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TEMPERATURES AND DENSITIES IN NUCLEAR MATTER OBTAINED IN Au-Au COLLISIONS AT RHIC-BNL ENERGIES

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Abstract: Ultrarelativistic heavy ion collisions are useful “tools” to investigate highly excited dense nuclear matter. At sufficiently high temperature, nuclear matter is expected to undergo a phase transition to quark-gluon plasma. Some predictions and experimental results on the rapidity and pseudorapidity distributions, as well as on hadron spectra are included in this paper. For predictions the UrQMD and HIJING codes have been used. The rapidity density, respectively, pseudorapidity density are used to estimate energy density. From transverse mass spectra and transverse momentum spectra are extracted pions, kaons, protons and antiprotons temperatures. The mass dependence of the slope parameters provides evidence of collective transverse flow. Comparisons with the two codes predictions are included. Taking into account the fact that some information on the collision dynamics and the thermalisation degree is obtained from the spectral shapes of the interesting physical quantities and their dependencies on rapidity in this paper the dependencies of the average transverse momentum on the rapidity densities and on the pseudorapidity densities are studied. The values of the energy and baryonic densities – over 10 normal values - as well as the agreement between the experimental values on participants and phenomenological model estimations, represent a support for the estimated thermodynamic parameters of the nuclear matter in *Au-Au* collisions at RHIC-BNL energies, as well as for the possibility to evidence phase transitions to the quark plasma and quark-gluon plasma in these collisions.

Key words: relativistic heavy ion collisions, nuclear density, nuclear temperature, collective flow, and collider, phase transition

INTRODUCTION

The **B**road **RA**nge **H**adron **M**agnetic **S**pectrometers (BRAHMS) experiment is designed to gather information on the interesting physical quantities characterizing the various emitted particles in heavy ion reactions as functions of transverse momentum, p_T, and rapidity, y. The yields as function of rapidity offer information on the nuclear density in the given collision, as well as on the produced entropy. The spectral shapes and their y-dependence reveal the collision dynamics and the degree of thermalisation attained.

BRAHMS experiment offers the opportunity to study particle production mechanisms and the properties of the highly excited nuclear matter in two different regimes, namely: (i) a baryon poor region with a high energy density, created at mid-rapidity; (ii) a region near the initial nuclei, at high rapidities, very rich in baryons at relatively high temperature.

The main goal of the BRAHMS experiment is to investigate the phase transition to quark-gluon plasma and the nature of this plasma. For this phase transition is necessary a study of the critical parameters: energy density and temperature [7].

Energy density estimation

The rapidity density, respective, pseudorapidity density can be used to estimate energy density [4]. The average charged particle multiplicity for the most central collisions (0-6%) is *5100±300*. The charged particle pseudorapidity density at $\eta = 0.0$ is $\frac{dN_{ch}}{d\eta}\Big|_{\eta=0.0} = 610 \pm 50$.

Taking into account the rapidity range, namely [-4.7, 4.7], and the number of charged particle (*5100±300*) we can use the following relation for energy density estimation:

$$\varepsilon = \frac{dN}{dy}\Big|_{y=0} < m_T > \frac{1}{\tau\pi R^2} \qquad . \qquad (1)$$

Here $<m_T>$ is the average transverse mass of the secondary particles, ô is the proper time, $\frac{dN}{dy}$ is the rapidity density, and R is the nucleus radius.

We can estimate the energy density for the pions, supposing different proper time. The UrQMD code supplies us temporal sequences. Using these simulated data we can also compute the pion's temperature as a function of time. From this dependency (Fig.1), we could estimate the proper time range from *10 fm/c* to *50 fm/c* (the maximum temperature region). For proper times between *10 Fm/c* and *50 Fm/c* the energy density varies from $1.17\ GeV/Fm^3$ to $0.24\ GeV/Fm^3$.

The energy density can be estimate, also, using the phenomenological geometric picture [8,9]. For example, at $b = 0.0\ Fm$ the energy density at the initial time moment (maximum compression) is $\mathring{a}_{in} = 3.27\ GeV/Fm^3$ (without selection in rapidity). For pion emission the estimated value of the energy density is only $0.44\ GeV/Fm^3$, corresponding at a proper time of *26.6 Fm/c* [5].

Thermalisation and collective flow

Transverse momentum distributions are important in the study of the heavy-ion collisions at high energies because the transverse motion is generated during the collision and is sensitive to the collision dynamics.

In the reference [1], it discusses the possibility that $p_T - n$ correlation could provide a signal for the phase transition to the quark–gluon plasma, where n is the multiplicity in a small rapidity region:

$$n = \int_{-y_0}^{y_0} \left(\frac{dn}{dy}\right) dy \qquad (2)$$

In the Landau's hydrodynamical model $\frac{dn}{dy}$ reflects the entropy and p_T spectrum reflects the temperature and the transverse expansion of the central region of the hadron matter. The central multiplicity $n \sim s \cdot V$, where V is the volume of the expanding hadron matter and ó is the average entropy density. In a phase transition $\frac{dn}{dy}$ increases while temperature remains constant, this leads to the flat region in the $p_T = f\left(\frac{dn}{dy}\right)$ distribution.

Two simulation codes have been used: HIJING and UrQMD [2]. The HIJING code is a parton model based on perturbative quantum chromodynamics. It emphasizes the initial interaction, gives a good description on the early stages of the collision, but it is not sensitive to final stage interaction. The UrQMD code takes into account the final stage interaction, the rescattering of the produced particles, and also more stopping than HIJING code that assumes less stopping for the projectile and target baryons.

From both codes dependencies “like-plateau” are observed at $\sqrt{s_{NN}} = 200 GeV$. The UrQMD code suggests a larger “plateau”, at an average transverse momentum under 390 MeV/c, and HIJING code suggests a narrow “plateau”, but at higher average transverse momentum (425 MeV/c) (see Fig.4.c,d). Such “plateaus” do not appear at $\sqrt{s_{NN}} = 130\, GeV$ (Fig.4.a,b). If we use the pseudorapidity densities the “plateau” appears again, but we cannot observe the increase at very high values of the pseudorapidity densities, as in the rapidity density case (Fig.4.e,f).

The different lengths of the “plateaus” in the mean transverse momentum dependence on the rapidity (pseudorapidity) densities could justify the assumption of the effect of the hot and dense nuclear matter on the behaviors of the different interesting physical quantities. The effect of the nuclear medium is not evident for particles related to the later collision stages. The influences are smaller, because de density energy is smaller, namely: $\mathring{a}_{in} = 1.74\ GeV/Fm^3$, respectively, $\mathring{a}_{ð} = 0.29\ GeV/Fm^3$ (using the phenomenological geometric picture), respectively, in the range $0.54\ GeV/Fm^3$ and $0.11\ GeV/Fm^3$ from the relation (1), with the same proper times. The corresponding proper time for the first case is *18.6 Fm/c.*

Temperature estimation

The slope parameter T for different species of particles (ð$^+$, ð$^-$, K^+, K^-, p and $\overline{p}$) detected at BRAHMS experiment in $Au–Au$ collisions at $\sqrt{s_{NN}} = 200 GeV$ can be estimated fitting transverse momentum spectra or transverse mass spectra using the next relationships:

$$\frac{dN}{dp_T}\ a\ p_T \cdot e^{-\frac{p_T}{T}} \qquad (3)$$

$$\frac{1}{m_T}\frac{dN}{dm_T}\, a.\exp(-\frac{m_T}{T}) \qquad (4)$$

where $m_T = \sqrt{m_N^2 + p_T^2}$ is the transverse mass.

The slope parameter T increases with the particle mass. Using these two simulation codes, the HIJING code, respectively, the UrQMD code, we calculated temperatures at different rapidities, as well as on different intervals in rapidity. As the rapidity increases, the temperatures decrease, the central region being the hottest one (see *Table I* and *Table II*):

Table I: Temperatures obtained from the simulated data with HIJING code

y	0	1	2	3
$T(\boldsymbol{p}^{+})\,\|_{HIJ}$	179.9 ± 1.5	180.1 ± 0.8	177.7 ± 1.1	158.2 ± 1.6
$T(\boldsymbol{p}^{-})\,\|_{HIJ}$	181.5 ± 0.9	179.3 ± 0.5	177.3 ± 0.9	157.0 ± 1.7
$T(K^{+})\,\|_{HIJ}$	236.6 ± 3.2	221.5 ± 2.6	211.4 ± 1.7	193.6 ± 3.3
$T(K^{-})\,\|_{HIJ}$	213.1 ± 4.5	212.3 ± 3.7	201.2 ± 2.9	167.9 ± 3.7
$T(p)\,\|_{HIJ}$	285.7 ± 4.6	272.6 ± 4.1	263.2 ± 4.7	247.7 ± 4.1
$T(\bar{p})\,\|_{HIJ}$	263.2 ± 5.7	258.1 ± 4.8	244.1 ± 5.1	200.0 ± 6.4

Table II: Temperatures obtained from the simulated data with UrQMD code and with HIJING code

y	(-6, 6)	(-4.5, 4.5)	(-2.2, 2.2)
$T(\boldsymbol{p}^{+})\,\|_{UrQMD}$	169.8 ± 0.5	170.1 ± 0.4	171.7 ± 0.5
$T(\boldsymbol{p}^{+})\,\|_{HIJ}$	167.1 ± 0.2	169.3 ± 0.9	175.9 ± 0.7
$T(\boldsymbol{p}^{-})\,\|_{UrQMD}$	166.6 ± 0.3	169.9 ± 0.2	170.9 ± 0.3
$T(\boldsymbol{p}^{-})\,\|_{HIJ}$	169.2 ± 0.7	173.3 ± 1.8	176.2 ± 3.8
$T(K^{+})\,\|_{UrQMD}$	219.7 ± 2.1	220.4 ± 2.3	222.4 ± 3.6
$T(K^{+})\,\|_{HIJ}$	220.33 ± 1.6	220.2 ± 2.9	225.2 ± 2.7
$T(K^{-})\,\|_{UrQMD}$	212.6 ± 2.5	215.6 ± 2.7	218.2 ± 2.3
$T(K^{-})\,\|_{HIJ}$	209.5 ± 1.6	207.9 ± 2.2	217.5 ± 3.8
$T(p)\,\|_{UrQMD}$	282.6 ± 3.6	286.8 ± 2.9	288.8 ± 3.4
$T(p)\,\|_{HIJ}$	281.2 ± 0.7	302.8 ± 2.9	303.8 ± 2.6

Some theories consider that the rest masses of particles modify in nuclear matter [10]. They predict that pion mass modify slowly as the nuclear density grows; this fact implies small differences between the temperature associated to positive pion and negative pion (they are relative equal). Using the simulated data with HIJING, we calculated temperatures for a few intervals in rapidity and we observe a decrease by 15 – 20 MeV of the central region pionic temperatures, in comparison with those from the “target” and “projectile” fragmentation regions (see *Table III*).

Table III: Temperatures obtained from the simulated data with HIJING code for different intervals in rapidity

y	$T(\mathbf{p}^{+})$	$T(\mathbf{p}^{-})$	$T(K^{+})$	$T(K^{-})$	$T(p)$
(0; 2.2)	179.17 ± 0.93	184.16 ± 1.58	224.66 ± 2.26	216.21 ± 3.22	312.86 ± 4.58
(2.2; 4.5)	158.13 ± 1.24	162.45 ± 1.07	209.46 ± 3.93	189.07 ± 5.61	292.86 ± 5.16
(-2.2; 0)	185.69 ± 1.81	184.04 ± 1.14	234.85 ± 4.63	220.05 ± 2.38	307.52 ± 2.68
(-4.5; -2.2)	170.95 ± 2.40	167.56 ± 1.77	212.84 ± 4.34	199.25 ± 2.83	293.61 ± 2.19

The two codes predict for K^+ a temperature greater than for K^-, but experimental proves deny this fact. Experimentally, we obtained $T(K^{+}) = 250 \pm 20$ MeV, respectively, $T(K^{-}) = 268 \pm 15$ MeV at y=0. So, the experiment agrees with the hypothesis that the K^- rest mass is smaller than K^+ rest mass when the nuclear density grows (see Fig.3.). The theories mentioned above predict the kaon rest mass separation in hot and dense nuclear matter.

The experimental temperatures are greater than those obtained with the codes (by 40-50 MeV) (see Fig.2.). Experimentally, the pion’s temperature is much greater than the pion’s rest mass, and this fact implies possible pion disintegration. Because this process does not place, some other processes could be involved.

Collective transverse flow in high-energy heavy ion collisions

In reference [5], the authors discuss the correlation between the slope parameter and particle mass, which it can be described by the relationship:

$$T = T_{fo} + m\langle v_T \rangle^2, \qquad (5)$$

where T_{fo} is the freeze-out temperature (the temperature when the particles cease to interact with each other), which is due to the thermal motion and v_T is the average collective flow velocity (see Fig.5.). The slope parameter measures the particle energy, which contains both thermal (random) and collective contributions. In heavy ion collisions, the density of produced particles is high comparatively with $p + p$ collisions; because of that the number of secondary collisions among the produced particles or the number of rescatterings is high and thus collective transverse motion increases. The mass dependence of the slope parameters provides evidence of collective transverse flow.

Using the slope parameters predicted by the two simulation codes: HIJING and UrQMD, for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200\ GeV$, we calculated the collective transverse flow velocity for the positive particles (pions, kaons and protons). In the central region, at midrapidity, the collective transverse flow is much stronger than the collective transverse flow from the fragmentation regions of the projectile and the target, which are situated at higher rapidities. The values obtained using UrQMD predictions (see *Table IV*) are higher than the values obtained from HIJING predictions (see *Table V*), but these values are smaller than experimental values. These results indicate that collective transverse motion is much stronger in experimental case and the simulation codes underestimated this motion.

Table IV: Transverse collective flow velocity obtained from the simulated data with UrQMD code

y	0	0.7	2	-2
$\frac{v_T^+}{c}\|_{UrQMD}$	0.314	0.305	0.293	0.271

Table V: Transverse collective flow velocity obtained from the simulated data with HIJING code

y	0	0.7	2	3	4	-0.7	-2	-3
$\frac{v_T^+}{c}\|_{HIJING}$	0.225	0.235	0.228	0.201	0.180	0.212	0.228	0.201

Table VI: Transverse collective flow velocity obtained from the experimental data

Collision	$\sqrt{s_{NN}}\ [GeV]$	y	v_T^+ / c
$Au + Au$	200	0	0.608
$Au + Au$	200	0.45	0.500
$Pb + Pb$	17.2	2.9	0.410
$S + S$	19.4	2.9	0.280
$p + p$	23	2.9	0.090

As the size of the system produced in heavy ions collisions at relativistic energies grows, the collective transverse flow velocity increases, because the produced particle density rises up. At midrapidity ($y \approx 0$) the collective transverse flow velocity is greater than those at higher rapidities, because in the central region the transverse motion becomes stronger (see *Table VI* and Fig.6.).

CONCLUSIONS

The value of the energy density (over 10 normal values), as well as the values for the temperatures, which are very high, represents a support for the estimated thermodynamic parameters of the nuclear matter in *Au-Au* collisions at RHIC-BNL energies. Also, additional information on the possibility to evidence the quark plasma and quark-gluon plasma formation in these collisions is obtained.

Some interesting results on time evolution of the central region are obtained. Therefore, an analysis of the space-time characteristics of the central region by identical particle interferometry will be necessary.

The contributions of the nuclear matter flow at the complete description of the interaction mechanisms in relativistic and ultrarelativistic nuclear collisions are evidenced, too. Some possible connections with the behaviours of the particle ratios, at different energies and in diverse rapidity ranges, as well as some arguments for the dependence of the particle rest mass on the nuclear density are suggested, too.

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Figure captions

Fig.1. The dependence of the pion’s temperature on the time in *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with UrQMD code

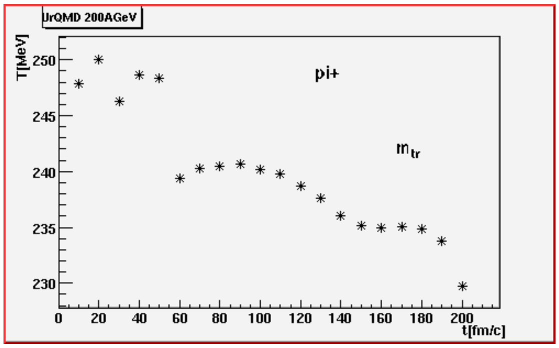


Fig.2. The experimental temperatures for species of particles detected at BRAHMS experiment on the rapidity at $\sqrt{s_{NN}} = 200\ GeV$

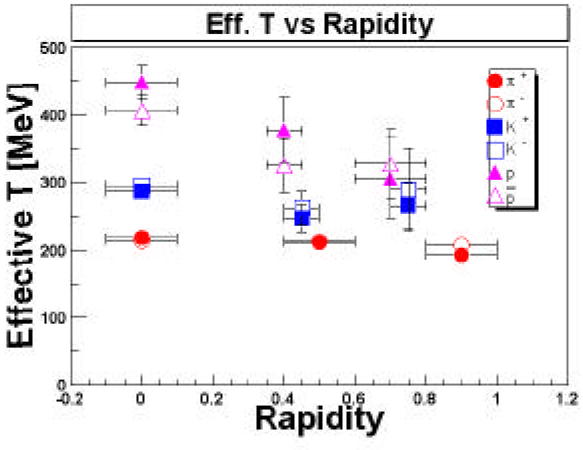


Fig.3. The dependence of the kaons’s temperatures ratio on the rapidity in *Au-Au* collisions at $N(E)dE \propto E^{-\alpha}dE$; estimation with UrQMD code, HIJING code, and experimental data from BRAHMS experiment

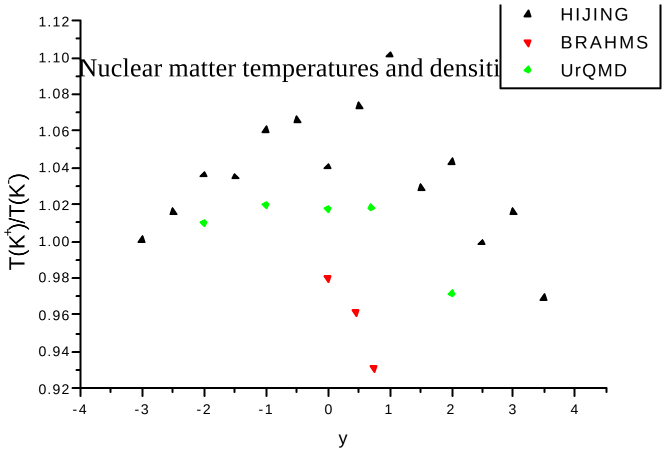


Fig.4.a. The dependence of the mean transverse momentum on the rapidity density in *Au*-*Au* collisions at $\sqrt{s_{NN}} = 130\ GeV$; estimation with UrQMD code

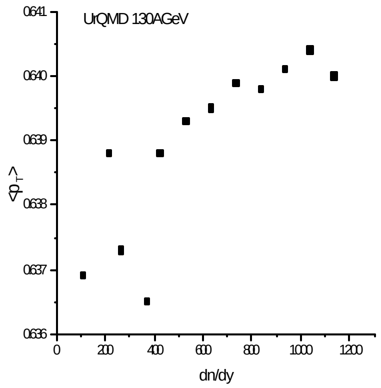


Fig.4.b. The dependence of the mean transverse momentum on the rapidity density in *Au*-*Au* collisions at $\sqrt{s_{NN}} = 130\ GeV$; estimation with HIJING code

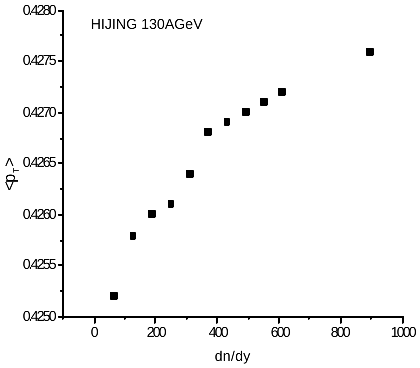


Fig.4.c. The dependence of the mean transverse momentum on the rapidity density in *Au*-*Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with UrQMD code

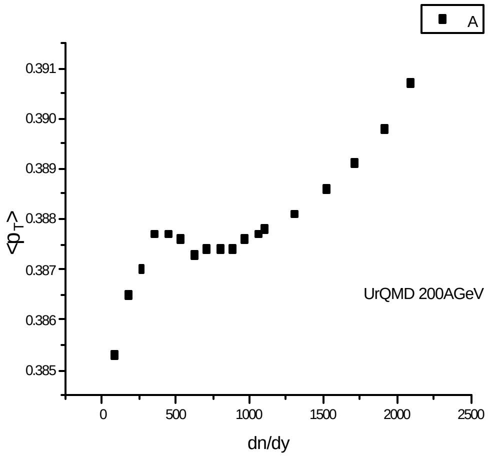


Fig.4.d. The dependence of the mean transverse momentum on the rapidity density in *Au*-*Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with HIJING code

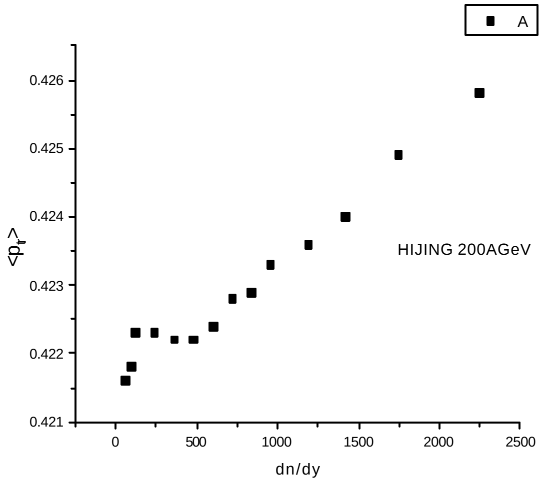


Fig.4.e. The dependence of the mean transverse momentum on the pseudorapidity density in *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with HIJING code

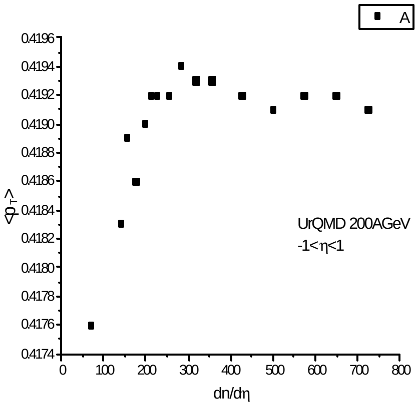


Fig.4.f. The dependence of the mean transverse momentum on the pseudorapidity density in *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with UrQMD code

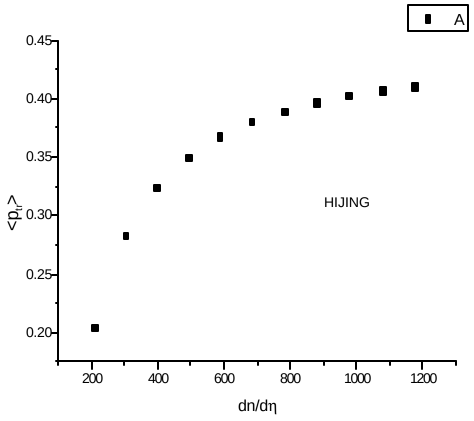


Fig.5. The mass dependence of the temperatures for species of positive particles detected at BRAHMS experiment in *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$; estimation with UrQMD code at 200 fm/c

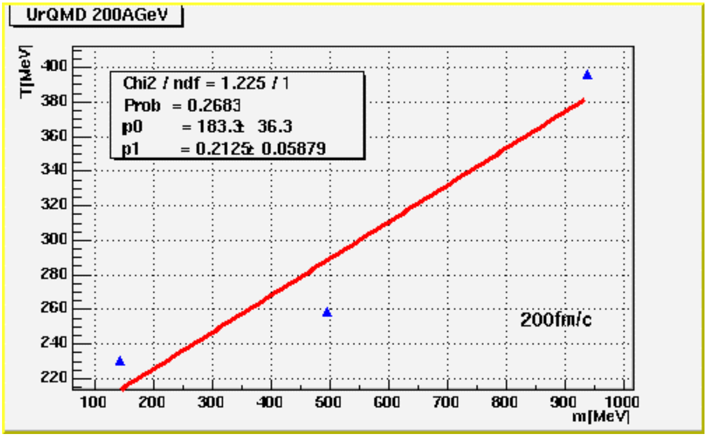
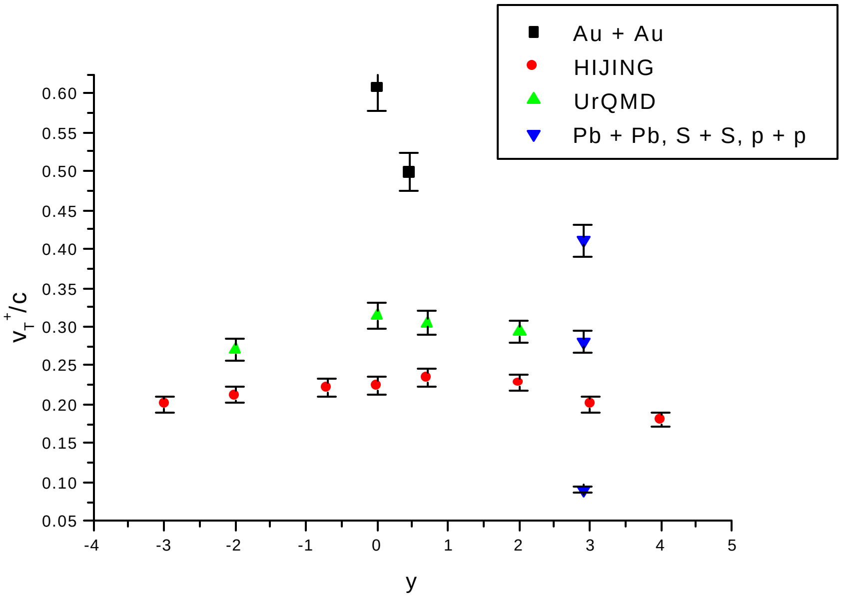


Fig.6. The rapidity dependence of the transverse collective flow velocity for the positive particles (pions, kaons, protons) for different collisions ($p + p$, $S + S$, $Pb + Pb$, $Au + Au$) at different energies; estimation with HIJING code and UrQMD code for *Au-Au* collisions at $\sqrt{s_{NN}} = 200\ GeV$


Au + Au
HIJING
UrQMD
Pb + Pb, S + S, p + p
v_T^+/c
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
-4
-3
-2
-1
0
1
2
3
4
5
y