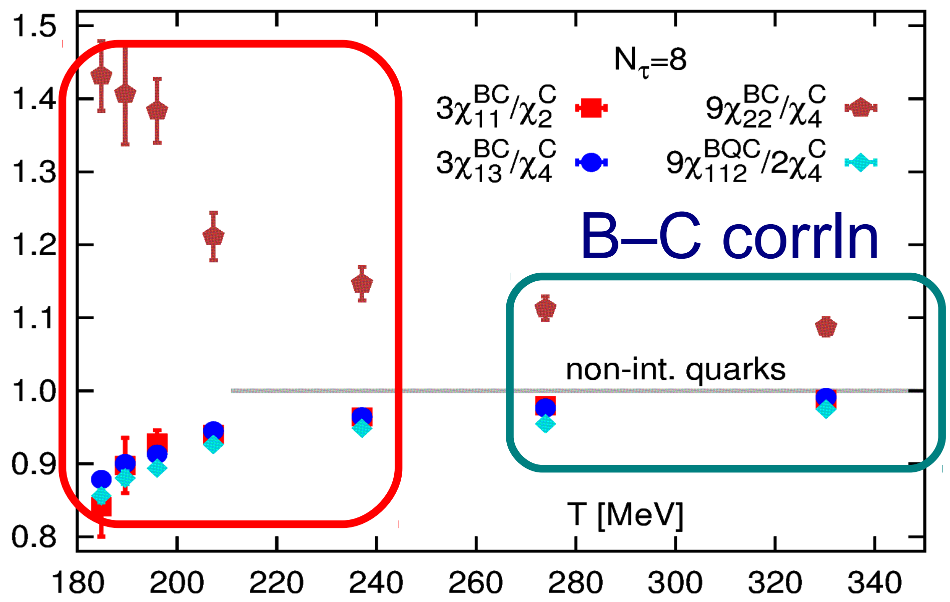
B–Q–S correlation

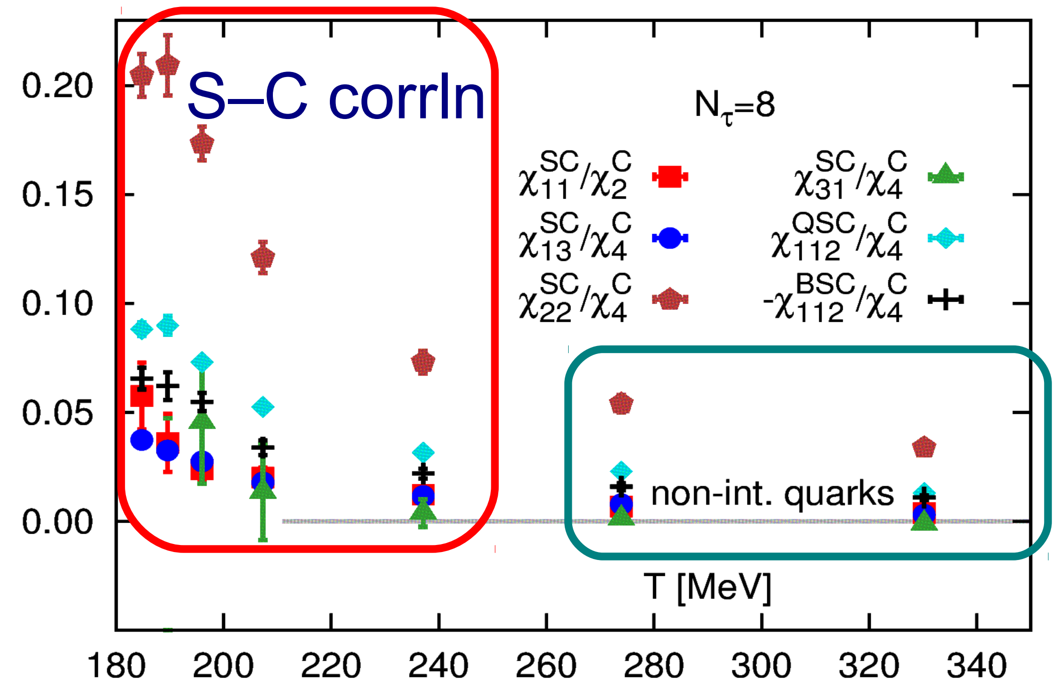
$$\chi^{BQS}_{lmn}/\chi^{S}_{n} = B^l Q^m S^n = \frac{(-1)^{m+n}}{3^{l+m}}$$

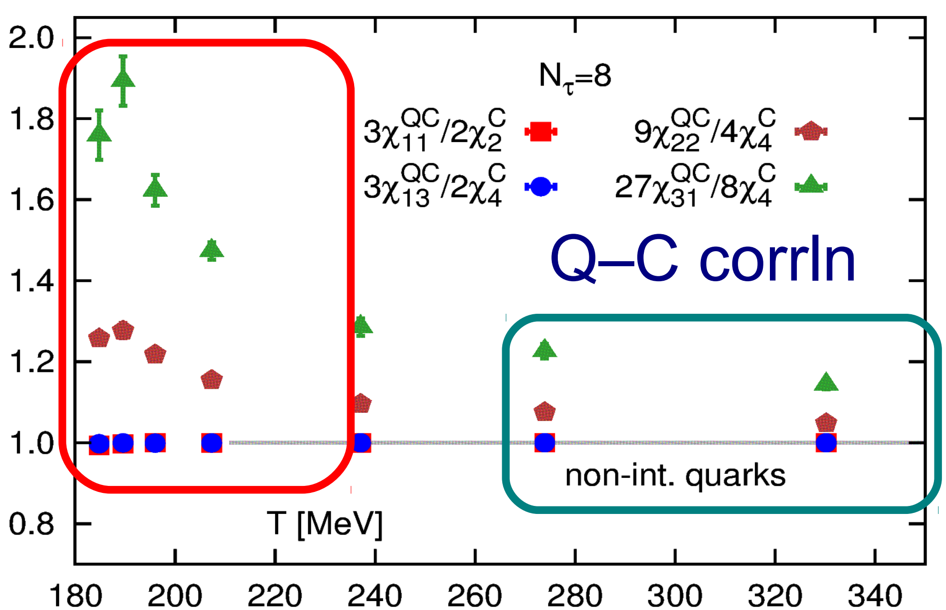
weakly interacting strange quasi-quarks for $T \gtrsim 2T_C$

strongly interacting sDoF for $T_c \lesssim T \lesssim 2T_C$

Deconfined cDoF







strongly interacting cDoF
for $1.1T_c \lesssim T \lesssim 2T_C$

weakly interacting charm
quasi-quarks for $T \gtrsim 2T_C$

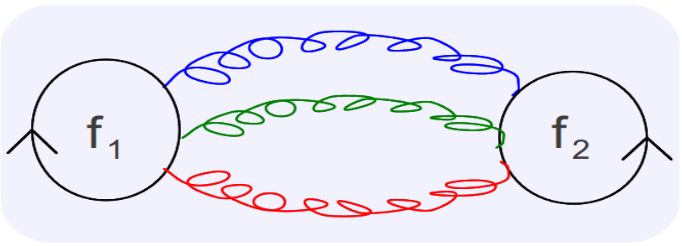
deconfined cDoF looks very similar to deconfined sDoF

Flavor correlations in QGP

$$\chi_{mn}^{f_1 f_2} / \chi_{m+n}^{f_2}$$

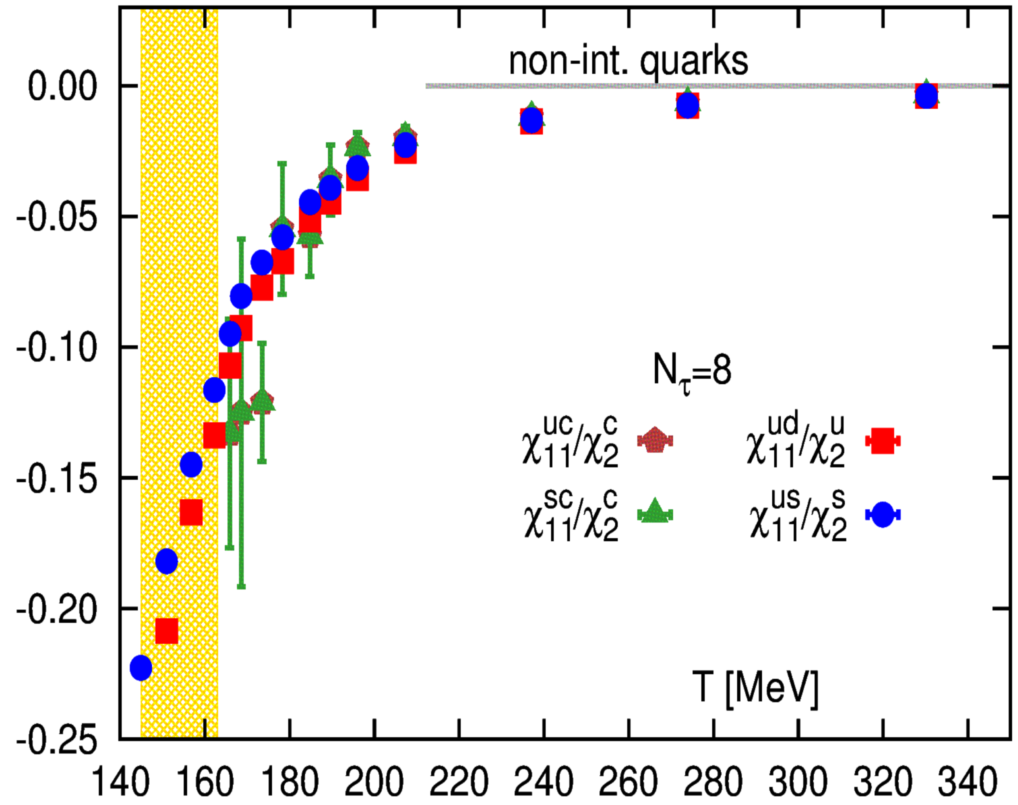
normalization by $\chi_{m+n}^{f_2}$ partly neutralizes the flavor mass dependence

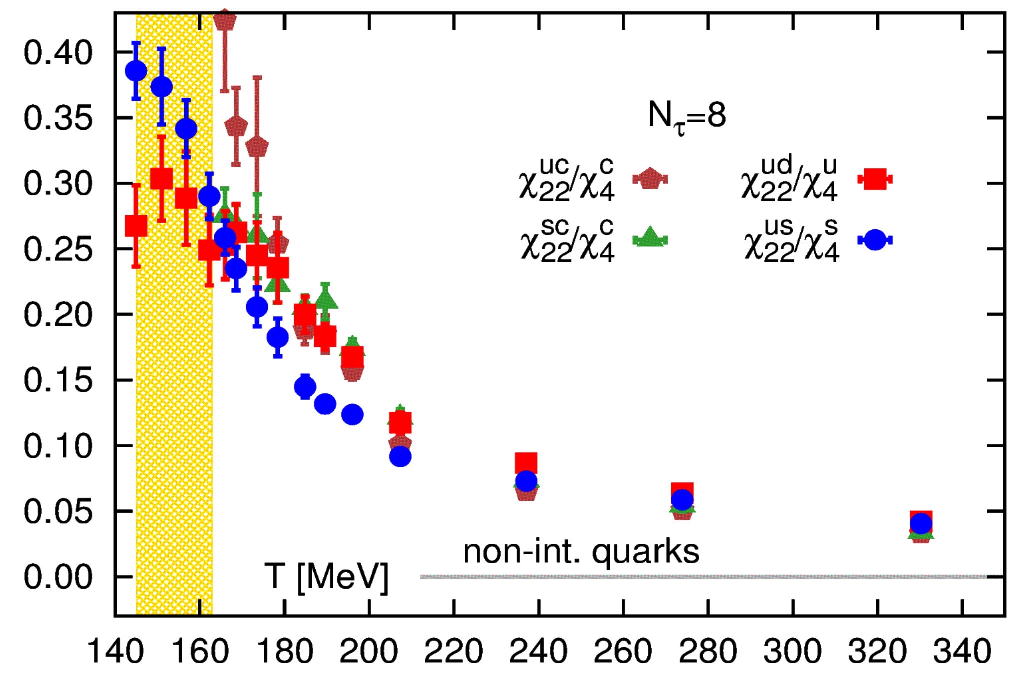
strong correlations among various flavors are almost flavor blind for $T \gtrsim 1.1 T_c$



dominated by gluonic interactions in the deconfined phase

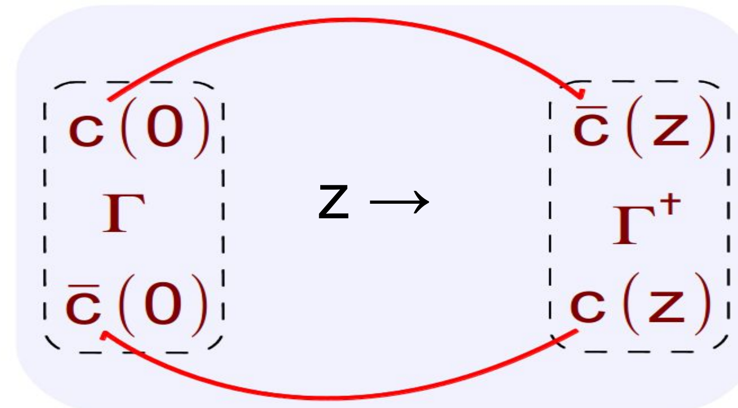
weak correlations among various flavors for $T \gtrsim 2T_c$





Spatial correlations of charmonia

closed charm states cannot be probed using quantum number correlations



spatial (screening) correlation functions of charmonia

$$C(z,T)=\int_0^{\infty}\frac{2\,d\omega}{\omega}\int_{-\infty}^{\infty}dp_z\, e^{izp_z}\rho(\omega,p_z,T)$$

in contrast to the usual temporal correlation function

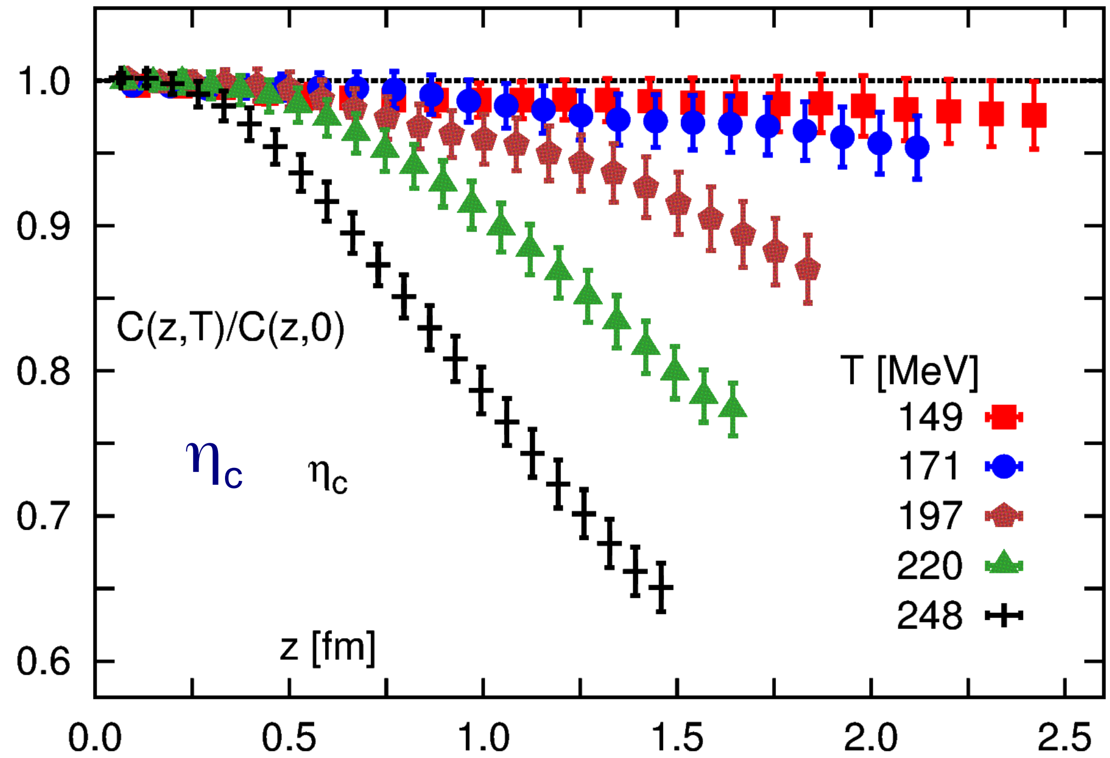
$$C(\tau,T)=\int_0^{\infty}\frac{d\omega}{2\pi}\rho(\omega,0,T)\frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)}$$

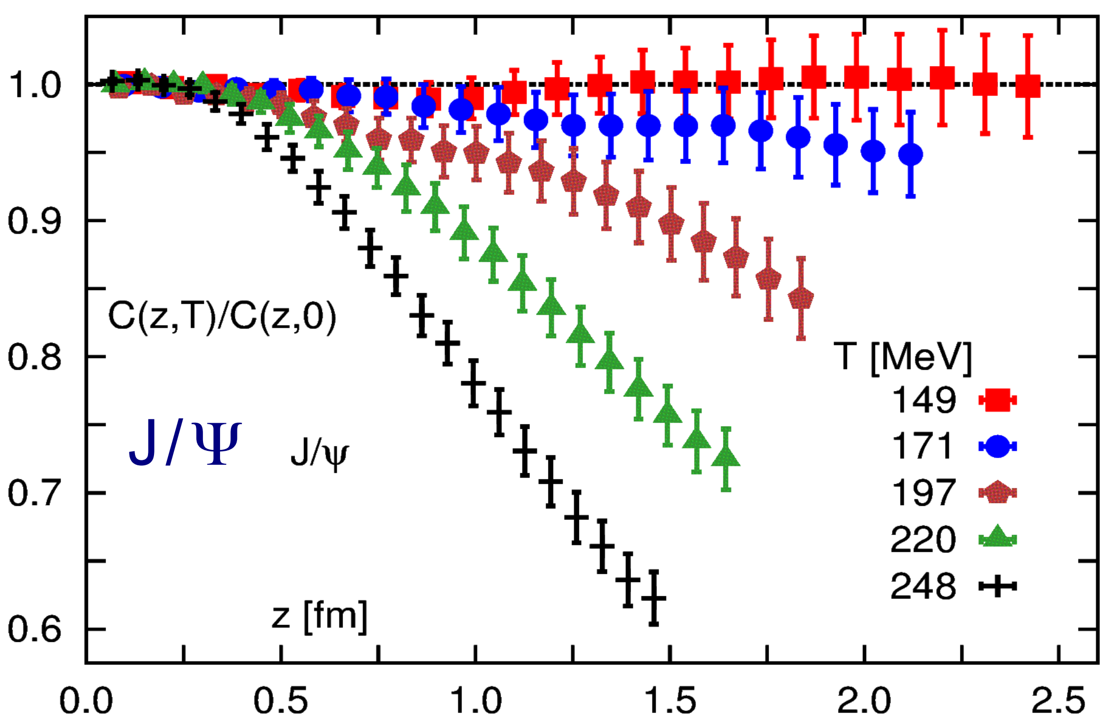
spatial correlation function:

- is not limited to the physical distance of 1/T
- transport-type zero mode contribution to the spectral function does not lead to a non-decaying constant at large distances and only generates a contact term
- the kernel is T independent → direct comparison with T=0 correlation function possible

1S charmonia

comparison of T=/= & T=0
spatial correlation functions
provide direct signatures for
significant thermal modifications





1S charmonium states are significantly modified for

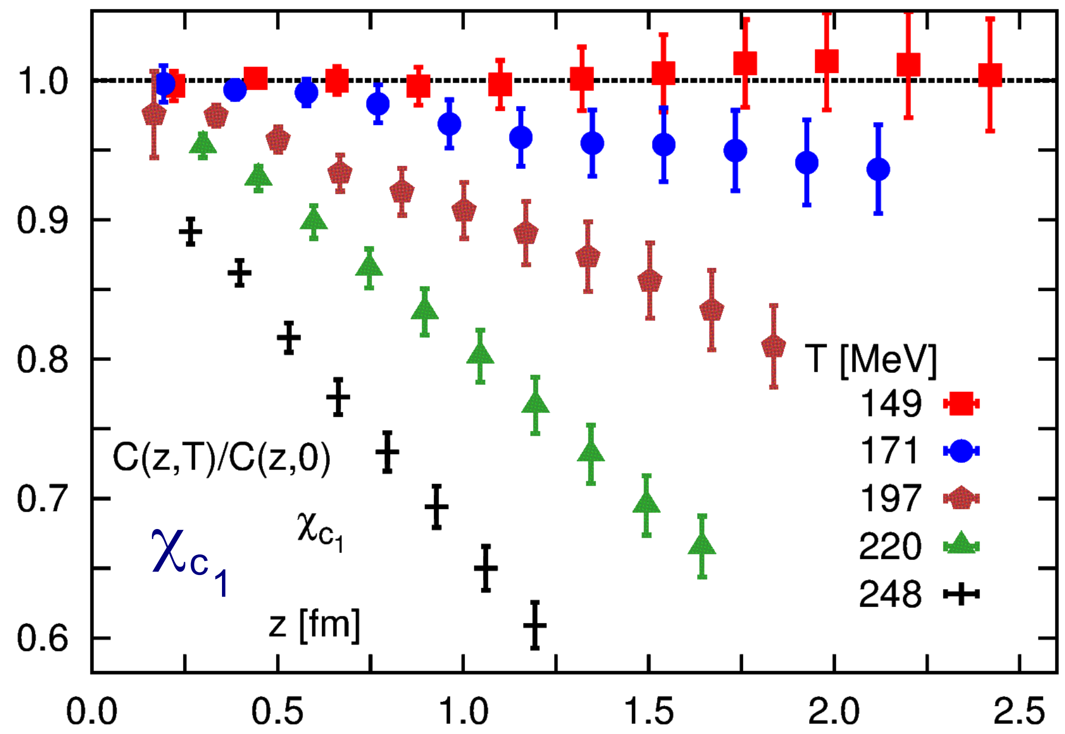
$T \gtrsim 175$ MeV

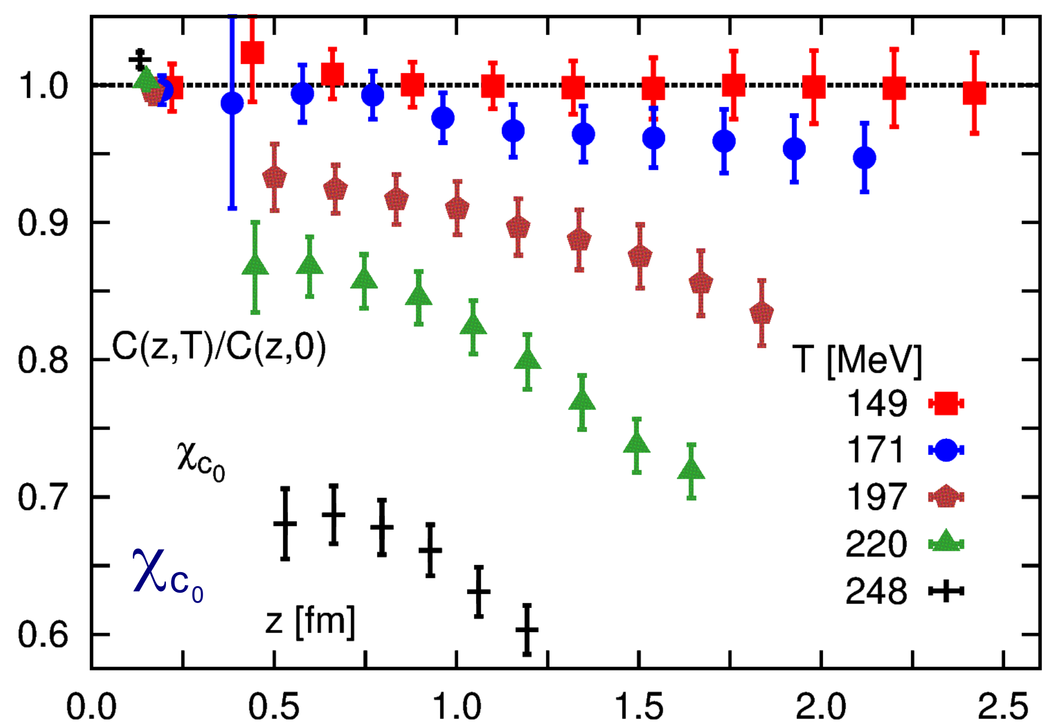
Yu Maezawa *et.al.*, Lattice 2013

1P charmonia

similar significant thermal modifications of the 1P charmonium states for

$T \gtrsim 175$ MeV





Screening masses of charmonia

$$C(z,T)=\int_0^{\infty}\frac{2\,d\omega}{\omega}\int_{-\infty}^{\infty}dp_z\,e^{izp_z}\rho(\omega,p_z,T)$$

$$C(z\to\infty,T)\sim e^{-Mz}$$

M : screening mass

high T, non-interacting quark–antiquark pair: $\Rightarrow$ $M=2\sqrt{(\pi T)^2+m_c^2}$

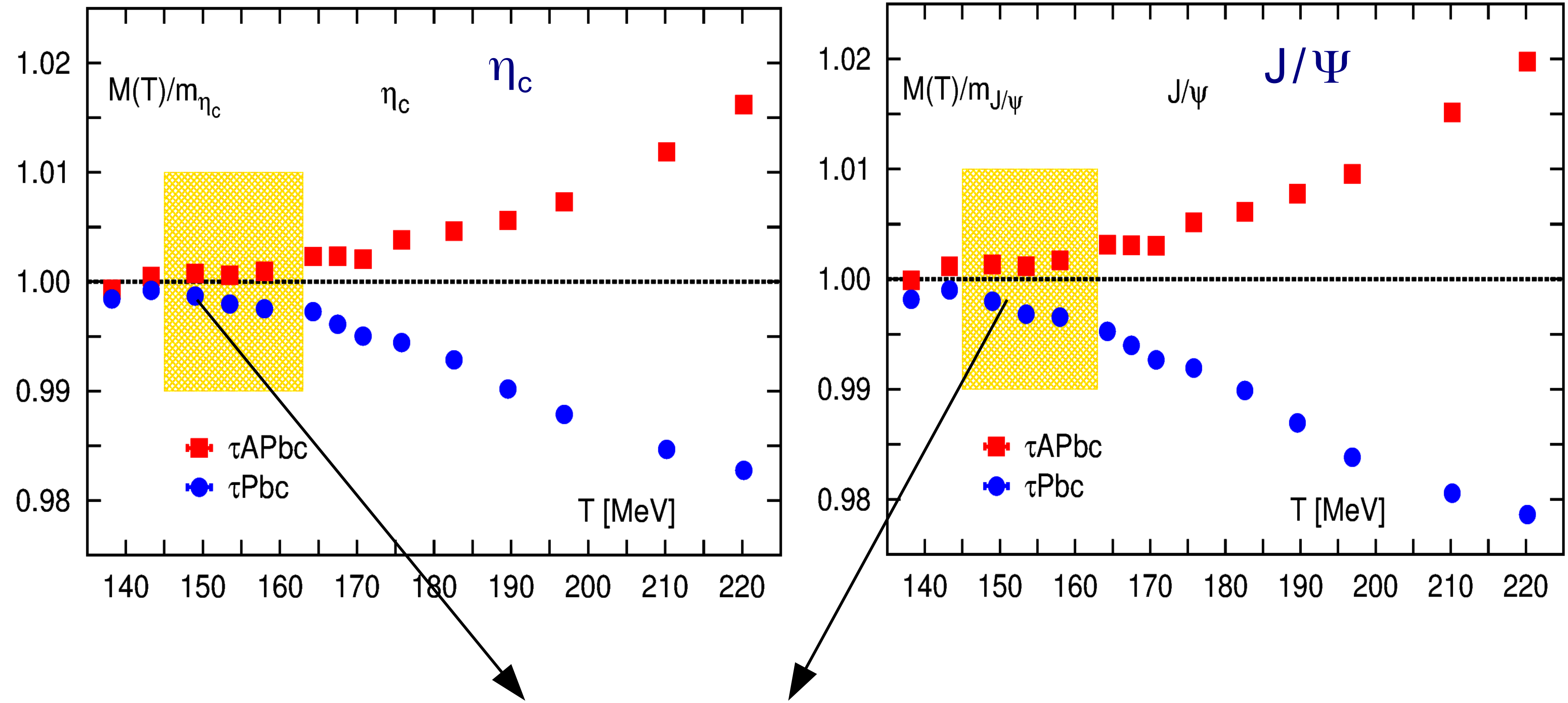
low T, well-defined mesonic bound state: $\rho(\omega,p_z)\sim\delta(\omega^2-p_z^2-m_{mes}^2)$ $\Rightarrow$ $M=m_{mes}$

a trick: one can study the onset of T dependence of M more clearly by imposing a periodic temporal boundary conditions for the valence charm quarks along with the usual anti-periodic ones

high T, no minimal Matsubara mode: $\Rightarrow$ $M=2\,m_c$

low T, bosonic meson bound states insensitive to fermionic b.c at the quark level: $\Rightarrow$ $M=m_{mes}$

Screening masses of charmonia



thermal modifications to charmonia are not significant, well-described by their vacuum masses for $T \lesssim T_c$

significant thermal modifications and possible dissolution of charmonium states for $T \gtrsim 1.1T_c$

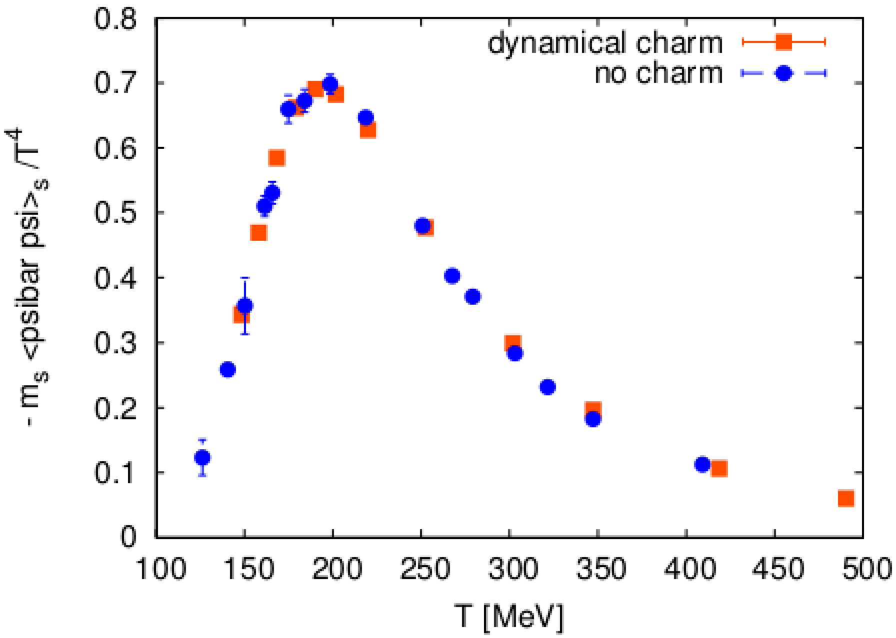
Recapitulation

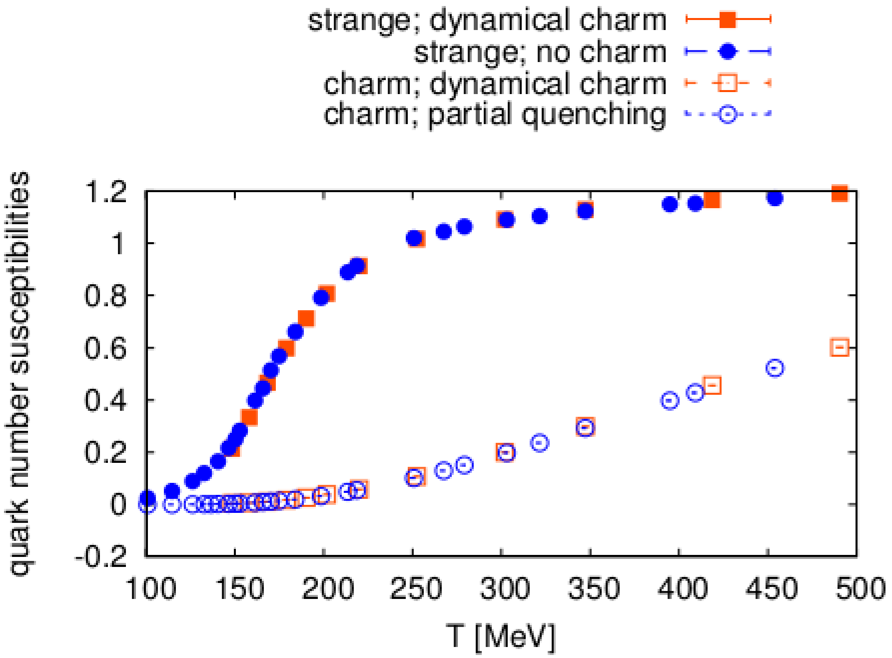
the emerging strange / charm story from LQCD ...

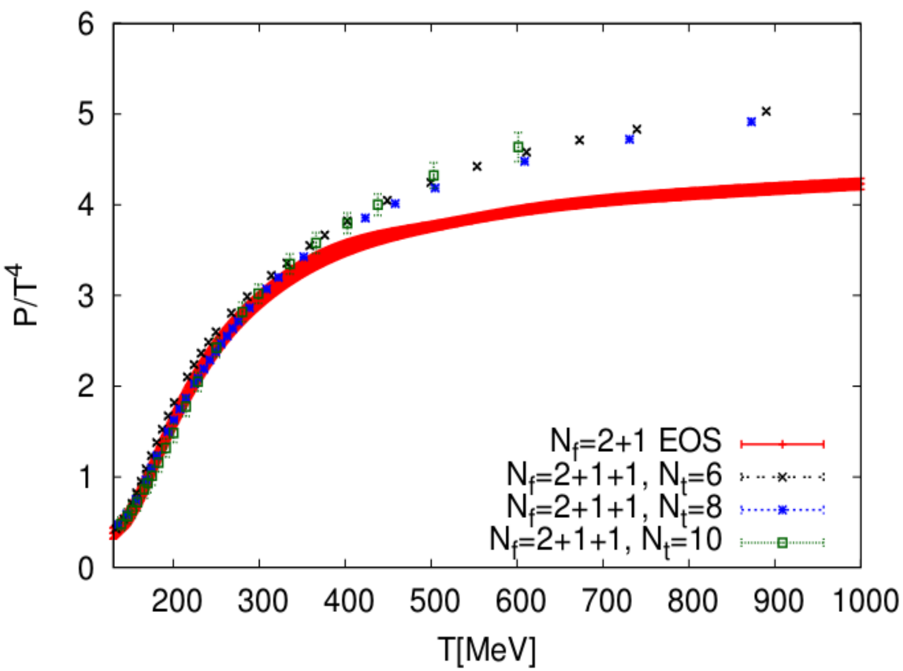
- no strange hadrons for $T \gtrsim T_C$, no open charm hadrons for $T \gtrsim 1.1T_C$, charmonia are significantly modified for $T \gtrsim 1.1T_C$
- for $T \lesssim T_C$ sDoF and cDoF are well described by hadrons having vacuum masses
- sDoF and cDoF remain strongly interacting till $T \lesssim 2T_C$
- sDoF and cDoF appear consistent with weakly interacting quasi-quarks for $T \gtrsim 2T_c$

Backup slides

Influence of dynamical charm quark







preliminary results from the Wuppertal-Budapest collaboration

PoS LATTICE2011 (2011) 201

effects of dynamical charm quark negligible for $T \lesssim 400$ MeV