HIJING code predictions for interesting particles at BRAHMS in the CMS energy range 56-200 A GeV

Introduction

Among the main goals of the ultrarelativistic heavy ion collision programs is to find and to quantify a new phase transition from hadronic matter to the quark-gluon plasma [1]. The experiments performed at the AGS from BNL (energies between 10 A GeV and 15 A GeV, in Laboratory System (LS)) and SPS from CERN (energies up 200 A GeV in Laboratory System) are expected to produce a mixed phase during the initial collision stages [2]. Up to now are some indirect evidences for this state [1-4].

The experiments at the Relativistic Heavy Ion Collider (RHIC) begun in this spring and their higher energies (up to 200 A GeV in the Center of Mass System (CMS)) could offer the expected conditions (baryonic density, energy density, temperature, pressure) to produce the quark-gluon plasma [5-7].

Because many experimental features of the relativistic nuclear collisions were well reproduced [1-7] by different simulation codes involving different hypothesis [8-10] it seems reasonable the assumption that these codes could offer interesting "highlights" on these new collisions. Therefore, many simulation codes have been used to describe what's happen in Au-Au collisions at energies in CMS among 56 A GeV and 200 A GeV. Here the simulation results obtained with the HIJING code are discussed.

Physical background of the HIJING code

The HIJING Code [8] is a Monte Carlo program for parton and particle production in high energy hadronic and nuclear collisions. The program is based on some QCD-inspired models for multiple jet production. It includes different physical aspects to study jet and the associated particle production in high energy pp, pA and AA collisions. The Physics background consists in consideration of the multiple minijet production, soft excitation, nuclear shadowing of parton distribution functions and jet interactions in dense matter.

The main idea of this program is that in high energy hadron and nuclear interactions the multiple minijet production becomes more and more important. In relativistic nuclear collisions this production could dominate the transverse energy production in the central rapidity region. To recognize the quark-gluon plasma formation particle production and correlation due *to minijets production must be investigated.*

Some problems appear at the consideration of the soft interactions. Therefore, minijet production can be incorporated in models related to the perturbative Quantum Chromodynamics (pQCD). The parameters of these models are tested using a wide range of data obtained in pp collisions. Therefore, the HIJING code is based on a pQCD-inspired model. For relativistic heavy ion production this code consider nuclear effects (for example, parton shadowing and final state interactions). It includes multiple minijet production taking into account the soft interactions by using a Lund-type model. The Lund-type model considers mainly the large transverse momenta and automatically the minijet production is enhanced. For the pA and AA collisions simulations the binary approximation and Glauber geometry for multiple interactions are taken into consideration. The parton shadowing is assumed using a parametrized distribution function inside a nucleus. The energy lost by partons during they traverse the produced dense nuclear matter, dE/dz, is introduced to consider the jet quenching. The Lund jet fragmentation model is introduced to describe the hadronization, and the simplest color configuration is assumed for the multiple jet system.

The HIJING code can be used in a wide energy range, from 4 A GeV in CMS up to 10 A TeV in CMS, for some systems (for example, Pb-Pb that will be used at CERN-LHC).

Simulation results with HIJING code

To perform simulations for Au-Au collisions at CMS energies among 56 A GeV and 200 A GeV the version 1.2 of the HIJING code has been used. 3 CMS energies have been considered, namely: 56 A GeV, 130 A GeV and 200 A GeV. Simulation results have been obtained for the following impact parameters: 0.0 Fm, 1.5 Fm, 2.0 Fm, 3.0 Fm, 5.0 Fm, 7.5 Fm, 10.0 Fm and 17.5 Fm. To study the dependence of the multiplicities of different interesting particles at BRAHMS on the collision centrality simulations for the following impact parameter ranges have been done: [0.0,3.0]Fm, [0.0,3.5]Fm, [0.0,5.0]Fm, [0.0,7.5]Fm, [0.0,17.5]Fm, [3.5,17.5]Fm. 1000 events have been simulated for each impact parameter at a given energy. The results, interesting for BRAHMS, are included in the Table Ia-c.

Table I The dependences of the interesting particle multiplicities on the impact parameters for the three CMS energies: (a) sqrt(s) = 56 A GeV; (b) sqrt(s) = 130 A GeV; (c) sqrt(s) = 200 A GeV

(a) sqrt(s) = 56 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$\langle m_{total} \rangle$	4477.1	4326.0	4206.7	3881.8	3012.2	1821.6	805.7	23.5
$\langle m_{ch} \rangle$	2671.9	2581.7	2509.8	2317.6	1798.1	1089.7	484.2	13.8
$\langle m_{neutral} \rangle$	1819.9	1758.9	1711.5	1578.8	1228.6	746.3	329.7	9.7
$\langle m_{p} \rangle$	180.3	174.8	170.5	159.0	126.0	76.7	36.2	1.0
$\langle m_{p} \rangle$	27.2	26.1	25.2	23.1	17.3	10.2	4.3	0.1
$\langle m_{n} \rangle$	192.3	187.3	183.5	170.7	135.2	84.7	39.2	1.2
$\langle m_{n} \rangle$	27.0	26.2	25.0	23.0	17.6	10.2	4.1	0.1
$\langle m_{\pi}^{+} \rangle$	1112.6	1075.9	1045.4	966.1	750.7	454.8	197.9	5.7
$\langle m_{\pi}^{-} \rangle$	1142.2	1103.1	1072.6	990.6	770.3	468.3	204.6	5.9
$\langle m_{K}^{+} \rangle$	113.0	108.9	106.1	97.7	75.2	45.5	19.3	0.55
$\langle m_{K}^{-} \rangle$	78.2	76.0	73.8	68.0	52.2	31.6	13.8	0.43

(b) sqrt(s) = 130 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$\langle m_{total} \rangle$	8351.1	8036.6	7773.3	7128.4	5417.0	3132.8	1332.2	32.3
$\langle m_{ch} \rangle$	5007.5	4819.2	4659.0	4274.3	3247.8	1879.8	802.1	19.2
$\langle m_{neutral} \rangle$	3358.2	3232.0	3128.9	2868.8	2183.8	1267.6	545.7	13.1
$\langle m_{p} \rangle$	194.5	192.3	187.9	174.8	138.8	86.3	40.1	1.04
$\langle m_{p} \rangle$	45.4	43.9	42.3	38.6	29.1	16.5	6.8	0.18
$\langle m_{n} \rangle$	209.3	202.7	198.6	186.1	148.0	91.9	43.3	1.26
$\langle m_{n} \rangle$	45.3	43.2	42.3	38.5	28.8	16.3	6.6	0.14
$\langle m_{\pi}^{+} \rangle$	2145.3	2064.5	1994.4	1830.5	1390.3	805.9	341.7	8.1
$\langle m_{\pi}^{-} \rangle$	2175.3	2093.1	2022.5	1855.6	1410.1	818.4	348.7	8.3
$\langle m_{K}^{+} \rangle$	228.6	218.5	211.9	193.5	146.2	83.2	34.6	0.79
$\langle m_{K}^{-} \rangle$	190.3	182.2	176.3	160.8	120.9	68.4	28.1	0.69

(c) sqrt(s) = 200 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$\langle m_{total} \rangle$	11872.8	11366.3	11037.3	10059.4	7551.8	4321.7	1782.2	36.8
$\langle m_{ch} \rangle$	7130.7	6827.9	6628.6	6040.6	4535.2	2595.5	1072.1	21.9
$\langle m_{neutral} \rangle$	4756.7	4533.0	4423.3	4033.3	3031.1	1740.8	727.7	15.0
$\langle m_{p} \rangle$	213.6	207.5	201.7	188.8	150.0	92.9	43.6	1.1
$\langle m_{p} \rangle$	62.0	59.2	57.3	52.4	39.2	22.0	9.1	0.2

$<m_n>$	224.0	217.8	214.5	199.4	158.6	99.4	46.1	1.3
$<m_n>$	62.1	58.8	57.4	52.0	38.7	21.9	9.0	0.2
$<m_{\pi}{}^{+}>$	3084.8	2953.2	2866.4	2610.2	1958.7	1121.7	463.8	9.2
$<m_{\pi}{}^{-}>$	3115.4	2982.1	2894.1	2632.7	1979.6	1134.7	471.3	9.5
$<m_K{}^{+}>$	331.5	317.3	308.9	281.6	209.5	118.4	47.8	0.93
$<m_K{}^{-}>$	291.9	279.4	271.8	246.1	182.4	102.5	40.7	0.84

Making the balance of the multiplicities we can observe a difference, in average, of only 14.6, between total multiplicity and the sum between charged multiplicity and neutral multiplicity. This difference increases if the number of simulated events decreases (for example, for only 100 simulated events, the difference is around 60).

The relative errors for the data obtained by simulation is below 1%, for all interesting particles.

The simulation results included in this table indicate that up to an impact parameter of 2 Fm the multiplicities of the interesting particles decrease very slow (around 6%, from b =0.0 Fm up to b = 2.0 Fm at 56 A GeV and 7.5% at 200 A GeV). At higher impact parameters the decrease is more faster. At an impact parameter of 17.5 Fm the multiplicity of any type of interesting particle represent only 0.5% from the corresponding value at b = 0.0 Fm.

The charged particles represents around 60% from the particles obtained by simulation in an event. from the negative hadrons 98% are hadrons of the same type with those detected at BRAHMS.

It is important to stress that the multiplicity obtained for antiprotons is equal, in the limit of the statistics errors, with the multiplicity of antineutrons.

A strong increase of the particle production with the increase of the CMS energy is observed (almost twice (1.86) at 130 A GeV, in comparison with 56 A GeV, and almost 3 times (2.65) at 200 A GeV, in comparison with the same CMS energy). At higher energies the decrease of the mean multiplicity with the increase of the impact parameter is faster.

These results could be related with the number of participant at each impact parameters, both in a geometric phenomenological model and in some simulation codes [7,12] . These aspects will be discussed after the presentation of the other simulation results.

Other interesting results are related to the ratios of the particle multiplicities detected with BRAHMS. The following ratios have been considered: π^-/π^+, $(K/\pi)^{\pm}$, K^-/K^+ *and* p^*/p. *The interesting simulation results* *are included in the Table II.*

Table II. The dependences of the interesting particle multiplicity ratios on the impact parameters for the three CMS energies: (a) sqrt(s) = 56 A GeV; (b) sqrt(s) = 130 A GeV; (c) sqrt(s) = 200 A GeV

(a) sqrt(s) = 56 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$<\pi^-/\pi^+>$	1.027	1.025	1.026	1.025	1.026	1.029	1.034	1.035
$<K^+/\pi^+>$	0.101	0.101	0.101	0.101	0.100	0.100	0.098	0.097
$<K^-/\pi^->$	0.069	0.069	0.069	0.069	0.068	0.067	0.067	0.073
$<K^-/K^+>$	0.692	0.698	0.696	0.696	0.694	0.694	0.715	0.782
$<p/p>$	0.150	0.149	0.148	0.145	0.137	0.133	0.119	0.100

(b) sqrt(s) = 130 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$<\pi^-/\pi^+>$	1.014	1.014	1.014	1.014	1.014	1.016	1.020	1.025
$<K^+/\pi^+>$	0.107	0.106	0.105	0.106	0.105	0.103	0.101	0.095
$<K^-/\pi^->$	0.087	0.087	0.087	0.087	0.085	0.084	0.080	0.083
$<K^-/K^+>$	0.832	0.834	0.832	0.831	0.827	0.822	0.812	0.873
$<p/p>$	0.233	0.228	0.225	0.221	0.210	0.191	0.170	0.173

(c) sqrt(s) = 200 A GeV

b[Fm]	**0.0**	**1.5**	**2.0**	**3.0**	**5.0**	**7.5**	**10.0**	**17.5**
$<\pi^-/\pi^+>$	1.010	1.010	1.010	1.008	1.011	1.012	1.016	1.033
$<K^+/\pi^+>$	0.107	0.107	0.108	0.108	0.107	0.106	0.103	0.101
$<K^-/\pi^->$	0.094	0.094	0.094	0.093	0.092	0.090	0.086	0.088
$<K^-/K^+>$	0.881	0.881	0.880	0.874	0.871	0.866	0.851	0.903
$<p/p>$	0.290	0.285	0.284	0.277	0.261	0.237	0.209	0.182

From the Table II a few interesting behaviours are observed for simulated data and are expected for experimental results.

First of all, the $<\pi^->/<\pi^+>$ ratio do not change significantly with the energy increase. This increase is only 1.3% at 130 A GeV in comparison with 56 A GeV, respectively, 1,7% at 200 A GeV in comparison with the *same energy. Also the ratio do not change significantly at the same energy with the impact parameter increase. Only at very high parameters appear some fluctuations related to the poor statistics. These results confirm the assumption that at high velocities the Coulomb effects are not important [13and the references quoted in this paper]. They are a support for the hypothesis of similar production mechanism, too [14].*

The K/π ratios, for positive and negative mesons, could offer additional information [14]. They had been considered as a possible signal of the quark-gluon plasma formation [15]. The first interesting observation is that at the same energy the ratios are almost constant; only a few fluctuations related to the lower statistics appear at very high impact parameters. The second important observation is related to the saturation of the $<K^+/\pi^+>$ ratio at 200 A GeV. Its value is the same with the value at 130 A GeV. An increase of 6% of this ratio is observed at 130 A GeV in comparison with 56 A GeV.

A different behaviour is observed for $<K^-/\pi^->$ ratio. An increasing of 20% is observed at 130 A GeV in comparison with 56 A GeV>. At 200 A GeV this increase is around 27%, in comparison with the same energy. A small decrease with the increase of the impact parameter could be expected. The different behaviours of the two ratios could be related to the different behaviours of the rest mass with the modification of the baryonic density observed for the two types of kaons: the positive kaon rest mass increases with the increase of the baryonic density, and the negative kaon rest mass decreases with the increase of the same quantity [13,6,17 and references]. In the same time the rest masses of the two types of pions increase with the baryonic density increasing [13,16,17].

The $<K^-/K^+>$ ratio could reflect such assumptions, too. An increase with CMS energy increase is observed (17%, respectively, 22%). A possible higher absorption at higher sizes of the particle source could be expected. too.

The $<p^*/p>$ ratio has a different behaviour when the increase of the impact parameter, at a given energy, is discussed. This time, a decrease with the increase of the impact parameter is observed. This decrease is around 1.5 times at each energy. The ratio increase with the increase of the energy, as the other ratios. These increases are around 35%, respectively, 48%, in comparison with the CMS energy of 56 A GeV.

The behaviour of the ratios respect the general behaviours predicted up to now [18,19].

Comments on participants and collision centrality

Important problems in the observing the quark-gluon plasma formation are related to the conditions for baryonic density, energy density, pressure and temperature. To establish some of these physical quantities the total number of participants is useful [7,14,17,20,21]. The phenomenological geometric model, adapted for colliders [7,21], has been used to calculate the total number of participants. The obtained values for the total number of participant, at the CMS energy of 130 A GeV, at different impact parameters, at included in the Table III. The predictions of a simulation with RQMD models is included [12].

Table III *The calculated and the simulated values for the number of participant at the CMS energy of 130 A GeV and different impact parameters*

	sqrt(s) = 130 A GeV						
b[Fm]	***0.0***	***1.5***	***2.0***	***3.0***	***5.0***	***7.5***	***10.0***	***17.5***
$<Q_N>_c$	*393.6*	*385.3*	*370.2*	*360.4*	*301.6*	*186.5*	*25.4**	*-***
$<Q_N>_s$	*394.0*	*384.0*	*368.5*	*354.0*	*300.0*	*180.0*	*150.0*	*<10.0*

**The model has high errors for too peripheral collisions*
***The model it is not able to give values at impact parameters higher than $2R_P$*

From the Table III a good agreement is observed.

Before to estimated the mentioned physical quantities a discussion on the predictions of the HIJING code on the participants is important. In Fig.1 is presented the distribution of the total number of participants for 1000 events simulated with HIJING code, for impact parameters between 0.0Fm and 5.0Fm.The average value of the total number of participant is 324.6. This values is in a god agreement with the mean value obtained from calculation, namely 332.6. From the Fig.1 some distinct zones could be considered. This think is better reflected in the distribution of participants in projectile and target nucleus (Fig.2 and Fig.3). The average is 160.5and 161.0, respectively, in a very good agreement with the calculated value. Taking into account the evident split in the participant distribution for the "target" nucleus, which appears at 164, and the less evident split in the participant distribution for the "projectile" nucleus, which appears at 172, as well as the calculated values of the participant for different impact parameters around 30% of the simulated particles seem to have a impact parameter $b \leq 3.5$ Fm.

An other important observation is related to the evident split from 185 *observed in the participant distribution from the "projectile" nucleus. The weight of this part is of 0.072. This can be related to the "5% central" problem. The associated number of participant is 370, and the impact parameter is $b \leq 3.0$ Fm.*

To confirm this observation 4 simulations have been done, using HIJING code, for different range of impact parameters, at the CMS energy of 130 A GeV. The results obtained for charged particles multiplicities in the four ranges are the following:

$$m_{b\in[0.0Fm;3.0Fm]} - m_{ch} = 4631.3$$
$$m_{b\in[0.0Fm;3.5Fm]} - m_{ch} = 4532.5$$
$$m_{b\in[0.0Fm;17.5Fm]} - m_{ch} = 1202.5$$
$$m_{b\in[3.5Fm;17.5Fm]} - m_{ch} = 951.2$$

A relationship of the following form:

$$w_1(m_{ch})_1 + w_2(m_{ch})_2 = (m_{ch})_{all}$$

can be used. Considering that the weight w_1 is associate to the first simulation, for $b\in[0.0Fm;3.0Fm]$ and $m_{ch} = 4631.3$, and the weight w_2 is associated with the fourth simulation, with $b\in[3.5Fm;17.5Fm]$ and $m_{ch} = 951.2$, the previous equation can be solved, taking the charged particle multiplicity as $(m_{ch})_{all}$ from the third simulation. The result is the following: $1212.1 \approx 1202.1$. The result is in the limit of variation of the simulated data ($\Delta m = -14.6$). Therefore, a limit of 7% of very central events can be considered.

<u>Some estimations for the particle production at midrapidity</u>

Taking into account that the fact that BRAHMS spectrometers cover a relative wide range of rapidities and pseudorapidities for the detected particles ($\pi^{\pm}$, $K^{\pm}$, p, p) the rapidity and pseudorapidity distributions have been constructed with the HIJING simulated data for the 6 particles, in the impact parameter range 0.0 Fm up to 5.0 Fm .

The pseudorapidity distributions for each interesting particle are presented in the Figures 4-9. The values obtained for each type of particle, at $\eta = 0.0$, are the following:

- *protons: $\Delta N/\Delta\eta = 8.5$*
- *antiprotons: $\Delta N/\Delta\eta = 4.3$*
- *negative kaons: $\Delta N/\Delta\eta = 17.9$*
- *positive kaons: $\Delta N/\Delta\eta = 20.8$*
- *negative pions: $\Delta N/\Delta\eta = 270.5$*
- *positive pions: $\Delta N/\Delta\eta = 282.5$*

The value obtained by summing the previous values is: $\Delta N/\Delta\eta$ = 604.5. This value can be considered as a minimum value for the considered impact parameter range, taking into account the specific assumptions of the HIJING code. The first experimental data on charged particles multiplicities from tiles and BBC support this assumption. Also, the UrQMD simulation, for short evolution times led at similar results.

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