Recent lattice QCD results and phase diagram of strongly interacting matter

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XXIV Quark Matter, Darmstadt, May 18-24, 2014

- G. Endrodi, "Effects of magnetic fields on the quark-gluon plasma", Tuesday 09:40
- P. Hegde, "The QCD Equation of State at O((μ_B)**4)", Tuesday 11:50
- D. Sexty, "Simulating full QCD at nonzero density using the complex Langevin equation", Tuesday 12:10
- H. Meyer, "Vector screening masses in the quark gluon plasma and their physical significance", Tuesday 12:30
- A. Bazavov, "The QCD equation of state", Tuesday 12:50
- M. Panero, "Jet quenching from the lattice", Tuesday 11:10
- T. Hatsuda, "New approach to lattice QCD thermodynamics from Yang-Mills gradient flow", Tuesday 11:30
- O. Kaczmarek, "Towards continuum results of heavy quark diffusion coefficient", Tuesday 15:40
- C. Ratti, "Freeze-out conditions from fluctuations of conserved charges: lattice meets experiment", Wednesday 11:30
- C. Schmidt, "From conserved charge fluctuations to the QCD critical point", Wednesday 12:30

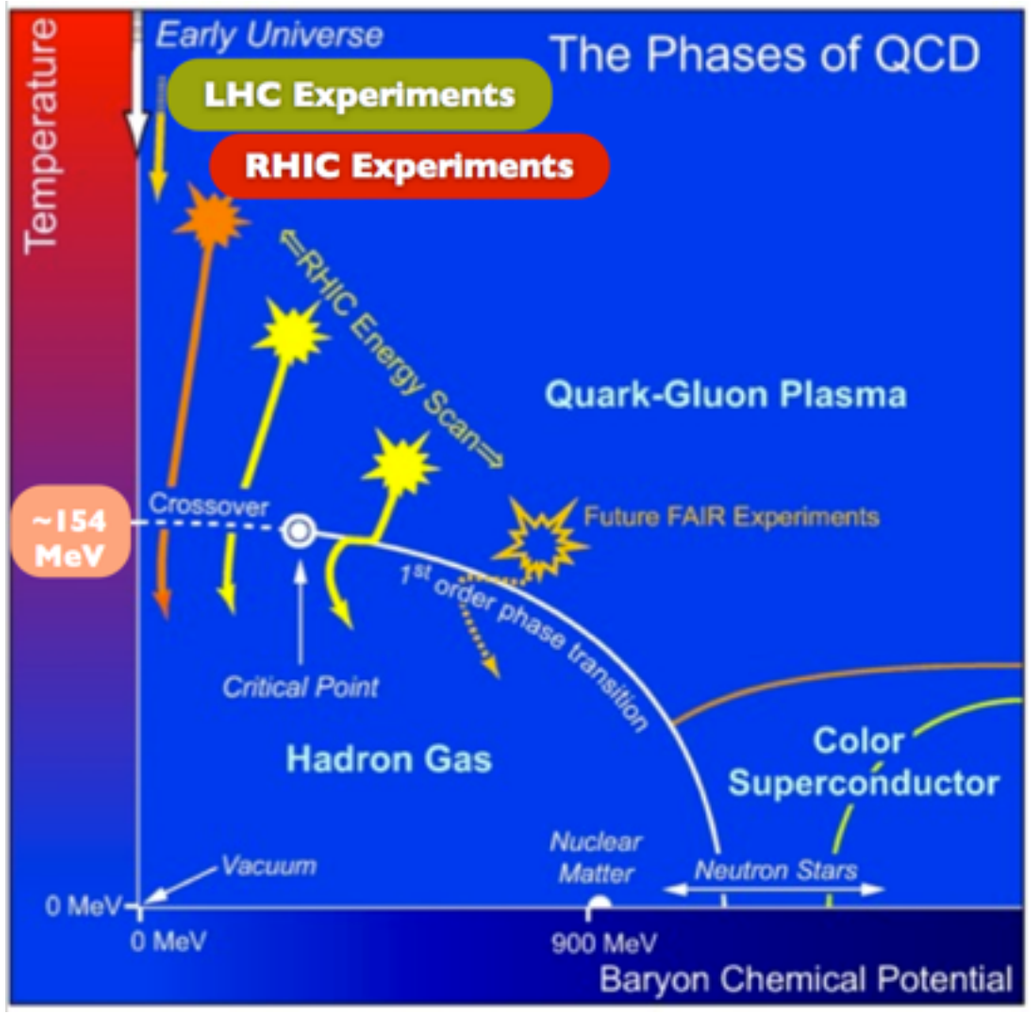
Talks

- Y. Burnier, "Complex heavy quark potential at high temperature from lattice QCD", A-05
- A. Francis, "The second order hydro-coefficients kappa_t and anti screening of QED and QCD plasma from lattice QCD", A-06
- E.-M. Ilgenfritz, "Towards the continuum limit of thermodynamics from lattice QCD with dynamic charm", A-11
- A. Ohnishi, "Phase diagram of lattice QCD in auxiliary field Monte-Carlo method in the strong coupling region", B-13
- D. Scheffler, "Chiral restoration and deconfinement in two-flavors of staggered quarks", B-17
- W. Unger, "QCD phase diagram from the lattice at strong coupling: Staggered v.s. Wilson fermions", B-23
- T. Harris, "Bottomonium at finite temperature from lattice QCD", F-17
- H. Ohno, "Lattice QCD study on quark mass dependence of quarkonium properties at finite temperature", F-40
- T. Kim, "First principle calculation of dilepton production rate in strongly interactiing QGP", G-17
- S. Borsanyi, "Freeze-out parameters for the Large Hadron Collider", I-07
- S. Sharma, "The thermodynamics of heavy light hadrons at freeze out", J-13

Posters

Outline

- EoS at zero and non-zero μ_B
  - new results of EoS at zero μ_B
  - EoS at finite μ_B
- Deconfinement aspects of QCD transition
  - deconfinement of open charm & strange hadrons
  - fate of charmonia & bottomonia
- Freeze-out/hadronization conditions in HIC
  - conserved charge fluctuations & freeze out parameters from LQCD
  - Influence of experimentally yet unobserved hadrons on the freeze out conditions



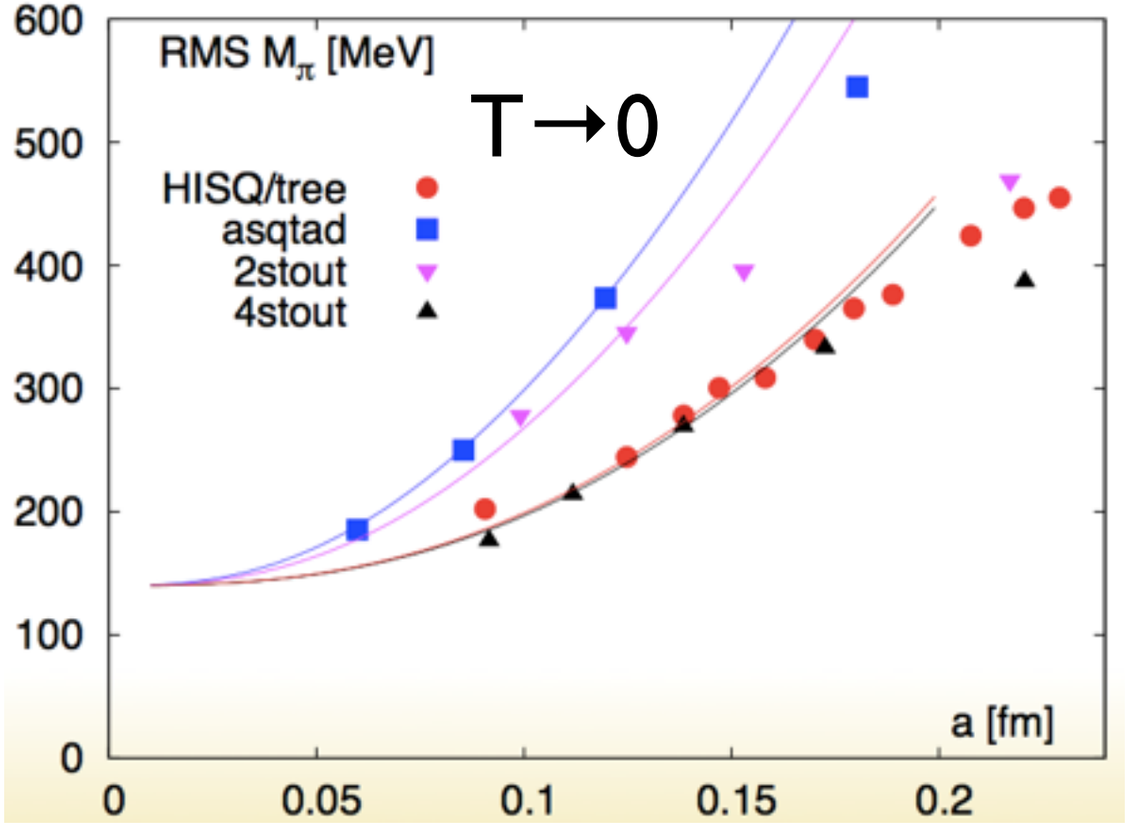
Lattice QCD

Lattice QCD: discretized version of QCD on a Euclidean space-time lattice, reproduces QCD when lattice spacing $a \to 0$ (continuum limit)

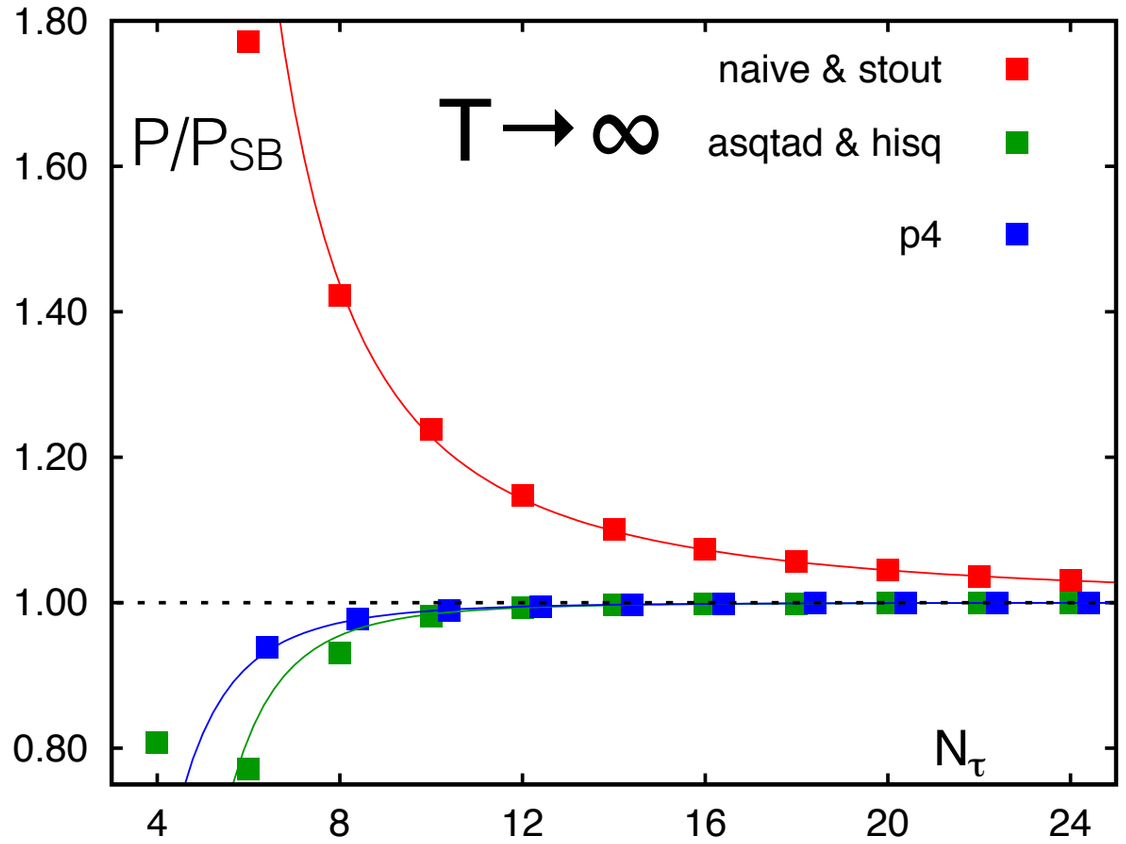
- Staggered actions at $a \neq 0$: taste symmetry breaking
  - 1 physical Goldstone pion +15 heavier unphysical pions
  - averaged pion mass, i.e. Root Mean Squared (RMS) pion mass
  - Smaller RMS pion mass → Better improved action
- Chiral fermions(Domain Wall/Overlap) at $a \neq 0$
  - preserves full flavor symmetry and chiral symmetries
  - computationally expensive to simulate, currently starts to produce interesting results on QCD thermodynamics
  - Chiral crossover temperature T_c is confirmed by studies using Domain Wall fermions [arXiv:1402.5175], the fate of $U(1)_A$ symmetry at finite T is under investigation using chiral fermions[Phys.Rev. D89 (2014) 054514, PRD87 (2013) 11, 114514…]

Improved staggered action

action(group)	improvements at T→0	improvements at T→∞
naïve (Mumbai)	none	none
p4(BNL-Bi)	poor	very good
asqtad(hotQCD)	ok	good
2stout(WB)	good	none
4stout(WB)	very good	none
HISQ(hotQCD)	very good	good

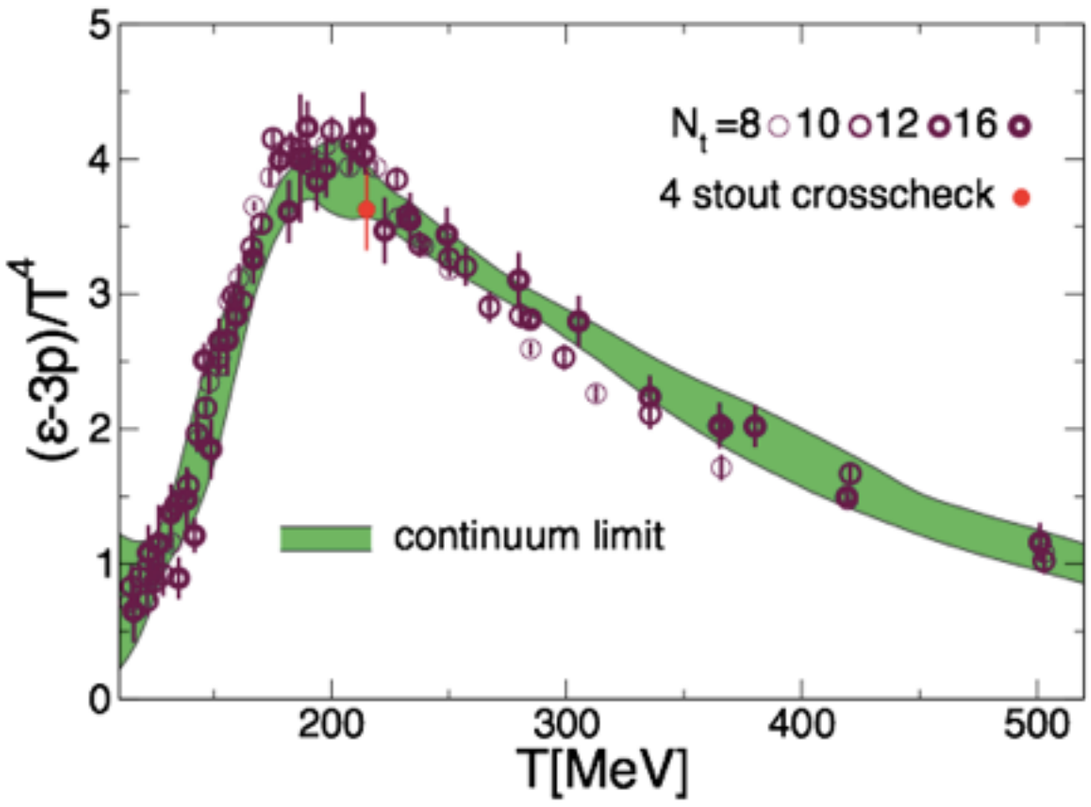


S. Borsanyi, QM 2012



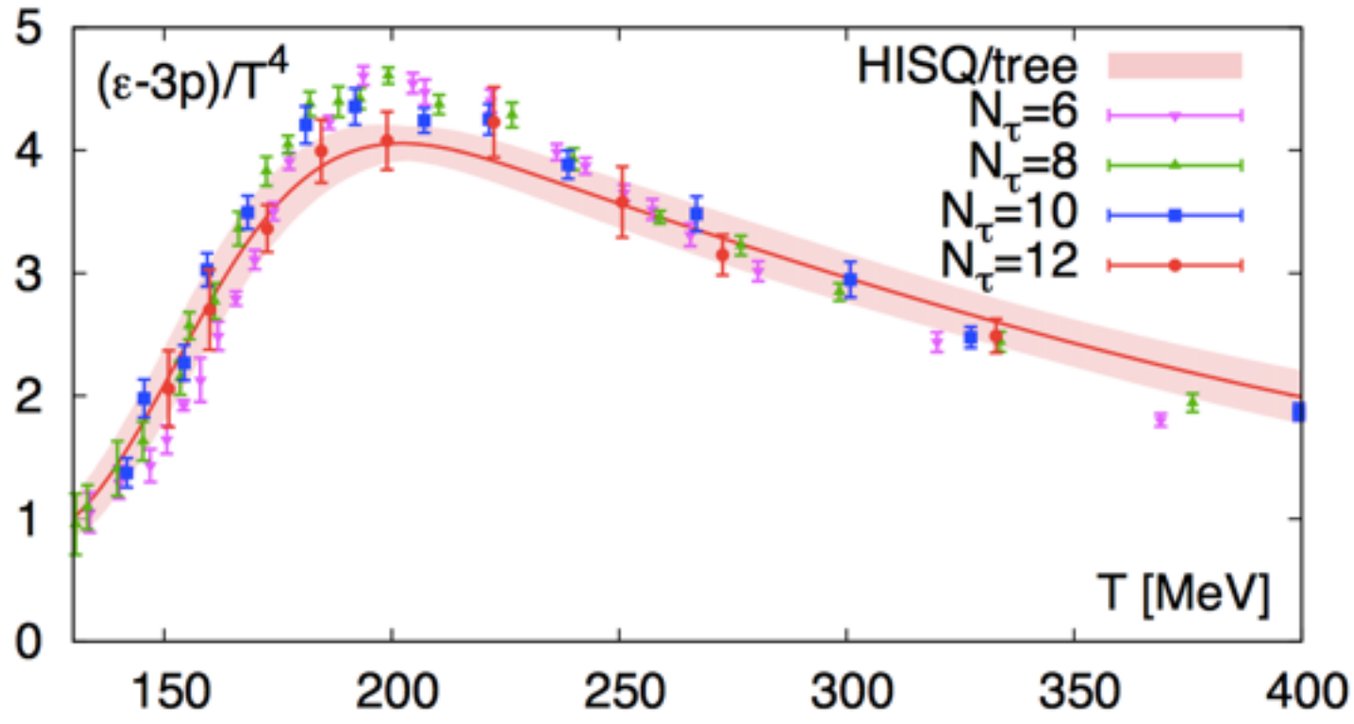
S. Mukherjee, QM 2011

Updated results of interaction measure from Wuppertal-Bupdapest and hotQCD



Wuppertal-Budapest, Phys.Lett. B730 (2014) 99

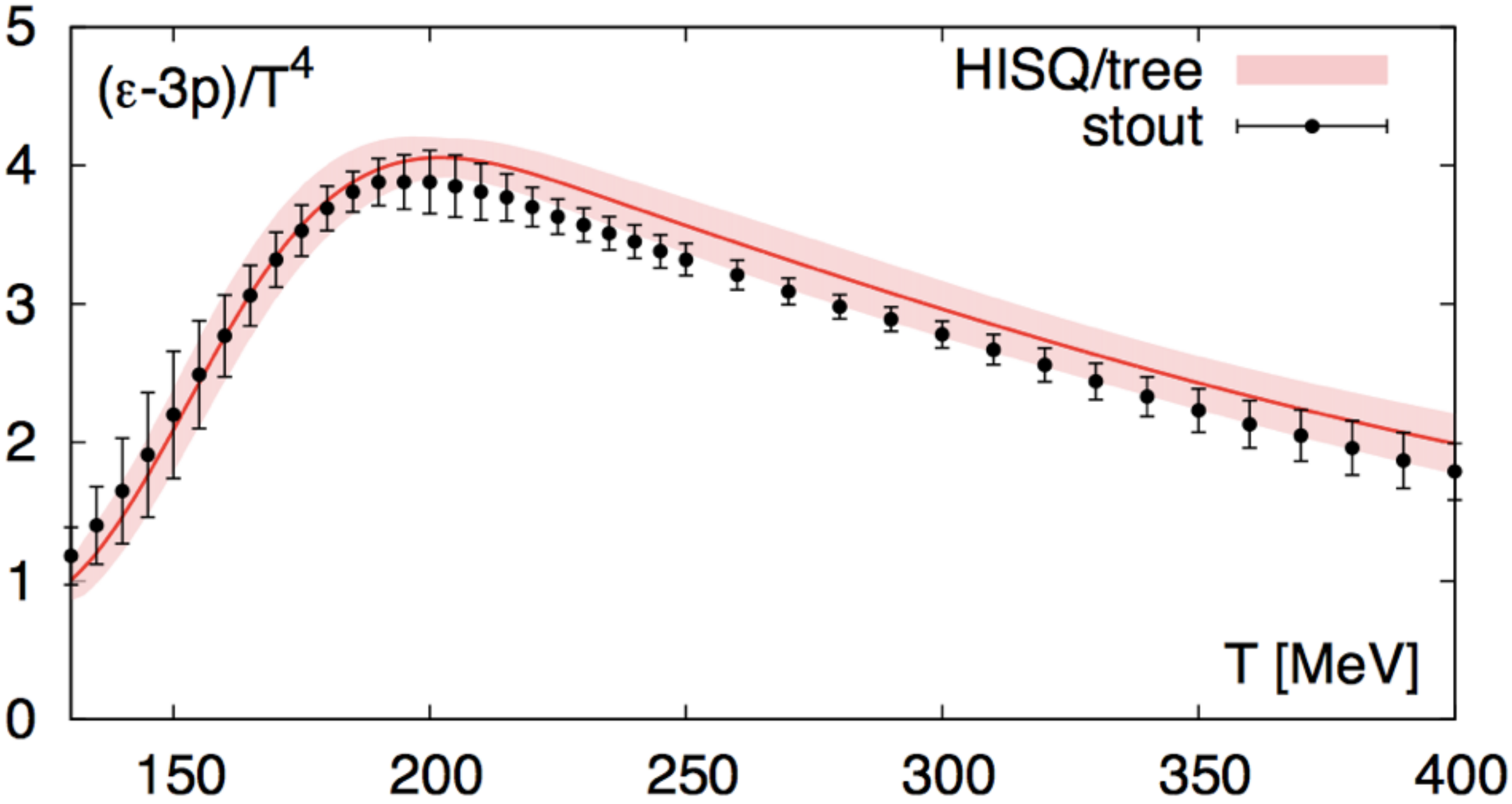
Calculations at a high temperature value using the 4 stout action have been done



A. Bazavov[hotQCD], talk on Tuesday

Continuum extrapolation is performed with additional results on N_T=10 and 12 lattices

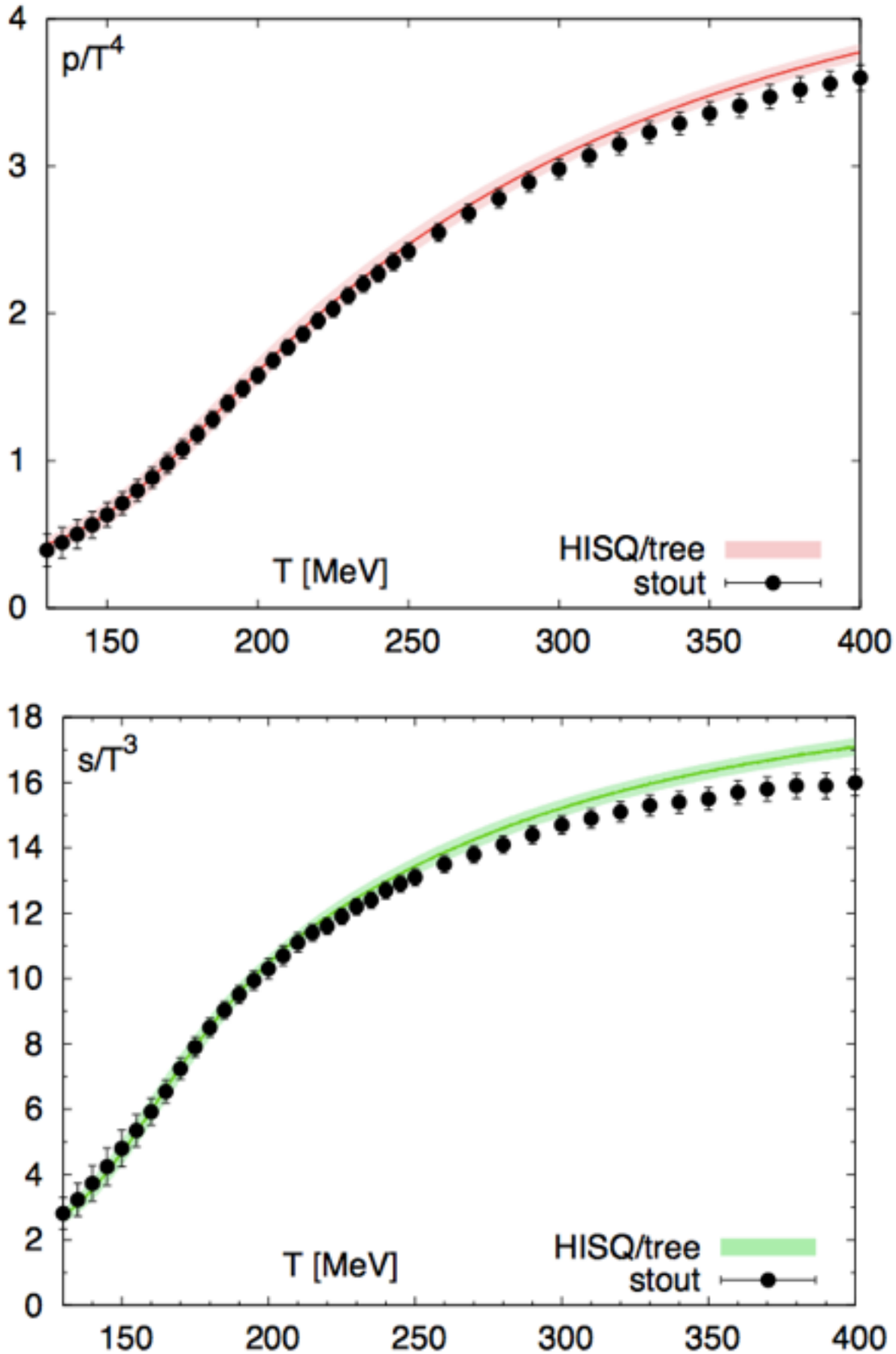
EoS results in the continuum limit

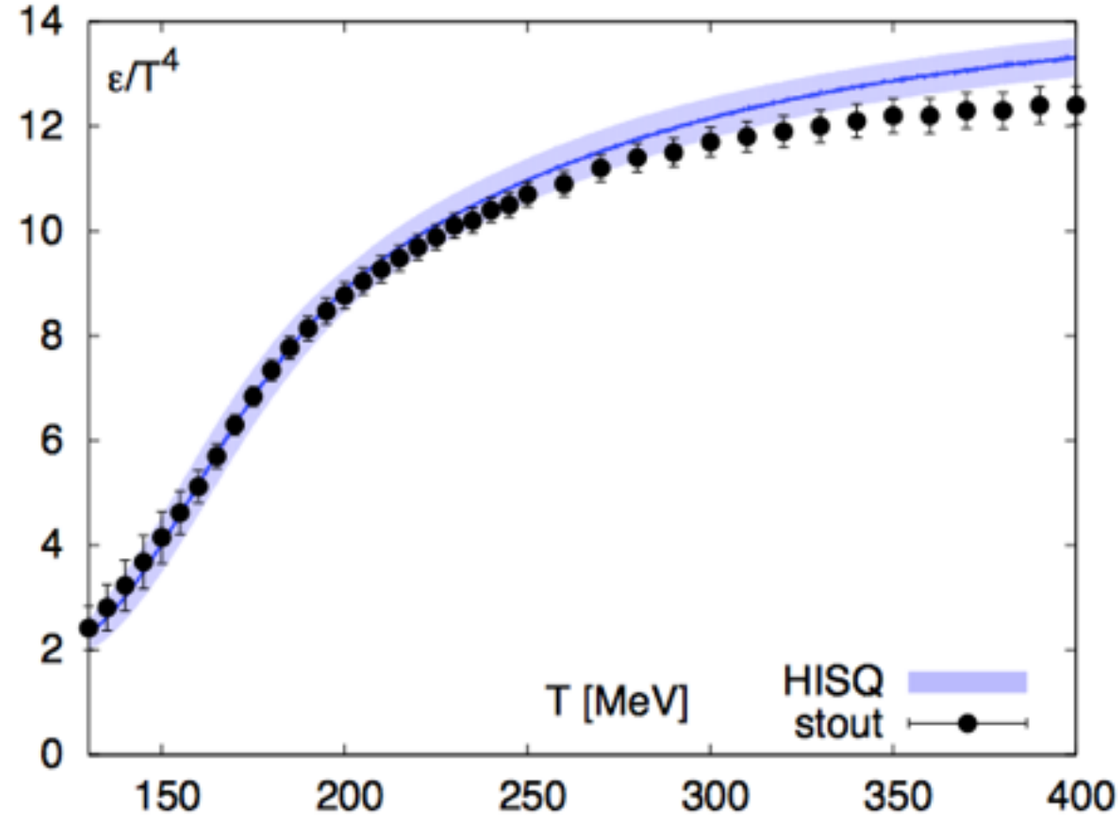


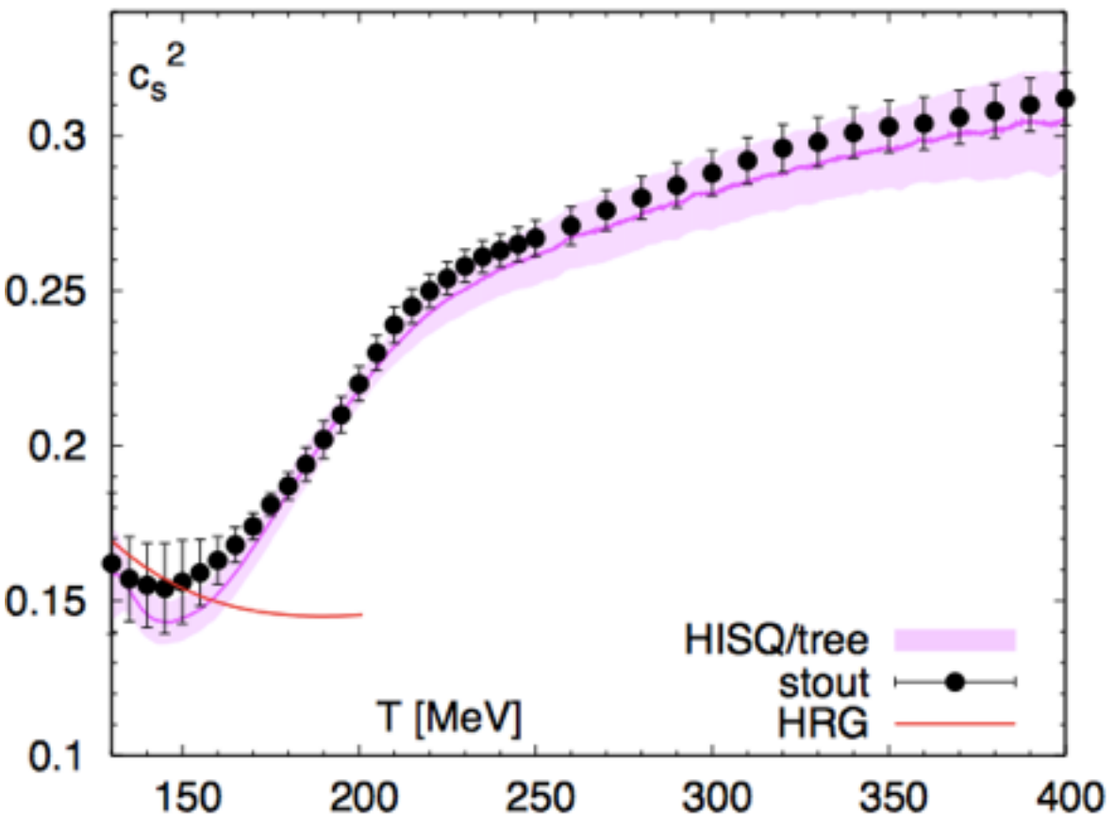
Consensus of HISQ and stout results

A. Bazavov[hotQCD], talk on Tuesday

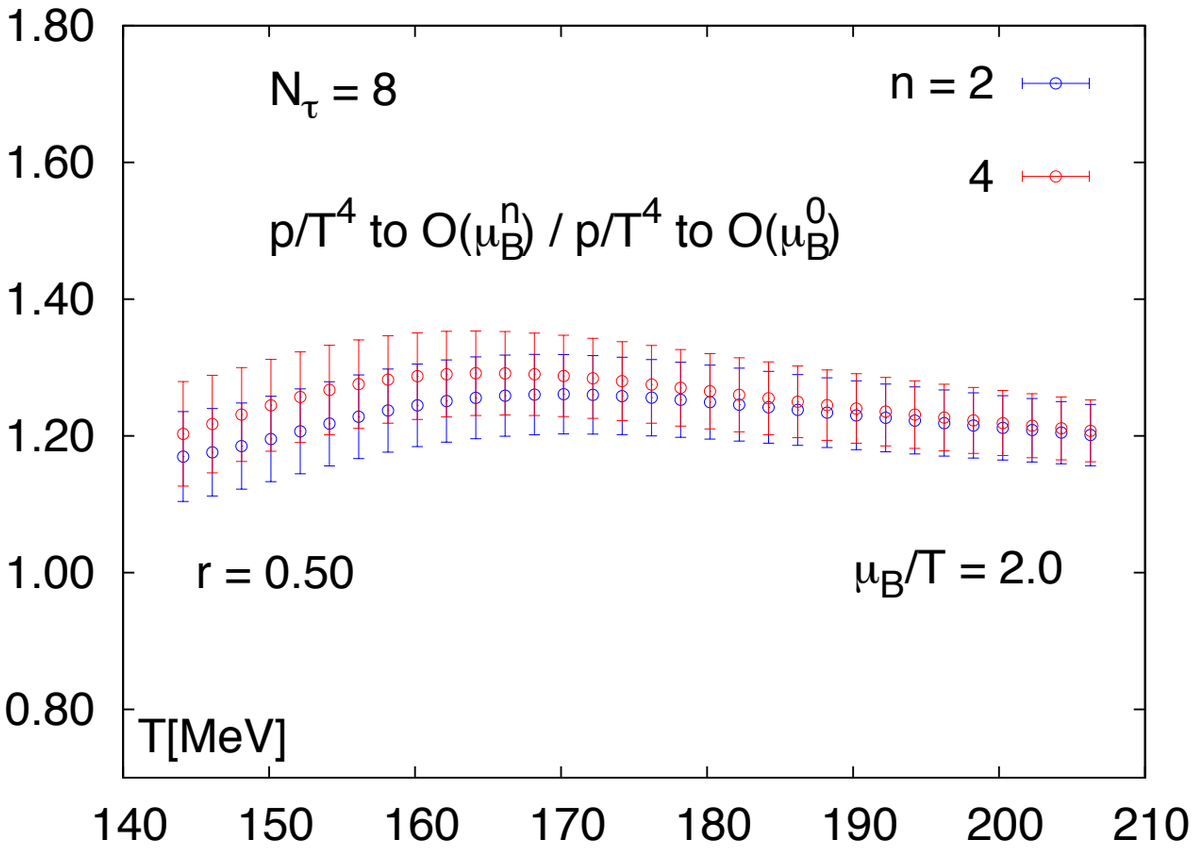
EoS results in the continuum limit

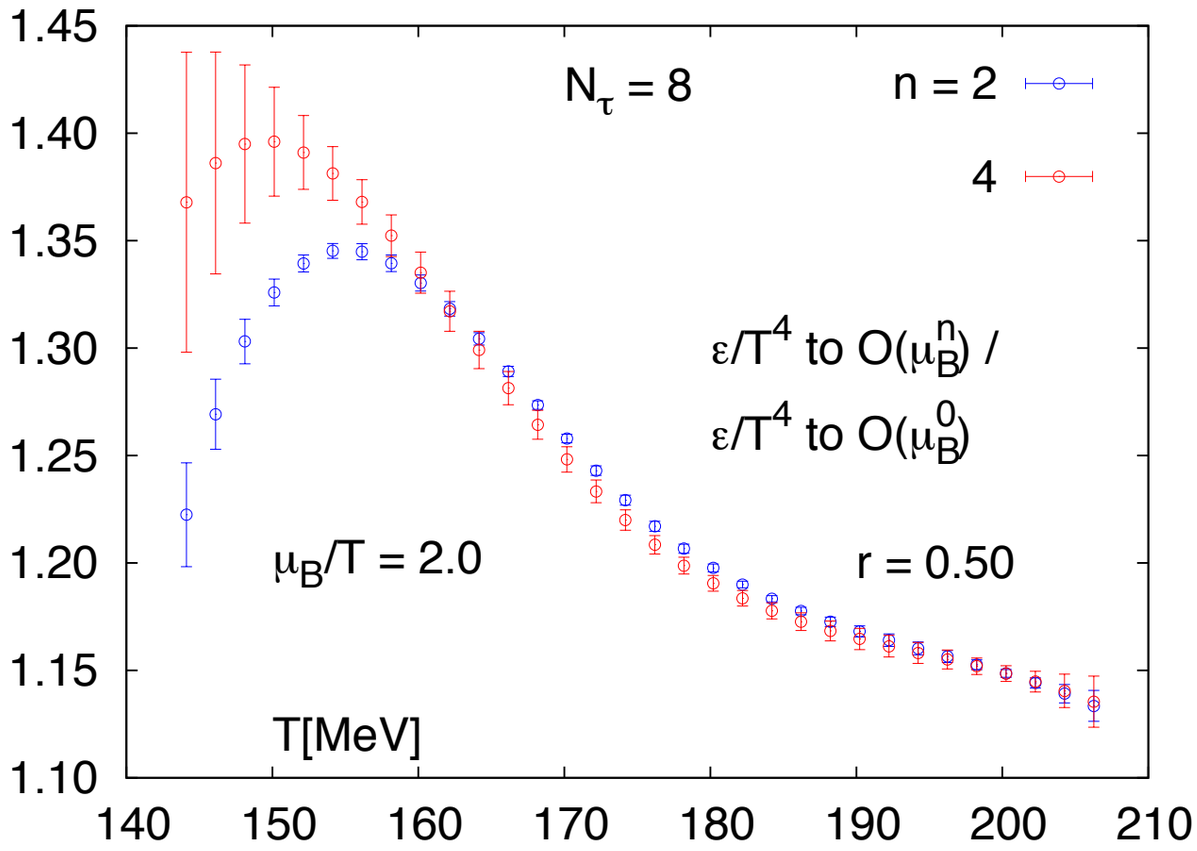






EoS at finite μ_B





finite μ_B corrections in p/T^4 at $\mu_B/T \lesssim 2$ under control

4th order μ_B corrections in ε/T^4 needed at $T \lesssim 160$ MeV with $\mu_B/T \lesssim 2$

P. Hegde [BNL-Bielefeld-CCNU], talk on Tuesday

second order corrections obtained from HISQ and stout action agree
corrections up to second order has been computed with stout action

Wuppertal-Budapest, JHEP 08(2012)053

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

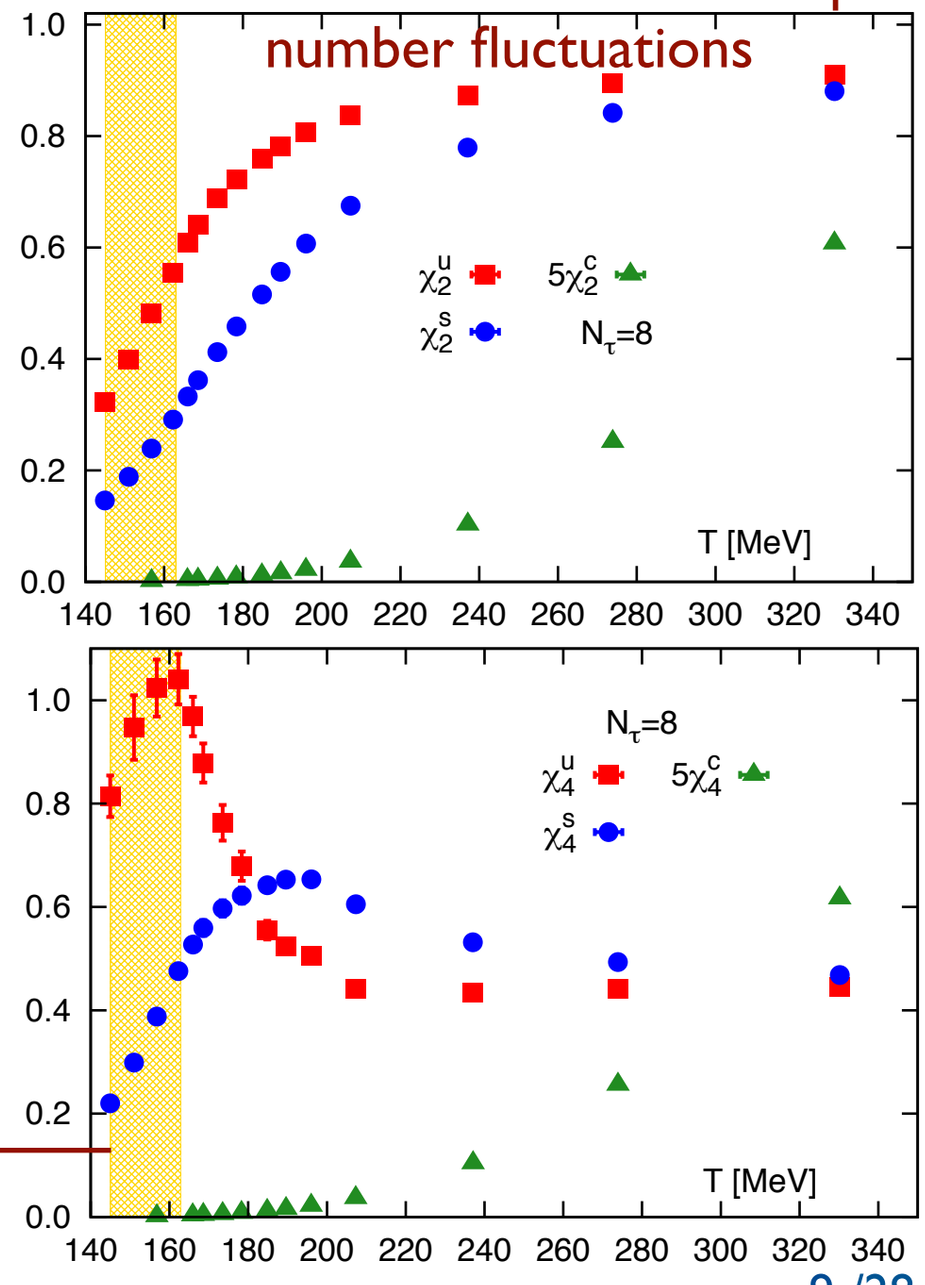
Strange quark, less affected by chiral symmetry, may remain confined at $T > T_c$?

Do strange hadrons survive at higher temperature ?

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

How about open charm 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

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

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

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

strangeness in a gas of uncorrelated hadrons

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

partial pressure arising from open strange hadrons

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

partial pressure arising from open strange mesons

partial pressure arising from strange baryons with strange number S=1,2,3

differences of baryon-strangeness correlation:

$$v_1 = \chi_{31}^{BS} - \chi_{11}^{BS} = \sum_B (B^3 - B)\times g_B(m_S^{hadron}) \longrightarrow$$

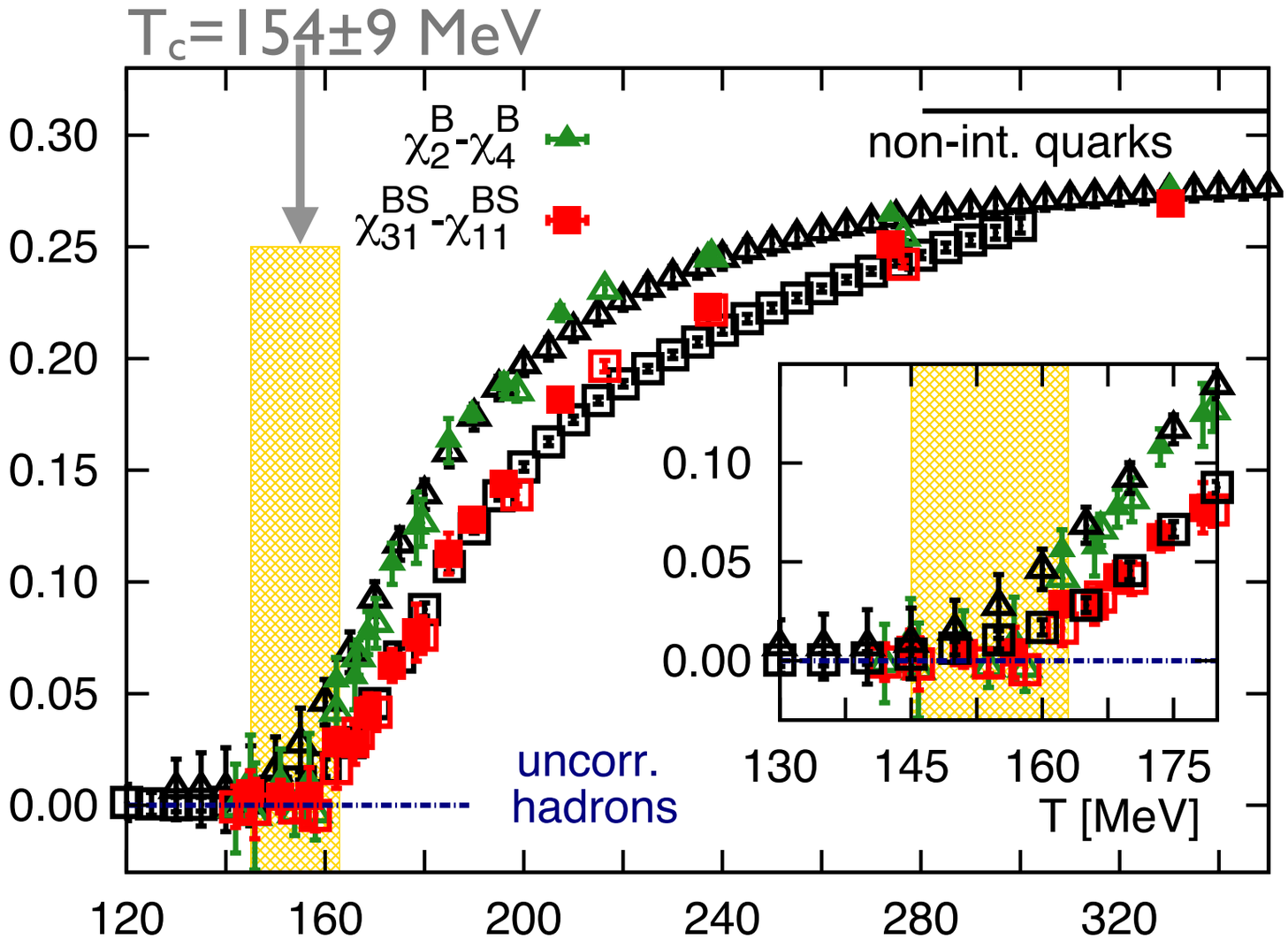
depends on hadron spectrum

if B=0,1, degrees of freedom are hadrons, then v_1=0;

if B=1/3, degrees of freedom are quarks, then $v_1 \neq 0$

Similarly: differences of 2nd and 4th order cumulants of net baryon number fluctuations $\chi_2^B - \chi_4^B$

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

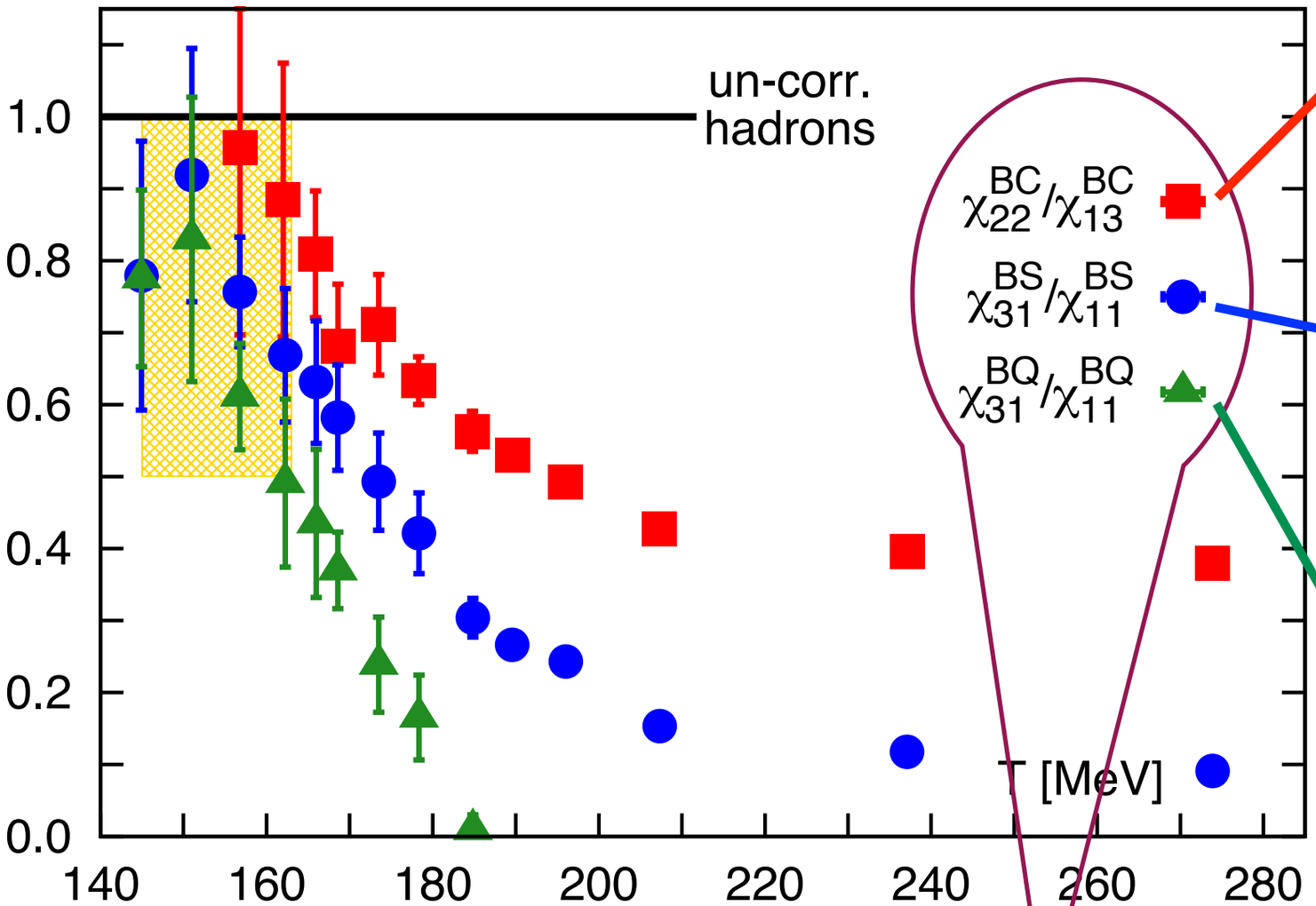
$T \lesssim T_c$: strangeness carrying d.o.f. (sDoF) come with integer baryon numbers

$T > T_c$: 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

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

deconfinement of open charm 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

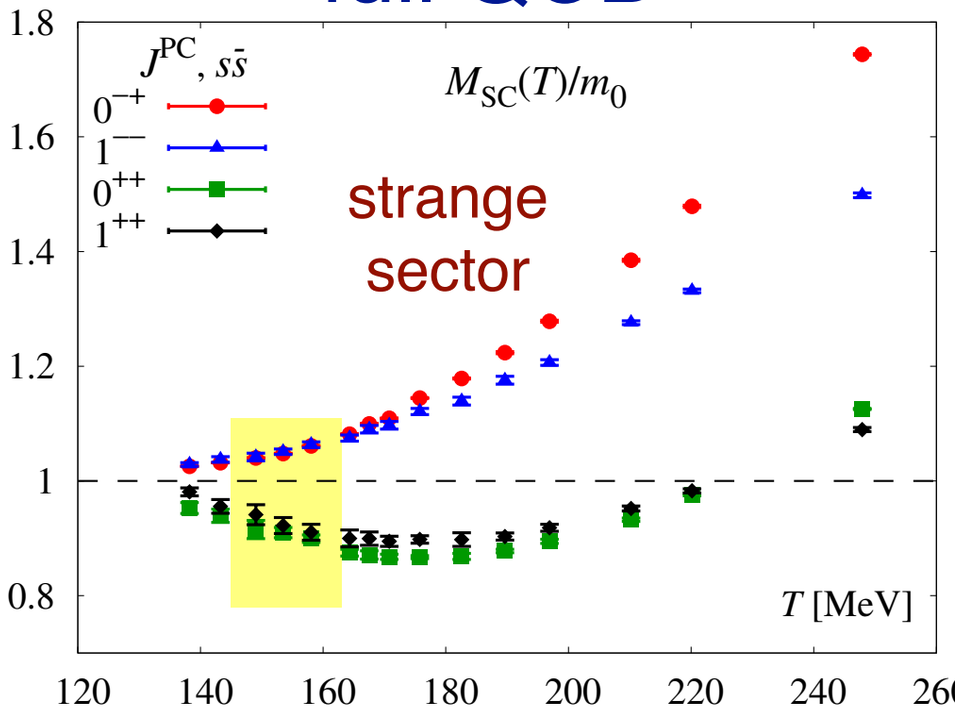
Both open strange and charm hadrons starts to get deconfined in the chiral crossover region

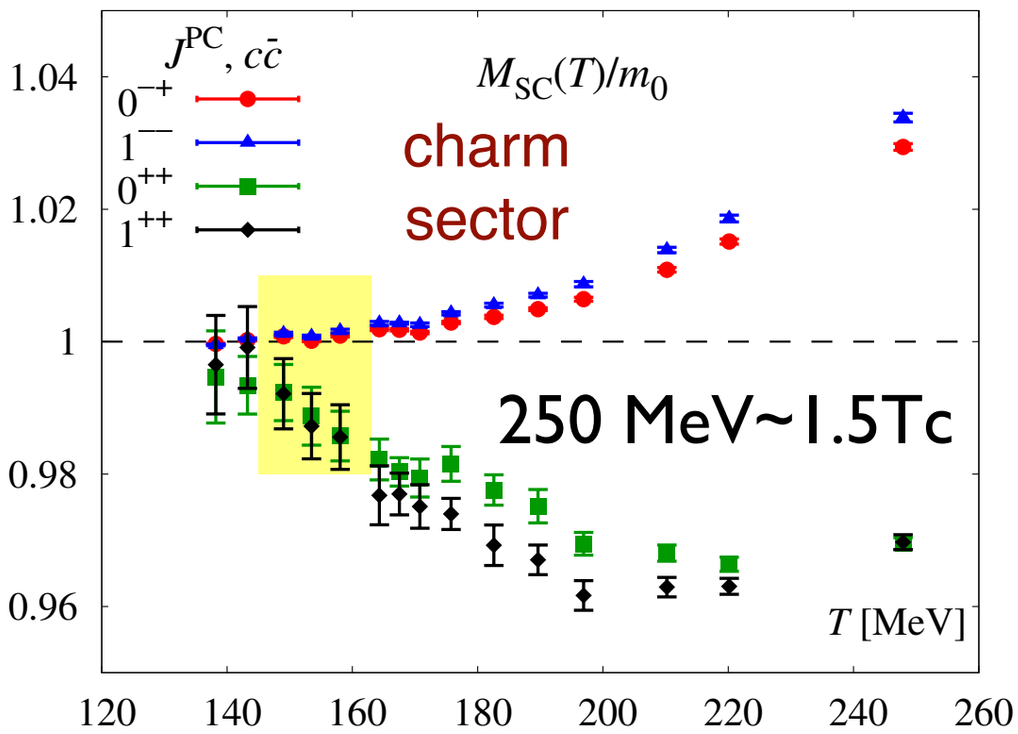
S. Sharma, Poster J-13, arXiv:1404.4043

fate of hidden strange,charm & bottom mesons

ratios of screening mass to meson mass

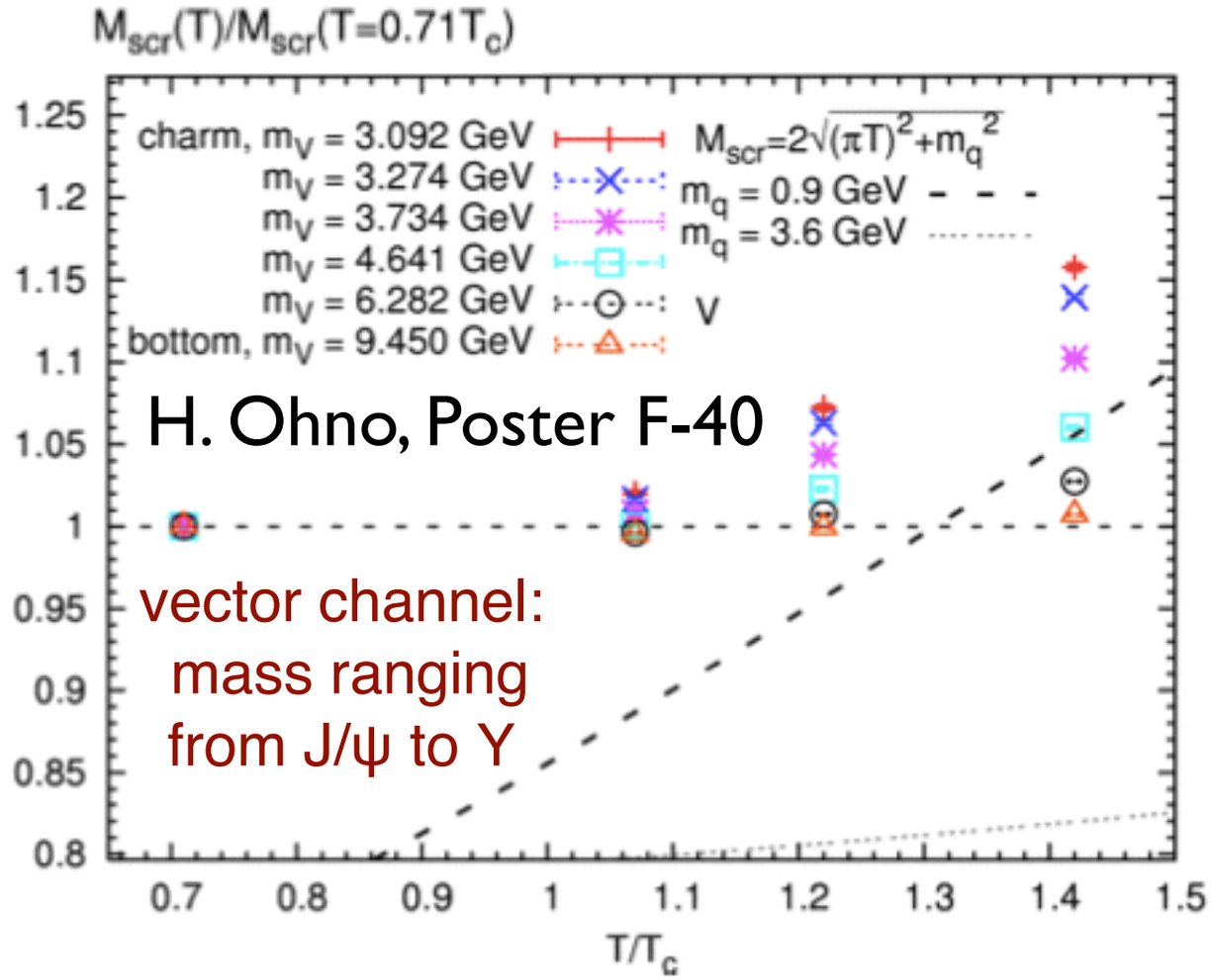
full QCD





Y. Maezawa et al., arXiv:1312.4375

QCD w/o sea quarks



Hidden strange mesons seem to melt at T~Tc

Heavier mesons have smaller T dependence

Dynamic quark effects?

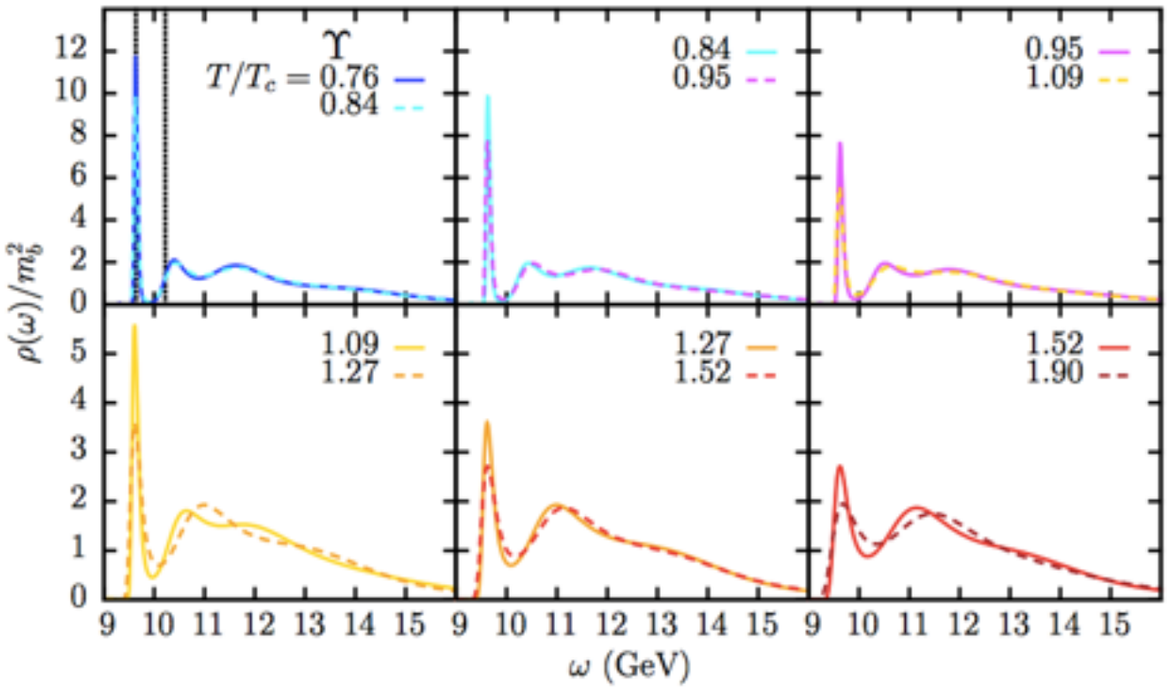
spectral function analyses are needed

S. Borsanyi et al., JHEP1404(2014)132 , HTD et al., 86(2012)014509

effective theory studies of Bottomonia on the lattice

spectral function from Non-Relativistic QCD studies on the lattice with $m_\pi \approx 400$ MeV

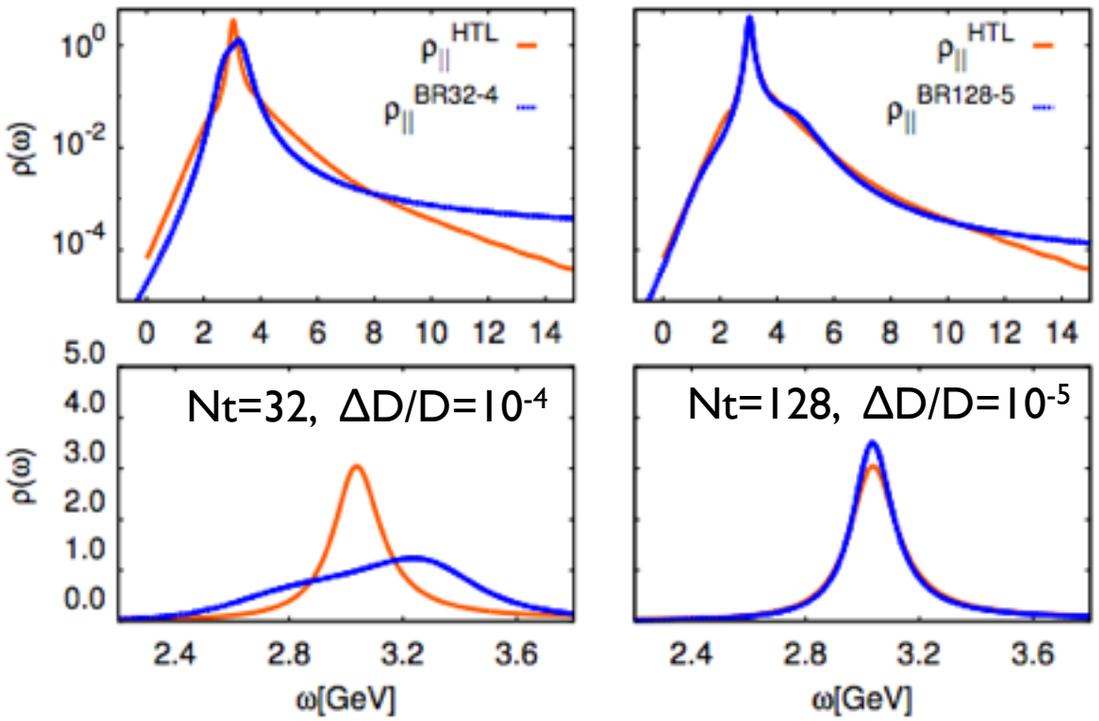
No continuum limit by construction



T. Harris, Poster F-17

Potential model approach based on real + imaginary potential from lQCD

Rothkopf, Hatsuda, Sasaki '12, Burnier, Rothkopf '13



Y. Burnier, Poster A-05

NRQCD study: S wave ground states (Υ and η_b) survive up to at least $2T_c$ and P wave ground states (χ_{b0} and χ_{b1}) melt immediately above T_c

G. Aarts et al., arXiv:1402.6210, JHEP 1111(2011)103

Hard to extract the imaginary potential as being the peak width in the Wilson loop spectral function, developments have been made along this line

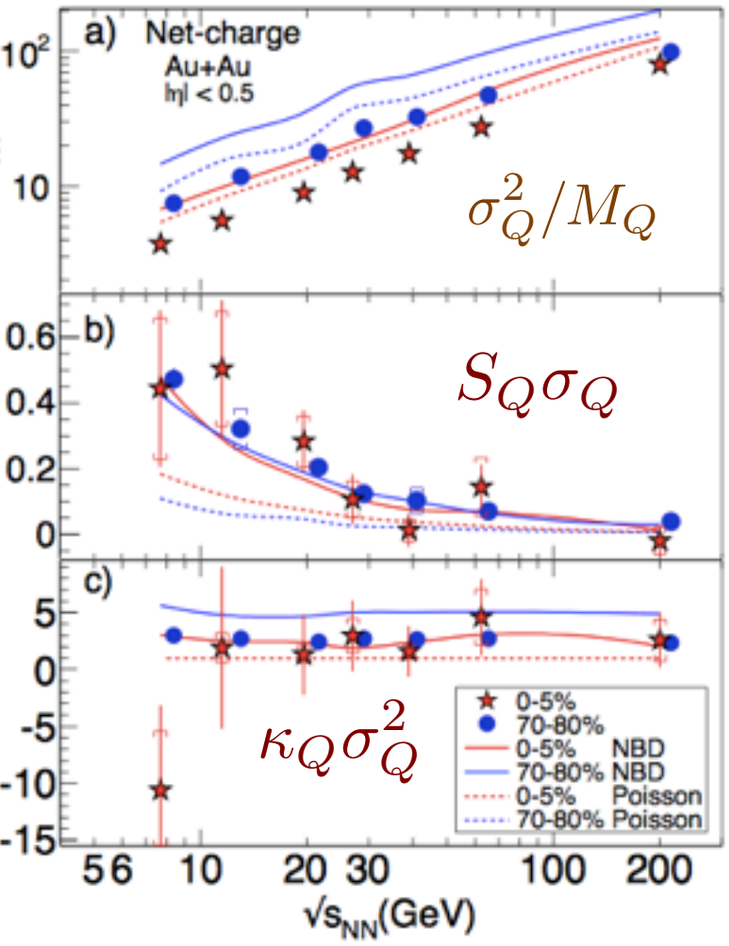
A. Bazavov, Y. Burnier and P. Petreczky, arXiv:1404.4267,
Y. Burnier and A. Rothkopf, arXiv:1310.0645…

freeze out condition in HIC from lattice QCD

How to get freeze out conditions of hadrons in experiments

$$\left(T_f, \mu_B^f, \mu_Q^f, \mu_S^f\right)$$ from lattice QCD?

By matching experimentally measured higher order cumulants of conserved charges to those from LQCD



STAR: arXiv:1402.1558

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\langle N_Q\rangle}{\langle(\delta N_Q)^2\rangle} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)} = R_{12}^Q(T,\mu_B)$$

$$\frac{S_Q(\sqrt{s})\,\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\langle(\delta N_Q)^3\rangle}{\langle N_Q\rangle} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)} = R_{31}^Q(T,\mu_B)$$

HIC

mean: M_Q

variance: σ_Q^2

skewness: S_Q

kurtosis: κ_Q

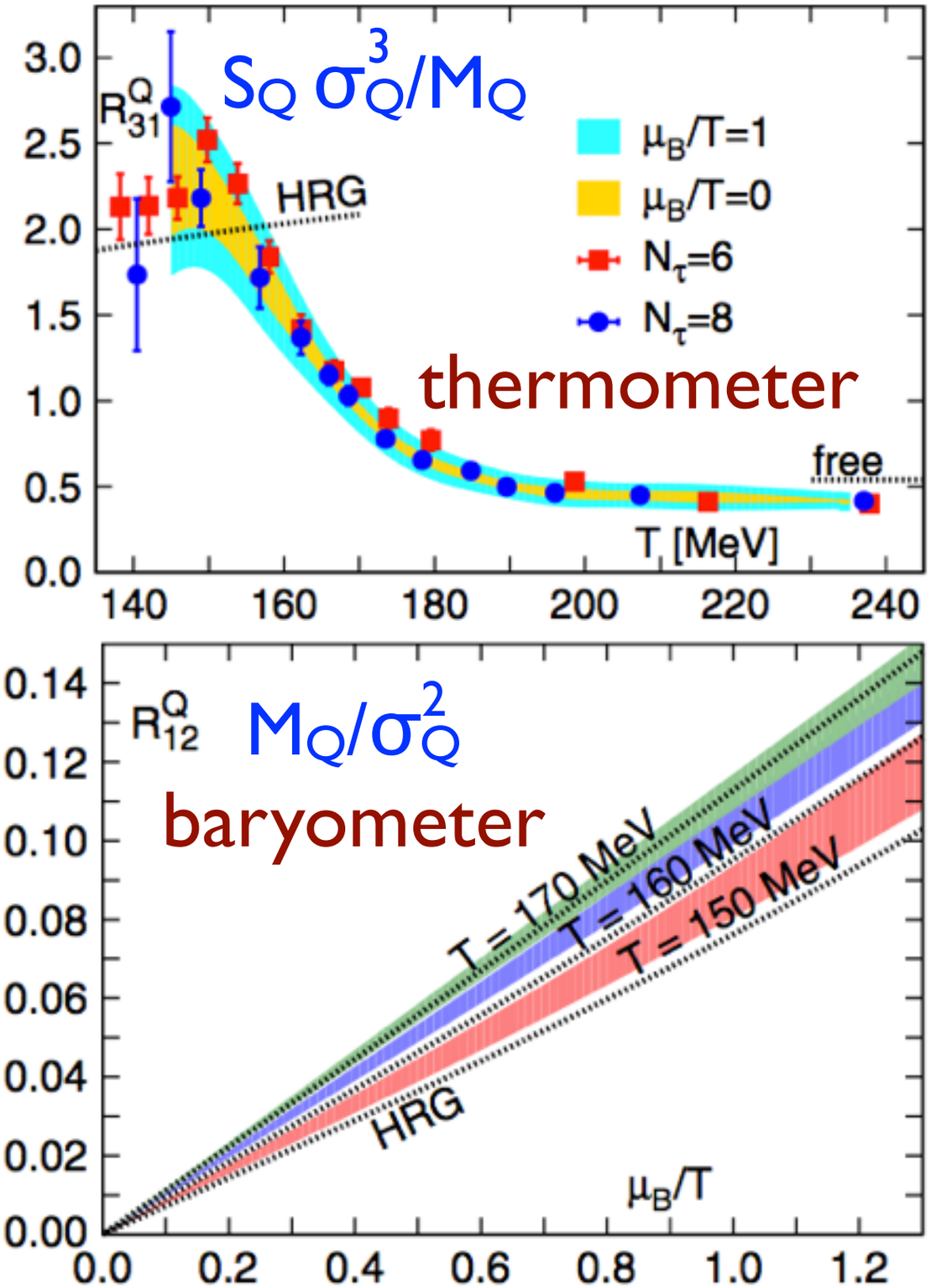
LQCD

generalized susceptibilities

$$\chi_n^Q(T,\vec{\mu}) = \frac{1}{VT^3}\frac{\partial^n \ln Z(T,\vec{\mu})}{\partial(\mu_Q/T)^n}$$

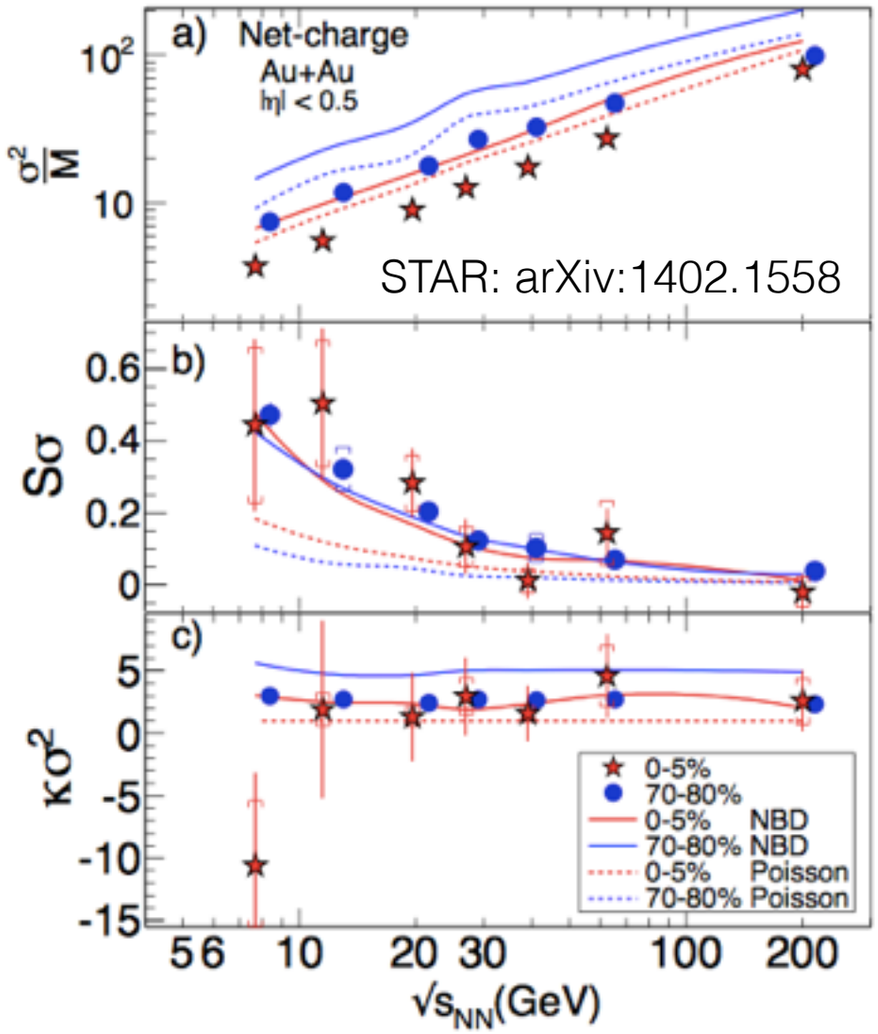
BNL-Bielefeld, Phys. Rev. Lett. 109 (2012) 192302

net charge fluctuations as thermo- & baryo- meters



BNL-Bielefeld, Phys. Rev. Lett. 109 (2012) 192302

S. Mukherjee & M. Wagner, CPOD 2013, arXiv:1307.6255

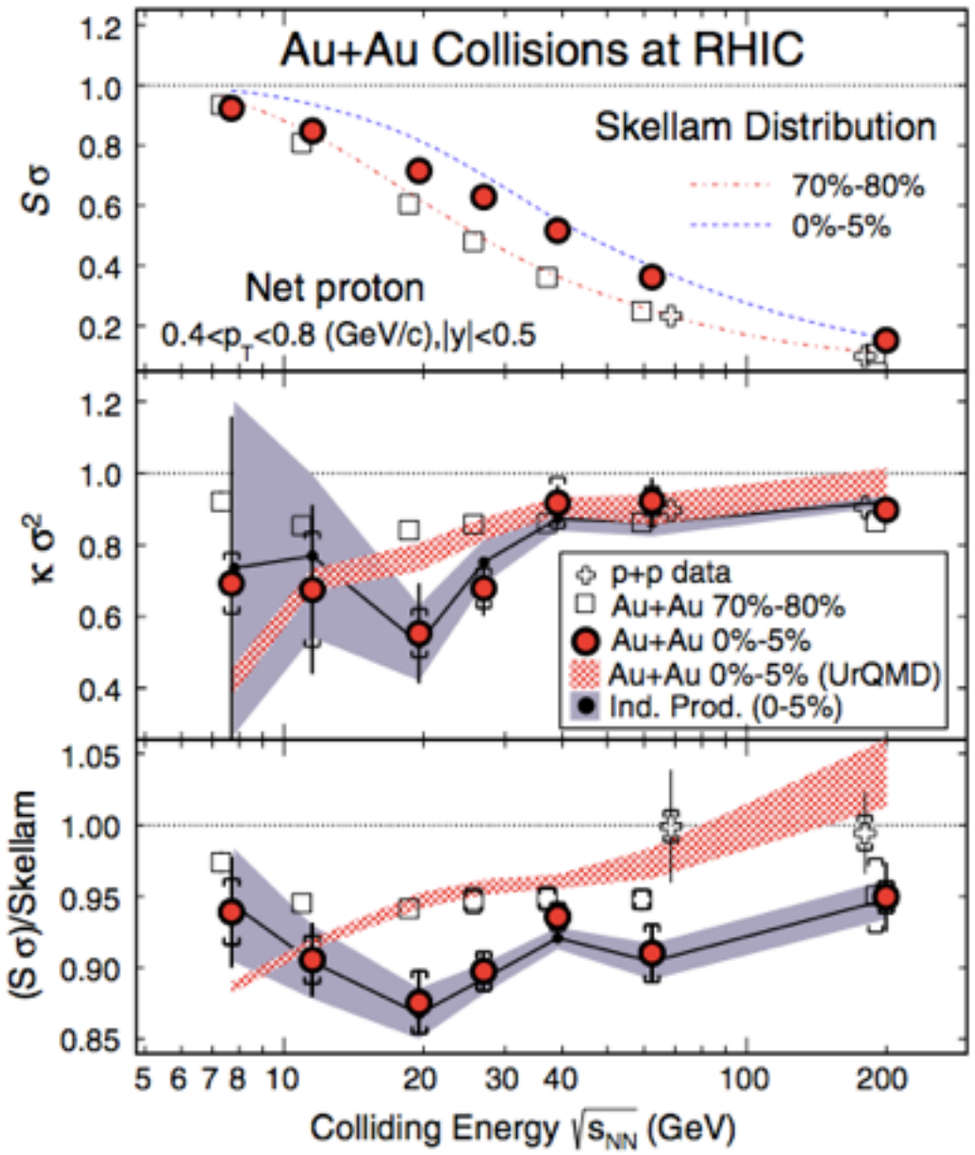


A precise determination of T^f from the current net-charge fluctuation data by comparing with LQCD results remains difficult

Net-charge fluctuation data from BES with higher precision is needed!

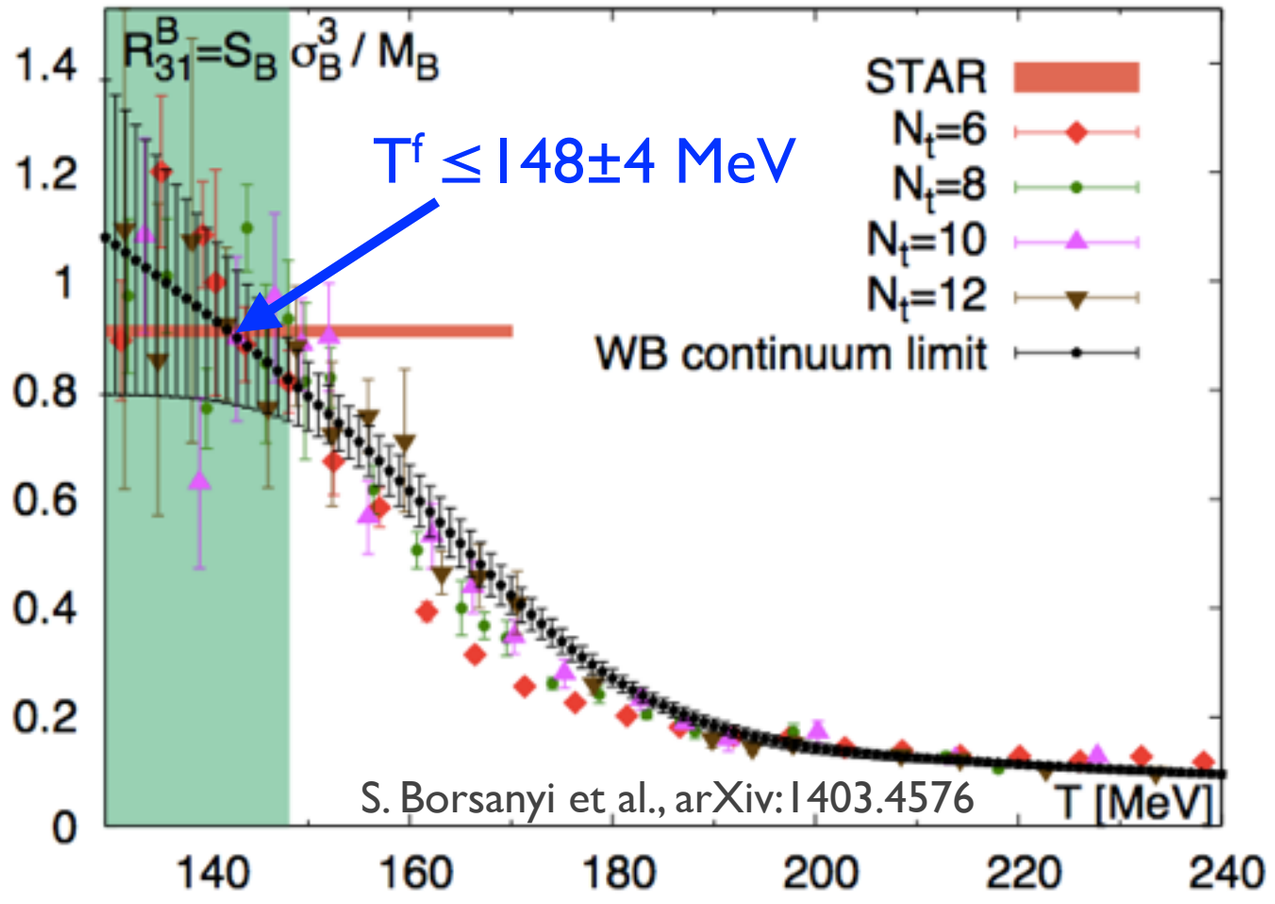
BES-II will help!

net proton vs. net baryon number fluctuations



STAR: PRL112(2014)032302

obtain freeze out temperature using net baryon number fluctuation



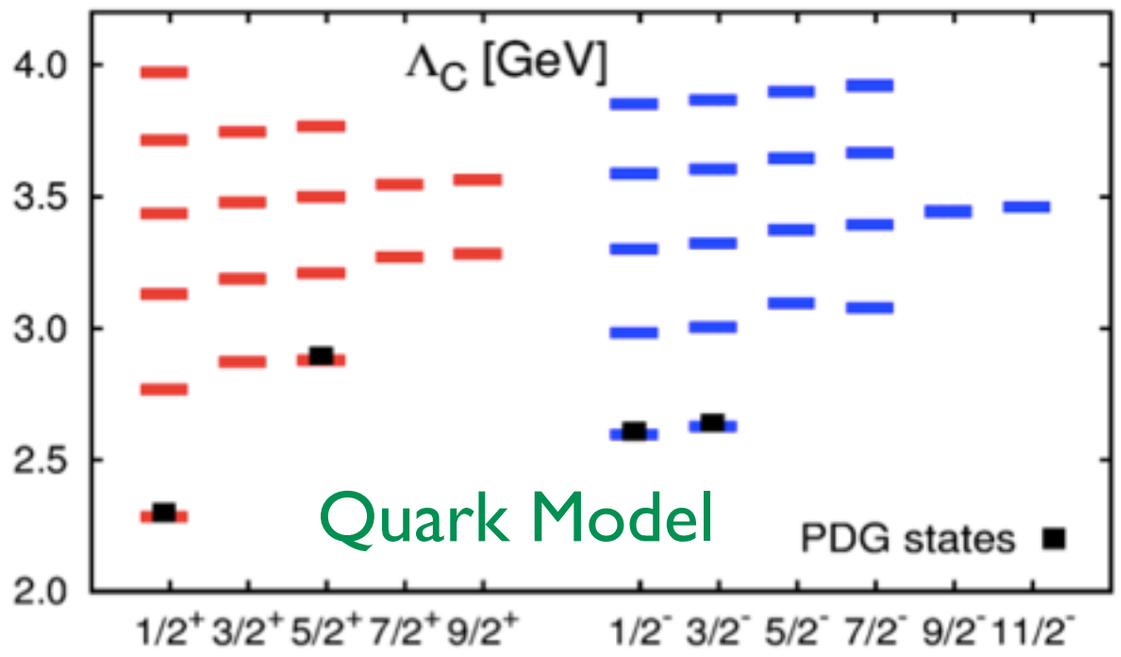
C. Ratti, talk on Wednesday

Caution: only net proton number fluctuations are measured in the experiment

M. Kitazawa, talk this afternoon

Alternative way of obtaining freeze out conditions: Hadron yields from Hadron Resonance Gas model…?

Hadron Resonance Gas model: revisited

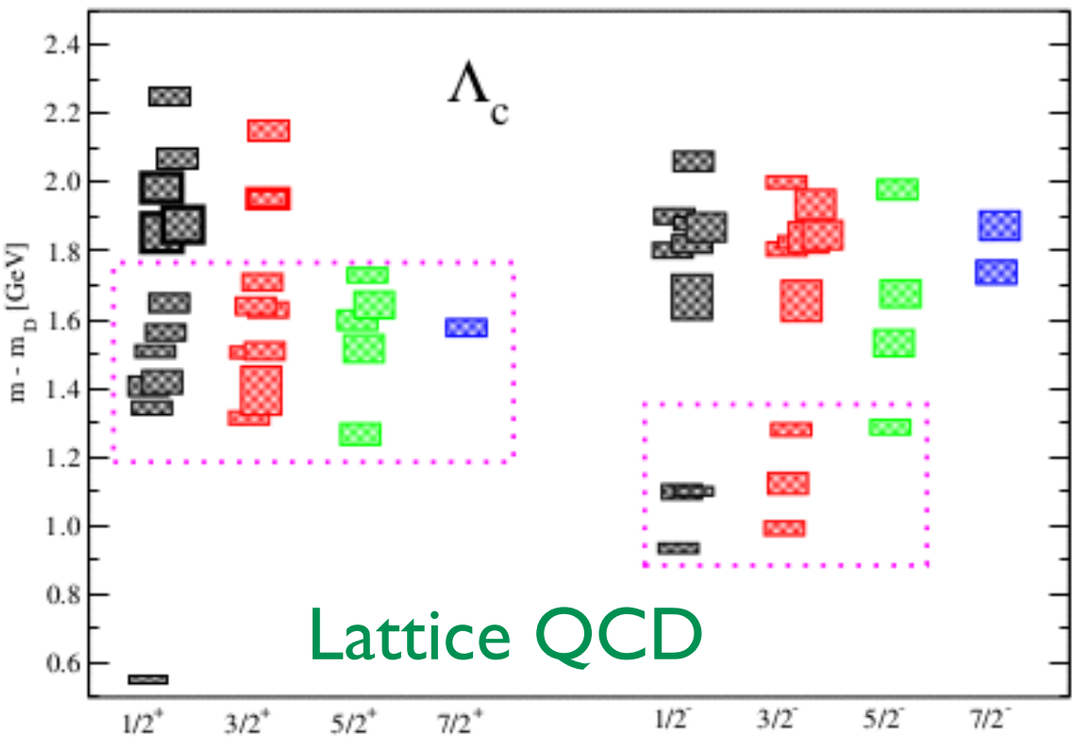


Ebert et. al., EPJC66(2010)197, PRD84(2011)014025

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

hadrons listed in PDG + ???

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

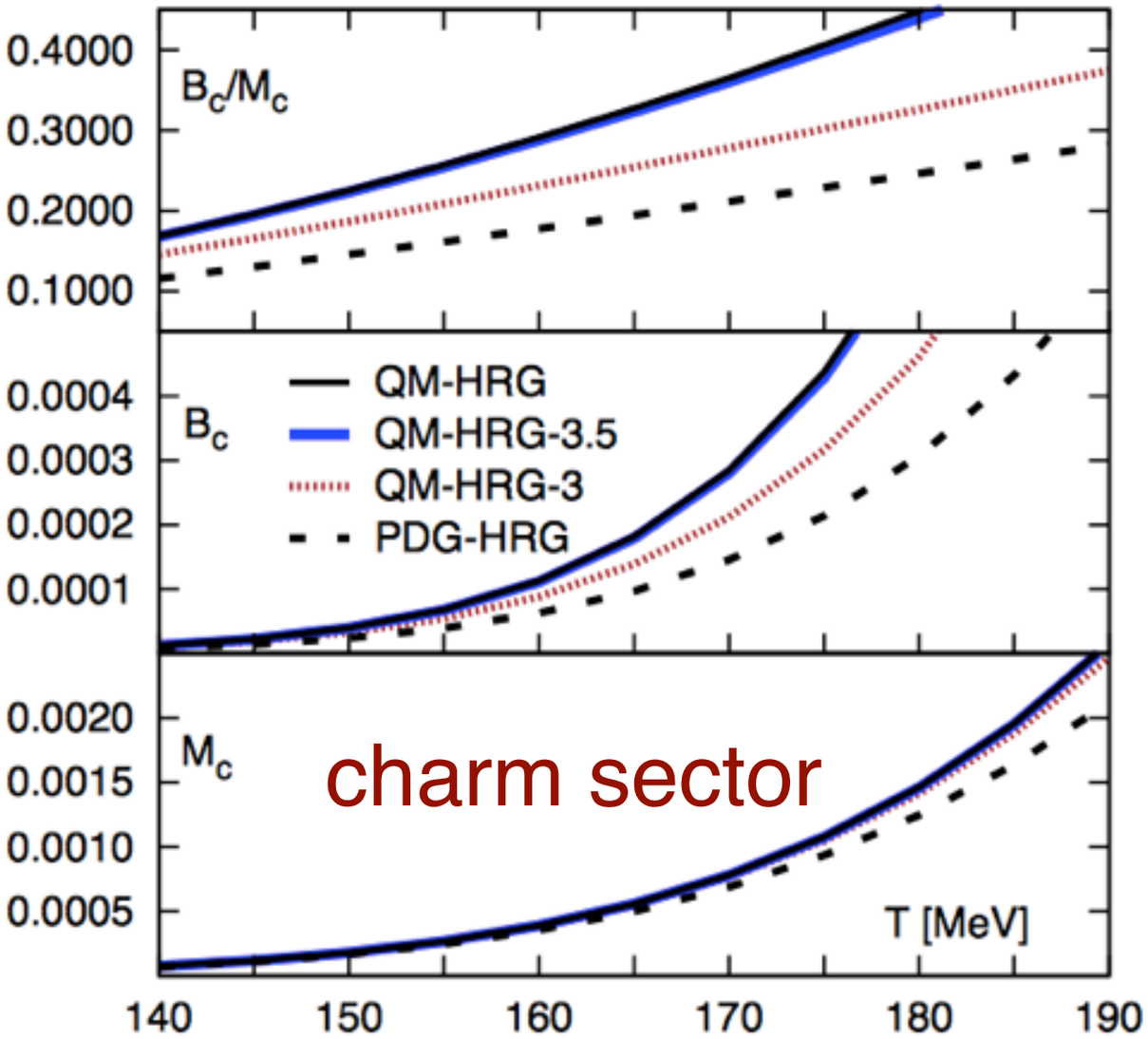


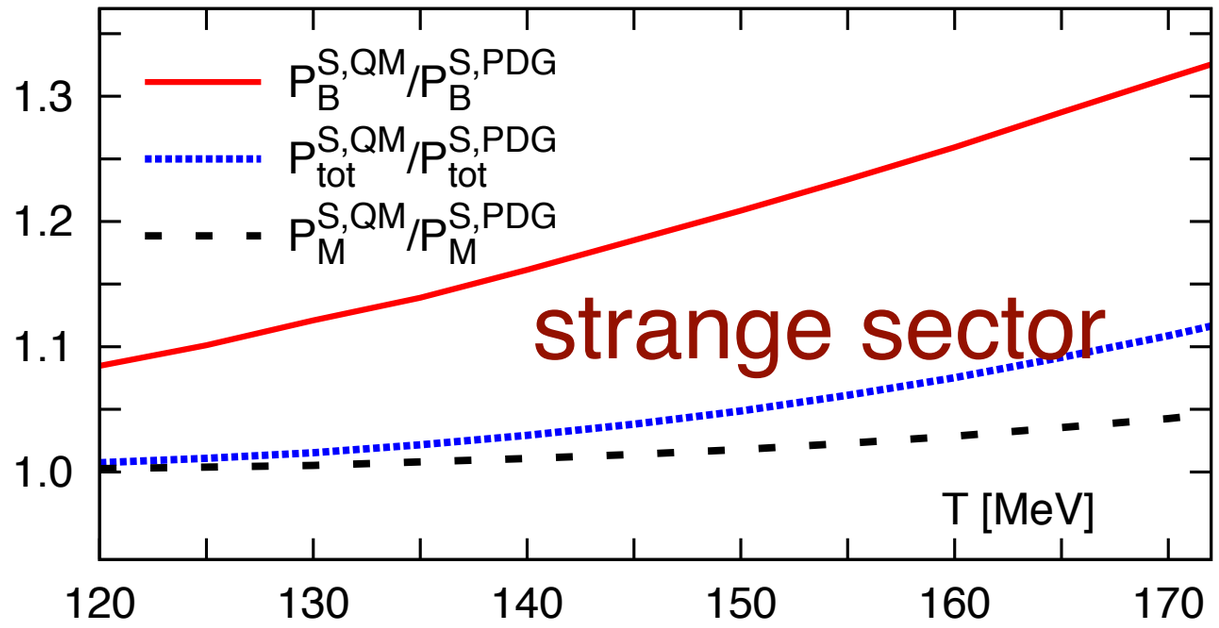
Padmanath et.al., arXiv:1311.4806 [hep-lat]

LQCD calculations give similar results with QM

Differences in thermodynamic quantities with different hadron spectrum from PDG and QM?

Additional open charm/strange hadrons in HRG





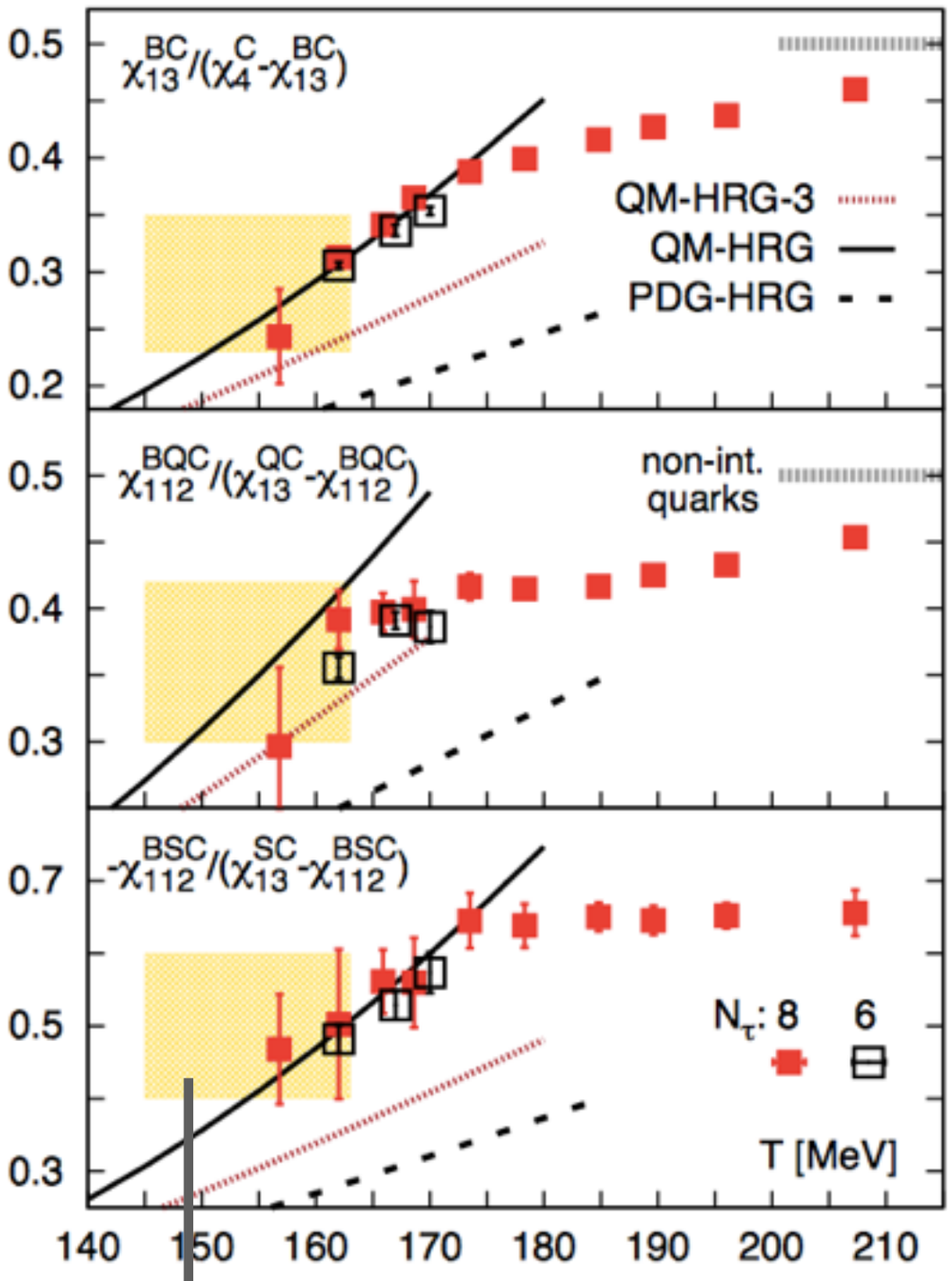
B: pressure from baryons
M: pressure from mesons

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 et al., arXiv:1404.6511,1404.4043

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

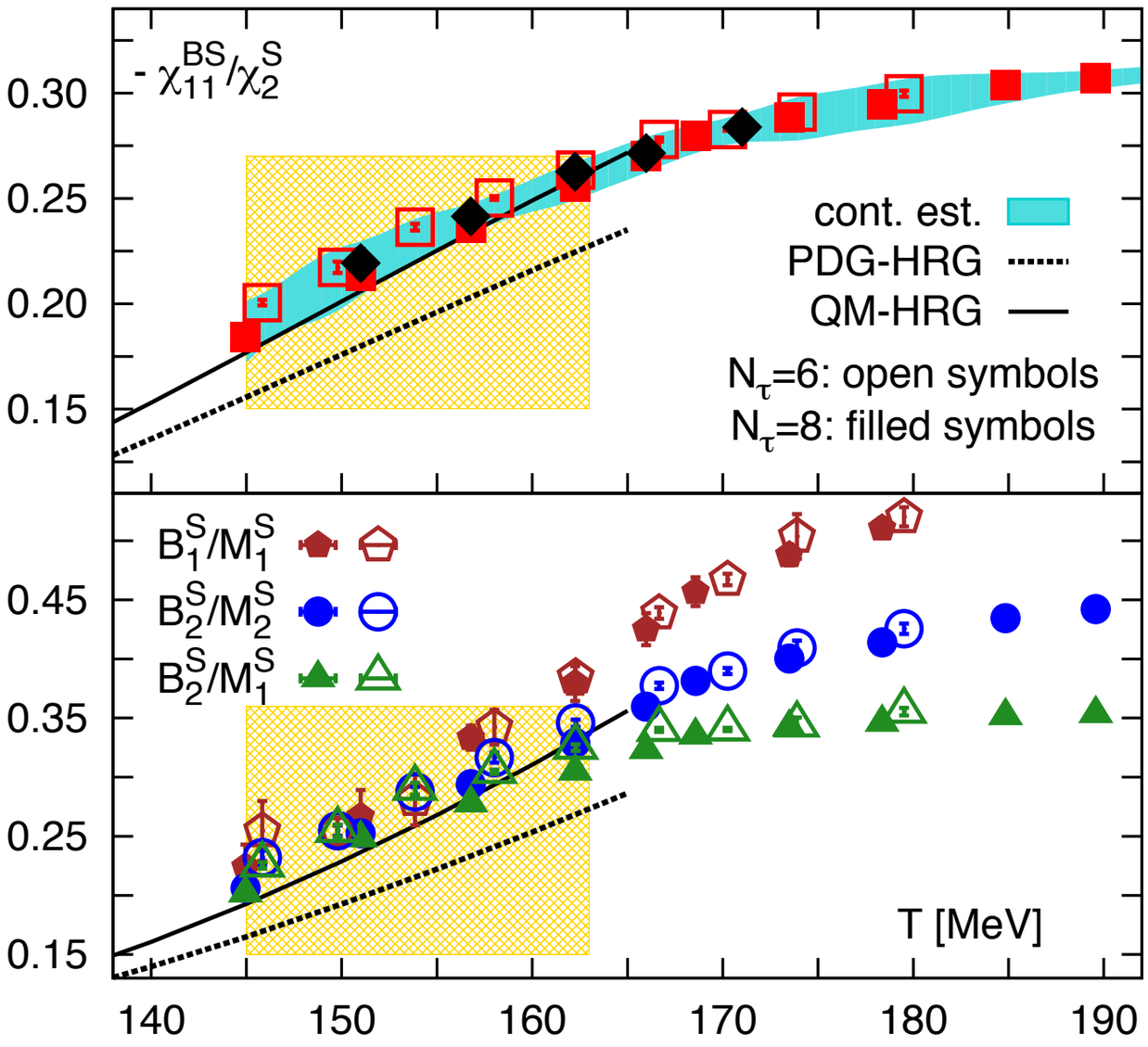
Clear evidence of the additional, non-PDG listed states from QCD thermodynamics is found

S. Sharma, Poster J-13, arXiv: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

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

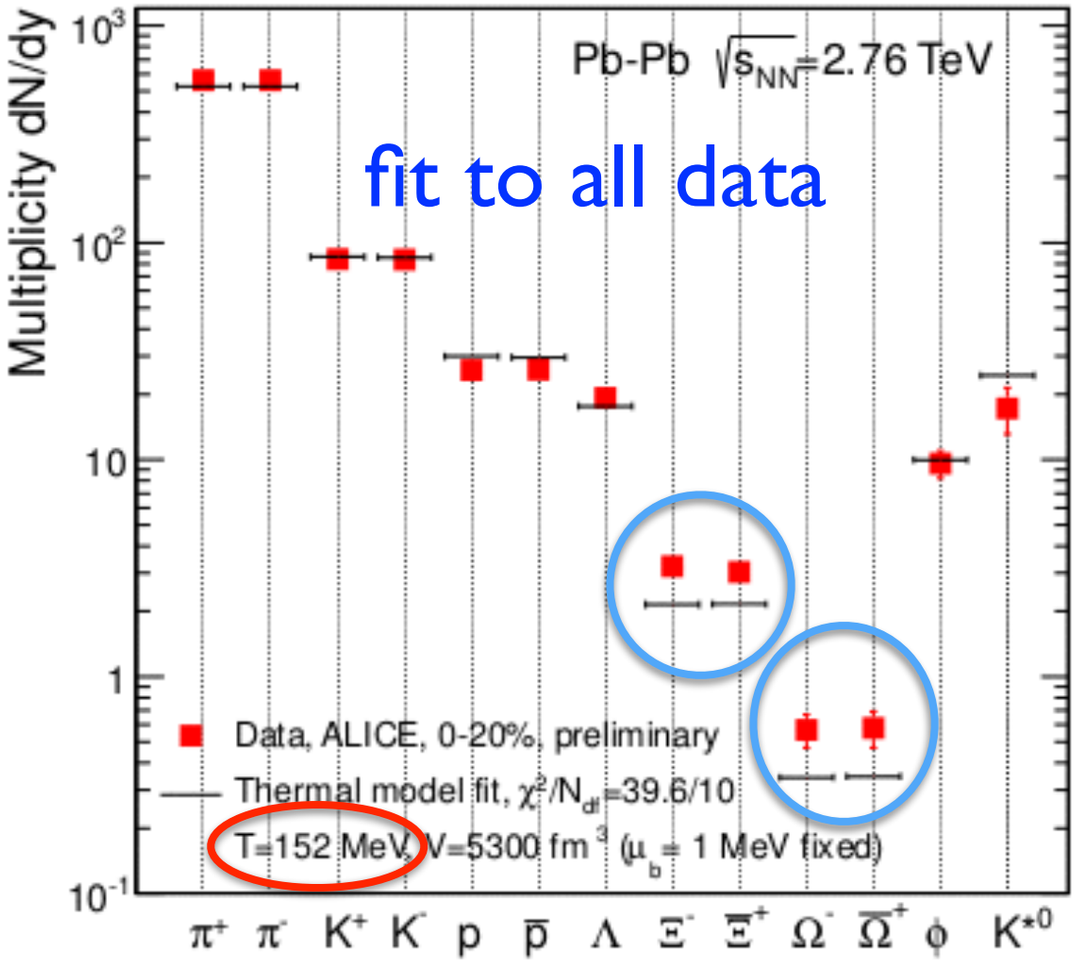
Evidence of contributions of additional, experimental yet unobserved open strange hadrons to the QCD thermodynamics

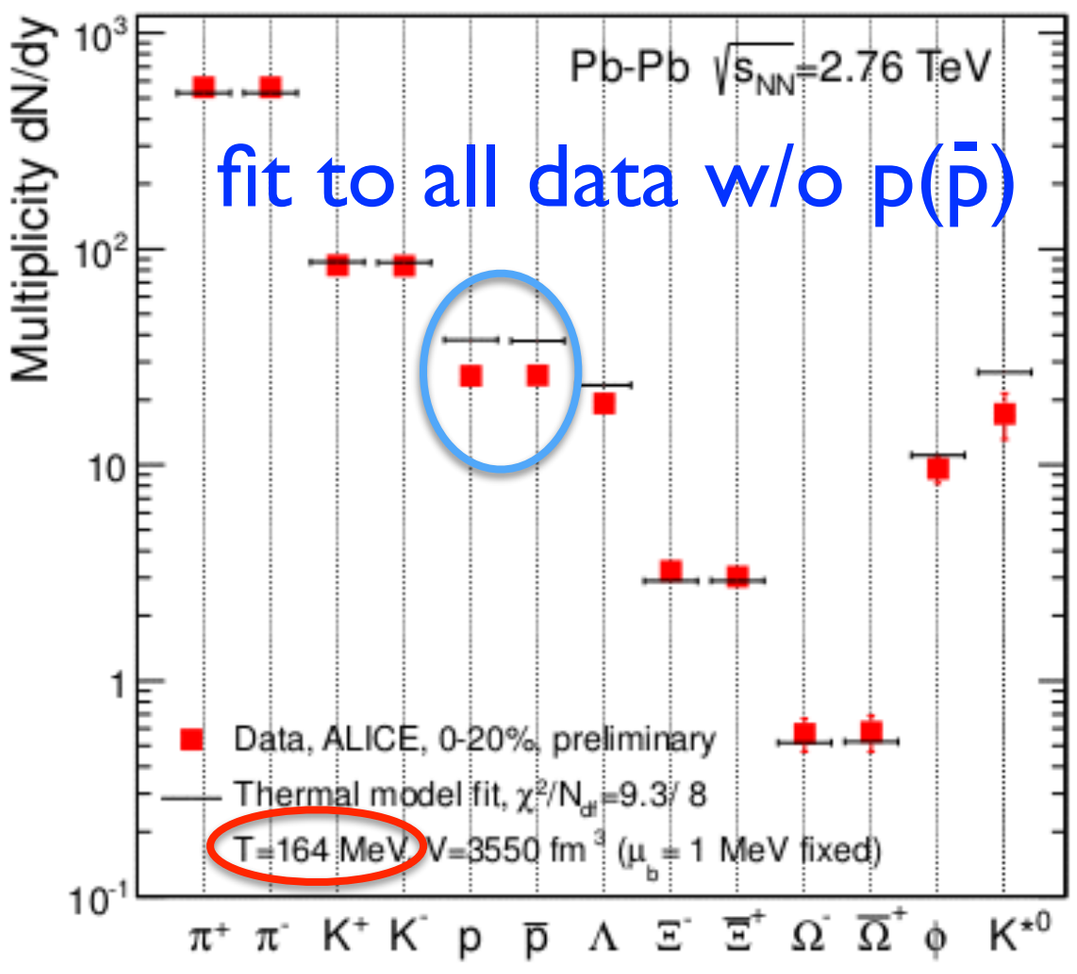
Talk by C. Schmidt on Wednesday

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, Poster J-04,
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

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,
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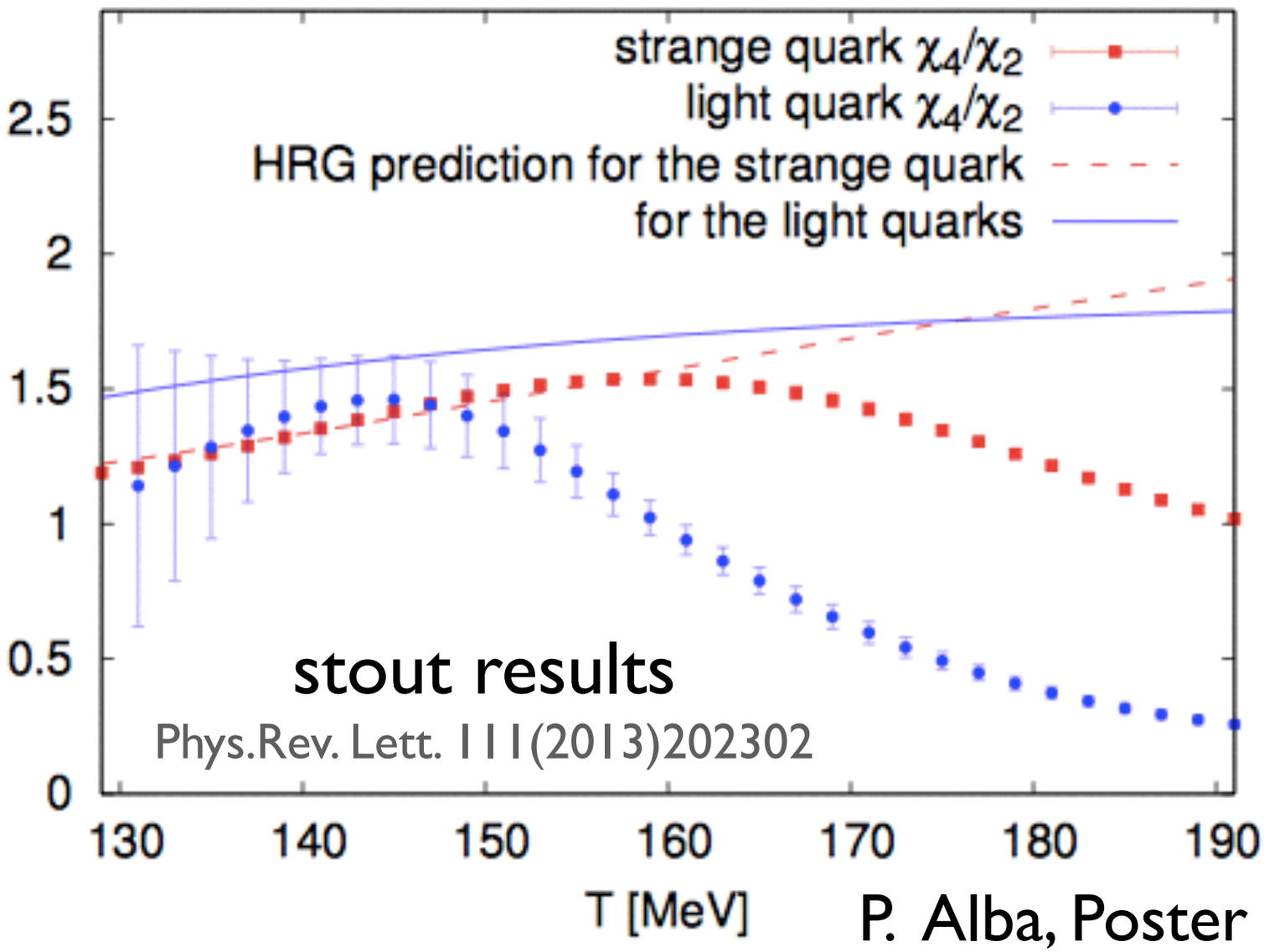


P. Alba, Poster B-01

strangeness chemical potential in HIC

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

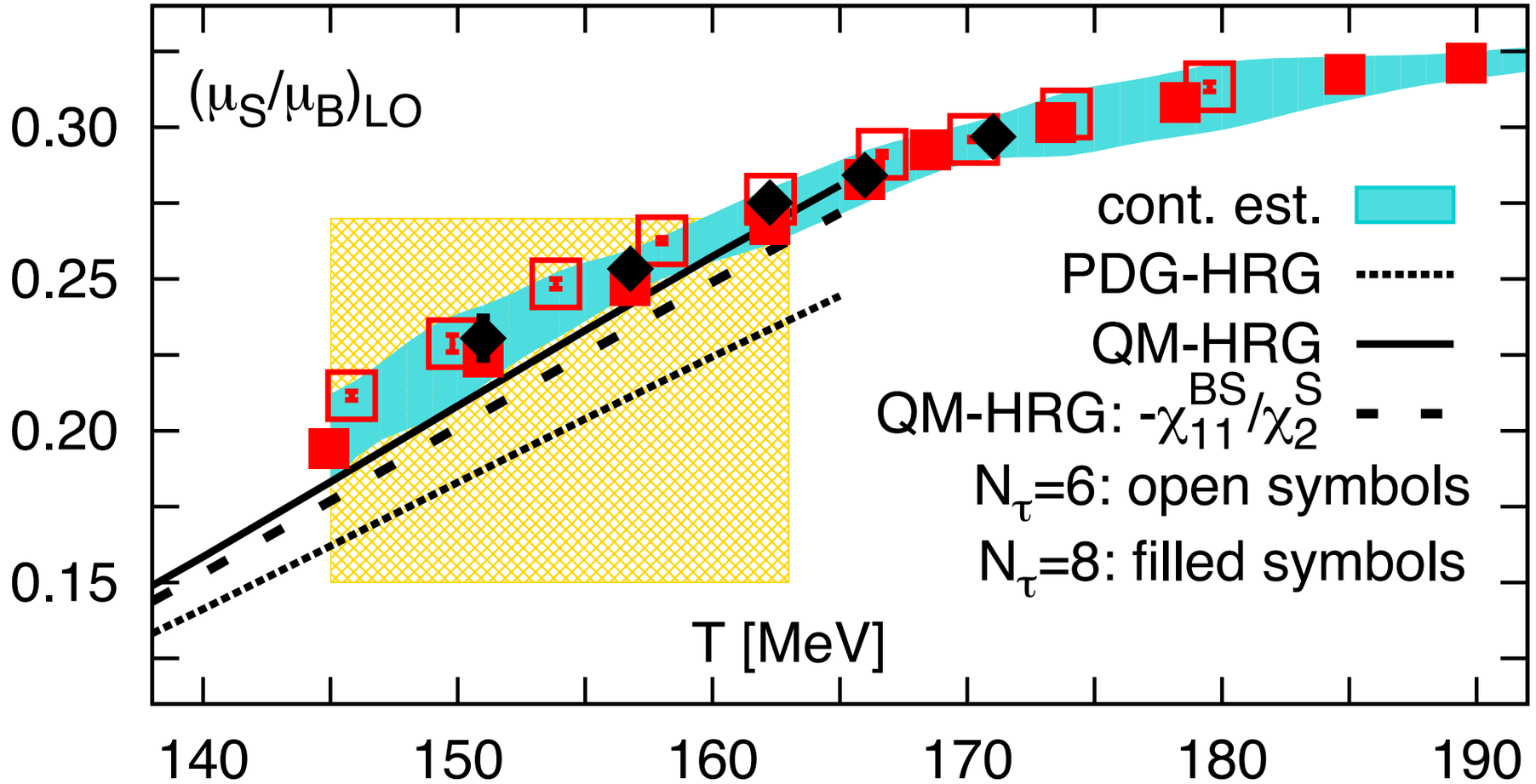
expand μ_S/μ_B in a Taylor series of μ_B:

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

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 et al., arXiv:1404.6511

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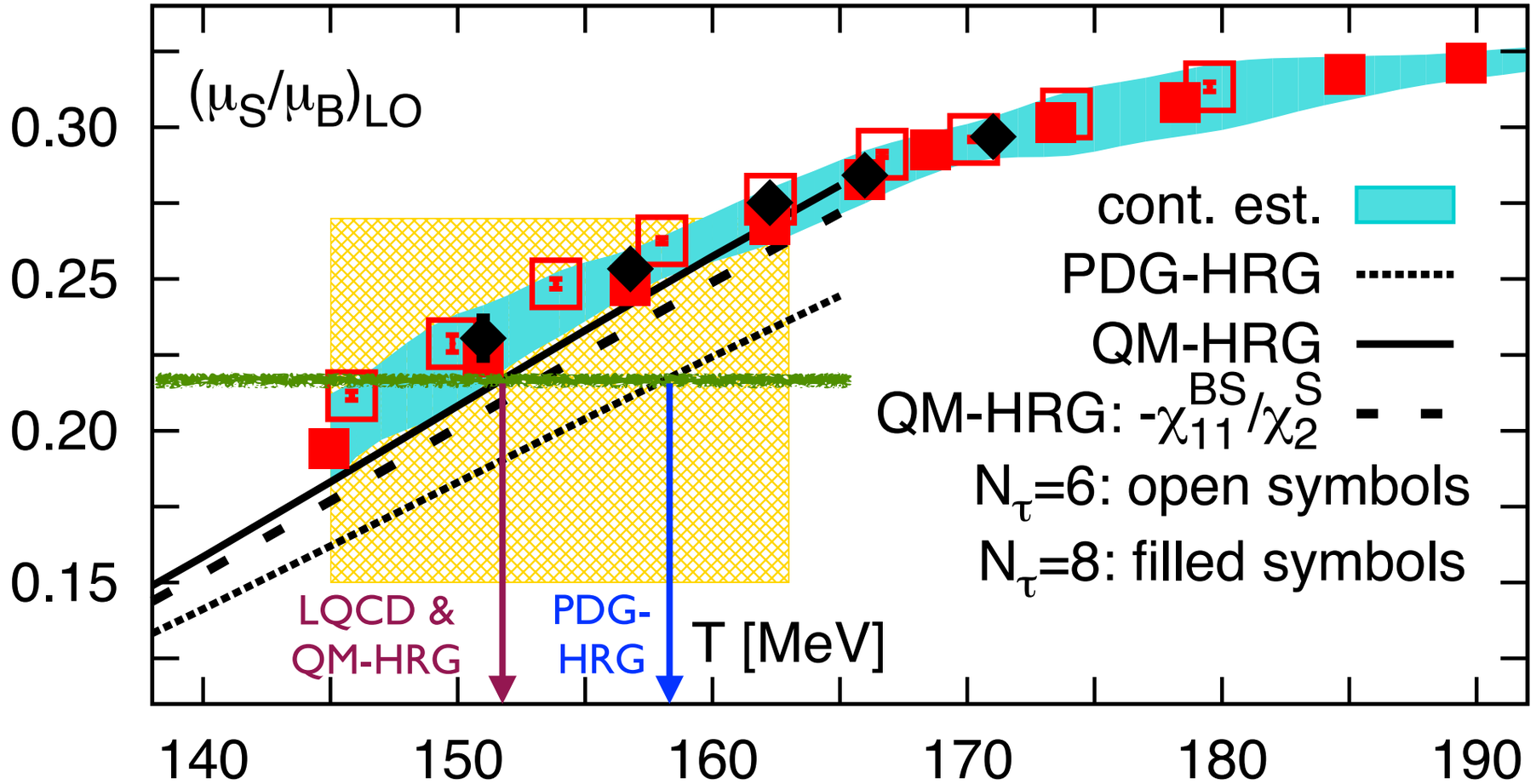


A. Bazavov et al., arXiv:1404.6511

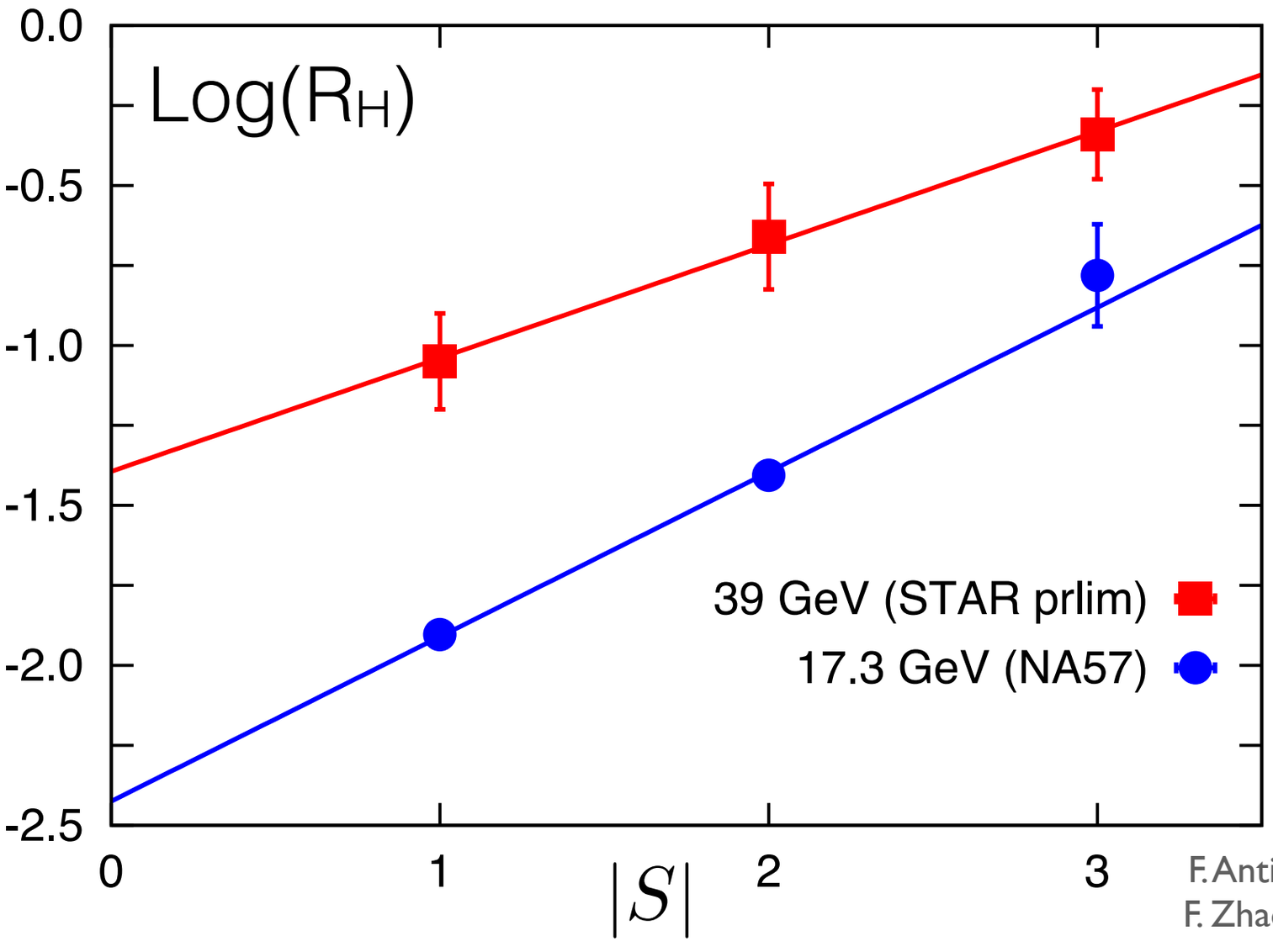
Strange hadron yields in HIC

Two-parameter fit to experiment data using HRG ansatz

irrespective of the details of hadron spectrum

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

$\bar{\Lambda}/\Lambda$ $\bar{\Xi}/\Xi$ $\bar{\Omega}/\Omega$

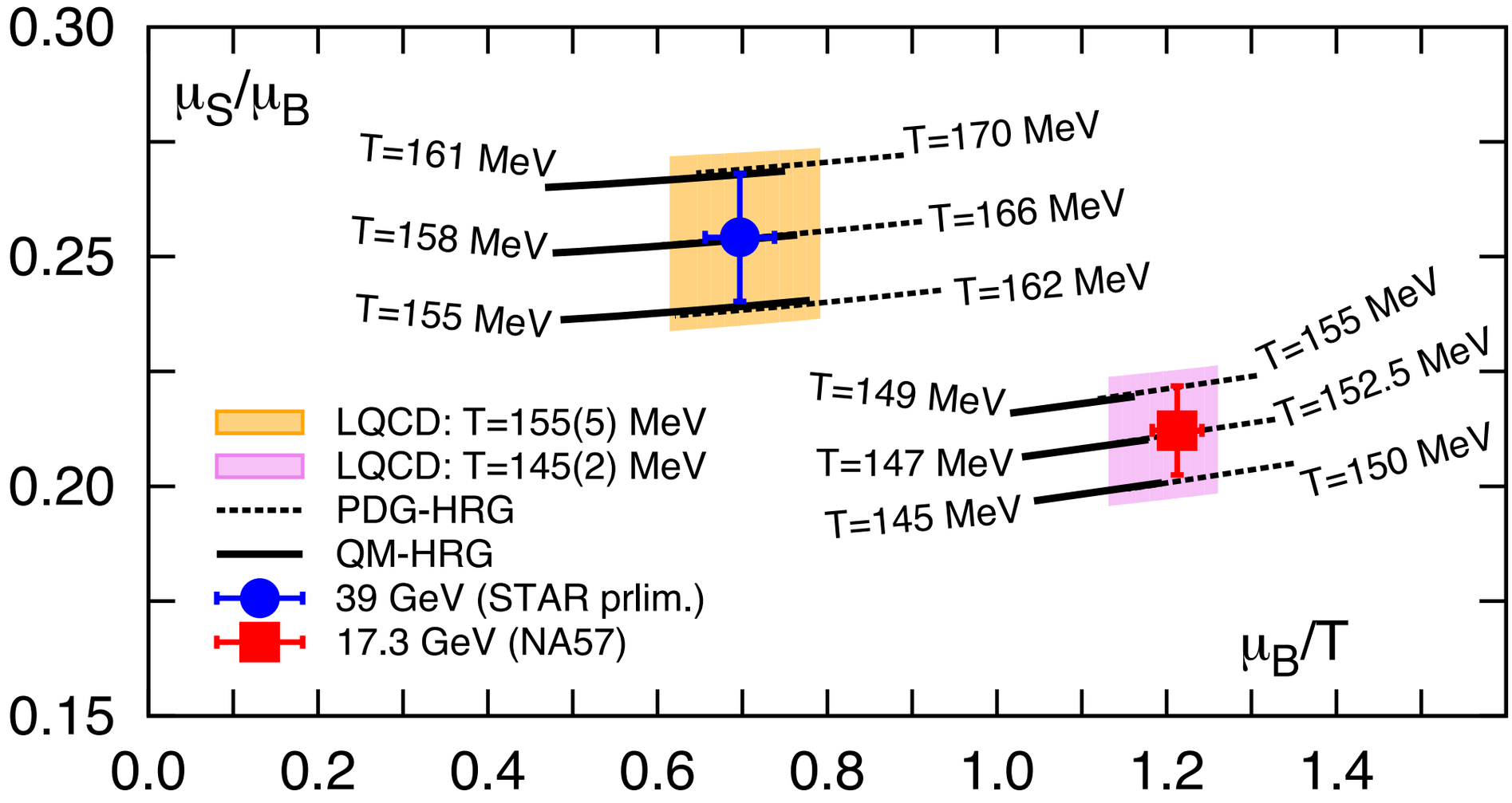


imprinted by the presence of experimentally yet unobserved strange hadrons

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

Imprints of unobserved states in strangeness freeze out in HIC

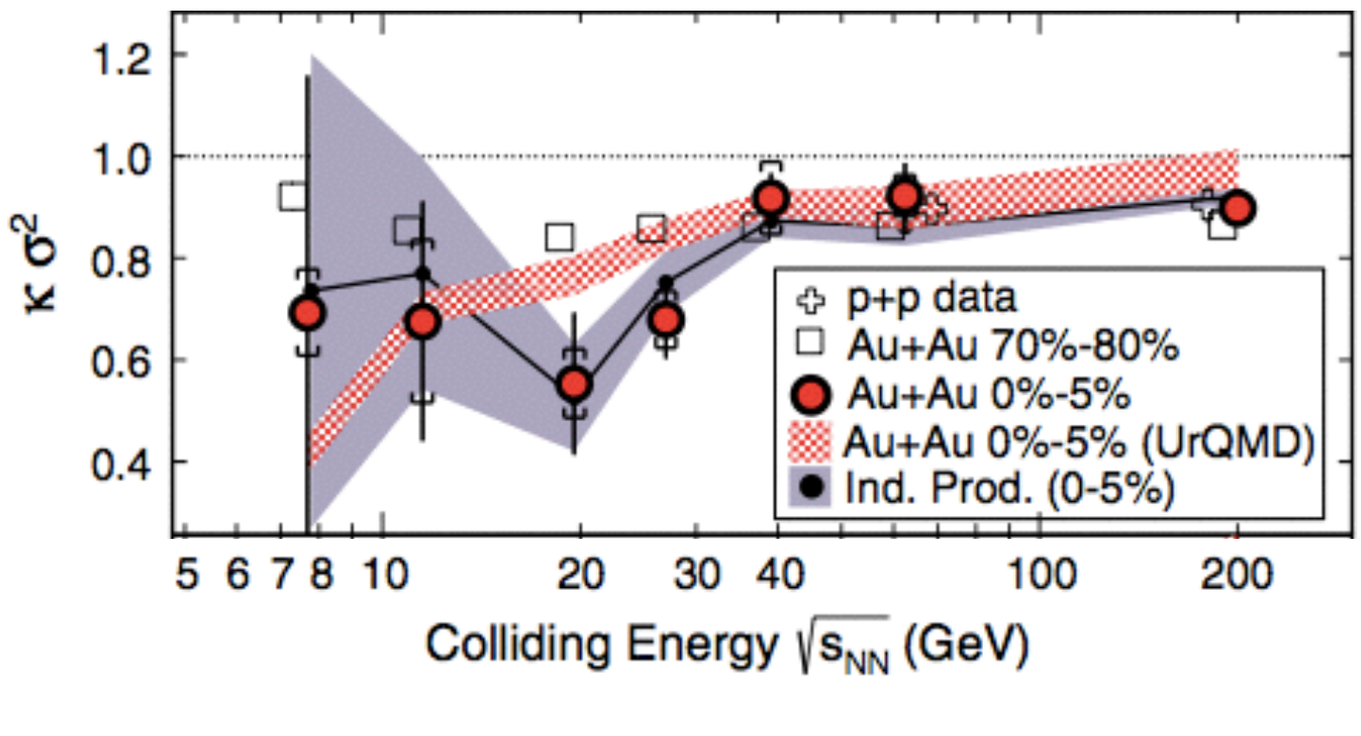


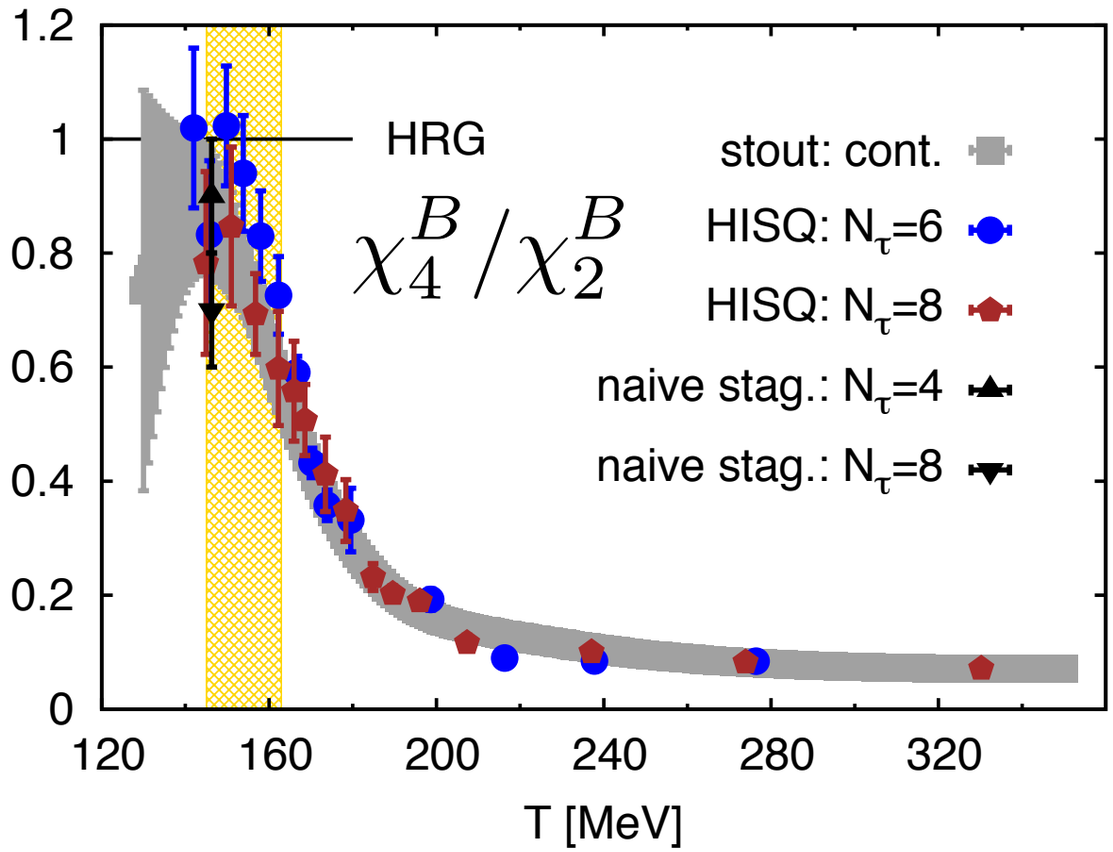
In the strange sector, the PDG-HRG based analysis give larger freeze out temperature than QM-HRG & LQCD by about 5-8 MeV

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

A. Bazavov et al., arXiv:1404.6511

search for the critical point: no real news from lQCD, but…





$$(\kappa\sigma^2)_B = \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4}{\chi^B_2}\left[1 + \left(\frac{\chi^B_6}{\chi^B_4} - \frac{\chi^B_4}{\chi^B_2}\right)\left(\frac{\mu_B}{T}\right)^2 + \cdots\right]$$

WB, PRL111(2013)062005, BNL-Bielefeld, PRL109 (2012) 192302, Mumbai arXiv:1405.2206

In the O(4) universality class: $\chi^B_6 < 0\,, \qquad T \sim T_c$ consistent with data

LQCD: 2nd and 4th order cumulants of baryon number fluctuations are now well understood,
precise determination of 6th order is crucially needed

Summary

- New results on EoS from HotQCD and Wuppertal-Budapest collaborations agree

- The EoS is extended to non-zero μ_B up to μ_B**4

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

- Evidence is found for the contribution of 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 Tc. Such an HRG is preferable to be used to determine freeze out temperatures in HIC

χ_4/χ_2 are not order parameters

strange quark χ_4/χ_2

light quark χ_4/χ_2

HRG prediction for the strange quark

for the light quarks

2.5

2

1.5

1

0.5

0

130

140

150

160

170

180

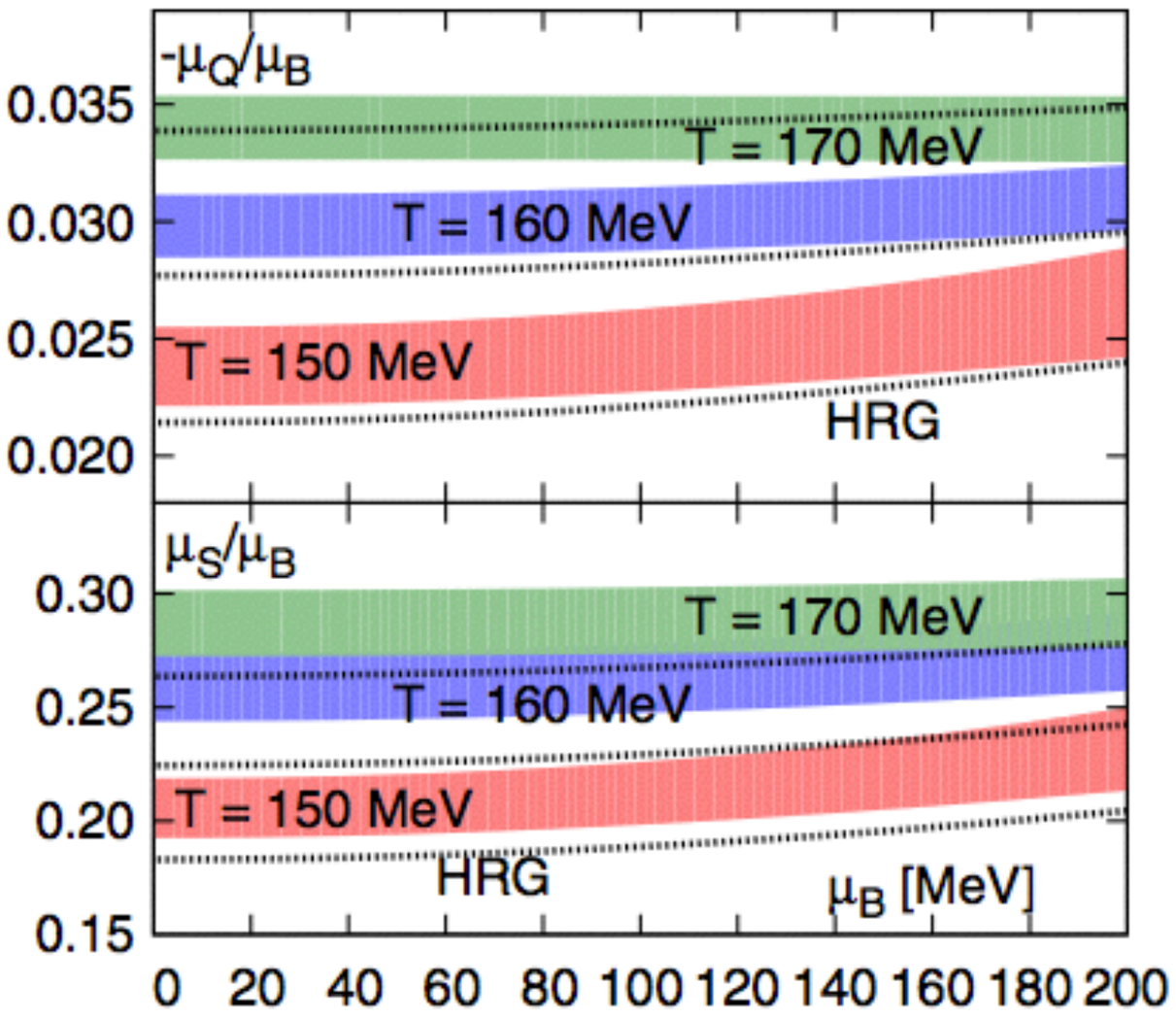
190

T [MeV]

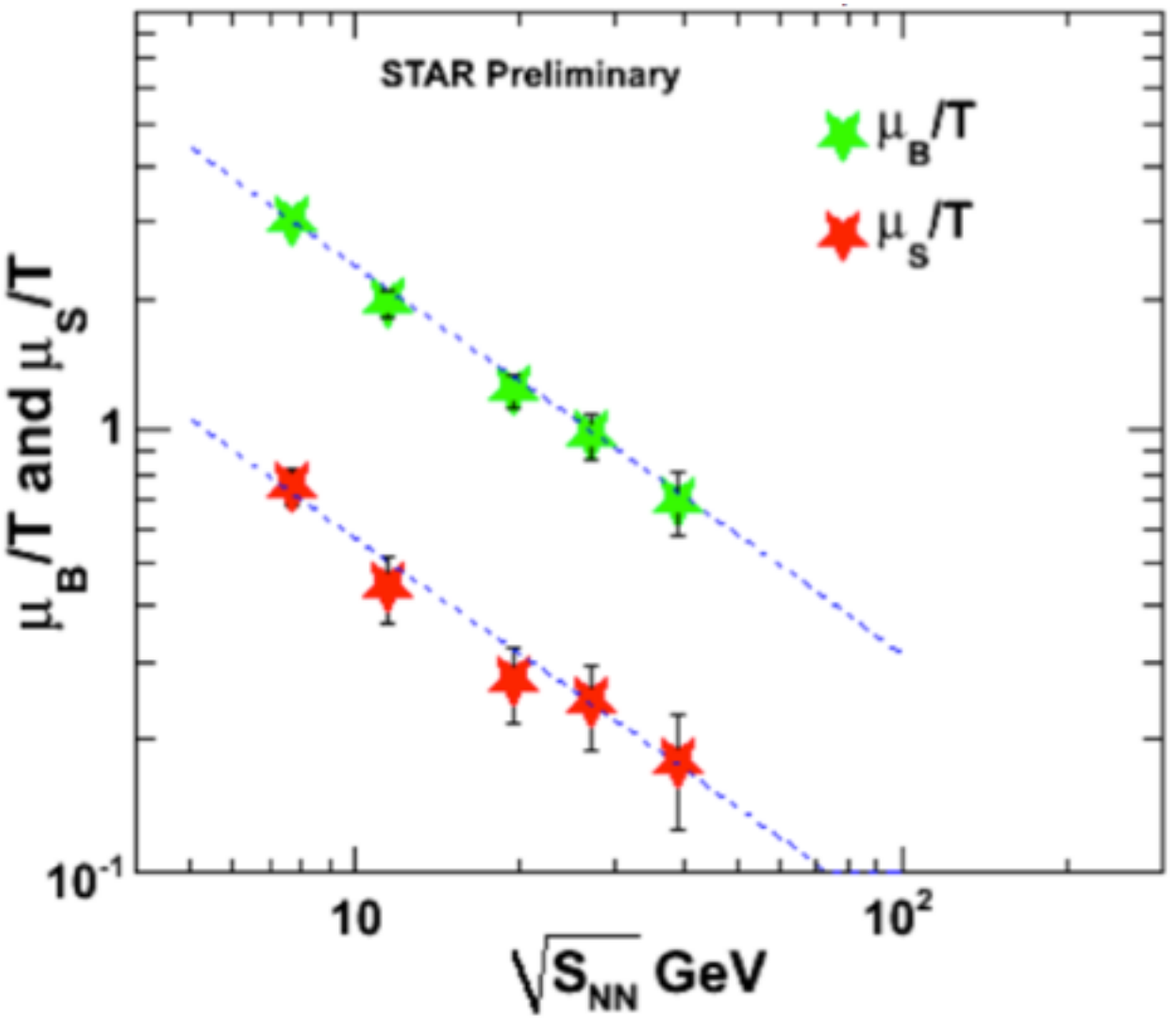
T_c=154±9 MeV

isospin & strangeness constrained

Initial condition in LQCD:
strangeness neutrality: $\langle M_S \rangle = 0$
isopin asymmetry: $\langle M_Q \rangle = r \langle M_B \rangle$



BNL-Bielefeld, Phys. Rev. Lett. 109 (2012) 192302



consistent with STAR data
$\mu_S/\mu_B \approx 0.24$

F. Zhao, CPOD 2013

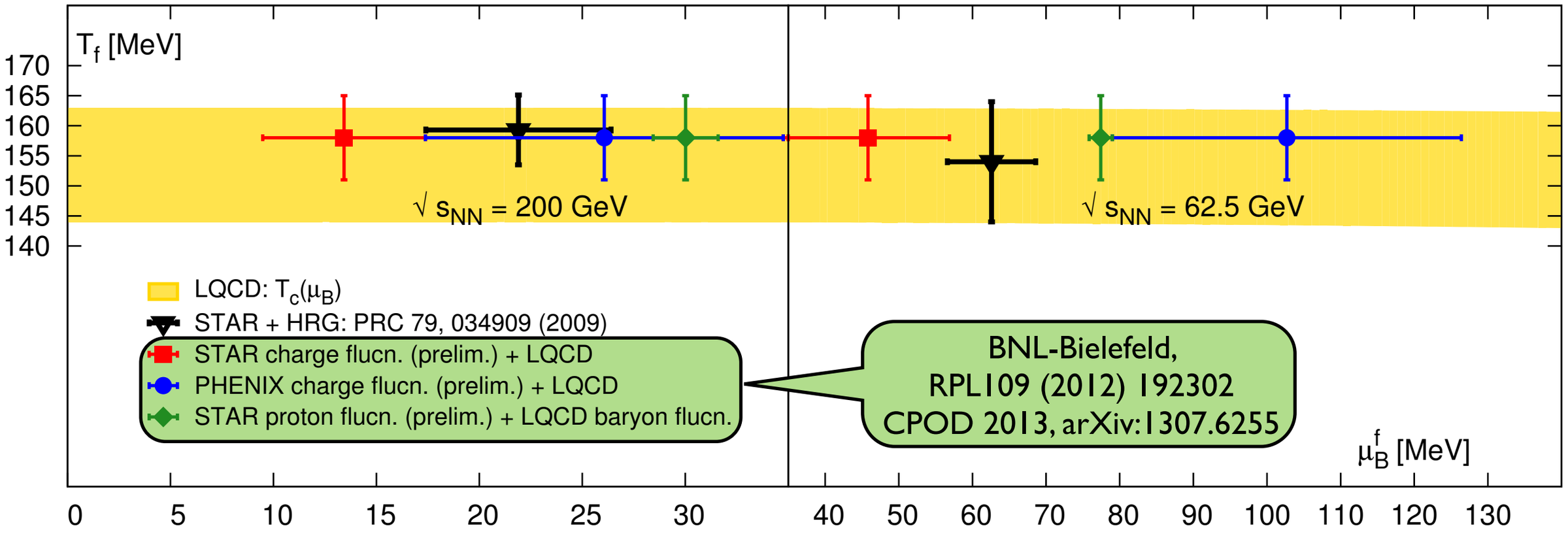



illustration of principle