Higher Order Moments of Proton Number
Fluctuations in Au+Au Collisions at 1.23 AGeV
studied with HADES

Melanie Szala for the HADES collaboration
Goethe Universität, Frankfurt am Main, Germany
E-mail: m.szala@gsi.de

Abstract.
The HADES (High Acceptance DiElectron Spectrometer) experiment at the SIS18 accelerator of the GSI Helmholtzzentrum für Schwerionenforschung investigates heavy-ion collisions at kinetic beam energies of a few GeV per nucleon. We have carried out a detailed moment analysis of (net-)proton distributions of Au+Au collisions with 1.23A GeV ($\sqrt{s_{NN}}=2.41$ GeV). We present here the correction techniques used in this investigation.

1. Introduction
Heavy-ion collisions at kinetic beam energies of a few GeV per nucleon provide access to the thermodynamics of QCD in the low T and high $\mu_B$ region of the phase diagram. In particular, higher order moments of conserved quantities (e.g. baryon number, charge, strangeness) are predicted to be sensitive to a first order phase transition and especially to the critical point of the QCD phase diagram [1]. Indeed, fluctuations characteristic of the latter features would modify these moments. On the other hand, all kind of detector effects might also modify the measured distributions, hence careful investigations of the efficiency corrections are mandatory. Measuring at SIS18, the HADES detector allows to extend the data taken in the RHIC beam-energy scan [2] to bombarding energies in the few-GeV regime. In this contribution we discuss our investigations of efficiency corrections to the observed fluctuation signal.

The first four moments of a particle number distribution are its mean ($M$), its variance ($\sigma$), its skewness ($S$) and its kurtosis ($\kappa$). To cancel the volume effect of the collision system to first order the scaled skewness $S \cdot \sigma$ and kurtosis $\kappa \cdot \sigma^2$ are often used instead. It is assumed that these experimental observables are related to thermodynamic susceptibility ratios which can be directly calculated in Lattice QCD or in models, e.g. the Hadron Resonance Gas (HRG) model.

2. Experimental Setup
The HADES spectrometer is a fixed target experiment located at the heavy-ion synchrotron SIS18 of the Helmholtzzentrum für Schwerionenforschung GSI in Darmstadt, Germany [3]. Since 2002, the HADES experiment operates with the aim of investigating dense matter in the energy regime of a few GeV per nucleon.

The spectrometer was constructed to have a large geometrical acceptance covering polar angles
from 18 to 85 degrees and almost the full azimuthal angle (see Fig. 1). Further characteristics of the spectrometer are its good momentum resolution and high read-out rate. In 2012 HADES has recorded about seven billion Au+Au collisions at a bombarding energy of 1.23 GeV/u ($\sqrt{s_{NN}} = 2.41$ GeV). With these large statistics the higher order moments of proton number distributions can be investigated in great detail.

Figure 1. Cross section of the HADES spectrometer. The spectrometer is divided into 6 identical sectors that are placed symmetrically around the beam axis.

Figure 2. Correlation between the momentum and $\beta$ of all selected tracks. Black lines correspond to the expected values for different particle species.

The particle identification is based on a velocity vs. momentum x polarity correlation (Fig. 2), where the velocity is determined from the time-of-flight measurement in the TOF and RPC detectors with respect to the time-zero information of the START detector and the tracked flight path. If needed, additional particle discrimination power is gained from the energy loss (dE/dx) information in the MDC and TOF. Particle multiplicity is usually used in the centrality determination. However, for the moment analysis, a proton-independent centrality determination is necessary to avoid autocorrelations between protons involved in our moment analysis and the centrality definition. Therefore, the projectile spectators of the collision are detected by a forward wall installed at the end of the HADES spectrometer (Fig. 1). It consists of plastic scintillators and covers the small polar angle range ($\theta = 0.5 - 7.5^\circ$). In the scintillators energies deposited by the spectators and the centrality of the collision can be derived therefrom.

Our analysis investigates fluctuations of conserved quantities. When considering the entire reaction system, there will be no fluctuations in the conserved quantities. In the investigation of a sufficiently small subsystem, fluctuations occur because the subsystem can exchange conserved quantities with the rest of the reaction volume. The entire system corresponds to the total rapidity distribution of all particles. The subsystem used for our further analysis is defined by the particles within a smaller subsystem of the total rapidity distribution. In Figure 3 the measured rapidity distribution for protons in Au + Au collisions at $\sqrt{s_{NN}} = 2.41$ GeV is shown. For the further analysis a phase space bin of $y_{accept} = y_{lab} \pm 0.2$ was selected and additionally a transversal momentum of $p_T = 400 - 1600$ MeV/c in order to investigate a reasonably large subsystem avoiding spectator contributions and edge effects of the detector.
Figure 3. Experimental phase space distribution of protons within HADES and our phase space selection (green rectangle) for Au+Au collisions at $\sqrt{s_{NN}} = 2.41$ GeV.

Figure 4. Uncorrected $N_p$ multiplicity distributions within the selection for 0-10% (red), 10-20% (yellow), 20-30% (green) and 30-40% (blue) central collisions.

3. Efficiency Correction

The efficiency correction is an important step in obtaining the true higher order moments of the proton multiplicity distribution. It has been shown in [4] that the moments of the proton multiplicity distributions are drastically influenced by acceptance and efficiency. In order to make valid statements about the properties of the created system the true distributions have to be extracted. For this purpose, detailed investigations of different efficiency correction methods were performed with Au + Au UrQMD events and full scale GEANT detector simulations. Two different approaches were tested: correction of the moments (as proposed in [4, 5]) and unfolding of the distributions [6].

The first method is based on the calculated cumulants of the measured particle distribution (see Fig. 4). To correlate the true cumulants with the experimentally measured cumulants, a correction was derived assuming a binomial probability parameter [4].

Figure 5. Combined efficiency and acceptance correction factor for protons in the analysed phase space cells in 30-40% central collisions.

Figure 6. Centrality dependent efficiency shown for two different sectors of the HADES spectrometer. With this correlation, a sector and centrality dependent event-by-event efficiency correction is performed.
The correction was subsequently extended so that the efficiencies depend on the particle species as well as the phase space, such as transverse momentum and rapidity [5]. The efficiencies for the different centrality classes inside the selected phase space window are obtained from UrQMD events and a GEANT detector simulation (see Fig. 5 and 6). A special feature of the HADES spectrometer is its subdivision into 6 identical sectors which are placed symmetrically around the beam axis and are read out separately. Because of anisotropic particle emission in non-central collisions, the efficiencies differ from sector to sector within an event due to the orientation of the event plane. The resulting approach is a dynamic efficiency correction, which is carried out sector-by-sector and event-by-event (E-by-e). For each sector, the average track density is determined for different centrality selections and then linearly interpolated. The centrality dependance is shown in Figure 6 as an example for two different sectors. A dynamic efficiency can now be determined and used for each event in dependence on the centrality, the sector, the track density within the sector and the phase space.

Unfolding is a mathematical method that is used to deconvolute two folded functions. While a convolution can be easily calculated, its inversion is not always possible. For this purpose, the TUnfold package implemented in ROOT, which is essentially based on a regularized matrix inversion, is used in this analysis. The unfolding is based on the least squares method, including Tikhonov regularisation and an optional area conservation [6]. To determine the strength of the regularization parameter, the L-curve method and the scans of global correlation coefficients are implemented.

![Figure 7. Simulated response matrix for the unfolding correction method.](image)

In the experiment, the proton distributions are measured only within the acceptance of the detector and under the influence of detector and trace reconstruction efficiency. For this purpose, a detector response matrix $A$ is required for the unfolding. In order to determine this response matrix, a realistic detector simulation is used.

The response matrix $A$ for the HADES detector is shown in Figure 7 and is filled using an UrQMD and Geant simulation. On the x-axis, the number of all UrQMD protons per event is shown; it corresponds to the true number of protons. The number of protons per event after particle detection and reconstruction is shown on the y-axis. The response matrix is only filled with particles within the previously selected phase space window of $y_{accept} = y_{lab} \pm 0.2$ and $p_T = 400 - 1600$ MeV/c.

To compare the two methods of efficiency correction, the unfolding method was applied in the same centrality classes and the same phase space bin. Within error bars, the unfolding method delivers a reliable result.

After their successful assessment in the simulation, both methods were applied to the HADES experimental data and the higher moments of the proton distributions were extracted. We find
that the two methods provide plausible and consistent results in the Au + Au data (see Fig. 8 for preliminary results).

Figure 8. Measured $S \cdot \sigma$ and $\kappa \cdot \sigma^2$ of protons as function of mean number of participants. Two different methods of efficiency correction were applied, correcting the moments (green) and unfolding (yellow). The results are modified further by volume fluctuation corrections based on a Glauber model (see text).

4. Volume Fluctuations
Experimentally measured dynamical event-by-event fluctuation signals such as cumulants of (net-)particle distributions can also be modified by the fluctuations of the number of participants in a given centrality selection [7, 8]. To correct the data for this effect, we have applied the procedure of Skokov et al. [7] on the higher order moments (see Fig. 8).

For the volume correction we assume that the volume scales like the number of participants and the corresponding $N_{part}$ distributions were modeled with the Glauber and IQMD models. The volume corrections are thus model-depend and investigations of systematic effects are on-going.

5. Summary and Outlook
The results shown here are only preliminary results and the analysis of the higher moments is on-going. Investigations of the influence of the centrality selection and the model-dependance of volume fluctuations on the higher moments are needed to obtain systematic uncertainties. The necessary corrections need to be carefully studied, before any comparison with other experiment and theory becomes meaningful.

References
[1] M.A. Stepanov, Phys. Rev. Lett. 102 (2009) 03230
[2] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 112 (2014) 032302
[3] G. Agakishiev et al. [HADES Collaboration], Eur. Phys. J. A 41 (2009) 243-277
[4] A. Bzdak and V. Koch, Phys. Rev. C 86 (2012) 044904
[5] A. Bzdak and V. Koch, Phys. Rev. C 91 (2015) no.2, 027901
[6] S. Schmitt, JINST 7 (2012) T10003
[7] V. Skokov, B. Friman, K. Redlich, Phys. Rev. C 88 (2013) 034911
[8] P. Braun-Munzinger, A. Rustamov, J. Stachel, Nucl. Phys. A 960 (2017) 114-130