Freeze-out properties from net-Kaon fluctuations at RHIC

Claudia Ratti\textsuperscript{a}, Rene Bellwied\textsuperscript{a}, Jacquelyn Noronha-Hostler\textsuperscript{b}, Paolo Parotto\textsuperscript{a}, Israel Portillo Vazquez\textsuperscript{a}, Jamie M Stafford\textsuperscript{a}

\textsuperscript{a} Department of Physics, University of Houston, Houston, TX, USA 77204
\textsuperscript{b} Department of Physics and Astronomy, Rutgers University, Piscataway, NJ USA 08854

E-mail: cratti@uh.edu

Abstract. We calculate the net-kaon mean-over-variance in the hadron resonance gas model and compare it to the experimental data by the STAR collaboration. We show that it is not possible to match the experimental values using the freeze-out parameters obtained from a combined fit of net-proton and net-electric charge mean-over-variance. At the highest collision energies, kaons need about 10-15 MeV higher freeze-out temperatures than the light hadrons. We also predict the variance-over-mean and skewness-times-variance for net-Λ particles at light and strange chemical freeze-out parameters. It turns out that these Λ fluctuations are sensitive to the difference in the freeze-out temperatures observed in our analysis.

1. Introduction
Relativistic heavy ion collisions, currently taking place at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), are routinely creating a new phase of matter, the Quark-Gluon Plasma (QGP), which permeated the universe just a few microseconds after the Big Bang. First principle simulations of the theory of strong interactions (QCD) on a discretized lattice show that the transition from hadronic degrees of freedom to the QGP is an analytical crossover at low baryonic density [1, 2, 3].

After hadronization, it is possible to define two important points in the evolution of a heavy-ion collision: the chemical freeze-out, at which all inelastic collisions between the hadrons cease (the chemical composition of the system is fixed at this point), and the thermal freeze-out, at which also elastic collisions cease (the particle spectra are fixed at this point). The measured particle yields and fluctuations carry information about the chemical freeze-out. Thermal fits of particle yields and ratios allow us to extract the freeze-out temperature and chemical potential, \(\{T_f, \mu_B\}\) [4, 5, 6, 7, 8]. It was pointed out that, at small baryon densities, there is a tension between the yields of light particles versus strange particles [9]: it appears that light hadrons prefer a lower \(T_f\) compared to strange hadrons. A similar effect was observed at RHIC [10].

Additional information can be gained by studying fluctuations of conserved charges: fluctuations are more sensitive than yields to the freeze-out parameters [11], and they can be calculated from first-principle lattice QCD simulations [12, 13, 14, 15, 16, 17, 18], thus providing a valuable tool to investigate this issue further (for a recent review, see e.g. [19]). The STAR collaboration recently published experimental measurements for the energy dependence...
of the fluctuations of net-protons [20], net-charge [21], and net-kaons [22]. Experimentally, one can only measure charged particles, so that $K^0$s, $\pi^0$s, and neutrons are not included in these measurements. A previous study in the Hadron Resonance Gas (HRG) model with all experimental effects, such as acceptance cuts in $p_T$ and rapidity and isospin randomization [23], found that the net-proton and net-charge fluctuations indicate a lower chemical freeze-out temperature than the one quoted in the thermal fits [24].

In our analysis [25], we calculate the net-kaon fluctuations in the HRG model, taking into account resonance decays and with the same experimental cuts in rapidity and momentum, and compare them to the recent STAR data from the Beam Energy Scan [22]. We find that, even when using the most up-to-date particle data list as an input for the model, the kaons need larger freeze-out temperatures, compared to the light hadrons. We also predict the values of the $\Lambda$ fluctuations, calculated in the HRG model at the freeze-out parameters of the kaons and of the light hadrons. The results show a clear separation, which can hopefully be resolved by the forthcoming experimental results.

2. Results and conclusions
We calculate the net-kaon fluctuations using the following formula:

$$\tilde{\chi}_n^{K^\pm} = \frac{N_{HRG}}{\sum_i (Pr_{i\rightarrow K^\pm} S_i)} \frac{d_i}{4\pi^2 \partial \mu_S^2} \left\{ \int_{-0.5}^{0.5} dy \int_{0.2}^{1.6} dp_T \times \right.$$

$$\left. \frac{p_T \sqrt{p_T^2 + m_K^2 \cosh[y]}}{(-1)^{B_k+1} + \exp((\cosh[y]/\sqrt{p_T^2 + m_K^2}) - (B_i \mu_b + S_i \mu_S + Q_i \mu_Q))/T) / \mu_B \right\}. \quad (1)$$

Here $Pr_{i\rightarrow K^\pm} = B r_{i\rightarrow K^\pm} n_i(K^\pm)$ is the probability for a resonance $i$ to decay into a charged kaon where $Br_{i\rightarrow K^\pm}$ is the branching for the resonance $i$ to decay into $K^\pm$, and $n_i(K^\pm)$ is the number of times particle $i$ appears in the channel $K^\pm$. We use the same acceptance cuts as described in [22]. Notice that, for $n \geq 2$, there are cross-terms appearing in the above equation.

Since the experimental error-bar is smaller for lower order fluctuations, and the possible sources of non-thermal fluctuations should have a negligible effect in this case, we consider only the ratio of net-kaon mean over variance $\chi_n^K / \chi_n^K$ in our analysis. Since we need two quantities to independently fit $T_f$ and $\mu_B f$, we calculate $\chi_n^K / \chi_n^K$ along the isentropic trajectories from Ref. [26], obtained using Lattice QCD results for the Taylor reconstructed QCD phase diagram at finite $\mu_B$. These isentropes were determined by starting from the chemical freeze-out points for light hadrons from Ref. [23], calculating $S/N_B$ at those points, and imposing that the ratio is conserved on the corresponding trajectory. In this way we take into account the possibility that kaons can freeze-out at a different moment in the evolution of the system at a given collision energy, related to the light particle freeze-out point by the conservation of $S/N_B$. The strangeness and electric charge chemical potentials are fixed by imposing the following conditions to match the experimental situation

$$\sum_{i \in S} n_i(T, \mu_B, \mu_Q, \mu_S) = 0$$

$$\sum_{i \in Q} n_i(T, \mu_B, \mu_Q, \mu_S) = 0.4 \sum_{i \in B} n_i(T, \mu_B, \mu_Q, \mu_S). \quad (2)$$

This procedure allows us to determine both $\{T_f, \mu_B f\}$ for kaons. The curves for $\chi_n^K / \chi_n^K$ as functions of the temperature, calculated along the isentropes, are shown in Fig. 1. They are compared to the experimental values for the same quantity, from which the chemical freeze-out temperature can be determined. In a recent paper [27], Blium and Nahrgang performed a fit of
In conclusion, our analysis points out a tension between the freeze-out parameters obtained, within the same HRG model, from a combined fit of $\chi^p_1/\chi^p_2$ and $\chi^Q_1/\chi^Q_2$ vs. $\chi^K_1/\chi^K_2$. This tension, already pointed out in thermal fits at the LHC and RHIC, could be due to different effects. From lattice QCD there is an indication that strange particles might hadronize at a higher temperature [15], naturally leading to a higher chemical freeze-out temperature as well. Interactions in the hadronic phase might be partially responsible for this observation [28, 29, 30, 31, 32, 33]. Hopefully, future experimental data on net-Λ fluctuations will help to clarify this issue.

**Acknowledgements**

This material is based upon work supported by the National Science Foundation under grants no. PHY-1654219 and OAC-1531814 and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, within the framework of the Beam Energy Scan Theory (BEST) Topical Collaboration. We also acknowledge the support from the Center of Advanced Computing and Data Systems at the University of Houston. The work of R. B. is supported through DOE grant...
Figure 2. Freeze-out parameters at the highest five energies from the Beam Energy Scan at RHIC. The red points were obtained from the combined fit of $\chi^K_1/\chi^K_2$ and $\chi^O_1/\chi^O_2$ [23], the gray bands are obtained from the fit of $\chi^K_1/\chi^K_2$ in this work. Also shown are the freeze-out parameters obtained by the STAR collaboration at $\sqrt{s} = 39$ GeV [10] from thermal fits to all measured ground-state yields (orange point) and only to protons, pions and kaons (blue point).

Figure 3. Left panel: $\chi^K_2/\chi^K_1$ as a function of $\sqrt{s}$. Right panel: $\chi^O_3/\chi^O_2$ as a function of $\sqrt{s}$. In both panels, the red points are calculated at the values of $T_f$ and $\mu_Bf$ extracted from the fit of $\chi^K_1/\chi^K_2$, while the blue points are calculated at the values of $T_f$ and $\mu_B f$ extracted from the combined fit of $\chi^K_1/\chi^K_2$ and $\chi^O_1/\chi^O_2$ in Ref. [23].

DEFG02-07ER41521.

References
[1] Aoki Y, Endrodi G, Fodor Z, Katz S D and Szabo K K 2006 Nature 443 675–678 (Preprint hep-lat/0611014)
[2] Borsanyi S, Fodor Z, Hoelbling C, Katz S D, Krieg S, Ratti C and Szabo K K (Wuppertal-Budapest) 2010 JHEP 09 073 (Preprint 1005.3508)
[3] Bazavov A et al. 2012 Phys. Rev. D85 054503 (Preprint 1111.1710)
[4] Cleymans J, Oeschler H and Redlich K 1999 Phys. Rev. C59 1663 (Preprint nucl-th/9809027)
[5] Andronic A, Braun-Munzinger P and Stachel J 2009 Phys. Lett. B673 142–145 [Erratum: Phys. Lett.B678,516(2009)] (Preprint 0812.1186)
[6] Manninen J and Becattini F 2008 Phys. Rev. C78 054901 (Preprint 0806.4100)
[7] Abelev B I et al. (STAR) 2010 Phys. Rev. C81 024911 (Preprint 0909.4131)
[8] Aggarwal M M et al. (STAR) 2011 Phys. Rev. C83 034910 (Preprint 1008.3133)
[9] Floris M 2014 Nucl. Phys. A931 103–112
[10] Adamczyk L et al. (STAR) 2017 Phys. Rev. C96 044904 (Preprint 1701.07065)
[11] Alba P, Bellwied R, Bluim M, Mantovani Sarti V, Nahrgang M and Ratti C 2015 Phys. Rev. C92 064910
[12] Karsch F 2012 Central Eur. J. Phys. 10 1234–1237
[13] Bazavov A et al. 2012 Phys. Rev. Lett. 109 192302
[14] Borsanyi S, Fodor Z, Katz S D, Krieg S, Ratti C and Szabo K K 2013 Phys. Rev. Lett. 111 062005
[15] Bellwied R, Borsanyi S, Fodor Z, Katz S D and Ratti C 2013 Phys. Rev. Lett. 111 202302
[16] Borsanyi S, Fodor Z, Katz S D, Krieg S, Ratti C and Szabo K K 2014 Phys. Rev. Lett. 113 052301
[17] Bazavov A et al. 2016 Phys. Rev. D93 014512
[18] Noronha-Hostler J, Bellwied R, Gunther J, Parotto P, Pasztor A, Vazquez I P and Ratti C 2016 (Preprint 1607.02527)
[19] Ratti C 2018 (Preprint 1804.07810)
[20] Adamczyk L et al. (STAR) 2014 Phys. Rev. Lett. 112 032302 (Preprint 1309.5681)
[21] Adamczyk L et al. (STAR) 2014 Phys. Rev. Lett. 113 092301 (Preprint 1402.1558)
[22] Adamczyk L et al. (STAR) 2017 (Preprint 1709.00773)
[23] Alba P, Alberico W, Bellwied R, Bluim M, Mantovani Sarti V, Nahrgang M and Ratti C 2014 Phys. Lett. B738 305–310
[24] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2017 (Preprint 1710.09425)
[25] Bellwied R, Noronha-Hostler J, Parotto P, Portillo Vazquez I, Ratti C and Stafford J M 2018 (Preprint 1805.00088)
[26] Gunther J, Bellwied R, Borsanyi S, Fodor Z, Katz S D, Pasztor A and Ratti C 2017 EPJ Web Conf. 137 07008 (Preprint 1607.02493)
[27] Bluim M and Nahrgang M 2018 (Preprint 1806.04499)
[28] Becattini F, Steinheimer J, Stock R and Bleicher M 2017 Phys. Lett. B764 241–246 (Preprint 1605.09694)
[29] Rapp R and Shuryak E V 2001 Phys. Rev. Lett. 86 2980–2983 (Preprint hep-ph/0008326)
[30] Rapp R and Shuryak E V 2002 Nucl. Phys. A698 587–590 (Preprint hep-ph/0104006)
[31] Rapp R 2002 Phys. Rev. C66 017901 (Preprint hep-ph/0204131)
[32] Steinheimer J, Aichelin J and Bleicher M 2013 Phys. Rev. Lett. 110 042501 (Preprint 1203.5302)
[33] Becattini F, Bleicher M, Kollegger T, Schuster T, Steinheimer J and Stock R 2013 Phys. Rev. Lett. 111 082302 (Preprint 1212.2431)