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Examination of heavy-ion collisions using EPOS model in the frame of BES program

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***Abstract*—EPOS is a generator which allows one to simulate various types of collisions of divers systems with different initial parameters. It considers the parton-based Gribov-Regge theory. So far the EPOS model has been used to describe higher collision energies obtained with RHIC[1] or LHC[2] data. On the other hand, there is another program under investigation: Beam Energy Scan conducted at Brookhaven National Laboratory. The beams of gold ions are collided at energies such as $\sqrt{s_{NN}} - 7.7, 11.5, 19.6, 27, 39$, and 62.4 GeV in order to collect and analyze data needed in examination of QGP[3] Phase Diagram. The EPOS model could become a useful tool in such studies. Simulated with EPOS data will be verified using elliptic flow analyses and two-particles femtoscopic correlations, which allow one to measure the size of sources determined by newly created particle.**

I. Introduction

Studying the properties of the nuclear matter is an extremely difficult and complex challenge. In order to achieve conditions needed to create systems containing particles we are looking for the heavy-ions are collided in major experiments. The information about newly-created matted are collected in detectors and analyzed by experimental physicists. Scientists explain occurring processes in detailed theories. One of such descriptions is included in the EPOS model. It considers the pardon-based Gribov-Regge theory [1]. EPOS gives possibility to study different observables what helps to understand even complex reactions with heavy-ions. So far the EPOS model has been used to describe higher collision energies obtained with RHIC or LHC. On the other hand, there is another interesting program currently under investigation at RHIC: Beam Energy Scan (BES), conducted at Brookhaven National Laboratory. Main goals of this project are to examine the Phase Diagram, to study the characteristics of the first-order phase transition between Hadron Gas and Quark-Gluon Plasma phases of nuclear matter, to search signatures of turn-off the QGP. The search of Critical Point between first-order phase transition and transition of "cross-over" is also significant topic. The variety of initial conditions allows to cover as widest part of Phase Diagram of nuclear matter as possible.

II. Beam Energy Scan

Beam Energy Scan is a scientific project run on the RHIC complex. The main goal, besides investigation of properties of QGP, is understanding the QCD phase diagram structure (Fig. [1]). Only a few pieces of information have been discovered yet. The QCD phase diagram is being mapped out in order to look for the evidences of:

- critical point fluctuations
- turn-off the signatures of QGP
- signals of 1^{st} order phase transition [2]

The gold ions are collided with such energies as: $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ GeV. Femtoscopic correlations or analysis of elliptic flow are two of ways of studying transitions of matter.

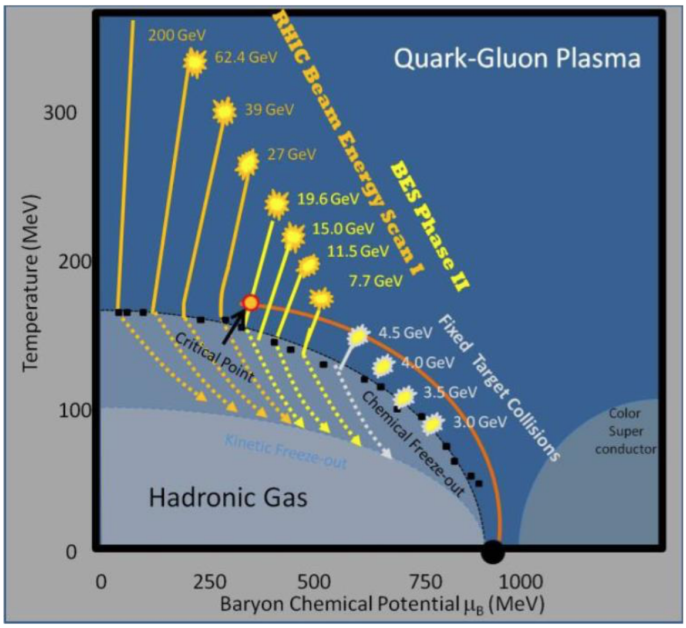

Fig. 1. *Studies of phase diagram peformed in a frame of BES program [3]*

III. Femtoscopy correlations

A. Two-particle correlations

The method inspired by HBT[4] interferometry [4] considers the smallest sizes in nature, about 10^{-15}m (femtometre), the sizes of nuclei. Studies of two-particle correlations allows one to investigate space-time extension of the emitting source created during the collisions of nuclei. The size of area where the given kind of particles are produced is called *homogeneity length* [5].

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[1]Relativistic Heavy-Ion Collider

[2]Large Hadron Collider

[3]Quark Gluon Plasma

[4]R. Hanbury-Brown and R. Q. Twiss

1) Correlation function: A two-particle correlation function defines ratio between the probability of detecting two particles with given momenta and position simultaneously to the product of detecting them separately [5].

$$C(p_1, p2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)} \tag{1}$$

The source is often treated as a three-dimensional sphere and described with parametrization proposed by G. Bertsch and S. Pratt [6] in Longitudinally Co-Moving System where: $p_{1,L} + p_{2,L} = 0$. The correlation function is represented in the -out -side -long (o-s-l) coordinate system [7]. Kopylov and Podgoretsky proposed the three-vector $\vec{q} = \vec{p_1} - \vec{p_2}$ so that the correlation function is represented with the equation (assuming Gaussian source parametrization):

$$C(q_{out}, q_{side}, q_{long}, \lambda) =$$
$$1 + \lambda exp(-q_{out}^2 r_{out}^2 - q_{side}^2 r_{side}^2 - q_{long}^2 r_{long}^2) \tag{2}$$

where $r_{out,side,long}$ are lengths of the source in $out, side$ and $long$ directions (three-dimensional femtoscopy radii) and λ is a chaosity parameter [Fig. 2].
In the three-dimensional analysis the values of the R_{out}, R_{side} and R_{long} are considered to be optimal in studies of the time-space characteristic of the particle-emitting source [8] [5].

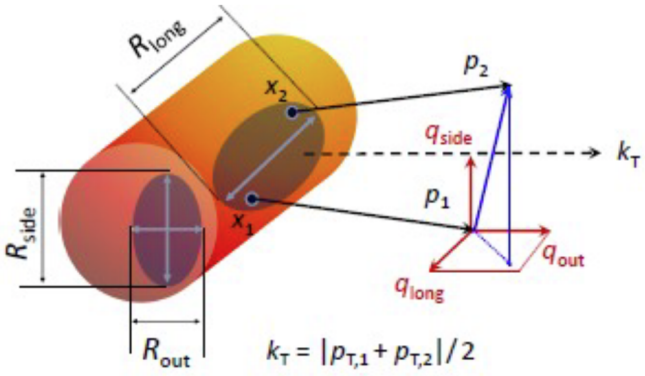

Fig. 2. Definition of the three-dimensional femtoscopy radii.

In analysis of the experimental data the function is parametrize with the following form:

$$C_2(\vec{q}) = \frac{A(\vec{q})}{B(\vec{q})} \tag{3}$$

where A (signal) is a momentum distribution of particles built in the same event, while B (background) is a reference momentum distribution obtained from different events.

IV. Azimuthal anisotropy

The azimuthal anisotropy characterizes expansion of highly-compressed matter created in heavy-ion collisions [Fig. 3]. It is one of the most significant tool used in studying hot and dense matter, described more detailed in Ref. 9.
The shape of the expansion could be expressed with the

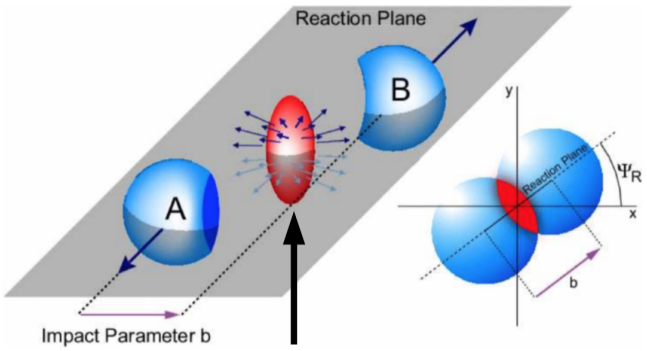

Fig. 3. *Nucleus after collision. [10]*

Fourier decomposition. The second order contribution responds to *elliptic flow*. One of the standard methods used in order to calculate the flow is *event plane method*. The crucial part is to estimate the reaction plane from the measured particles. It is defined as an *event plane* in range $\Psi_n(-\pi/n \geq \Psi_n < \pi/n)$. In order to calculate the *event plane* for elliptic flow one can use equation:

$$\Phi_2 = \tan^{-1}\left(\frac{\sum_i w_i sin(2\phi_i)}{\sum_i w_i cos(2\phi_i)}\right)/2 \tag{4}$$

where: i - selected particle, ϕ_i - azimuthal angle of particles, w_i -weight of i particle [11]. In proposed $\eta - sub$ method, from all measured particles there are selected two groups with "forward" and "backward" pseudorapidity with a gap between them. This method is introduced with a view to reducing the effect of "non flow" (e.g. decay of resonances to several charged daughter particles, jets or HBT correlations). [12]
To express the observed v_2 of particles with respect to already investigated event plane one uses:

$$v_2^{obs}(p_T, y) = \langle \cos[2(\phi_i - \Phi_2)] \rangle \tag{5}$$

This is average over all particles in all events. As a consequence of final multiplicity limitation in the investigation of the angle of the reaction plane, the correction of v_2 with *event plane* resolution have to be done.

$$R_2 = \sqrt{\langle \cos[2(\Phi_2^A - \Phi_2^B)] \rangle} \tag{6}$$

where: Φ_n^A - *event plane* calculated only using "forward-pseudorapidity" particles while Φ_n^B - with "backward-pseudorapidity" ones. The final result of v_2 calculation is given by:

$$v_2 = \frac{v_2^{obs}}{R_2} \tag{7}$$

V. EPOS

EPOS is a model which consists:
Energy conserving quantum mechanical multiple scattering approach, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**plitting of parton ladders [1].
EPOS is a generator based on Parton-Based Gribov-Regge theory which is the mixture of two diverse theories. First

one, Gribov-Regge uses effective field principies and it focuses on the soft aspects of particle collision. The interactions are described with theoretical objects called *Pomerons*, which are crucial in calculation the cross-section in multiple scattering (Fig. 4). The eikonalized parton model introduces quarks and gluons, what results with a more precise description of the interactions such as a gluon exchange. The QCD[5] and QED[6] are included in the description as well. [1] [13]

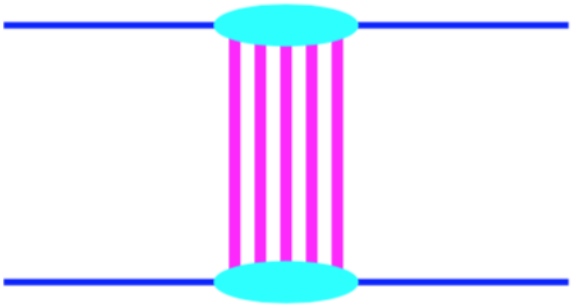

Fig. 4. Hadron - hadron multiple scattering. Navy blue lines are hadrons and each of pink line illustrate Pomeron. [1]

The combination of Gribov - Regge theory and parton model ensures that the energy is shared properly between both the particle production and the cross section. With the parton model there are hard processes added as well. The production of partons is represented by Lund model strings [14]. There are introduced objects called *parton ladders*. The open ones contribute to inelastic scattering which supports particles production. Meanwhile the closed ladders illustrates elastic scattering (Fig. 5). In third version of EPOS there is applied the procedure consists hydrodynamic effects described in Ref. 15.

VI. Results

Three different kinds of analysis were performed: one-particle analyze - p_T spectra, azimuthal anisotropy - v_2, two-particles analysis - femtoscopy correlations, in order to compare simulated and experimental data.

A. Transverse momentum spectra

Studies of the transverse momentum are the most elementary in High-Energy analysis. The obtained distributions are compared with the experimental data published in Ref. 16. Such measurements were done for Au + Au collisions at two centrality ranges: $0-5\%$ (central) and $60\%-80\%$ (peripheral events). Particles with rapidity $|y| < 0.5$ were taken into consideration. Below there are placed the obtained p_T distributions for $\frac{h_+ + h_-}{2}$, the sum of positive-charged hadrons (p, π^+, K^+) and negative once $(\bar{p}, \pi^-, K^-)$.

There is high agreement between experimental and theoretical data registered for the most central collisions. However, for lower energies for higher values of p_T the slopes of plotted

[5]Quantum Chromodynamics
[6]Quantum Electrodynamic

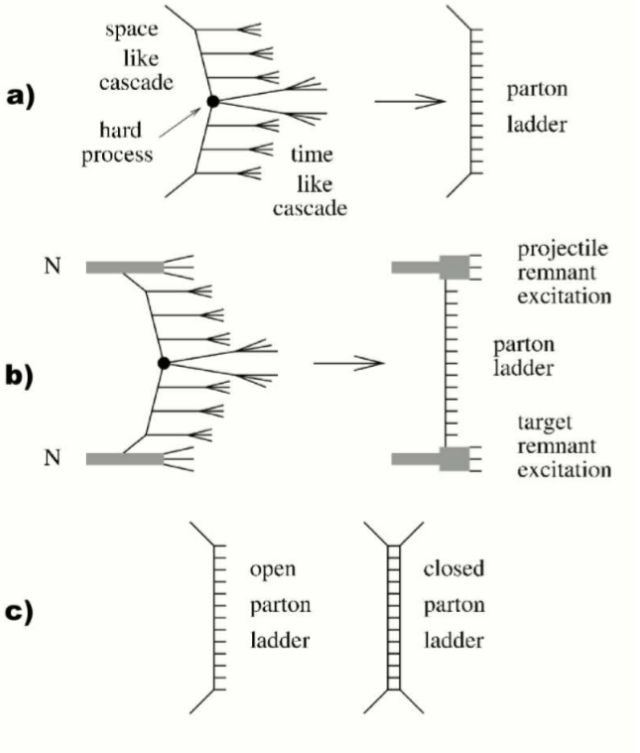

Fig. 5. a) Elementary parton - parton scattering and representation as parton ladder. b) Full presentation of scattering, completed with remnants. c) Open and closed parton ladder [13]

data are slightly different. The strong expansion of the matter in the transverse direction is too low in comparison with the experimental results. In case of peripheral collisions the difference is more visible.

B. Correlation function

There was performed positively charged pions femtoscopic analysis in Au+Au collisions. In order to study beam energy in femtoscopy the were calculated and parametrized three-dimensional correlation functions. The π^+ pairs were taken into consideration at $\sqrt{s_{NN}} = 11.5$GeV 19.6 and 39 GeV at different centralities or k_T ranges. With a view to inferring size of emitting source the fitting procedure was used (equation 2). Obtained radii and λ parameter from calculation of simulated data were compared with published experimental results and presented in different combinations.

With the decrease of energy of collision $\sqrt{s_{NN}}$ the differences becomes more relevant. Calculated values of R_{out} are in the range of expectations. The duration of particle emission is similar for compared systems. In case of measurements of R_{side} the experimental results are higher then the simulated once, especially for lower k_T bins. The sizes of sources created in STAR are bigger then simulated in EPOS. However, the most visible discrepancy is in studies of R_{long}. In order to explain these differences the elliptic flow analyze was performed.

It is possible in EPOS generator to turn off some physics

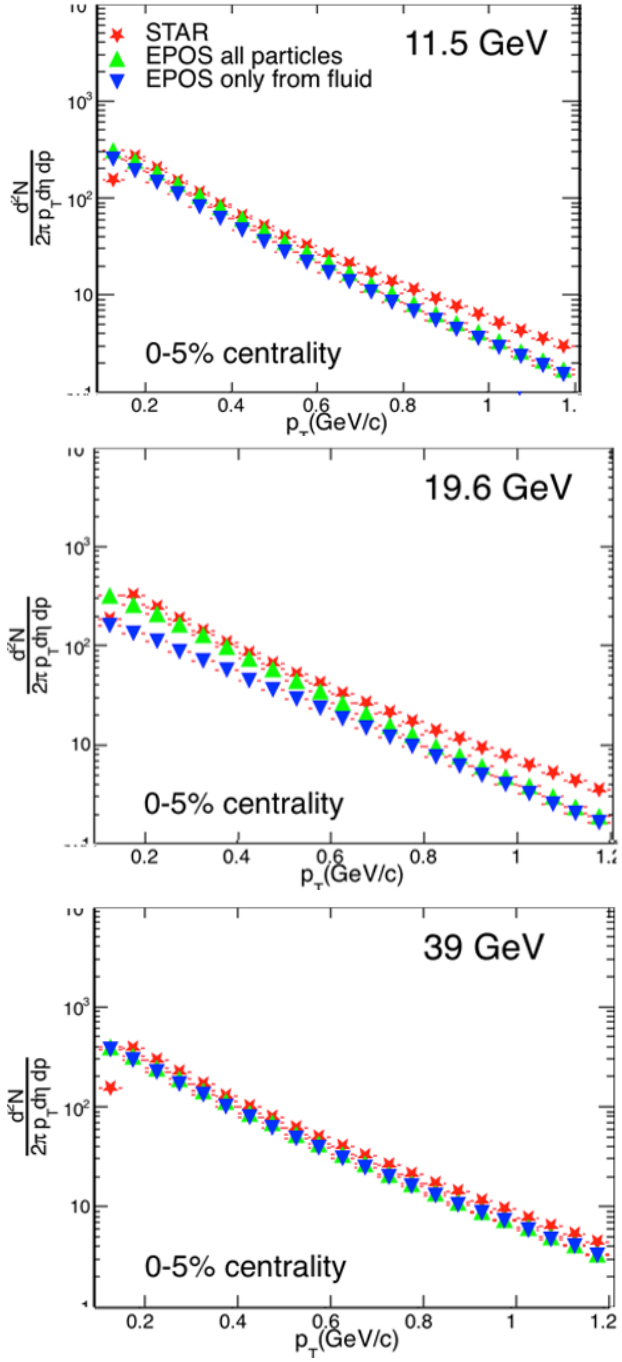

Fig. 6. p_T spectra for energies $\sqrt{s_{NN}} = 11.5, 19.6, 39$ GeV at $0-5\%$ centrality range.

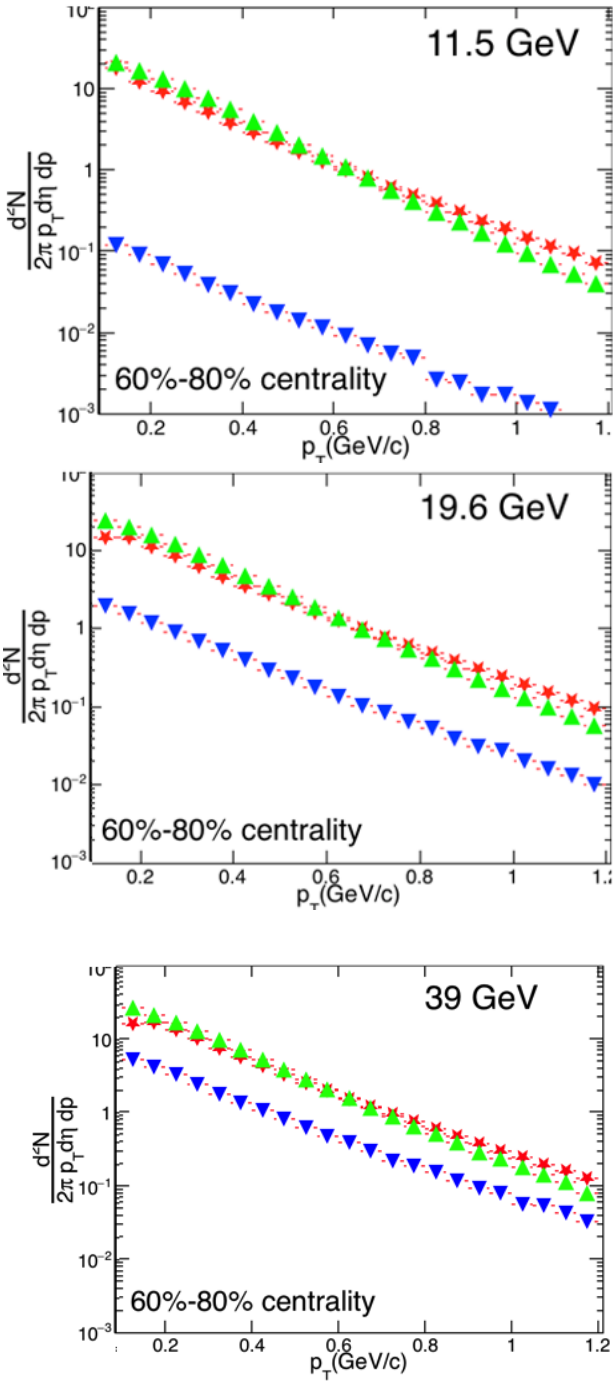

Fig. 7. p_T spectra for energies $\sqrt{s_{NN}} = 11.5, 19.6, 39$ GeV at $60\%-80\%$ centrality range.

processes occur in heavy-ion collisions. In order to study the impact of hadron cascades on size of emitting source, they were turn off and turn on in simulation. The results are presented in Figure 8. Hadron cascades have relevant influence on values of calculated radii and λ parameter. When they are present the size of the source is bigger and more similar to experimental studies. The λ parameter and R_{out} are in the range of expectations, while rest of parameters are considerably lower then in experimental results. Too high value of ratio R_{out}/R_{side} means that the lifetime of the source is shorter for simulated collisions than those obtained in experiments.

C. *Elliptic flow*

The studies of the elliptic flow were preformed in order to examine the description of matter expansion included in EPOS model. The data simulated with the EPOS were compared with STAR results published in Ref. 12. The studies of beam energy were performed at mid-rapidity region for p, $\bar{p}$, π^+, π^-, K^+, K^- at $\sqrt{s_{NN}} = 11.5, 19.6, 39$GeV in minimum bias $(0-80\%)$ using η-*method*. Particles with $|\eta| < 1$, momentum between 0.15 and 5 GeV/c were taken into consideration.

The calculated values for pions and kaons coming from

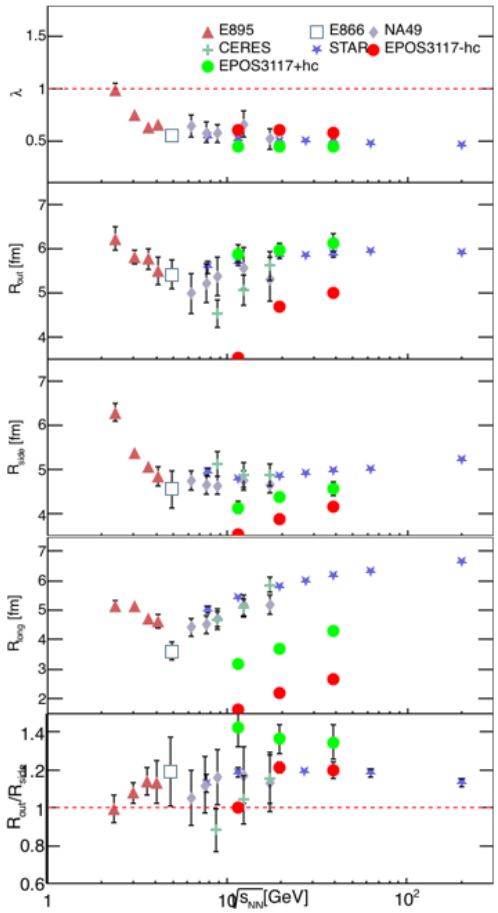

Fig. 8. λ and radii dependence on energy $\sqrt{s_{NN}}$ for different experiments and EPOS data ($k_T \approx 0.225 GeV/c$). [17]

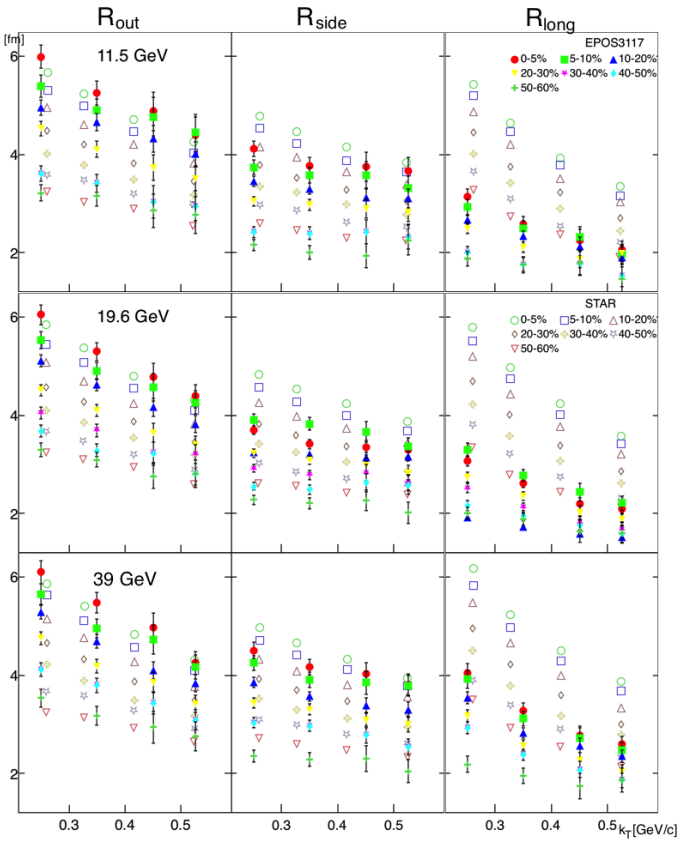

Fig. 9. Radii calculated for various centralities and k_T bins [17]

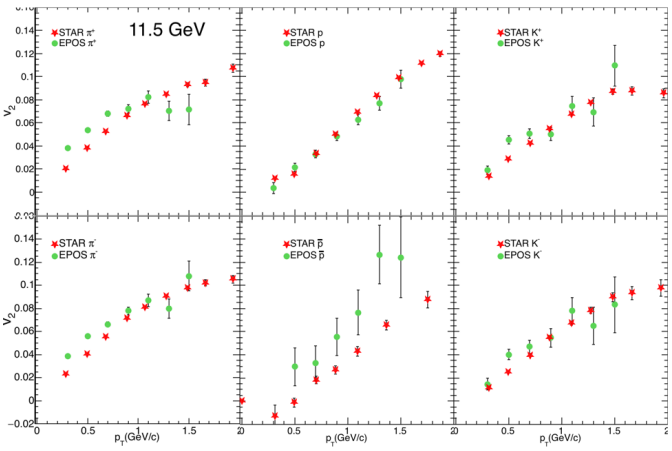

Fig. 10. Elliptic flow dependence on p_T, $\sqrt{s_{NN}} = 11.5$ GeV [12].

simulation are slightly higher than expected. Although for $p_T > 1.2$GeV and $\sqrt{s_{NN}} = 11.5$ GeV the pions flow is low. The pions are about 90% of all produced particles in the event, so they have a strong impact on the shape of p_T spectra shown before. The low flow could result in the discrepancies in the slopes of the spectras. The same tendency is visible for antiprotons. The elliptic flow of protons in all p_T bins are comparable for both data sets.

VII. Conclusion

The EPOS model predictions for Au+Au collisions at BES energy spectrum are verified with results obtained with experimental data. The p_T spectra, correlation functions for identical pions and elliptic flow at 11.5 , 19.6 and 39 GeV for both simulated and STAR data were compared and presented. Observed discrepancies can be caused by too small impact of particles origin in *core*. The transparency of the collision should be investigated as well. The work is still in progress.

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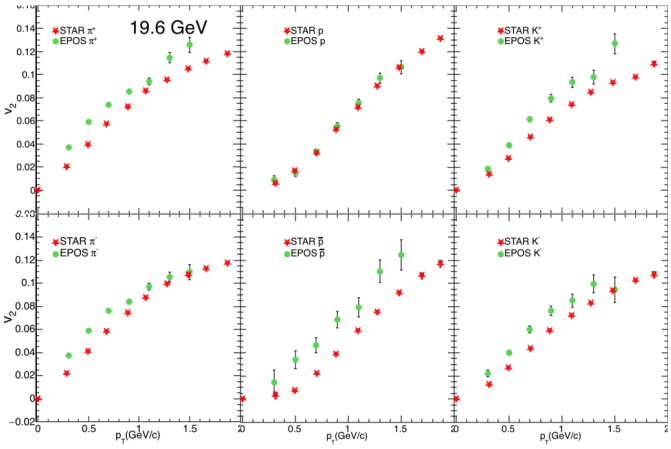

Fig. 11. Elliptic flow dependence on p_T, $\sqrt{s_{NN}} = 19.6$ GeV [12].

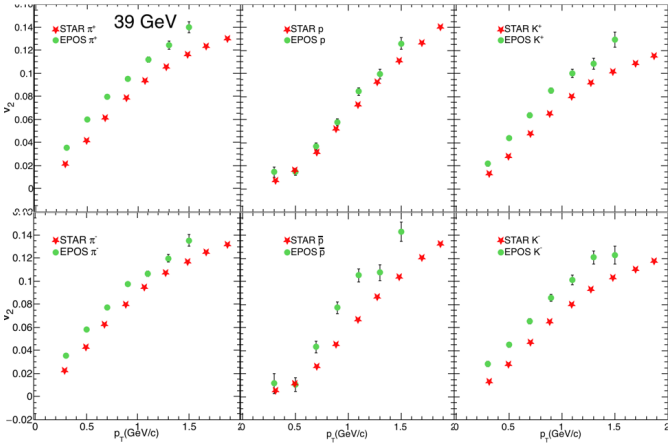

Fig. 12. Elliptic flow dependence on p_T, $\sqrt{s_{NN}} = 39$ GeV [12].

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