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# Rapidity Distribution of Charged Pions From Pb+Pb and Au+Au Central Collisions

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## Abstract

Rapidity distributions for charged pions produced from central collisions Pb+Pb and Au+Au at (b ≤ 3.4 fm.) in range of energy 2 GeV up to $\sqrt{s_{NN}}$ = 200 GeV are investigated. The experimental results are studied in terms of the Ultra-relativistic Quantum Molecular Dynamic Model Ur-QMD. In general, the model can give suitable predictions of rapidity distributions for production of charged pions from interactions with energies below 160 A GeV. This model is supported the assumption that the onset of de-confinement is located at low energies. It treats the initial nucleon-nucleon interactions within a string-hadronic framework. In addition, it includes effects such as string-string interactions and hadronic re-scattering that expected to be relevant in A+A collisions. There is a kind of similarity for mechanism responsible for production of the two charge states of pions and it can extended to other hadrons. Ultra-relativistic quantum molecular dynamic model give good description on energy dependence for charged pion productions and points of maximum rapidity.

## Key words

rapidity distribution, charged pion production, theoretical model

## 1. Introduction

Experimentally, it is impossible to measure all parameters that are characterizing the kinematics of high-energy nucleus-nucleus collisions. Some of these parameters can be measured and others can calculate from theories, which assumed to describe this collision. These quantities give the details and properties of the interactions such as the pseudorapidity or rapidity distributions, transverse momentum distributions, azimuthal correlations, flow effects, and some other interesting information have been obtained [1]. Many experimental laboratories aim to study the fine properties of nuclear matter especially at high values of temperature and nuclear density. One of these accelerators is Super Proton Synchrotron (SPS) [2–4] and colliders such as the Relativistic Heavy Ion Collider (RHIC) [5–8] and the Large Hadron Collider (LHC) [9–12]. The primary purpose of the heavy ion program at CERN SPS is the search for a transient de-confined state of strongly interacting matter during the early stage of nucleus–nucleus collisions [13]. When a sufficiently high initial energy density is reached, the formation of such a state of quasi-free quarks and gluons, the quark gluon plasma QGP), is expected. The main problem is the identification of experimental signatures of QGP creation [14,15]. In such collisions, the matter has evolved from a heated and compressed gas of nucleons into a hot dense gas of hadrons, predominantly pi-mesons. Thus, the energy region from 2 to 8 A GeV represents a transition regime. Studies of nuclear stopping suggest the maximum density achieved increases from three times normal nuclear density at 1 A GeV [16-18] to eight times normal nuclear density at 10 A GeV [19]. This additional available energy goes primarily into pion production. By studying the pion production across this regime, we are able to observe nuclear matter in transition. Therefore, we consider the pion production from heavy ion collisions is one of the early possible signatures of a transition to de-confined state of matter. However, in the early studies of pion yields in the 1 A GeV energy range at the Bevalac [20-22], it was observed that the measured pion production cross-sections were smaller than predicted at the time. This observation led to the conjecture, which was later experimentally demonstrated, that the excess kinetic energy was converted into hydrodynamic flow effects. The strong radial flow observed at this energy implies a significant expansion and cooling, which limits the freeze out pion multiplicities [23,24]. More recently, more detailed measurements of the pion yields from 1 A GeV Au+Au collisions have become available from the SIS experiments [25-28]. In full energy AGS collisions (Au+Au at 10.8 A GeV), pion production has been studied at mid-rapidity [29] and at target rapidity [30]. There is still an asymmetry between $\pi^-$ and $\pi^+$ production.

It is more important to compare the experimental data with the corresponding predictions which are based on the theoretical concepts describe the interactions between collided nuclei. Many theoretical models are partly able to give new concepts on nuclear materials under these conditions and special formulations for treatments of the assumed processes that are responsible for the creations and production of experimentally observed secondary particles. One of the important of these models is Ultra-relativistic Quantum Molecular Dynamic model UrQMD [31,32]. This model is a microscopic many body approach for studying hadron-hadron, hadron-nucleus and heavy ion collisions at relativistic energies from $E_{lab}$=100 A MeV to $\sqrt{s_{NN}}$ = 200 GeV. Its microscopic transport approach is based on the covariant propagation of color strings, constituent quarks and di-quarks (as string ends) accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of ingoing and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. At higher energies, the treatment of sub-hadronic degrees of freedom is of major importance. In the present model, these degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [33-35]. The major aspects and formulation of UrQMD are discussed in Refs. [36, 37]. Details on rapidity distributions will discussed in section 2. A comparison and discussions for rapidity distributions of charged pions produced from central and mid rapidity from Pb-Pb and Au-Au collisions at relativistic energies and results suggested by UrQMD model will be in section 3.

## 2. Concepts on rapidity distributions and UrQMD model

Ultra-relativistic Quantum Molecular Dynamics [31,38] is a microscopic transport model, which attempts to simulate heavy ion collisions by propagating individually all particles through the six dimensions of phase space in the fireball. Such a microscopic model based on a phase space description of the reaction. It contains many unknown parameters, which will have to be check and fixed by experimental data or by further model assumptions. This theoretical approach allows pinning down physical ingredients that determine the values of certain observables like rapidity distributions. Interaction probabilities are approximated by using published interaction cross-sections of free hadrons and the relative phase space proximity of pairs of particles at each time step of the reaction. Inelastic collisions may produce new particles, such as pions, which propagated through phase space along with the nucleons. The reaction ends when the phase space density reaches a low enough threshold such that the probability of further interactions is small the freeze-out point. It mean that the model attempt to describe the full time-evolution from the initial state of the heavy ion reaction (i.e. the two colliding nuclei) up to the freeze-out of all initial and produced particles after the reaction. Simplified thermal equilibrium models neglect most of these dynamical effects, but make physical assumptions on the initial part of the reaction, e.g. thermalization or plasma creation. This is of most importance if one wants to find evidence for new physical phenomena like the phase transition to the quark gluon plasma. Since the particles propagate in a hot, dense, and even not equilibrated medium of highly excited hadrons, the properties of the particles might change significantly. Consequently, properties like effective masses, effective momenta, in medium cross sections and decay widths should be calculated for the actual local situation in which the particle propagates.

In this and other cascade models, particle distributions of the final-state are frozen at the end of the reaction. Hadronic transport models are well able to predict or reproduce the measured rapidity distributions over a vast energy range, if baryon and meson re-scattering and particle production via string decay [39-42] are incorporated. This model has been reasonably successful in describing many final state of experimentally observables which are measured in the beam energy range studied for this analysis. According to this model, the main points of interest is the physical properties of the formed new phase of nuclear matter from participating nucleons of projectile and target nucleons. The high-energy interacting nucleons create highly excited nuclear matter [43,44] and cause the creation zone of high energy density. At first moment of the reactions, there are suggested nuclear shock waves as a primary mechanism of creating high energy densities [43-45]. The degrees of stopping powers between collided nuclei [45] are characterizing the interactions where heavy ion collisions such as Pb+Pb or Au+Au, are the best conditions for strongly power and high density. During this reaction, a part of the respective longitudinal momenta is converted into transverse momentum and secondary particles. Productions of charged pions are one of the secondary produced baryons, which give important signals of the formations of these conditions. In previous work [46] there are strong signal for varying cross-sections for baryon–baryon interactions with collision energy [47-49]. Now we will study the rapidity distributions for charged pions emitted from central interactions for heavy nuclei Pb+Pb and Au+Au at (b ≤ 3.4 fm.). A change in the shape of the scaled dN/dy distribution with varying incident beam energy is a clear signal for new degrees of freedom entering the reaction (i.e. de-confinement) or for phenomena such as critical scattering [50]. One often assumes that particles produced at $y = y_{CM}$ originate from the central reaction zone and the initial proper time $\tau_0$. The rapidity distribution of these produced particles can used to estimate the initial energy density in the central reaction zone [51]:

$$\epsilon_0 = \frac{m_T}{\tau_0\, A} \frac{dN}{dy}\bigg|_{y=y_{CM}}$$

Here $A$ is the transverse overlapping region area in the collision and $m_T$ the transverse mass of the produced particles. The proper production time $\tau_0$ is estimated to be of the order of 1 fm/c. Estimates for the CERN/SPS energy region were in the order of 1 to 10 GeV/fm$^3$ [51]. The following section will concern the rapidity distributions of charged pions emitted from heavy nuclei collisions Pb+Pb and Au+Au at (b ≤ 3.4 fm) compared with the corresponding predictions by UrQMD.

## 3. Experimental results and discussions

In this section, we will study the behavior of the rapidity distributions for charged pions produced from collisions Pb+Pb and Au+Au at central events (b ≤ 3.4 fm.) in energy range 2 GeV up to $\sqrt{s_{NN}}$ = 200 GeV. The experimental results are collected from different experiments [52-56]. This results compared by the theoretical approaches and predictions of dynamical model of A+A collisions, UrQMD. This model is supported the assumption that the onset of de-confinement is located at low energies. It treats the initial nucleon-nucleon interactions within a string-hadronic framework. In addition, it includes effects such as string-string interactions and hadronic re-scattering that expected to be relevant in A+A collisions. Figure 1 show the rapidity distributions for positive pions, emitted from central collisions (b ≤ 3.4 fm) Pb+Pb and Au+Au at energies 2 A GeV shown in fig. 1a, 4 A GeV in fig. 1b, 6 A GeV in fig. 1c, 8 A GeV in fig. 1d, 11 A GeV in fig. 1e and at energy $\sqrt{s_{NN}}$ = 200 GeV in fig.1f. In addition, figure 2 shows the rapidity distributions for negative pions at energies 2 A GeV in fig. 2a, 4 A GeV in fig. 2b, 6 A GeV in fig. 2c, 8 A GeV in fig. 2d, 11 A GeV in fig. 2e, 20 A GeV in fig. 2f, 30 A GeV in fig. 2g, 40 A GeV in fig. 2h, 80 A GeV in fig. 2i, 160 A GeV in fig. 2j and at energy $\sqrt{s_{NN}}$ = 200 GeV in fig. 2k. The corresponding smooth solid line represents the prediction using the art version UrQMD-2.3 calculations. It is noticed that in general, the model can describe the rapidity distributions of two charged pions especially at values of interaction energies below 160 A GeV. The energy dependence is observed for productions of charged pions in both experimental and theoretical predictions. Similar conclusion was obtained in Refs. [57-59]. This calculations lead to a lower pion yield, which is in better agreement with the experimental data over the given range of energy. The shapes of the distributions in the middle regions of rapidity look very similar to experimental one. For energies below 8 A GeV and in range of rapidity y= ±1 to 1.5 the model predictions are very close to the experiment data for two charged pions. Above, especially for energy 200 A GeV the model require an additional approach of new mechanisms of cascading of interactions between participating collided nucleons.

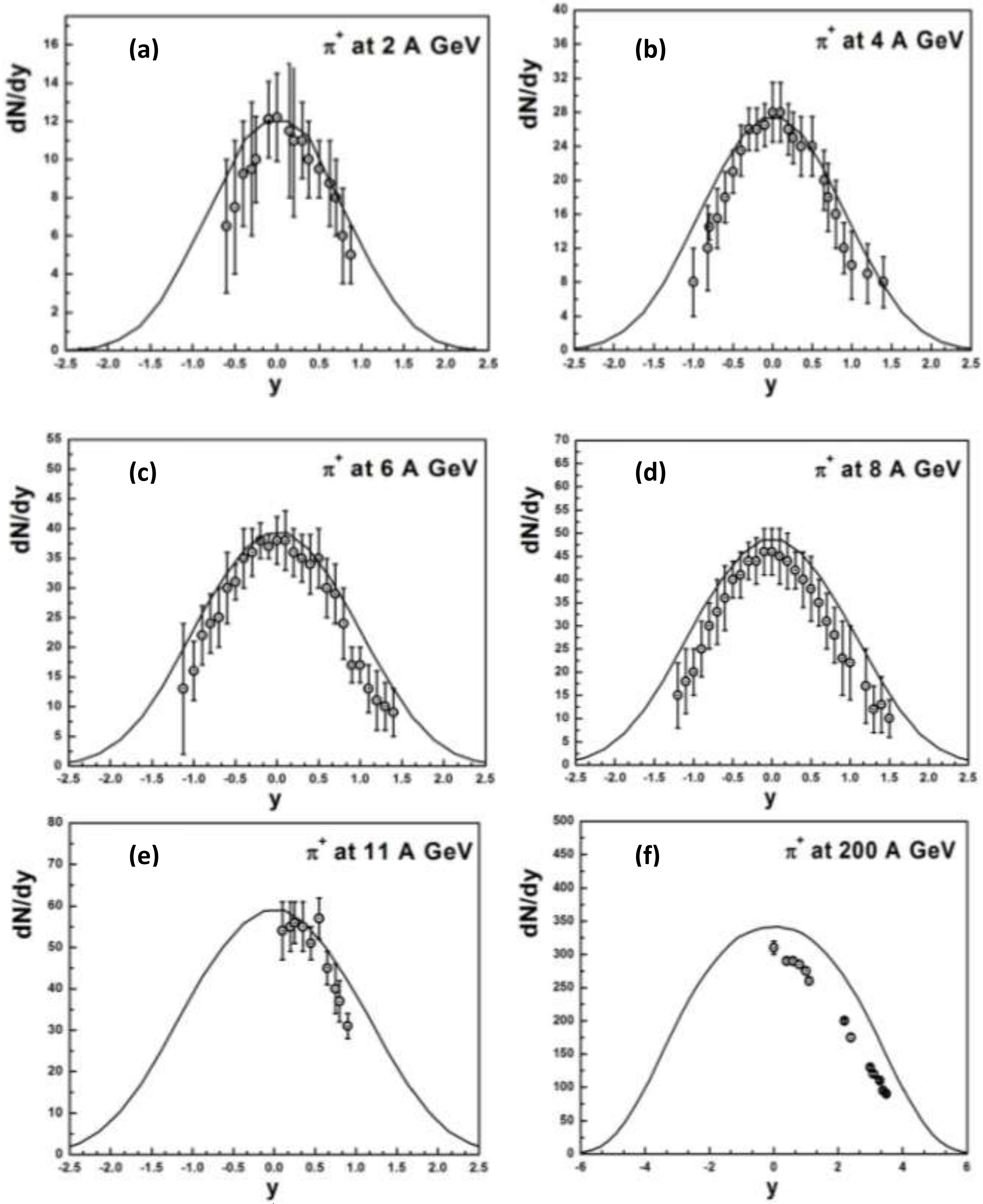
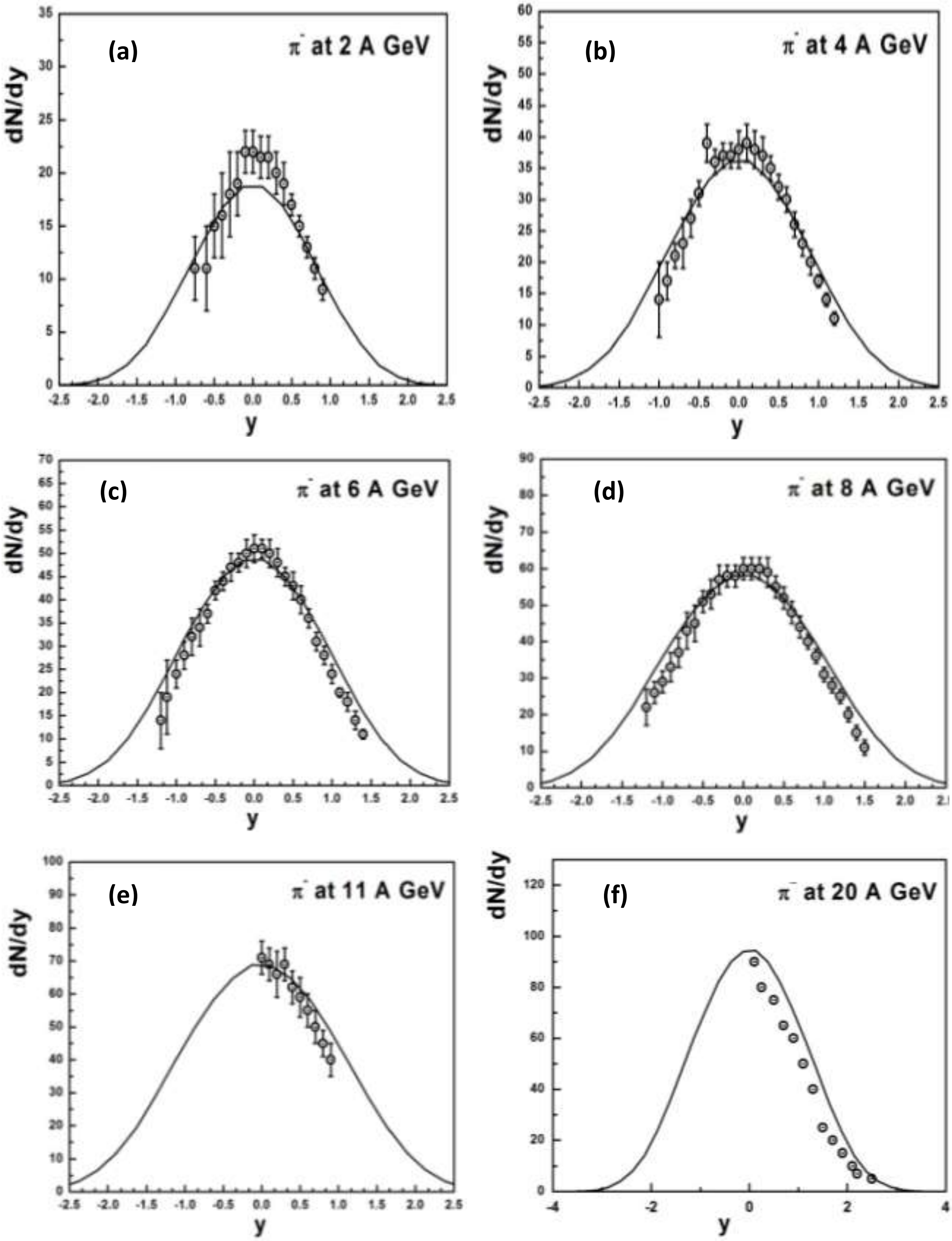



**Fig. 1:** Rapidity distribution of $\pi^+$-mesons emitted from central (b < 3.4 fm) Au+Au/Pb+Pb collisions from $E_{lab}$ = 2 A GeV to $\sqrt{s_{NN}}$ = 200 GeV. The smooth lines represent UrQMD-2.3 calculations.


(a)
π⁻ at 2 A GeV
(b)
π⁻ at 4 A GeV
(c)
π⁻ at 6 A GeV
(d)
π⁻ at 8 A GeV
(e)
π⁻ at 11 A GeV
(f)
π⁻ at 20 A GeV
dN/dy
y

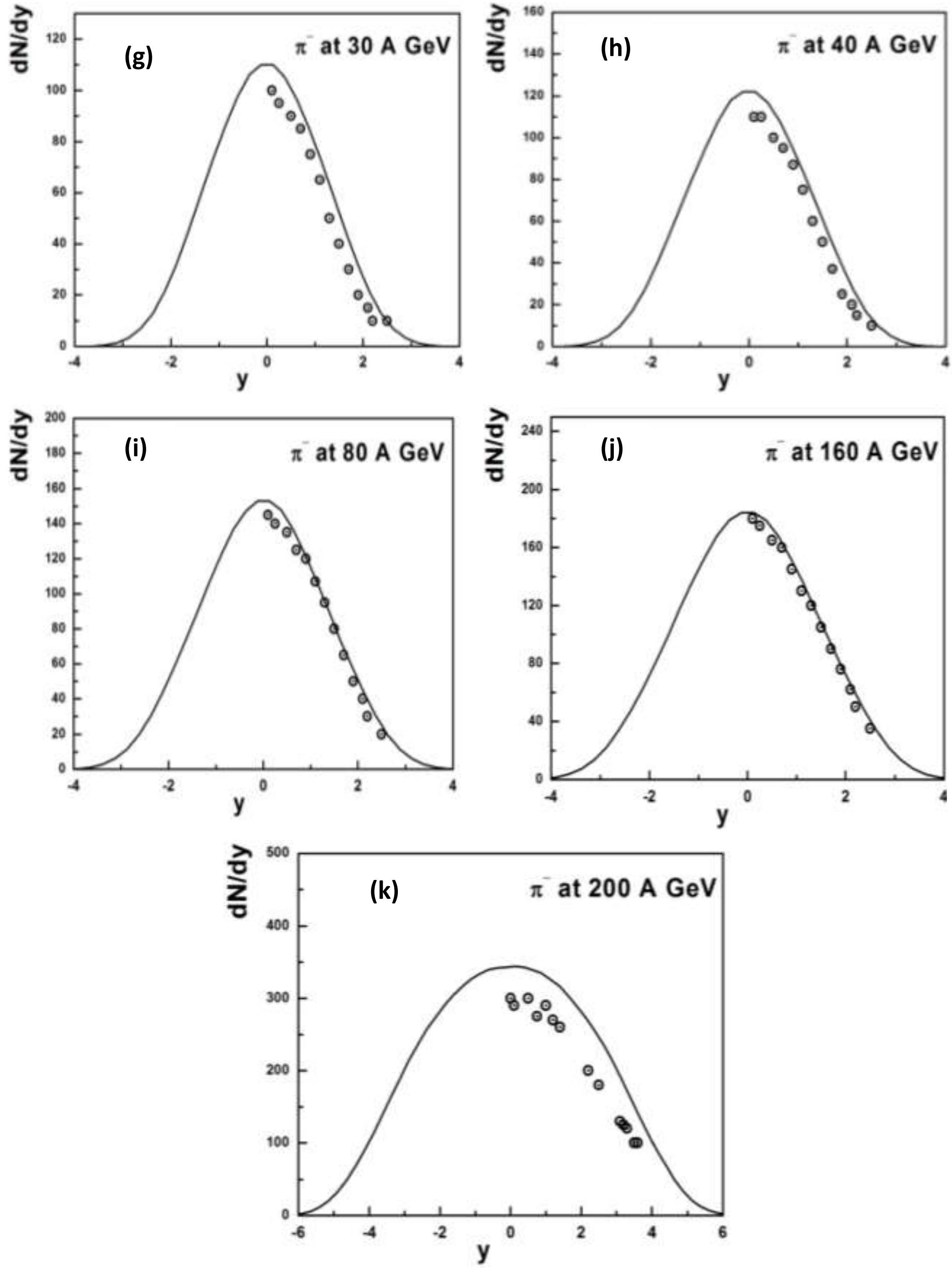



**Fig. 2:** Rapidity distribution of $\pi^-$-mesons emitted from central (b < 3.4 fm) Au+Au/Pb+Pb collisions from $E_{lab}$ = 2 A GeV to $\sqrt{s_{NN}}$ = 200 GeV. The smooth lines represent UrQMD-2.3 calculations

The number of the produced charged pions per each bin of rapidity increases with collision energy to reach maximum at $\sqrt{s_{NN}} = 200$ GeV. The width of rapidity distribution increases with collision energy. It explains by considering the increasing of collision energy allowed to make several collisions with sufficient energy and secondary particle productions emitted with wide range of emission angles and so wide range of rapidity distributions.

An important results are the magnitude of the points of maximum rapidity, $(dN/dy)_{max}$ This points are around $y = 0$, its indicates presence a similarity for the mechanism which describe the interaction system responsible for productions of the charged pions. Point of maximum rapidity increases with collision energy. This dependence is shown in fig. 3. The smooth lines are the corresponding representations by UrQMD. At this range of collision energies, the model can give good description of the experiment values. At this points the productions of charged pions are comes from two parts, first is from hot and dens matter created from heavy ion collisions. This part of production is similar between two charge states of pions and may be extended to other possible and expect hadrons. For large values of impact parameters, there are productions of new particles and called leading particles. Its productions depend on the number of participant interacting nucleons and sensitive to both energy and number of collisions. The production of charged hadrons from this part is symmetry and my take normal or Gaussian distribution and independent on the self-properties of secondary hadrons.

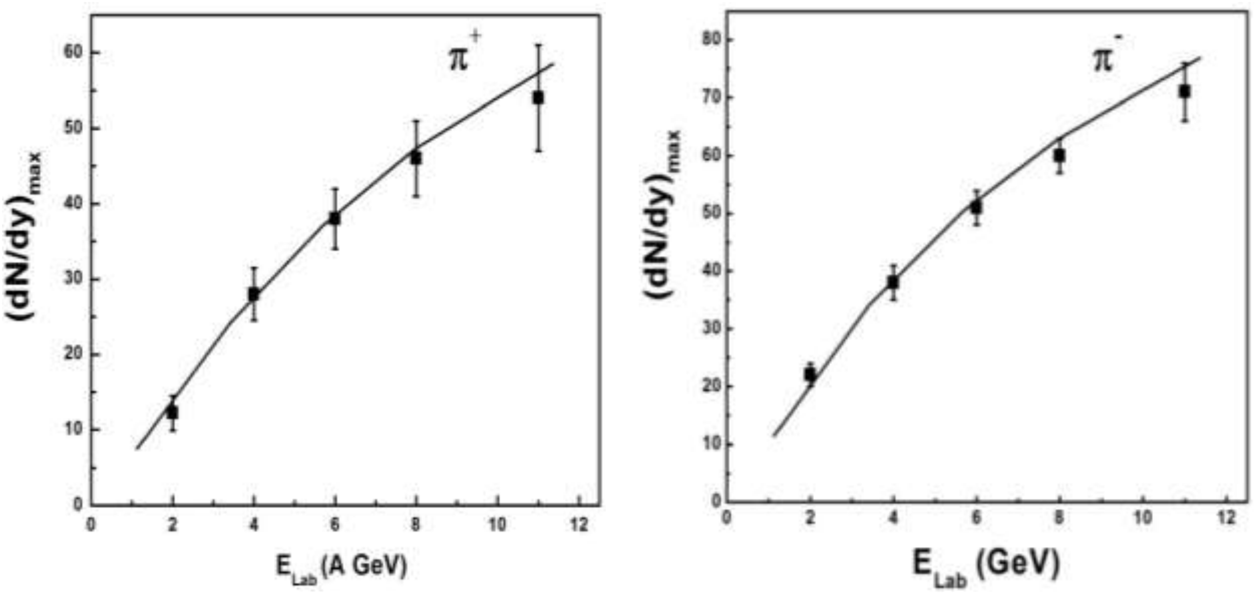



**Fig.3:** Dependence of the maximum rapidity spectra on the energy of central collisions Au+Au/Pb+Pb at (b < 3.4 fm). UrQMD-2.3 calculations are shown by the full lines.

## 4. Conclusions

The behavior of the rapidity distributions for charged pions produced from collisions Pb+Pb and Au+Au at central events (b ≤ 3.4 fm.) in a energy range 2 GeV up to $\sqrt{s_{NN}}$ =200 GeV can represent by the theoretical approaches and predictions of dynamical model of A+A collisions, UrQMD. The model describes the energy dependence of the production charged pions. There is kind of similarity between two charge states of pions and may be extended to other possible expect hadrons. The multiplicity of the produced charged pions per rapidity pen and points of maximum rapidity are sensitive for interaction energy. Points of maximum rapidity are observed at zero rapidity and it well described by UrQMD model.

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