Freeze-out parameters for the Large Hadron Collider and the Equation of State

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We explore various moments of conserved charges that can act as a **freeze-out thermometer** at large collision energies.
We present the continuum extrapolated lattice results of the Wuppertal-Budapest collaboration for these candidates and compare to the expectations based on the hadron resonance gas model.
We present the continuum extrapolated **equation of state** and provide a parametrization and a table for download.

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Chemical Freeze-out

Heavy ion experiments at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) have set out the goal to produce and study new forms of strongly interacting matter, such as the quark gluon plasma. Besides direct emissions, we can observe this matter at the point of break-up through the hadrons leaving the system. Prominent approaches include the hydrodynamical modelling of the angular distribution and the study of the event-by-event distribution of conserved charges.
The net charge and proton event-by-event statistics are measured by the STAR, PHENIX (RHIC, BNL) and ALICE (LHC, CERN) experiments for various the beam energies [1,2,3].
Baryon number (B), electric charge (Q) and strageness (S) are conserved charges in QCD. Their even-by-event fluctuations can be calculated from first prinicples, this is the main goal of this study. Comparing the temperature dependence of these fluctuations to experment we can determine the temperature where hadrons freeze out from the quark guon plasma [4,5,6].

In a grand canonical ensemble we obtain the fluctuations as derivatives of the partition function with respect to the chemical potentials:

$$\frac{\chi^{BSQ}_{lmn}}{T^{l+m+n}} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_B/T)^l\partial(\mu_S/T)^m\partial(\mu_Q/T)^n}. \qquad (1)$$

and they are related to the moments of the distributions of the corresponding conserved charges by

$$\text{mean}: M=\chi_1 \qquad \text{variance}: \sigma^2=\chi_2$$
$$\text{skewness}: S=\chi_3/\chi_2^{3/2} \qquad \text{kurtosis}: \kappa=\chi_4/\chi_2^2. \qquad (2)$$

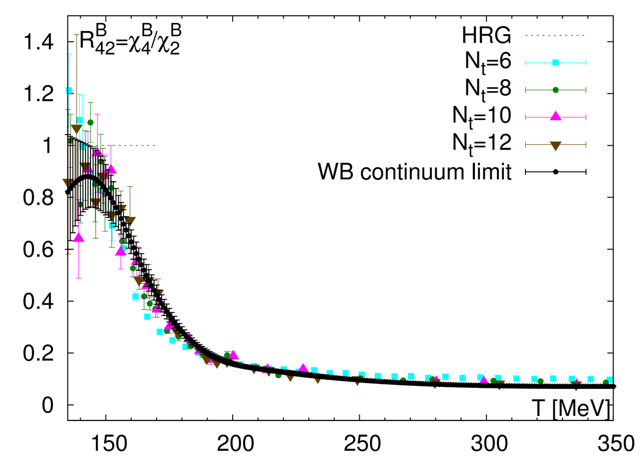
With these moments we can express the volume independent ratios

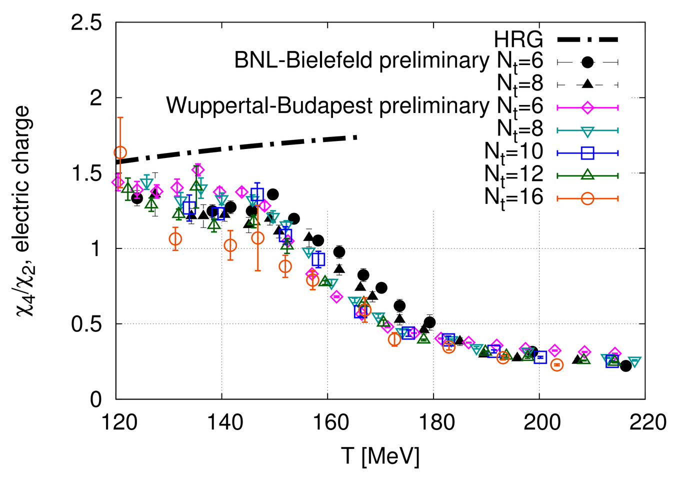
$$S\sigma=\chi_3/\chi_2 \quad ; \quad \kappa\sigma^2=\chi_4/\chi_2$$
$$M/\sigma^2=\chi_1/\chi_2 \quad ; \quad S\sigma^3/M=\chi_3/\chi_1. \qquad (3)$$

In this work we calculate the kurtosis ratios that are direct experimental observables. These will be measured by the ALICE experiment at LHC.

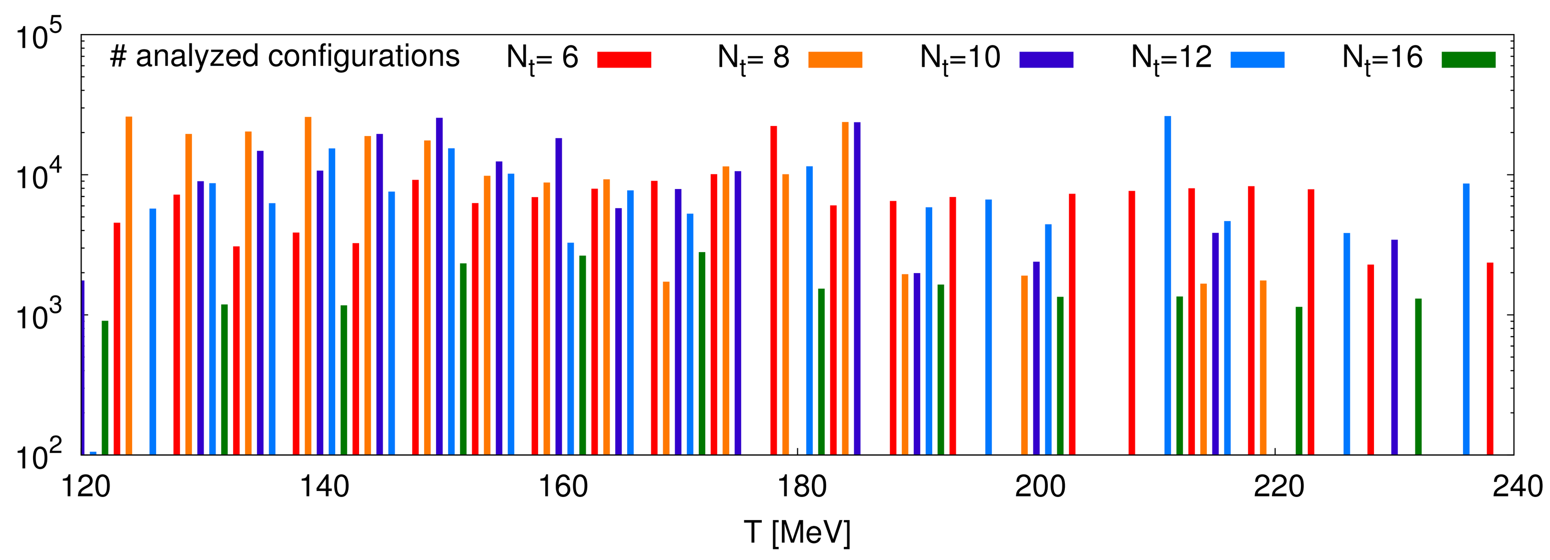
Freeze-out thermometer

While at RHIC the mean and skewness (see Ref [9]) could be calculated, at LHC energies they nearly vanish. One may use the kurtosis of the net baryon (proton) or electric charge distribution, normalized to the variance. At the freeze-out temperature exepriment is expected to agree with the lattice data.



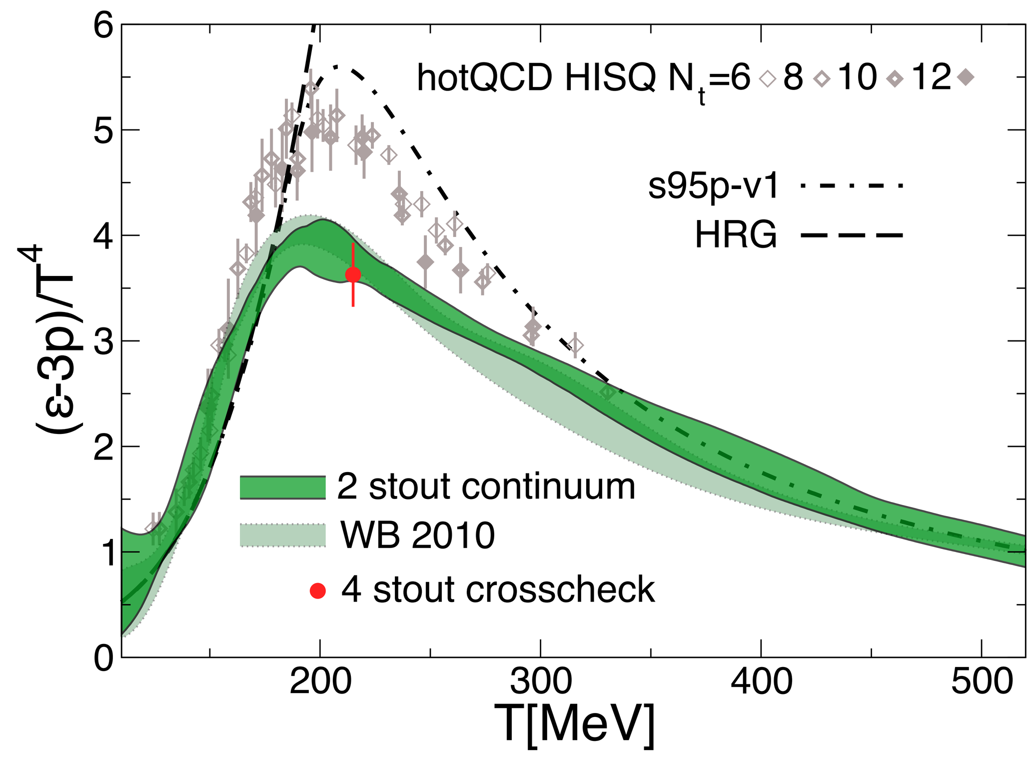


Finite temperature statistics



The number of analyzed configurations exceeds 10^4 for several temperatures. Each bar refers to the respective color-coded lattice resolution.

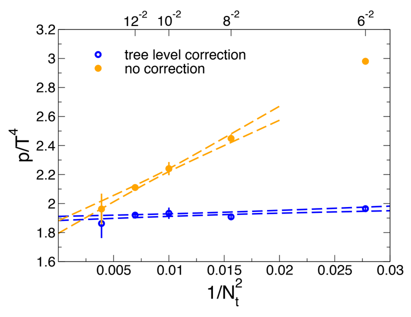
Equation of State

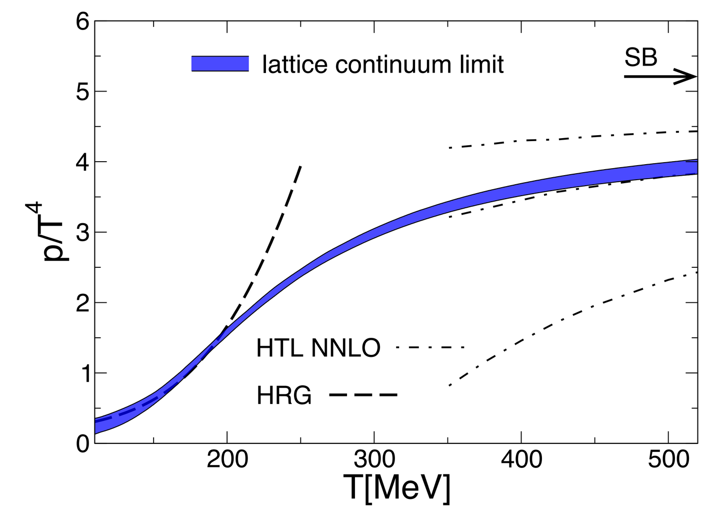


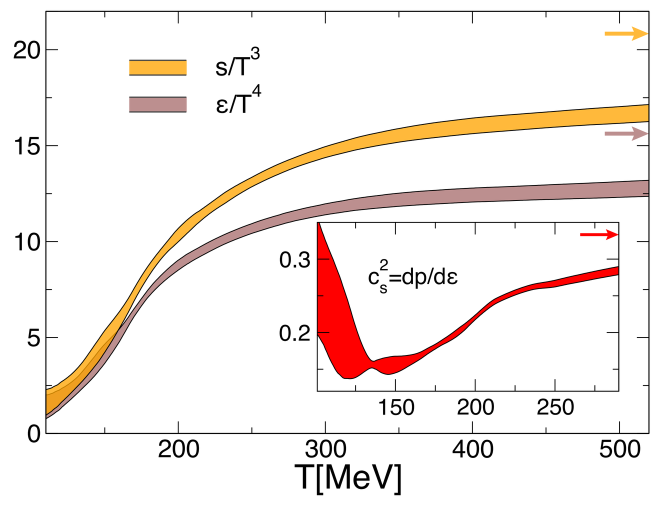
Comparison:

The Hadron Resonance Gas model (solid lines) gives proper description in the hadronic phase. Our results confirm our 2010 result. HISQ data show the status at the 2012 Quark Matter conference.

The pressure and entropy is found by integrating the trace anomaly with respect to the temperature. The constant in the integral is found from first principles by studying the mass dependence of the pressure. The continuum limit is based on $N_t=6,8,10$ and 12 lattices.

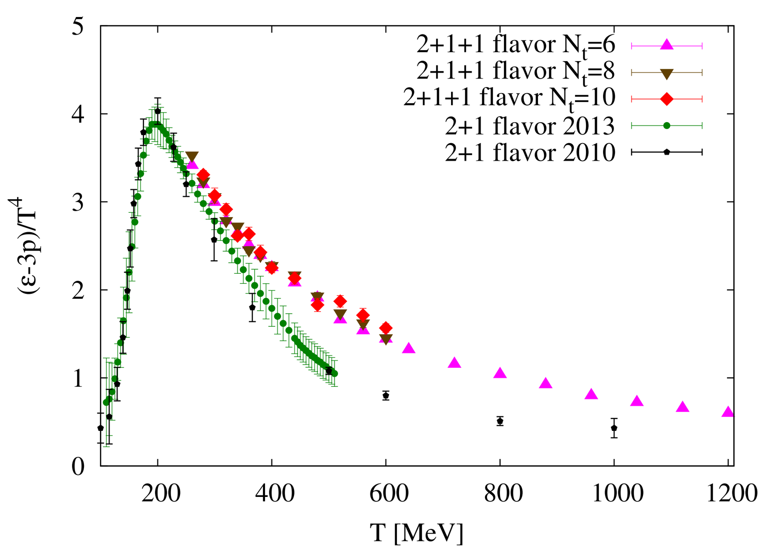


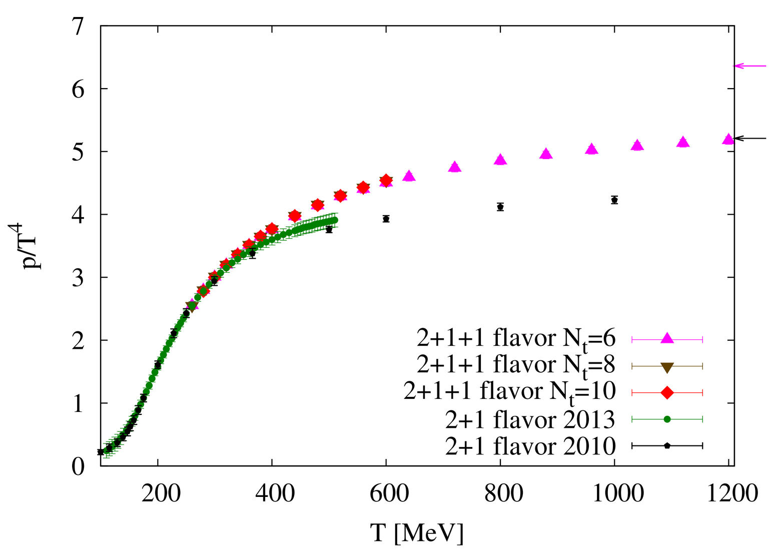




Effect of the charm

If the charm quark is thermalized at very high energies its contribution to the free energy must be taken into account. Preliminary studies with dynamical charm show a deviation about 350 MeV temperature.





Fluctuations an RHIC and LHC

Equation of State for download

click on the ancillary files

Fluctuations: S. Borsanyi, Z. Fodor, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, JHEP 1201 (2012) 138 ; Phys. Rev. Lett. **111** (2013) 062005 ; arXiv:1403.4576 [hep-lat].
Equation of state: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg and K. K. Szabo, Phys. Lett. B **730** (2014) 99
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