SPC perspective on USQCD thermodynamics

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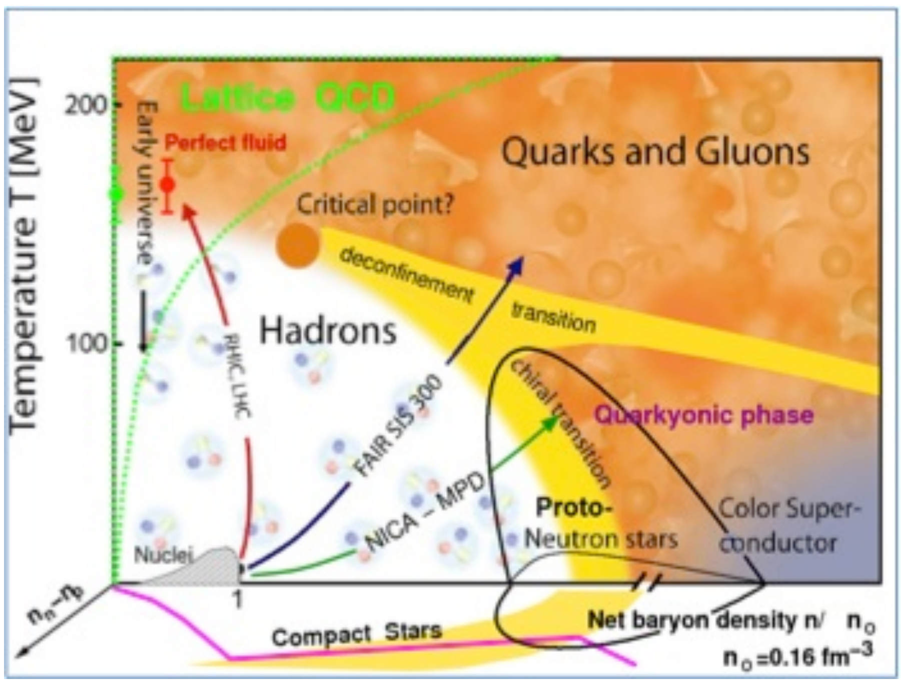
Tools : LQCD, Heavy ion experiments and phenomenology

LQCD results → models of dynamical evolution → RHIC experiments



Strategic goals outlined in 2013 White paper, "Computational Challenges in QCD Thermodynamics":

1) EoS at zero chemical potentials in the continuum limit

⇒Hydro models in HIC at top energies ✓

2) EoS at non-zero chemical potentials, fluctuations of conserved charges
⇒Freezout condition in HIC, BES@RHIC

3) Universal properties of the chiral transition, $T_c(\mu)$
Freezout condition in HIC, BES@RHIC

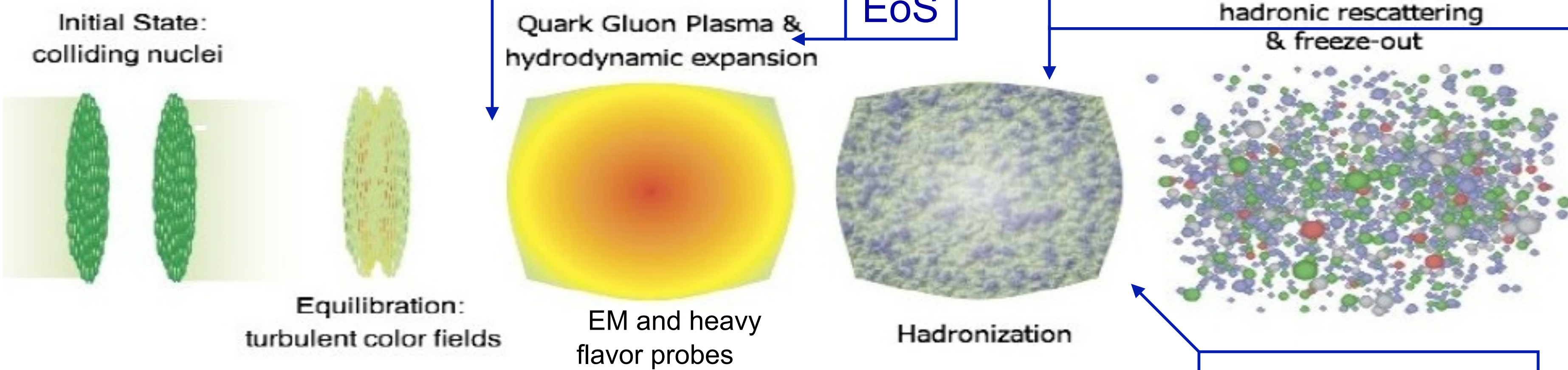
4) In-medium hadron properties
⇒dileptons/quarkonia

Physics of heavy ion collisions and LQCD

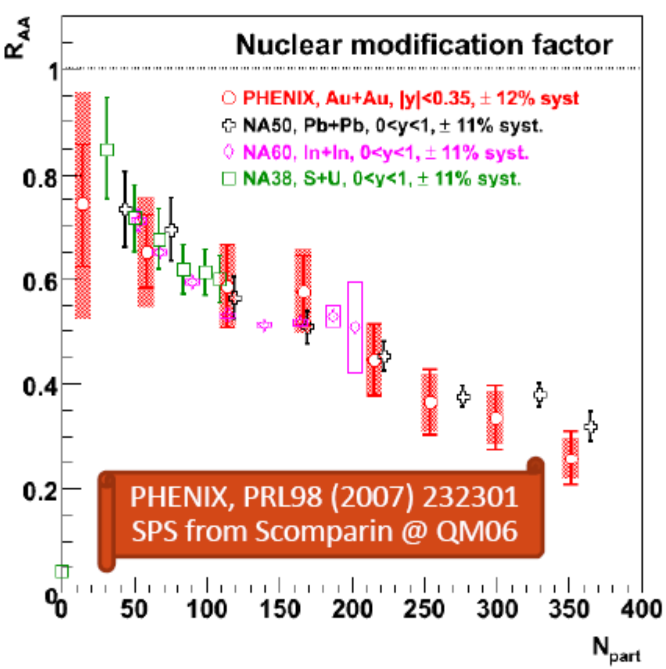
high temperature QCD
weak coupling ?

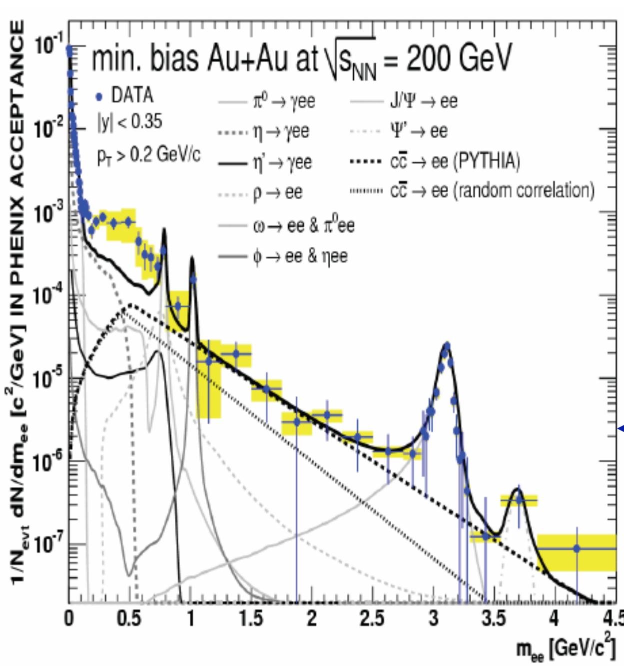
EoS

Chiral transition, T_c fluctu-
ations of conserved charges



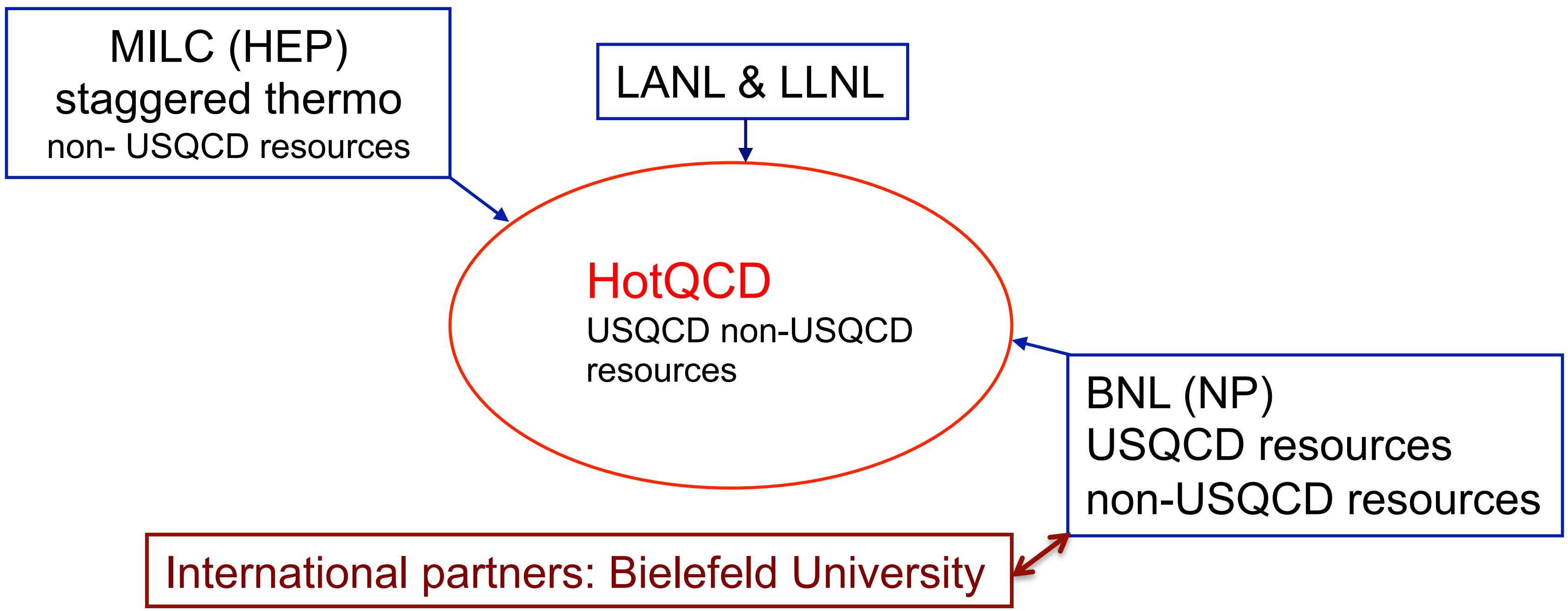
test of Hadron
Resonance Gas
(HRG)
using LQCD





quarkonium spectral
functions,
heavy quark diffusion,
thermal dileptons

Structure of thermo LQCD community and USQCD proposals



USQCD proposals in 2015 (time requested in M J/psi core h and GPU node h) :

HotQCD (PI Karsch) Fluctuations : ALCF, zero priority 20%; Titan, 62.5M (15% of INCITE)

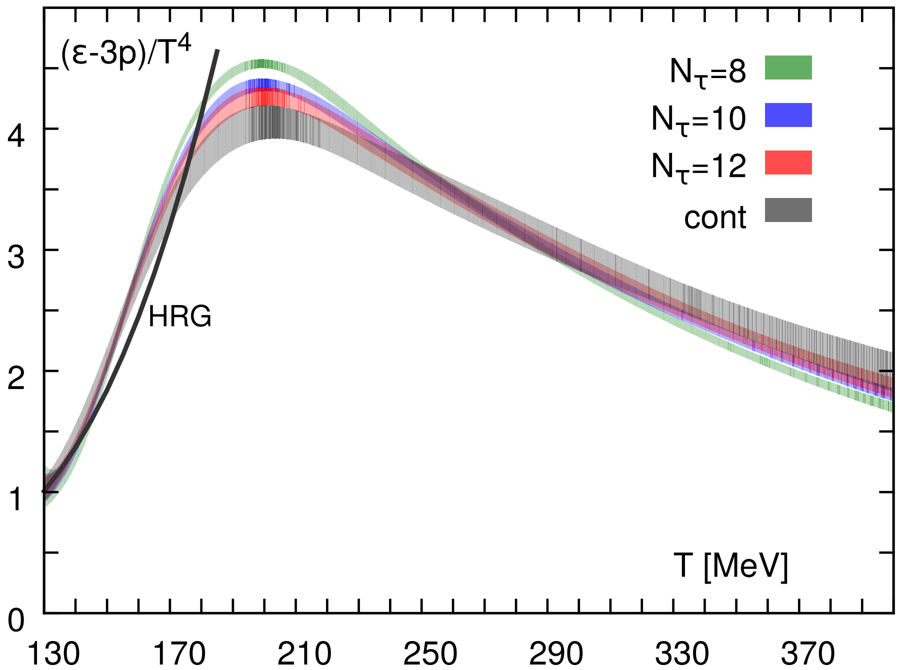
BNL (PI P. Petreczky) Transition temperature for $\mu_B>0$: Clusters, 57.3M (14%)

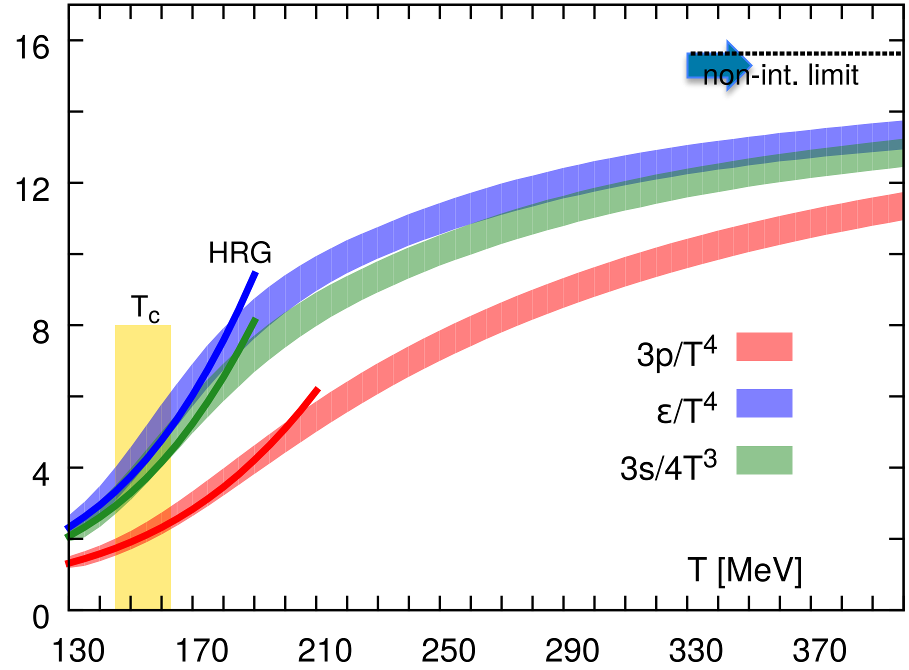
BNL (PI S. Mukherjee) EoS at $\mu_B>0$: GPUs 2.48M GPU hours (31%)

BNL (PI H.-P. Schadler) High-T QNS: Clusters, 8.67M (2%)

Equation of state at zero baryon density

Bazavov et al, PRD90 (2014) 094503





Hadron resonance gas (HRG):
Interacting gas of hadrons = non-interacting gas of hadrons and hadron resonances
(virial expansion, Prakash & Venugopalan)

HRG agrees with the lattice for *T*< *145* MeV

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

$$\epsilon_c \simeq 300\mathrm{MeV/fm}^3$$

$$\epsilon_{low} \simeq 180\mathrm{MeV/fm}^3 \leftrightarrow \epsilon_{nucl} \simeq 150\mathrm{MeV/fm}^3$$

$$\epsilon_{high} \simeq 500\mathrm{MeV/fm}^3 \leftrightarrow \epsilon_{proton} \simeq 450\mathrm{MeV/fm}^3$$

QCD thermodynamics at non-zero chemical potential

Taylor expansion :

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!l!} \chi_{ijk}^{BQS} \cdot \left(\frac{\mu_B}{T}\right)^i \cdot \left(\frac{\mu_Q}{T}\right)^j \cdot \left(\frac{\mu_Q}{T}\right)^k$$

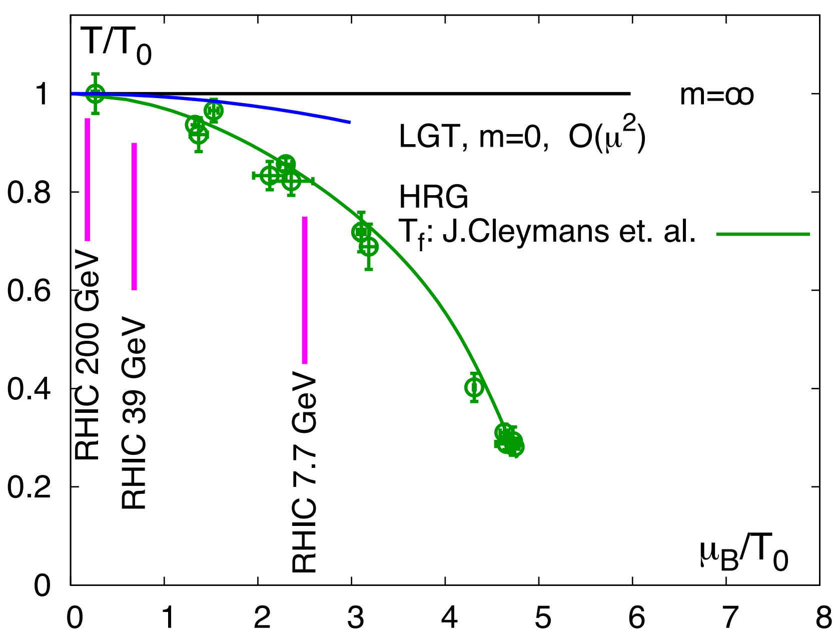
Taylor expansion coefficients give the fluctuations and correlations of conserved charges, e.g.

$$\frac{\chi_2^X}{T^2} = \frac{\chi_X}{T^2} = \frac{1}{VT^3}(\langle X^2\rangle - \langle X\rangle^2) \qquad \frac{\chi_{11}^{XY}}{T^2} = \frac{1}{VT^3}(\langle XY\rangle - \langle X\rangle\langle Y\rangle)$$

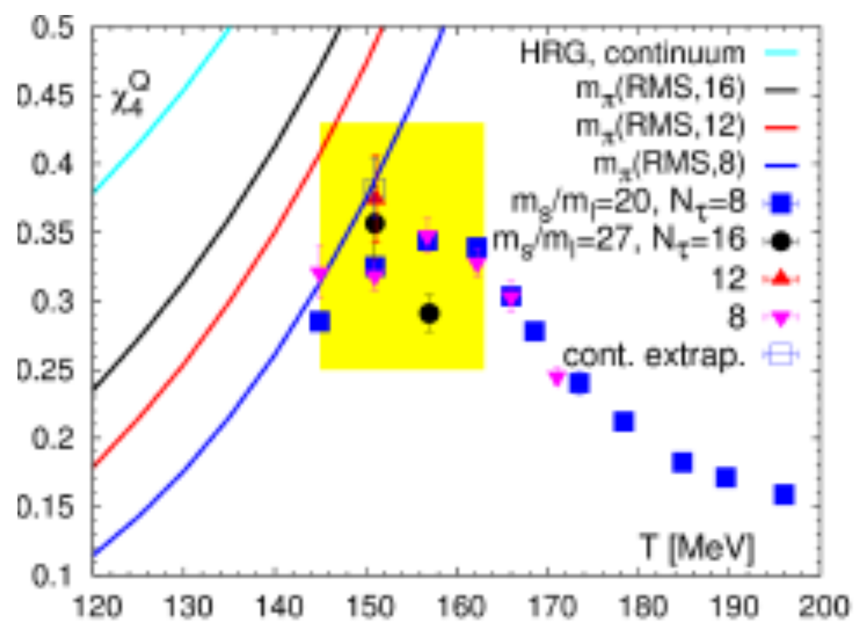
$R_{nm} = \chi_n^Q / \chi_m^Q$ ⇒ BES @ RHIC and freezout conditions

can be done very efficiently on GPUs

BNL-BI proposal (PI: PP)



HotQCD proposal (PI: Karsch)



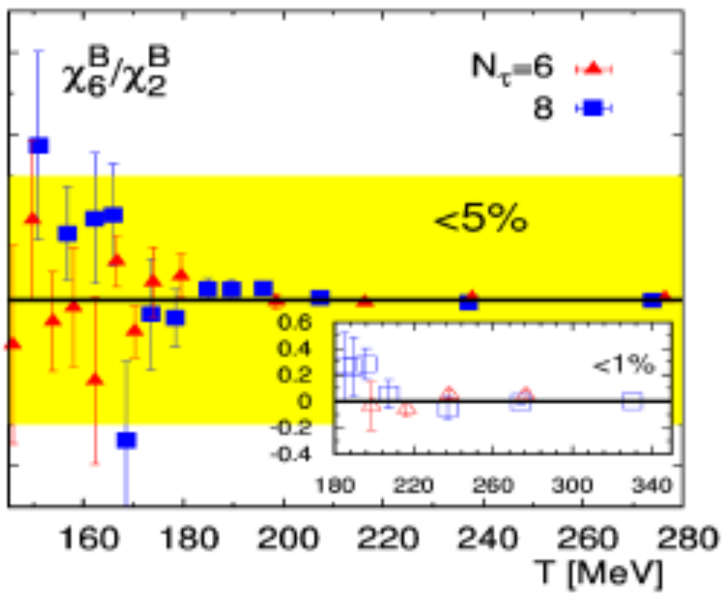
Need large N_τ

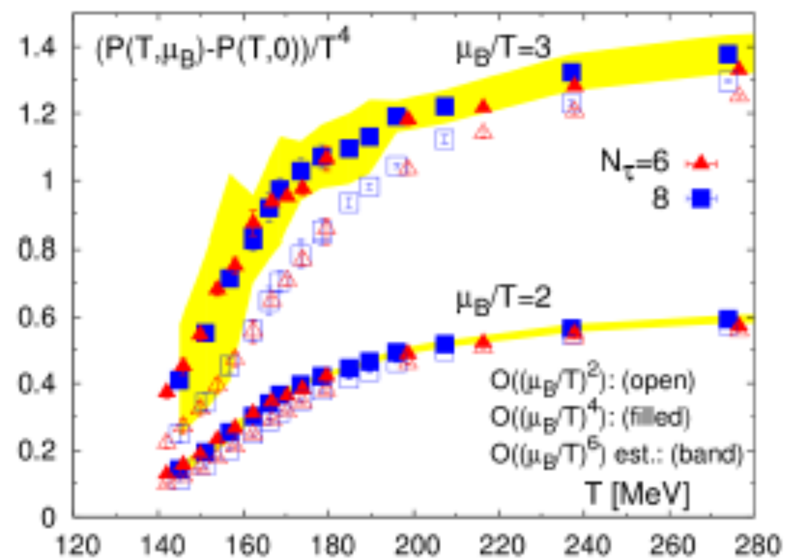
Equation of state at zero baryon density

Proposal by BNL-BI (PI:Mukherjee)

$$\frac{\Delta(T,\mu_B)}{T^4} = \frac{P(T,\mu_B)-P(T,0)}{T^4} = \frac{\chi_2^B}{2}\left(\frac{\mu_B}{T}\right)^2\left(1+\frac{1}{12}\frac{\chi_4^B}{\chi_2^B}\left(\frac{\mu_B}{T}\right)^2\right)$$

estimating the $\mathcal{O}((\mu_B/T)^6)$ correction: $\sim \frac{1}{720}\frac{\chi_6^B}{\chi_2^B}\left(\frac{\mu_B}{T}\right)^6$



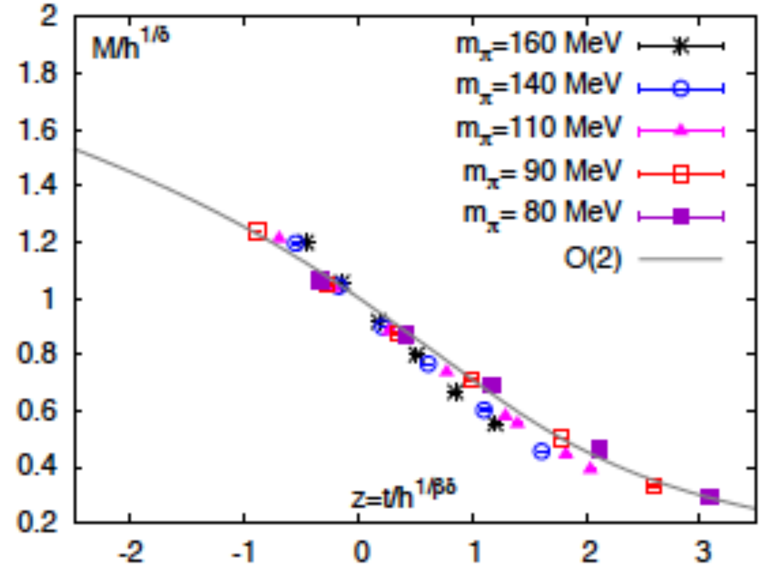


The EoS is well controlled for $\mu_B/T \leq 2$

Need high statistics but can be done for smaller N_τ

What is the transition temperature ?

Zero net baryon density, HotQCD:
Bazavov et al, Phys. Rev. D85 (2012) 054503



$$M_b = \frac{m_s\langle\bar{\psi}\psi\rangle_l}{T^4} = h^{1/\delta} f_G(t/h^{1/\beta\delta}) + f_{M,reg}(T,H)$$

$$H = m_q/m_s,\ \ h = H/h_0,\ \ t = (T-T_c)/T_c/t_0$$

$$T_c = (154 \pm 8 \pm 1(scale))\text{MeV}$$

Non-zero baryon density: $t = \frac{1}{t_0}\left(\frac{T-T_c}{T_c} + \sum_{i,j}\frac{\mu_i\mu_j}{T}\right)$

$$\frac{T_c(\mu_q,\mu_s)}{T_c(0)} = 1 - \kappa_q\left(\frac{\mu_q}{T}\right)^2 - \kappa_{qs}\frac{\mu_q}{T}\frac{\mu_s}{T} - \kappa_s\left(\frac{\mu_s}{T}\right)^2 + \mathcal{O}\left(\left(\frac{\mu_q}{T}\right)^4\right)$$

Curvature parameters are determined by the mixed susceptibility and scaling relation

$$\frac{\chi_{q,\mu,n}}{T} = \frac{\partial^2\langle\bar{\psi}\psi\rangle_l/T^3}{\partial(\mu_q/T)^n(\mu_s/T)^{2-n}} = \frac{KT}{t_0 m_s} h^{(1/\delta-1/\beta\delta)} f'_G(z) \qquad K = 2\kappa_q, \kappa_{qs}, \kappa_s$$

Current estimates of the curvature do not agree:

0.059(5) (p4, scaling, BI-BNL, 2010), *0.059(18)* (stout, Taylor, WB2011),

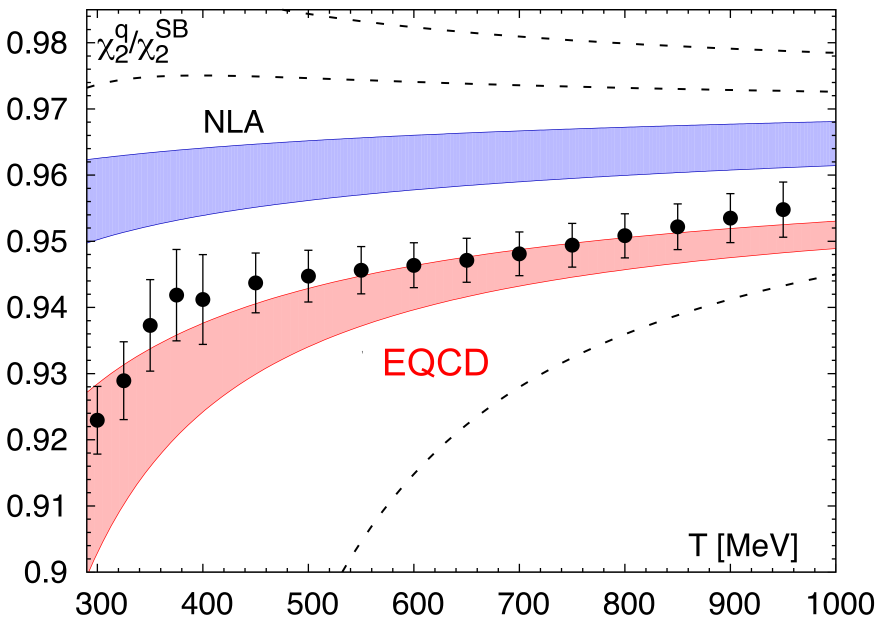
0.162(4) (HISQ, imag. *μ*, Cea et al, 2014), *0.117(27)* (stout, imag. *μ*, Bonatti et al)

Phenomenological Freezout curve: ~ 0.21(2)

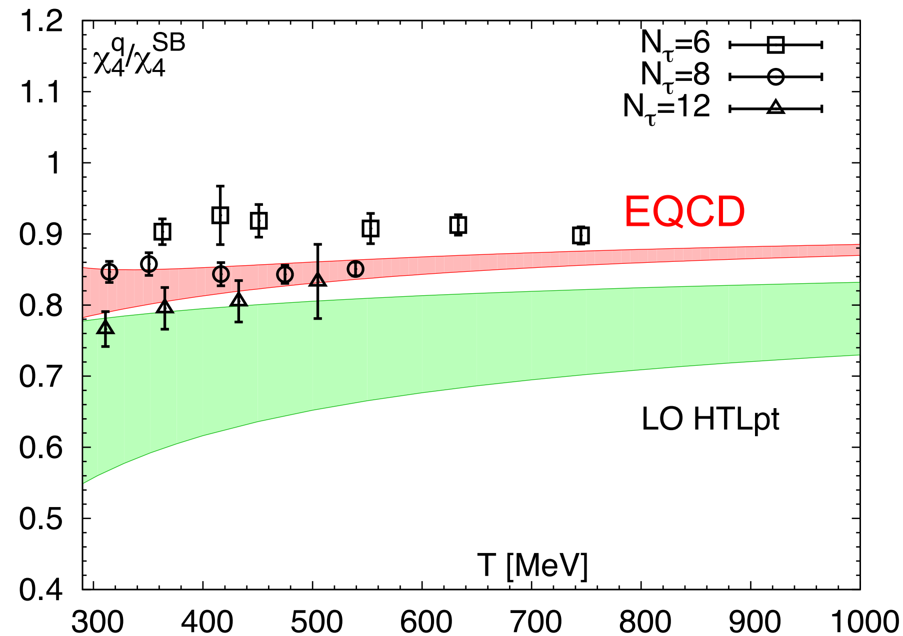
Quark number fluctuations at high T

At high temperatures quark number fluctuations can be described by weak coupling approach due to asymptotic freedom of QCD

2nd order quark number fluctuations



4th order quark number fluctuations



Bazavov et al, PRD88 (2013) 094021

- Good agreement between lattice and the weak coupling approach for 2nd order quark number fluctuations
- For 4th order no continuum results => proposal by Schadler

In-medium meson properties

No proposals this year on but progress is being made using configurations generated by HotQCD are being used for study meson spectral functions:

Bazavov et al, Phys.Rev. D91 (2015) 5, 054503

Bazavov, Burnier, PP, arXiv:1404.4267

Kim, PP, Rothkopf, Phys.Rev. D91 (2015) 054511

Conclusions

Lattice QCD starts to provide quantitative results that provide important input for interpreting the experimental results from HIC

Main focus:
T_c, EoS, fluctuation of conserved charges at non-zero baryon density
=> RHIC BES II program

SPC: When the results are needed ?

They were due yesterday ! BES II is likely to happen in 2019/2020, phenomenological modeling is in progress and need input from lattice QCD now

⇒ BEST Topical Collaboration (PI : S. Mukherjee)

In-medium meson properties (some progress)
Relevant for heavy flavor program at RHIC
(STAR upgrade, sPHENIX, ALICE, CMS)
⇒ Topical Collaboration for Heavy Flavor Probes of QGP
(PI : R. Rapp, co-PI, P. Petreczky)