Determining freeze-out conditions from QCD

i.e. without input from a HRG model

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State-of-the-art:

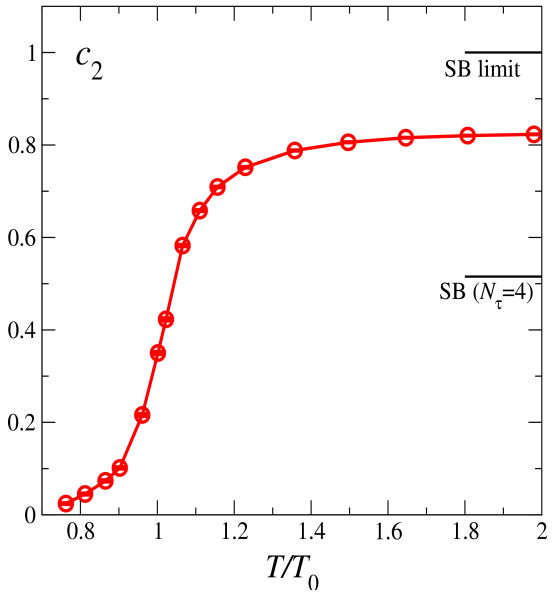
the thermal conditions at freeze-out are determined by comparing experimental results for ratios of particle yields with the Hadron Resonance Gas (HRG) model

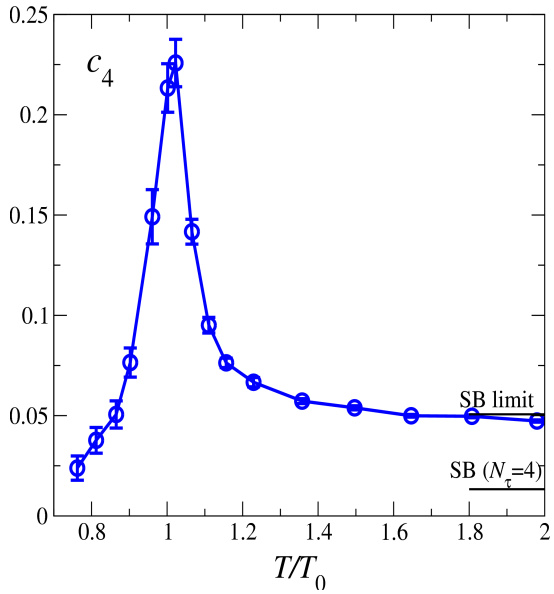
the goal:

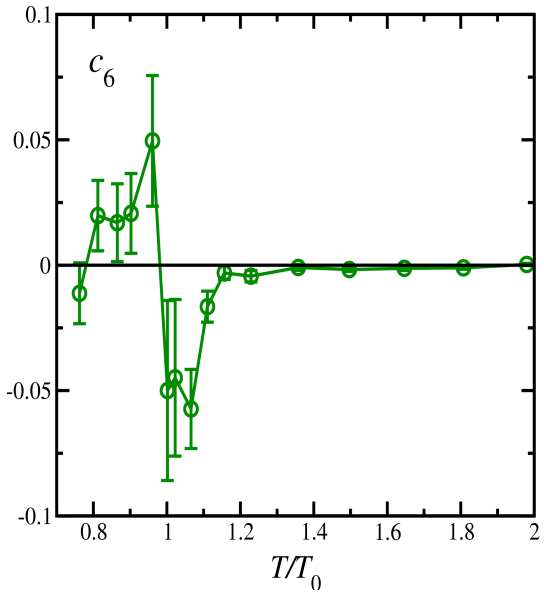
eventually we should get rid of model calculations and should be able to determine the freeze-out parameters directly by comparing experimental results with (lattice) QCD calculations

The past:
Baryon number susceptibilities

These times are over: C.R. Allton et al, PRD71 (2005) 054508







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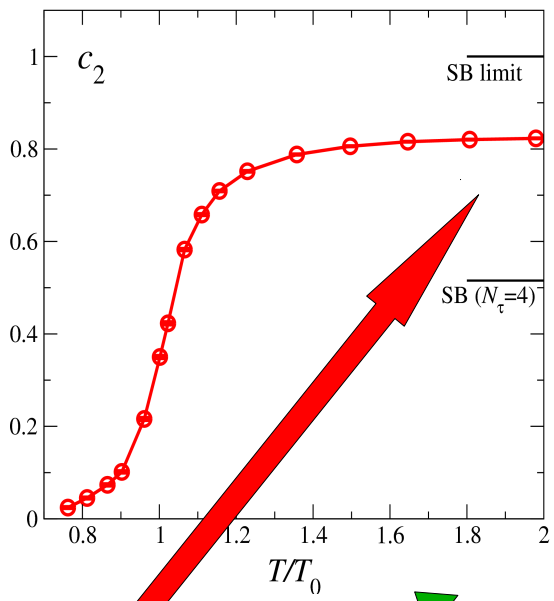
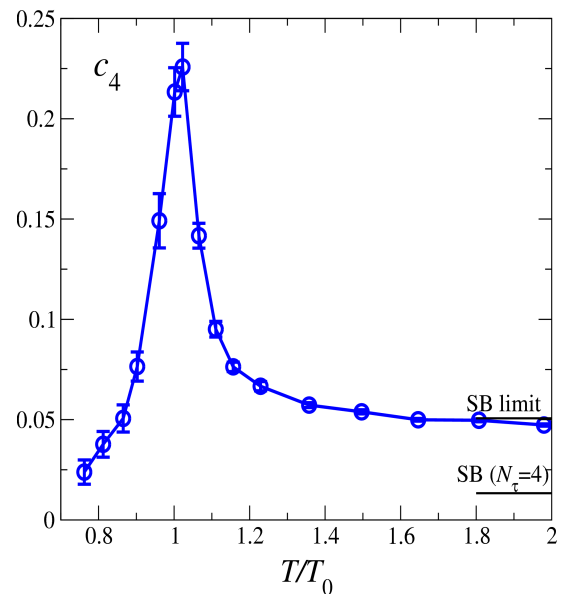
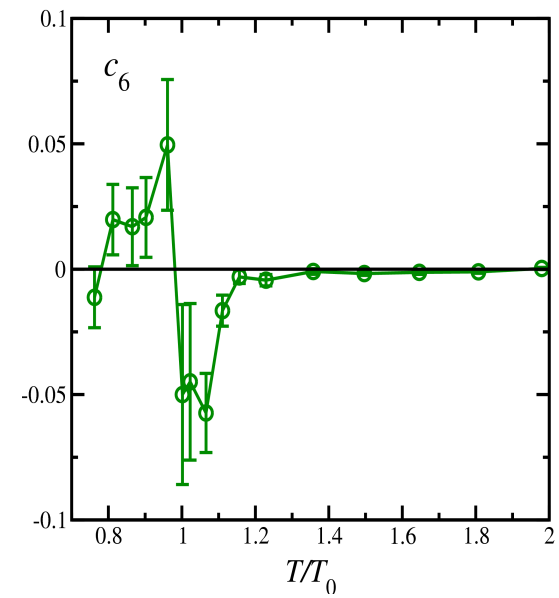




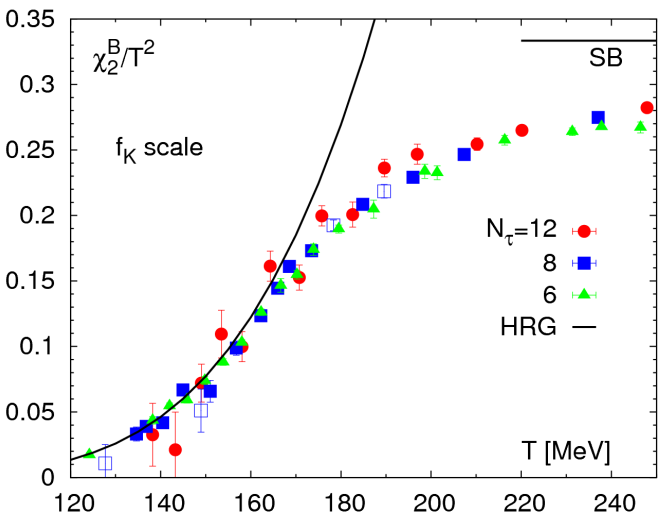


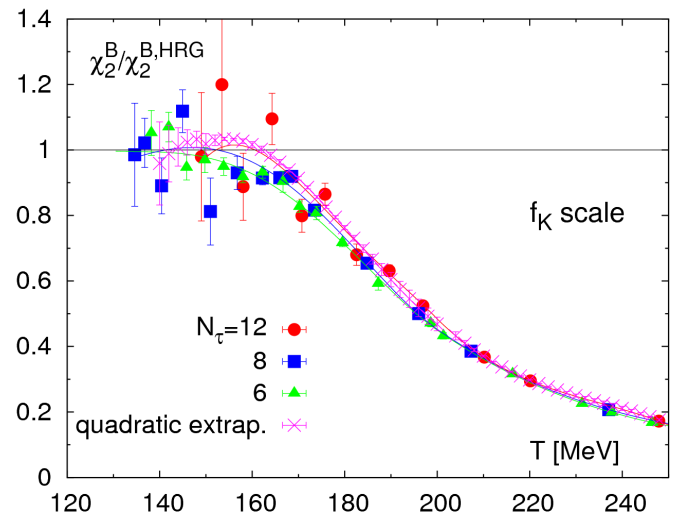
there is no need anymore to present lattice results in terms of T/Tc; we know absolute temperature scales within 2MeV accuracy

there is no need for arguing about cut-off effects; improved fermion actions do control these (almost everywhere)

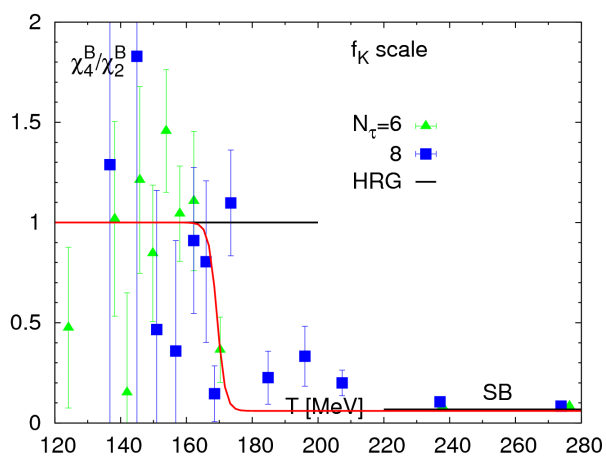
The present:
Baryon number susceptibilities

HotQCD preliminary





The (near) future:

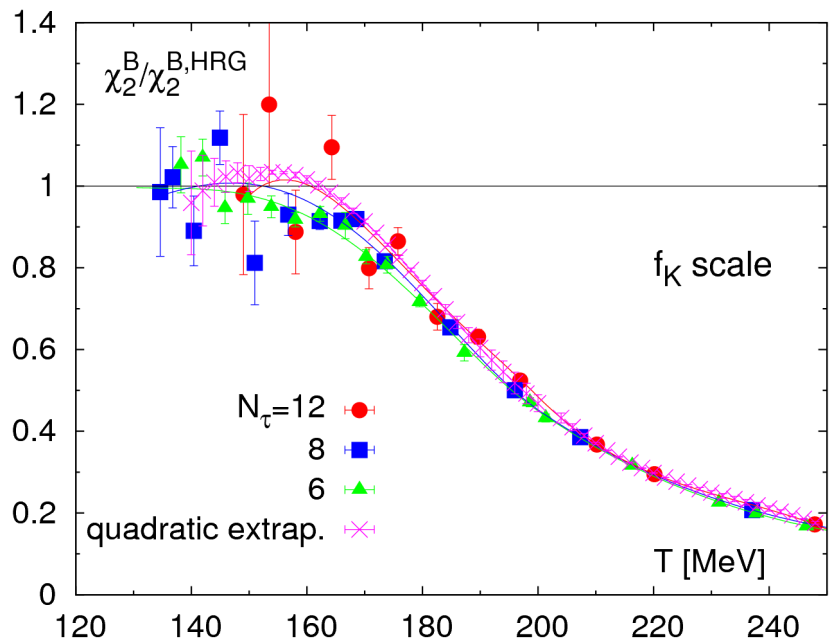


deviations of χ_4^B/χ_2^B from HRG will soon be under control

Net-baryon number susceptibility controls widths of probability distribution

P(N) may be expressed in terms of a cumulant expansion; leading order corresponds to Gaussian approximation:

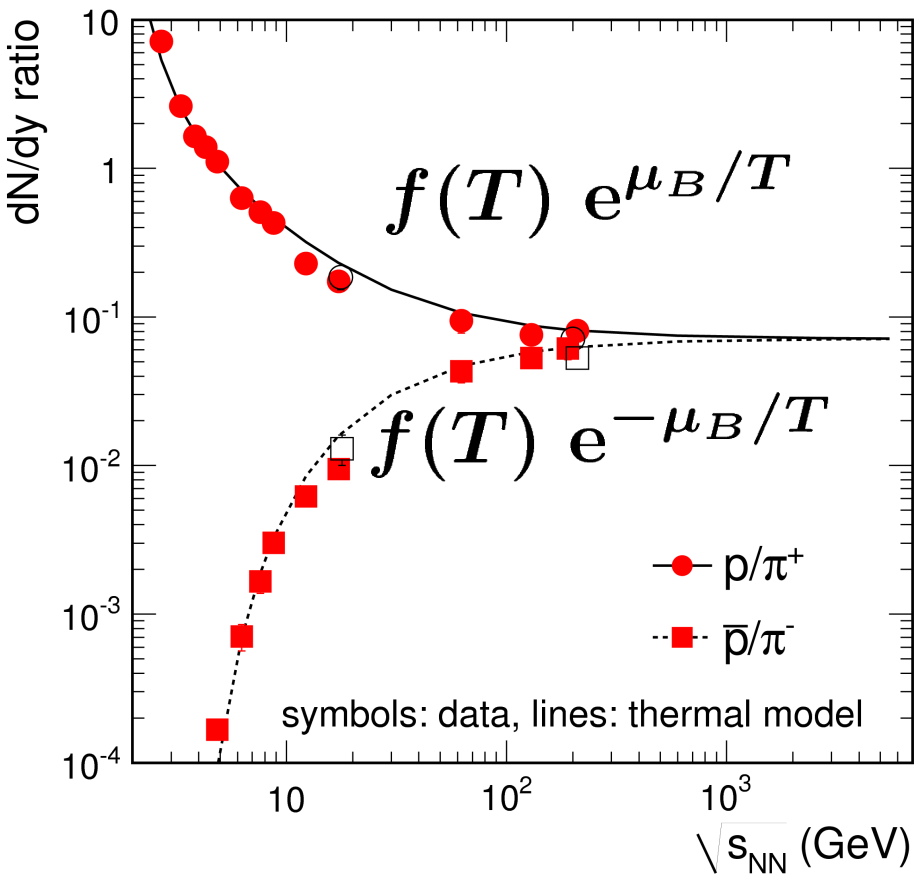
$$P(N) \sim \exp[-N^2/(2VT^3\chi_B^{(2)})]$$

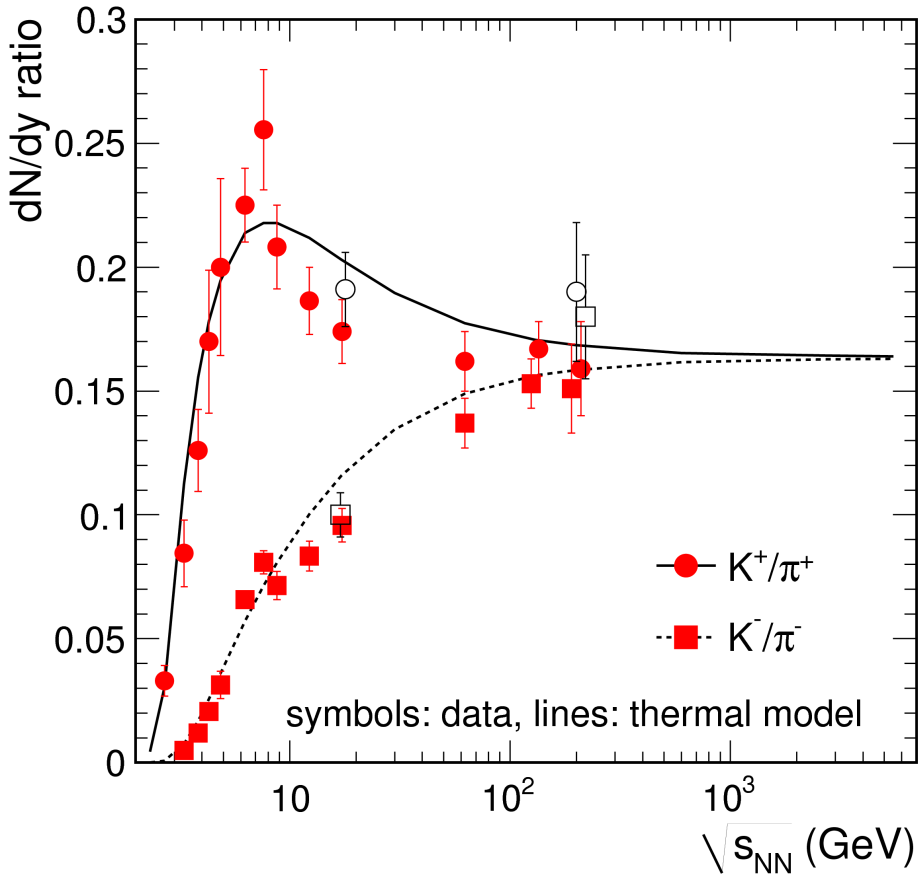


HISQ action:
hotQCD, preliminary

in the transition region the net baryon number probability distribution derived in leading order from QCD may become narrower than the HRG model result

Recall: Determining T and muB in the Hadron Resonance Gas

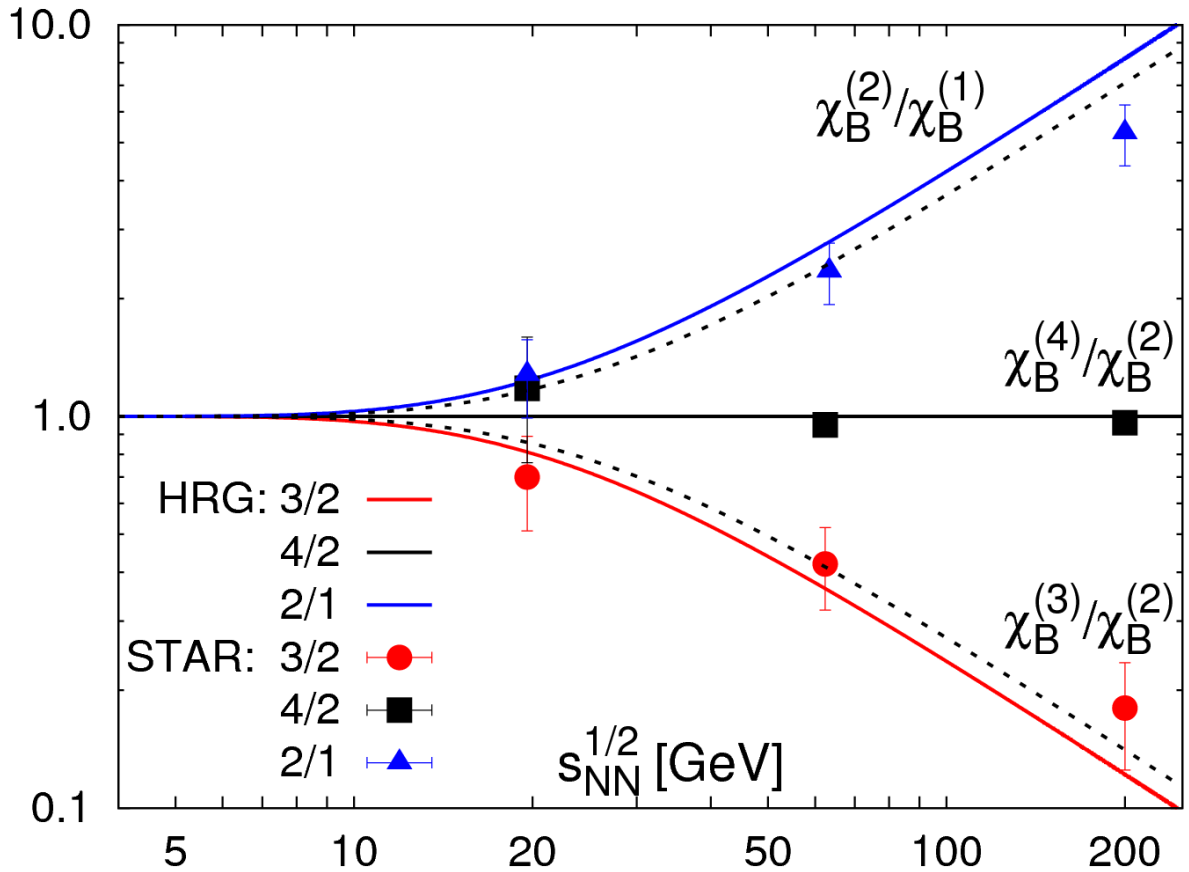




$$\frac{N_B}{N_{\bar{B}}} = e^{2\mu_B/T} \Rightarrow \frac{\mu_B}{T_f} \qquad \frac{N_{K^-}}{N_{\pi^-}} \sim e^{(m_\pi - m_K)/T} \Rightarrow T_f$$

figs. from A. Andronic et al., arXiv:1106.6321[nucl-th]

Using cumulants of net-baryon fluctuations to determine T,muB



from (lattice) QCD !!!

today
discuss only 200GeV:

$$\frac{\chi_B^{(2)}}{\chi_B^{(1)}} = 5.3(9)$$

$$\frac{\chi_B^{(4)}}{\chi_B^{(2)}} = 0.96(3)$$

FK, K Redlich, arXiv:1007.2581
data from STAR: arXiv:1004.4959

charge fluctuations at freeze-out agree 'almost' with HRG model predictions

significant deviations between HRG model and data for the variance ($\chi_B^{(2)}$)?

Ratios of cumulants in QCD (using Taylor expansions)

LGT:

e.g.: $$\frac{\chi^{(2)}_{B,\mu}}{\chi^{(1)}_{B,\mu}} = \frac{\chi^{(2)}_{B,0} + \frac{1}{2}\chi^{(4)}_{B,0}(\mu_B/T)^2 + \ldots}{\chi^{(2)}_{B,0}(\mu_B/T) + \frac{1}{6}\chi^{(4)}_{B,0}(\mu_B/T)^3 + \ldots}$$

$$= \frac{T}{\mu_B}\left[\frac{1 + \frac{1}{2}\frac{\chi^{(4)}_{B,0}}{\chi^{(2)}_{B,0}}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{6}\frac{\chi^{(4)}_{B,0}}{\chi^{(2)}_{B,0}}(\mu_B/T)^2 + \ldots}\right]$$

→ at 200 GeV: $$\frac{\chi^{(2)}_{B}}{\chi^{(1)}_{B}} = 5.3(9)$$ (STAR)

→ $$\frac{\mu_B}{T_f} = 0.19(3)$$

LO LGT;
NLO contributes less than 2%

Ratios of cumulants in QCD (using Taylor expansions)

LGT:

$$\frac{\chi^{(4)}_{B,\mu}}{\chi^{(2)}_{B,\mu}} = \frac{\chi^{(4)}_{B,0} + \frac{1}{2}\chi^{(6)}_{B,0}(\mu_B/T)^2 + \ldots}{\chi^{(2)}_{B,0}(\mu_B/T) + \frac{1}{2}\chi^{(4)}_{B,0}(\mu_B/T)^3 + \ldots}$$

$$= \frac{\chi^{(4)}_{B,0}}{\chi^{(2)}_{B,0}} \left[\frac{1 + \frac{1}{2}\frac{\chi^{(6)}_{B,0}}{\chi^{(4)}_{B,0}}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi^{(4)}_{B,0}}{\chi^{(2)}_{B,0}}(\mu_B/T)^2 + \ldots} \right]$$

at 200 GeV: $\frac{\chi^{(4)}_B}{\chi^{(2)}_B} = 0.96(3)$ (STAR)

$T_f = 165(5) MeV$

$\mu_B = 31(5) MeV$

these numbers are for orientation only; do not (yet) cite them!!

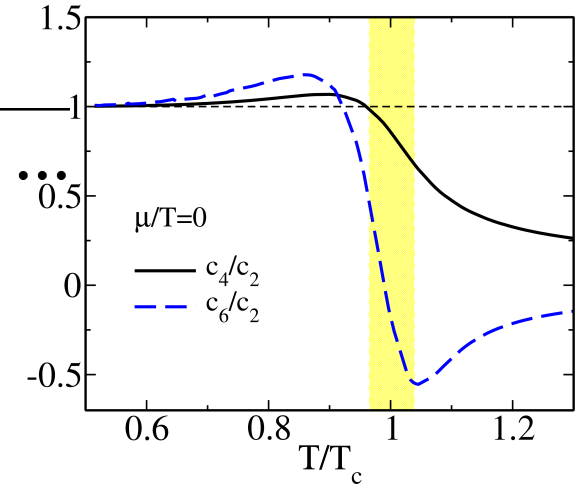
this needs to be substantiated by better LGT results

Charge fluctuations in LGT, HRG and experiment

all other ratios become predictions from LGT

e.g.:
$$\frac{\chi^{(4)}_{B,\mu}}{\chi^{(3)}_{B,\mu}} = \frac{\chi^{(4)}_{B,0} + \frac{1}{2}\chi^{(6)}_{B,0}(\mu_B/T_f)^2 + \ldots}{\chi^{(4)}_{B,0}(\mu_B/T_f) + \frac{1}{6}\chi^{(6)}_{B,0}(\mu_B/T_f)^3 + \ldots}$$

$$= \frac{1 + \frac{1}{2}\frac{\chi^{(6)}_{B,0}}{\chi^{(4)}_{B,0}}(\mu_B/T_f)^2 + \ldots}{\mu_B/T_f + \frac{1}{6}\frac{\chi^{(6)}_{B,0}}{\chi^{(4)}_{B,0}}(\mu_B/T_f)^3 + \ldots}$$



B. Friman, FK, K. Redlich, V. Skokov, arXiv:1103.3511

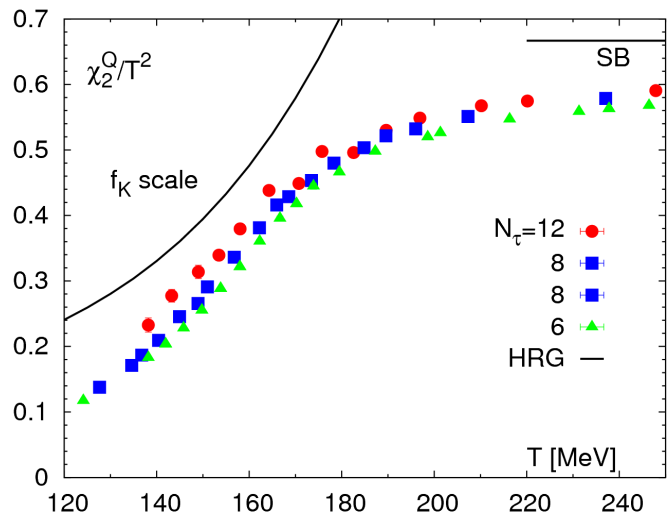
$T \ll T_c$ →
$$\frac{1 + \frac{1}{2}(\mu_B/T_f)^2 + \ldots}{\mu_B/T_f + \frac{1}{6}(\mu_B/T_f)^3 + \ldots} = \frac{\cosh(\mu_B/T_f)}{\sinh(\mu_B/T_f)}$$

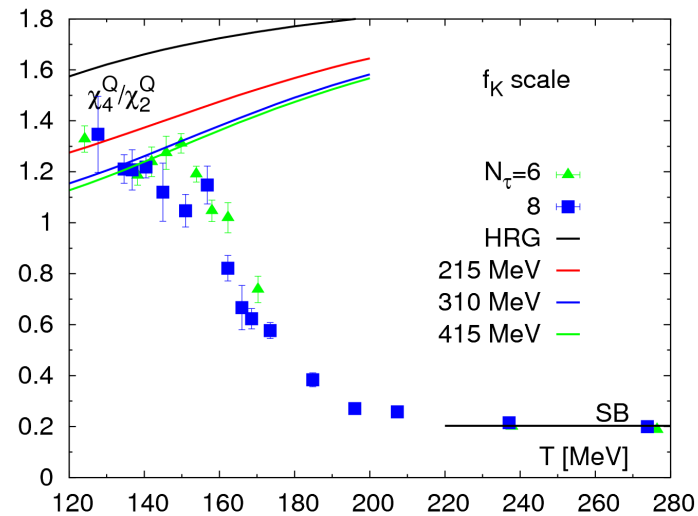
there is no need to know Tc in order to compare ratios of cumulants from LGT with experiment

FK, K. Redlich, arXiv:1107.1412

The future:
Electric Charge Fluctuations

All what has been discussed here can also be done with electric charge susceptibilities





– experimentally cleaner ??

– theoretically more difficult (larger cut-off effects, due to light quark contributions)