Freeze-out Conditions from Lattice QCD

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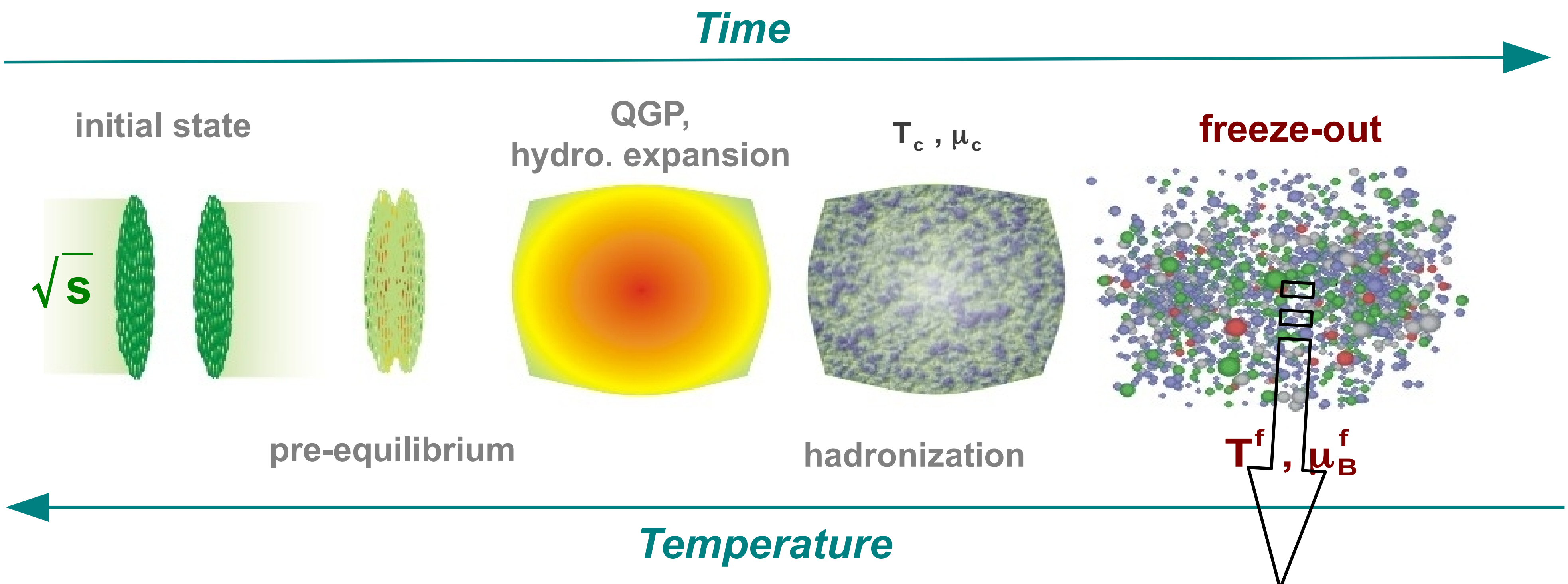
Quark Matter 2012, Washington D.C.

Chemical freeze-out condition in HIC



$\left(T^f, \mu_B^f, \mu_Q^f, \mu_S^f\right)$

by comparing hadron yields from HIC expt.

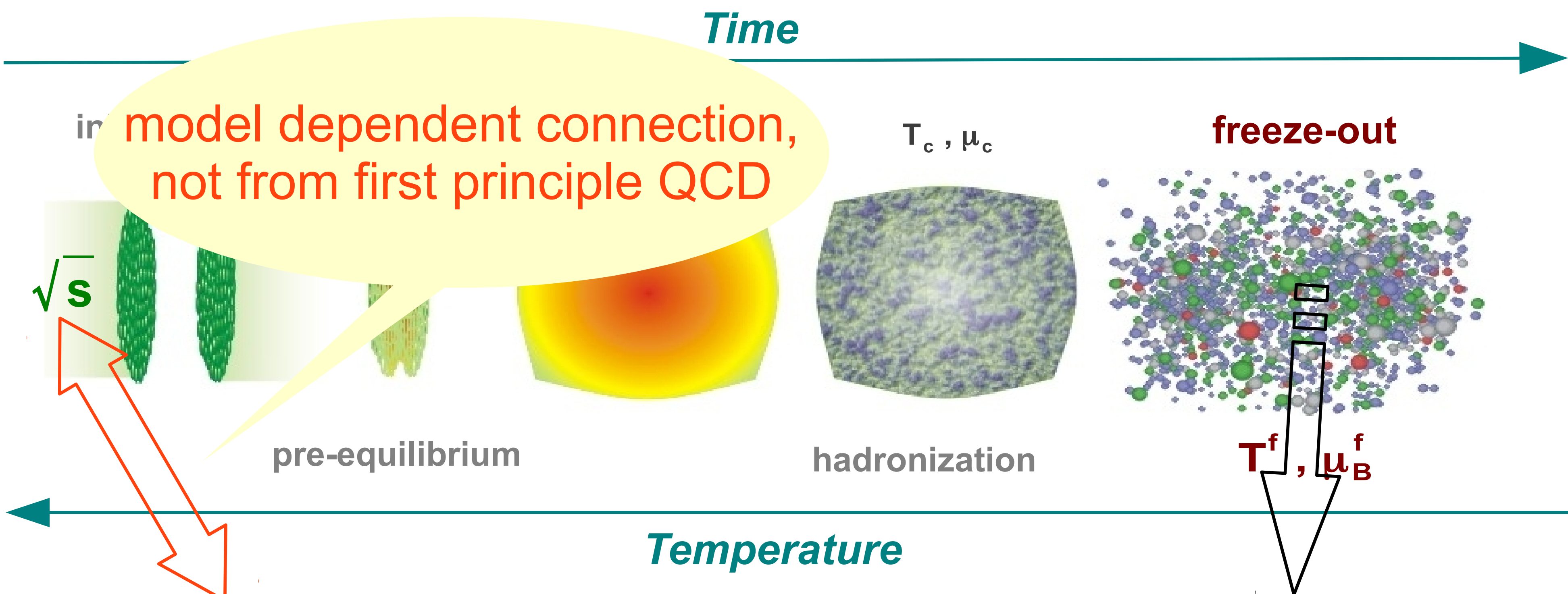
statistical / thermal / hadron resonance gas (HRG) model

thermalized, non-interacting hadrons & resonances

chemical freeze-out

no inelastic scattering, hadron abundances unchanged (freezes-out), chemical equilibration

Chemical freeze-out condition in HIC



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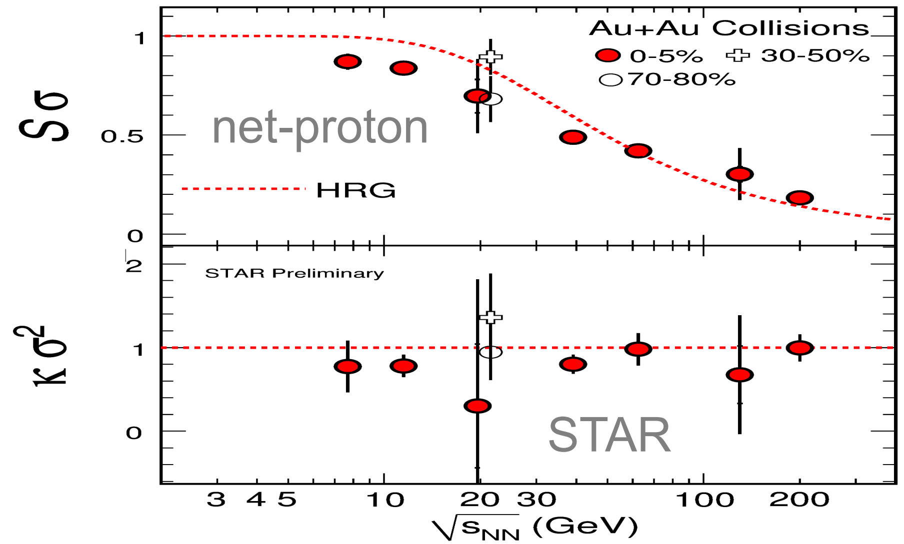
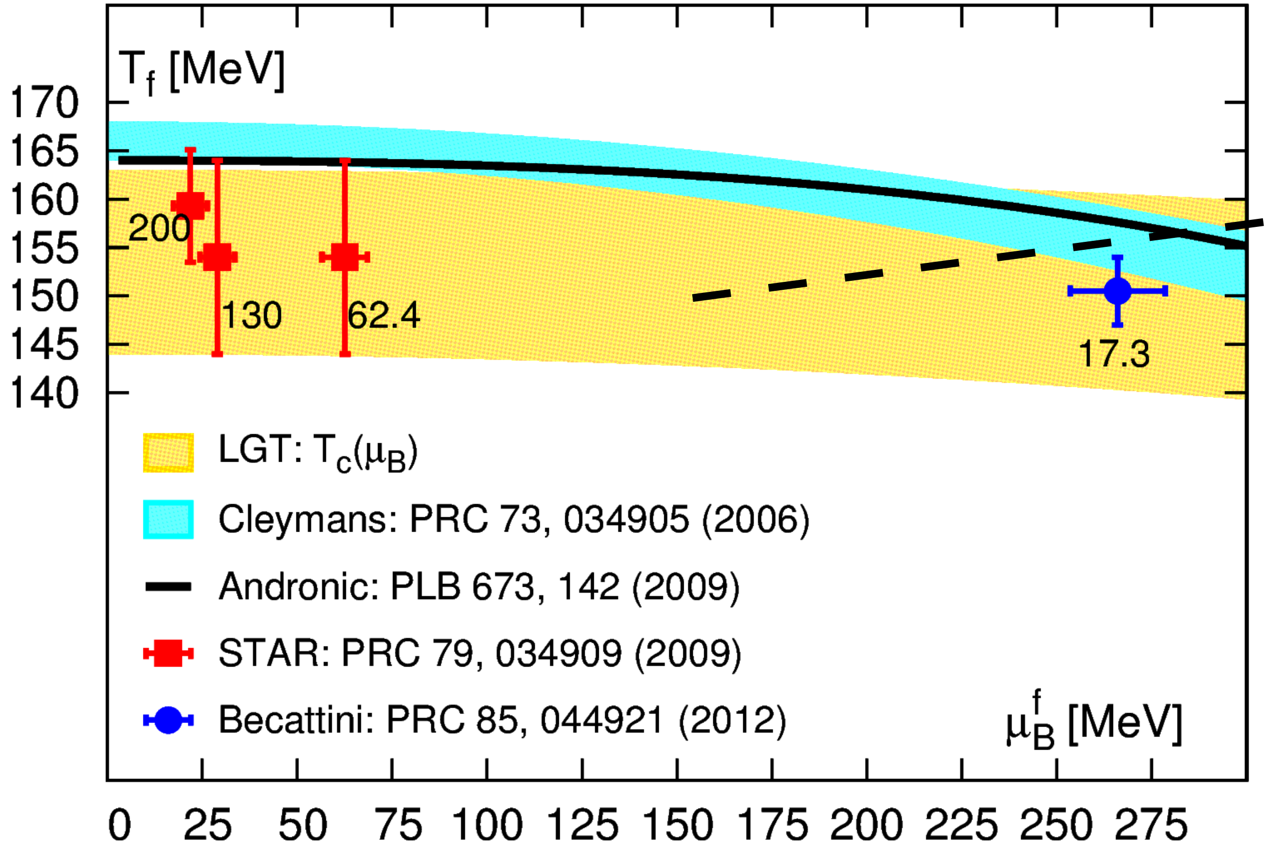
Search for QCD critical point in RHIC BES

fluctuations of conserved charges

net-proton, net-charge, ...

characterize the chemical freeze-out condition





LQCD: $T_c(\mu_B)$

QCD critical point will be situated somewhere along this critical region

Freeze-out conditions from (L)QCD ?

✓ how far is the critical region from the freeze-out line ?

❄ if they are far enough, then locating QCD critical point in HIC experiments will be difficult

✓ to what extent the experimental observables are governed by non-critical QCD thermodynamics ?

1) fix the freeze-out conditions from QCD
2) QCD calculations of observables at these freeze-out parameters
3) comparison with experiments

✓ do thermal models work perfectly for the freeze-out conditions at LHC ? (ALICE, 2012)

freeze-out parameters $\left(T^f, \mu_B^f, \mu_Q^f, \mu_S^f\right)$ from LQCD

Strangeness and electric charge chemical potentials

1) strangeness neutrality: $\langle n_S \rangle = 0$

2) isospin asymmetry: $\langle n_Q \rangle = r \langle n_B \rangle$

Au-Au & Pb-Pb: $r \simeq 0.4$

fixed using HIC initial conditions

$$\langle N_S \rangle = 0$$

$$\langle n_S \rangle = 0$$

$$\langle n_Q \rangle = r \langle n_B \rangle$$

$$\frac{\langle N_Q \rangle}{\langle N_B \rangle} = \frac{\langle N_p \rangle}{\langle N_p \rangle + \langle N_n \rangle} = r$$

assume: homogeneous system

expand these two relations in powers

of μ_B, μ_Q, μ_S around $\mu_B = \mu_Q = \mu_S = 0$

$$\mu_Q(T, \mu_B) = q_1(T)\mu_B + q_3(T)\mu_B^3 + \cdots$$

$$\mu_S(T, \mu_B) = s_1(T)\mu_B + s_3(T)\mu_B^3 + \cdots$$

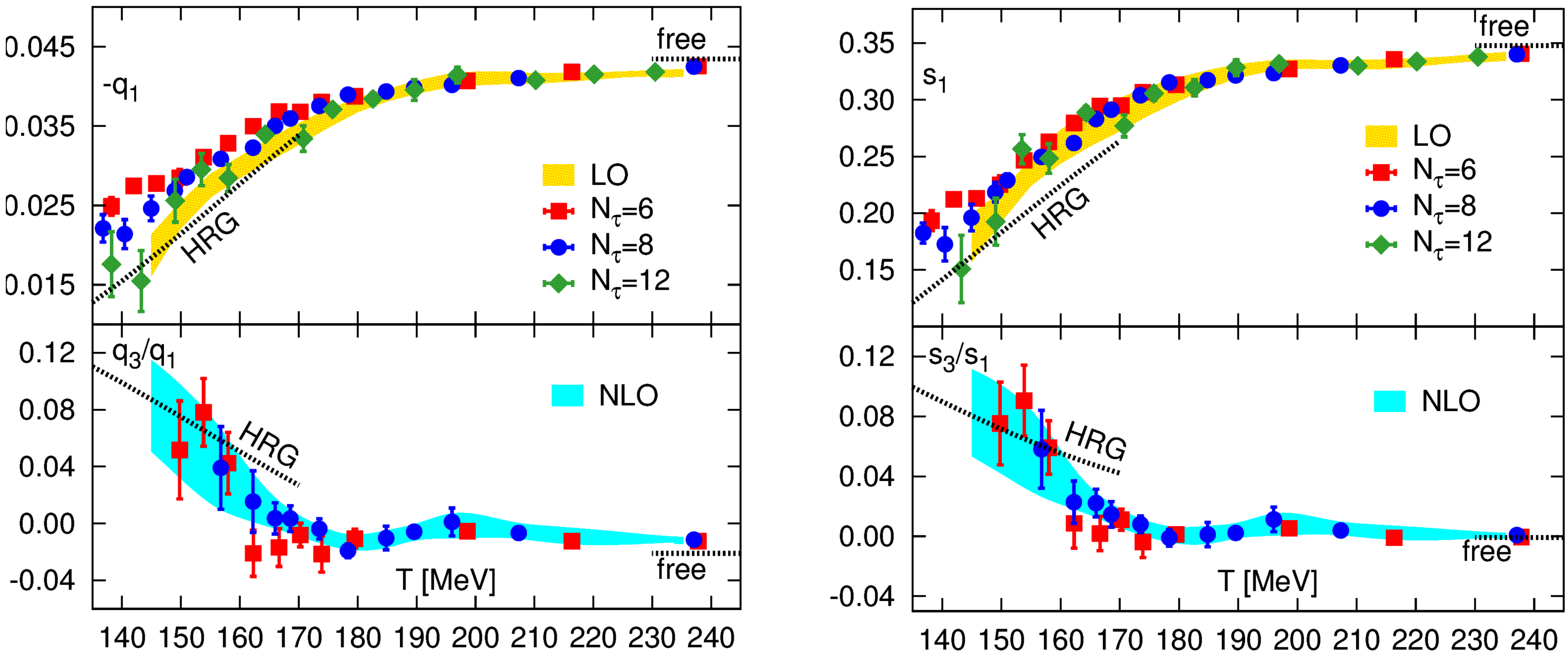
LO NLO

$\mu_Q^f(T^f, \mu_B^f)$ $\mu_S^f(T^f, \mu_B^f)$

B: baryon, Q: charge, S: strangeness
p: proton, n: neutron

$N_X = N_X - N_{\bar{X}}$, $n_X = N_X / V$

Strangeness and electric charge chemical potentials



$$\mu_Q(T,\mu_B)=q_1(T)\mu_B+q_3(T)\mu_B^3 \qquad \mu_S(T,\mu_B)=s_1(T)\mu_B+s_3(T)\mu_B^3$$

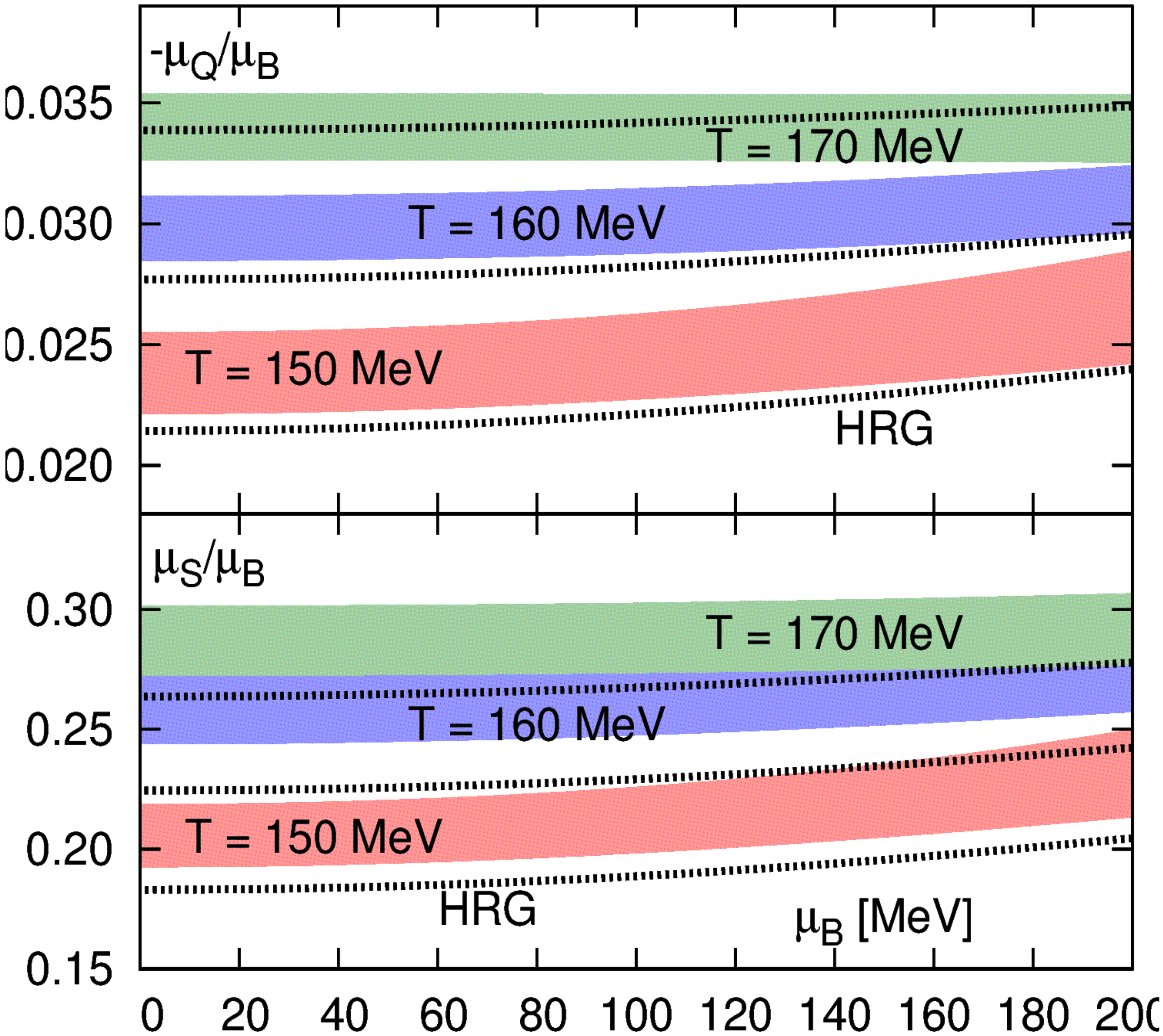
LO: continuum extrapolated

NLO: $N_\tau=6,8$, small cut-off dependence, *continuum estimate*

NLO corrections < 10%

$\mu_B/T \lesssim 1.3$

Strangeness and electric charge chemical potentials



$\mu_Q(T,\mu_B)$

$\mu_S(T,\mu_B)$

BNL-BI, arXiv:1208.1220

5-15% deviations from HRG

Temperature and baryon chemical potential

hadron yields are inaccessible in LQCD

all observables can now be obtained as function of two independent parameters T, μ_B

comparison of 2 expt. measured ratios of cumulants of conserved charge fluctuations with LQCD calculations fixes 2 freeze-out parameters T^f, μ_B^f

proton fluctuations (expt.) ?=? baryon fluctuations (LQCD)

Asakawa-Kitazawa; Bzdak-Skokov

safe to work with net electric charge fluctuations

measured both in expt. and LQCD

ratio of cumulants: cancels the unknown volume of the fireball

Temperature and baryon chemical potential

fixes μ_B^f

LO linear in μ_B

$$\frac{M_Q(\sqrt{s})}{\sigma_Q^2(\sqrt{s})} = \frac{\langle N_Q \rangle}{\langle (\delta N_Q)^2 \rangle} = \frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)} = R_{12}^{Q,1}(T)\mu_B + R_{12}^{Q,3}(T)\mu_B^3 + \cdots = R_{12}^Q(T,\mu_B)$$

$$\frac{S_Q(\sqrt{s})\sigma_Q^3(\sqrt{s})}{M_Q(\sqrt{s})} = \frac{\langle (\delta N_Q)^3 \rangle}{\langle N_Q \rangle} = \frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)} = R_{31}^{Q,0}(T) + R_{31}^{Q,2}(T)\mu_B^2 + \cdots = R_{31}^Q(T,\mu_B)$$

fixes T^f

LO independent of μ_B

STAR, PHENIX

HIC

mean: M_Q

variance: σ_Q^2

skewness: S_Q

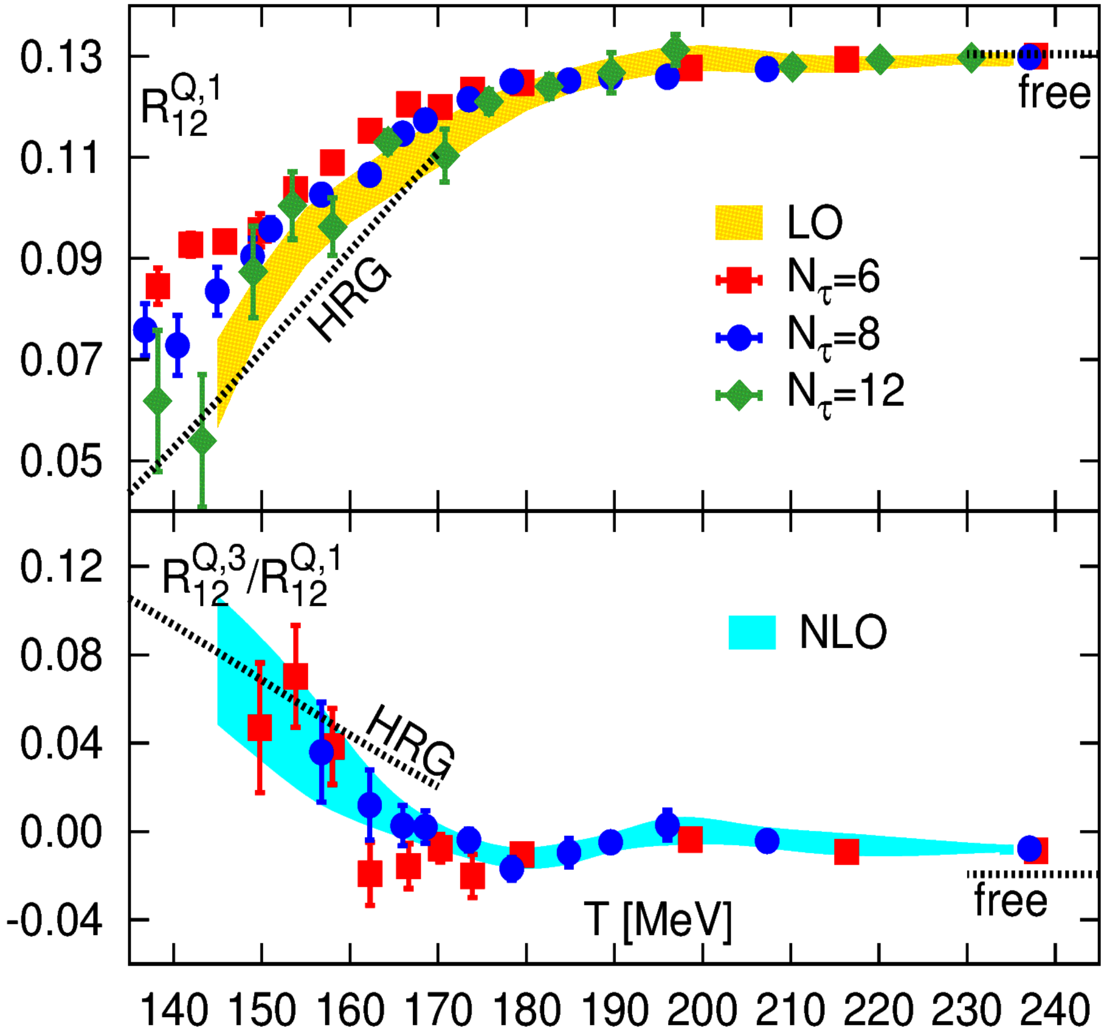
$$\delta N_Q = N_Q - \langle N_Q \rangle$$

LQCD

generalized charge susceptibilities:

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

Temperature and baryon chemical potential



LO: continuum extrapolated

NLO: $N_\tau = 6,8$

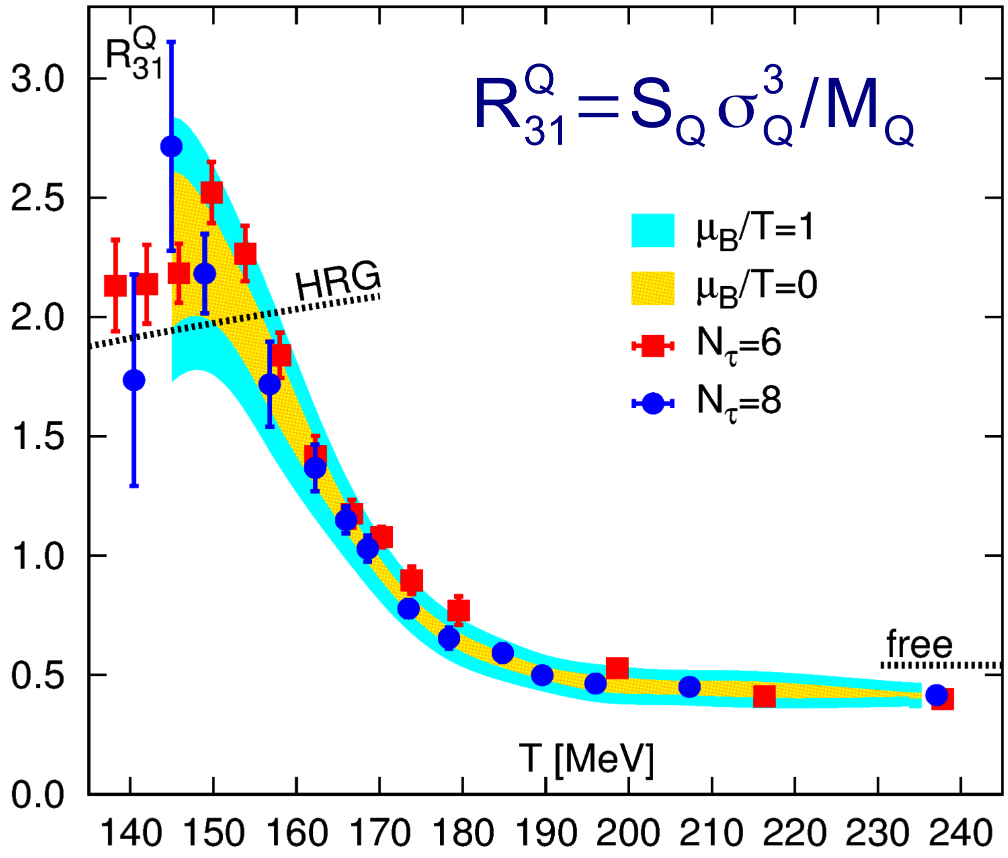
NLO corrections < 10%

$\mu_B/T \lesssim 1.3$

$$R_{12}^{Q} = M_Q/\sigma_Q^2$$

$$R_{12}^{Q}(T,\mu_B) = R_{12}^{Q,1}(T)\mu_B + R_{12}^{Q,3}(T)\mu_B^3$$

Temperature and baryon chemical potential



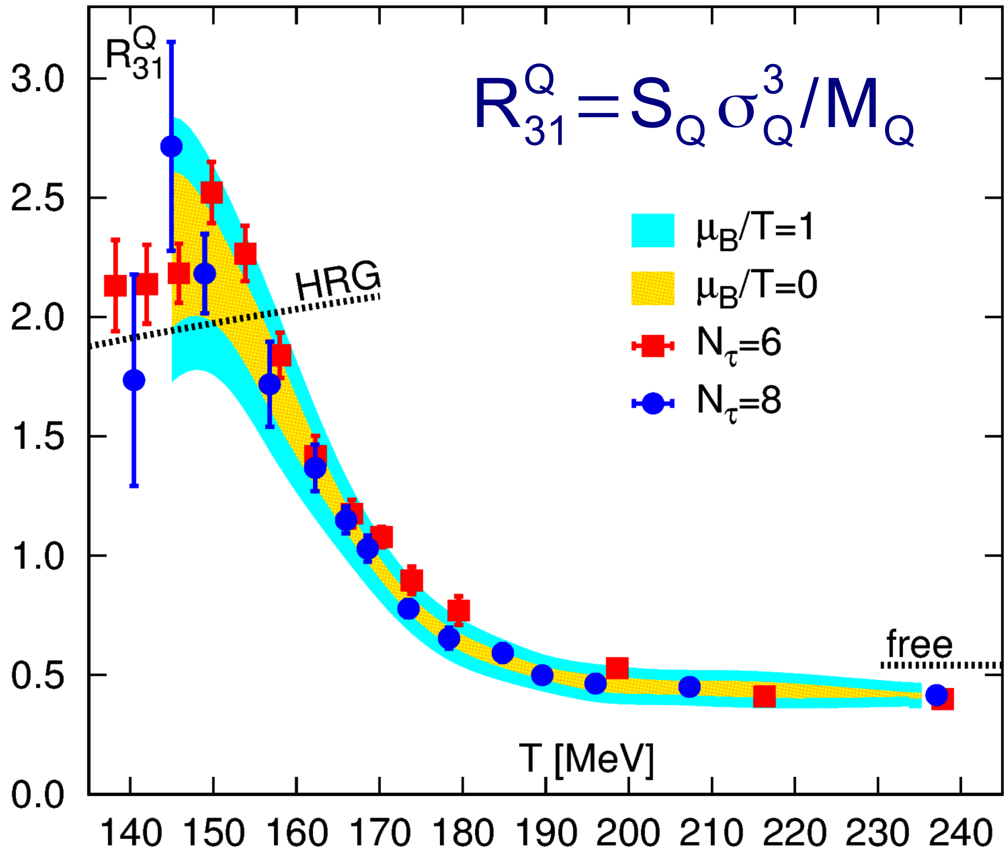
$$R^Q_{31}(T,\mu_B) = R^{Q,0}_{31}(T) + R^{Q,2}_{31}(T)\mu_B^2$$

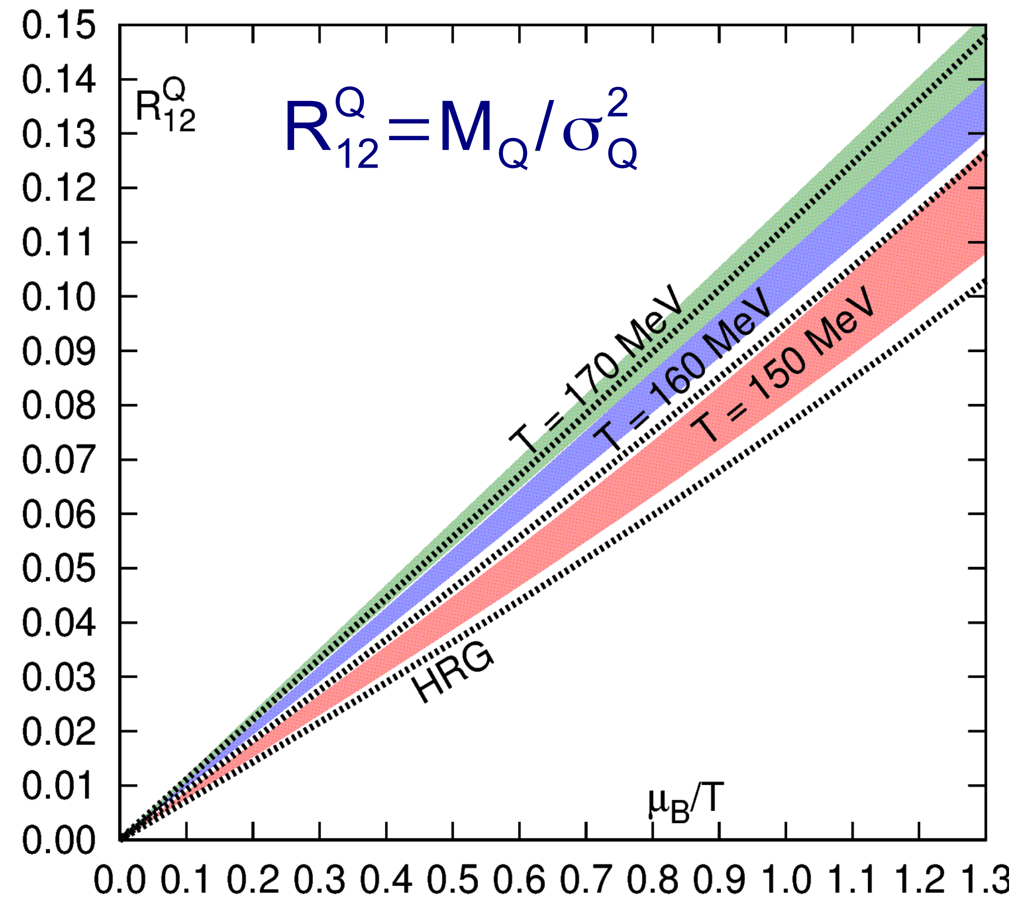
large deviation from HRG
for T > 155 MeV

LO: $N_\tau = 6,8$

NLO corrections: $\lesssim 10\%,\ \mu_B/T \lesssim 1.3$

Temperature and baryon chemical potential





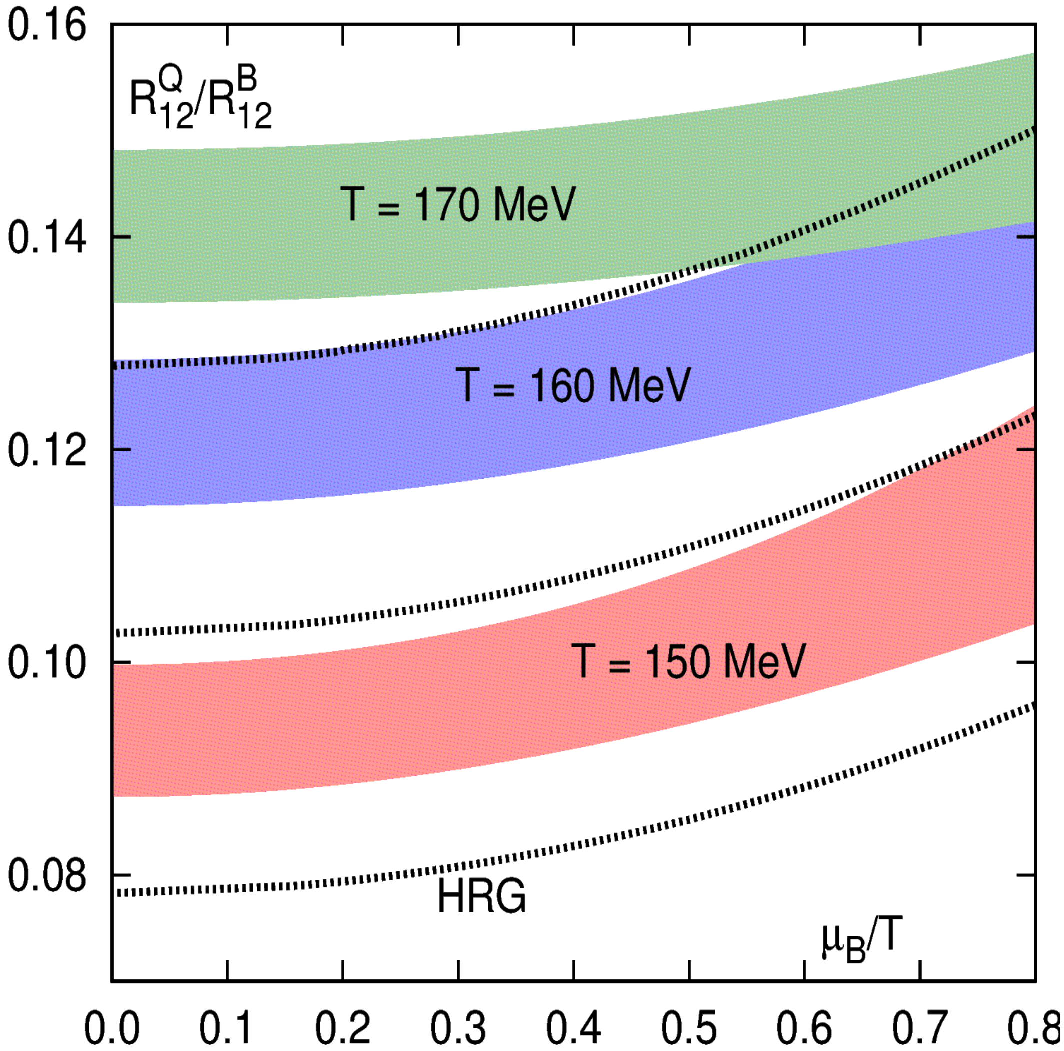
$S_Q\sigma_Q^3/M_Q$	T^f [MeV]
$\lesssim 2$	$\lesssim 155$
~ 1.5	~ 160
$\lesssim 1$	$\gtrsim 170$

M_Q/σ_Q^2	μ_B^f/T^f
0.01 − 0.02	0.1 − 0,2
0.03 − 0.04	0.3 − 0.4
0.05 − 0.08	0.5 − 0.7

for: $T^f \sim 160$ MeV

BNL-BI, arXiv:1208.1220

Thermodynamic consistency

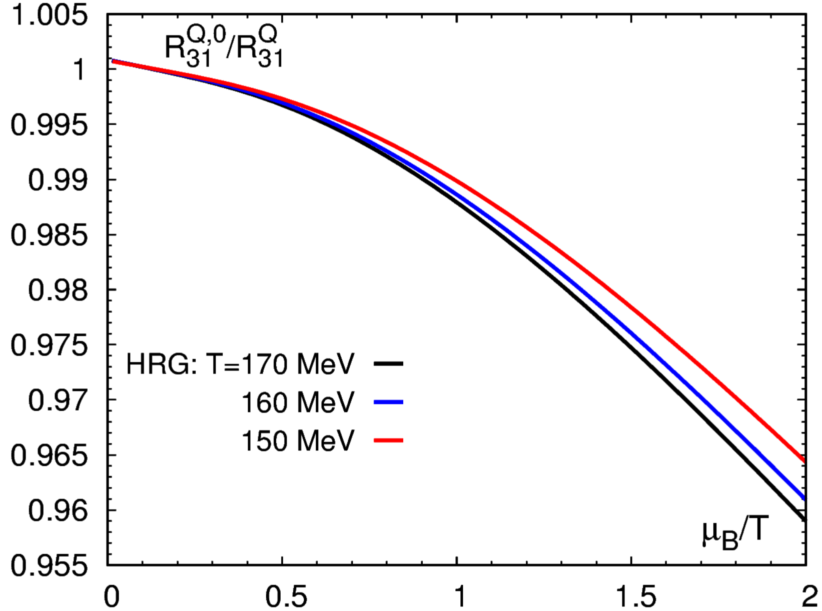


$$\frac{R^Q_{12}}{R^B_{12}} = \frac{M_Q/\sigma_Q^2}{M_B/\sigma_B^2}$$

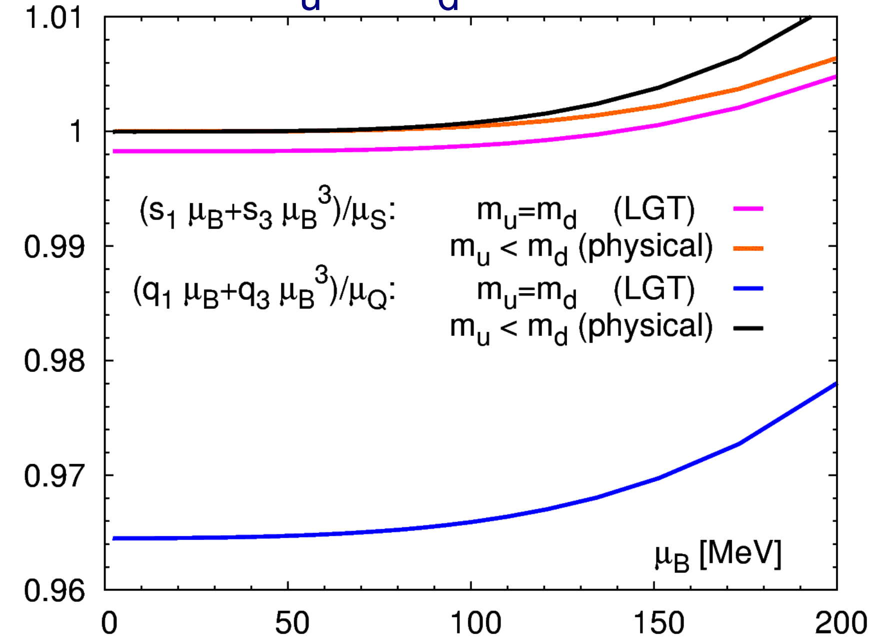
all other cumulant ratios should be reproduced w/o fixing any further parameter, provided the system is in thermal & chemical equilibrium

Systematic: estimates using HRG

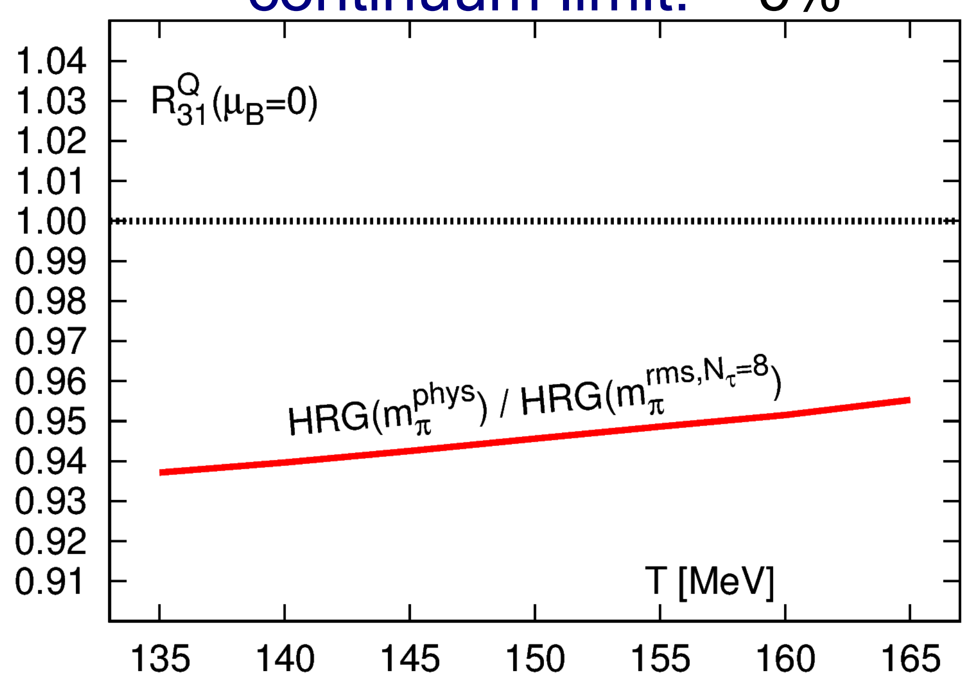
series truncation: ~ 5%



$m_u \neq m_d$: ~5%



continuum limit: ~ 5%



Summary

chemical freeze-out conditions can be determined
from first principle (lattice) QCD calculations by
comparing with cumulants of net charge fluctuations
currently being measured by STAR, PHENIX

controlled NLO Taylor expansion up to
$\mu_B \sim 200$ MeV, $\sqrt{s} \sim 19.6$ GeV

general agreement with thermal models within 15%