Determination of freeze-out conditions from fluctuation observables measured at RHIC

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many thanks to:

P. Alba, W. Alberico, R. Bellwied, V. Mantovani Sarti, M. Nahrgang and C. Ratti

based on 1402.1238, 1403.4903 and 1408.4734

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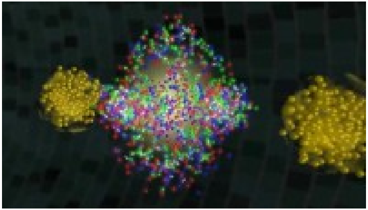
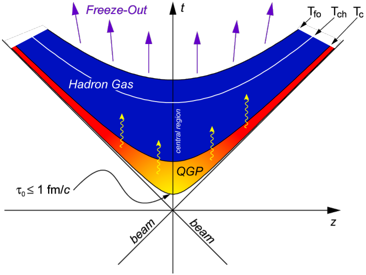
Non-exhaustive introduction



heavy-ion collision

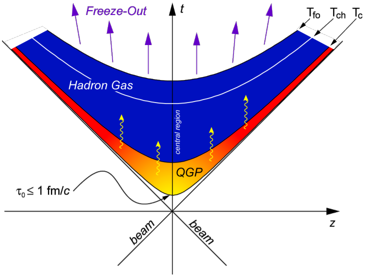


temporal evolution

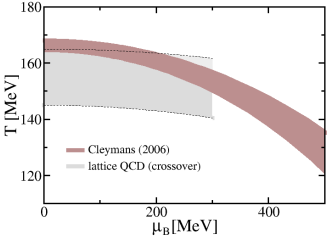
- chemical composition fixed at chemical freeze-out (FO) $\rightarrow$ location in QCD phase diagram?
- **traditional approach**: comparison of measured particle yields or ratios with thermal model calculations (statistical hadronization models (SHMs): hadronic degrees of freedom, various refinements exist!)

  minimal set of fitted parameters: (T, μ_B) for yield ratios; (T, μ_B, V) for yields

Non-exhaustive introduction



temporal evolution



T-μ_B diagram

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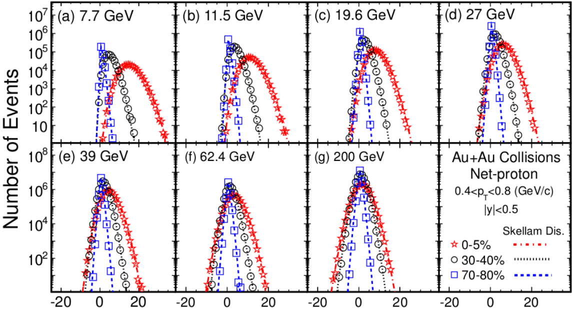
  cf. e.g. J. Cleymans et al., PRC 73 (2006)

Complementary approach

Event-by-event fluctuations of conserved charges

- originally proposed to study the **phase structure** of QCD matter in heavy-ion collisions by varying the beam energy
- suitable observables because behavior of fluctuations sensitive to the state of the matter
- susceptibilities of **conserved charges**: B, Q, S, ...
  - local charge densities only varied through slow diffusion processes
  - show characteristic behavior at a phase transition, e.g. diverge at a critical point
- if the properties of the created matter freeze-out close to the phase transition, signatures are expected to be seen in the data
- experimentally, net-proton number as proxy for net-baryon number determined
- approach used in **lattice QCD** studies (limitations)
- use efficiency corrected data for net-proton number (net-p, 1309.5681) and net-electric charge (net-Q, 1402.1558) fluctuations measured in BES@RHIC by STAR to obtain the chemical FO conditions in a thermal model approach:
  - assumes that fluctuations originate from an equilibrated source

Event-by-event net-distributions

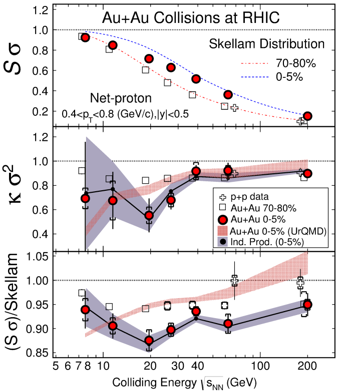


net-p distributions, STAR, PRL 112 (2014) [1309.5681]

- number of measured particles varies from event to event $\rightarrow$ fluctuations
- fluctuations in conserved charges only seen if restricted kinematic acceptance window considered
- determine statistical moments of distributions:
  - mean M,
  - variance σ^2,
  - skewness S,
  - kurtosis κ, ...

Event-by-event net-distributions

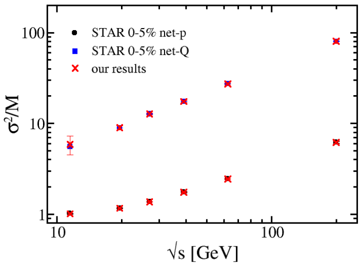
Statistical moments and fluctuations

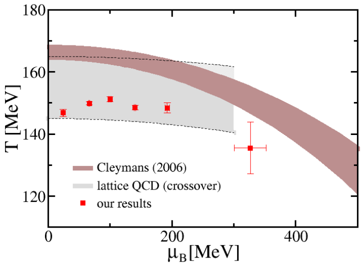


net-p, PRL 112 (2014) [1309.5681]

- fluctuations in the net-number N of interest around its mean $M = \langle N \rangle$ are $\Delta N = N - \langle N \rangle$
- cumulants of the distribution are: $C_1 = \langle N \rangle$, $C_2 = \langle (\Delta N)^2 \rangle$, $C_3 = \langle (\Delta N)^3 \rangle$, $C_4 = \langle (\Delta N)^4 \rangle - 3\langle (\Delta N)^2 \rangle^2, \ldots$
- cumulants are related to the statistical moments as $C_1 = M$, $C_2 = \sigma^2$, $C_3 = S\sigma^3$, $C_4 = \kappa\sigma^4, \ldots$
- for an equilibrated system, cumulants related to generalized susceptibilities $C_n = VT^3\chi_n$, i.e. given by appropriate derivatives of $\ln Z$ w.r.t. chemical potentials
- in this case, cumulant ratios to leading order V-independent: $C_2 / C_1 = \sigma^2 / M$, $C_3 / C_2 = S\sigma$, $C_4 / C_2 = \kappa\sigma^2, \ldots$

Extraction of FO-parameters





- FO-parameters (T, μ_B) extracted from *simultaneous* comparison of experimental data for net-p and net-Q fluctuations with thermal model calculation (μ_Q, μ_S fixed by physical constraints)
- thermal model approach:
  - hadron resonance gas in grand canonical ensemble
  - influence of strong decays of resonances included
  - kinematic cuts in line with experimental analysis applied
  - influence of radial flow accounted for
  - impact of isospin randomization of N ($\overline{N}$) included
- qualitative behavior of net-Q fluctuations dominated by π and p; K give minor quantitative modifications

Isospin randomization

- net-proton number not conserved; final state effects may lead to significant modifications
- reactions of the form

$$p(n) + \pi^0(\pi^+) \rightarrow \Delta^+ \rightarrow n(p) + \pi^+(\pi^0)$$
$$p(n) + \pi^-(\pi^0) \rightarrow \Delta^0 \rightarrow n(p) + \pi^0(\pi^-)$$

  modify primordial protons into undetectable neutrons

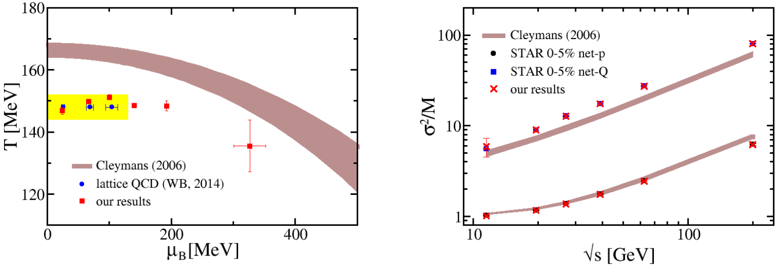
- isospin of nucleons randomized after 2 cycles; depends on pion density and on duration of hadronic phase compared to time for resonance regeneration plus decay

  $\Rightarrow$ binomial distribution of $N_{p(\overline{p})}$ among $N_{N(\overline{N})}$

- allows reconstruction of *thermal* net-B fluctuations (*difficult to measure*) from measured $N_{\overline{p}}$- and N_p-distributions (M. Kitazawa, M. Asakawa, PRC 85 and 86 (2012))
- allows determination of net-p fluctuations from net-B fluctuations calculated in a thermal model, and extraction of FO-conditions from comparison with experimental data

$\rightarrow$ inclusion of this effect was essential to find common FO-conditions for net-p and net-Q fluctuations

Comparison of FO-conditions



- our FO-temperatures are significantly below previous SHM fits
- agreement with recent lattice QCD analysis (WB Collaboration, 1403.4576)
- particle ratios at $\sqrt{s} = 200$ GeV well described except for (multi-)strange hyperon to pion ratios; overall quality of description comparable: $\chi^2/\text{NDF} \approx 5.6/8$ vs. $5.1/8$
- considered fluctuation observables sensitive to light quark sector

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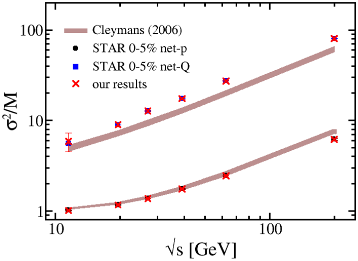

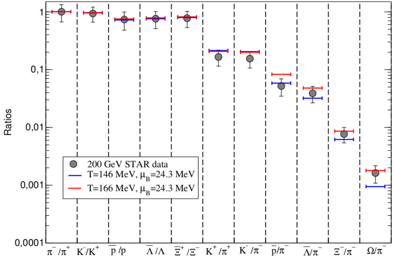

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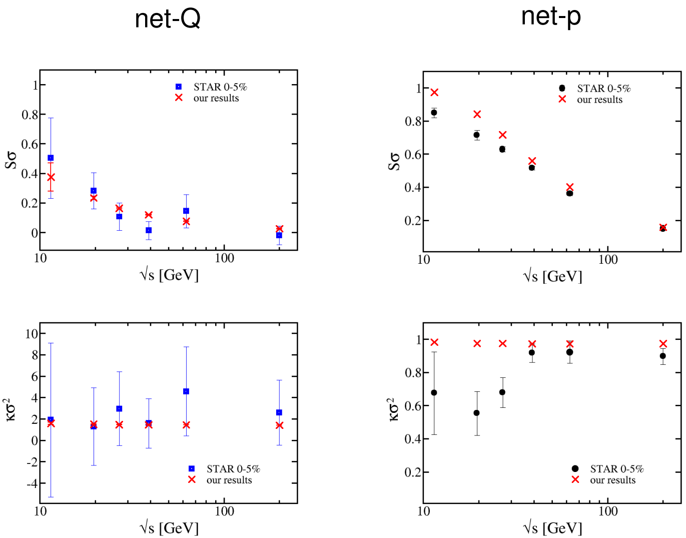
Higher-order cumulant ratios



→ within errors net-Q fluctuations described (errors not limited by statistics)

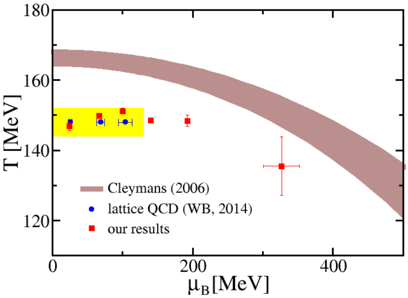
→ toward lower $\sqrt{s}$ visible deviations in higher-order net-proton cumulant ratios

Impact of other fluctuation sources on net-p

source	effect	comments	negligible for high $\sqrt{s}$ in our σ^2/M-analysis?
exact baryon number conservation	reduction of cumulant ratios	effect stronger for HO cumulant ratios and lower $\sqrt{s}$	✓
volume fluctuations	at $\mu_B = 0$ enhancement of cumulant ratios	strongly suppressed in central collisions	✓
excluded volume corrections	reduction of cumulant ratios	effect stronger for HO cumulant ratios and lower $\sqrt{s}$	✓
critical fluctuations	non-monotonic behavior	2^{nd} order PT $\rightarrow C_2$ at $\mu_B = 0 \rightarrow C_6$	non-monotony not seen in σ^2/M-data

A. Bzdak et al., PRC 87 (2013); V. Skokov et al., PRC 88 (2013); M.I. Gorenstein et al., PRC 76 (2007); J. Fu, PLB 722 (2013); V. Skokov et al., PLB 708 (2012); K. Redlich, CEJP 10 (2012); ...

Conclusions



- extraction of FO-conditions from fluctuation observables measured at RHIC:
  - common for net-Q and net-p (as proxy for net-B)
  - comparable with recent lattice QCD results
  - significantly lower FO-temperatures compared to SHM fits
- comparison with measured particle ratios suggests light quark flavor sensitivity of considered fluctuations
- strangeness seems to behave differently $\rightarrow$ fluctuation data needed!