Fluctuations and correlations in multiparticle production processes

Research Project Objectives (scientific problem aimed to be solved by the proposed project, project's research hypotheses)

Collisions of relativistic nuclei have been intensively analyzed for over two decades. The main goal of these efforts is to understand properties of strongly interacting matter at high energy collisions. In such conditions the transition from hadronic matter to a new state - quark-gluon plasma (QGP) is expected. In the case of QGP we have to deal with quarks and gluons free to move in the whole volume of the system [1, 2]. Indeed, the different characteristics of the collision and their energy dependence suggests that the phase transition takes place at energies of about 30 GeV/nucleon in the laboratory frame [3].

Fluctuations of physical observables in collisions of ions have become in recent years one of the main topics of interest, as they can provide some important signals for the formation of QGP. With a large number of particles produced in collisions of heavy ions in the Super Proton Synchrotron (SPS) and the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), one can analyze fluctuations using the event-by-event method [4]. In the thermodynamic description of the strongly interacting system formed in the collision, fluctuations in the number of produced particles [5–8], the average transverse momentum [9] and other global characteristics are related to the fundamental properties of the system, such as specific heat [10, 11], chemical potential, or matter compressibility [12]. These, in turn, can reveal some information about the properties of the equation of state near the phase transition [10, 13, 14].

There is no longer any doubt that the fluctuations in the initial conditions are crucial to the full understanding of the dynamics of collisions of relativistic ions. The simplest way of modeling these fluctuations is based on random selection of positions of nucleons in each nucleus before the collision and deterministic designation, obtained after a collision, energy density according to the made assumptions. That is what happens, for example, in the standard Glauber Monte Carlo (GMC) model [15] or Kharzeev-Levin-Nardi (KLN) Monte Carlo [16], which have been widely used for many years. Although such modeling includes a substantial part of the fluctuations of initial transverse energy density, it is not sufficient for a quantitative comparison with experimental data. In recent years there has been tremendous progress in the development of a more realistic description of the initial state in the collisions of relativistic ions. Multiple variants of the above GMC and KLN models have been tested, containing e.g. realistic nucleon-nucleon collision profile [17] or two body nucleon-nucleon correlations [18]. In addition, the dynamical transport models are often used to describe an initial nonequilibrium evolution of a system produced in reactions with relativistic ions. It is important to emphasize that we are not dealing with an alternative choice between two competing models of the initial state. There are many possible implementations, e.g. modeling inspired by the color glass condensate (CGC) approach [19] is not synonymous with a certain KLN model, but there are many different versions based on the CGC or GMC. An excellent overview of characteristics of the initial state in collisions of relativistic ions can be found in [20, 21].

Nucleon correlations in projectile and target nuclei, the range of the underlying nucleon-nucleon interactions, and cross-section fluctuations are all important for determining fluctuations in the number of nucleon-nucleon collisions and thus observables in nuclear collisions [22]. Due to gluon saturation, the growth of the inelastic nucleon-nucleon cross section with increasing collision energy results in a broadening of the nucleons density distribution in coordinate space. This leads to a natural smoothing of the initial energy density distribution in the transverse plane of the matter created near midrapidity in heavy-ion collisions. The smoothing effects of a larger effective nucleon size at higher energies also influence the anisotropic flow generated in heavy-ion collisions. This effect has been studied, up to now, for fluctuating initial conditions generated with the Monte Carlo KLN model for Au+Au collisions at RHIC and LHC energies [23]. Fluctuations in the nucleon-nucleon cross section induce a large fluctuations in the number of participants, N_{part} in a central p+Pb events. The apparent universality of the large N_{part} tails of p+Pb and Pb+Pb collisions suggests these fluctuations arise from a spatially over-extended nucleon wave function, which includes configurations that are so spatially extended that their inelastic cross section is much larger than the average [24]. Having a larger geometric size, it is natural to expect that the incident proton will have a much larger cross section with the nucleus when it finds itself in one of these configurations. As a result, more energy will be deposited and more particles will be produced [24]. In [25], co-authored by the Principal Investigator of the proposed project, we studied an influence of the fluctuations of nucleon-nucleon cross section for the shape of nucleon-nucleon collision profile. It turns out, that the presence of the Gaussian nucleon-nucleon collision profile, which is essential for description of elastic differential cross sections in p+p interactions e.g. at CERN Intersecting Storage Rings (ISR) [26], directly results from the fluctuations of nucleon-nucleon cross section. In the framework of the proposed project we perform a novel analysis of the particle's production mechanisms, using cross section fluctuations in the earliest phases of nuclear collision.

At the LHC, and at any other collider, the quantity $\sqrt{s} = \sqrt{\left(q_1^{inc} + q_2^{inc}\right)^2} = 2E_{inc}$, where E_{inc} is the incident energy of colliding proton and q^{inc} is its four-momentum, was considered to be the total energy available in the centre-of-mass (CM) system. In proton-proton interactions the CM energy $\sqrt{s}$ should be treated as nominal and *not effective* value of energy available for particle production. In fact, the incoming proton can carry a large fraction of the primary energy away into the final state [27, 28]. If one examine the final state of a proton-proton interaction, in a large majority of cases one can find in each hemisphere a "leading" particle with four-momenta $q_1^{leading}$ and $q_2^{leading}$. On average, they carry 50% of the nominal energy, $2E_{inc}$. The hadronic system produced in each hemisphere has at its disposal the four-momentum $q^{had} = q^{inc} - q^{leading}$. The quantity $\sqrt{\left(q_1^{had} + q_2^{had}\right)^2} = 2E_{had} = K\sqrt{s}$ is called an effective energy in the interaction. *The inelasticity K* of hadronic reactions, understood as the fraction of the incident beam energy used for the production of secondary particles, is (next to the inelastic cross section σ^{in}) the most significant variable for all cosmic ray physics experiments [29]. Inelasticity fluctuates event-by-event, in a sense of single nucleon-nucleon interactions. Inelasticity fluctuations are caused by the presence of *subnucleonic degrees of freedom* in colliding systems. In the framework of the proposed project we will carefully analyze the influence of the inelasticity fluctuations for the multiparticle production processes in the proton-proton, proton-nucleus and nucleus-nucleus collisions in the wide energy range.

As the first major objective of the project we wish to carefully analyze the influence of *a new sources of fluctuations and correlations* present in the collisions of relativistic atomic nuclei for the mechanisms of multiparticle production. Introduction of nucleon-nucleon cross section fluctuations and fluctuations of effective energy available for particle production to the mechanisms of particle production will allow to test their influence for many important and experimentally observed effects of the collisions (for example centrality and system size dependence of multiplicity fluctuations as measured in WA98 [5], NA49 [6] experiments at CERN and PHENIX [8] at BNL). We expect that such studies done with use of tools that contain new sources of fluctuations are expected to provide very valuable new information in the question of the onset of deconfinement.

Near the border energy characterizing phase transition a different critical phenomena may appear. This may be reflected in energy dependence on various types of fluctuations. Recent lattice calculations [30] suggest that fluctuations and correlations can be a sensitive probe of the quark and gluon deconfinement because fluctuations are sensitive to hadronic or partonic degrees of freedom. Moreover, fluctuations and correlations may help to localize the critical point of strongly interacting matter – a phenomenon similar to the critical opalescence observed in most liquids. The critical opalescence, an enhanced scattering of light on density fluctuations of medium at a molecular scale, grows and then decreases as we approach and then move away from the critical point where the gas and liquid have the same density and specific entropy [31]. Since the inelasticity and cross section fluctuations cause changes in the amount of energy which is used for particle production in multiparticle production processes, taking them into account in the models may significantly help in localization of the mentioned above critical point.

The possibility of inclusion of dynamical fluctuations in the study of the energy of phase transition and the search for the critical point of strongly interacting matter has become a motivation for extensive program of fluctuations analyzes at the SPS, LHC as well as at RHIC. The NA49 experiment found a non-monotonic behavior of the fluctuations in transverse momentum [32] and multiplicity [6] as a function of centrality of the collision at the highest SPS energy. This intriguing result may be the first sign of the presence of the critical point. Therefore, the NA49 efforts will be continued in the NA61/SHINE experiment, where the two-dimensional (energy and system size) studies of the phase diagram are planned [33].

The second main objective concerns the modeling of mechanisms of particle production in Extensive Air Showers (EAS). The discovery of cosmic rays (CR), more than 100 years ago, allowed us to deal with particles produced in collisions at energies that are far beyond the capabilities of even today's accelerators. It appears that the process of shower development is particularly sensitive to new sources of fluctuations discussed above. Proper modeling of particle production processes in this energy range can allow us to clarify many important, however unclear so far experimental results, like recent measurements done by the ALICE experiment at the CERN LHC, on the registration of large muon groups produced in EAS [34].

Finally, the third major question is very basic. We are interested to examine an impact of subnucleonic components of matter on the dynamics of the early stage of the collision of relativistic nuclei. We expect that simultaneous consideration of various fluctuation observables, made using novel methods will allow for verification of models of dynamics of particle production and to put relevant constraints on the elementary (i.e., coming from a single source) production of particles in the early phase.

The significance of the project, as well as our detailed tasks and methods are described in the sections below.

Significance of the project (state of the art, justification for tackling specific scientific problems by the proposed project, pioneering nature of the project, the impact of the project results on the development of the research field and scientific discipline, economic and societal impact)

Accurate understanding of the dynamics of nuclear collisions at highest available energies is one of the main challenges of present-day strong-interaction physics, as it deals with matter under the conditions as extreme as in the early Universe, where the quark-gluon plasma was formed. The principal purpose of the project is the modeling of multiparticle production processes in relativistic collisions of atomic nuclei at energies available at accelerators and beyond, in cosmic ray physics experiments. The models will incorporate numerous effects, phenomenologically crucial for understanding the physics of relativistic nuclear collisions and will be used in analyses of results of the ongoing and future experiments. An early stage dynamics determines the initial condition for further collective dynamics of the system (hydrodynamics, transport). For this reason, this issue affects such fundamental issues as determination of the initial energy or entropy density in the quark-gluon plasma.

There are competing theoretical approaches of modeling the initial state, with calculations based on transport models on the one side, and CGC [35–37] on the other side. The initial conditions for hydrodynamics typically come from the Glauber framework [15, 38, 39] or the KLN model [16], motivated with the QCD saturation. However, the modeling of the initial condition for the one-body (rapidity- and transverse-momentum spectra) and multi-body observables (multiplicity) were sensitive to event-averaged initial conditions only. Important exception (but this, in essence, is a correlation observable), is the harmonic flow, in particular, the famous triangular flow. *A key feature* behind our project is that the imprints of the initial state can be clearly seen in fluctuations of the final hadron distributions, and this fact is in the core of our methodology. Moreover, our project will provide the initial conditions not only in spatial coordinates, but also fluctuating from collision to collision in such a way that various correlation/fluctuation data are jointly reproduced. This will have a large practical impact on the field, as all phenomenological simulations use models of the initial state.

Analyses will be based on both the analytical calculations in sufficiently simple models as well as advanced massive numerical simulations of the dynamics of the early phase. All tasks described in the project are novel studies. While carrying out the project, we will be responsive to upcoming results, which undoubtedly will become available in the near future. The models will include a variety of effects which are crucial for understanding the physics of collisions of relativistic nuclei and will be used in the analysis of the results of current and future measurements. Research carried out in the project contributes to a better understanding of the fundamental issues of the dynamics of dense and hot strongly interacting matter.

The project will be realized in the Institute of Physics at the Jan Kochanowski University in Kielce, and will have a significant impact on the development of research conducted there in collisions of relativistic nuclei. Employment of a post-doc and sponsoring of one master and one Ph. D. scholarships will contribute to the development of the university academic staff in this small but very active research center.

Work plan (outline of the work plan, critical paths, state of preliminary and initial research indicating feasibility of research objectives)

Preliminary results which show the feasibility of the project tasks, were recently published in [40] with the Principal Investigator of the present proposal as a co-author. One of the main results of [40] is that taking into account subnucleonic constituents in the description of early phase collision one can naturally obtain the linear dependence of production of particles as a function of the number of wounded constituents, see Fig. 1. The basic effect of the subnucleonic degrees of freedom in particle production is an increase of combinatorial factor when compared to wounded nucleon model, which in turn leads to the approximately linear scaling of production with the number of constituents shown in Fig. 1. We note that in the quark-diquark model [27] the combinatorial factor, which is smaller than in the three-quark model allows one to proper description of the RHIC data as well as the proton-proton differential elastic cross-sections at the CERN ISR energies.

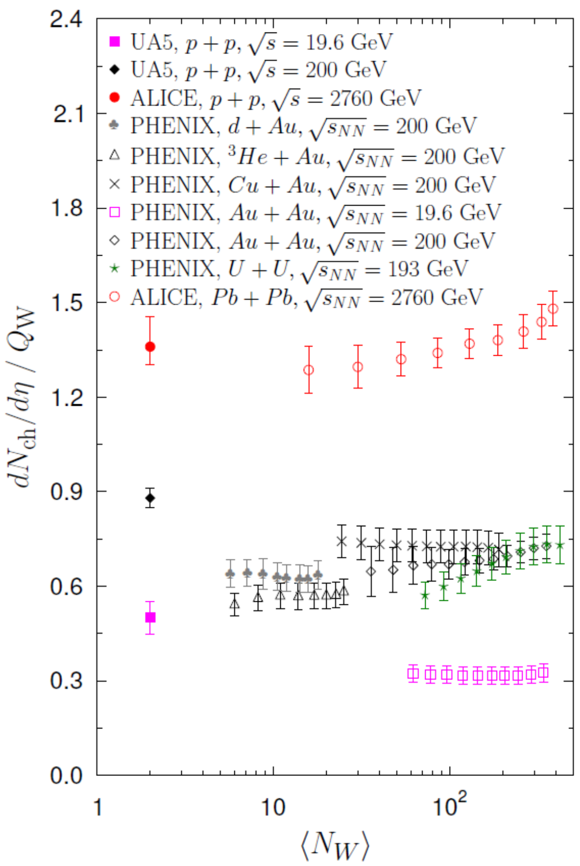

Fig. 1. Experimental multiplicity of charged hadrons per unit of pseudorapidity (at mid-rapidity) divided by the number of wounded quarks, $\frac{dN_{ch}}{d\eta}/Q_W$, plotted as function of centrality expressed via the number of wounded nucleons. The results for the proton-proton interactions at $\langle N_W \rangle = 2$ are shown by filled symbols. Plot taken from [40].

As already mentioned in previous sections, the principal purpose of the project is to model multiparticle production in collisions of relativistic nuclei in the broadest possible range of collision energy, both at energies available in modern accelerators and beyond, observed in the cosmic ray physics experiments. We will develop the models which will include new sources of fluctuations and correlations, like nucleon-nucleon cross-section fluctuations and fluctuations of inelasticity of collision. In the case of modeling of Extensive Air Showers development, the recent experimental results on cross-sections obtained in CERN and DESY laboratories will be taken into account. The plan of work is as follows.

1. Analysis of multiplicity fluctuations

Recently, the PHENIX Collaboration suggested [41] that the wounded quark model [42-44] works better than the popular wounded nucleon model [45, 46], in particular in describing the multiplicity distributions. The agreement with the data may be achieved without the introduction of the binary-collision component [47, 48], which introduces nonlinearity between the number of participating nucleons and the multiplicity of the produced hadrons. In the proposed project we shall extend and generalize the approach proposed in [40] to describe the energy, centrality and system size dependence of multiplicity fluctuations of charged particles registered by WA98 [5], NA49 [6, 7] and PHENIX [8] Collaborations. Although there are some models trying to describe the non-monotonic behavior of the scaled variance of multiplicity distribution as a function of collision centrality expressed by the number of nucleons participants, see Fig. 2 for the NA49 result measured in the centre-of-mass rapidity range $1.1 < y_\pi < 2.6$ (rapidity calculated assuming that all particles have pion mass), up to now there is no commonly accepted explanation of this phenomenon.

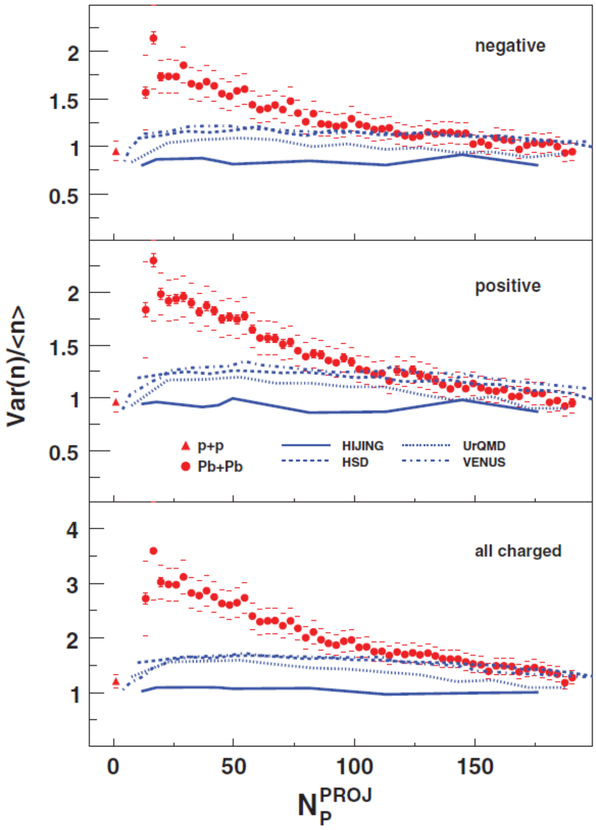

Fig. 2. The scaled variance of the multiplicity distribution for negatively (upper panel), positively (middle panel), and all (bottom panel) charged particles as a function of the number of projectile participants as measured by the NA49 Collaboration in the centre-of-mass rapidity range $1.1 < y_\pi < 2.6$ (rapidity calculated assuming that all particles have pion mass) compared with model simulations in the NA49 acceptance. Plot taken from [6].

Moreover, there is a recent NA61/SHINE Collaboration paper [49] showing a very intriguing result on multiplicity fluctuations in p+p and central Pb+Pb collisions. Namely, the scaled variance of multiplicity distributions of charged particles measured in broad rapidity range ($0 < y_\pi < y_{max}$) is significantly higher in inelastic p+p interactions than in the 1% most central Pb+Pb collisions measured by NA49 at the same energy per nucleon. The largest difference is observed at the top SPS energy. This result is in qualitative disagreement with the predictions of the wounded nucleon model assuming that particle production in nucleon–nucleon and nucleus–nucleus collisions is an incoherent superposition of particle production from wounded nucleons (nucleons which interacted inelastically and whose number is calculated using the Glauber approach). Properties of wounded nucleons are assumed to be independent of the size of the colliding nuclei, e.g. they are the same in p+p and Pb+Pb collisions at the same collision energy per nucleon [49]. In the proposed project we shall describe this phenomenon basing on our new approach [40].

The proper description will allow for verification of models of dynamics of particle production and to put relevant constraints on the elementary entropy deposition in the early phase. We will also prepare predictions for multiplicity fluctuations at energies available at the LHC.

2. Analysis of multiparticle production processes in Extensive Air Showers

Experiments such as the Pierre Auger Observatory [50], KASCADE-Grande [51], Ice-Top [52] or the Telescope Array [53] use models for the interpretation of measurements. However, there is mounting evidence that current models give a poor description of muon production in air showers (see e.g. [54-56]). A very important aspect of understanding of primary cosmic ray flux and its composition is a proper description of recent measurement done by the ALICE experiment at CERN LHC, in its dedicated cosmic ray run. ALICE Collaboration registered the presence of large groups of muons produced in EAS by cosmic ray interactions in the upper atmosphere [34]. A special emphasis has been given to the study of high multiplicity events containing more than 100 reconstructed muons and corresponding to a muon areal density $\rho_{\mu} > 5.9\ m^{-2}$. Similar events have been studied in previous underground experiments such as ALEPH [57], DELPHI [58] and L3 [59] at CERN Large Electron-Positron (LEP) Collider. While these experiments were able to reproduce the measured muon multiplicity distribution with Monte Carlo simulations at low and intermediate multiplicities, their simulations failed to describe the frequency of the highest multiplicity events. The measured by ALICE muon multiplicity distribution compared with the fits obtained from CORSIKA [60] simulations with proton or iron primary cosmic rays indicates that the expected rate of higher multiplicity muon events is sensitive to assumptions made about the dominant hadronic production mechanisms in air shower development. Although it is roughly possible to describe the presence of low and intermediate muon bundles, assuming the presence of the only Fe nuclei in the primary flux, the conventional models of EAS development completely fail in its predictions about muon groups at high multiplicities. Surprisingly, the ALICE Collaboration shows in their paper [34] only fits for muon multiplicities up to about 70 (Figure 5 in [34]), neglecting many events with measured muon multiplicities up to 270, see Figure 3.

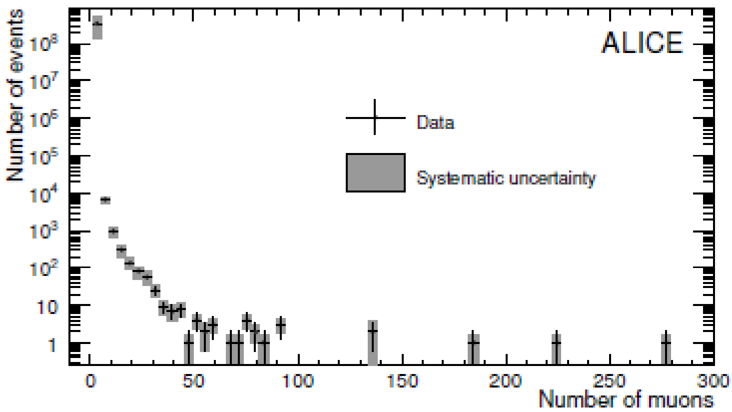

Fig. 3. Muon multiplicity distribution as seen by the ALICE Collaboration. Plot taken from [34].

Fluctuations of the nucleon-nucleon cross-section causes the fluctuations of the projectile particle mean free path, λ, in the atmosphere. Fluctuating λ changes the distribution of the projectile particle interaction points in the air from exponential to quasi power-law one, which is characterized by the long tails. This will influence the distribution of the EAS maximum, what is important from the point of view of multiplicity of secondary particles produced in the air shower.

Unfortunately, there exist no comprehensive and precise particle production measurements for the most numerous projectile in air showers, the π-meson. Therefore, new data with pion beams at 158 and 350 GeV/c on a thin carbon target (as a proxy for nitrogen) were collected by the NA61/SHINE experiment at the CERN SPS [61]. Preliminary spectra of unidentified hadrons which have been previously derived from this data set revealed discrepancies between the data and predictions from generators for hadronic interactions

[62-63]. In the framework of proposed project it is planned to use a new method based on the recently obtained by NA61/SHINE experiment data on identified charged pions production in $\pi^{-} + C$ interactions at 158 and 350 GeV/c [61] for description of muon bundles production in total range of experimentally observed multiplicities. Since the Principal Investigator of the proposed project is an active member of the NA61/SHINE Collaboration, having long-term experience in data taking, software development and data analysis, it can additionally ease the realization of proposed analysis.

3. **Analysis of the influence of inelasticity and nucleon-nucleon cross section fluctuations on multiparticle production processes in proton-proton, proton-nucleus and nucleus-nucleus collisions**

In [64] there is shown the effectiveness of the concept of inelasticity (or effective energy available in an elementary nucleon-nucleon interaction) to describe the production of the average number of particles in nuclear collisions. The influence of nucleon-nucleon cross section fluctuations on the shape of nucleon-nucleon collision profile was checked in Ref. [25]. In this task we develop and generalize those approaches through comprehensive analysis of the influence of *inelasticity fluctuations* and nucleon-nucleon *cross section fluctuations* on multiparticle production processes in proton-proton, proton-nucleus and nucleus-nucleus collisions in a wide range of energy available in the present-day accelerator, as well as in cosmic ray physics experiments. The results will serve as an important verification process for models of particle production, using defined *a priori* multiplicity distributions of secondary particles, given in Poisson or negative binomial forms. Like the other cases, our analyses will serve as a reference point for present and further experimental studies.

4. **Analysis of the influence of conservation principles on the fluctuations and correlations in multiparticle production processes**

We plan to carefully check the influence of symmetry constraints and conservation principles on the fluctuation measures in the analyzed tasks. We focus, in particular, on the energy conservation. It causes, during the production of entropy in the sources, a global constraints for the number of finally produced particles and most of all for the widths of the multiplicity distributions. It should be noticed that inadequate implementation of conservation principles, e.g. energy, momentum or electrical charge, especially during the modeling of particle production mechanisms in Monte Carlo generators, may induce many of artificial correlations in the studied systems, which can substantially influence the obtained results. Also, the influence of experimental constraints, like limited rapidity coverage or cross talk between rapidity bins would constitute a substantial ingredient on the applicability of conservation laws.

All tasks of the proposal are sharply focused on a compact, well defined, timely, and very important aspect of ultra-relativistic nuclear collisions. Predictions will be new and relevant for the on-going analysis of the LHC data. Our analyses will cover a very rich spectrum of cases and apply several state-of-the art methods developed specifically for the correlation studies, hence the time span of three years for a four-person team (a post-doc for two years, one master student for 12 months and one Ph. D. student for 24 months) seems appropriate. The Principal Investigator of the project has a long experience in the field, documented in numerous publications. Moreover, since the Principal Investigator, is an active member of the NA61/SHINE [65] and the JEM-EUSO [66] Collaborations, having many years of experience in collecting, analyzing experimental data and software development, it can also facilitate the implementation of the proposed research. Physical results obtained from the study will be published in peer-reviewed, international physics journals, as well as discussed with other members of the JEM-EUSO and NA61/SHINE Collaborations during collaboration meetings and meetings of analysis, and also presented at international conferences.

Research Methodology (underlying scientific methodology, data reduction and treatment schemes, type and degree of access to the equipment to be used in the proposed research)

The research methodology will be based on both the analytical calculations in sufficiently simple models, as well as on advanced numerical simulations in the case of more complex variants of the models. In all cases, numerical calculations are necessary to obtain the fluctuation measures for the number of sources in Glauber-related approaches. Methods used in the proposed project are as follows.

1. Development of the software

The introduction of the novel mechanism of nucleon-nucleon cross section fluctuations in the various forms and inelasticity fluctuations as proposed by e.g. [25] and [67] will be done in the existing code of GLISSANDO software which is nowadays a commonly used tool for the modeling of early phases of nuclear collisions. The Principal Investigator of the proposed project is fully qualified for such tasks being a co-author of the papers [68, 69] published in Computer Physics Communications, a dedicated journal for software developed for physics.

The new functionalities will be added to the *distrib* class, where the distributions of nucleons in nuclei are generated event-by-event and to the *collision* class, where the generation of all interaction characteristics is realized. The introduced modifications will be flexible enough to be used with various distributions of nucleon-nucleon cross section and a various scenarios of collisions with varying nucleon size, e.g. nucleons with constant size during collision event, nucleon's sizes generated for each nucleon-nucleon interaction within collision event, etc. The collisions between nucleons/partons (wounding or binary) result in deposition of a certain amount of the energy (or entropy) at the location of the source, which is then carried away by the produced particles. The inelasticity fluctuations will be implemented by generating profiles of entropy depositions based on the amount of energy carried by interacting partons and in accordance with the energy conservation. The possibility to use different distributions for such entropy deposition will be added. Various new utility scripts for analysis of physical quantities (evaluation of the total cross-section of the reaction, determination of the centrality on base of multiplicity, estimates of corrections for limited acceptance, multiplicity fluctuations, Fourier shape parameters and their event-by-event fluctuations, three-dimensional density profiles of produced particles, the tilt and torque effects, influence of nucleon-nucleon correlations, significance of the wounding profile, implementation of the core-corona picture, etc.) will be supplied with the package. The modified GLISSANDO code will be publicly available via the web-page of the project.

The modifications of the widely used software for Extensive Air Showers simulations, like SHOWERSIM package [70] or CORSIKA generator [60] will be performed as a next step of the project. Since the software used for modeling, do not contain the results of the newly obtained results, like cross sections for pion and muon production from the recent CERN NA61/SHINE experiment data on $\pi^{-}+C$ interactions [61], they have to be implemented. Also a new mechanism of fluctuation of the projectile mean free path in the atmosphere will be implemented into existing software. Then a massive tests of the modified software will be performed to check its compatibility with the software in standard versions as well as influence of the introduced modifications into standard observables, like energy distributions of primary particles or lateral distributions of simulated secondary particles.

The sufficiently powerful notebook computers, planned to be acquired from the project resources, will be used for the development of and testing of the modified GLISSANDO software. The notebooks will allow for the implementation of various operating systems in the form of virtual machines, which is a very important testing element, as it will check the portability of the code from platform to platform. Such tests are not possible on the available computer cluster, as virtual machines are not allowed to be installed there.

2. Performing physics analyses for accelerator and cosmic ray physics experiments

The methodology of the proposed analyses will be based on massive computer simulations done with use of developed or modified in the project tools. The simulations, especially those of Extensive Air Showers induced by hadrons and atomic nuclei, will need a sufficiently powerful computers. For that purpose we will use an existing computer cluster located at the Institute of Physics, Jan Kochanowski University. The configuration of the cluster is following:

- ✓ 25 multi-core (90 cores in total) Intel XEON processors,
- ✓ 120 GB operational memory,
- ✓ 3 RAID arrays with 30 TB storage volume,
- ✓ 4 UPS power supplies,
- ✓ Scientific Linux operating system.

The big storage volume will help us to store all the simulated events in the binary and ASCII format. The cluster makes it possible to execute simultaneously 90 batch jobs at the use of nearly 100% of the systems CPU, which is sufficient for the numerical tasks of the project. More involved analytic calculations will be carried out with the help of Wolfram Mathematica software. The license for Mathematica 10 (or higher) will be provided by the Jan Kochanowski University.

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