Melting of Open Charm

and

Screening properties of Charmonia

Swagato Mukherjee

BROOKHAVEN NATIONAL LABORATORY

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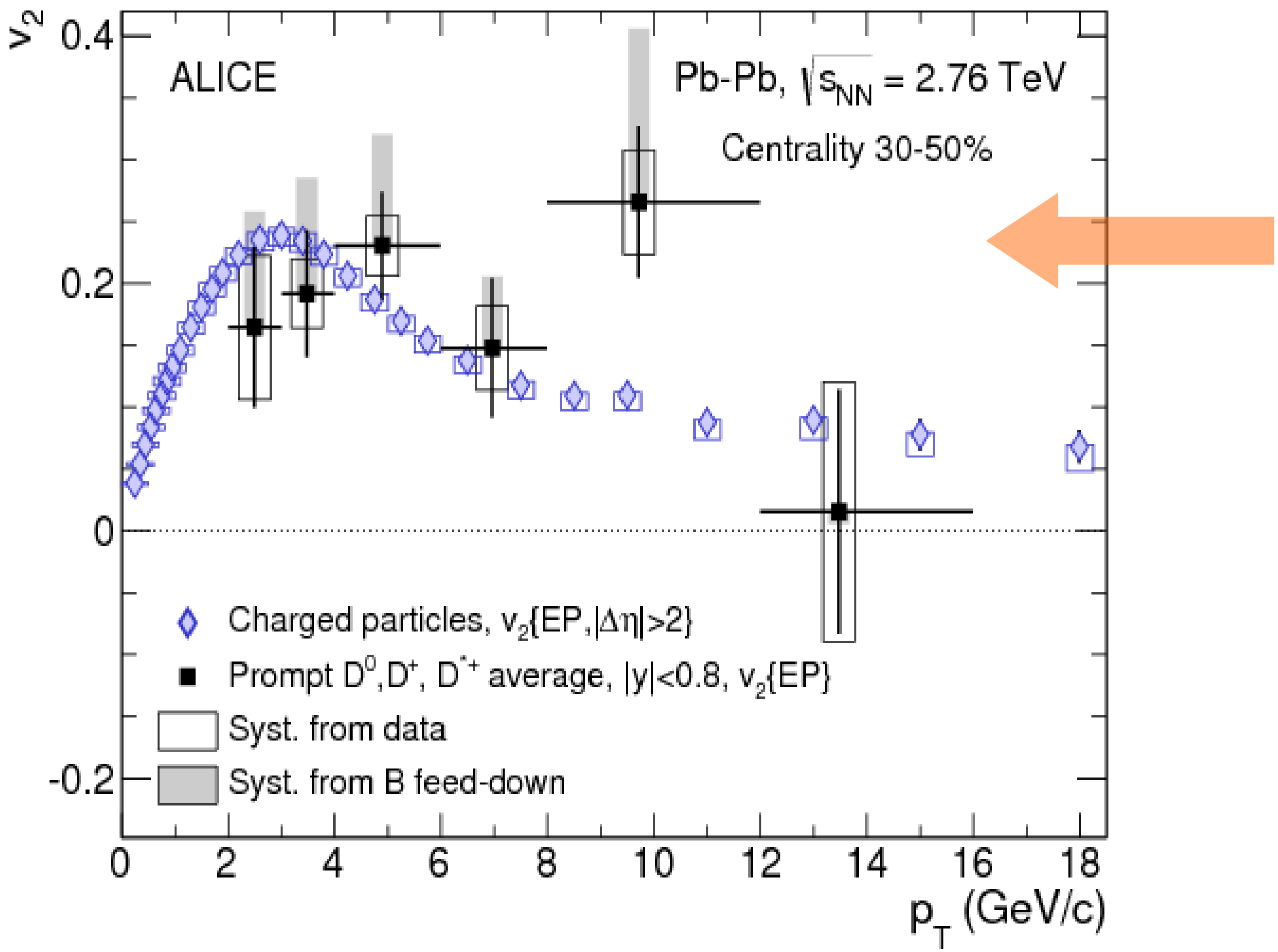
Deconfined open charm in HIC ?



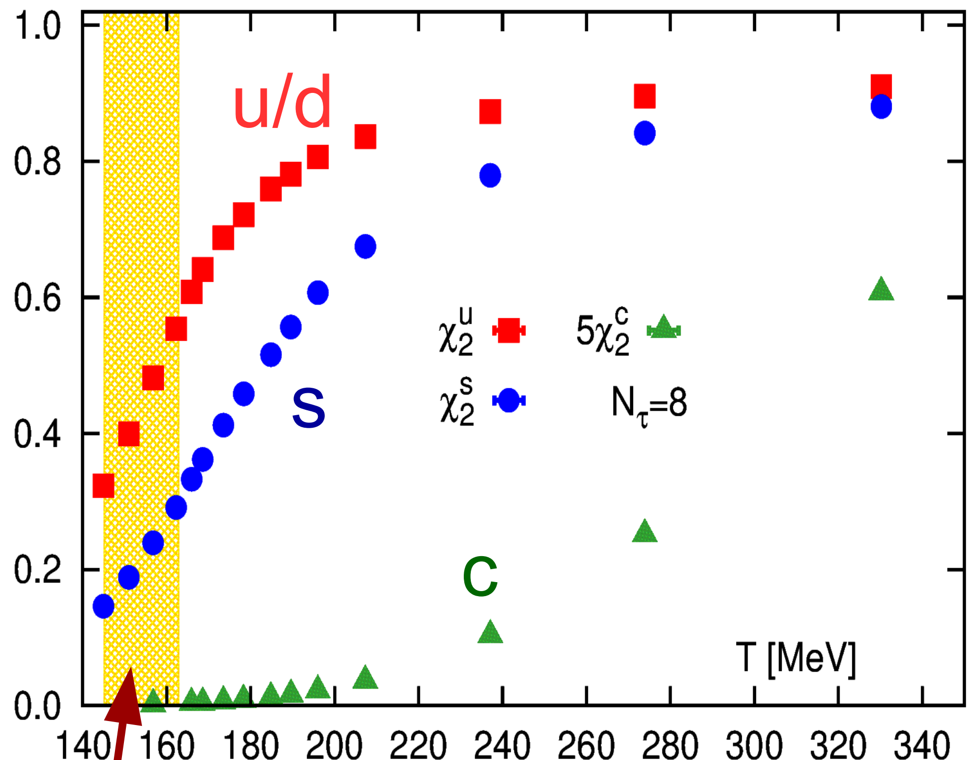
ALICE: Phys. Rev. Lett. 111 (2013) 102301

partonic nature of charm degrees of freedom

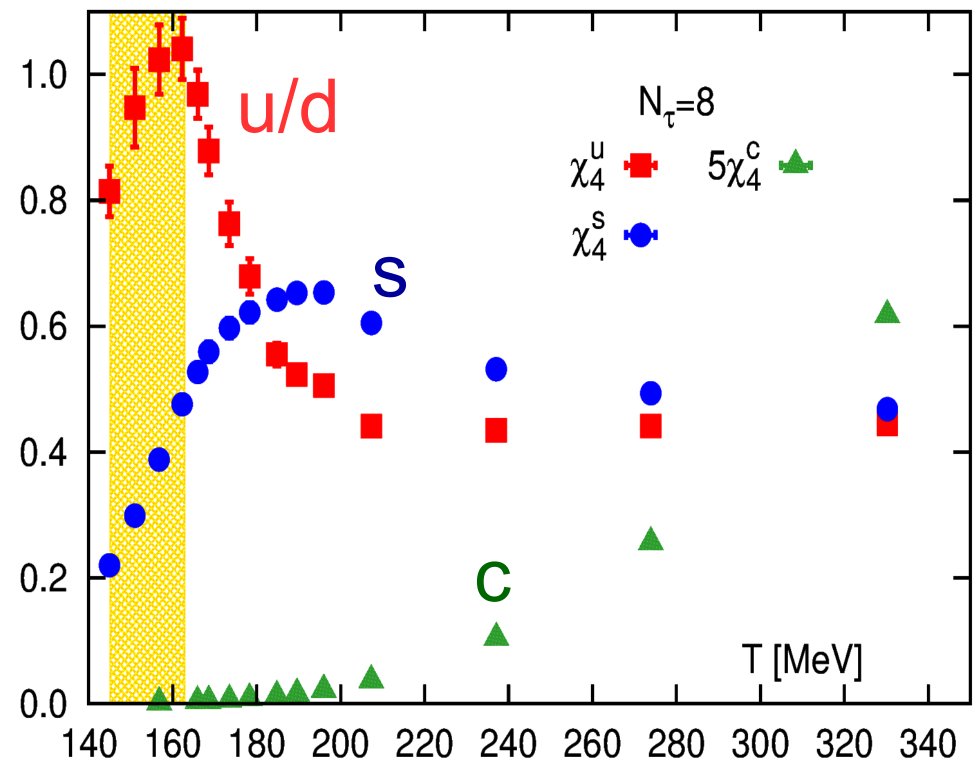
- ✔ when do the open charm hadrons start to deconfine ?
- ✔ role of chiral crossover ?
- ✔ what are the open charm hadrons during the freeze-out ?

Lattice QCD

Role of chiral crossover on charm deconfnement ?



2[nd] order quark number fluctuations



4[th] order quark number fluctuations

chiral crossover:

$T_c = 154 \pm 9$ MeV

liberation of quark DoF: $N_c^0 \rightarrow N_c$

rise in quark number fluctuations

HotQCD: Phys. Rev. Lett. 113 (2014) 082001

HotQCD: Phys. Rev. D85 (2012) 054503

Proper observables: conserved number correlations

probe quantum numbers associated with the DoF

baryon(B)/charge(Q)/strangeness(S)/charm(C) correlations

$P = p/T^4$

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

$\hat{m} = m/T$

$$\chi_{mn}^{XY} = \left. \frac{\partial^{m+n} P}{\partial^m \hat{\mu}_X \partial^n \hat{\mu}_Y} \right|_{\mu_X=\mu_Y=0}$$

$$\chi_{0n}^{XY} \equiv \chi_n^Y$$

hadron gas: $P_h \sim f(\hat{m}_h) \exp[-B_h \hat{\mu}_B - Q_h \hat{\mu}_Q - S_h \hat{\mu}_S - C_h \hat{\mu}_C]$

$$\chi_{nm}^{BX} = B^n \times F(\hat{m})$$

$$\chi_{nm}^{BX} - \chi_{km}^{BX} = (B^n - B^k) \times F(\hat{m})$$

depends on hadron spectra

= 0 when B=1, DoF are hadronic

=/= 0 when B=1/3, DoF are quark like

irrespective of the hadron spectra

Example: strangeness

$$S_1 = \chi_{31}^{BS} - \chi_{11}^{BS}$$

$$\chi_{mn}^{XY} = \frac{\partial^{m+n} P}{\partial^m \hat{\mu}_X \partial^n \hat{\mu}_Y}$$

if sDoF are hadrons with S=1,2,3 and B=0,1

$$S_1 = \chi_{31}^{BS} - \chi_{11}^{BS} = (B^3 - B) \times f(m_S^{had})$$ → depends on the hadron spectrum

$$S_1 = 0 \ \text{ for } \ B = 0,1$$

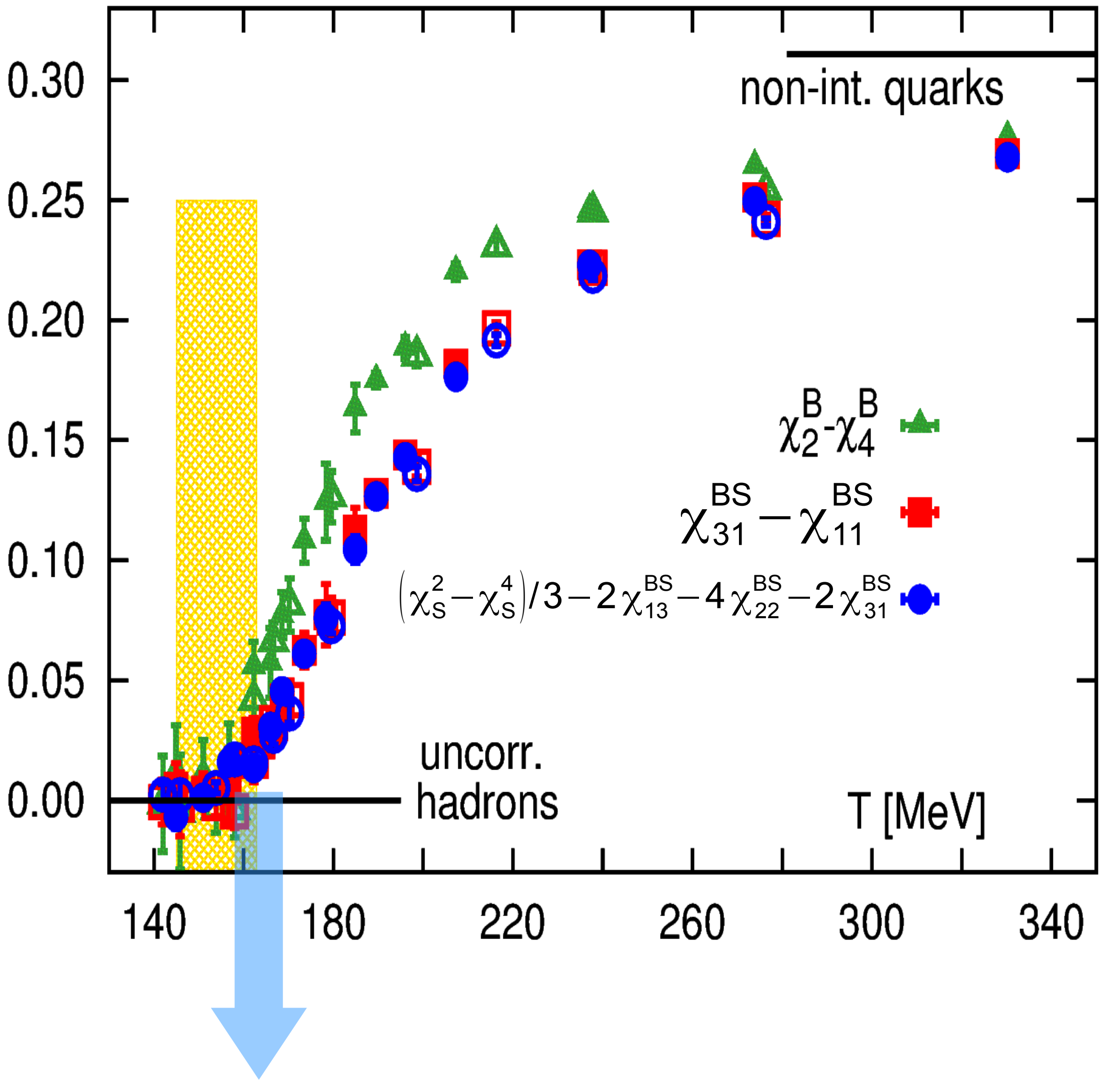
irrespective of the hadron spectrum

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

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

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

Example: strangeness



deconfinement & chiral crossovers in same temperature range

sDoF appears with fractional baryon number

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

Charm DoF

hadron gas: $P^C = P_M^C \cosh[\hat{\mu}_C] + \sum_{k=1,2,3} P_B^{C=k} \cosh[B\hat{\mu}_B + k\hat{\mu}_C]$

P_M^C : partial pressure of |C|=/=0 mesons

$P_B^{C=k}$: partial pressure of |C|=k baryons

$$\chi_{mn}^{BC} = B^m P_B^{C=1} + B^m 2^n P_B^{C=2} + B^m 3^n P_B^{C=3} \simeq B^m P_B^{C=1}$$

relative contribution of C=2,3 baryons negligible: x1000 suppressed for T~150 MeV

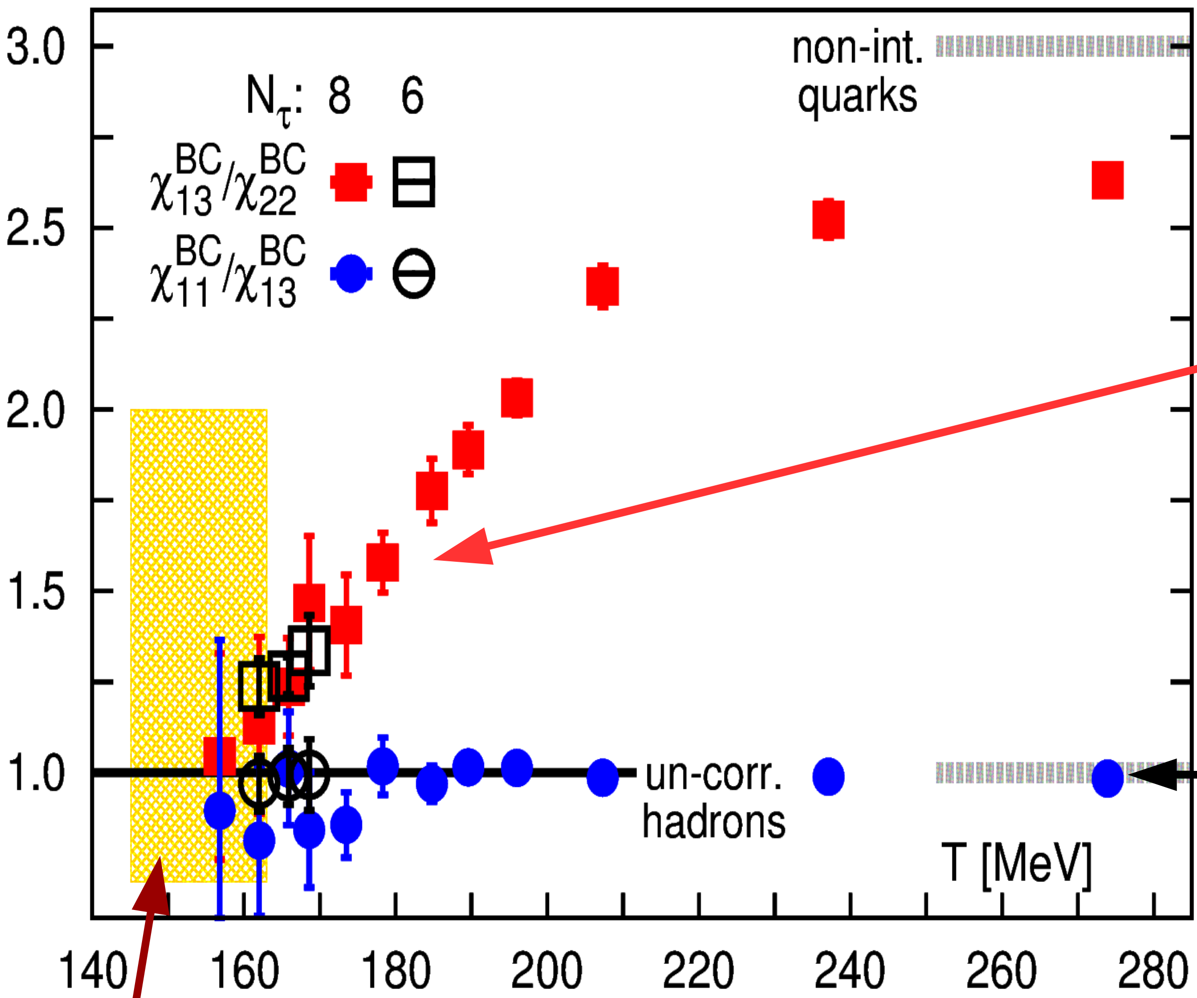
weakly interacting charm quasi-quarks: $P^C = F(m_c) \cosh[B\hat{\mu}_B + \hat{\mu}_C]$

$$\chi_{mn}^{BC} = B^m F(m_c)$$

$$\frac{\chi_{mn}^{BC}}{\chi_{m+1,n-1}^{BC}} = B^{-1} \qquad \frac{\chi_{mn}^{BC}}{\chi_{m,n+2}^{BC}} = 1$$

independent of mass spectra

Deconfinement of open charm baryons



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deconfinement & chiral crossovers
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BNL-Bi: Phys. Lett. B737 (2014) 210

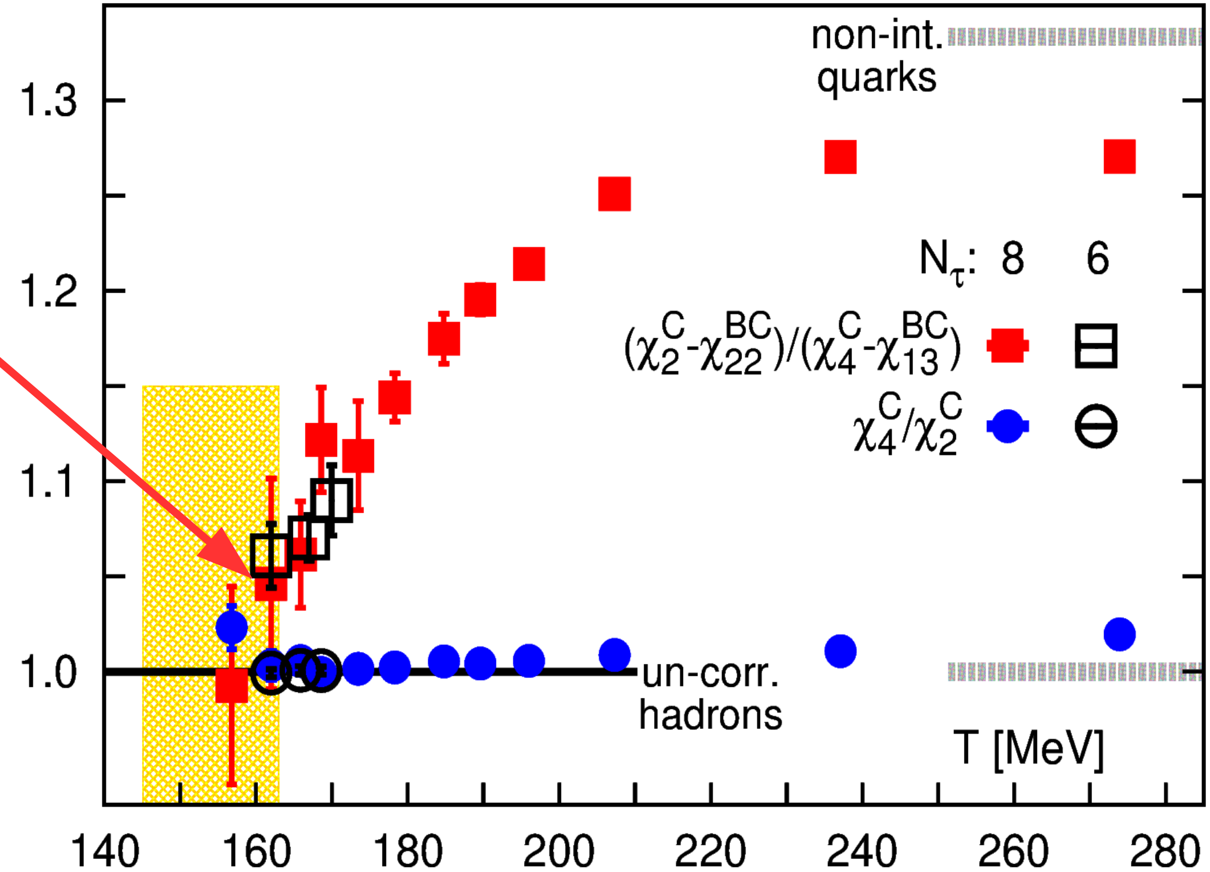
Deconfinement of open charm mesons

hadron gas: $P^C = P^C_M \cosh[\hat{\mu}_C] + \sum_{k=1,2,3} P^{C=k}_B \cosh[\hat{\mu}_B + k\hat{\mu}_C]$

$$\chi^{BC}_{mn} = P^{C=1}_B + 2^n P^{C=2}_B + 3^n P^{C=3}_B \simeq P^{C=1}_B$$

$$\chi^C_k = P^C_M + P^{C=1}_B + 2^n P^{C=2}_B + 3^n P^{C=3}_B \simeq P^C_M + P^{C=1}_B$$

$$P^C_M = \chi^C_2 - \chi^{BC}_{22} = \chi^C_4 - \chi^{BC}_{13}$$



deconfinement & chiral crossovers in same temperature range

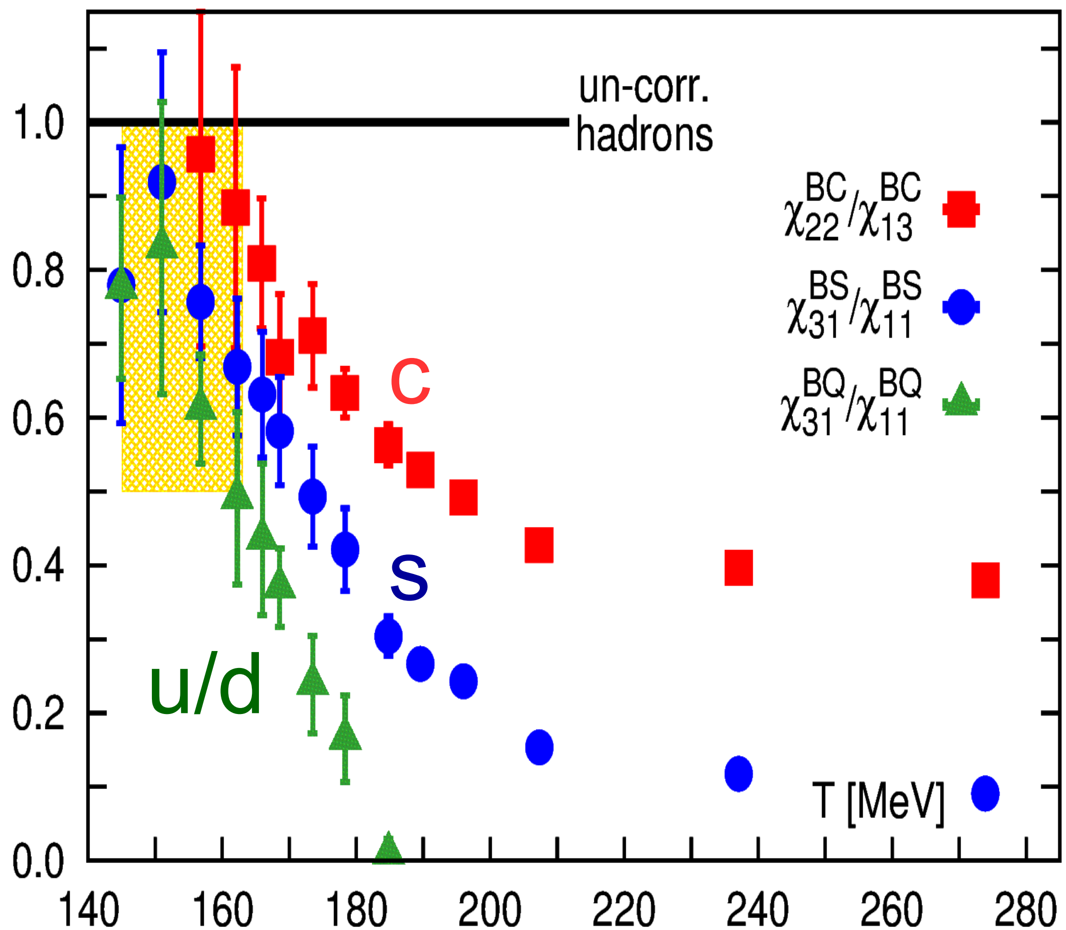
BNL-Bi: Phys. Lett. B737 (2014) 210

Flavor blind deconfinement ?

$\chi_{BX}^{nm}/\chi_{BX}^{km} = B^{n-k}$

= 0 when B=1, DoF are hadronic

=/= 0 when B=1/3, DoF are quark like

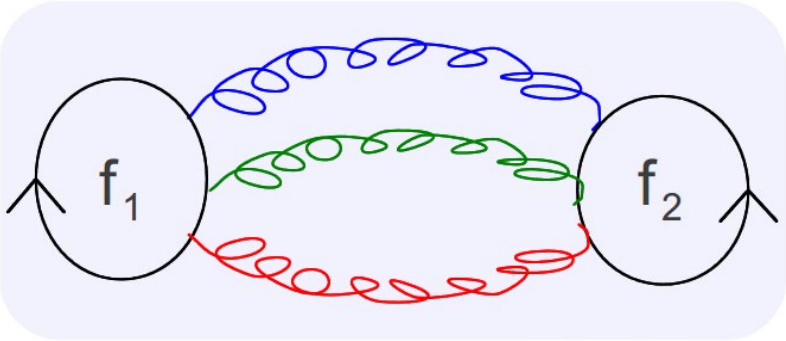


BNL-Bi: Phys. Lett. B737 (2014) 210

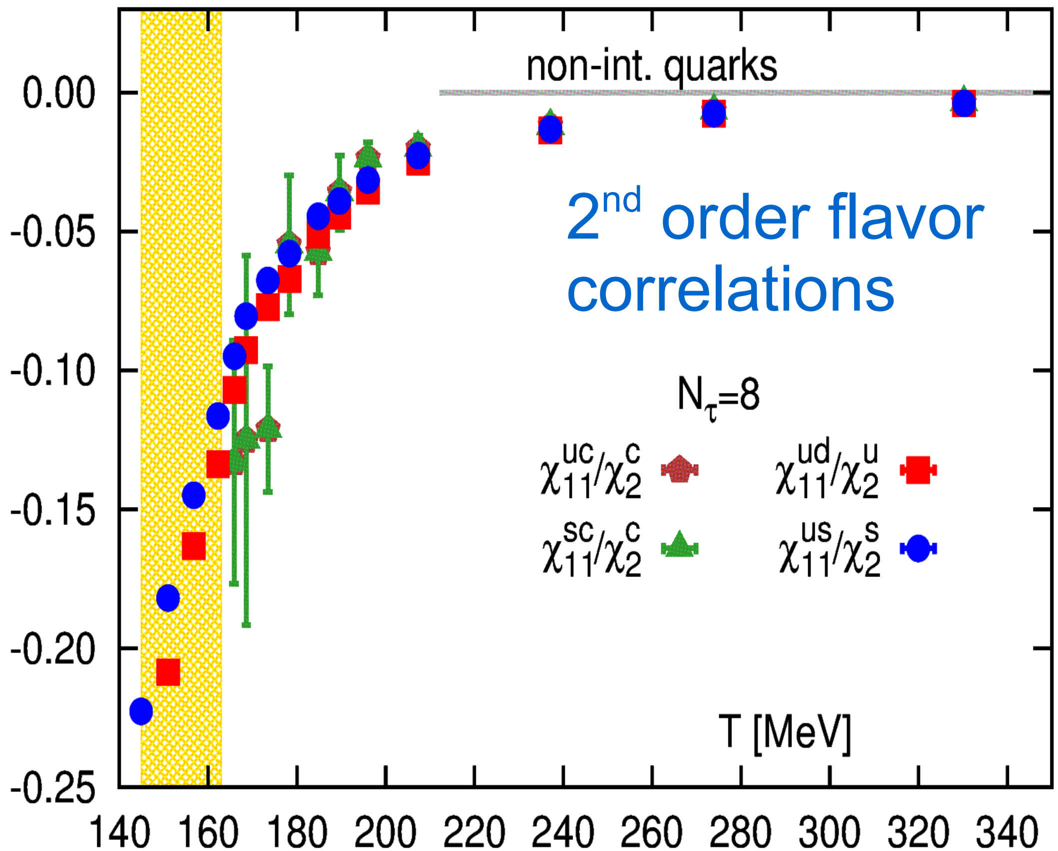
Flavor blind deconfinement ?

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

$$\chi_{mn}^{f_1 f_2} = \frac{\partial^{m+n} P}{\partial^m \hat{\mu}_{f_1} \partial^n \hat{\mu}_{f_2}}$$



in deconfined phase gluon dominated interactions: flavor blind



$T_c \lesssim T \lesssim 2T_c$

strong flavor correlations, but almost flavor blind

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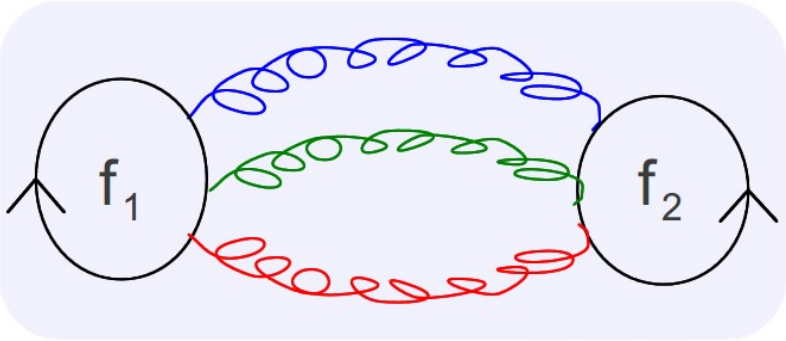

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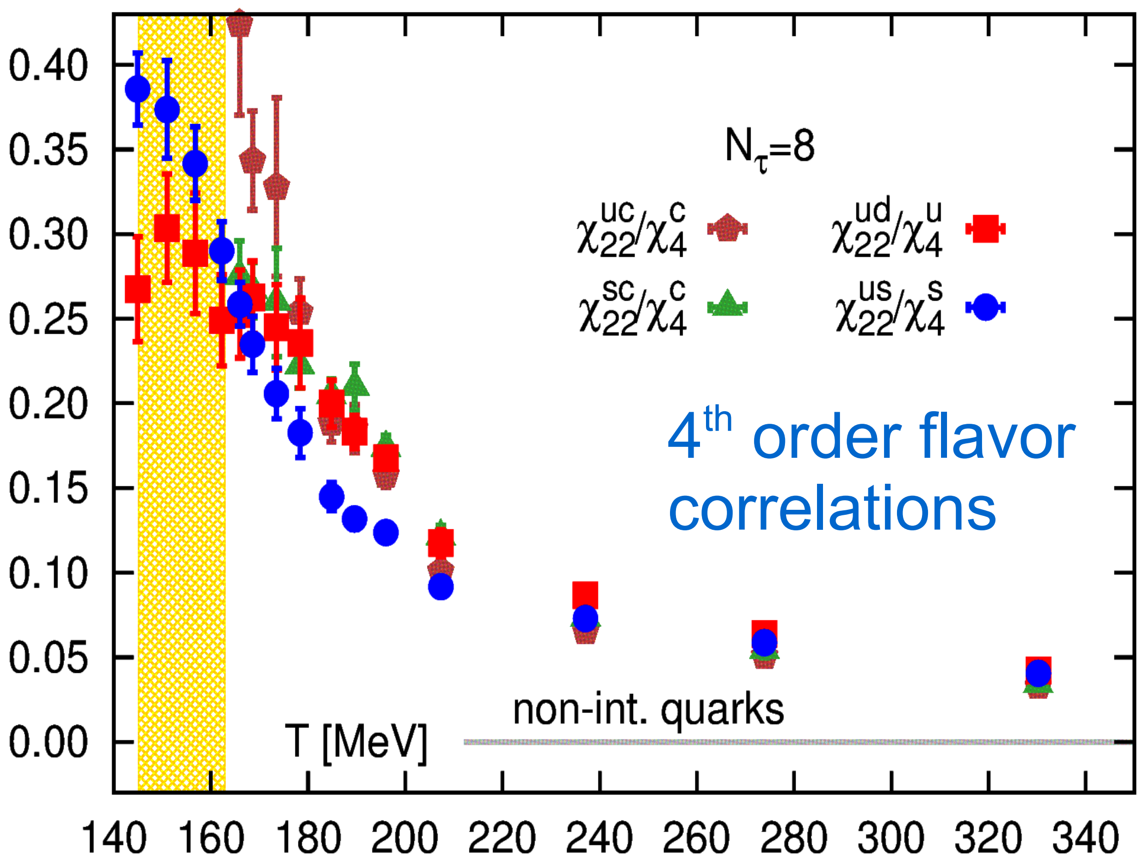

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Probing open charm hadron spectrum

hadron gas: $P^C = P_M^C \cosh[\hat{\mu}_C] + \sum_{k=1,2,3} P_B^{C=k} \cosh[\hat{\mu}_B + k\hat{\mu}_C]$

P_M^C : partial pressure of |C|=/=0 mesons
$P_B^{C=k}$: partial pressure of |C|=k baryons

$$\chi_{mn}^{BC} = P_B^{C=1} + 2^n P_B^{C=2} + 3^n P_B^{C=3} \simeq P_B^{C=1}$$

$$\chi_k^C = P_M^C + P_B^{C=1} + 2^n P_B^{C=2} + 3^n P_B^{C=3} \simeq P_M^C + P_B^{C=1}$$

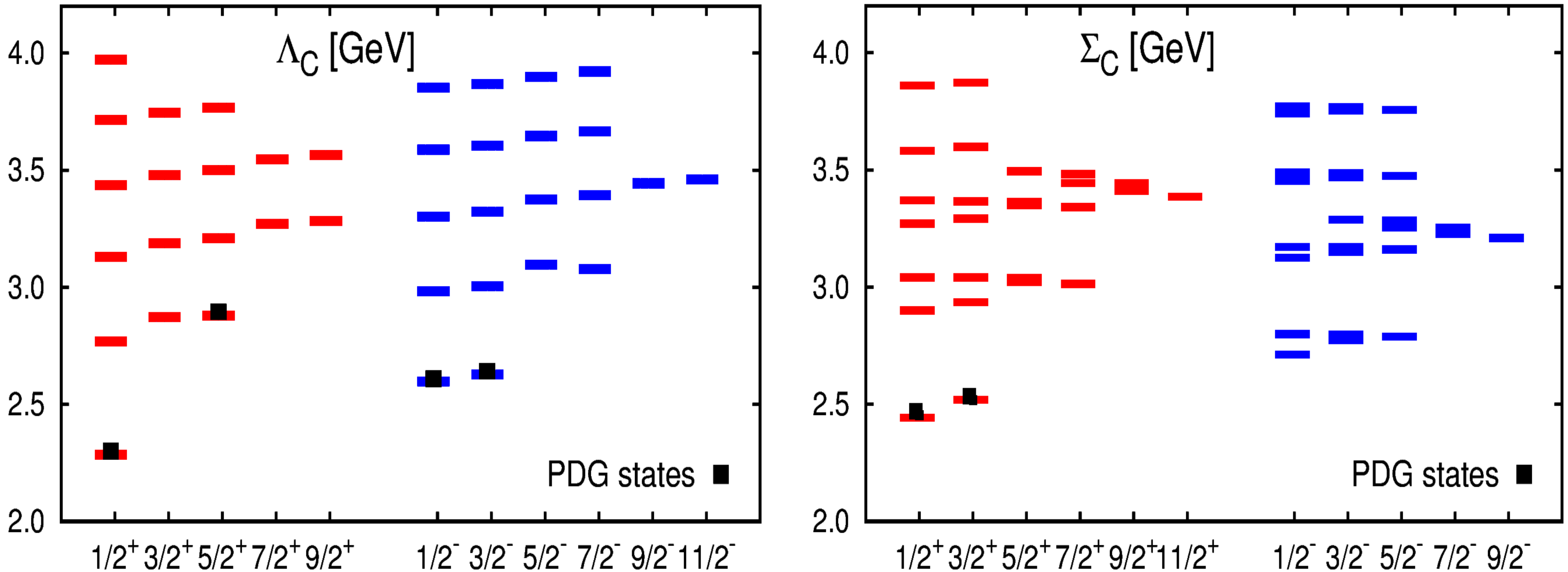
$$\frac{\chi_{13}^{BC}}{\left(\chi_4^C - \chi_{13}^{BC}\right)} = \frac{P_B^{C=1}}{P_M^C}$$

Probing open charm hadron spectrum

hadronic pressure: $P^C = \sum_{h \in \text{all hadrons}} P_h$

expt. observed hadrons
+ unobserved ones

Quark Model



Ebert et. al.: Eur. Phys. J. C66, 197 (2010);
Phys. Rev. D84, 014025 (2011)

Probing open charm hadron spectrum

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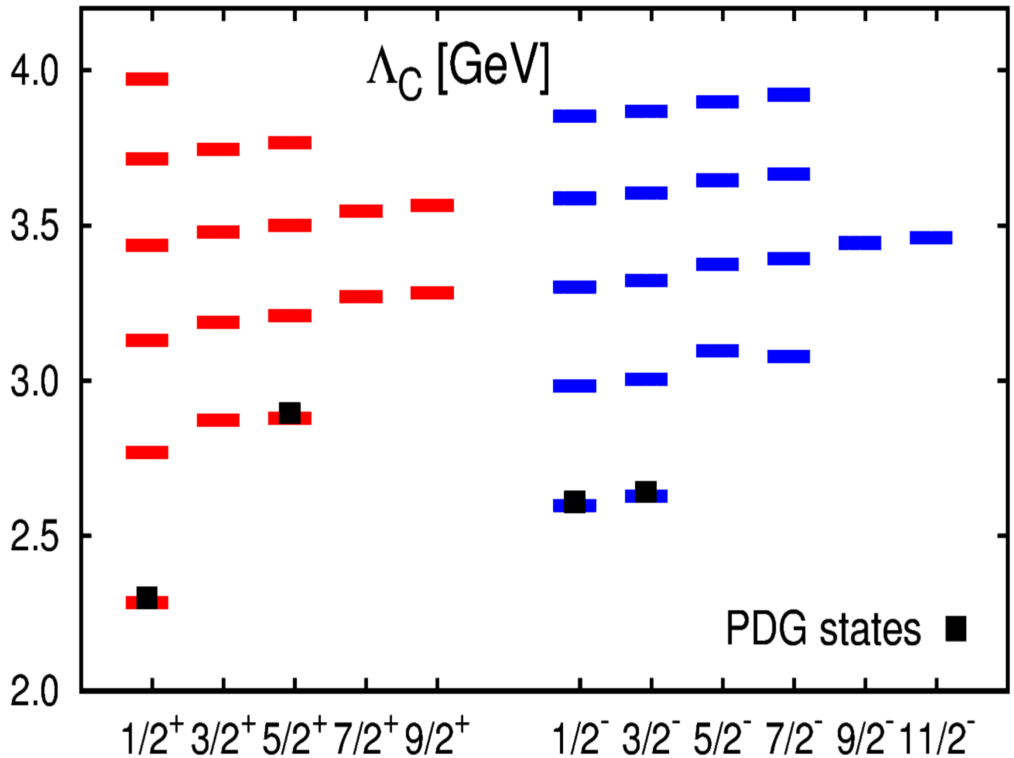
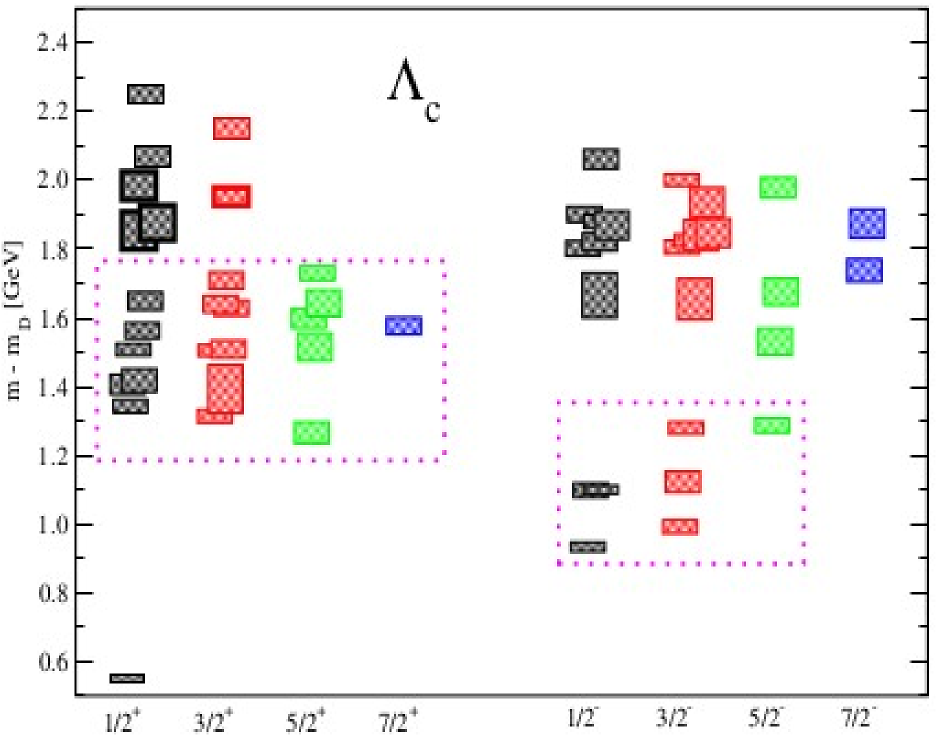


LQCD



Padmanath et.al.: arXiv:1311.4806 [hep-lat]

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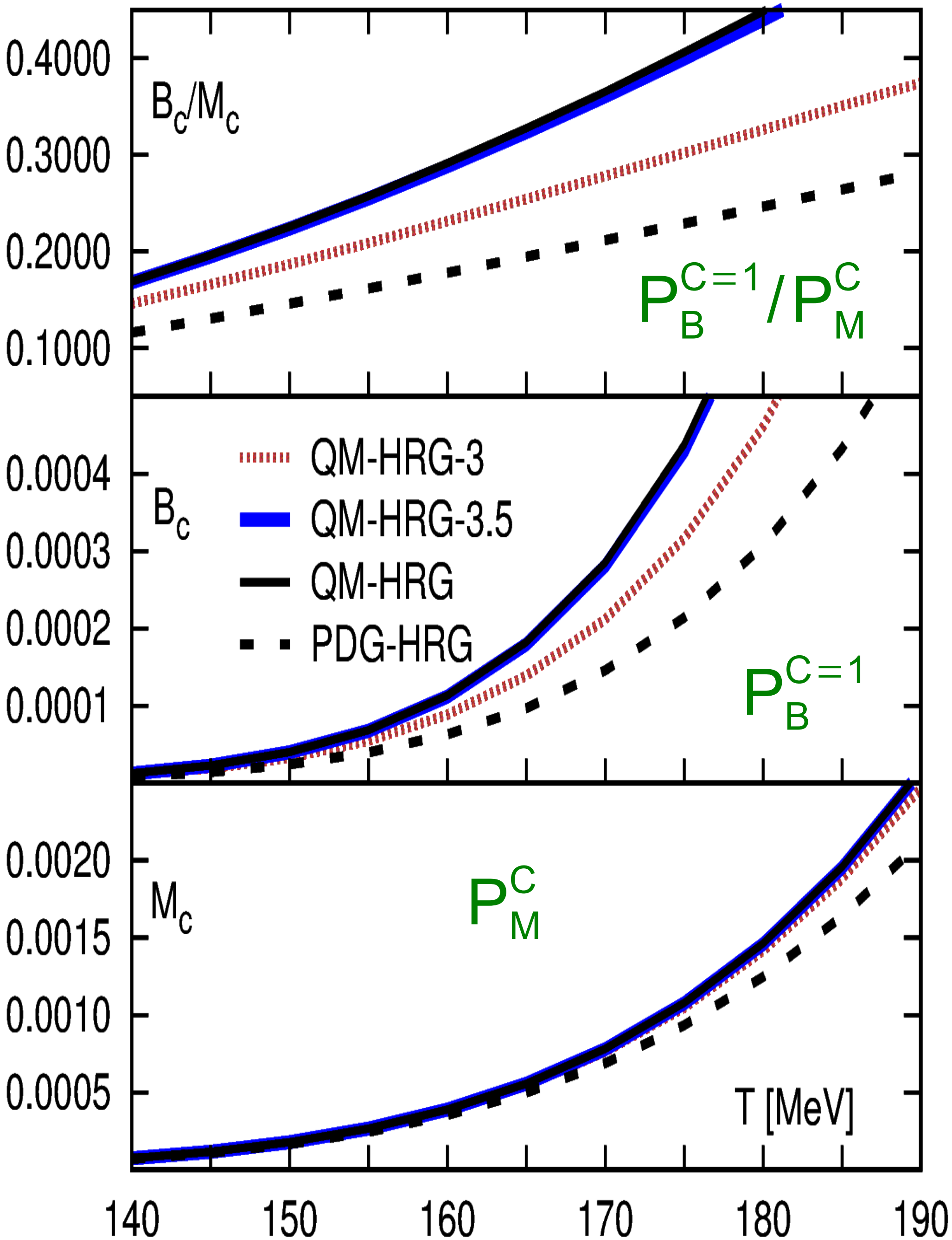
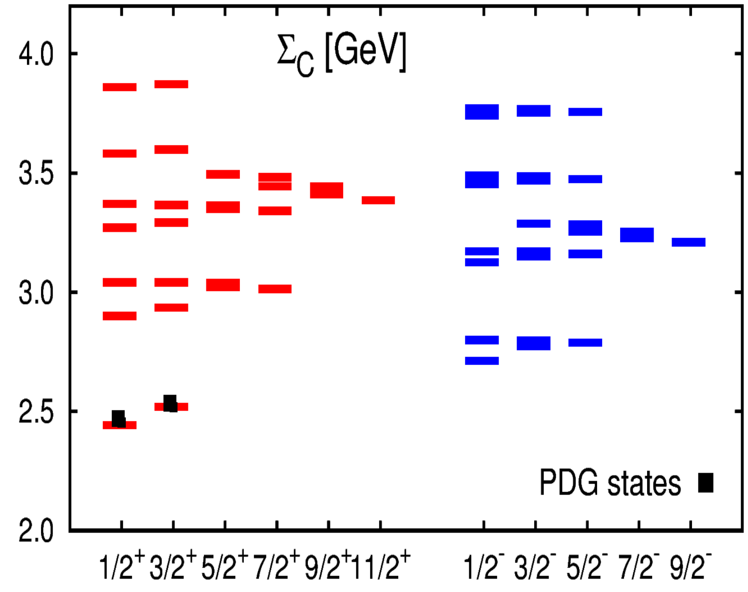
Probing open charm hadron spectrum

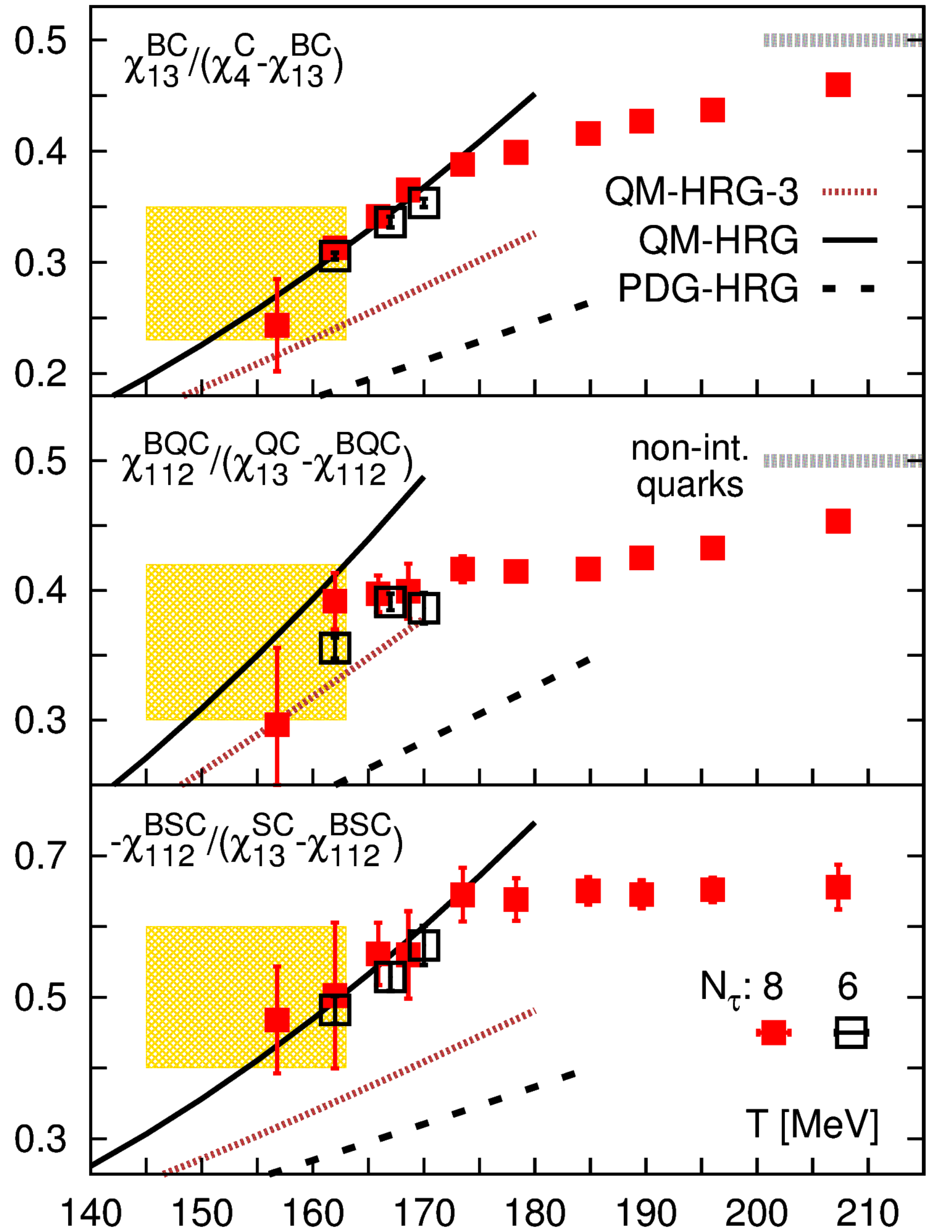




$P_B^{C=1}$: partial pressure of |C|=1 baryons

P_M^C : partial pressure of C=/=0 mesons

Signature of unobserved charm baryons



BNL-Bi: Phys. Lett. B737 (2014) 210

relative contributions:

charm baryons to charmed mesons

$$\chi_{13}^{BC}/(\chi_4^C-\chi_{13}^{BC})=P_B^{C=1}/P_M^C$$

charged charm baryons to charged charmed mesons

strange charm baryons to strange charmed mesons

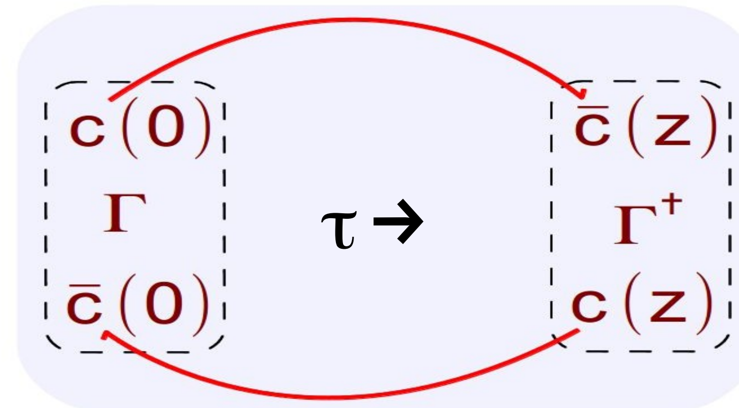
signatures of additional, unobserved charm baryons from QCD thermodynamics

Charmonia melting from LQCD via analytic continuation

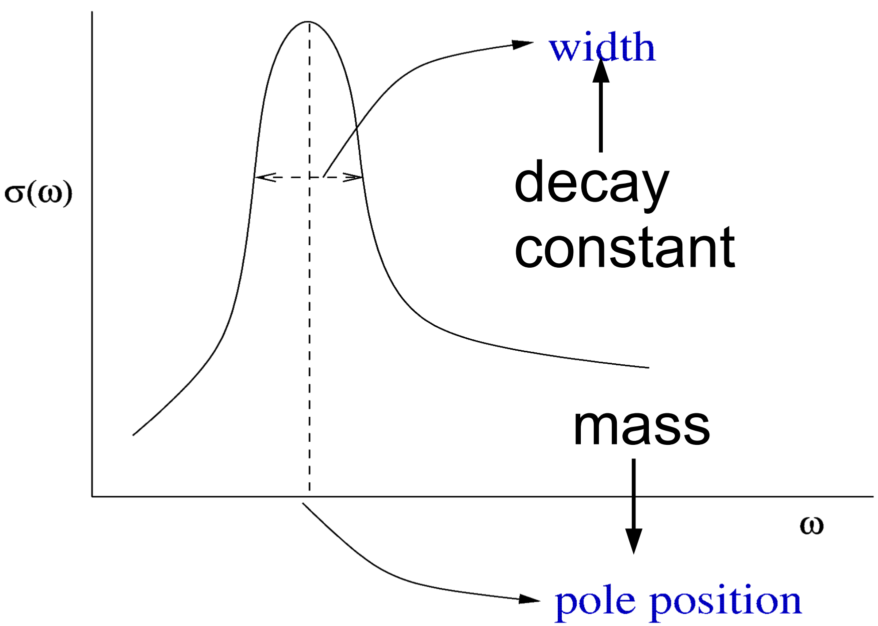
temporal correlation function of charmonia

always limited to physical distance of 1/T

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



spectral function



reconstruct through analytic continuation:
Euclidiean → Minkowski

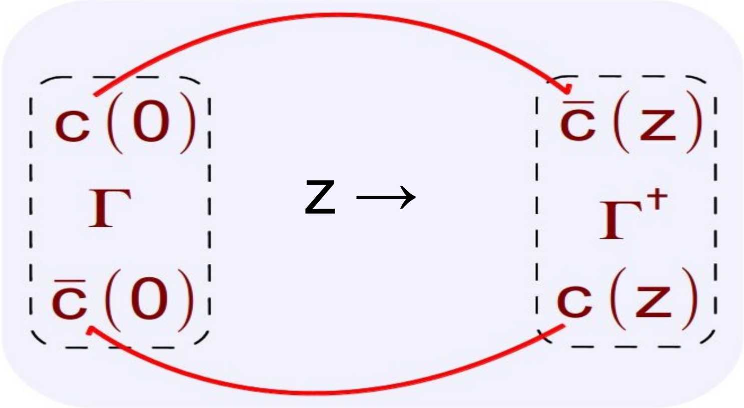
ill-posed:
Bayesian (maximum entropy) method

require lattices with vary large temporal extents

complementary avenue: spatial correlation functions

Spatial correlations of charmonia

spatial (screening) correlation functions
of charmonia



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

temporal correlation function: $C(\tau,T)=\int_0^\infty \frac{d\omega}{2\pi}\,\sigma(\omega,T)\,\frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)}$

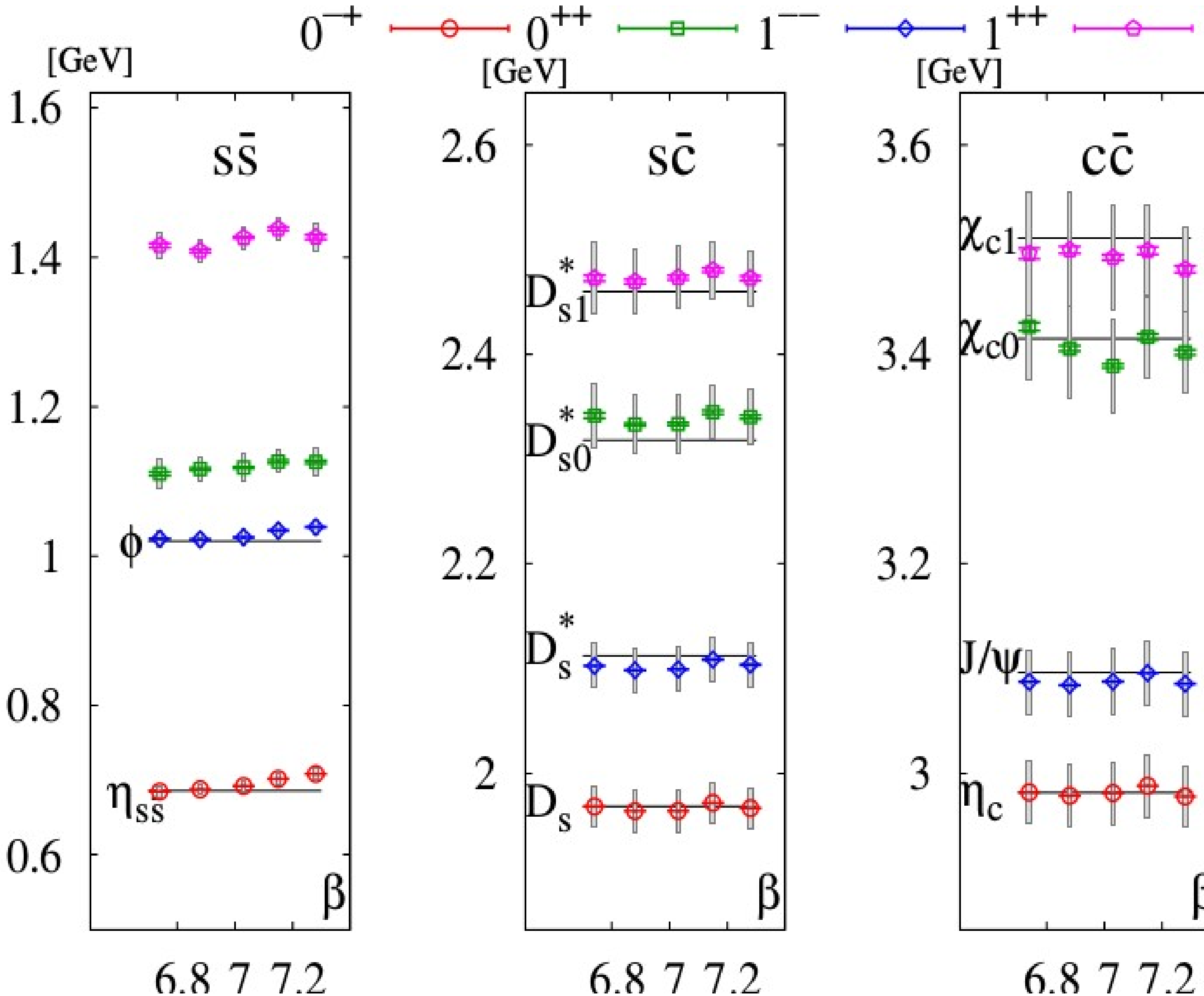
spatial correlation function:

✔ is not limited to the physical distance of 1/T

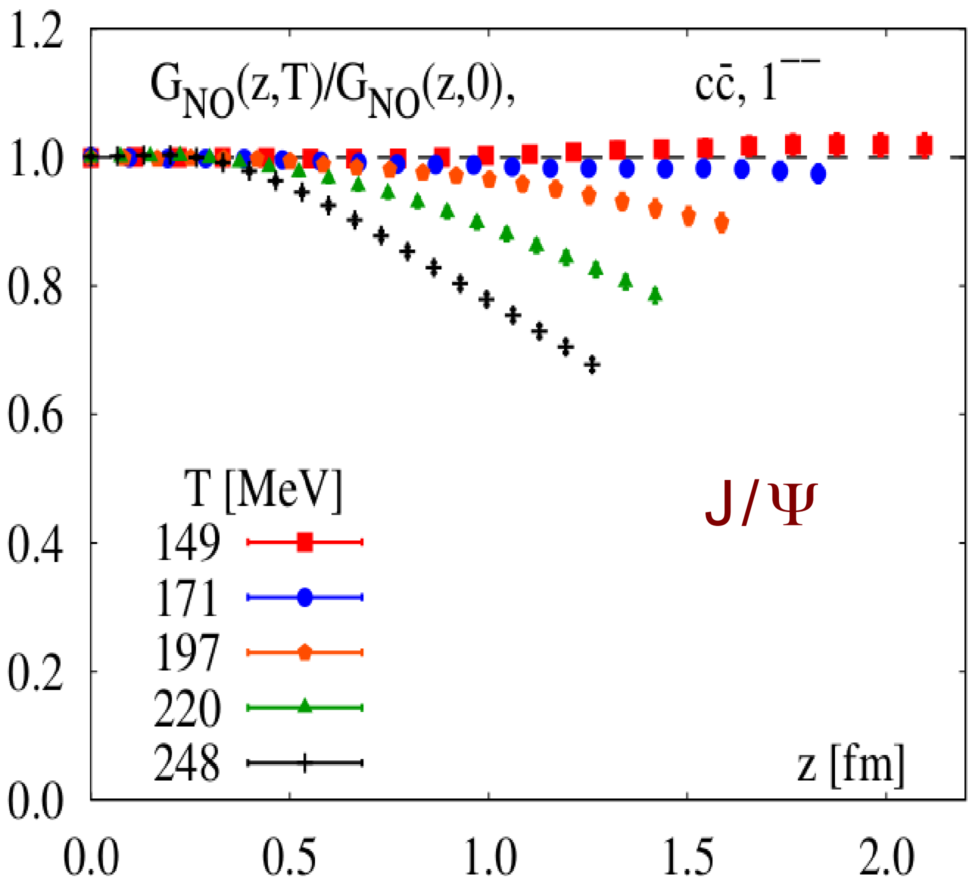
✔ transport-type zero mode contribution: $\sigma(\omega)\sim\omega\,\delta(\omega)$
does not lead to a non-decaying constant at large distances,
only generates a contact term

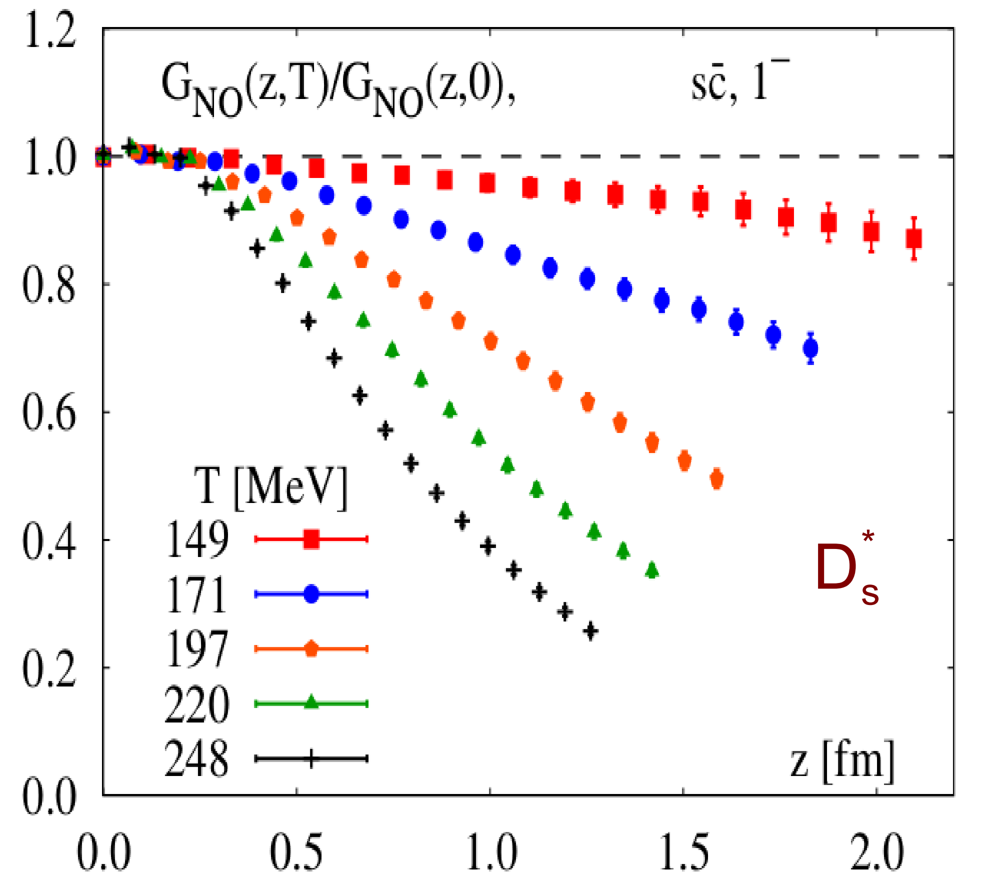
✔ the kernel is T independent → direct comparison with T=0,
thermal modification of spectral
function itself

Charm meson spectra at T=0



In-medium charm mesons: J/Ψ vs. D_s^*

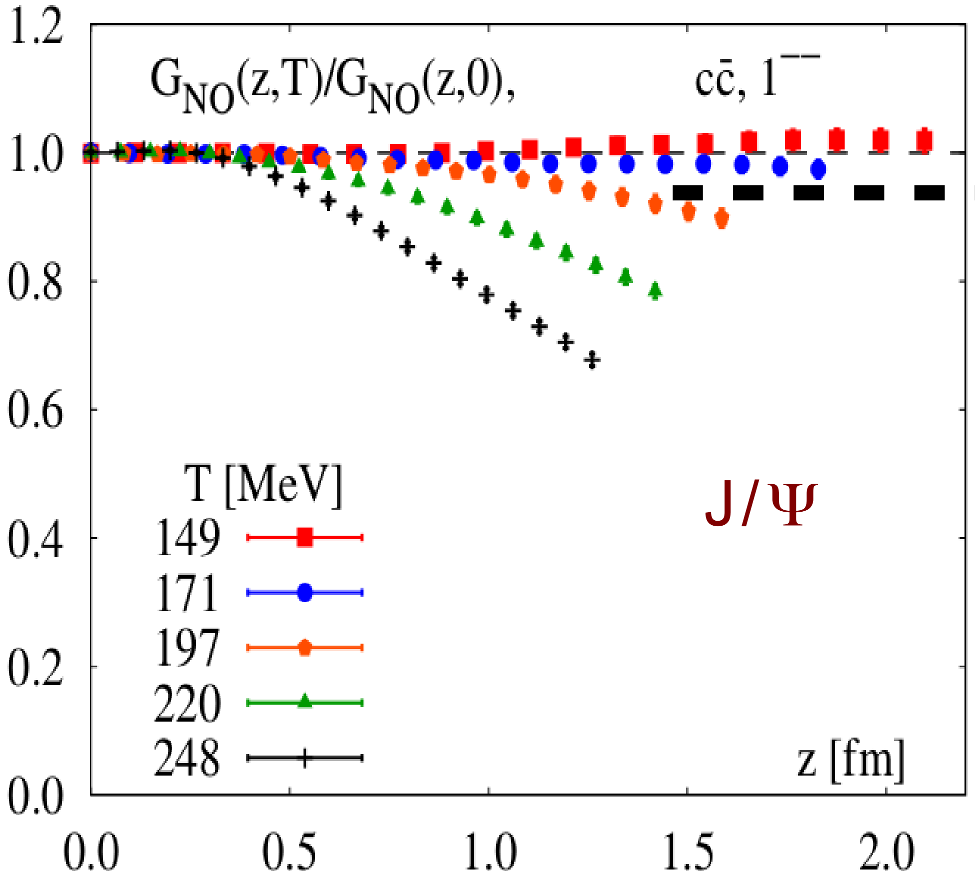


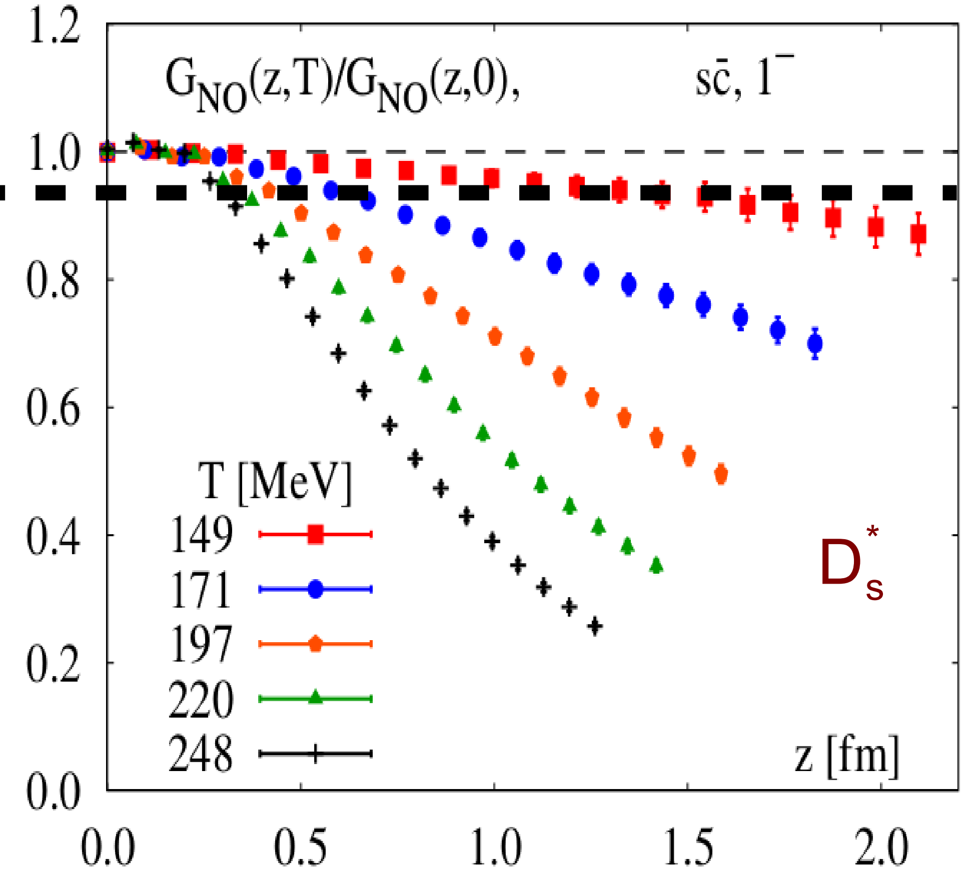


ratios of T>0 to T=0 spatial correlators

=/=1 ← thermal modification of the spectral function

In-medium charm mesons: J/Ψ vs. D_s^*

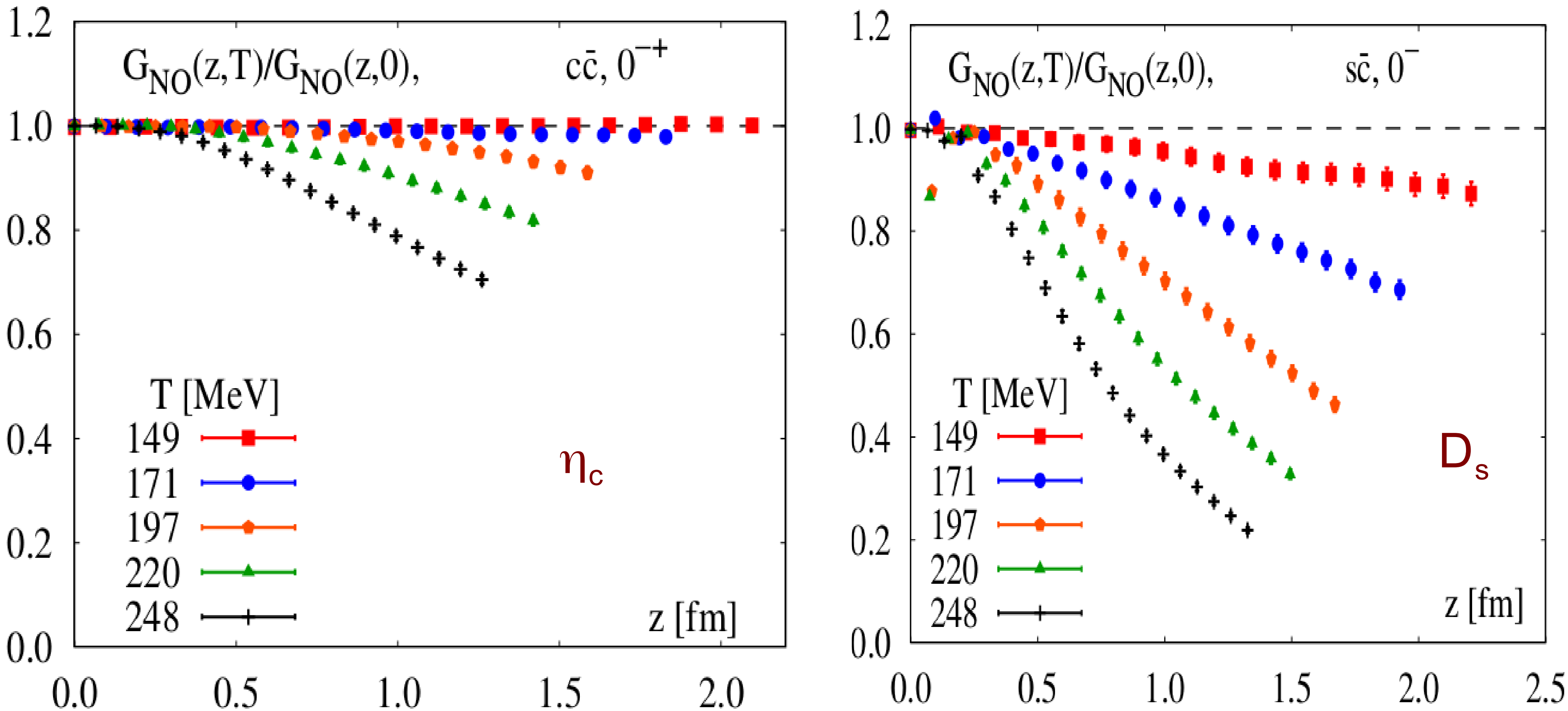




thermal modifications are already significant for $T \gtrsim T_c$?

remember:
open charm mesons starts to deconfine at $T \simeq T_c$

In-medium charm mesons: η_c vs . D_s



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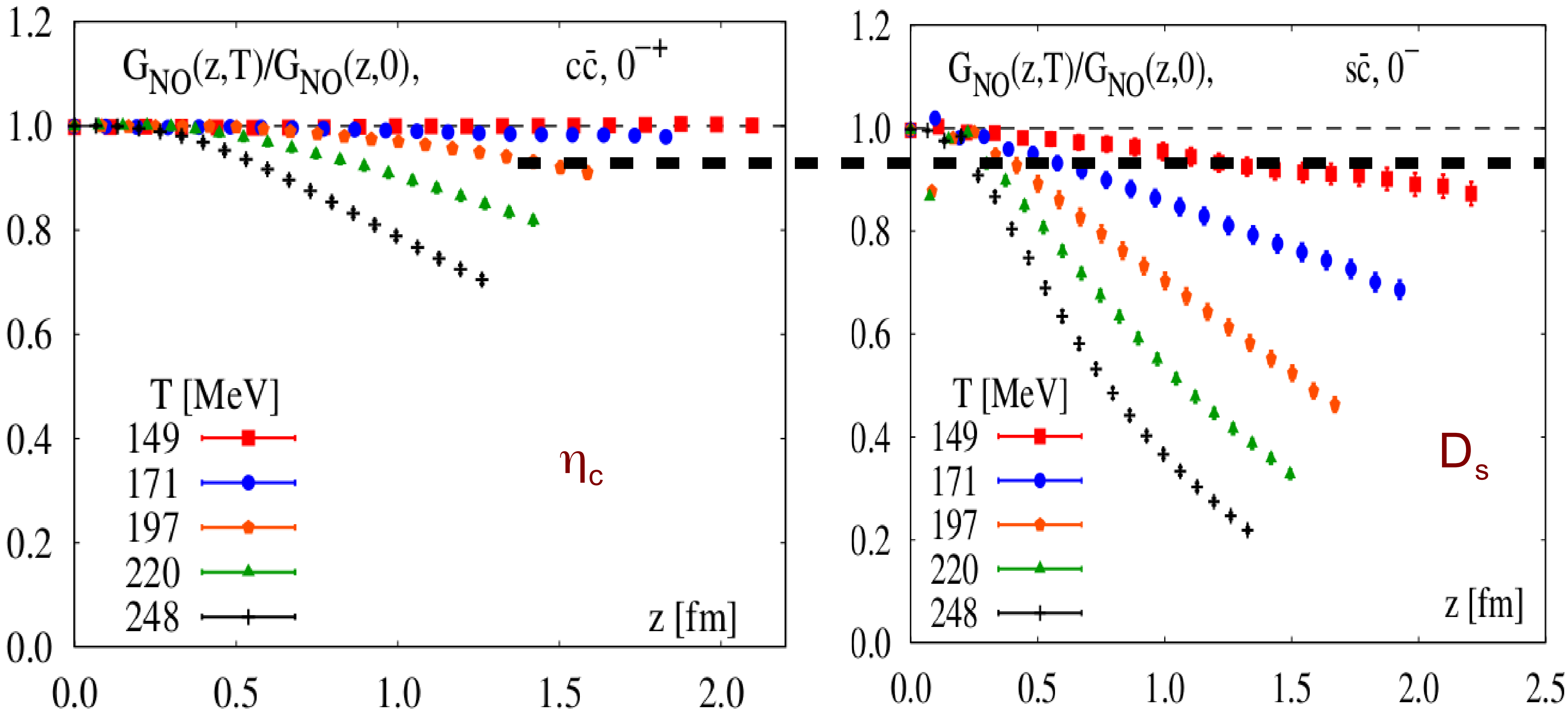


thermal modifications are already significant for $T \gtrsim T_c$?

Screening masses of charmonia

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

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

M : screening mass

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

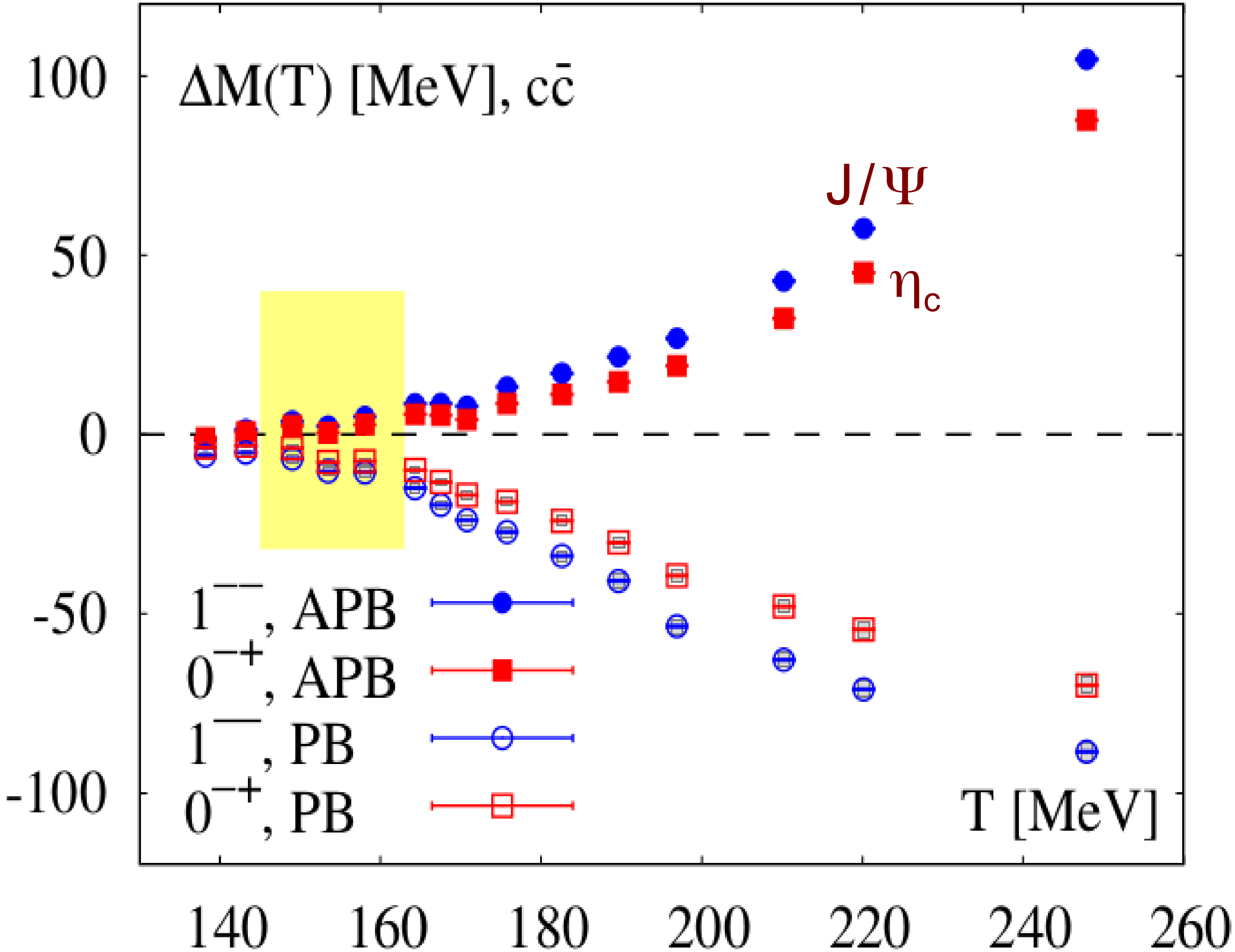
low T, well-defined mesonic bound state: $\sigma(\omega,p_z)\sim\delta(\omega^2-p_z^2-m_{mes}^2)$ $\Rightarrow$ $M=m_{mes}$

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: $\Rightarrow$ $M=m_{mes}$

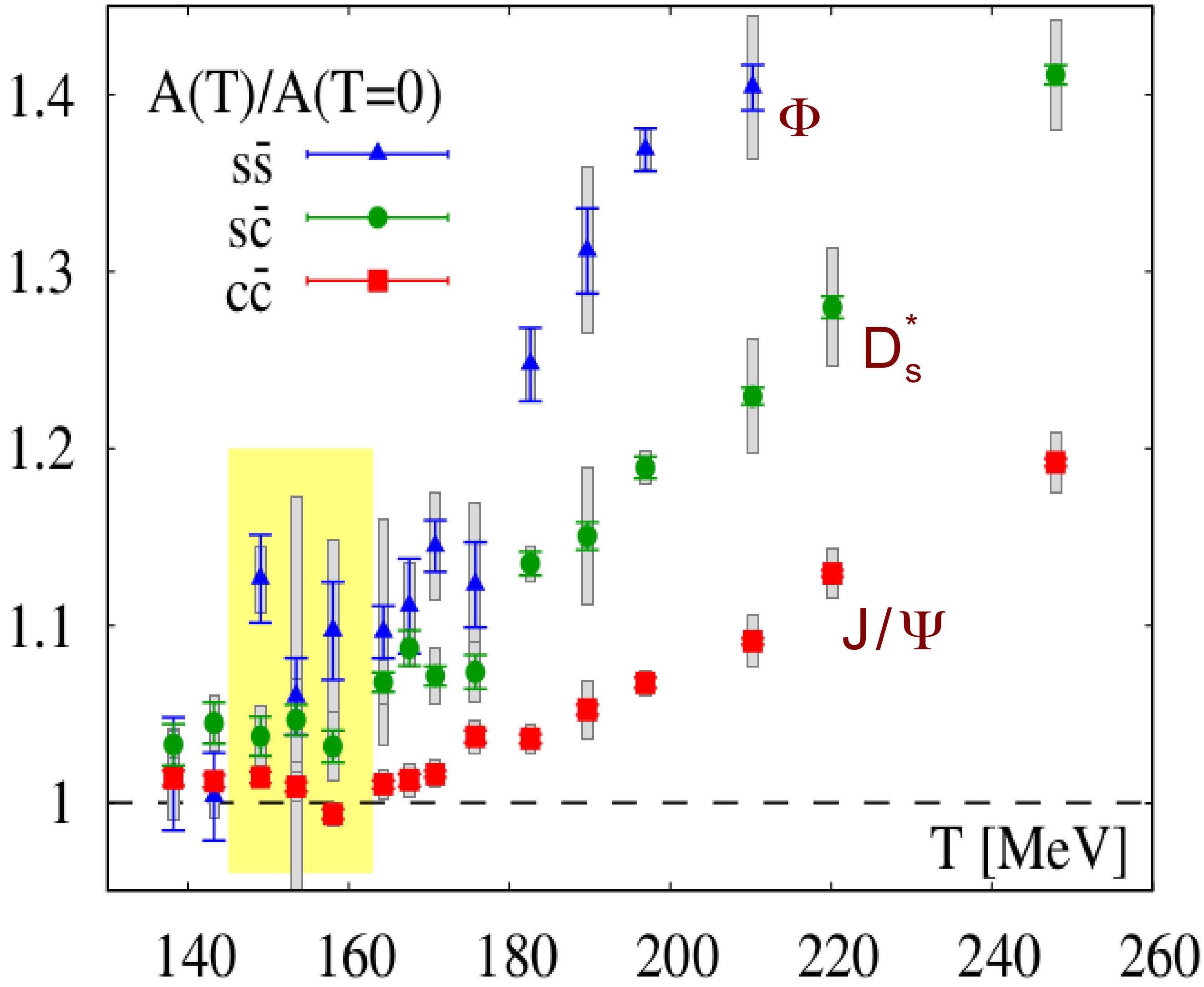
Screening masses of 1S charmonia



$$\Delta M(T) = M_{scr}(T) - m_{mes}(0)$$

'proxy' for mass shift

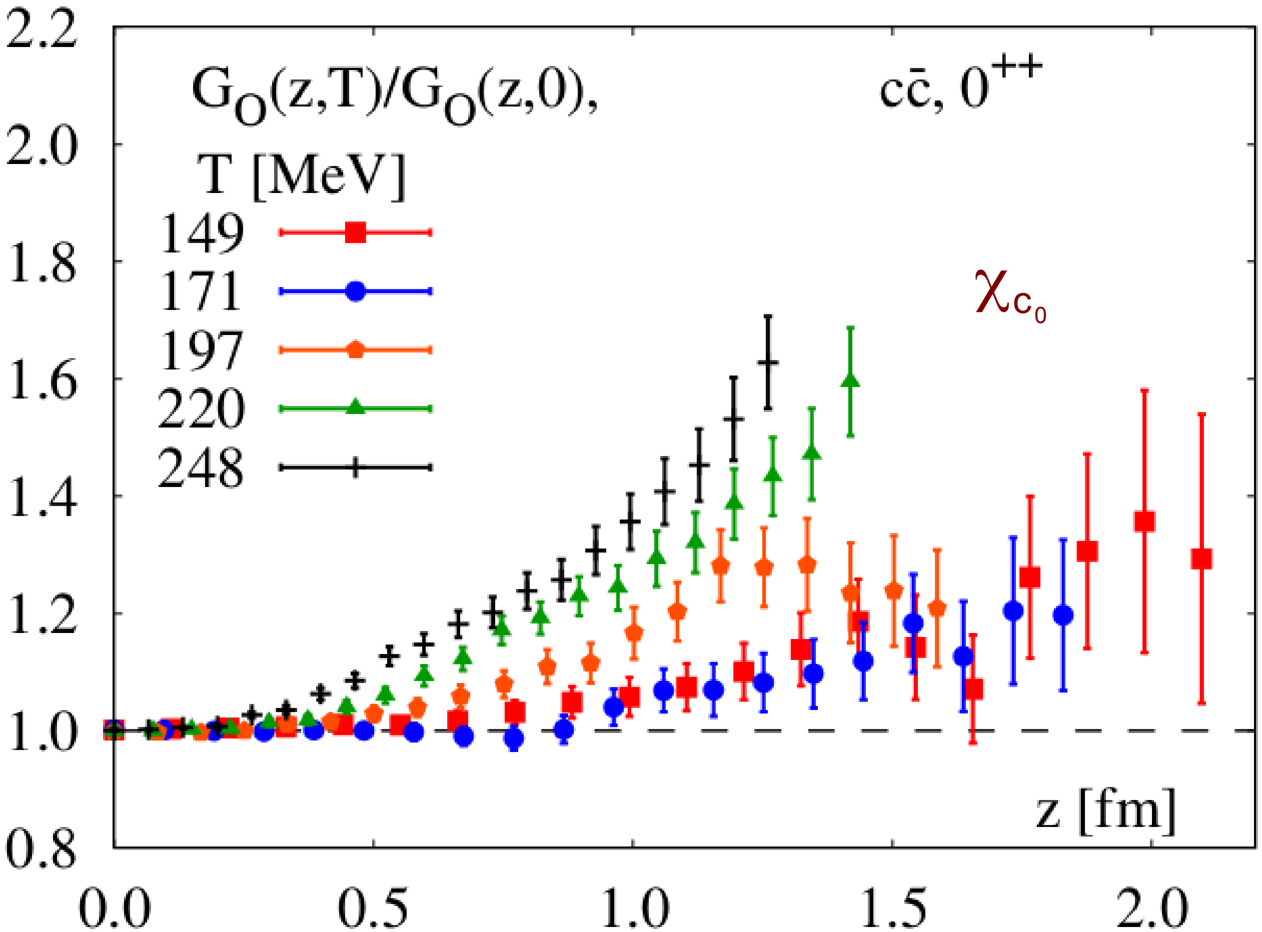
Screening masses of 1S charmonia

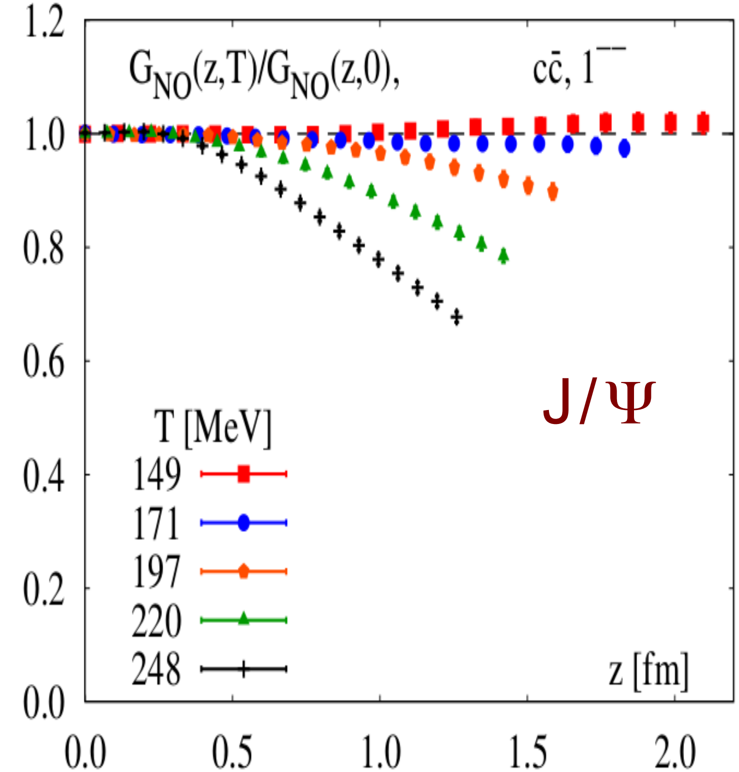


ratio of amplitudes $\sim |\psi(0,T)|^2 / |\psi(0,0)|^2$

'proxy' for broadening

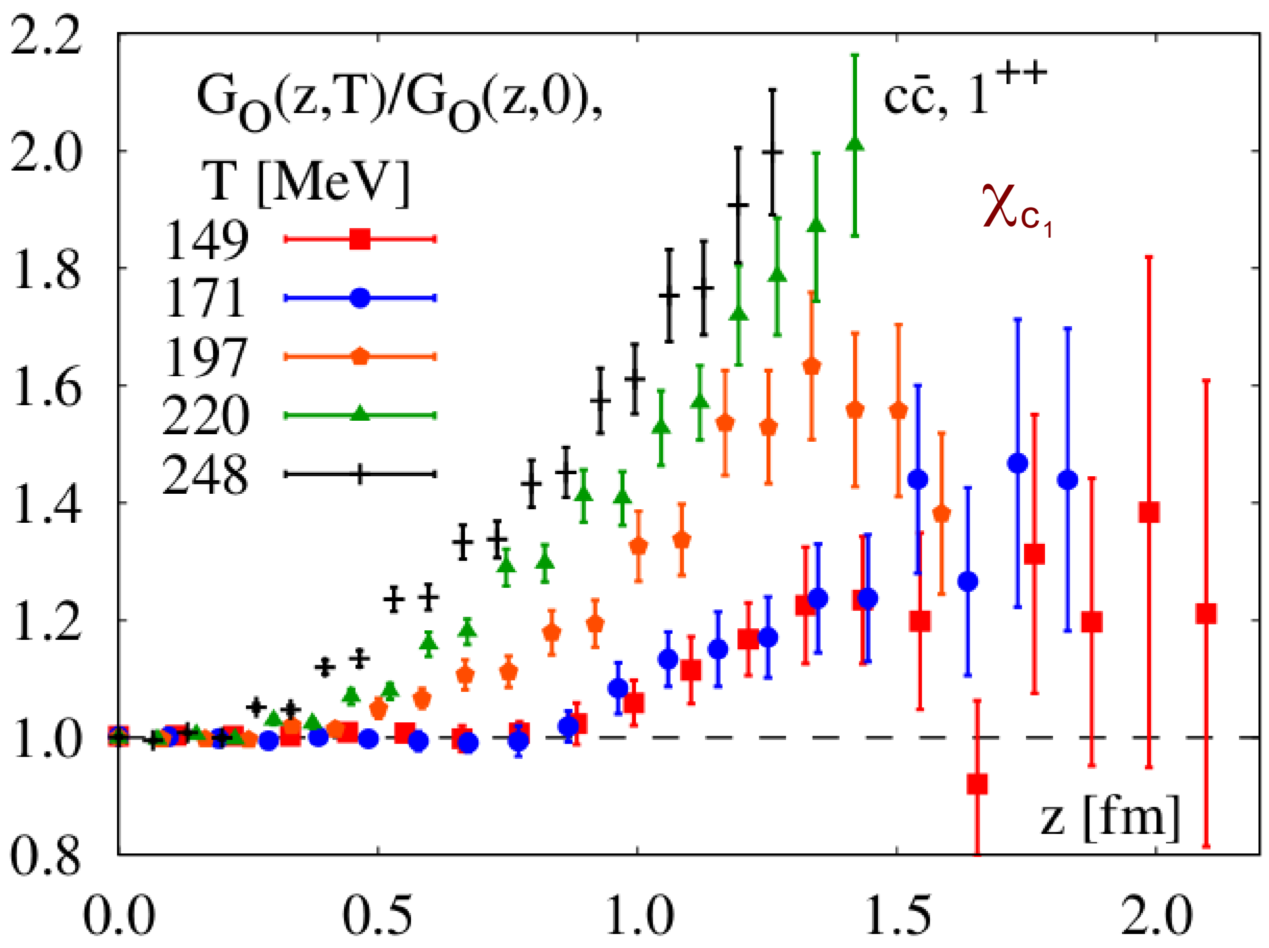
In-medium 1P charmonia: χ_{c_0} vs. J/Ψ

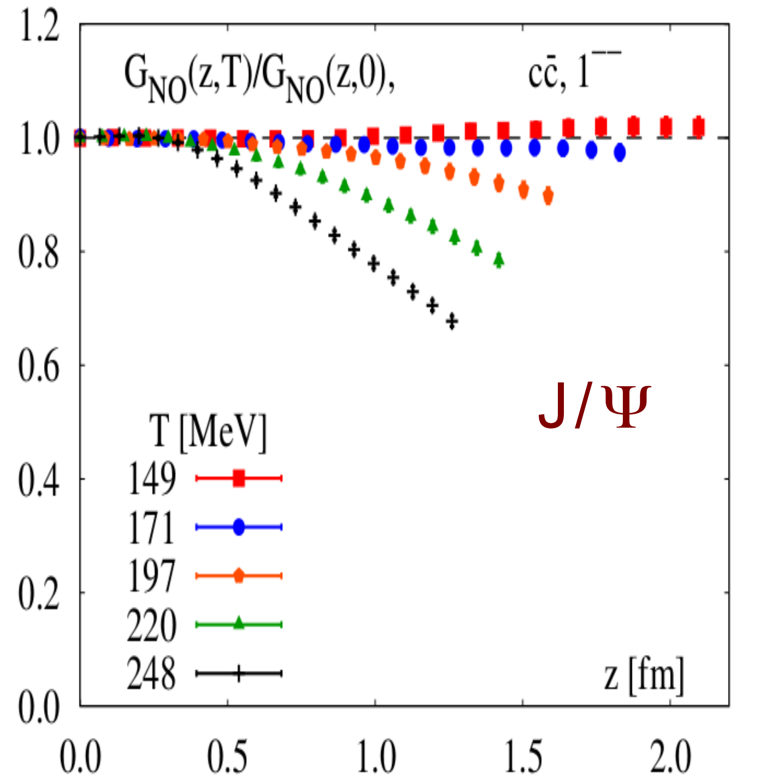




thermal modifications are already significant for $T \lesssim T_c$?

In-medium 1P charmonia: χ_{c_1} vs. J/Ψ





thermal modifications are already significant for $T \lesssim T_c$?

Summary

open charm hadrons starts to deconfine at $T \simeq T_c$

hits for additional, unobserved charmed baryons
from QCD thermodynamics

thermal modifications of 1S charmonia may be
significant already for $T \gtrsim T_c$

thermal modifications of 1P charmonia may be
significant already for $T \lesssim T_c$