Thermodynamics of heavy-light hadrons

Heng-Tong Ding (丁亨通)

Central China Normal University (CCNU)

arXiv:1404.6511, 1404.4043

BNL-Bielefeld-CCNU collaboration

A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, Y. Maezawa, S. Mukherjee, H. Ohno, P. Petreczky, C. Schmidt, S. Sharma, W. Söldner, M. Wagner

Lattice 2014, Manhattan NY, 23-28 June

Outline

- Onset of deconfinement of open charm & strange hadrons

- Evidence for the thermodynamic contribution from experimentally not yet observed hadrons

- Influence of missing hadron states in the determination of hadronization T in the strange hadron sector

Deconfinement aspects of QCD transition

Light-quark hadrons get deconfined around T_c, charmonia and bottomonia may survive at $T>T_c$ Matsui & Satz PLB '86

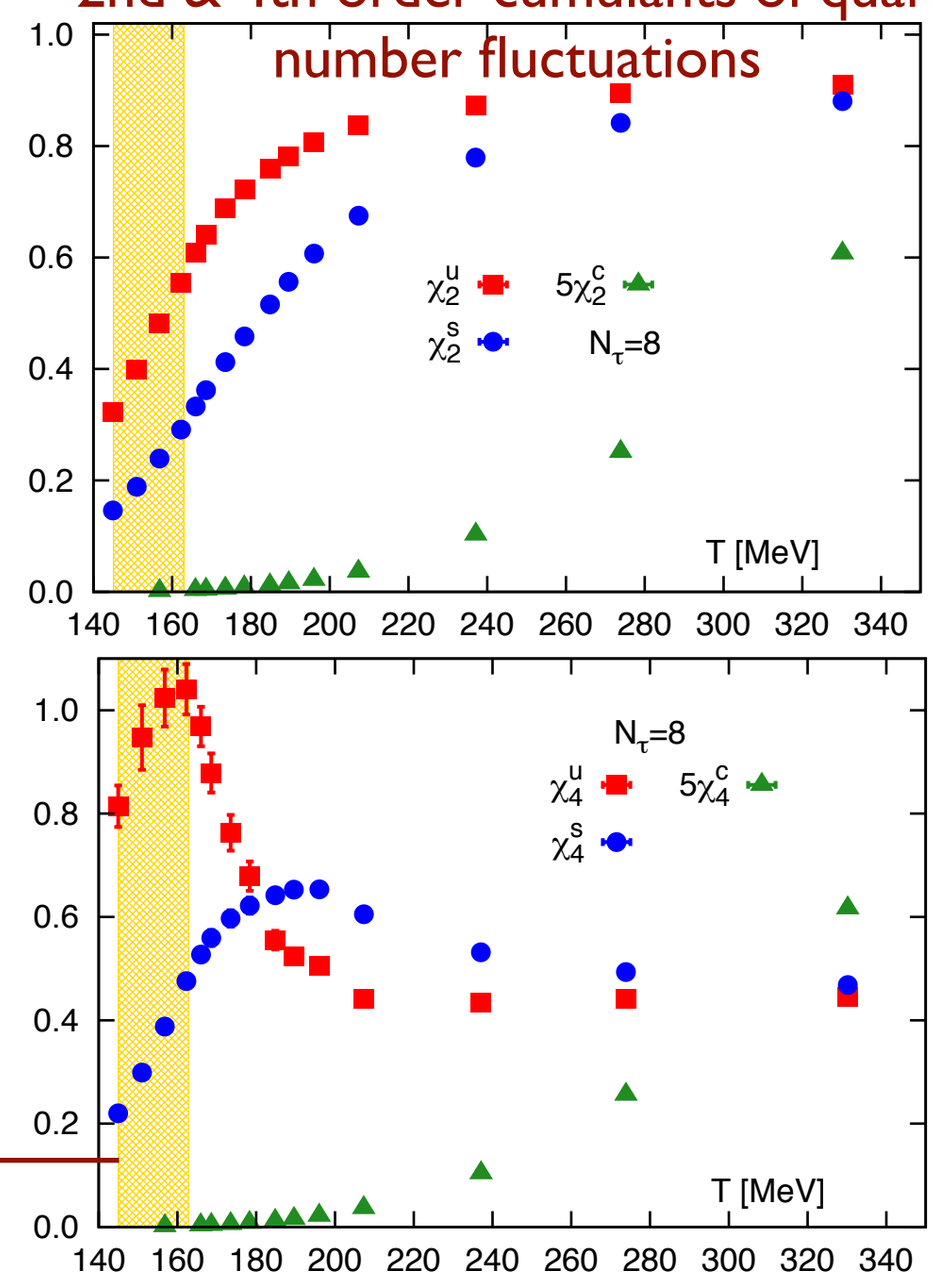
How about open charm & strange hadrons ?

Strange quark, less affected by chiral symmetry, may remain confined at $T > T_c$?

Do strange hadrons survive at higher temperature ?

Freeze-out/hadronization hierarchy between light-quark & strange hadrons ?

2nd & 4th order cumulants of quark number fluctuations



T_c=154(9) MeV

HotQCD, PRD85(2012)054503
Wuppertal-Budapest, JHEP 1009 (2010) 073

fluctuations of conserved quantum numbers

In the confined hadronic phase: electric charge Q, baryon number B of hadrons are integer numbers

In the deconfined QGP phase: Q and B of quarks are fractional numbers

fluctuations of B/Q/S/C and their correlations: probe the deconfined degrees of freedom for strange (S) and charm (C), irrespective of quark mass

$$\chi_{mn}^{XY} = \frac{\partial^{(m+n)}\left(p(\hat{\mu}_X, \hat{\mu}_Y)/T^4\right)}{\partial \hat{\mu}_X^m \partial \hat{\mu}_Y^n}\Big|_{\vec{\mu}=0}, \quad \hat{\mu}=\mu/T, \; X,Y=\{B,Q,S,C\}$$

"order parameters": construct observables that vanish in one phase and are nonzero in the other phase

Bazavov, HTD et al., Phys.Rev. Lett. 111(2013)082301

Partial pressure of heavy-light hadrons from HRG

- In the Hadron Resonance Gas (HRG) model, open heavy (strange or charm) mesons and baryons follow Boltzmann statistics as m/T >>1

$$P_{M/B}(T,\vec{\mu}) = \sum_{i\in \text{ open C/S hadrons}} P^i_{M/B}\cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S + C_i\hat{\mu}_C)$$

differences of baryon-X correlations (X=Q,S,C):

$$\chi^{BX}_{31} - \chi^{BX}_{11} = \sum_i (B_i^3 - B_i)\times g_i(m^{hadron})$$

→ depends on hadron spectrum

if B=0,1, degrees of freedom are hadrons, $\chi^{BX}_{31} = \chi^{BX}_{11}$

if B=1/3, degrees of freedom are quarks, $\chi^{BX}_{31} \neq \chi^{BX}_{11}$

- the decomposition of partial pressure arising from open charm baryons

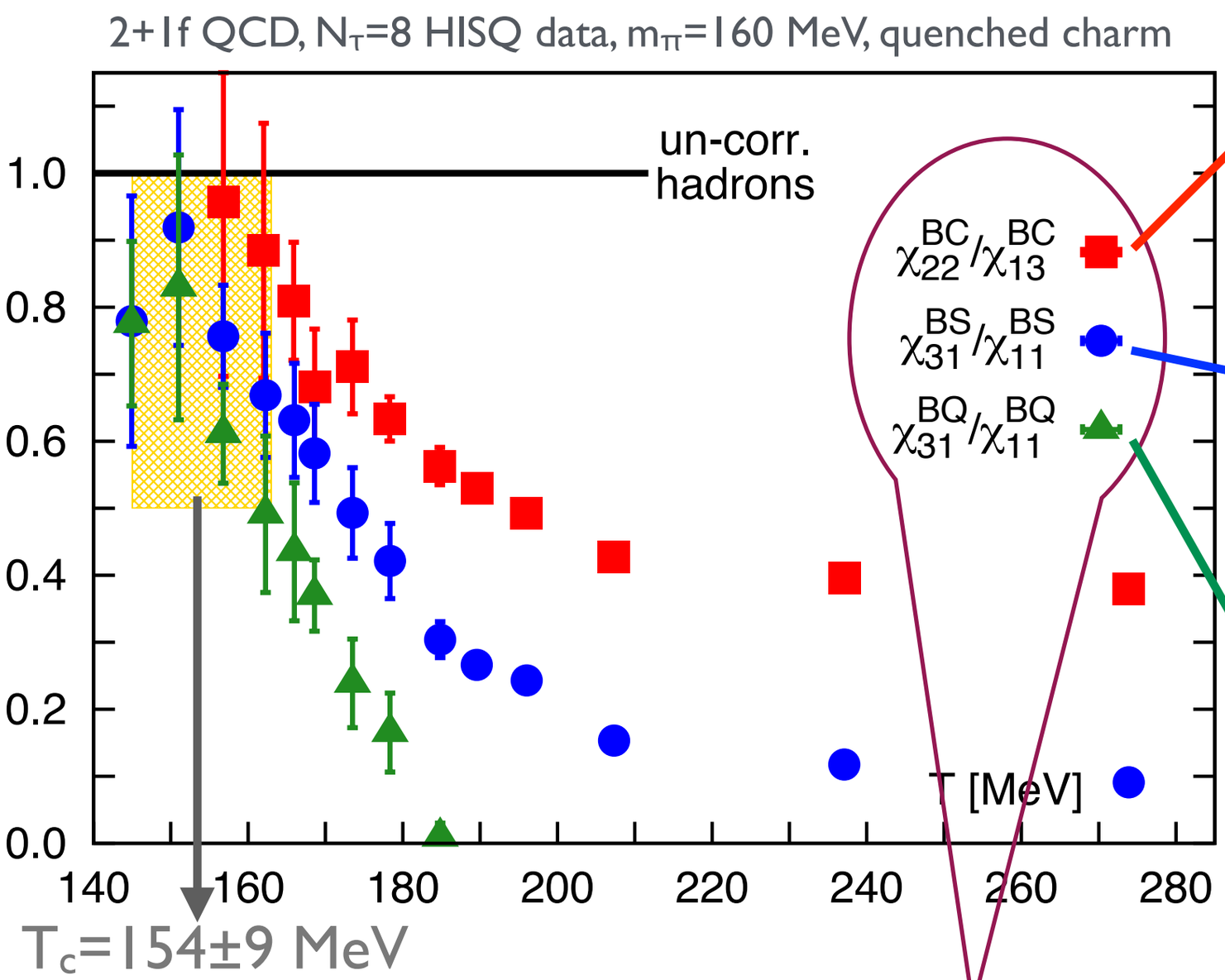
$$P^C_B(T,\vec{\mu}) = B_{C,1} + B_{C,2} + B_{C,3} \Rightarrow \chi^{BC}_{mn} = B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3}$$

P^C_B is dominated by |C|=1 baryons due to large mass of |C|=2,3 baryons

↓ m+n>2 and even

in the hadronic phase: $\chi^{BC}_{mn} \simeq B_{C,1}$,e.g. $\chi^{BC}_{13} \simeq \chi^{BC}_{22}$

deconfinement of open charm & strange hadrons



ratio of baryon-charm correlation: receives contributions only from charm d.o.f

ratio of baryon-strangeness correlation: receives contributions only from strange d.o.f

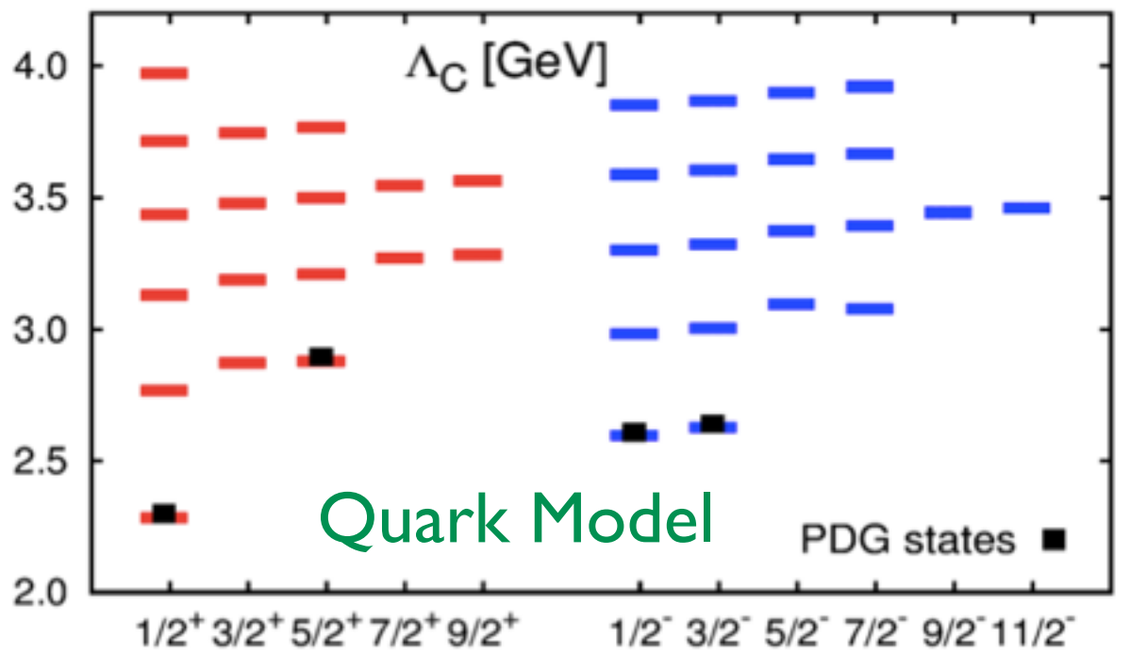
ratio of baryon-charge correlation: receives contributions from all quark d.o.f

all equal to unity in an uncorrelated hadron resonance gas

Both open strange and charm hadrons start to get deconfined in the chiral crossover region

Bazavov, HTD et al., [BNL-Bielefeld-CCNU], arXiv:1404.4043

Hadron Resonance Gas model: revisited

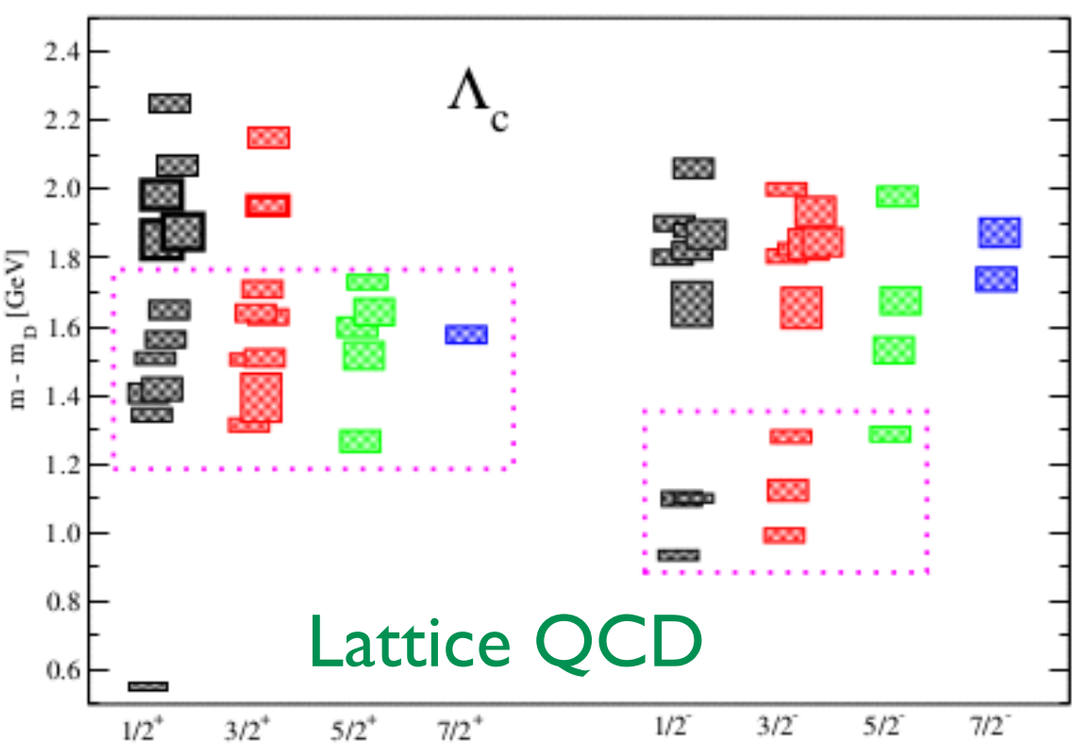


Ebert et. al., EPJC66(2010)197, PRD84(2011)014025

$$P_{\text{total}} = \sum_{\text{all hadrons}} P_h$$

hadrons listed in PDG + ???

More states are predicted in relativistic Quark Model (QM) than listed in PDG

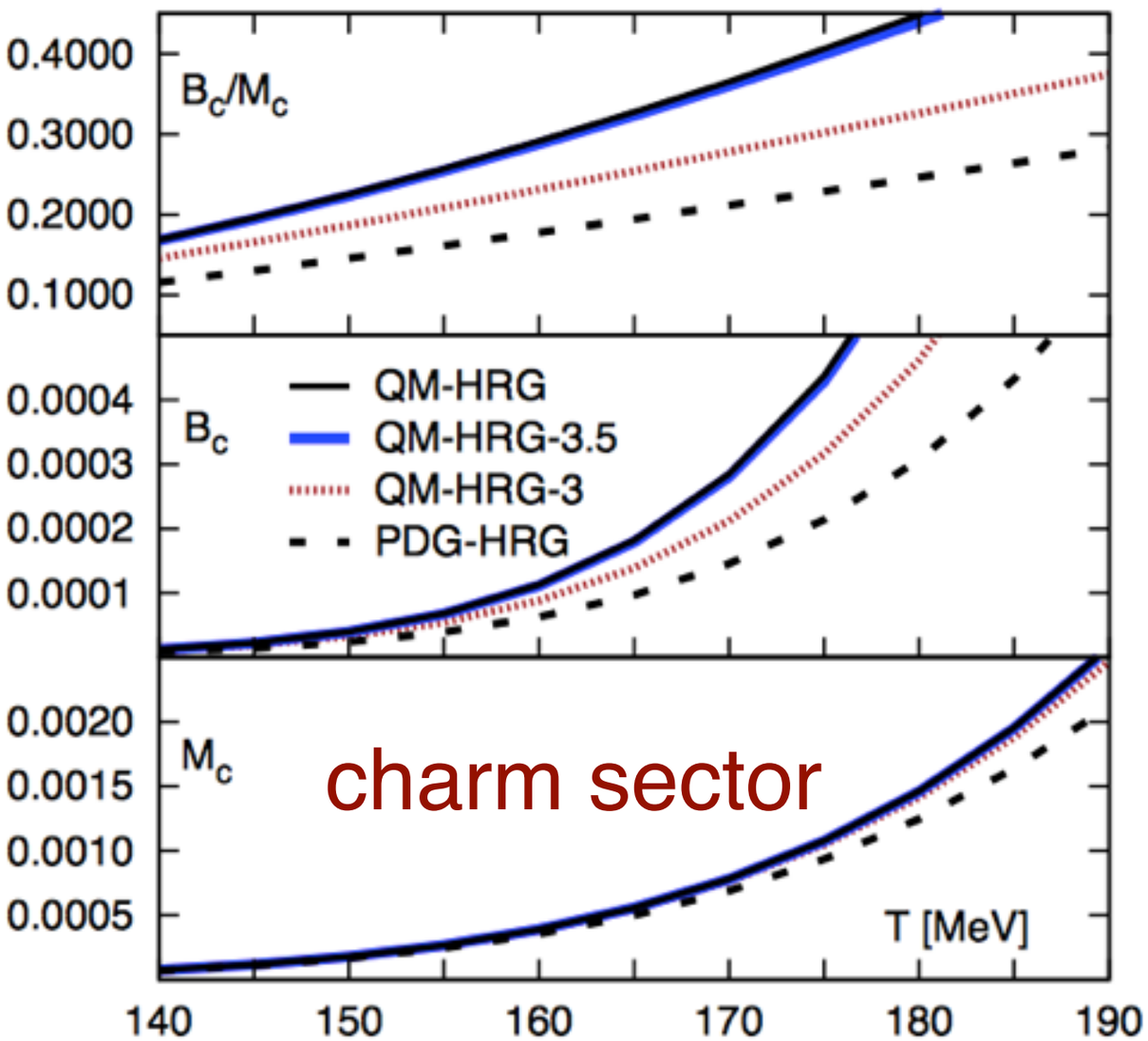


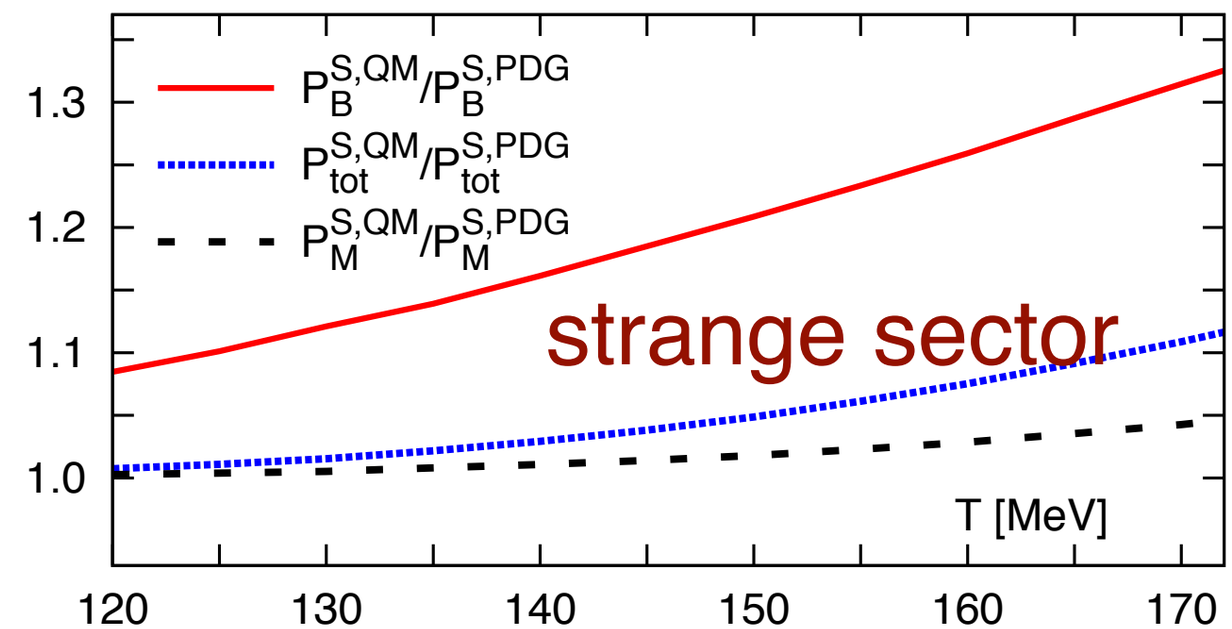
Padmanath et.al., arXiv:1311.4806 [hep-lat]

LQCD calculations give similar results with QM

Any thermodynamic significance from additional hadron states predicted in QM?

Additional open charm/strange hadrons in HRG





B: pressure from baryons
M: pressure from mesons

Less baryons than mesons are listed in PDG

The additional states from the Quark Model (QM) give considerable contributions to partial pressures at T<154 MeV

A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], arXiv:1404.6511,1404.4043

Construction of observables to probe the abundance

decomposition of partial pressure (P) arising from heavy-light hadrons in HRG:

$$P_{M/B}(T,\vec{\mu}) = \sum_{i\in \text{ open C/S hadrons}} P^i_{M/B} \cosh(B_i\hat{\mu}_B + Q_i\hat{\mu}_Q + S_i\hat{\mu}_S + C_i\hat{\mu}_C)$$

charm sector:

$$P^C_M(T,\vec{\mu}) = M_C, \qquad P^C_B(T,\vec{\mu}) = B_{C,1} + B_{C,2} + B_{C,3}$$

$$\chi^{BC}_{mn} = B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3} \simeq B_{C,1}$$ ← partial P arising from baryons

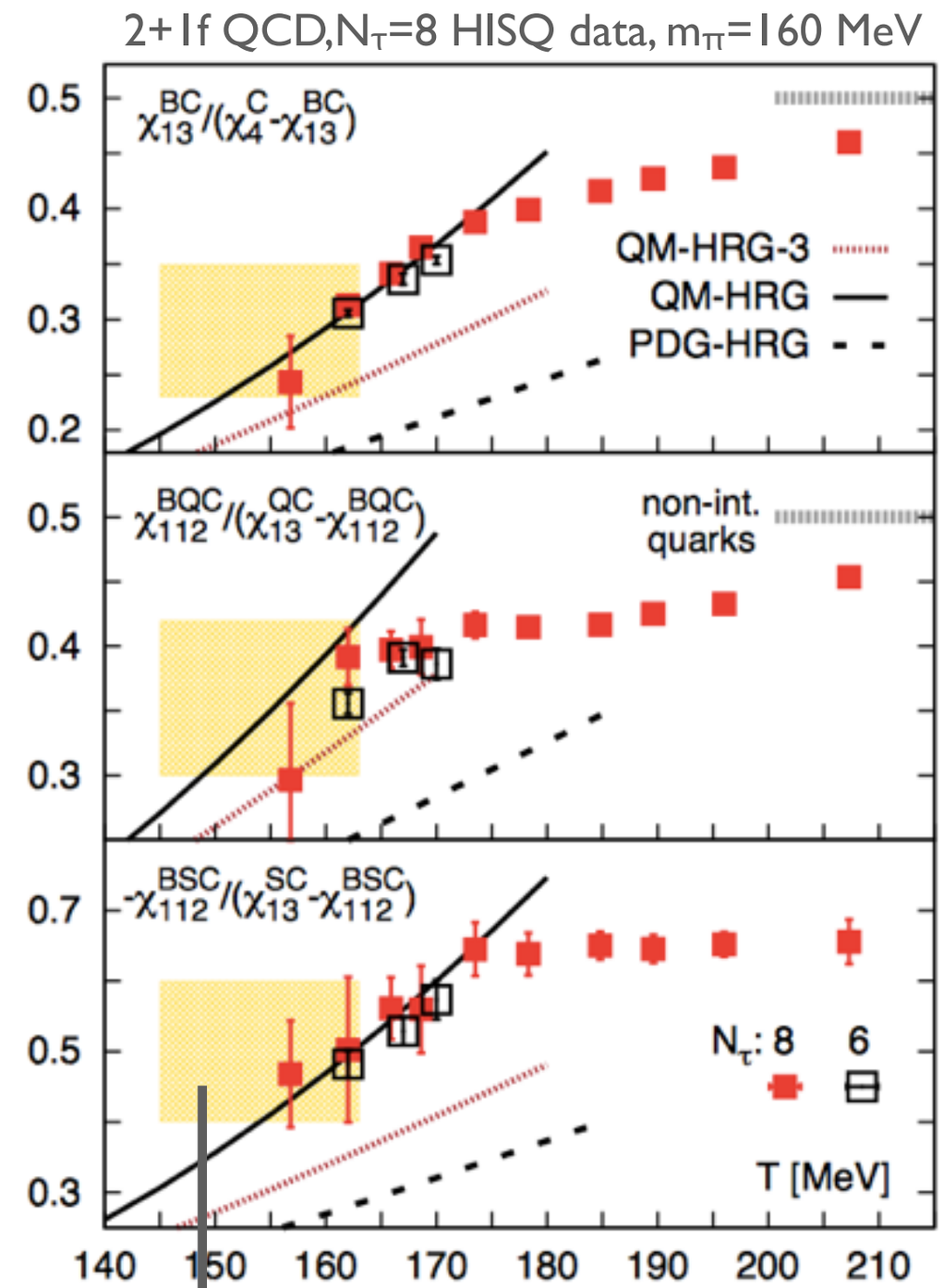
$$\chi^{C}_{n} = M_C + B_{C,1} + 2^n B_{C,2} + 3^n B_{C,3} \simeq M_C + B_{C,1}$$ with n even

$$\chi^{C}_{n} - \chi^{BC}_{mn} \simeq M_C$$ ← partial P arising from mesons

- observables probing the relative contribution of baryons and mesons to the partial pressures

$$\chi^{BC}_{mn}/(\chi^{C}_{n} - \chi^{BC}_{mn})$$, e.g. $$\chi^{BC}_{13}/(\chi^{C}_{4} - \chi^{BC}_{13})$$

Abundance of open charm hadrons



T_c=154±9 MeV

Use appropriate projections to check the relative contributions of:

charm baryons to open charm mesons

charged charm baryons to open charm mesons

strange-charmed baryons to strange-charmed mesons

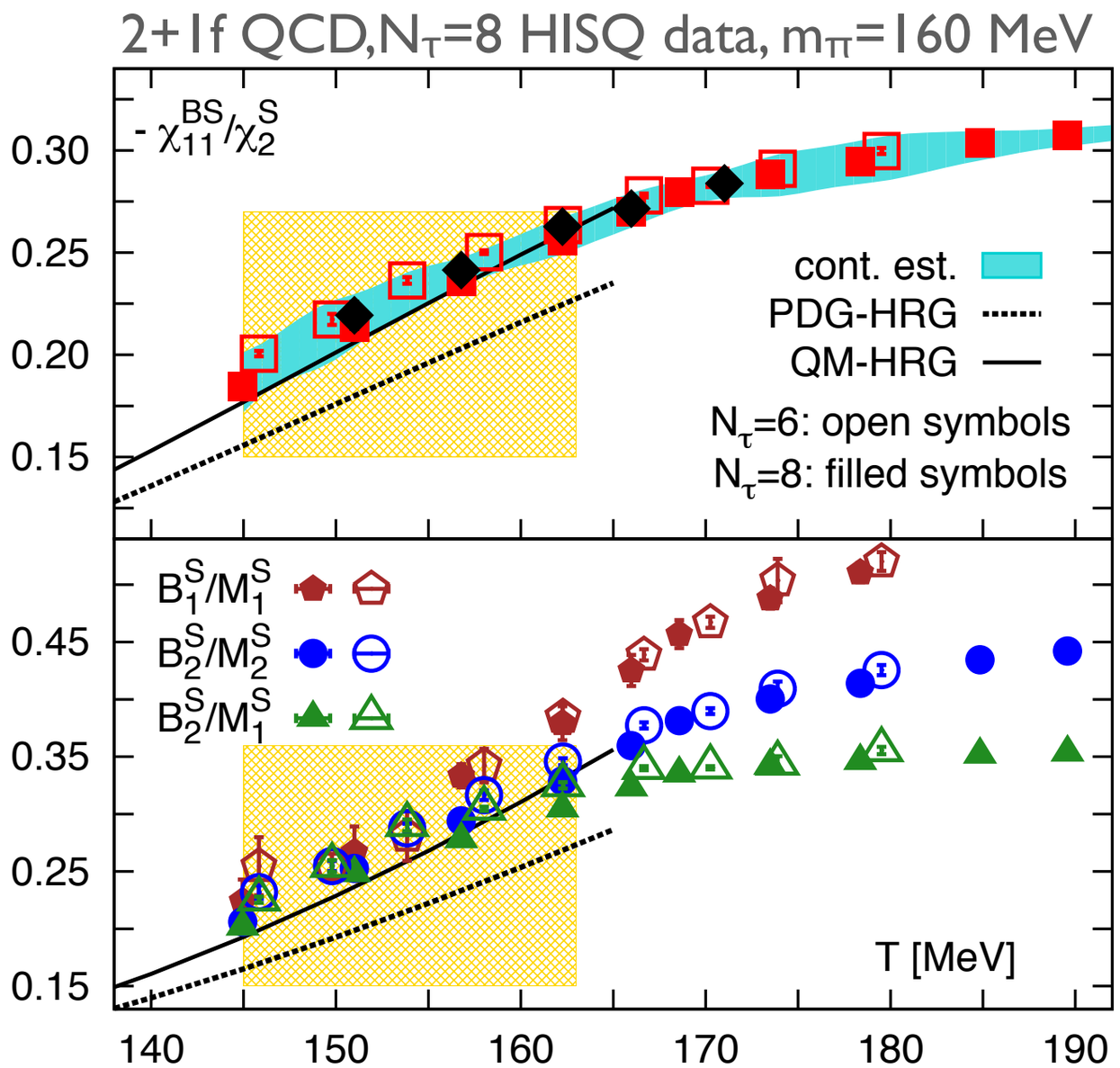
Clear evidence of the additional, non-PDG listed states from QCD thermodynamics is found

A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU],1404.4043

Importance of additional states has also been pointed out in

Majumder and Mueller, PRL 105(2010)252002 & Beitel, Gallmeister and Greiner,1402.1458

Additional open strange hadrons from QCD thermodynamics



Relative contributions of strange baryons to open strange mesons

in strange-baryon correlations

in partial pressures

B_i/M_j are identical in the hadronic phase

reconfirms that the onset of the deconfinement of open strange hadrons is same as light-quark hadrons

QM-HRG describes the lattice data better than PDG-HRG

Evidence of contributions of additional, experimental yet unobserved open strange hadrons to the QCD thermodynamics

strangeness chemical potential in HIC

strangeness neutrality in HIC: $N_S=0$ enforces dependence of μ_S on μ_B and T

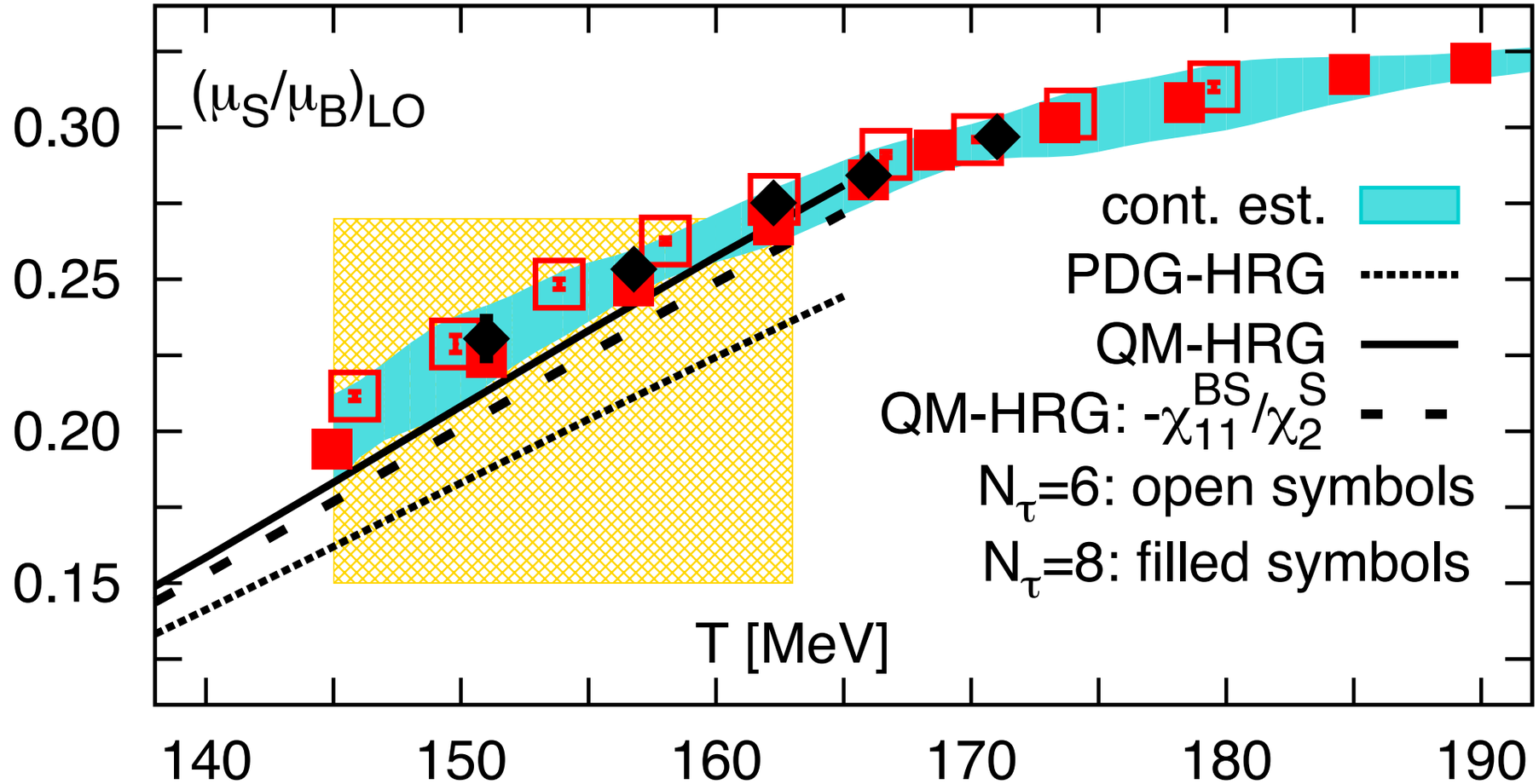
expand μ_S/μ_B in a Taylor series of μ_B:

$$\frac{\mu_S}{\mu_B} \simeq -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B} + \mathcal{O}(\mu_B^2)$$

NLO corrections are small at μ_B <200 MeV

additional states contribute to the relative abundance of strange baryons to open strange mesons

In the strange hadron sector, the PDG-HRG based analyses give a larger freeze out temperature than QM-HRG and lattice QCD



A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], arXiv:1404.6511

strangeness chemical potential in HIC

strangeness neutrality in HIC: $N_S=0$ enforces dependence of μ_S on μ_B and T

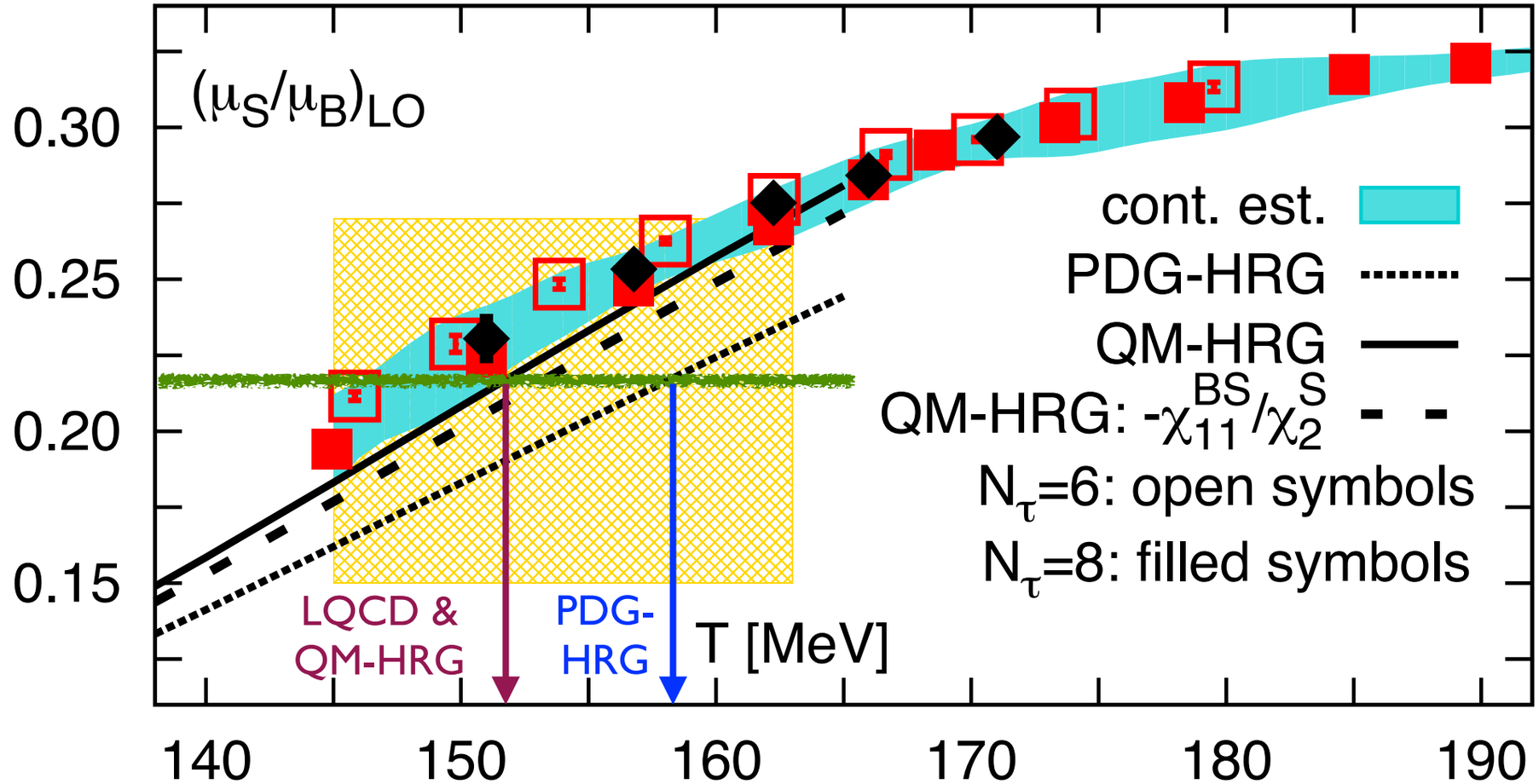
expand μ_S/μ_B in a Taylor series of μ_B:

$$\frac{\mu_S}{\mu_B} \simeq -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B} + \mathcal{O}(\mu_B^2)$$

NLO corrections are small at μ_B <200 MeV

additional states contribute to the relative abundance of strange baryons to open strange mesons

In the strange hadron sector, the PDG-HRG based analyses give a larger freeze out temperature than QM-HRG and lattice QCD



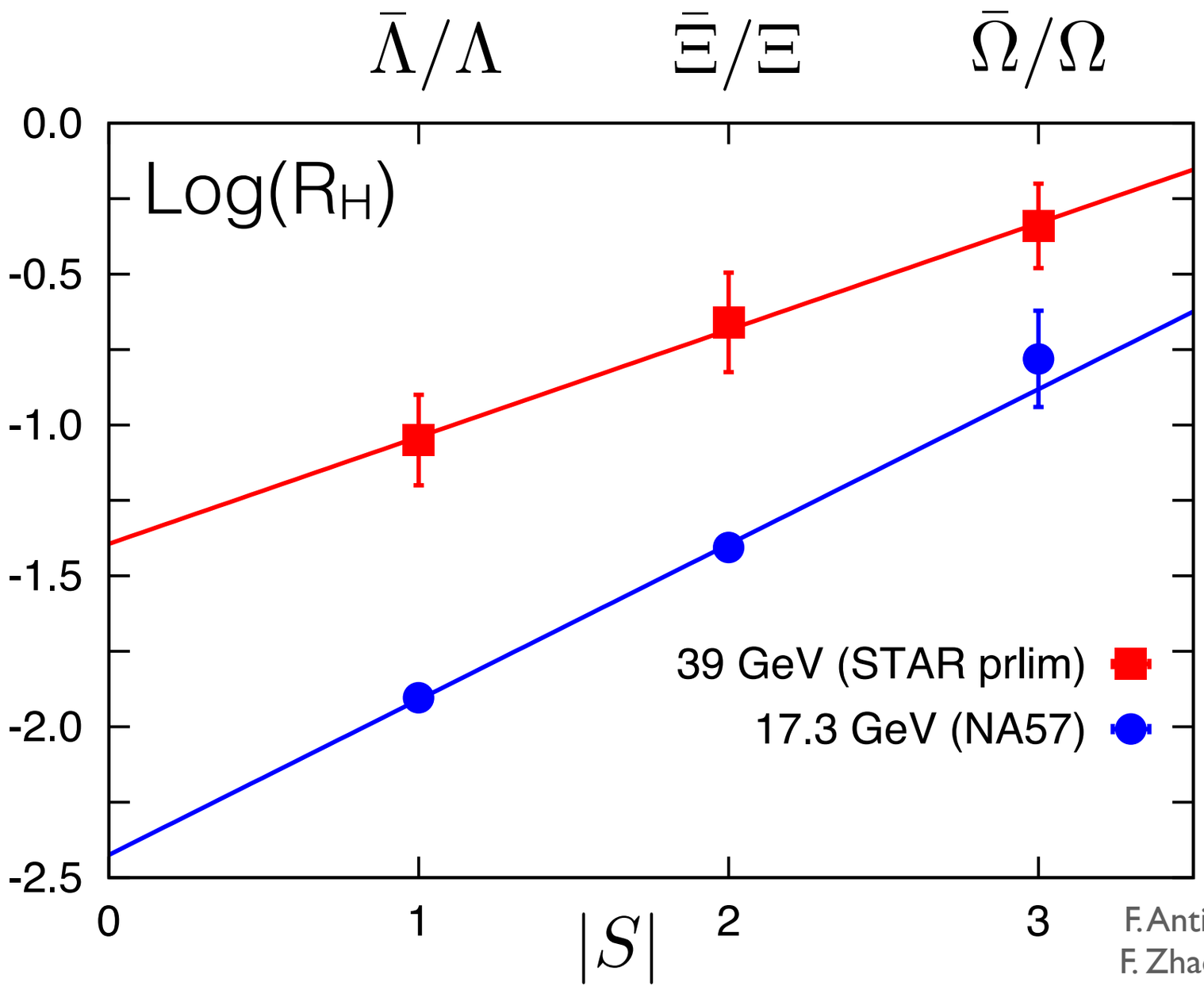
A. Bazavov, HTD et al., [BNL-Bielefeld-CCNU], arXiv:1404.6511

Strange hadron yields in Heavy Ion Collisions

Two-parameter fit to experiment data using HRG ansatz

irrespective of the details of hadron spectrum

$$R_H \equiv \frac{\bar{H}_S}{H_S} = \exp\left[-2(\mu_B^f/T^f) \times \left(1 - (\mu_S^f/\mu_B^f)|S|\right)\right]$$



imprinted by the presence of experimentally yet unobserved strange hadrons

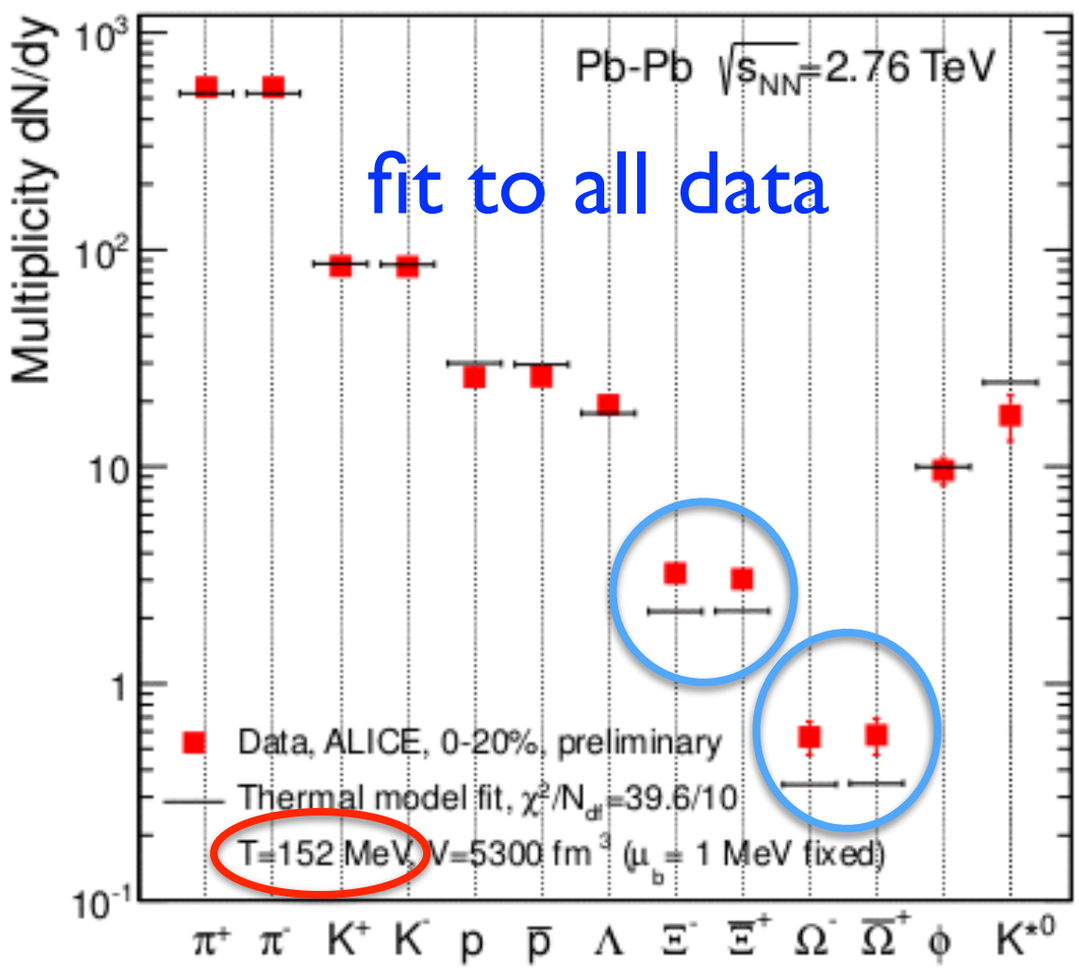
Compare the extracted μ_S/μ_B and μ_B/T with those from HRG & Lattice QCD

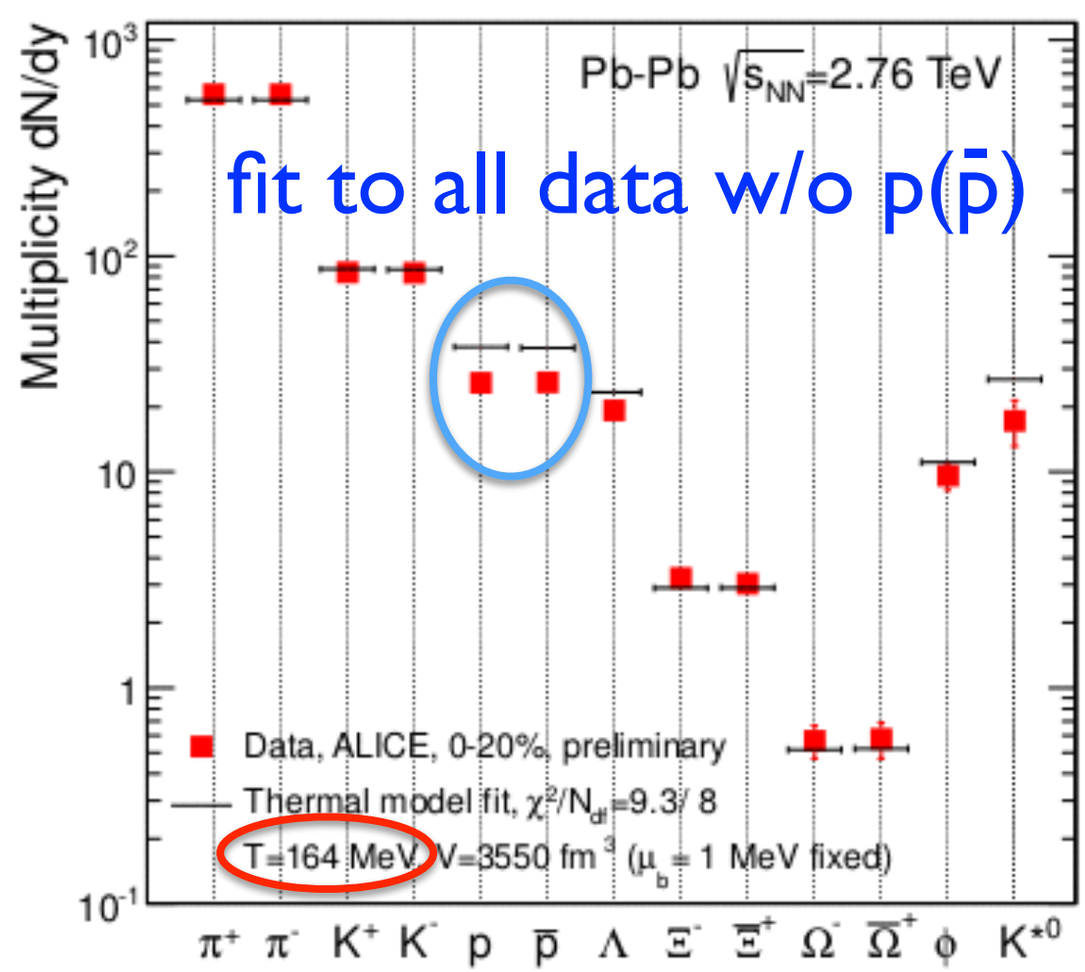
F. Antinori et al., PLB 595(2004)68,
F. Zhao, PoS CPOD2013(2013)036

Do strange hadrons require a higher freeze out temperature than non-strange hadrons?

The possibility has been discussed frequently

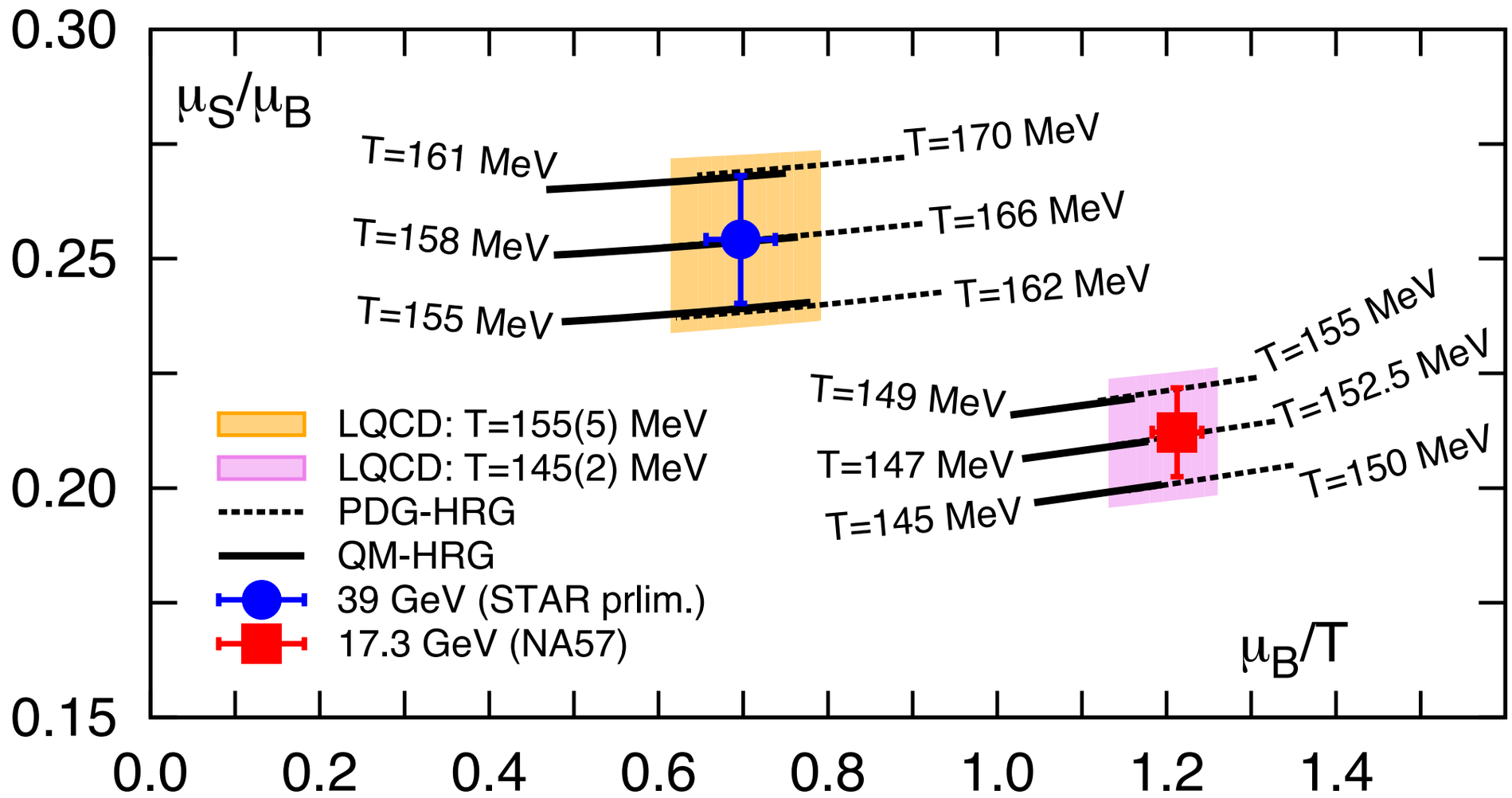
Alba et al., arXiv:1403.4903,
Bugaev et al., EPL 104(2013)22002
Bellwied et al., [WB Collaboration], Phys.Rev. Lett. 111(2013)202302,
Chatterjee, Godbole, Gupta, PLB 727(2013)554





Andronic et al., Nucl. Phys. A904 (2013) 535c

Imprints of unobserved states in strangeness freeze out in HIC



In the strange sector, the PDG-HRG based analysis give larger freeze out temperature than QM-HRG & LQCD by about 5-8 MeV

QM-HRG should be the preferable choice to determine freeze out temperature at large μ_B where LQCD is not applicable

A. Bazavov, HTD et al.,[BNL-Bielefeld-CCNU], arXiv:1404.6511

Summary

- We have performed simulations on Nt=6,8 lattices using HISQ action with a light to strange quark mass ratio of 1/20 and having charm quarks treated in the quenched approximation

- Open strange/charm hadrons start to get deconfined at temperatures in the chiral crossover region

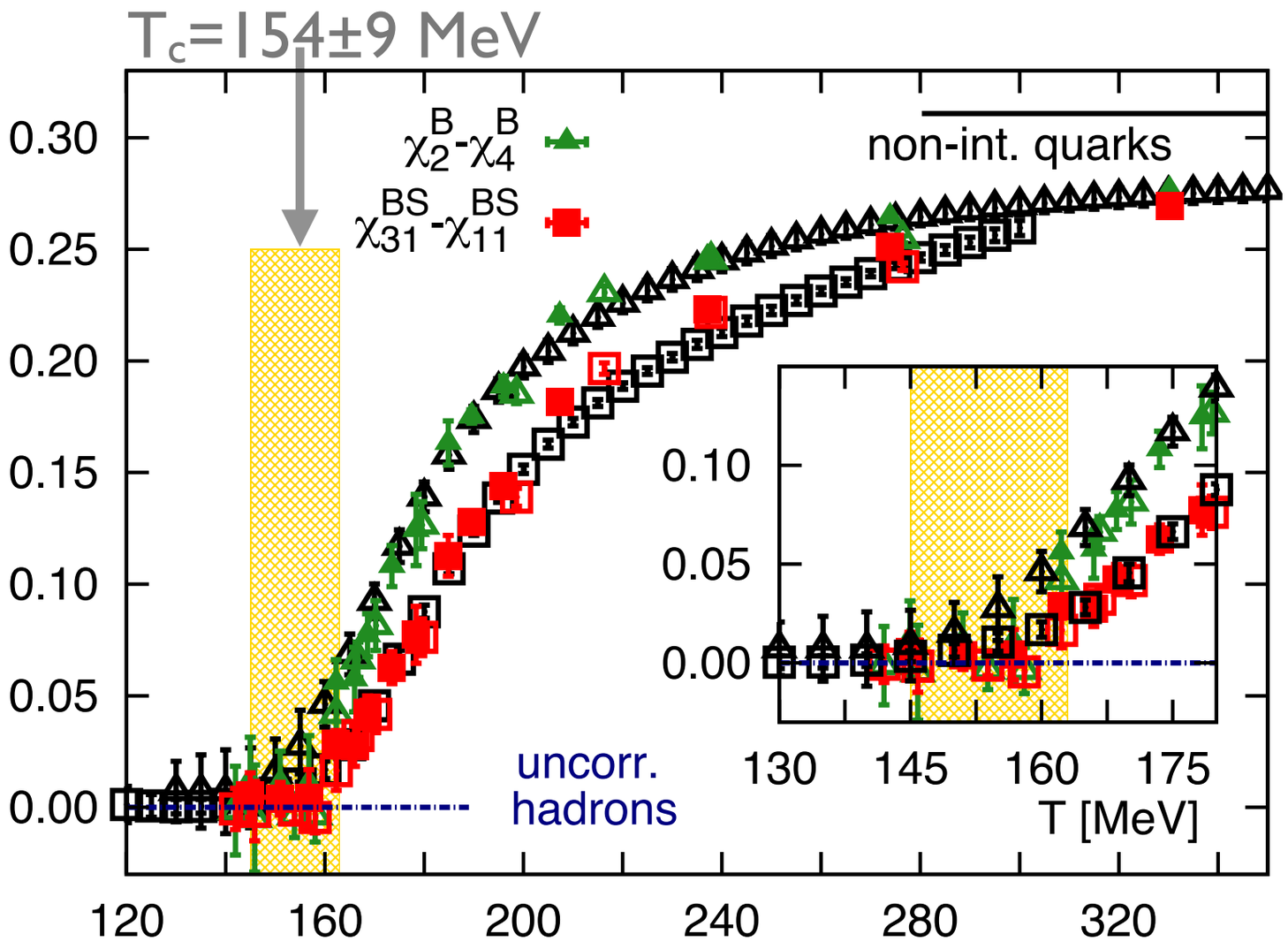
- Evidence is found for the contribution from experimentally yet unobserved open strange and charm hadrons to the QCD thermodynamics

- Hadron Resonance Gas model including non-PDG listed states are consistent with Lattice QCD below T_c. Such an HRG is preferable to be used to determine freeze out/hadronization temperatures in HIC

Lattice setup

- 2+1 flavor configurations with HISQ/tree action
- 24^3x6 and 32^3x8 lattices
- physical strange quark with m_l/m_s=20 $\Rightarrow m_\pi$=160 MeV
- quenched charm quark, determined by setting spin average $(m_{\eta c}+3m_{J/\psi})/4$ to its physical value
- ~ 5000 configurations at lower temperatures
- 1500-6000 stochastic estimators

Deconfinement of hadrons carrying strangeness



$\chi_2^B-\chi_4^B$:receives contributions from all hadrons

$\chi_{31}^{BS}-\chi_{11}^{BS}$: receive contributions only from open strange hadrons

Agreement between stout (black points) and HISQ (green & red points) results

stout data from Wuppertal-Budapest, Phys.Rev. Lett. 111(2013)202302

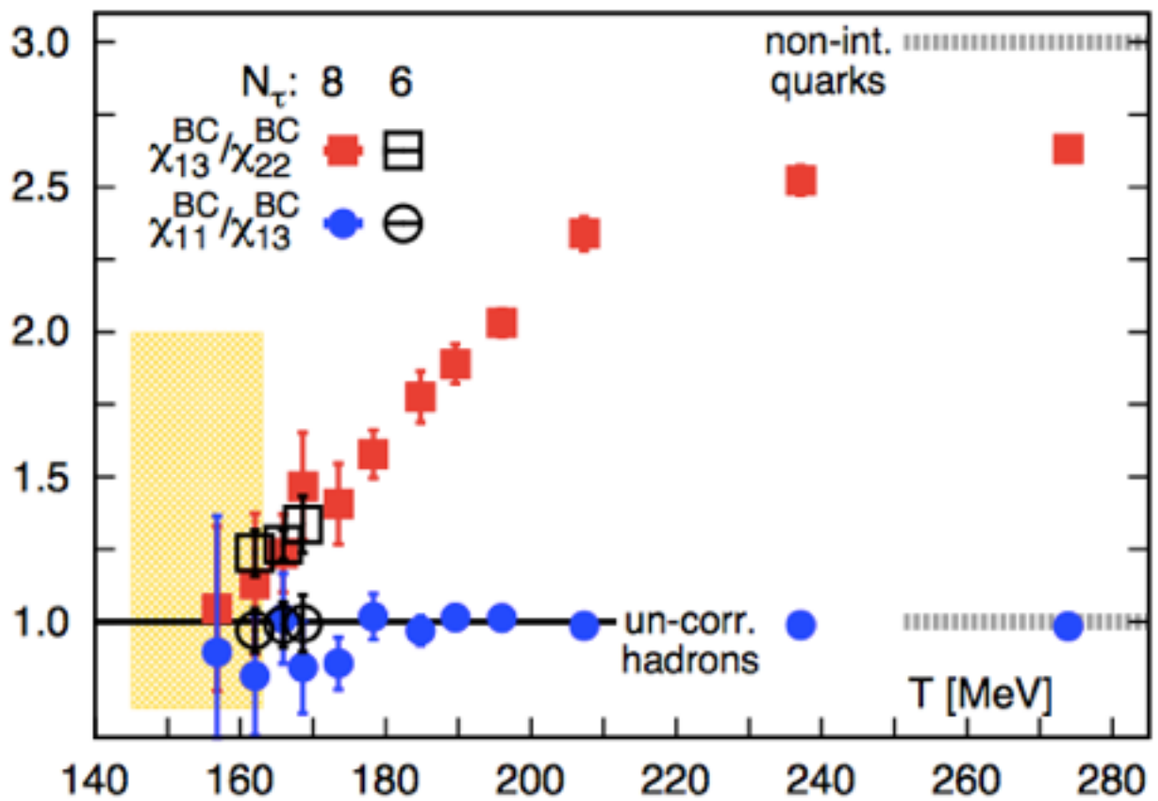
$T \lesssim T_c$: strangeness carrying d.o.f. (sDoF) come with integer baryon numbers

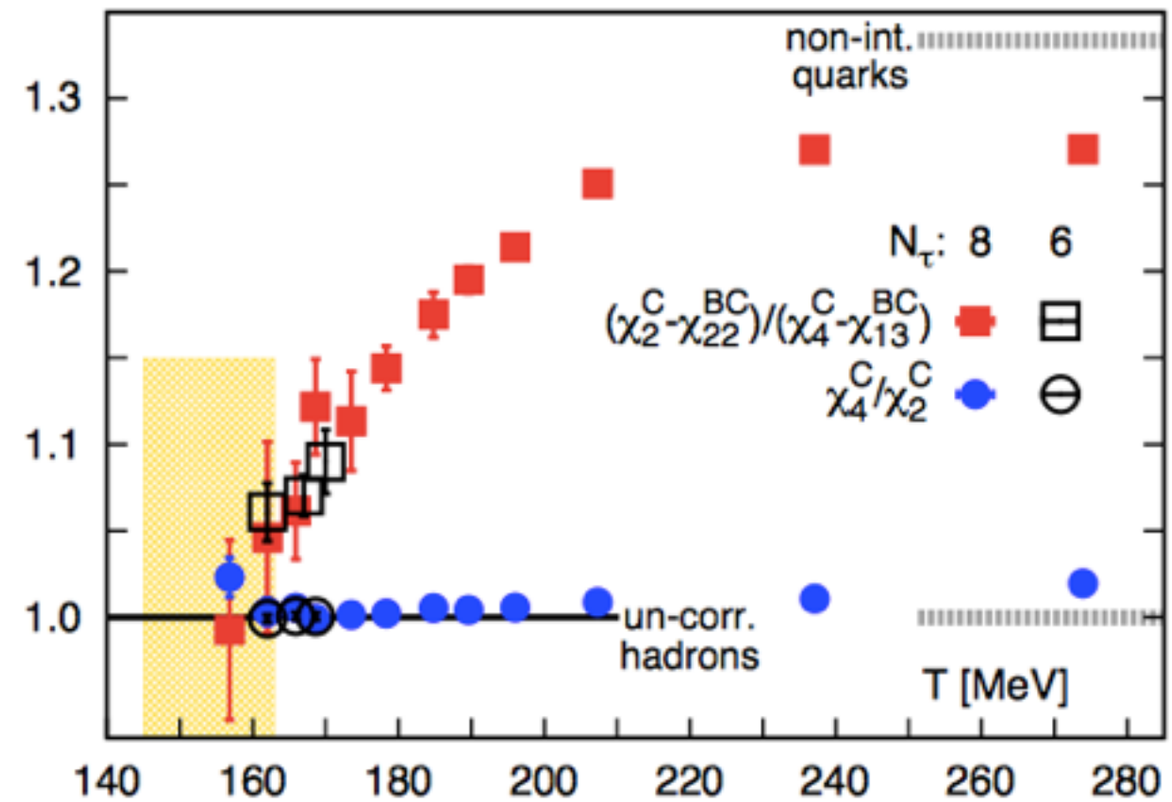
$T > T_c$: sDoF come with fractional baryon numbers and behave like light quark d.o.f.

deconfinement of open strange hadrons starts to take place in the chiral crossover region

Bazavov, HTD et al., Phys.Rev. Lett. 111(2013)082301

Onset of the dissociation of open charm hadrons





$$P_{c,free}(m_c/T,\vec{\mu}/T)/T^4 \propto \cosh\left(\frac{\hat{\mu}_B}{3}+\frac{2\hat{\mu}_Q}{3}+\hat{\mu}_C\right)$$