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 1403.4903 and 1402.1238

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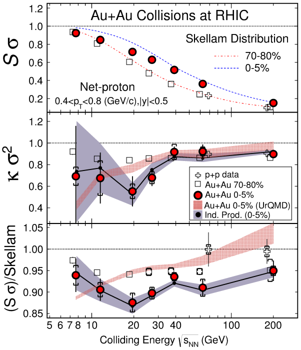
Study of the QCD phase diagram in HIC

- phase structure of QCD matter studied in HIC by varying the beam energy (NA49@SPS; BES@RHIC)
- behavior of fluctuations sensitive to the state of the matter $\rightarrow$ suitable observables
- susceptibilities of conserved charges:
  - $\Rightarrow$ show characteristic behavior at a phase transition
  - $\Rightarrow$ e.g. diverge at a critical point
  - $\Rightarrow$ can be calculated in lattice QCD
- If the properties of the created matter freeze-out close to the phase transition, signatures are expected to be seen in the data.

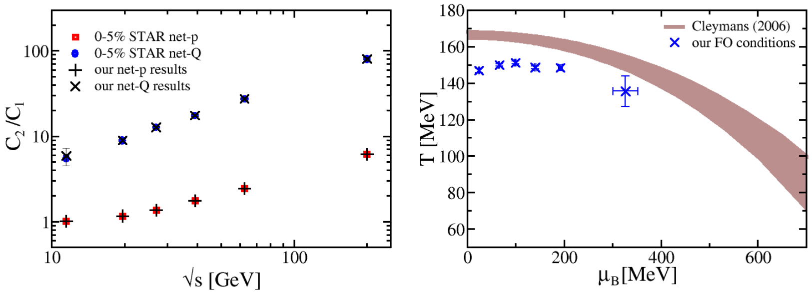


STAR, PRL 112 (2014) [1309.5681]

- Chemical freeze-out (FO) conditions are usually determined from statistical hadronization model (SHM) fits to particle ratios (yields).
- Here, we use recent, efficiency corrected data for net-proton (1309.5681) and net-electric charge (1402.1558) fluctuations measured in BES@RHIC by STAR to obtain the chemical FO conditions!

Main results

Freeze-out conditions



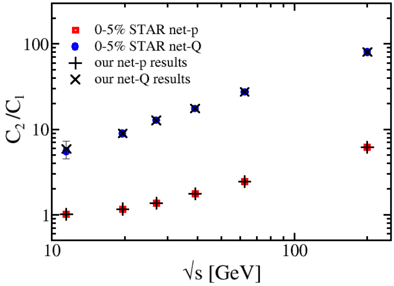
- FO conditions obtained by fit to *efficiency corrected* STAR data of C_2/C_1 for net protons and net-electric charge simultaneously
- approach based on Hadron Resonance Gas (HRG) model in grand canonical ensemble:

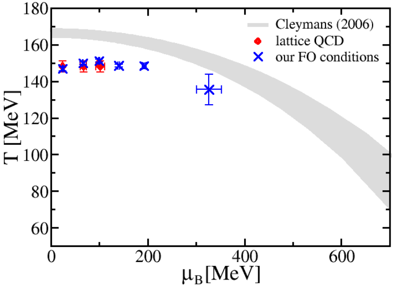
  impose net-strangeness neutrality and fixed $N_Q^{\text{net}}/N_B^{\text{net}}$-ratio; kinematic cuts in line with experimental analysis; contributions from resonance decays included

  for net-Q: π, K, p considered
  for net-p: impact of resonance regeneration in hadronic phase taken into account

Main results

Freeze-out conditions





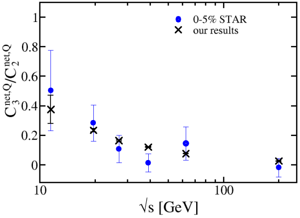
$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

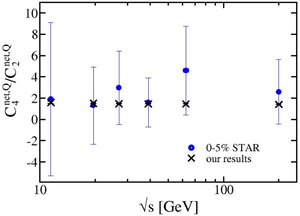
- our FO temperature is significantly below previous SHM fits (J. Cleymans et al., PRC 73 (2006))
- agreement with recent lattice QCD analysis (1403.4576; cf. talk by C. Ratti)
- particle ratios at $\sqrt{s} = 200$ GeV well described except for strange vs. non-strange ratios; cf. poster by P. Alba → flavor hierarchy

Main results

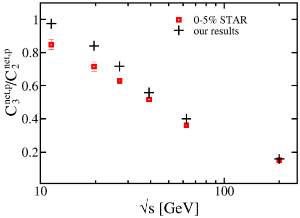
Higher-order cumulant ratios

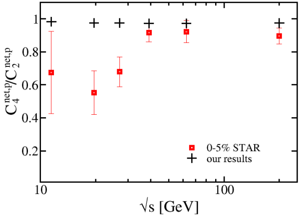
net-Q:





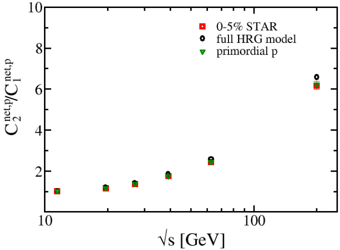
net-p:



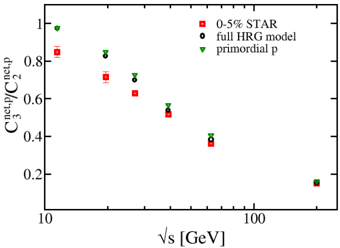


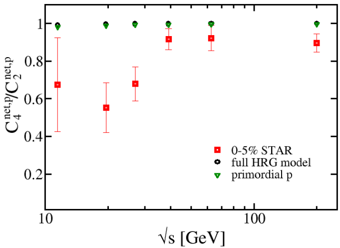
→ toward lower $\sqrt{s}$ visible deviations in higher-order net-proton cumulant ratios remain

Baseline for net protons



- HRG model with 319 hadrons and resonances in *grand canonical ensemble* formulation
- in full HRG model, $C_n^{\mathrm{net},B}$-ratios shown
- primordial p and $\bar{p}$ agree already well with exp. data for $C_2^{\mathrm{net},p} / C_1^{\mathrm{net},p}$ and show deviations in higher-order ratios; numerically close to the corresponding *Skellam limit*





Impact of kinematic cuts and resonance decays

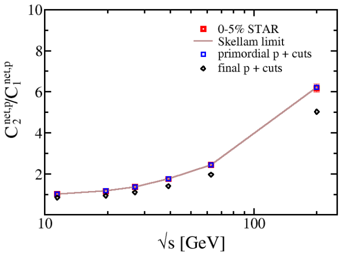
- kinematic cuts:
  - in exp. analysis fluctuations studied in restricted phase space
  - appropriate cuts in y, η and p_T used in model approach (cf. P. Garg et al., PLB 726 (2013))
  - caveat: final kinematics should be studied at the kinetic FO
- resonance decays:
  - contribute to final particle numbers and their fluctuations
  - cumulants of final particle distributions follow from generating function (cf. V.V. Begun et al., PRC 74 (2006); J. Fu, PLB 722 (2013))
  - neglecting contributions accounting for probabilistic character of resonance decays:

$$\widehat{C}_n^{\mathrm{net},p} = \widehat{C}_n^{p} + (-1)^n \, \widehat{C}_n^{\bar{p}} \quad \text{(independent production)}$$

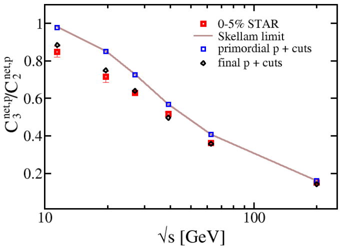
$$\widehat{C}_n^{p} = C_n^{p} + \sum_R C_n^{R} \langle n_p \rangle_R^n$$

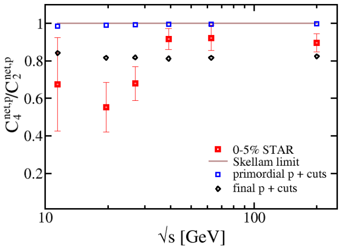
    $\rightarrow 0 \leq \langle n_p \rangle_R \leq 1$ induces deviations from Skellam limit
  - $\widehat{C}_n$ can be obtained as derivatives of the pressure (*partial chemical equilibrium*)
- no weak decay contributions

Impact of kinematic cuts and resonance decays



- primordial p and $\overline{p}$ negligibly affected by kinematic cuts; still close to Skellam limit
- resonance decay contributions result in visible (up to 20%) deviations of final cumulant ratios from Skellam limit (irrespective of kinematic cuts)





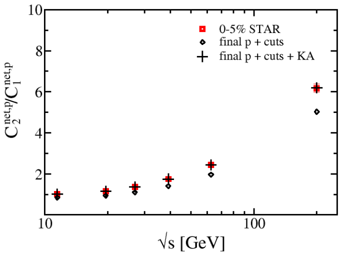
Impact of isospin randomization

- net-baryon number fluctuations difficult to measure (uncharged baryons)
- net-proton number not a conserved quantity; final state effects can modify its fluctuations significantly
- some reactions can change isospin identity of nucleons

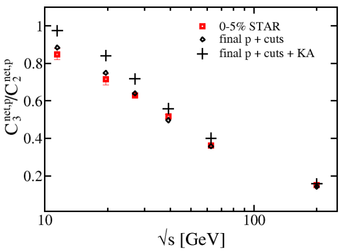
$$p(n) + \pi^0(\pi^+) \to \Delta^+ \to n(p) + \pi^+(\pi^0)$$
$$p(n) + \pi^-(\pi^0) \to \Delta^0 \to n(p) + \pi^0(\pi^-)$$

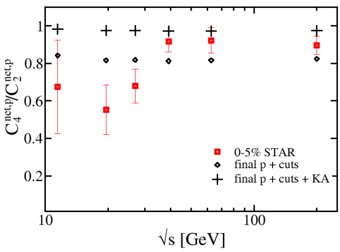
- for sufficiently high π-densities, resonance regeneration rates and a long duration of the hadronic phase (from chemical FO to kinetic FO) $\tau_{\mathrm{hadr.}} \gtrsim$ 1-2 $(\tau_\Delta + 1/\Gamma_\Delta)$ $\Rightarrow$ isospin randomization of nucleons: probability for N_p protons among N_N nucleons follows binomial distribution
- allows reconstruction of thermal N_B^{net}-fluctuations from experimental data on N_p and $N_{\bar{p}}$ distributions (M. Kitazawa, M. Asakawa, PRC 85 and 86 (2012))
- allows to include the effect of isospin randomization in our model on top of the (anti-)nucleon cumulants to obtain final net-proton fluctuations

Impact of isospin randomization



- isospin randomization effects lead to correlations among protons and neutrons
- crucial for the determination of our FO conditions (assumed complete isospin randomization for all $\sqrt{s} \gtrsim 10$ GeV)
- hides non-Skellam behavior induced by resonance decays; fluctuations again close to those of equilibrated hadronic matter



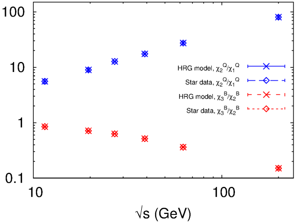


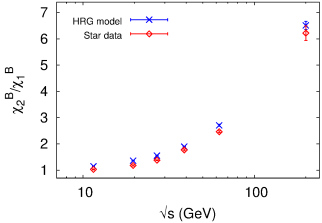
Alternative fit as crosscheck

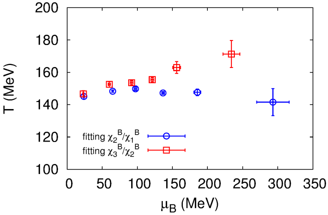
$\rightarrow$ Fit to higher-order ratios possible? How much would FO-conditions change?

- simultaneous fit to $C_2^{\mathrm{net},Q}/C_1^{\mathrm{net},Q}$ and $C_3^{\mathrm{net},p}/C_2^{\mathrm{net},p}$

  $\rightarrow$ leads to visible deviations from $C_2^{\mathrm{net},p}/C_1^{\mathrm{net},p}$ data







- for high $\sqrt{s}$ comparable FO conditions
- for lower $\sqrt{s}$ curvature opposite to lattice QCD expectations
- higher-order cumulants more sensitive to other effects

Estimating other fluctuation sources

A) Exact baryon number conservation: A. Bzdak et al., PRC 87 (2013)

$\sqrt{s}$ [GeV]	p	$\Delta(C_2/C_1)$	$\Delta(C_3/C_2)$
200	0.009	-1.0%	-1.8%
62.4	0.014	-1.4%	-2.8%

- stronger reduction for higher-order cumulant ratios and lower $\sqrt{s}$

B) Excluded volume corrections: M.I. Gorenstein et al., PRC 76 (2007); J. Fu, PLB 722 (2013)

- for reasonable hard-sphere radii ($\sim$ 0.2 - 0.5 fm):

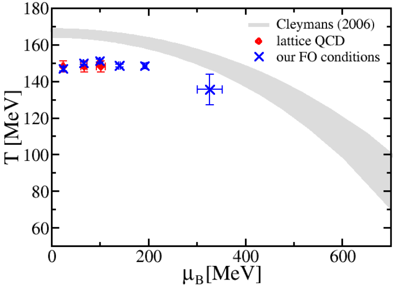
  $\Rightarrow$ negligible influence on $C_2^{\mathrm{net},p}/C_1^{\mathrm{net},p}$

  $\Rightarrow$ larger suppression for higher-order cumulant ratios and lower $\sqrt{s}$

C) Volume fluctuations: V. Skokov et al., PRC 88 (2013)

- estimate volume fluctuations with Glauber MC; strongly suppressed in very central collisions $\Rightarrow$ corrections negligible for $C_2^{\mathrm{net},p}/C_1^{\mathrm{net},p}$ at $\sqrt{s} = 200$ GeV

Conclusions



- comparison of STAR fluctuation data with HRG model:
  - ⇒ kinematic cuts in line with experiment
  - ⇒ contributions from resonance decays
  - ⇒ influence of isospin randomization

- It is possible to determine common FO conditions for net-electric charge and net protons.
- We find good agreement with a recent lattice QCD study.