PROCEEDINGS OF SCIENCE

Dynamical Study of Fluctuations in Relativistic Nuclear Collisions

PoS(CPOD07)021

Volodymyr Konchakovski[∗ †]
Helmholtz Research School, Frankfurt, Germany and
Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
E-mail: `voka@fias.uni-frankfurt.de`

Event-by-event multiplicity fluctuations in nucleus-nucleus collisions from low SPS up to RHIC energies have been studied within the HSD transport approach. Fluctuations of baryonic number and electric charge also have been explored for Pb+Pb collisions at SPS energies in comparison to the experimental data from NA49. We find a dominant role of the fluctuations in the nucleon participant number for the final hadron multiplicity fluctuations and a strong influence of the experimental acceptance on the final results.

Critical Point and Onset of Deconfinement - 4th International Workshop
July 9 - 13, 2007
Darmstadt, Germany

[∗]Speaker.
[†]In collaboration with E.L. Bratkovskaya and M.I. Gorenstein.

1. Introduction

The event-by-event fluctuations in high energy nucleus-nucleus (A+A) collisions (see e.g., the reviews [1]) are expected to be closely related to the transition between different phases of the QCD matter. Measuring the fluctuations one might observe anomalies of the onset of deconfinement [2] and dynamical instabilities when the expanding system goes through the 1-st order transition line between the quark-gluon plasma and the hadron gas [3]. Furthermore, the QCD critical point may be signaled by a characteristic pattern in fluctuations [4].

The microscopic Hadron-String-Dynamics (HSD) transport model [5] which gives rather reliable estimates for the inclusive spectra of charged hadrons in A+A collisions from SIS to RHIC energies [6] has been used to study fluctuations.

2. Fluctuations in the number of participants

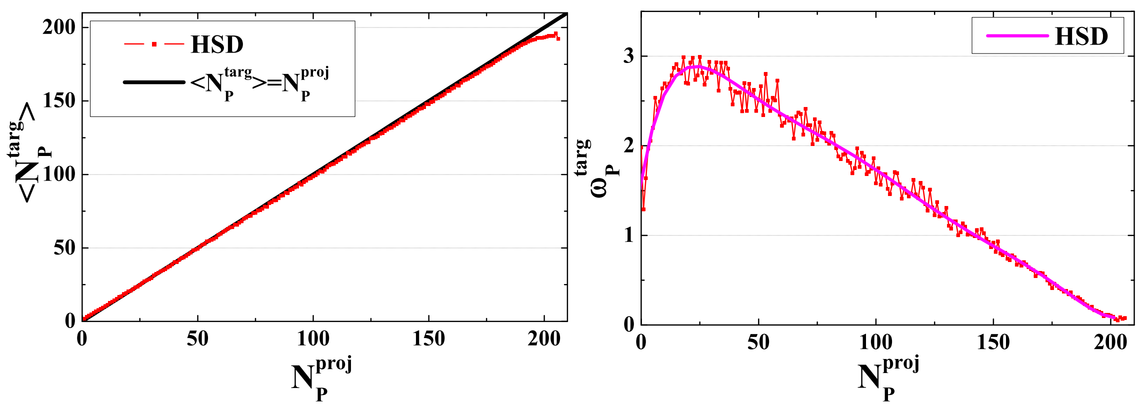

Figure 1: The HSD simulations in Pb+Pb collisions at 158 AGeV for the average value $\langle N_P^{targ} \rangle$ (*left*) and the scaled variances ω_P^{targ} (*right*) as functions of N_P^{proj}.

The centrality selection is an important aspect of fluctuation studies in A+A collisions. At the SPS fixed target experiments the samples of collisions with a fixed number of projectile participants N_P^{proj} can be selected to minimize the participant number fluctuations in the sample of collision events. This selection is possible due to a measurement of the number of nucleon spectators from the projectile, N_S^{proj}, in each individual collision by a calorimeter which covers the projectile fragmentation domain. However, even in the sample with $N_P^{proj} = const$ the number of target participants fluctuates considerably. In the following the variance, $Var(n) \equiv \langle n^2 \rangle - \langle n \rangle^2$, and scaled variance, $\omega \equiv Var(n)/\langle n \rangle$, where n stands for a given random variable and $\langle \cdots \rangle$ for event-by-event averaging, will be used to quantify fluctuations. In each sample with $N_P^{proj} = const$ the number of target participants fluctuates around its mean value, $\langle N_P^{targ} \rangle = N_P^{proj}$, with the scaled variance ω_P^{targ} (Fig. 1) Within the HSD and UrQMD transport models it was found in Ref. [7] that the fluctuations of N_P^{targ} strongly influence the charged hadron fluctuations. The constant values of N_P^{proj} and fluctuations of N_P^{targ} lead also to an asymmetry between the fluctuations in the projectile and target hemispheres. The consequences of this asymmetry depend on the A+A dynamics as discussed in Ref. [8].

PoS(CPOD07)021

3. Multiplicity fluctuations

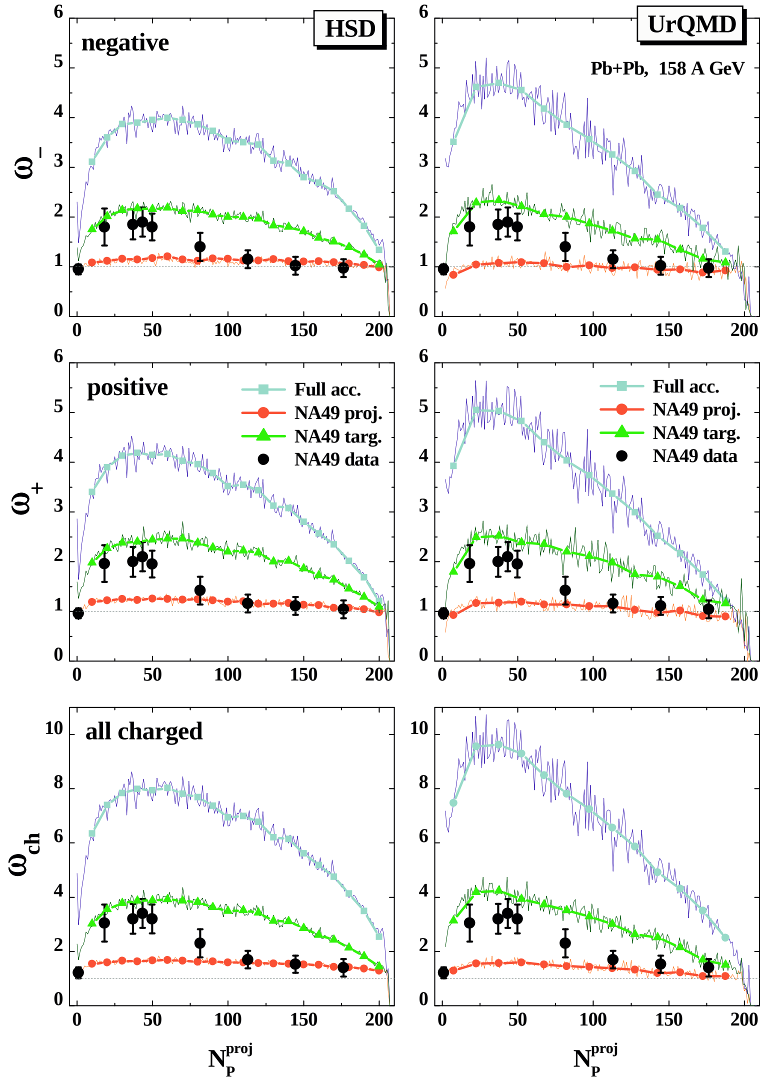

Figure 2: The results of the HSD (left) and UrQMD (right) simulations are shown for ω_-, ω_+, and ω_{ch} in Pb+Pb collisions at 158 AGeV as functions of N_P^{proj}. The black points are the NA49 data. The different lines correspond to the model simulations with the original NA49 acceptance, $1.1 < y < 2.6$, in the projectile hemisphere (lower lines), the NA49-like acceptance in the mirror rapidity interval, $-2.6 < y < -1.1$, in the target hemisphere (middle lines), and full 4π acceptance (upper lines).

From an output of the HSD and UrQMD minimum bias simulations we form the samples of Pb+Pb events with fixed values of N_P^{proj}. In Fig. 2 we present the HSD and UrQMD results and compare them with the NA49 data for the scaled variances of negatively, positively, and all charged particles in Pb+Pb collisions at 158 AGeV. The final particles in the HSD and UrQMD simulations are accepted at rapidities $1.1 < y < 2.6$ (we use particle rapidities in the Pb+Pb c.m.s. frame) in accord to the NA49 transverse momentum filter [9]. This is done to compare the HSD and UrQMD results with the NA49 data. The HSD and UrQMD simulations both show flat ω_i values, $\omega_- \approx \omega_+ \approx 1.2$, $\omega_{ch} \approx 1.5$, and exhibit almost no dependence on N_P^{proj}. The NA49 data, in contrast, exhibit an enhancement in ω_i for $N_P^{proj} \approx 50$. The data show maximum values, $\omega_- \approx \omega_+ \approx 2$ and $\omega_{ch} \approx 3$, and a rather strong dependence on N_P^{proj}.

Fig. 2 also shows results of the HSD and UrQMD simulations for the full 4π acceptance for final particles, and shows the NA49-like acceptance in the mirror rapidity interval, $-2.6 < y < -1.1$ of the target hemisphere. HSD and UrQMD both result in large values of ω_i, i.e. large fluctuations in the backward hemisphere: in the backward rapidity interval $-2.6 < y < -1.1$ (target hemisphere) the fluctuations are much larger than those calculated in the forward rapidity interval $1.1 < y < 2.6$ (projectile hemisphere, where the NA49 measurements have been done). Even larger fluctuations follow from the HSD and UrQMD simulations for the full acceptance of final particles.

4. Baryon number fluctuations

The fluctuations of the net baryon number have been studied in [10]. These fluctuations are most closely related to the fluctuations of the number of participant nucleons because of baryon number conservation.

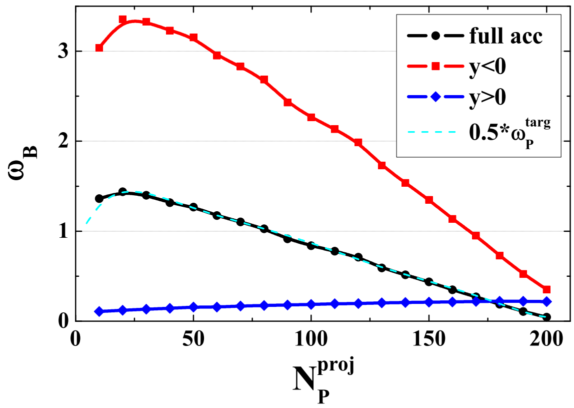

Figure 3: The HSD simulations for Pb+Pb collisions at 158 AGeV for fixed values of N_P^{proj}. The baryon number fluctuations in full acceptance, ω_B, in projectile hemisphere, ω_B^p (lower curve), and in target hemisphere, ω_B^t (upper curve). The dashed line corresponds to 0.5 ω_P^{targ}.

The HSD results for ω_B in Pb+Pb at 158 AGeV are presented in Fig. 3. In each event we subtract the nucleon spectators when counting the number of baryons. The net baryon number in the full phase space, $B \equiv N_B - N_{\overline{B}}$, equals then to the total number of participants $N_P = N_P^{targ} + N_P^{proj}$. At fixed N_P^{proj} the N_P number fluctuates due to fluctuations of N_P^{targ}. These fluctuations correspond to an average value, $\langle N_P^{targ} \rangle \simeq N_P^{proj}$, and a scaled variance, ω_P^{targ} (see Fig. 1). Thus, for the net baryon number fluctuations in the full phase space we find,

$$\omega_B = \frac{Var(N_P)}{\langle N_P \rangle} \simeq \frac{\langle \left(N_P^{targ}\right)^2 \rangle - \langle N_P^{targ} \rangle^2}{2\langle N_P^{targ} \rangle} = \frac{1}{2}\, \omega_P^{targ} \,. \qquad (4.1)$$

A factor $1/2$ in the right hand side of Eq. (4.1) appears because only half of the total number of participants fluctuates.

Let us introduce ω_B^p and ω_B^t, where the superscripts p and t mark quantities measured in the projectile and target momentum hemispheres, respectively. Fig. 3 demonstrates that $\omega_B^t > \omega_B^p$, both in the whole projectile-target hemispheres and in the symmetric rapidity intervals. On the other hand one observes that $\omega_B^p \approx \omega_B^t$ in most central collisions. This is because the fluctuations of the target participants become negligible in this case, i.e. $\omega_P^{targ} \to 0$ (Fig. 1, right). As a consequence the fluctuations of any observable in the symmetric rapidity intervals become identical in most central collisions.

5. Energy dependence of multiplicity fluctuations

In general, one can define two groups of hadron observables. The first group includes observables which are rather similar in A+A and p+p collisions, thus, they can be reasonably described within the WNM. The second group consists of A+A observables which are very different from those in p+p collisions. The question arises: are the multiplicity fluctuations in A+A collisions close to those in p+p reactions, or are they very different?

To answer this question let us first consider the model predictions. To compare central collisions of heavy nuclei and N+N collisions within the HSD model we construct the multiplicities and scaled variances of N+N using the HSD results for p+p, p+n and n+n collisions:

$$\langle N_i^{NN} \rangle \;=\; \alpha_{pp}\, \langle N_i^{pp} \rangle \;+\; \alpha_{pn}\, \langle N_i^{pn} \rangle \;+\; \alpha_{nn}\, \langle N_i^{nn} \rangle\;, \tag{5.1}$$

$$\omega_i^{NN} \;=\; \frac{1}{\langle N_i^{NN} \rangle}\, \left[\alpha_{pp}\, \omega_i^{pp}\, \langle N_i^{pp} \rangle \;+\; \alpha_{pn}\, \omega_i^{pn}\, \langle N_i^{pn} \rangle \;+\; \alpha_{nn}\, \omega_i^{nn}\, \langle N_i^{nn} \rangle\right]\;, \tag{5.2}$$

where $\alpha_{pp},\ \alpha_{pn},\ \alpha_{nn}$ are the probabilities of proton-proton, proton-neutron, and neutron-neutron collisions in Pb+Pb (A=208, Z=82) or Au+Au (A=197, Z=79) reactions.

In Fig. 4 the HSD model results are shown for the multiplicities per participating nucleons, $n_i = \langle N_i \rangle / \langle N_P \rangle$, and for the scaled variances, ω_i, in central collisions (zero impact parameter, $b = 0$) of Pb+Pb at $E_{lab} = 10$, 20, 30, 40, 80, 158 AGeV and Au+Au at $\sqrt{s_{NN}} = 62$, 130, 200 GeV. From Fig. 4 one concludes that the HSD results for the scaled variances in central A+A collisions are close to those in N+N collisions. For the SPS energy region all scaled variances, $\omega_\pm$ and ω_{ch}, in central A+A collisions are slightly below the N+N results. The reversed situation is observed for RHIC energies. Thus, the HSD results for multiplicity fluctuations are rather similar to those of the WNM. For the samples with a fixed number of nucleon participants, $N_P^{proj} = N_P^{targ} = const$, in Pb+Pb collisions at 158 AGeV, HSD shows fluctuations of the final hadrons close to those in N+N collisions at the same energy. This happens to be also valid for most central collisions ($b = 0$) considered in the present study. The influence of participant number fluctuations has been estimated and sown on Fig. 4 (for more details see ref [11]).

On the other hand in the statistical model the scaled variances $\omega_i = 1$ for the ideal Boltzmann gas in the grand canonical ensemble (GCE). The deviations of ω_i from unity in the hadron-resonance gas (HG) model stem from Bose and Fermi statistics, resonance decays, and exactly enforced conservations laws within the canonical ensemble (CE) or micro-canonical ensemble (MCE) [13, 14]. In Fig. 4 the scaled variances ω_i calculated within the MCE HG model along the chemical freeze-out line (see Ref. [13] for details) are presented by the dotted lines: ω_i reach their asymptotic values at RHIC energies. The HSD results for ω_i in central A+A collisions are very different. They remain close to the corresponding values in p+p collisions and, thus, increase with collision energy

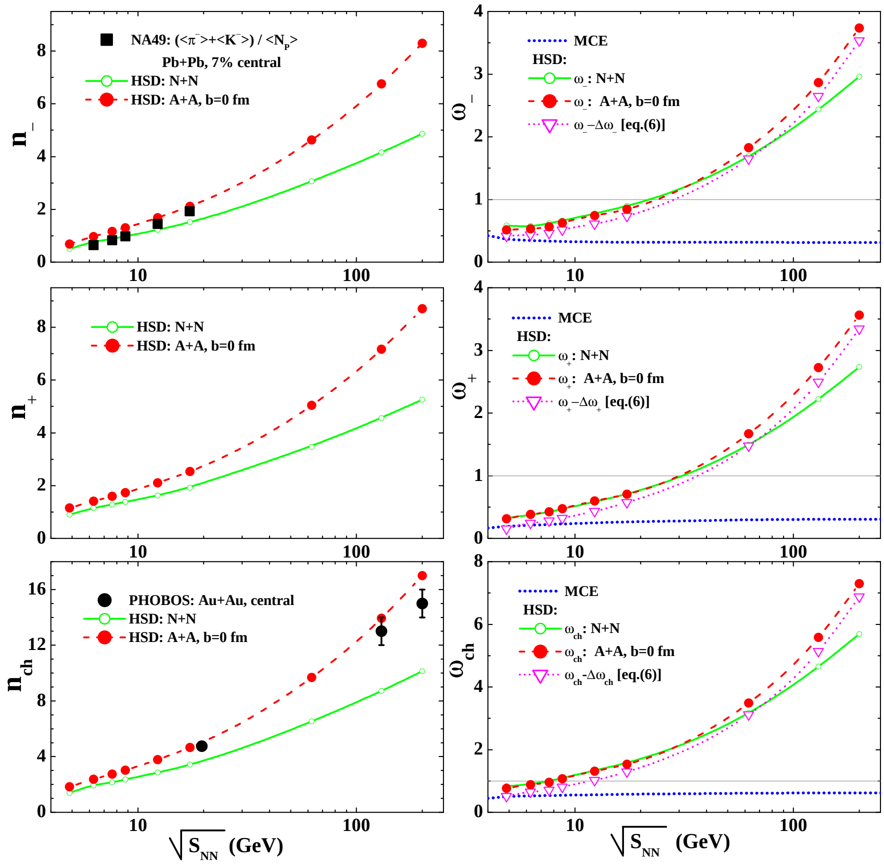

Figure 4: The multiplicities per participant, n_i (*left*), and scaled variances, ω_i (*right*). The solid lines are the HSD results for N+N collisions. The full circles are the HSD results for central A+A collisions for zero impact parameter, $b = 0$. The full squares for n_- are the NA49 data [12] for $(\langle\pi^-\rangle + \langle K^-\rangle)/\langle N_P\rangle$ in the samples of 7% most central Pb+Pb collisions. The HSD results for ω_i after the subtraction of the contributions of the participant number fluctuations are shown by open triangles. The dotted lines are the MCE HG model results for ω_i [13]. The HG parameters correspond to the chemical freeze-out conditions found from fitting the hadron yields.

as $\omega_i \propto n_i$. One observes no indication for 'thermalization' of fluctuations in the HSD results. This is especially seen for RHIC energies: ω_i(HSD)$/\omega_i$(MCE)≥ 10 at $\sqrt{s_{NN}} = 200$ GeV.

A rigid centrality selection has been recently done for the NA49 data [15] by fixing the number of projectile participants, $N_P^{proj} \cong A$. Only very central, $\leq 1\%$, collisions have been selected. The HG model was compared in Ref. [13] with the NA49 data [15]. It was found that the MCE results for $\omega_\pm$ are very close to the data, they are shown by the dashed lines in Figs. 5. In the statistical model the scaled variances $\omega_\pm^{acc}$ for the accepted particles are calculated from $\omega_\pm$ in the full space according to the acceptance scaling formulae (ASF) (see Ref. [13] for details): $\omega_\pm^{acc} = 1 - q + q\,\omega_\pm$.

Thus HSD predicts that the scaled variances ω_i in central A+A collisions remain close to the corresponding values in p+p collisions and increase with collision energy as the multiplicity per participating nucleon, i.e. $\omega_i \propto n_i$. The scaled variances ω_i calculated within the statistical

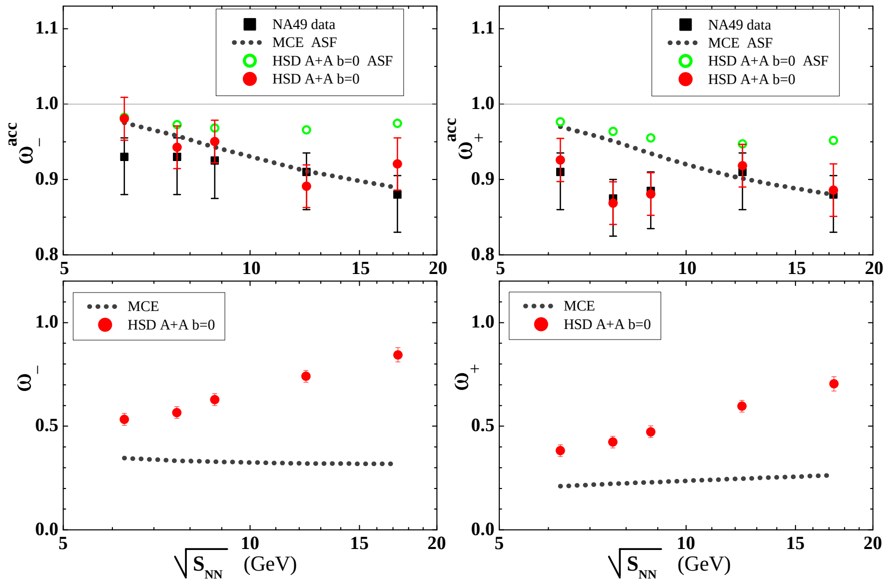

Figure 5: *Upper panel.* The scaled variances $\omega_{\pm}^{acc}$ for central Pb+Pb collisions. The squares with error bars are the NA49 data for 1% most central collisions [15]. The dotted lines show the MCE HG model results calculated from full 4π scaled variances using acceptance scaling formula (ASF). The full circles present the HSD results in Pb+Pb collisions for $b = 0$ with the NA49 experimental acceptance conditions, while the open circles are obtained from the 4π HSD scaled variances using acceptance scaling formula. *Lower panel.* The MCE HG (dotted line) and HSD (full circles) results for the 4π scaled variances $\omega_{\pm}$ are shown for SPS energies.

HG model along the chemical freeze-out line show a rather different behavior: ω_i approach finite values at high collision energy. At the top RHIC energy $\sqrt{s_{NN}} = 200$ GeV the HSD values of ω_i(HSD) is already about 10 times larger than the corresponding MCE HG values of ω_i(MCE). So, the HSD and HG scaled variances ω_i show a different energy dependence and are very different numerically at high energies. However, a comparison with preliminary NA49 data of very central, $\leq 1\%$, Pb+Pb collisions at the SPS energy range does not distinguish between the HSD and MCE HG results. This happens because of two reasons: First, the MCE HG and HSD results for ω_i at SPS energies are not too much different from each other and from ω_i in p+p collisions. Second, small experimental values of the acceptance, $q = 0.04 \div 0.16$, make the difference between the HSD and MCE HG results almost invisible. New measurements of ω_i for the samples of very central A+A collisions with large acceptance at both SPS and RHIC energies are needed to allow for a proper determination of the underlying dynamics.

6. Fluctuations at RHIC

The centrality selection at RHIC is different then at fix-target experiment. There are detectors which define the centrality of Au+Au collision called Beam-Beam Counters (BBC). At the c.m. pair energy $\sqrt{s} = 200$ GeV, the BBC measure the charged particle multiplicity in the pseudorapidity range $3.0 < |\eta| < 3.9$ [16]. We find a good agreement between the HSD shape of the BBC distribution and the PHENIX data (see [17]). Note, however, that the HSD $\langle N_P \rangle$ numbers are not exactly equal to the PHENIX values. It is also not obvious that HSD give the same values of the scaled variance ω_P for the participant number fluctuations to the experimental ones.

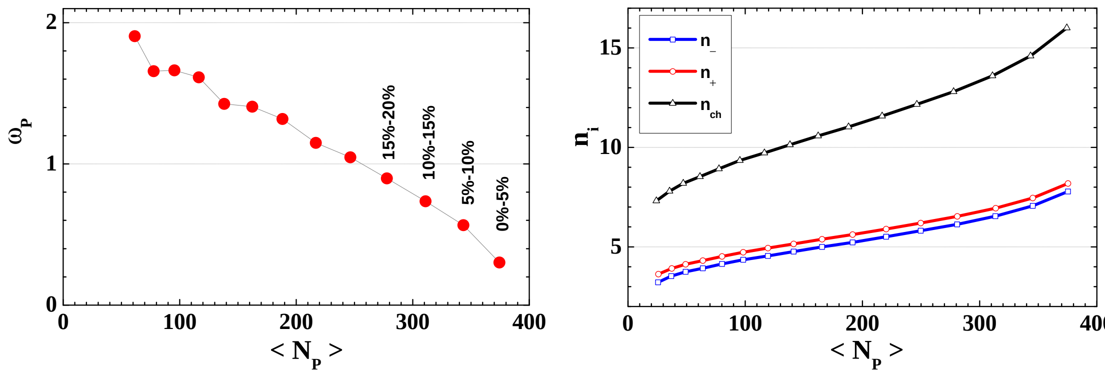

Figure 6: HSD results for different BBC centrality classes in Au+Au collisions at $\sqrt{s} = 200$ GeV. *Left:* The average number of participants, $\langle N_P \rangle$, and the scaled variance of the participant number fluctuations, ω_P, calculated for the 5% BBC centrality classes. *Right:* The mean number of charged hadrons per participant, $n_i = \langle N_i \rangle / \langle N_P \rangle$.

Defining the centrality selection via the HSD transport model (which is similar to the BBC in the PHENIX experiment) we calculate the mean number of nucleon participants, $\langle N_P \rangle$, and the scaled variance of its fluctuations, ω_P, in each 5% centrality sample. The results are shown in Fig. 6, left. The Fig. 6 (right) shows the HSD results for the mean number of charged hadrons per nucleon participant, $n_i = \langle N_i \rangle / \langle N_P \rangle$. Note that the centrality dependence of n_i is opposite to that of ω_P: n_i increases with $\langle N_P \rangle$, whereas ω_P decreases.

The PHENIX detector accepts charged particles in a small region of the phase space with pseudorapidity $|\eta| < 0.26$ and azimuthal angle $\phi < 245^o$ and the p_T range from 0.2 to 2.0 GeV/c [16]. The fraction of the accepted particles $q_i = \langle N_i^{acc} \rangle / \langle N_i \rangle$ also has been calculated within the HSD model. According to the HSD results only $3 \div 3.5\%$ of charged particles are accepted by the mid-rapidity PHENIX detector.

To estimate the role of the participant number event-by-event fluctuations we use the model of independent sources (see e.g., Refs [1, 7, 8, 10]), $\omega_i = \omega_i^* + n_i \, \omega_P$, where ω_i^* corresponds to the fluctuations of the hadron multiplicity from one source, and the second term, $n_i \, \omega_P$, gives additional fluctuations due to the fluctuations of the number of sources. As usually, we have assumed that the number of sources is proportional to the number of nucleon participants. To calculate the fluctuations ω_i^{acc} in the PHENIX acceptance we use the acceptance scaling formula: $\omega_i^{acc} = 1 - q_i + q_i \, \omega_i$. Putting all together one finds:

$$\omega_i^{acc} = 1 - q_i + q_i \, \omega_i^* + q_i \, n_i \, \omega_P \, . \tag{6.1}$$

The HSD results for ω_P (Fig. 6, left), n_i (Fig. 6, right), q_i (which is almost const), together with the HSD nucleon-nucleon values, $\omega_-^* = 3.0$, $\omega_+^* = 2.7$, and $\omega_{ch}^* = 5.7$ at $\sqrt{s} = 200$ GeV, define completely the results for ω_i^{acc} according to Eq. (6.1). We find a surprisingly good agreement of the results given by Eq. (6.1) with the PHENIX data shown in Fig. 7. Note that the centrality dependence of ω_i^{acc} stems from the product, $n_i \cdot \omega_P$, in the last term of the r.h.s. of Eq. (6.1).

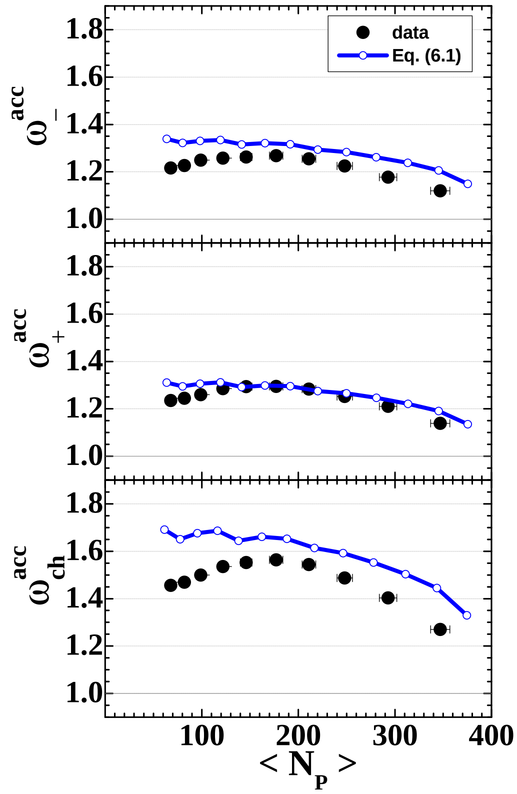

Figure 7: The scaled variance of charged particle fluctuations in Au+Au collisions at $\sqrt{s} = 200$ GeV with the PHENIX acceptance. The circles are the PHENIX data [16] while the open points (connected by the solid line) correspond to Eq. (6.1) with the HSD results for ω_P, n_i, and q_i.

One can conclude that both qualitative and quantitative features of the centrality dependence of the fluctuations seen in the present PHENIX data are the consequences of participant number fluctuations. To avoid a dominance of the participant number fluctuations one needs to analyze most central collisions with a much more rigid ($\leq$ 1%) centrality selection.

7. Summary and conclusions

- The fluctuations in the number of target participants — for fixed projectile participants — strongly influence all observable fluctuations.
- The measured fluctuations of the electric charge in different acceptance windows are consistent with HSD results.
- Statistical and transport models show different results in central A+A collisions for multiplicity fluctuations versus energy. New measurements at higher energies and with larger acceptance are needed.
- In collider-type experiments the fluctuations of the number of participants are significant. To avoid them one has to consider the most central collisions with more rigid events selection.

Acknowledgments

I would like to thank E.L. Bratkovskaya and M.I. Gorenstein for fruitful collaboration. I am also thankful to V.V. Begun, M. Gaździcki, M. Hauer, B. Lungwitz and H. Stöker for numerous discussions.

References

[1] H. Heiselberg, Phys. Rep. **351**, 161 (2001); S. Jeon and V. Koch, Review for Quark-Gluon Plasma 3, eds. R.C. Hwa and X.-N. Wang, World Scientific, Singapore, 430-490 (2004), [arXiv:hep-ph/0304012].

[2] M. Gaździcki, M. I. Gorenstein, and S. Mrowczynski, Phys. Lett. B **585**, 115 (2004); M. I. Gorenstein, M. Gaździcki, and O. S. Zozulya, Phys. Lett. B **585**, 237 (2004).

[3] I.N. Mishustin, Phys. Rev. Lett. **82**, 4779 (1999); Nucl. Phys. A **681**, 56 (2001); H. Heiselberg and A.D. Jackson, Phys. Rev. C **63**, 064904 (2001).

[4] M.A. Stephanov, K. Rajagopal, and E.V. Shuryak, Phys. Rev. Lett. **81**, 4816 (1998); Phys. Rev. D **60**, 114028 (1999); M.A. Stephanov, Acta Phys. Polon. B **35**, 2939 (2004).

[5] W. Ehehalt and W. Cassing, Nucl. Phys. A **602**, 449 (1996); E.L. Bratkovskaya and W. Cassing, Nucl. Phys. A **619** 413 (1997); W. Cassing and E.L. Bratkovskaya, Phys. Rep. **308**, 65 (1999); W. Cassing, E. L. Bratkovskaya, and S. Juchem, Nucl. Phys. A **674**, 249 (2000); W. Cassing, E.L. Bratkovskaya, and A. Sibirtsev, Nucl. Phys. A **691**, 753 (2001).

[6] H. Weber, *et al.*, Phys. Rev. C **67**, 014904 (2003); E.L. Bratkovskaya, *et al.*, Phys. Rev. C **67**, 054905 (2003); *ibid*, **69**, 054907 (2004); Prog. Part. Nucl. Phys. **53**, 225 (2004); Phys. Rev. Lett., **92**, 032302 (2004).

[7] V.P. Konchakovski, *et al.*, Phys. Rev. C **73**, 034902 (2006).

[8] M. Gaździcki and M.I. Gorenstein, Phys. Lett. B **640**, 155 (2006).

[9] M. Rybczynski et al. [NA49 Collaboration], J. Phys. Conf. Ser. **5**, 74 (2005).

[10] V.P. Konchakovski, *et al.*, Phys. Rev. C **74**, 064911 (2006).

[11] V.P. Konchakovski, M.I. Gorenstein, and E.L. Bratkovskaya, Phys. Lett. **B651**, 114-118 (2007).

[12] S.V. Afanasev *et al.*, [NA49 Collaboration], Phys. Rev. C **66**, 054902 (2002); T. Anticic *et al.*, [NA49 Collaboration], Phys. Rev. C **69**, 024902 (2004).

[13] V.V. Begun, *et al.*, Phys. Rev. C **76**, 024902 (2007).

[14] V.V. Begun, *et al.*, Phys. Rev. C **70**, 034901 (2004); *ibid.* C **71**, 054904 (2005); *ibid.* C **72**, 014902 (2005); A. Keränen, *et al.*, J. Phys. G **31**, S1095 (2005); J. Cleymans, K. Redlich, and L. Turko, Phys. Rev. C **71**, 047902 (2005); J. Phys. G **31**, 1421 (2005); F. Becattini, *et al.*, Phys. Rev. C **72**, 064904 (2005); V.V. Begun, *et al.*, J. Phys. G **32**, 935 (2006); V.V. Begun and M.I. Gorenstein, Phys. Rev. C **73**, 054904 (2006); V.V. Begun, *et al.*, Phys. Rev. C **74**, 044903 (2006).

[15] B. Lungwitz *et al.* [NA49 Collaboration], PoS **CFRNC2006**, 024 (2006).

[16] S.S. Adler *et al.*, [PHENIX Collaboration], Phys. Rev. C **71**,034908 (2005); J.T. Mitchell [PHENIX Collaboration], J. Phys. Conf. Ser. **27**, 88 (2005); J.T. Mitchell, private communications.

[17] V.P. Konchakovski, M.I. Gorenstein, and E.L. Bratkovskaya, Phys. Rev. C in press, arXiv:0704.1831[nucl-th].