# Study the signals of QGP using Monte Carlo for Pb+Pb for Energy from 500 to 2000 GeV

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The heavy-ion collisions (Pb+Pb) for LHC and RHIC energy are simulated by Monte-Carlo generator HIJING and HIDJET++ for ssudy signals of QGP. With help the factorial moments is studied posibility phase transition from QGP to hadrons. A comparison of Monte Carlo generators HIJING and HIDJET++ for modeling such phenomena as QGP-hadrons phase transition is conducted.

## 1. Introduction

The collision of high-energy heavy ions with atoms and atomic nucleus begins to manifest various collective phenomena. For example, the fluctuations of the multiplicity of secondary particles increase with the growing of initial energy of collisions. The final distribution of particles in the phase space has great depends from the dynamics of initial processes, i.e. the distribution and nature of the interactions of quarks and gluons. The study of such fluctuations can provide the necessary information about the dynamics of initial processes and, consequently, on the properties of strong interactions.

In collisions characterized by sufficiently high temperatures and/or energy density in accordance with the predictions of quantum chromodynamics should form a new superdense state of matter — quark-gluon plasma (QGP). The most promising for such purposes are the heavy ion collisions. Such experiments were carried out at RHIC (Au collisions) and curently are conducted at the LHC (Pb collisions). But detection of the QGP formation is a more difficult. Firstly, there is a large background due to the strong interaction between nucleons. Secondly, the duration of the QGP evolution of the nuclear system is a small fraction of the total evolution time. If the QGP was formed in a collision, then there should be observed a phase transition (PT) QGP→hadrons. Such PT can be defined by the study of the particles multiplicities fluctuations. The availability of sufficiently large fluctuations can be a indication of PT and correspondingly

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QGP formation.

In this paper we used Monte Carlo generators for simulation of the relativistic heavy ions collisions to investigated of the multiplicity fluctuations of secondary particles. We used difference factorial moments for analysis of such fluctuations and for the determination of QGP signals.

## 2. Monte Carlo generators

To carry out model calculations, we needed generators include the possibility to simulate heavy ion collisions at high energies. Also generators should have been simulate by various fluctuations. We have selected the following Monte Carlo generators:

- HIJING (Heavy Ion Jet INteraction Generator) is Monte Carlo generator with special emphasis on the role of minijets in pp, pA and AA reactions at collider energies [1, 2]. HIJING basically is designed to simulate multiple jets and particle production in pp, pA or AA collisions.

  Based on a pQCD-inspired model, multiple minijet production is combined together with Lund-type model for soft interactions. Within this model, triggering on large $P_T$ jet production automatically biases toward enhanced minijet production. Binary approximation and Glauber geometry for multiple interaction are used to simulate pA and AA collisions. A parametrized parton distribution function inside a nucleus is used to take into account parton shadowing. Jet quenching is modeled by an assumed energy loss $dE/dz$ of partons traversing the produced dense matter. A simplest color configuration is assumed for the multiple jet system and Lund jet fragmentation model is used for the hadronization. PYTHIA subroutines and Lund jet fragmentation scheme are used for calculations.

  The program is only valid for collisions with c.m. energy ($\sqrt{s}$) above 4 GeV/n. For central Pb+Pb collisions, some arrays have to be extended $\sqrt{s} = 10$ TeV/n.

  Currently the HIJING Monte Carlo model is updated with the latest parton distributions functions (PDF) and new set of the parameters in the two-component mini-jet model that controls total $p + p$ cross section and the central pseudorapity density [3].

- HYDJET++ (HYDrodynamics plus JETs) is the event generator to simulate relativistic heavy ion AA collisions as a superposition of the soft, hydro-type state and the hard state resulting from multi-parton fragmentation [4]. It is designed for studying of multi-particle production in the wide energy range of heavy ion experimental facilities: from FAIR and NICA to RHIC and LHC.

  A heavy ion event in HYDJET++ is a superposition of the soft, hydro-type state and the hard, multi-parton state. Both states are treated independently. HYDJET++ is the development and continuation of HYDJET MC model. The main program is written in the object-oriented C++ language under the ROOT environment. The hard part of HYDJET++ is identical to the hard part of Fortran-written HYDJET (version 1.5). The routine for generation of single hard NN collision, generator PYQUEN, modies the “standard“ jet event obtained with the generator of hadron-hadron interactions PYTHIA 6.4. The event-by-event simulation procedure in PYQUEN includes the generation of initial parton spectra with PYTHIA and production vertexes at given impact parameter; rescatteringby-rescattering simulation of the parton path length in a dense zone and radiative and collisional energy loss; nal hadronization according to the Lund string model for hard partons and in-medium emitted gluons. Then the full hard part of the event includes PYQUEN multi-jets generated according to the binomial distribution around its mean value. In order to take into account the effect of nuclear shadowing on parton distribution functions, the impact parameter dependent parameterization obtained in the framework of Glauber-Gribov theory is used.

The soft part of HYDJET++ event is the ”thermal” hadronic state generated on the chemical and thermal freeze-out hypersurfaces represented by a parameterization of relativistic hydrodynamics with preset freeze-out conditions. Fast soft hadron simulation procedure includes the generation of the 4-momentum of a hadron in the rest frame of a liquid element in accordance with the equilibrium distribution function; the generation of spatial position of a liquid element and its local 4-velocity in accordance with phase space and the character of motion of the uid; the standard von Neumann rejection/acceptance procedure to account for the difference between the true and generated probabilities; boost of the hadron 4-momentum in the center mass frame of the event; and nally the two- and three-body decays of resonances with the branching ratios taken from the SHARE particle decay table.

Although HYDJET++ is optimized for very high energies of RHIC and LHC colliders, in practice it can also be used for studying of multiparticle production in $\sqrt{s}$ a wider energy range of other heavy ion experimental facilities, down to $\sqrt{s} \sim 10$ GeV per nucleon pair.

HYDJET++ is only applicable for symmetric AA collisions of heavy ($A \gtrsim 40$) ions at high energies (c.m.s. energy $\sqrt{s} \gtrsim 10$ GeV per nucleon pair). The results obtained for very peripheral collisions (with impact parameter of the order of two nucleus radii, $b \sim 2R_A$) and for very forward rapidities may be not adequate.

## 3. The simulation of heavy ion collisions at high energies

To simulate the heavy ions interaction processes we use Monte Carlo generator HIJING and HYDJET++. But as for HYDJET++ we do not collected sufficient statistics, then further

FIG. 1. Distribution of the multiplicity of secondary particles for the pseudorapidity $\eta$ for $\sqrt{s} = 500, 700, 900, 1100, 1300$ GeV (with HIJING)

calculations were based on data obtained with HIJING.

We calculate the lead ions (Pb) collisions at high energies. We simulated $N = 10^5$ collisions for center of mass energies in range $\sqrt{s}$ from 500 to 1400 GeV ($N = 10^4$ from 1400 to 2000 GeV).

The highest energy density obtained in central collisions in which there exists the greatest probability of QGP formation. The probability of such events depends on the impact parameter. To simulate the distributions of particle collisions on impact parameter we have used Glauber model [7].

The highest energy density obtained in central collisions in which there exists the greatest probability of QGP formation. To study the most likely scenario of QGP formation we were selected the most central events, representing 5% of the total number of events.

Based on these data we calculated multiplicity distribution of charged secondary particles on pseudorapidity $\eta$ (FIG. 1), azimuthal angle $\Delta\phi$ (FIG. 2) and transverse momentum $p_t$ (FIG. 3).

FIG. 2. Distribution azimuthal angle of emission particle with respect to the reaction plane $\Delta\phi$ for energy 500, 700, 900, 1100, 1300 GeV

FIG. 3. Transverse momentum distribution for different energy (from 500 to 1400 GeV).

## 4. The calculation of the factorial moments and scaling exponent

Based on the distributions from figures 1, 2 and 3, it is possible to analyze the fluctuations of the secondary charged particles multiplicity. As it was shown in [8, 9], a sufficiently large fluctuations can serve as a criterion for the existence of a phase transition from QGP to hadrons. Convenient means for determining such fluctuations are the factorial moments (FM) [5]. In [5] it was shown that this method can help filter out statistical fluctuations and reveal the presence of fluctuations of the dynamic nature.

But the usage of factorial moments is a good means for detecting fluctuations in processes which have not very large average multiplicity of the event, for example, in $e^-e^+$, $pp$, as well as in collisions between ions of light elements. However, the average multiplicity in the event of heavy-ion collisions is high enough. In this case, the usual factorial moments are not effective. A new method for studying the particles distribution in events with very high multiplicity was proposed in [10]. The idea was to use the so-called factorial moments of the multiplicity difference, wich are multiplicity difference correlators (MDC). They are hybrid of usual moments and wavelets and have the form

$$\mathcal{F}_q(\delta,\Delta) = \frac{\sum_m m(m-1)...(m-q+1)Q_m(\delta,\Delta)}{\left(\sum_m mQ_m(\delta,\Delta)\right)^q} \tag{1}$$

where $m = m(\delta,\Delta) = |n_1 - n_2|$ is difference between the multiplicities in the two bins located at the distance $\Delta$ from each other, $Q_m(\delta,\Delta)$ is the multiplicities difference distribution.

Typically, for numerical calculations the factorial moments are averaged over several bins (see, [5] or review [11]) and are calculated as follows. Interval under consideration (for example pseudorapidity $\Delta\eta$) is divided into $M$ equal parts. Size of bin is defined as $\delta\eta = \Delta\eta/M$, where $\Delta\eta$ is considered interval of the phase space, $M$ is the number of bins in this interval. To calculate MDC we using the formula:

$$\mathcal{F}_q = M^{q-1}\frac{\left\langle\sum_{i=1}^{N} m_i(m_i-1)...(m_i-q+1)\right\rangle}{\left\langle\sum_{i=1}^{N} m_i\right\rangle^q} \tag{2}$$

where $m_i = |n_1 - n_2|$ is difference between the multiplisities of two bins of size $\delta$, separated by a distance $\Delta$, $(i = 1, \ldots M)$, $M$ is number of bins on the interval.

Averaging $\langle\ldots\rangle$ is the ensemble of events. By varying the number of bins $M$, and hence the size of the bin $\delta\eta$, we obtain the dependence of $\mathcal{F}_q(\delta\eta)$. Thus we calculated MDC of (2), for $q = 2, \ldots 7$. The examples of such dependencies are shown on figures 4, **??** and **??**.

FIG. 4. Dependence $\ln(\mathcal{F}_q(\delta\eta))$ on $-\ln(\delta\eta)$ for $\sqrt{s} = 500$ GeV, $q = 1\ldots7$ for $\eta$

FIG. 5. Example of dependence $\ln(\mathcal{F}_q)$ on $\ln(\mathcal{F}_2)$, $q = 1\ldots7$

In the series of works [5] it was shown that if there are fluctuations of the multiplicity particles, which are not statistical, it should be observed as power dependence of factorial moments of the size of the bin:

$$\mathcal{F}_q(\delta) \propto \delta^{-\alpha_q} \tag{3}$$

where $\delta$ is the bin size. The dependence of this type is called intermittency, where $\alpha_q$ is index of intermittency. In [5] it was shown that this dependence should be observed for the MDC. Power dependence of (3) is a criterion of dynamic fluctuations of multiplicity [11–14]. As was shown in [5, 17], if the system is characterized by the phenomenon of intermittency that may be observed the scaling behavior.

$$\mathcal{F}_q(\delta) \propto \mathcal{F}_2^{-\beta_q} \tag{4}$$

where coefficients $\beta_q$ can be obtained by using the following expression:

$$\beta_q = (q-1)^{\gamma} \tag{5}$$

Here $\gamma$ is difference universal scaling exponent. As the value of this magnitude can be tested on the presence in the phase transition from QGP into hadrons. Thus, the scaling exponent is the criterion by which to test whether the system has undergone a phase transition or not.

In the paper [10] it was shown that the presence of intermittency and the scaling are characteristic of the MDC. It within Ginzburg-Landau theory has been calculated the scaling exponent for the second order phase transition, a value of which is $1.09 \pm 0.02$. Consequently, if the system is observed scaling behavior of (4) and the value of the difference of the scaling exponent $\gamma$ is approximately equal to 1.1, then we can say that the system has undergone a phase transition of the second kind. In addition, was shown that if the system is not a phase transition occurs, then the value of the scaling exponent will be equal to $1.33 \pm 0.02$.

Figure 5 shows example of the dependence $\ln(\mathcal{F}_q)$ of $\ln(\mathcal{F}_2)$. This dependence is approximated by straight lines, which are also shown in the figure. Slope coefficients $\beta$ are obtained from lines on the figure. The value of the difference of the scaling exponents $\gamma$ are calculated by the formula (5) from slope coefficients $\beta$. The values of the scaling exponents obtained for different energies are presented in the table 1. There is lower value of that exponent means larger fluctuations.

If we compare our data with MDC obtained in the theory of Ginzburg-Landau phase transition [10], we can say that the value of the scaling exponent $\gamma$ indicates that in collisions may be seen the first order phase transition. But in these calculations existents rather large errors, which would make accurate conclusions. We have slightly modified the method of calculation. We were taken for calculations is not the whole interval $\delta\eta$, and that part where intermittensy most pronounced. These results are displayed in the table 2. From Data from the table we can conclude that on the possible existence of the first order phase transition above 1500 Gev. For energy from 1500 to 1700 GeV is the possible existence of the second order phase transition.

Table 1. The value of the difference of the scaling exponents for different energies of interaction (Pb + Pb)

| $\sqrt{s}$, GeV | $\gamma_\eta$ on [0; 5,0], $\Delta = 0,42$ | $\gamma_\phi$ on [0; 3,0], $\Delta = 0,19$ | $\gamma_{p_\perp}$ on [0; 2,0], $\Delta = 0,21$ |
|---|---|---|---|
| 500 | 1,21 ± 0,03 | 0,86 ± 0,03 | 1,22 ± 0,16 |
| 600 | 1,22 ± 0,03 | 0,86 ± 0,06 | 1,22 ± 0,16 |
| 700 | 1,23 ± 0,03 | 0,86 ± 0,07 | 1,22 ± 0,17 |
| 800 | 1,24 ± 0,03 | 0,86 ± 0,08 | 1,21 ± 0,20 |
| 900 | 1,25 ± 0,04 | 0,85 ± 0,08 | 1,21 ± 0,20 |
| 1000 | 1,28 ± 0,05 | 0,84 ± 0,11 | 1,20 ± 0,32 |
| 1100 | 1,26 ± 0,04 | 0,85 ± 0,10 | 1,21 ± 0,25 |
| 1200 | 1,27 ± 0,04 | 0,84 ± 0.10 | 1.24 ± 0.29 |
| 1300 | 1,28 ± 0,05 | 0.85 ± 0.11 | 1.20 ± 0.33 |
| 1400 | 1,29 ± 0,05 | 0.85 ± 0.10 | 1.20 ± 0.32 |

## 5. Conclusion

As part of this work it was carried out the Monte Carlo simulation of lead ions collisions for different energies and phase variables and also it was calculated scaling exponents of MDC $\gamma$. Comparing the results for $\gamma$ with the values calculated within the framework of the Ginzburg-Landau phase transitions general theory, we can say that the fluctuatians are grow wirh increasing collision energy. The simulation of collisions of heavy ions to indicate on the possible existence of the first order phase transition above 1500 Gev. For energy from 1500 to 1700 GeV is the possible existence of the second order phase transition.

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Table 2. The values of difference scaling exponents for $\eta$. Values of difference scaling exponents for different energies.

| **Collisions energy (Pb+Pb), GeV** | $\gamma_\eta$ **on the interval [0; 5,0],** $\Delta = 0,42$ |
|---|---|
| 500 | 1.4243 ± 0,0001 |
| 600 | 1.44377 ± 0,00008 |
| 700 | 1.39527 ± 0,00007 |
| 800 | 1.35893 ± 0,00008 |
| 900 | 1.33837 ± 0,00004 |
| 1000 | 1.29117 ± 0,00008 |
| 1100 | 1.21301 ± 0,00004 |
| 1200 | 1.19501 ± 0,00004 |
| 1300 | 1.17245 ± 0,00003 |
| 1400 | 1.18800 ± 0,00003 |
| 1500 | 1,15937 ± 0,00002 |
| 1600 | 1,11230 ± 0,00003 |
| 1700 | 1,07476 ± 0,00001 |
| 1800 | 1,01678 ± 0,00002 |
| 1900 | 1,03523 ± 0,00002 |
| 2000 | 1,02985 ± 0,00002 |

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