Is there a flavor hierarchy in the deconfinement transition of QCD?

Claudia Ratti

Università degli Studi di Torino and

INFN, Sezione di Torino

In collaboration with R. Bellwied, S. Borsanyi, Z. Fodor, S. Katz

Motivation

- We live in a very exciting era to understand the fundamental constituents of matter and the evolution of the Universe
- We can create the deconfined phase of QCD in the laboratory
- Lattice QCD simulations have reached unprecedented levels of accuracy
  - physical quark masses
  - several lattice spacings $\rightarrow$ continuum limit
- The joint information between theory and experiment can help us to shed light on QCD

Susceptibilities of conserved charges

- The deconfined phase of QCD can be reached in the laboratory
- Need for unambiguous observables to identify the phase transition
  - susceptibilities of conserved charges (baryon number, electric charge, strangeness)
    S. Jeon and V. Koch (2000), M. Asakawa, U. Heinz, B. Müller (2000)
- A rapid change of these observables in the vicinity of T_c provides an unambiguous signal for deconfinement
- They can be calculated on the lattice as combinations of quark number susceptibilities
- They can be directly compared to experimental measurements

The observables under study

- The chemical potentials are related:

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q;$$
$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q;$$
$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S.$$

- susceptibilities are defined as follows:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

- Quadratic susceptibilities:

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

- Correlators between different charges:

$$\chi_{11}^{XY} = \frac{1}{VT^3}\langle N_X N_Y \rangle.$$

Physical meaning

- Diagonal susceptibilities measure the response of quark densities to an infinitesimal change in the chemical potential

$$\chi_2^X = \frac{\partial^2 p/T^4}{\partial(\mu_X/T)^2} = \frac{\partial}{\partial(\mu_X/T)}\left(n_X/T^3\right)$$

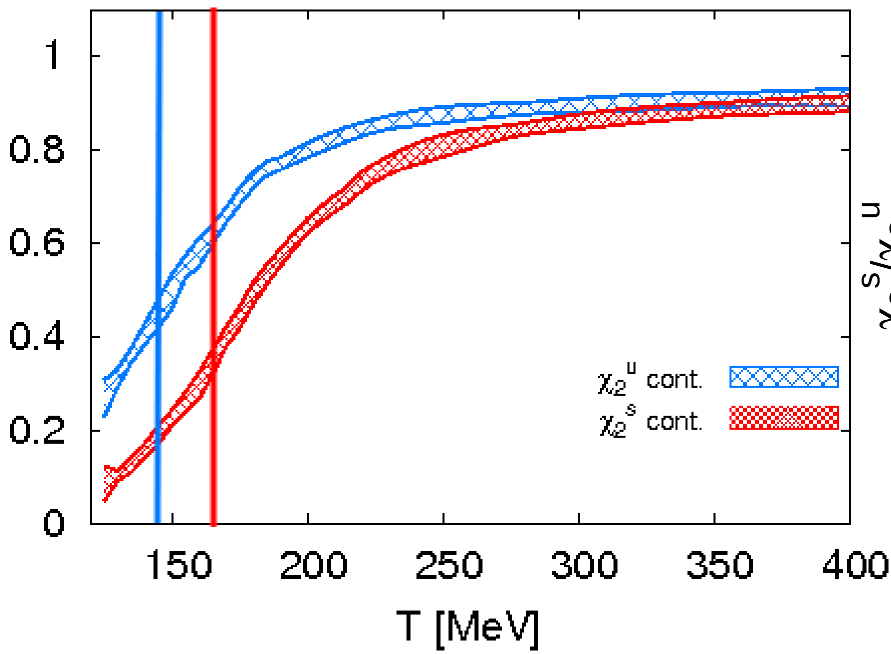
  - A rapid increase of these observables in a certain temperature range signals a phase transition

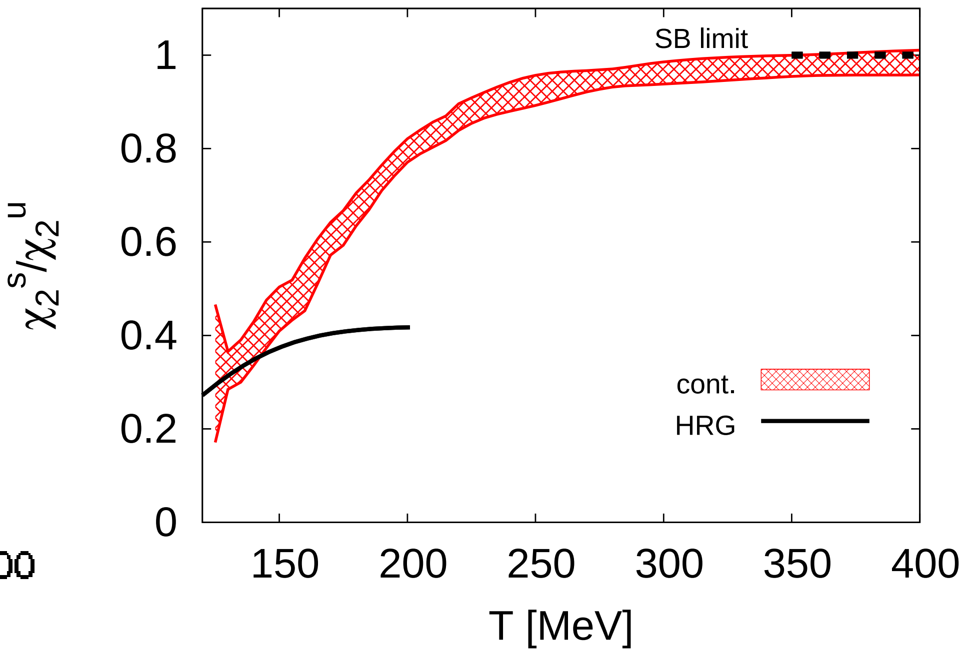
- Non-diagonal susceptibilities measure the correlation between different quark flavors

$$\chi_{11}^{XY} = \frac{\partial^2 p/T^4}{\partial(\mu_X/T)\partial(\mu_Y/T)} = \frac{\partial}{\partial(\mu_Y/T)}\left(n_X/T^3\right)$$

  - They can provide information about bound-state survival above the phase transition

Comparison between light and strange quark susceptibilities

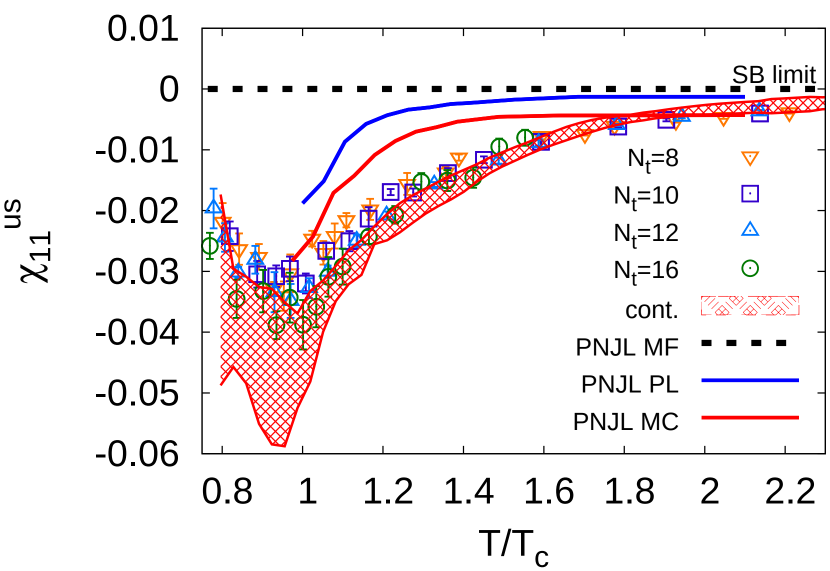




- strange quark susceptibilities have their rapid rise at larger temperatures compared to the light quark ones
- they rise more slowly as a function of T
- There is a difference of $\sim 15 - 20$ MeV between the inflection points of the two curves

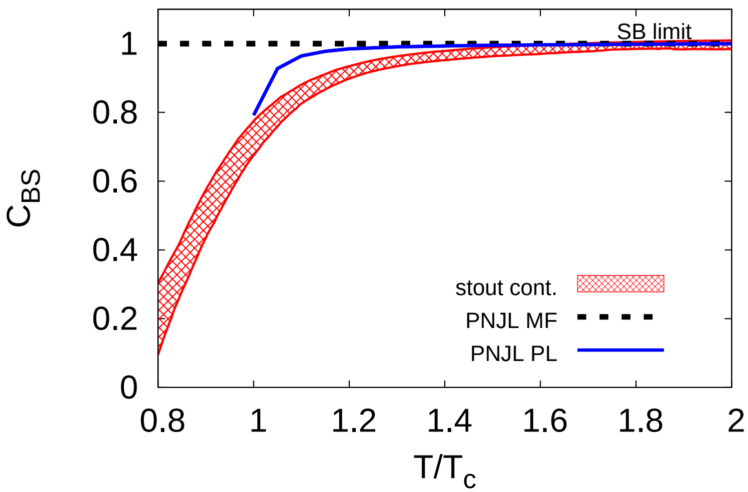
Are there bound states in the QGP?

- Comparison of lattice to PNJL (C.R., R. Bellwied, M. Cristoforetti, M. Barbaro, PRD (2012))



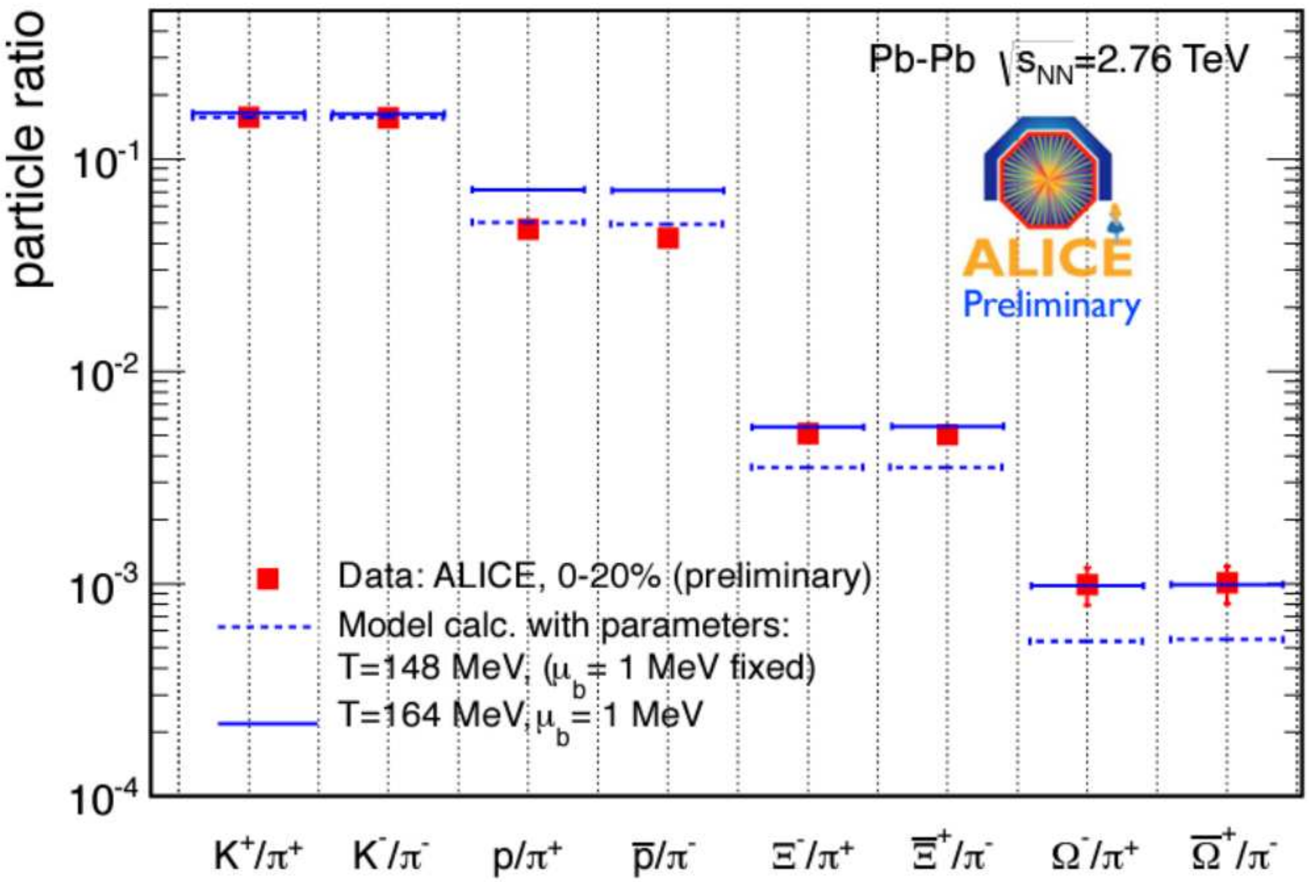
- PNJL MF: pure mean field calculation
- PNJL PL: mean field plus Polyakov loop fluctuations
- PNJL MC: full Monte Carlo result with all fluctuations taken into account
- the red curve falls on the blue for $V \to \infty$

- Even the inclusion of fluctuations is not enough to describe lattice data above T_c
- There has to be a contribution from bound states



Simple experimental verification

- Yields of strange particles should be enhanced relative to yields of non-strange particles
- yields of strange particles should result in a higher temperature than yields of non-strange particles when fitted with a statistical hadronization model (SHM)



R. Preghenella
for ALICE
SQM 2012
arXiv:1111.7080
Acta Phys. Pol.

Caveats

- Lattice results for susceptibilities are first-principle calculations

  - However, T_c cannot be univocally defined

- The experimental results are fitted by means of the Statistical Hadronization Model

- It would be nice to have a direct comparison between first-principle calculations and experimental results

Higher order susceptibilities and ratios

- susceptibilities are defined as follows:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

- we are now interested in fourth order susceptibilities (χ_4) and in particular in ratios χ_4/χ_2

  - Ratios have a very peculiar shape which allows to unambiguously spot the transition

  - They can be directly related to an experimental measurement: no need for model interpretation!

Relating lattice results to experimental measurement

- the first four cumulants are:

$$\chi_1 = \langle(\delta x)\rangle \qquad \chi_2 = \langle(\delta x)^2\rangle$$

$$\chi_3 = \langle(\delta x)^3\rangle \qquad \chi_4 = \langle(\delta x)^4\rangle - 3\langle(\delta x)^4\rangle^2$$

- we can relate them to higher moments of multiplicity distributions:

$$\text{variance}: \ \sigma^2 = \chi_2 \qquad \text{standard deviation}: \ \sigma = \sqrt{\chi_2}$$

$$\text{skewness}: \ S = \chi_3/\chi_2^{3/2} \qquad \text{kurtosis}: \ \kappa = \chi_4/\chi_2^2$$

$$S\sigma = \chi_3/\chi_2 \qquad \kappa\sigma^2 = \chi_4/\chi_2$$

- and therefore:

$$\kappa_B \sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi_4^B(T)}{\chi_2^B(T)} \left[\frac{1 + \frac{1}{2}\frac{\chi_6^B(T)}{\chi_4^B(T)}(\mu_B/T)^2 + \ldots}{1 + \frac{1}{2}\frac{\chi_4^B(T)}{\chi_2^B(T)}(\mu_B/T)^2 + \ldots} \right]$$

F. Karsch (2012)

Thermometer and Baryometer

- R_{31}^Q: thermometer

$$R_{31}^Q(T,\mu_B)=\frac{\chi_3^Q(T,\mu_B)}{\chi_1^Q(T,\mu_B)}=\frac{\chi_{31}^{QB}(T,0)+\chi_4^Q(T,0)q_1(T)+\chi_{31}^{QS}(T,0)s_1(T)}{\chi_{11}^{QB}(T,0)+\chi_2^Q(T,0)q_1(T)+\chi_{11}^{QS}(T,0)s_1(T)}+\mathcal{O}(\mu_B^2)$$

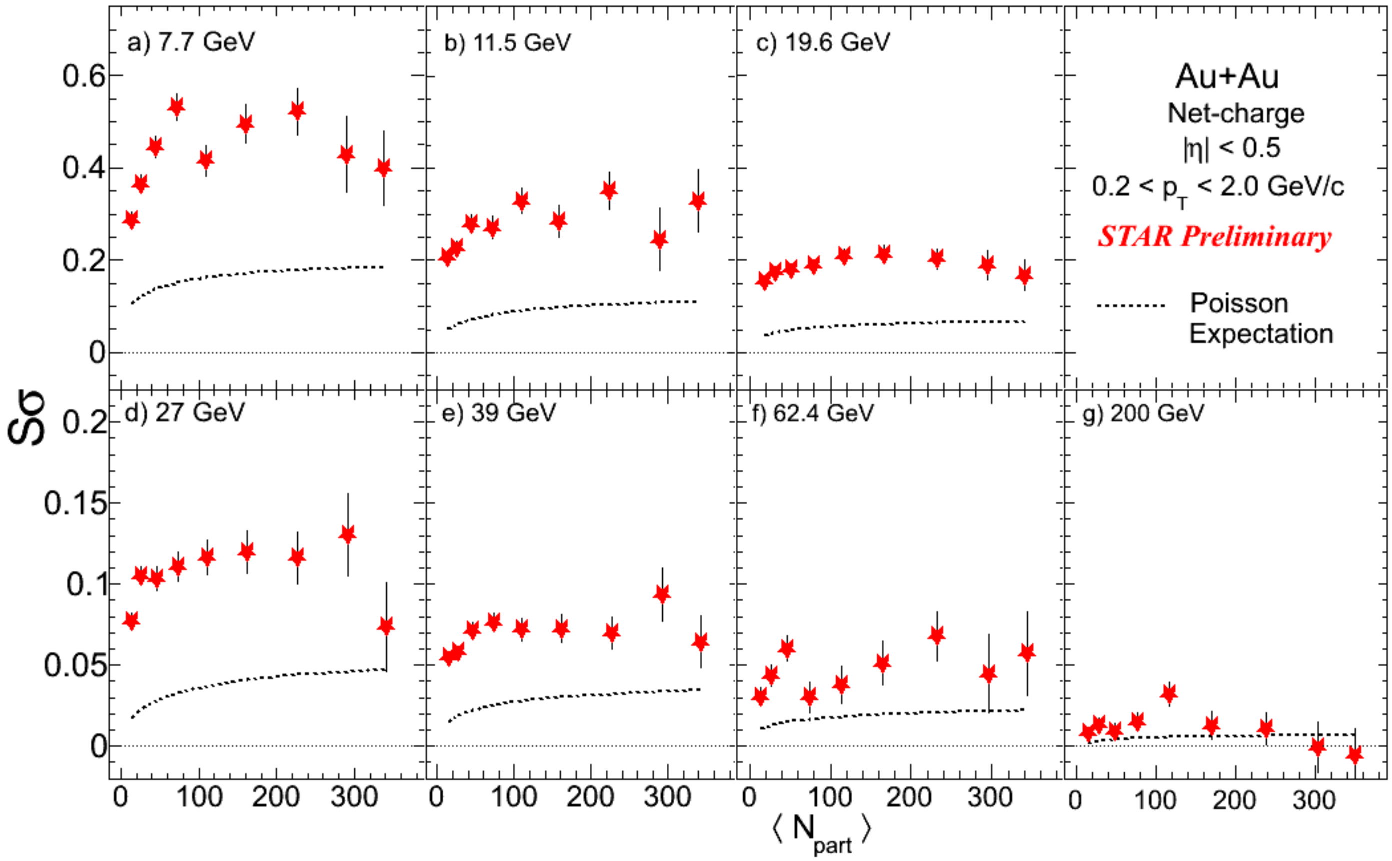
- Expand numerator and denominator around $\mu_B=0$: ratio is independent of μ_B

- R_{12}^Q: baryometer

$$R_{12}^Q(T,\mu_B)=\frac{\chi_1^Q(T,\mu_B)}{\chi_2^Q(T,\mu_B)}=\frac{\chi_{11}^{QB}(T,0)+\chi_2^Q(T,0)q_1(T)+\chi_{11}^{QS}(T,0)s_1(T)}{\chi_2^Q(T,0)}\frac{\mu_B}{T}+\mathcal{O}(\mu_B^3).$$

- Expand numerator and denominator around $\mu_B=0$: ratio is proportional to μ_B

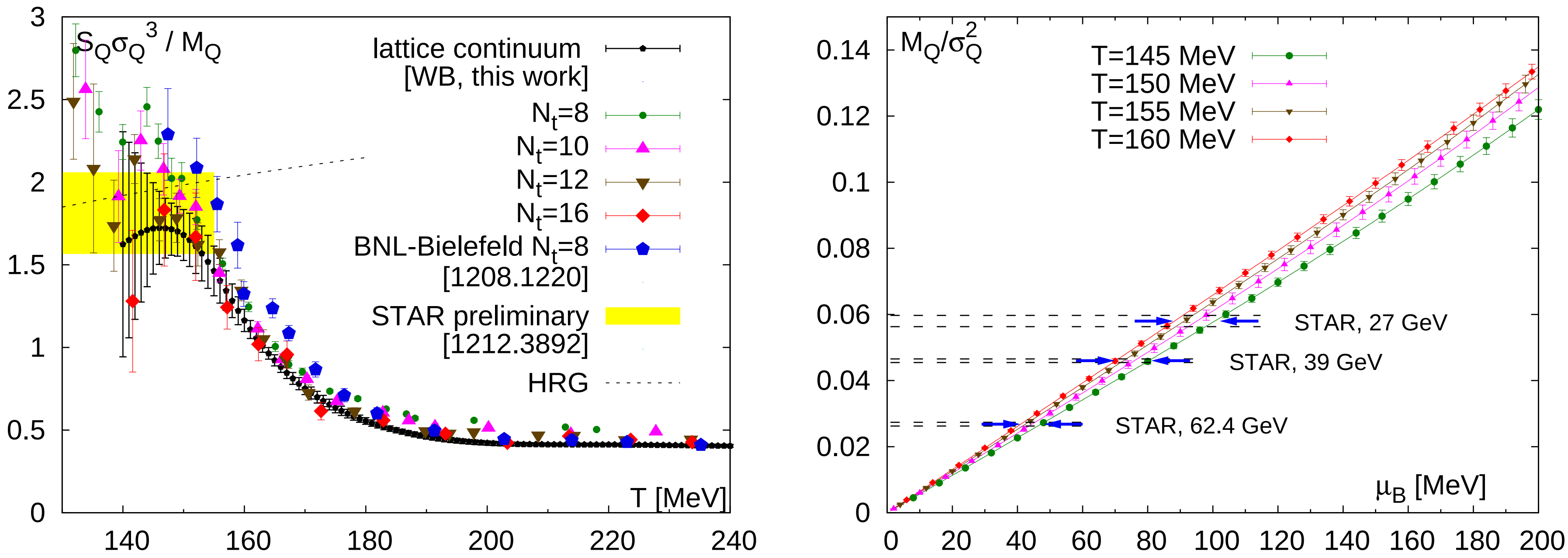
Experimental measurement



Star Collaboration: arXiv 1212.3892

- Average of two most central measurements over $\sqrt{s} = 27,\ 39,\ 62.4.$

Extracting freeze-out parameters

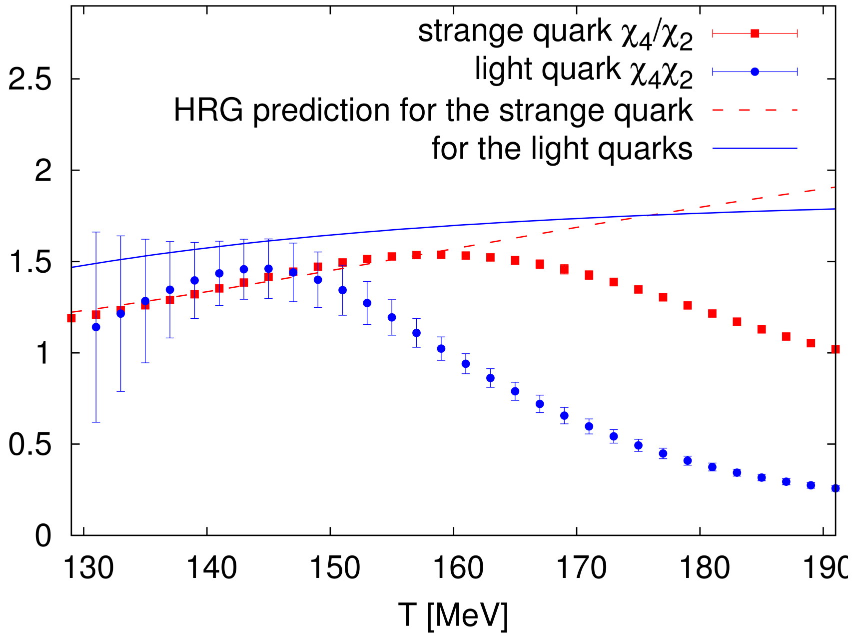


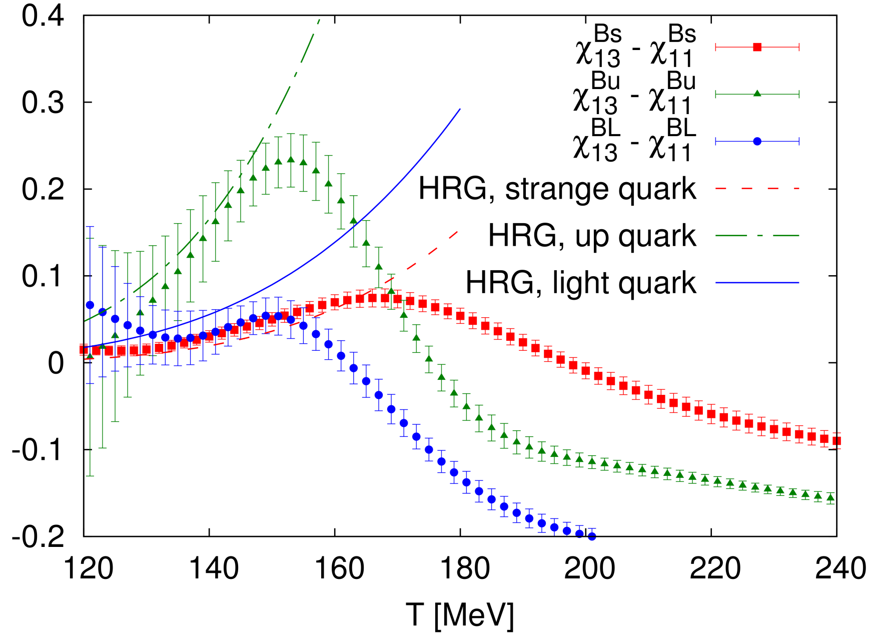
WB Collaboration: PRL (2013)

- Upper limit: $T_f \leq 157 \pm 4$ MeV

$\sqrt{s}[GeV]$	μ_B^f [MeV]
62.4	44(5)
39	75(7)
27	95(9)

Strange vs light thermometer





R. Bellwied *et al.*: PRL (2013)

- Flavor-specific kurtosis confirms separation between light and strange quarks
- $w_f = \chi_{13}^{Bf} - \chi_{11}^{Bf}$ more sensitive to flavor content: in the hadronic phase it only receives contribution from hadrons with more than one quark of flavor f

Defining the experimental measurement

- Problem: we need to go from the B, Q, S basis to the basis of $u,\ d,\ s$ quark flavors
- In principle we need to measure all light and strange quark final states
  - ➡ Experimentally impossible, most resonances are too rare and cannot be reconstructed
- Most resonances decay one to one to their ground state
- Strange weak decays need to be reconstructed

$$\kappa_s\sigma_s^2 = \kappa\sigma^2(K, K^0, \Lambda, \Xi, \Omega \text{ incl. } K^*, \Lambda^*, \Sigma, \Xi^*)$$
$$\kappa_u\sigma_u^2 = \kappa\sigma^2(\pi, p \text{ incl. } \rho, \omega, \Delta, N^*)$$

Ongoing project with P. Alba, W. M. Alberico, R. Bellwied, M. Bluhm, D. Chinellato and M. Weber

Conclusions

- High precision (continuum limit) lattice QCD predicts flavor separation in the crossover from the partonic to the hadronic matter.

- this could lead to a short mixed phase of degrees of freedom in which strange particle formation is dominant

- this should lead to measurable effects in the strange hadron yields (evidence from ALICE)

- new model-independent comparison between theory and experiment: χ_4/χ_2

- work in progress: define a meaningful experimental measurement