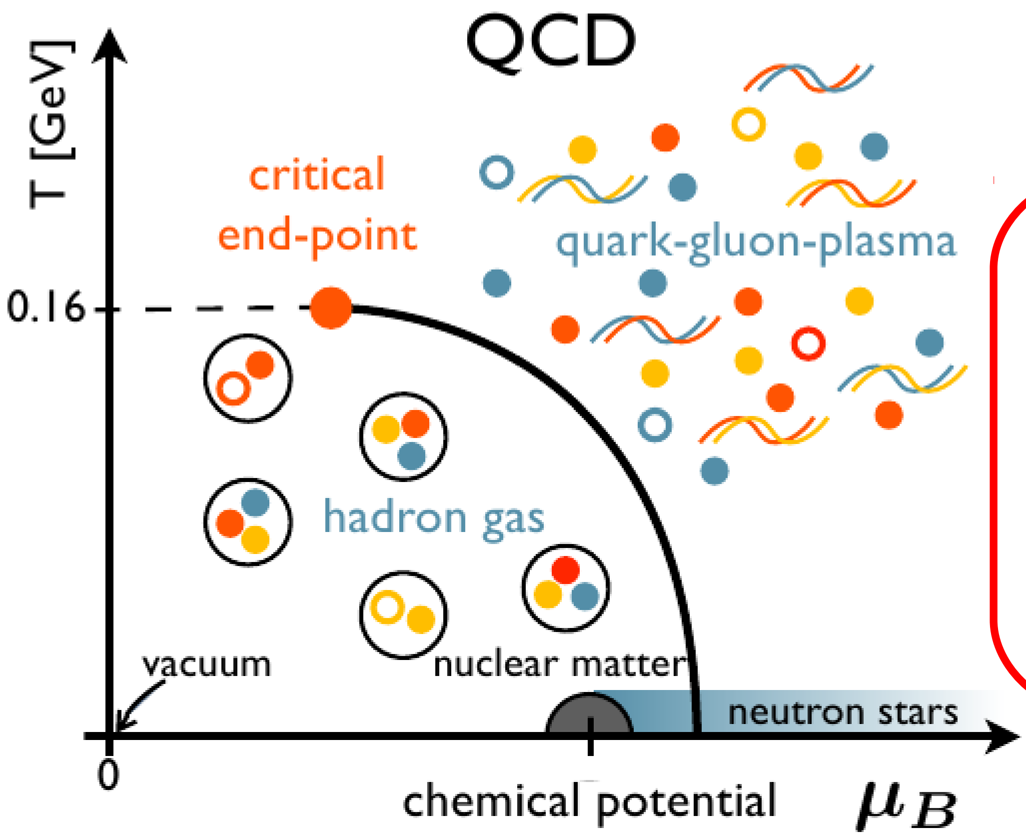
QCD thermodynamics

Frithjof Karsch, BNL/Bielefeld



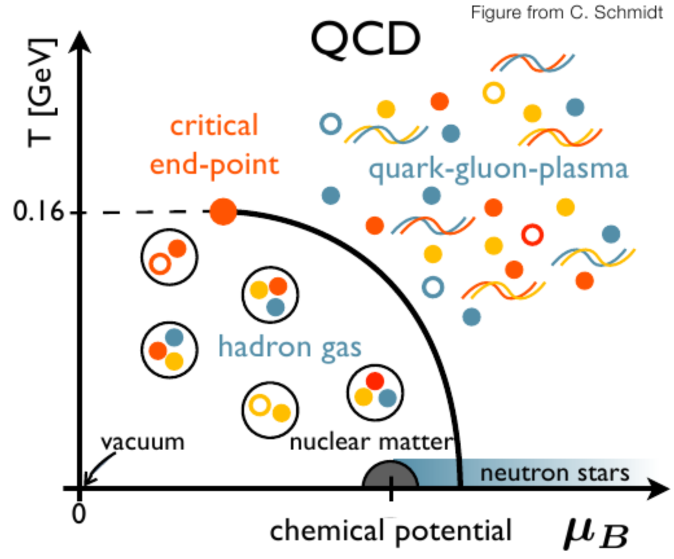
Key Questions

NSAC Long Range Plan 2007

- What are the phases of strongly interacting matter, and what role do they play in the cosmos?
- What does QCD predict for the properties of strongly interacting matter?
- What governs the transition of quarks and gluons into pions and nucleons?

Exploring the QCD phase diagram in Theory and Experiment

Phase Structure	Theory	Experiment Signatures
QGP Phase	EOS, densities, temperature, transport properties, Novel symmetries: LQCD + QCD based models	Jet quenching, Azimuthal anisotropy, strangeness enhancement, Quarkonia suppression, etc
Hadronic Phase	Hadron mass, spectral functions, freeze-out properties (temperature, volume, lifetime etc). LQCD + QCD models	Freeze-out properties (yields, ratios and spectra) source size and life time (HBT)
Cross over	Susceptibility volume dependence. LQCD	direct signature ? (indirect through EOS)
Critical point	Correlation lengths, Susceptibilities. LQCD + QCD based models	Fluctuations, Higher moments of conserved number distributions
New phases	Quarkyonic - QCD Models (lattice ?)	Baryon correlations
Transition line	LQCD, QCD models	Some signatures



Bedanga Mohanty (STAR), opening talk given at "Critical Point and Onset of Deconfinement 2013", Napa

5

Thermodynamics projects in 2013/14

Equation of state and the transition temperature:

M. I. Buchoff et al., The QCD chiral transition, UA(1) symmetry and the Dirac spectrum using domain wall fermions, Phys. Rev. D89 (2014) 054514

T. Bhattacharya et al. (hotQCD), The QCD phase transition with physical-mass, chiral quarks, arXiv:1402.5175

A. Bazavov et al. (hotQCD), *The QCD equation of state, in preparation*

Fluctuation of conserved charges using Taylor expansions:

A. Bazavov et al.(BNL-Bielefeld), *Strangeness at high temperatures: from hadrons to quarks*, Phys. Rev. Lett. 111, 082301 (2013)

A. Bazavov et al.(BNL-Bielefeld), The melting and abundance of open charm hadrons, arXiv:1404.4063

A. Bazavov et al.(BNL-Bielefeld), More strange hadrons from QCD thermodynamics and strangeness freeze-out in heavy ion collisions, arXiv:1404.6511

Heavy quark bound states and transport at high temperature

O. Kaczmarek et al., Thermal dilepton rates from quenched lattice QCD, arXiv:1301.7436

Y. Maezawa et al., Meson screening masses at finite temperature with Highly Improved Staggered Quarks, arXiv:1312.4375

USQCD projects 2013/14

Lattice meets Experiment in 2013/14

Workshops/Programs on Heavy Ion Physics:

– Probing the Phase Structure of Strongly Interacting Matter with Fluctuations: Theory and Experiment, Feb. 11 - 22 , 2013,
GSI Darmstadt, Germany, organizers: B. Friman (GSI), F. Karsch (BNL),
K. Redlich (Wroclaw), Nu Xu (LBNL)

– Heavy Flavors and Electromagnetic Probes in Heavy Ion Collisions,
INT, Seattle, Sept.15-Oct.10, 2014, organizers: A. Frawley, P. Petreczky,
E. Scomparin, R. Vogt

International Conference and Workshop Series:

– Extreme QCD
2012: Washington DC, organizers: A. Alexandru, A. Bazavov
2014: BNL&Stony Brook, organizers: F. Karsch, D. Kharzeev, J. Verbaarschot

– Critical Point and Onset of Deconfinement
2013: Napa valley, organizers: H.G. Ritter et al.
2014: Bielefeld, Germany, organizers: F. Karsch et al.

Outline

- QCD thermodynamics projects in 2013/14
- Equation of state and transition temperature
  – thermodynamics with chiral fermions;
  – insight into the role of topology close to Tc
- Charge fluctuations and the RHIC search for the critical point
  – evidence for many new strange and charmed baryons
  – using electric charge fluctuations to search for the critical point

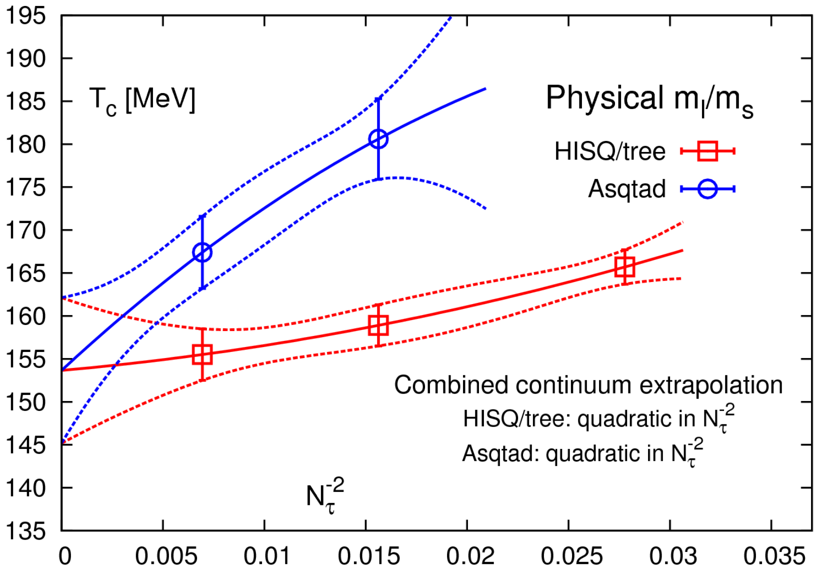
studies of QCD thermodynamics using two different fermion discretization schemes
– Highly Improved Staggered Quarks (HISQ)
– Domain Wall Fermions (DWF)

QCD phase transition in 2012/13

Equation of state and the transition temperature:

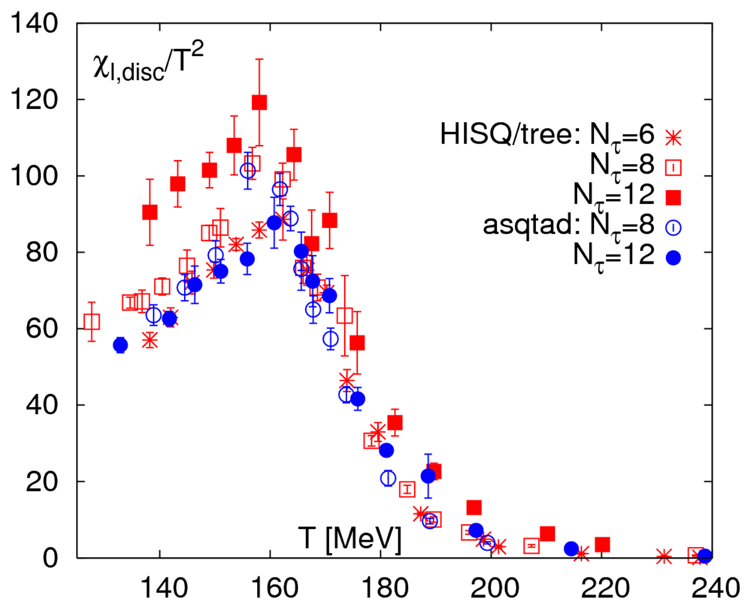
A. Bazavov et al. (hotQCD), *The chiral and deconfining aspects of the QCD transition*, Phys. Rev. D85, 054503 (2012) (266 cit.)

most cited hep-lat paper in 2012/13 and 2013/14



$$T_c = (154 \pm 9)\ \mathrm{MeV}$$

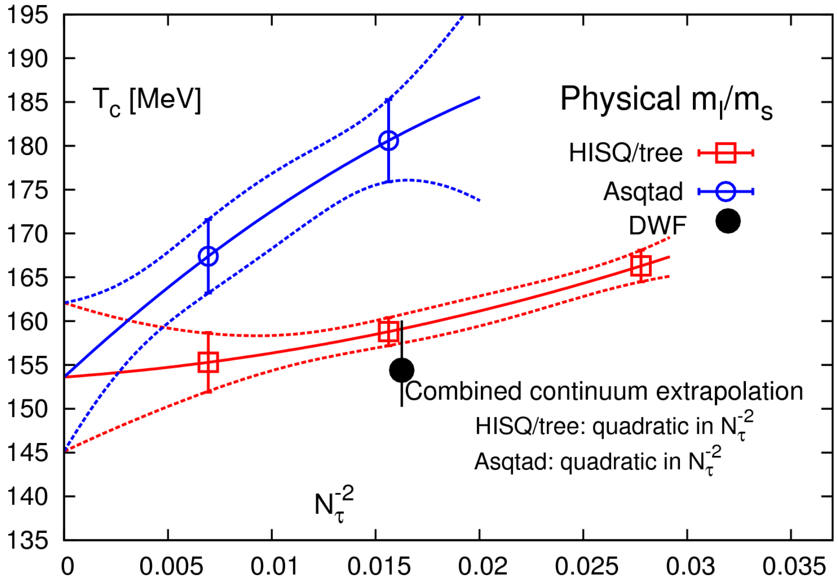
– well defined pseudo-critical temperature
– quark mass dependence of susceptibilities consistent with O(4) scaling



QCD phase transition in 2013/14

Equation of state and the transition temperature:

A. Bazavov et al. (hotQCD), *The chiral and deconfining aspects of the QCD transition*, Phys. Rev. D85, 054503 (2012) (266 cit.)

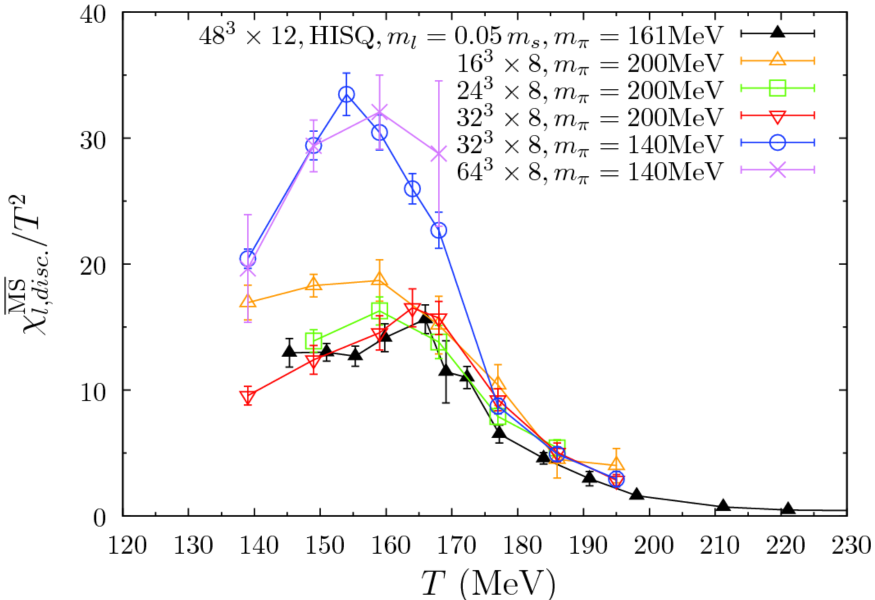


$$T_c = (154 \pm 9)\ \mathrm{MeV}$$

– pseudo-critical temperature from DWF agrees well with HISQ

M.I. Buchoff et al [hotQCD Collaboration] Phys. Rev. D 89, 054514 (2014); T. Bhattacharya et al [hotQCD Collaboration], arXiv:1402.5302

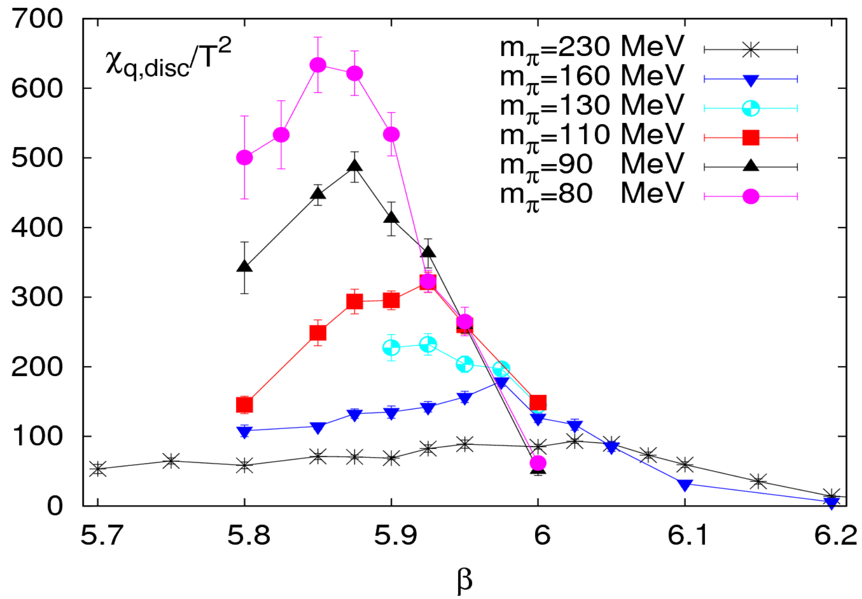
– some 'tension' in the structure of the chiral susceptibility



QCD phase transition in 2013/14

Equation of state and the transition temperature:

A. Bazavov et al. (hotQCD), *The chiral and deconfining aspects of the QCD transition*, Phys. Rev. D85, 054503 (2012) (266 cit.)

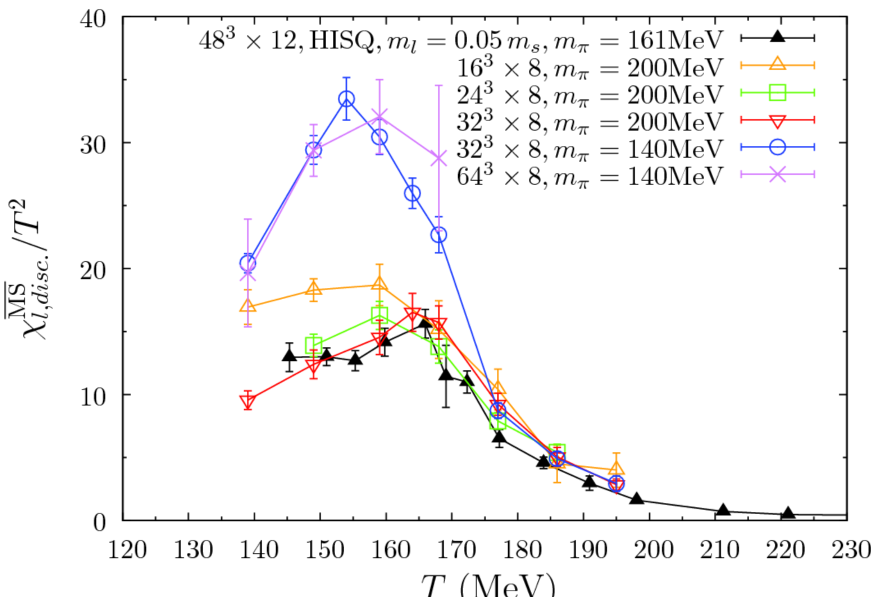


H.-T. Ding, arXiv:1302.5740

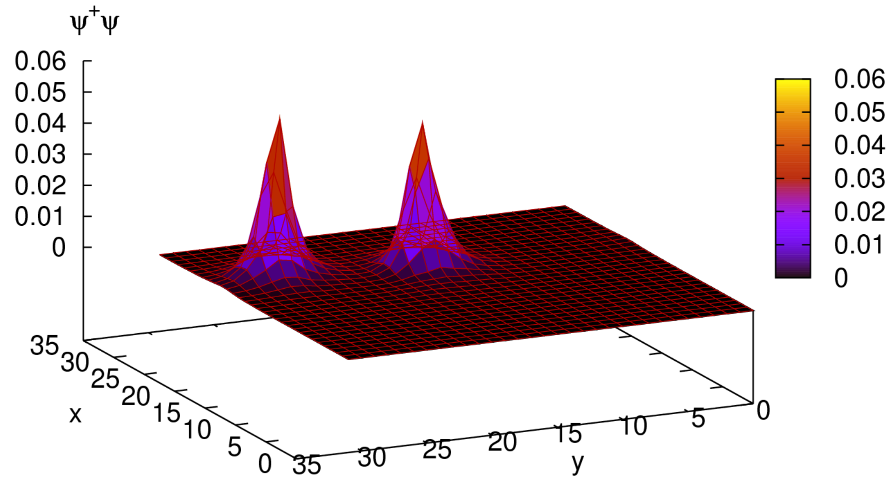
– scaling of the peak height consistent with a continuous transition (2^{nd} order) in the O(4) universality class

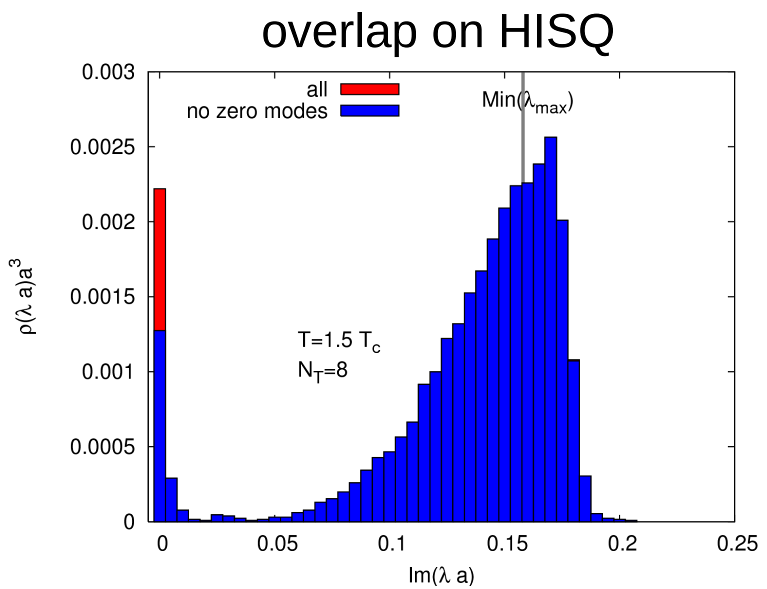
M.I. Buchoff et al [hotQCD Collaboration] Phys. Rev. D 89, 054514 (2014);
T. Bhattacharya et al [hotQCD Collaboration], arXiv:1402.5302

– some 'tension' in the structure of the chiral susceptibility

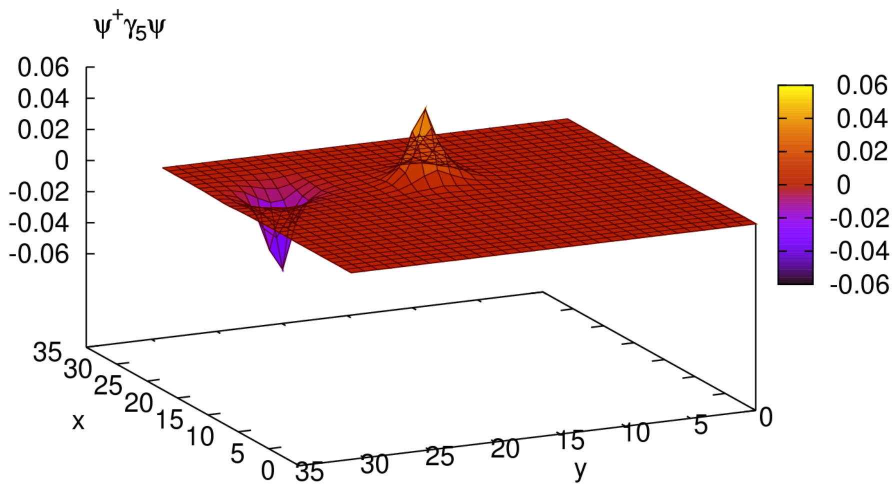


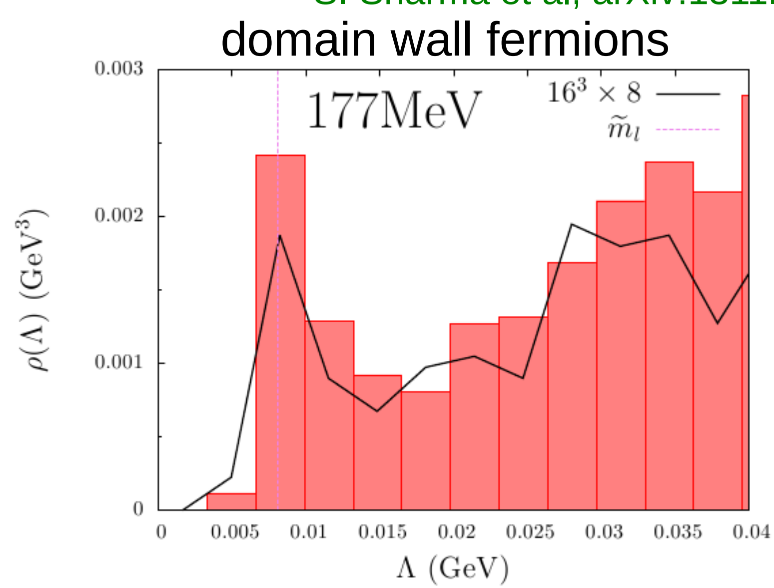
Chiral Transition





S. Sharma et al, arXiv:1311.3943





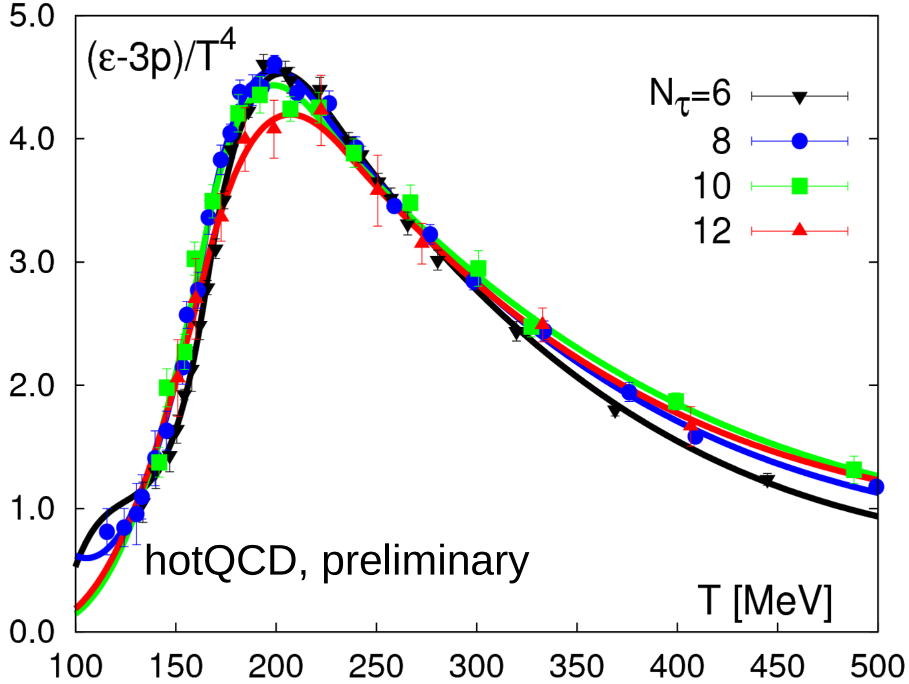
– near zero modes have well localized eigenstates
– consistent with instanton gas model
– UA(1) remains broken also above Tc

M.I. Buchoff et al (hotQCD), PR D89, 094503 (2014)

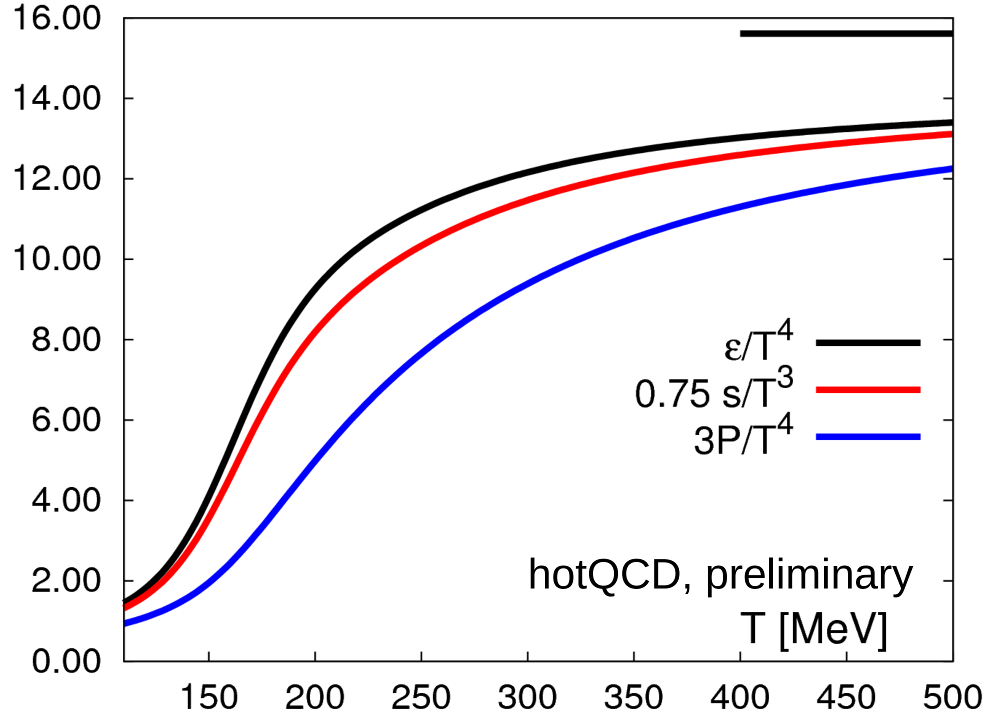
Equation of state

time evolution of the QGP (lifetime, time spend close to Tc)
depends on the equation of state

trace anomaly



energy density, entropy, pressure

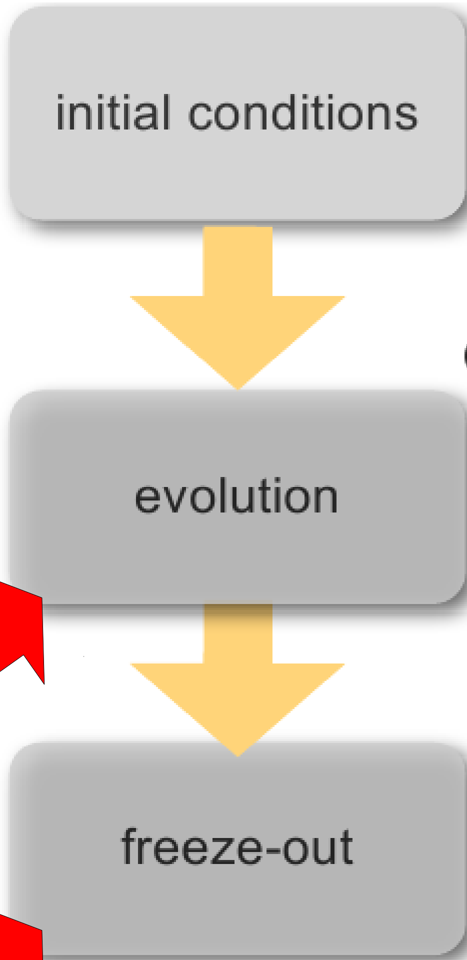


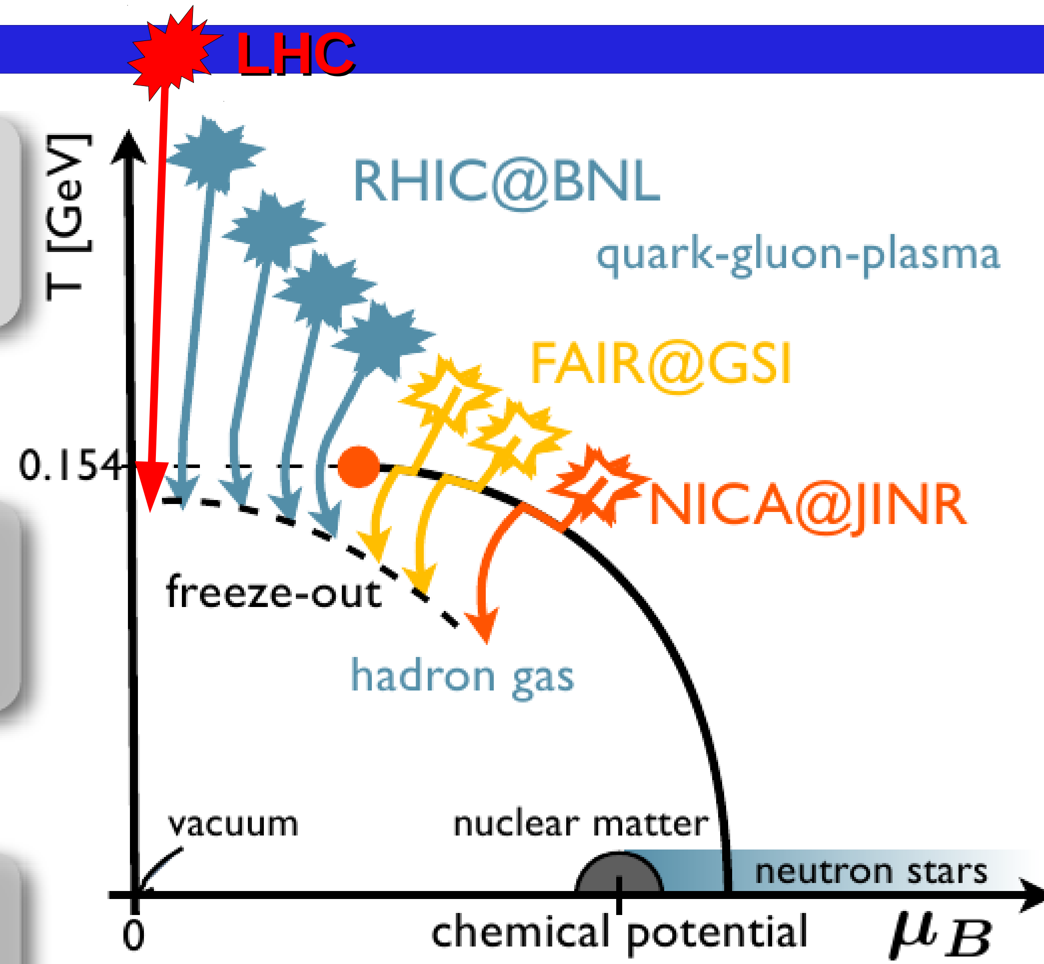
hotQCD to be published soon!!

consistent with:
S. Borsanyi et al., PL B730, 99 (2014)

improves over earlier hotQCD calculations:
Phys. Rev. D80, 014504 (2009)

Exploring the QCD phase diagram





controlled by the QCD equation of state, T_c

observable consequences: freeze-out/hadronization pattern of mesons and baryons, controlled by T_f, μ_B, μ_S

– LHC: establish contact with the QCD PHASE transition

– RHIC: establish contact with the QCD critical point

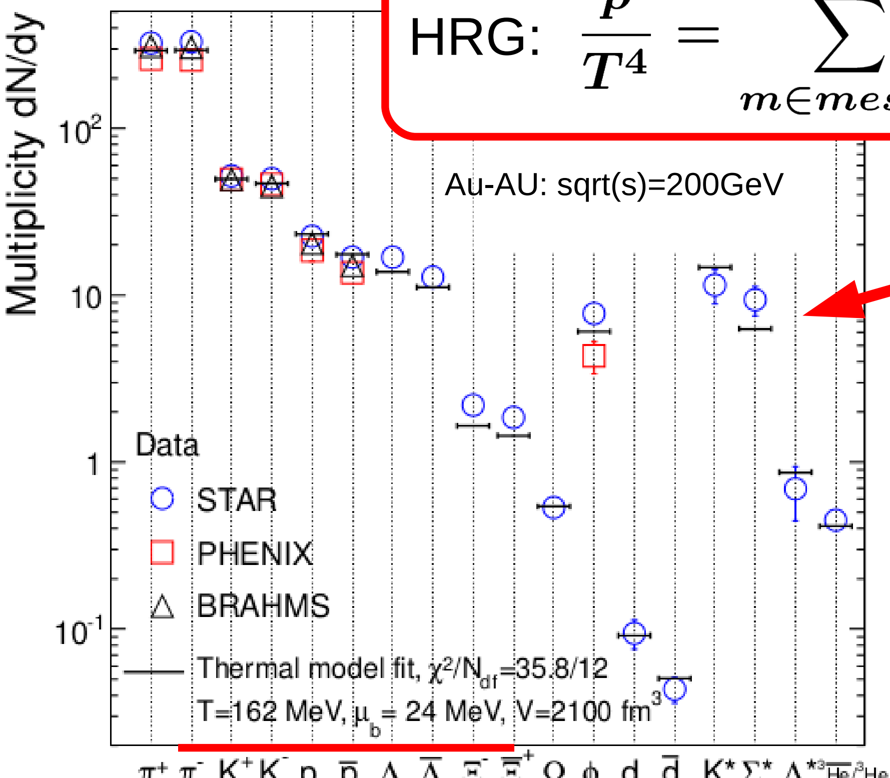
HRG model, lattice QCD and critical behavior

- **for a wide range of baryon chemical potentials freeze-out happens in or close to the QCD transition region:** predicted ➡ P. Braun-Munzinger et al., Phys. Lett. B596, 61 (2004)

caveat: freeze-out parameter extracted from experimental data by comparing to the Hadron Resonance Gas (HRG) model, i.e. not QCD

HRG: $$\frac{p}{T^4} = \sum_{m\in meson} \ln Z^b_m(T,V,\mu) + \sum_{m\in baryon} \ln Z^f_m(T,V,\mu)$$

$$\sim \mathrm{e}^{-m_H/T} \mathrm{e}^{(B\mu_B+S\mu_S+Q\mu_Q)/T}$$



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

goal: describe freeze-out in terms of QCD thermodynamics

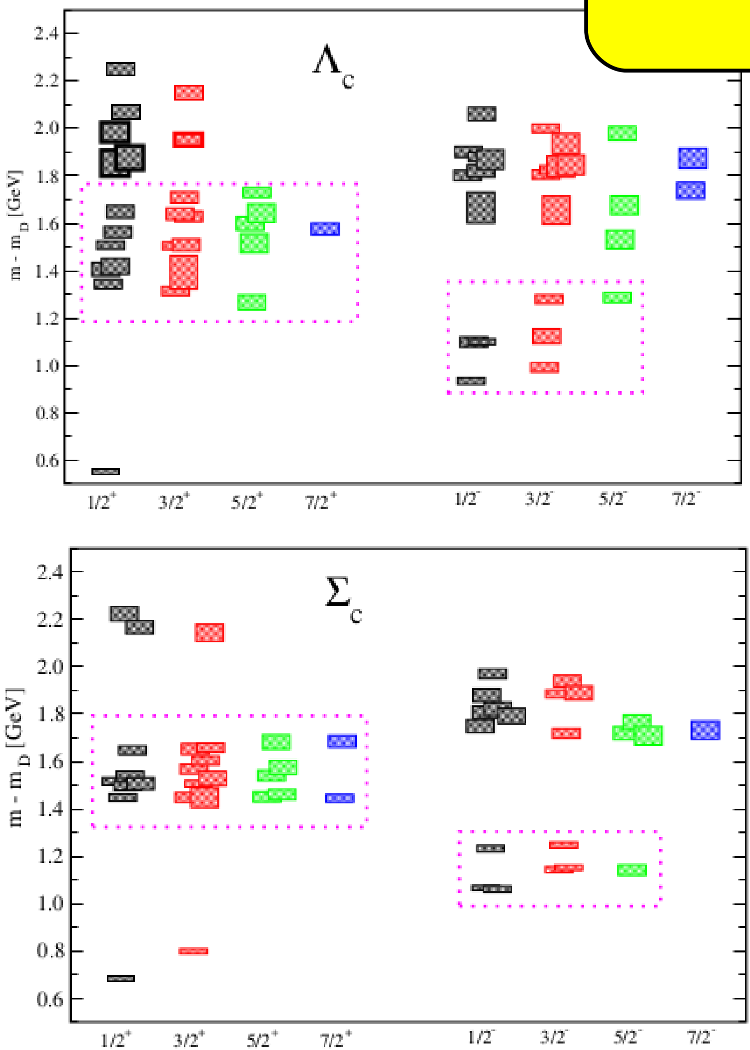
➡ freeze-out parameter from comparison of measured moments of charge fluct. with QCD calculation

BNL-Bielefeld, PRL 109, 12302 (2012)

Probing the hadron spectrum using QCD thermodynamics

$$P_{tot} = \sum_{h=\text{all hadrons}} P_h$$

Lattice QCD

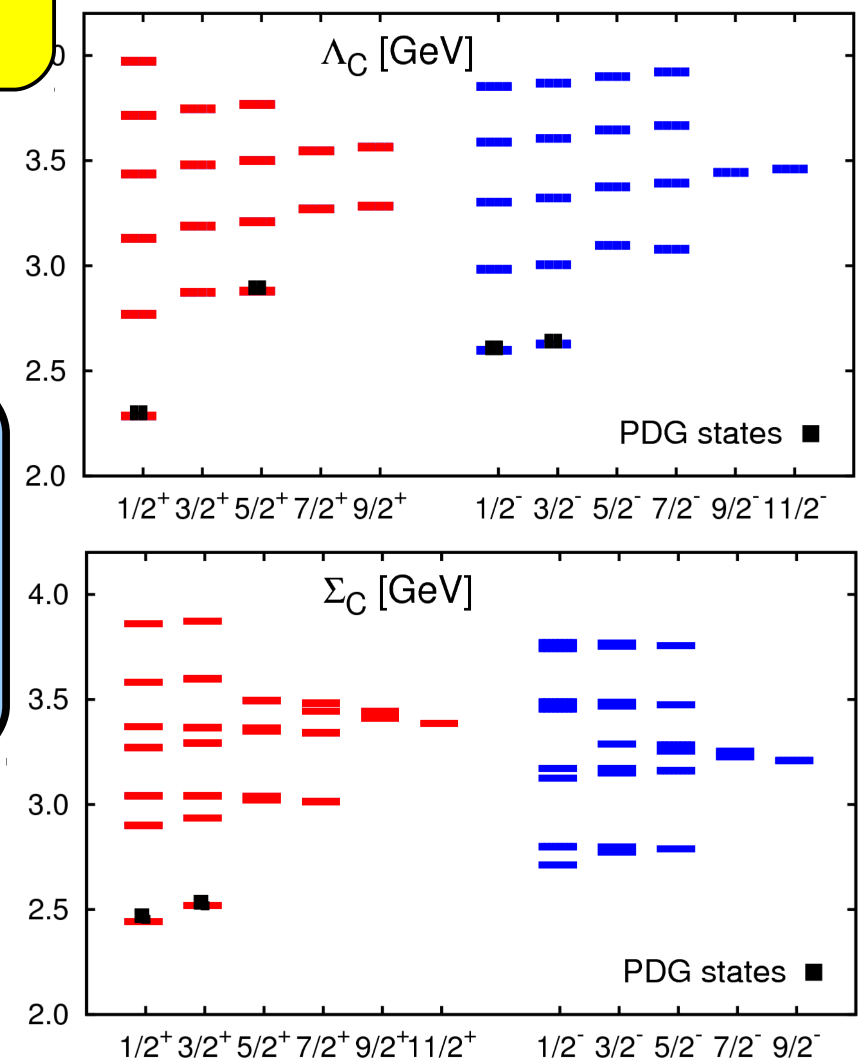


more charm

=

larger fluct.

Quark Model



M. Padmanath et.al., arXiv:1311.4806

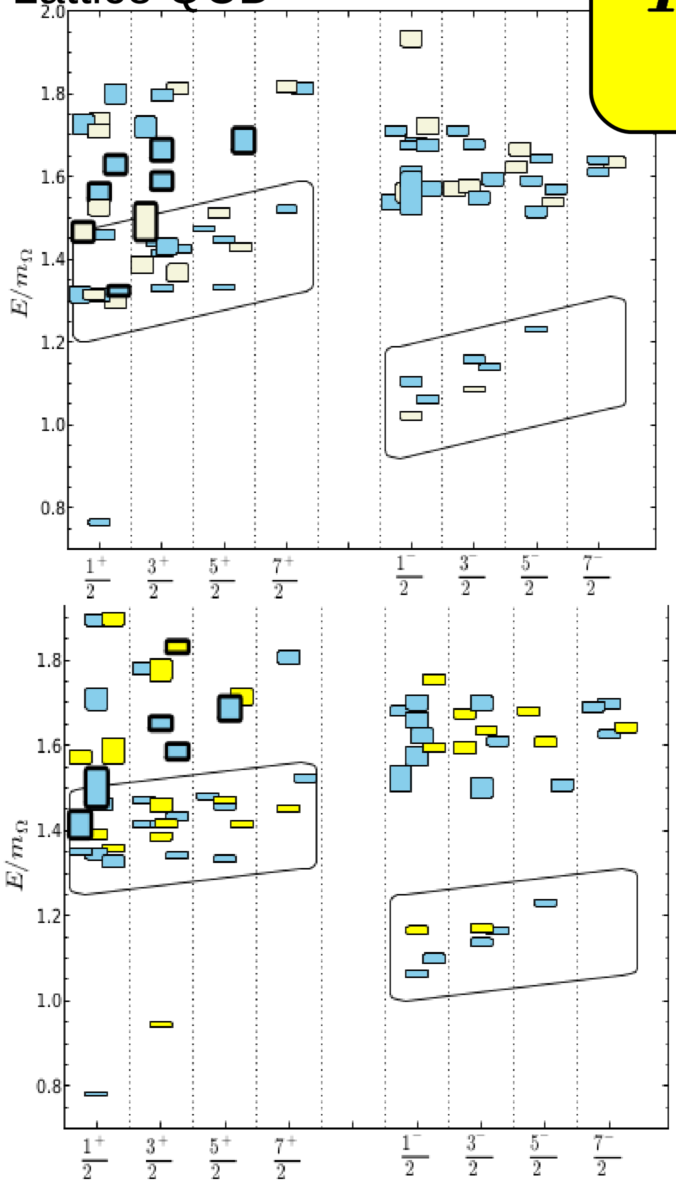
D. Ebert et. al., Eur. Phys. J. C66, 197 (2010); Phys. Rev. D84, 014025 (2011)

Probing the hadron spectrum using QCD thermodynamics

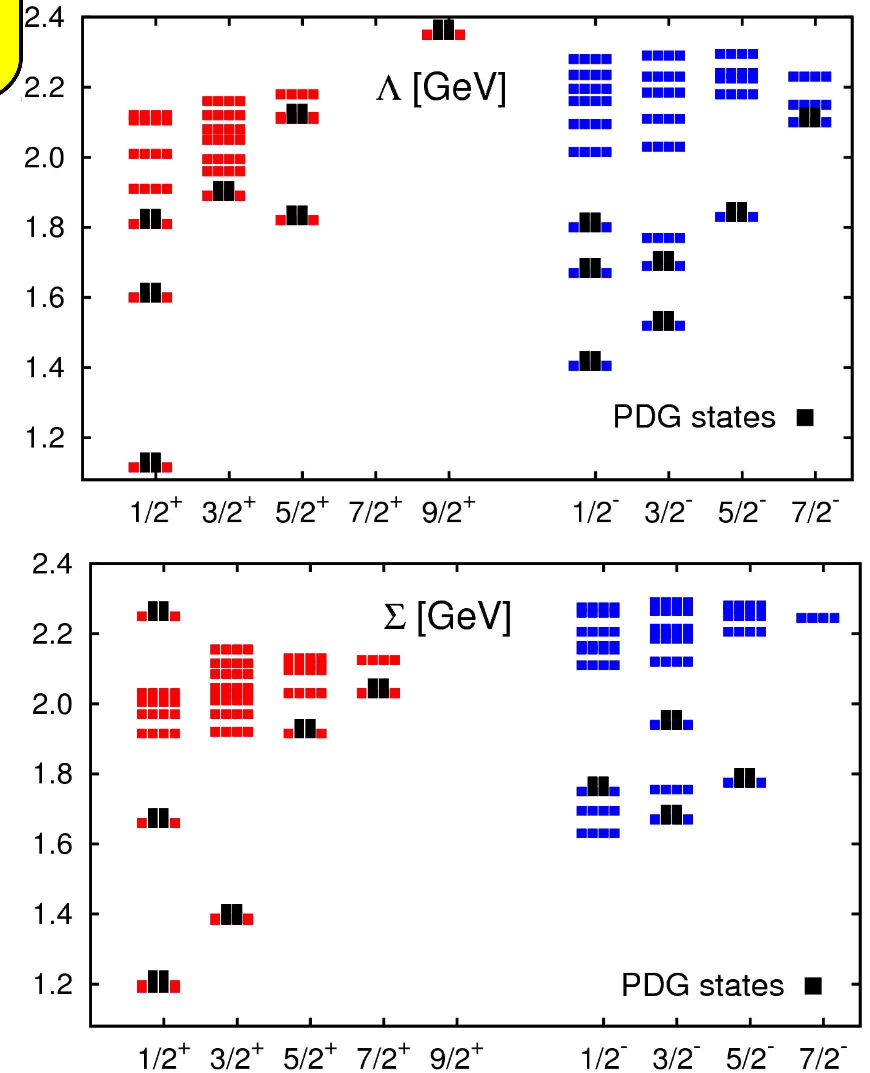
$$P_{tot} = \sum P_h$$

h=all hadrons

Lattice QCD



Quark Model



more strangeness

=

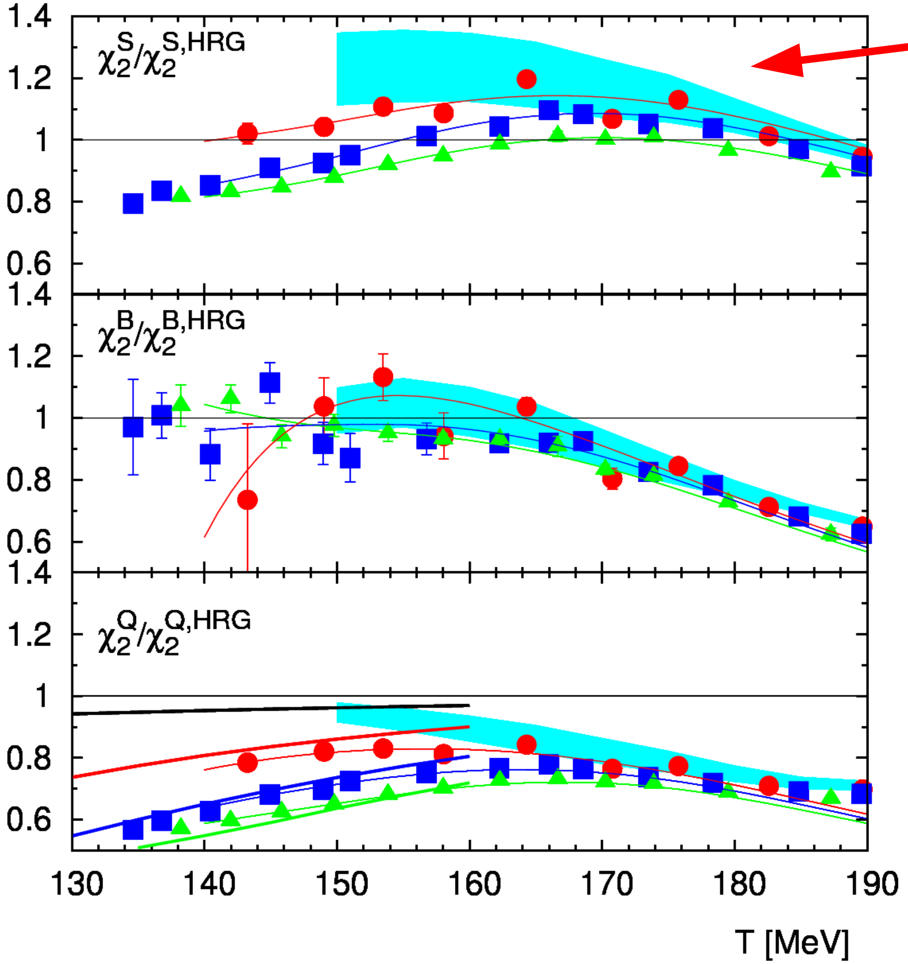
larger fluct.

R. Edwards et.al., Phys. Rev D87, 054506 (2013)

S, Capstick, N. Isgur: Phys. Rev. D34, 2809 (1986)

Hadron Resonance Gas vs. LQCD

Fluctuations and Correlations of net baryon number, electric charge, and strangeness:
A comparison of lattice QCD results with the hadron resonance gas model



O(20%) deviations from "ordinary" HRG model expectations

– continuum extrapolated results (band) for quadratic fluctuations of conserved charges

– comparison with HRG model calculations

– quantify validity range of the HRG model

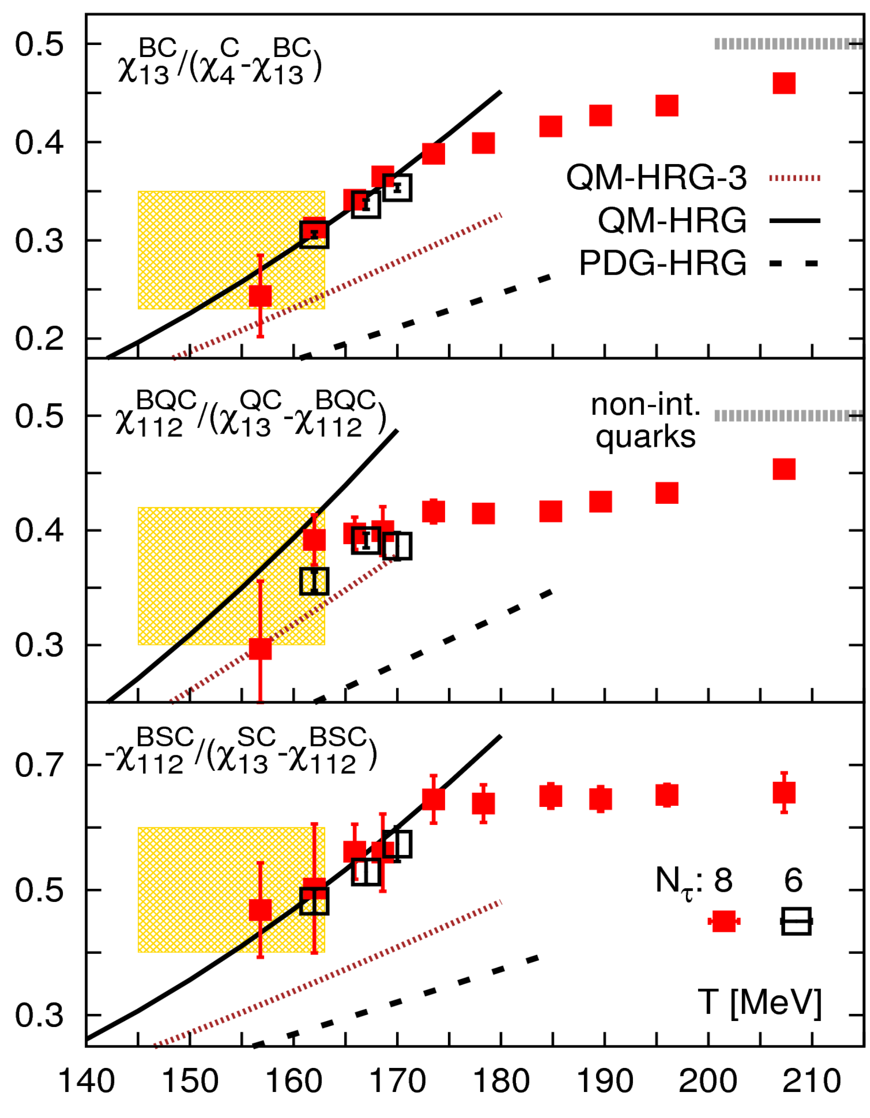
A. Bazavov et al. [HotQCD Collaboration], Phys. Rev. D 86, 034509 (2012)

Which HRG?

Hadronic fluctuations at the QCD phase transition signal change of degrees of freedom

S. Ejiri, F. Karsch, K. Redlich, Phys. Lett. B 633, 275 (2006)

Evidence for many charmed baryons in thermodynamics



A. Bazavov et al., arXiv:1404.4043

close to Tc charmed baryon fluctuations are about 50% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG)

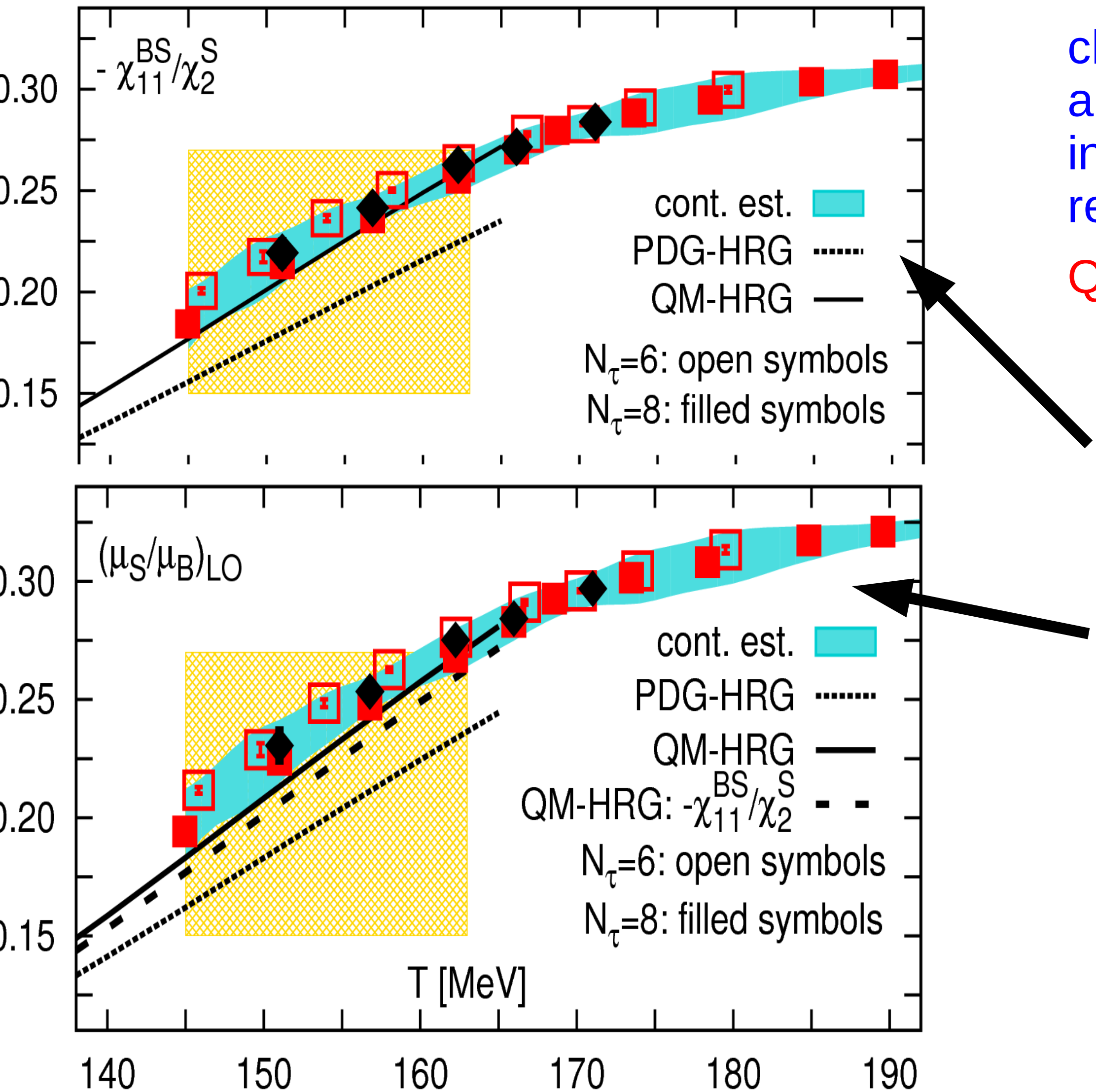
all charmed baryons/mesons

charged charmed baryons/mesons

strange charmed baryons/mesons

including resonance predicted in quark model calculations and observed in lattice QCD calculations allows for a HRG model (QM-HRG) description of lattice QCD results on conserved charge fluctuations and correlations

Evidence for more strange baryons in thermodynamics



A. Bazavov et al., arXiv:1404.6511

close to Tc charmed baryon fluctuations are about (10-20)% larger than expected in a HRG based on known charmed baryon resonances (PDG-HRG)

QM-HRG model agrees well with lattice QCD

enhanced
strangeness-baryon correlation over strangeness fluctuations

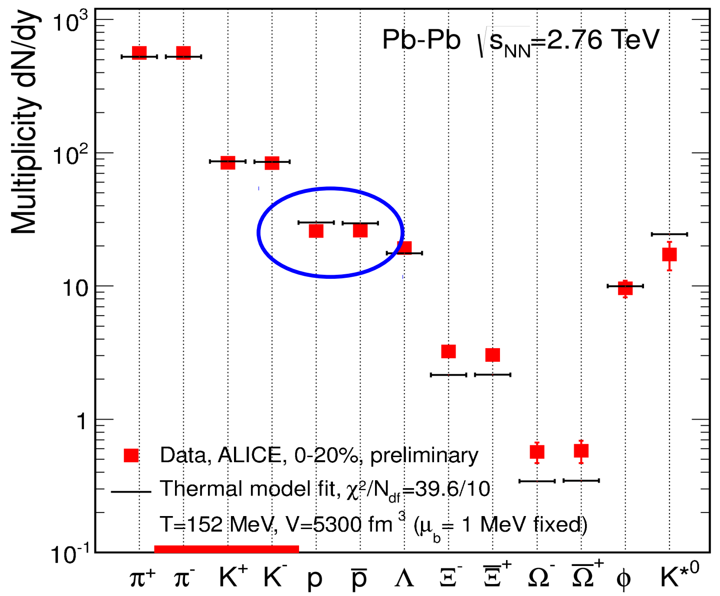
↓

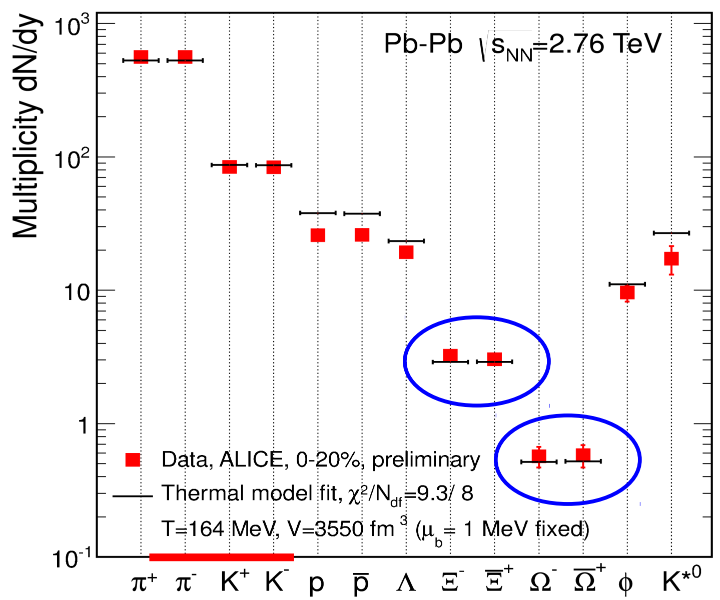
enhanced
strangeness over baryon chemical potential ratio

↓

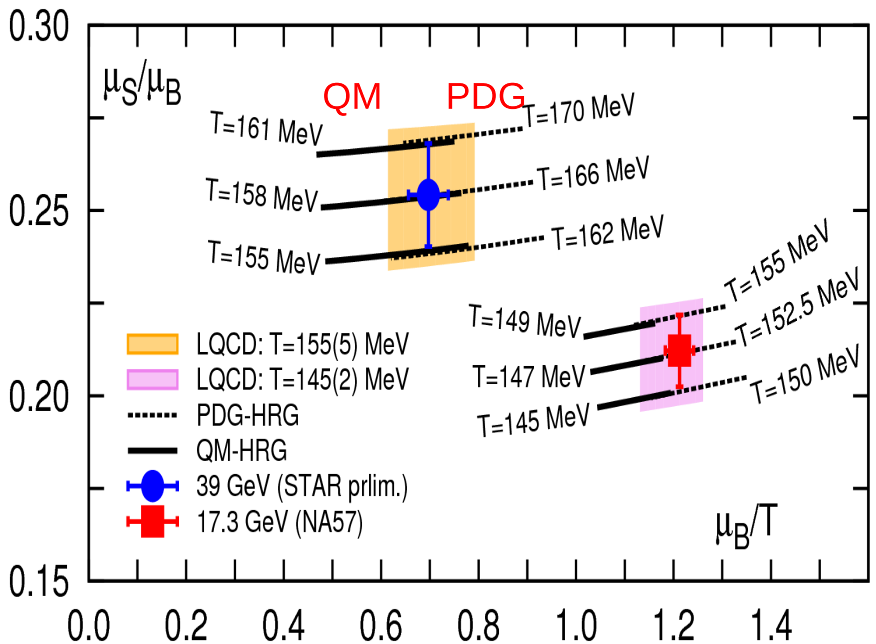
leads to the prediction of a
smaller freeze-out temperature

Impact on determination of freeze-out parameter





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



A. Bazavov et al., arXiv:1404.6511

including more strange baryons will change determination of freeze-out parameters

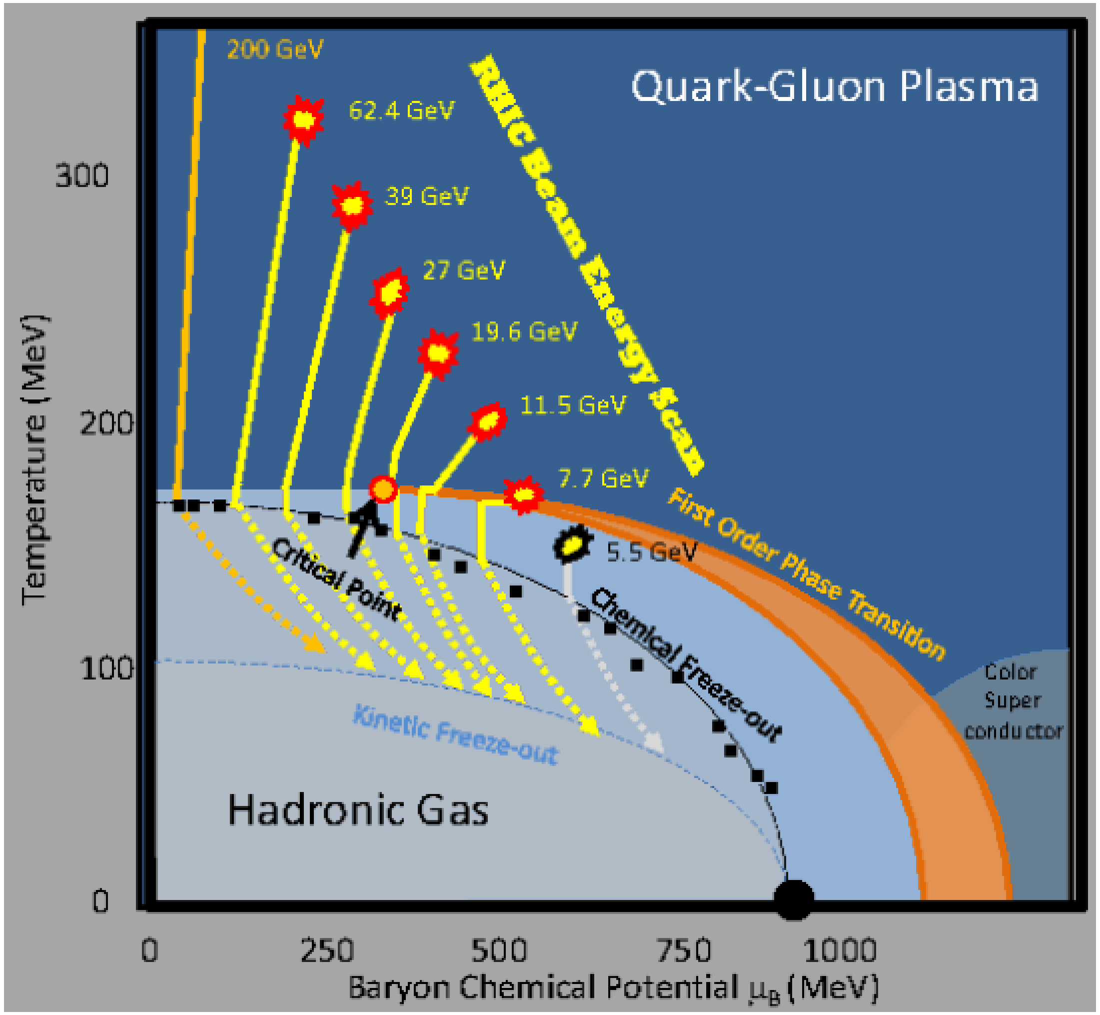
⬇

better agreement of strange and non-strange particle yields at lower freeze-out temperature

Exploring the QCD phase diagram with net charge fluctuations

RHIC beam energy scan: $\sqrt{s} = (5.5 - 200)\mathrm{GeV}/A$

search for the critical point



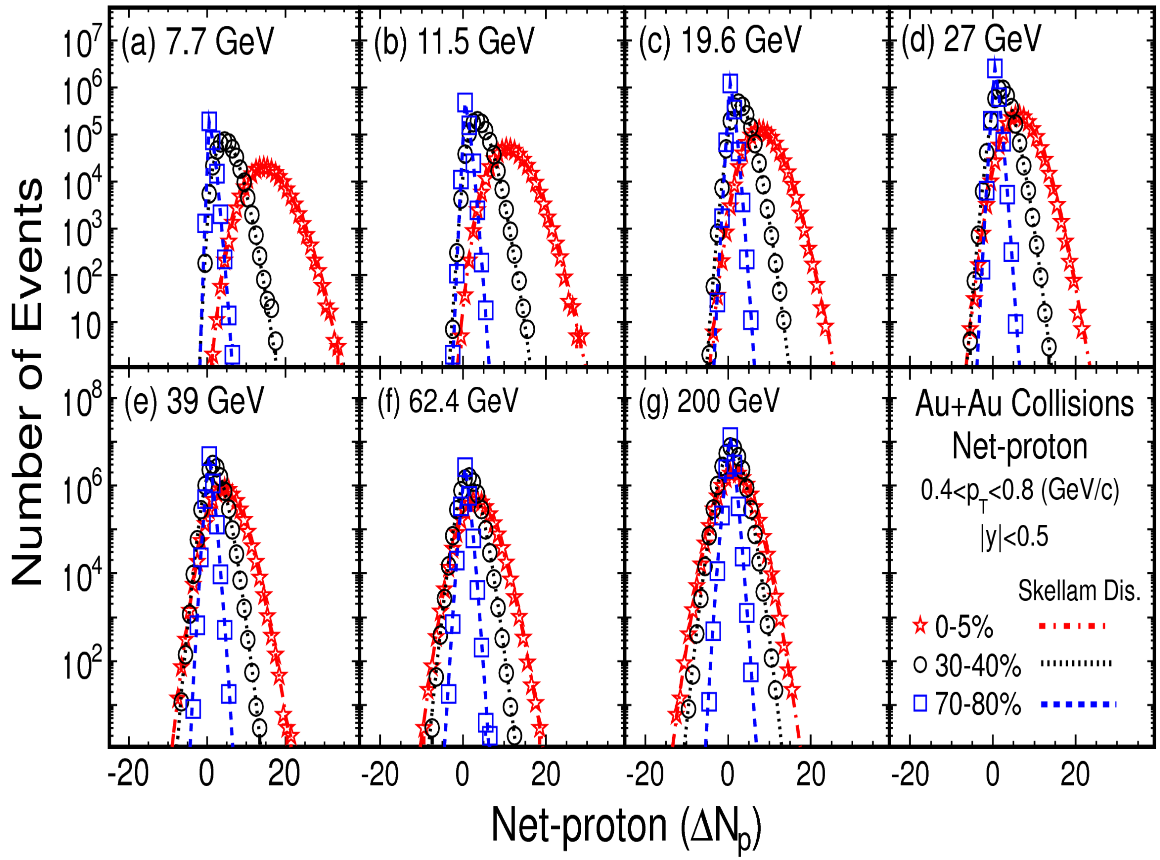
- charge fluctuations along the freeze-out line

- higher moments of charge fluctuations, e.g.

$$\chi_n^q = \frac{\partial^n p/T^4}{\partial(\mu_q/T)^n}$$

$$q = B,\ Q,\ S$$

Net proton number fluctuations at RHIC



mean $\langle \delta N_q \rangle \equiv \langle N_q - N_{\bar{q}} \rangle$

variance

$$\sigma_q^2 \equiv \langle (\delta N_q)^2 \rangle - \langle \delta N_q \rangle^2$$

skewness

$$S_q \equiv \langle (\delta N_q)^3 \rangle / \sigma_q^3$$

kurtosis

$$\kappa_q \equiv \langle (\delta N_q)^4 \rangle / \sigma_q^4 - 3$$

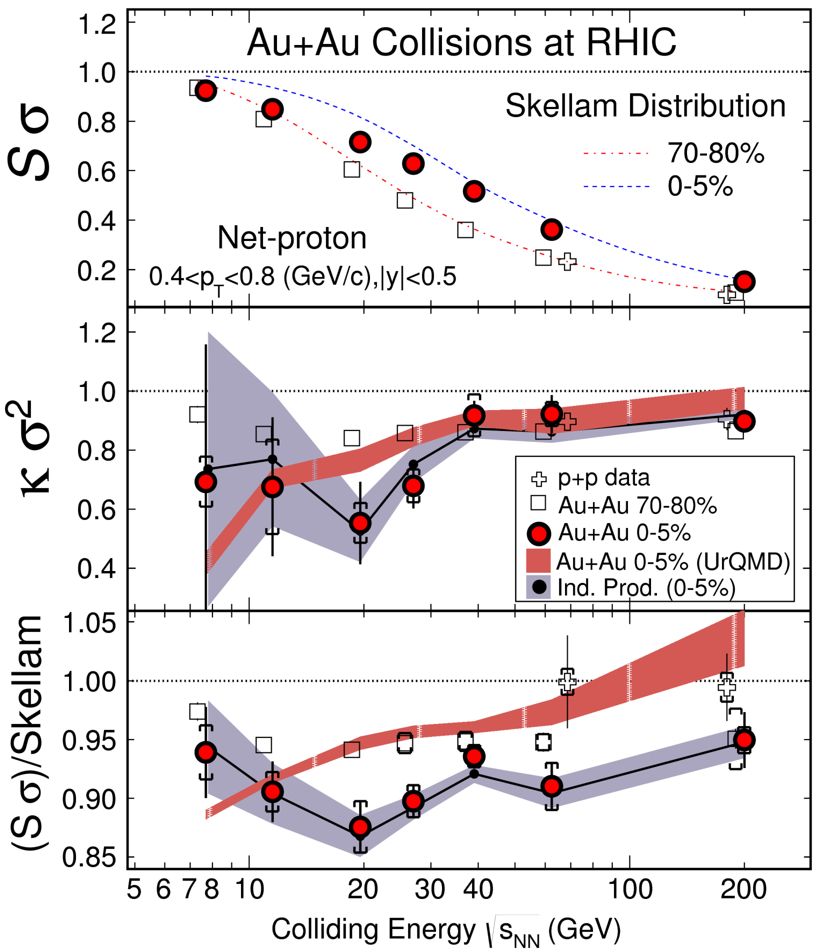
STAR Collaboration, PRL 112, 032302 (2014)

higher order cumulants characterize shape of conserved charge distributions

$$S_q \sigma_q = \frac{\chi_3^q}{\chi_2^q} \; , \; \kappa_q \sigma_q^2 = \frac{\chi_4^q}{\chi_2^q} \; \ldots \qquad \frac{S_Q \sigma_Q^3}{M_Q} = \frac{\chi_3^Q}{\chi_1^Q} \qquad \frac{M_Q}{\sigma_Q^2} = \frac{\chi_1^Q}{\chi_2^Q}$$

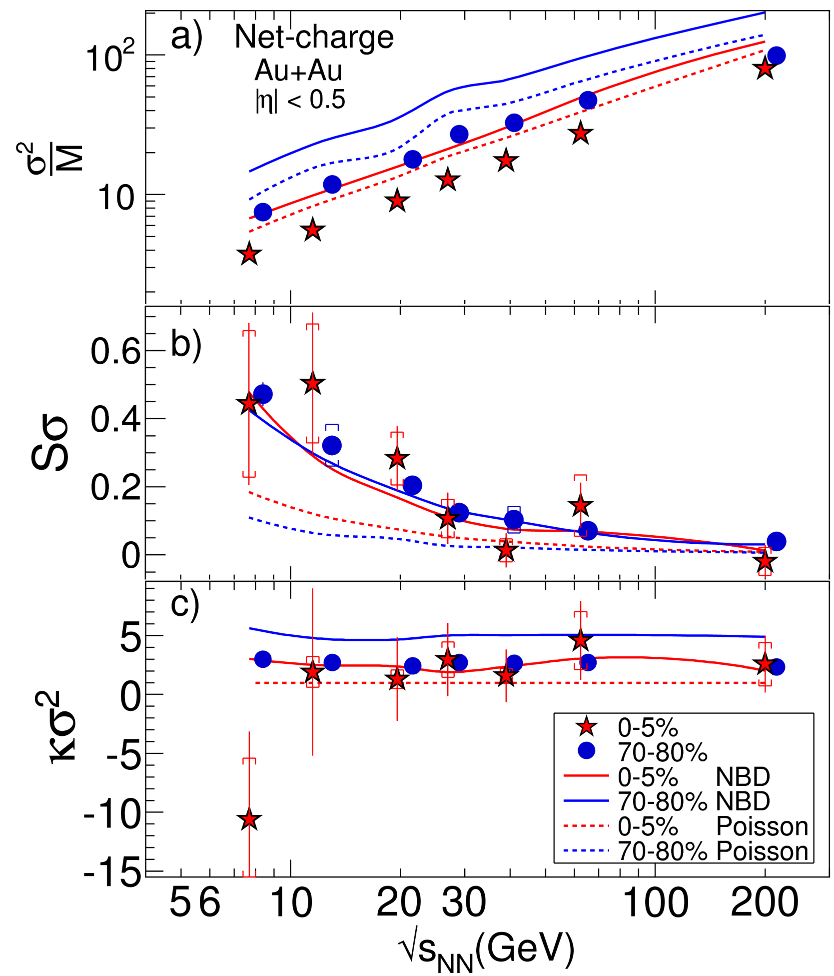
Cumulants of conserved charge fluctuations

net baryon number fluctuations



STAR Collaboration, PRL 112, 032302 (2014)

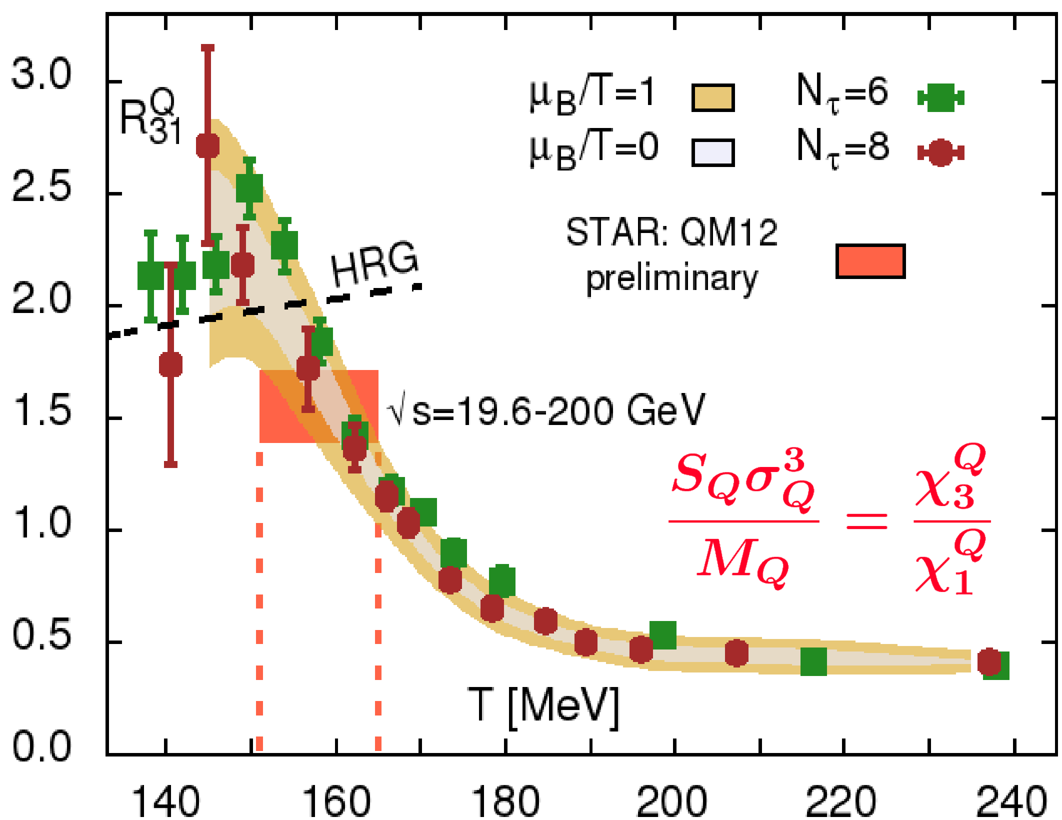
net electric charge fluctuations

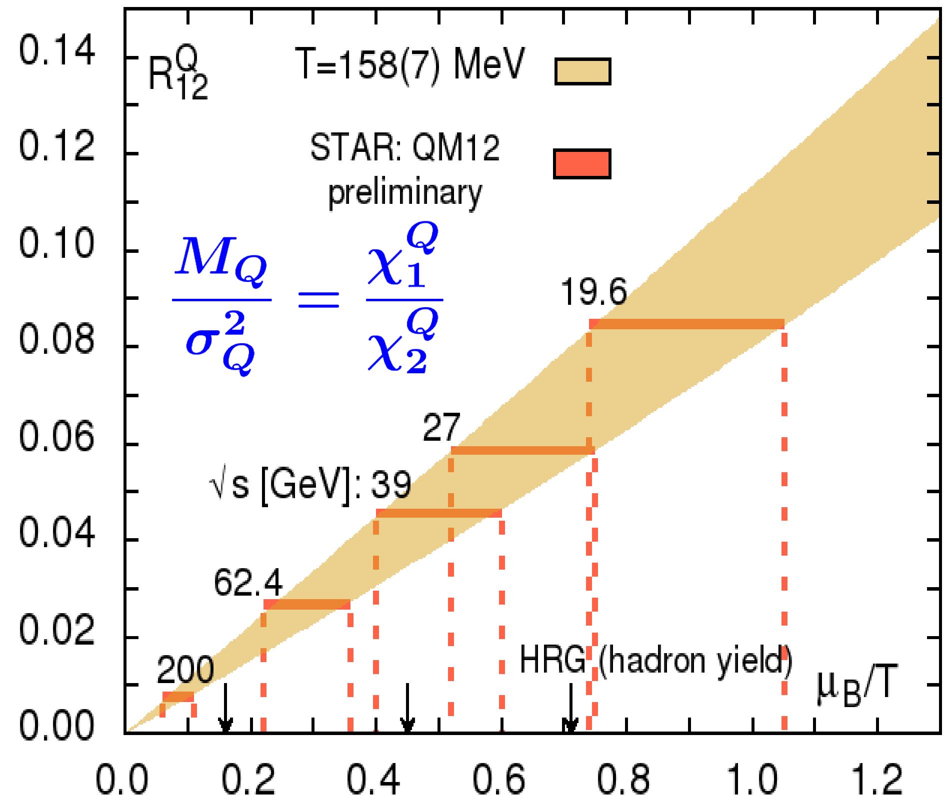


STAR Collaboration, arXiv1402.1558

Freeze-out in HIC from LQCD

net electric charge fluctuations





"thermometer": determines freeze-out temperature

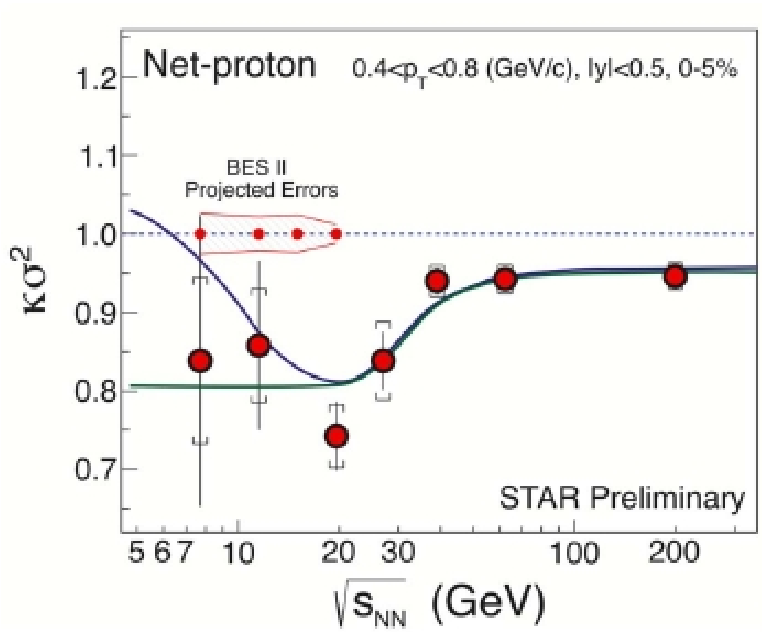
"baryometer": determines freeze-out chemical potential

T=158(7) MeV

BNL-Bielefeld: Phys. Rev. Lett. 109, 192302 (2012)
S. Mukherjee, M. Wagner, PoS CPOD2013, 039 (2013)

final data: STAR Collaboration, arXiv: 1402.1558

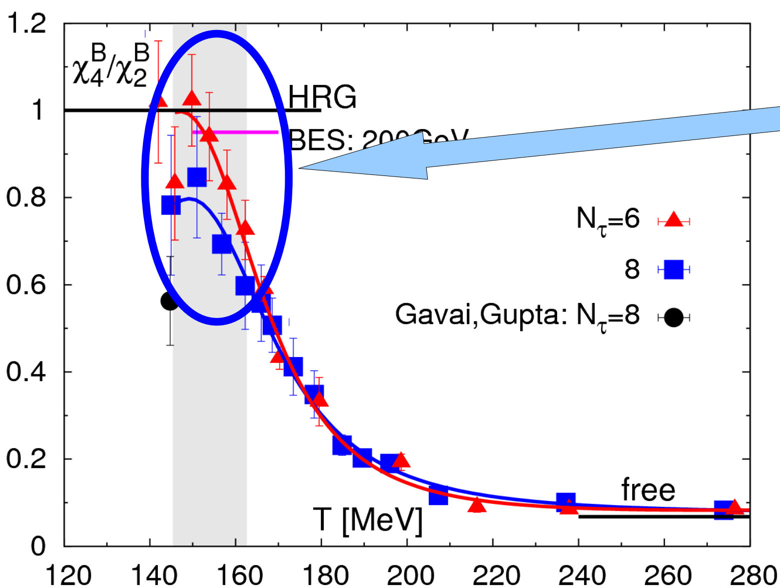
Higher order cumulants in HIC and LGT



current STAR results on net proton fluctuations and achievable accuracy in the planned BES II at RHIC

B. Mohanty, CPOD 2013

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



current & future
hotQCD focus

– should be negative close to Tc (O(4) scaling)
consistent with trend in data

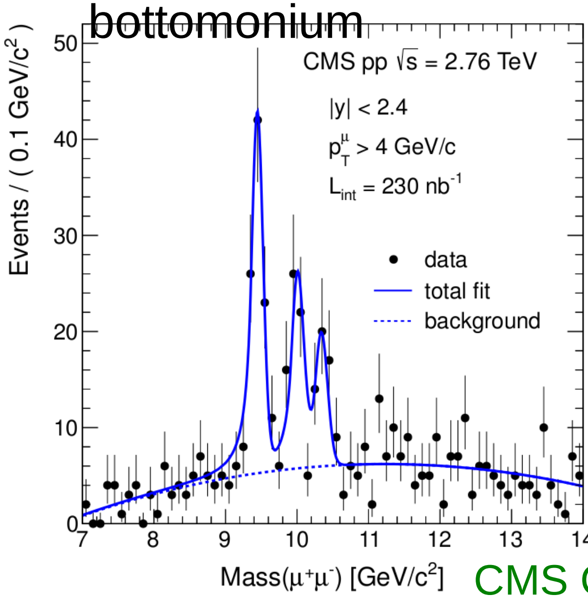
– should be large and positive at lower T to provide evidence for a critical point

LGT with HISQ action

BNL-Bielefeld, preliminary

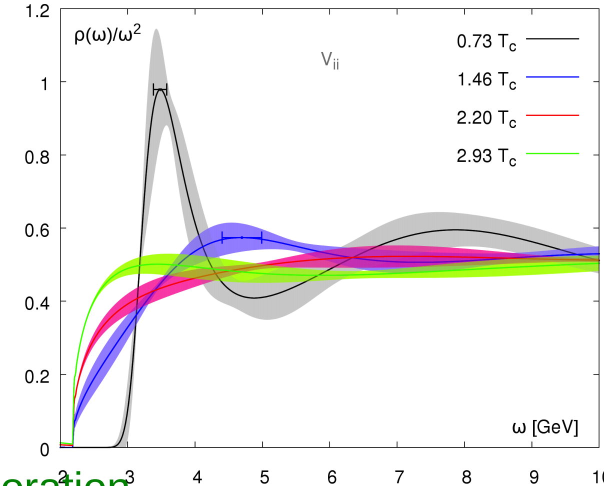
Heavy Quark spectroscopy, thermal dileptons, transport coefficients

bottomonium

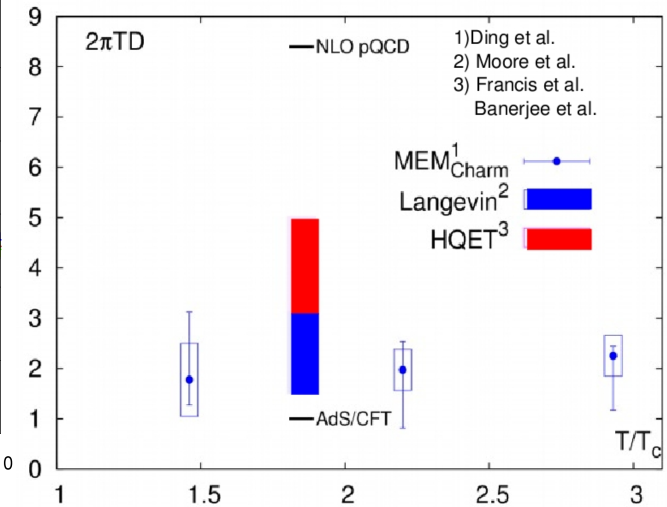


CMS Collaboration,
PRL 109, 222301 (2012)

heavy quark spectral functions

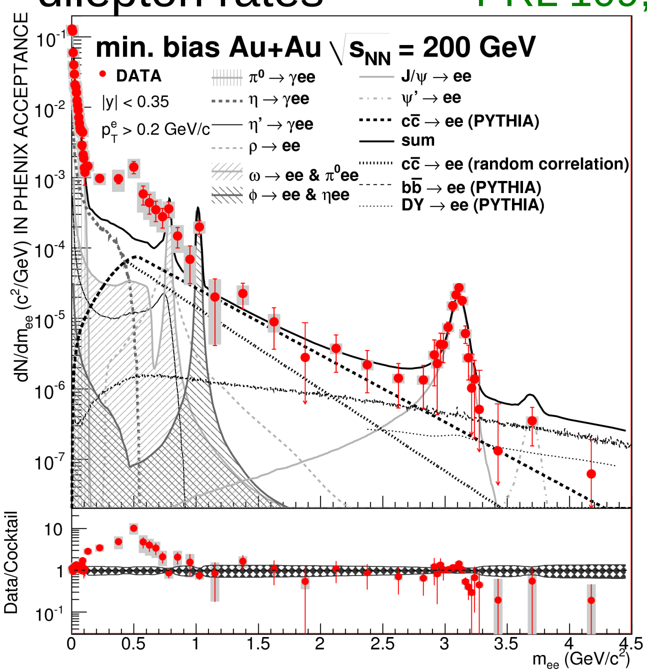


heavy quark diffusion

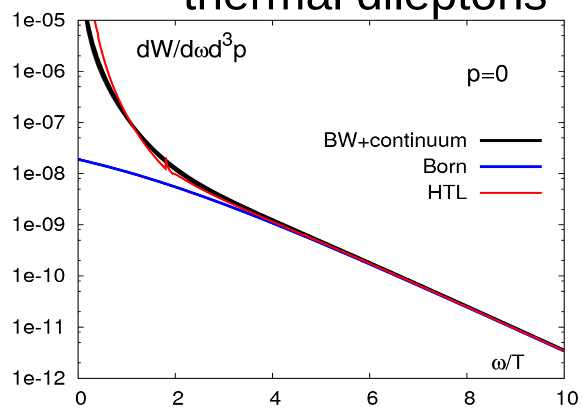


Bielefeld-BNL, PRD 86, 014509 (2012);
H.-T. Ding, arXiv:1210.5442

dilepton rates

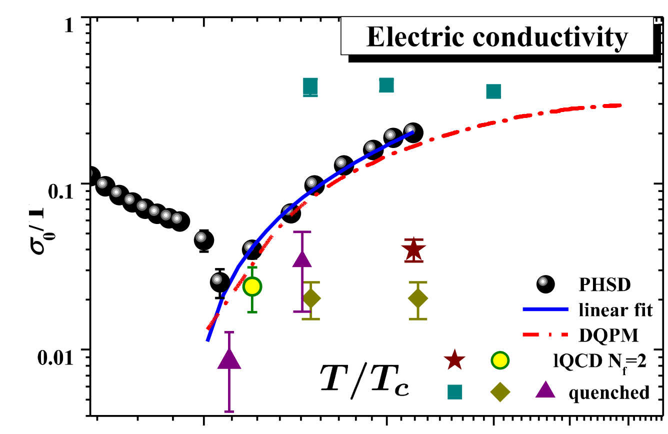


thermal dileptons



BNL-Bi, arXiv:1301.7436

A. Adare et al. (PHENIX Collaboration),
Phys. Rev. C81, 034911 (2010)



W. Cassing et al., arXiv:1302.0906

Computational requirements

Project	lattice size	no. of T's	no. of m_q's	trajecs (T, m_q)	cost [TFlop/s-years]
phase boundary at $\mu > 0$ in the chiral limit*	$(6A)^3 \times 6$, $6 \leq A \leq 12$	5	3	100,000	750
higher order cumulants of conserved charges*	$(4N_\tau)^3 \times N_\tau$, $N_\tau = 8,\ 12,\ 16$	4	1	100,000	2900
light and heavy quark spectral functions	$(4N_\tau)^3 \times N_\tau$, $N_\tau = 32,\ 48$	3	1	10,000	450
	$N_\tau = 64$	3	1	5,000	500
bulk and shear viscosities	$(3N_\tau)^3 \times N_\tau$, $N_\tau = 32,\ 48$	1	1	50,000	800
chiral transition with chiral fermions	$(8A)^3 \times 8$, $A = 6,\ 8$	5	2	10,000	500
total					5900

* predominantly calculations on GPUs

Summary of simulation parameters and cost estimates. Cost estimates are based on current experience with calculations on leadership class computers (BlueGene/Q) and GPU enhanced clusters

USQCD Thermodynamics White Paper 2013:
http://www.usqcd.org/documents/13thermo.pdf

Conclusions

- During the last 5 years LGT calculations have achieved two important goals: determination of Tc and calculation of the equation of state with physical quark masses in the continuum limit

- LGT calculations start to produce quantitative predictions on QCD thermodynamics that provide input to the interpretation of heavy ion experiments

  EoS, Tc, transport coefficients, spectral functions, phase boundary, fluctuations of conserved charges,.....

- **How sensitive is the QCD transition with physical quark masses to universal properties at the chiral phase transition?**

- **Can we provide evidence for the existence of a critical point in the energy range accessible to heavy ion experiments?**

- Fermion formulations with exact chiral symmetry (DWF, overlap) start to probe subtle aspects of QCD thermodynamics