Centrality dependence of mid-rapidity charged particles density in relativistic heavy ion collisions – energy scaling

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Centrality dependence of mid-rapidity charged particles density in relativistic heavy ion collisions - energy scaling

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Abstract. As far as details on the "Relativistic Heavy Ion Collisions - Expectations, Experimental Facts and Future Plans" lecture could be found on the Summer School web site, the present contribution will summarize the results considered to be of general interest, i.e. the energy scaling of centrality dependence of mid-rapidity charged particles density in relativistic heavy ion collisions, presented in the second part of the lecture, in the section dedicated to the global observables. The comparison of charged particle multiplicity in heavy ion central collisions and $e^+e^-$ as a function of $\sqrt{s}$, including the latest results obtained at LHC in Pb+Pb collisions at 2.76 is followed by the energy scaling of the pseudo-rapidity charged particle density in central rapidity as a function of centrality.

1. Introduction
The lecture "Relativistic Heavy Ion Collisions - Expectations, Experimental Facts and Future Plans" , accessible on the Summer School web site [1], has three main chapters. An overview of theoretical considerations on which are based the expectations on the properties of matter in extreme conditions of temperature and density which could be obtained in colliding two heavy ions at relativistic and ultra-relativistic energies is presented in the first part. The second part is dedicated to the latest results in the region of high temperature and vanishing chemical potential in Pb + Pb collisions at 2.76 TeV at CERN LHC compared with the previous Au + Au at 0.2 TeV RHIC. Results and expectations evidencing collective type phenomena in high multiplicity and nearly azimuthal isotropic events selected using event shape global observables, Directivity, Sphericity, Trust and Fox-Wolfram moments, in p+p and p+Pb at LHC energies are discussed at the end of this second chapter. In the last chapter is presented the physics program on detailed studies of the QCD phase diagram in the region of highest net baryon density of the CBM experiment at FAIR relative to the recent measurements at RHIC within the beam energy scan program. This chapter ends with a short overview on the main R&D activities in developing highly performant high counting rate Transition Radiation Detectors (TRD) and Multi Strip Multi Gap Resistive Plate Counters (MSMGRPC) for CBM Experiment. Due to the limited number of pages and considering to be a subject of general interest, we decided to concentrate in this written version on the energy scaling of centrality dependence of mid-rapidity charged particles density in relativistic heavy ion collisions, presented in the second part of the lecture, in the section dedicated to the global observables. Pseudo-rapidity charged particle density...
in central rapidity and its dependence on the collision geometry is an information sensitive to the underlying mechanism of particle production and properties and dynamics of strongly interacting matter in extreme conditions of temperature and density produced in relativistic heavy ion collisions. In the second chapter will be presented a comparison of charged particle multiplicity in heavy ion central collisions and $e^+e^-$ as a function of $\sqrt{s}$, including the latest results obtained at LHC in Pb+Pb collisions at 2.76 TeV. An energy scaling of the pseudo-rapidity charged particle density in central rapidity as a function of centrality is discussed in the third chapter. Conclusions are presented in chapter 4.

2. Charged particle multiplicity in heavy ion central collisions

Normalized average total multiplicity of primary charged particles, $<N_{ch}>/N_{part)/2}$, as a function of centrality was measured by PHOBOS Collaboration at RHIC energies in Au+Au collisions at $\sqrt{s_{NN}} = 19.6, 130$ and 200 GeV[2]. Within the error bars the $<N_{ch}>/N_{part/2}$ does not show any centrality dependence starting from $N_{part}$ of about 100. In the same paper it was shown that above $\sqrt{s} \sim 20$ GeV, for central events, the total average multiplicity per participating nucleon pairs as a function of $\sqrt{s_{NN}}$ is the same as in $e^+e^-$ data [3, 4]. Recently ALICE Collaboration measured the average total multiplicity as a function of centrality in Pb+Pb collisions at 2.76 TeV [5, 6, 7]. On the same centrality range, i.e. 125 - 375 $N_{part}$, the normalized average total charged particle multiplicity, $<N_{ch}>/N_{part/2}$, shows a small increase, i.e about $\sim 20\%$, as a function of centrality [6].

![Figure 1](image.png)

**Figure 1.** Upper plot - The average total multiplicity of primary charged particles normalized to the participating nucleon pairs, $<N_{ch}>/N_{part/2}$. Dotted line - $<N_{ch}> = a \cdot s^b$ with $a$ and $b$ parameters found by fitting the charged particle multiplicity in $e^+e^-$ annihilation. Dashed line - the results of the fit of normalized average total multiplicity of primary charged particles in A+A collisions. Bottom plot - The ratio between the results of the fits for A+A relative to $e^+e^-$ data.
In Fig.1 is represented the average total multiplicity of primary charged particles normalized to the participating nucleon pairs, \( < N_{ch} > / \left< N_{part} / 2 \right> \), for Au + Au at AGS (\( \sqrt{s_{NN}} = 2.6-4.3 \)) [8], Pb+Pb at SPS (\( \sqrt{s_{NN}} = 8.6, 12.2, 17.3 \text{ GeV} \)) [9], Au+Au at RHIC (\( \sqrt{s_{NN}} = 19.6, 56, 130, 200 \text{ GeV} \)) [2] and Pb+Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) [5, 6, 7] as a function of \( \sqrt{s_{NN}} \). The dotted line corresponds to the parametrization \( < N_{ch} > = a \cdot s^b \) with \( a=2.20\pm0.03 \) and \( b=0.252\pm0.002 \) found by fitting the charged particle multiplicity in \( e^-e^+ \) annihilation up to 91 GeV [4]. As could be seen, the fit follows rather well the normalized averaged total multiplicity in A+A collisions above 20 GeV, including RHIC data, as it was shown already in Ref. [2]. It has to be mentioned that the authors of Ref. [2] used a parametrization suggested by leading logarithm QCD [10]. In Ref [4] three parametrizations were used, i.e. \( < N_{ch} > = a \cdot s^b \) inspired by the fireball and hydrodynamical models for hadron-hadron interactions [11], empirical expression used in the analysis of p + p data [12] \( < N_{ch} > = a + b \cdot s + c \cdot \ln(s/Q_s^2) \) and \( < N_{ch} > = a + b \cdot \exp(c \cdot \ln(s/Q_s^2)) \) [10] and it was shown that they give similar values for \( \chi^2/\text{d.o.f.} \) if the fits do not include energies lower than 5 GeV. This was the main argument in deciding to use in the present analysis the first expression. Extrapolated to the highest energy, the fit of charged particle multiplicity in \( e^-e^+ \) annihilation is slightly above the ALICE data measured at 2.76 TeV.

The result of the fit of normalized average total multiplicity of primary charged particles, \( < N_{ch} > / \left< N_{part} / 2 \right> \), in A+A collisions above 20 GeV, including the recent result of ALICE, using the same parametrization, is represented in Fig.1 by the dashed line. The parameters of the above parametrization have the following values: \( a=2.096\pm0.161 \) and \( b=0.246\pm0.008 \). The ratio between the results of the fits using the same parametrization for A + A relative to \( e^+e^- \) can be followed in the bottom of Fig.1. In the average a difference of about 10% could be observed with a slight decrease of the ratio from 0.925 at 20 GeV to 0.865 at 2.76 TeV.

3. Energy scaling of the pseudo-rapidity charged particle density in central rapidity as a function of centrality

One of the observables which are sensitive to the particle production mechanism and partonic structure of the colliding objects is the charged particle density and its dependence on the collision geometry. Detailed information on centrality dependence of charged particle density at midrapidity in A + A collisions exists starting from AGS [13, 14], at SPS [15, 16] and RHIC [11], [17]-[23] energies. The systematic compilation of these results [23] and the recent data from ALICE Collaboration at 2.76 TeV [24] are represented in Fig.2.

At SPS and AGS energies, within the systematic errors of the measurements, the normalized charged particle density \( dN_{ch}/d\eta/(0.5N_{part}) \) is rather constant as a function of centrality, i.e. \( N_{part} \), estimated based on the Glauber model [25]-[27]. Although the shape of \( dN_{ch}/d\eta/(0.5N_{part}) \) dependence on \( N_{part} \) is quite the same at 130 and 200 GeV, a slight increase of charged particle density from peripheral towards central collision can be observed. This trend is rather enhanced going to the LHC energy of 2.76 TeV where the data published by ALICE [24], ATLAS [28] and CMS [29] are in a remarkable agreement. The data points for 2.76 TeV, represented by full dots in Fig.2, are taken from Ref. [24].

As it is expected and confirmed by the Monte Carlo Glauber approach, in very peripheral collisions where the two diffuseness zones of the colliding nuclei overlap, essentially binary collisions take place, therefore the normalized charged particle density should have the same value as the charged particle density in nucleon + nucleon inelastic collisions. Charged particle density in p + p inelastic collisions was measured at ISR [30, 31], RHIC [32] and LHC energies [33, 34] and the results are presented in Fig.3 [34].

Based on these data one could obtain scaling factors \( (dN_{ch}/d\eta)_{2.76\text{TeV}}/(dN_{ch}/d\eta)_{0.2\text{TeV}} \) and \( (dN_{ch}/d\eta)_{2.76\text{TeV}}/(dN_{ch}/d\eta)_{0.196\text{TeV}} \). The charged particle pseudorapidity density at 19.6 GeV (dark stars) and at 200 GeV (dark full squares) from Fig.2 scaled by the corresponding above
Figure 2. Charged particle density at midrapidity in A + A collisions at AGS [13, 14], SPS [15, 16] and RHIC [11], [17]-[23] energies.

Figure 3. Charged-particle pseudorapidity density in the central pseudorapidity region $-\eta - 0.5$ for inelastic (full black symbols and red squares) and non-single-diffractive collisions (open symbols). Red open stars represent the results for inelastic collisions in $-\eta - 1$ defined as collisions in which at least one charged and particle in $-\eta - 1$ was produced. The results of power low fits are indicated by dotted, continuous and dashed lines respectively [34].

ratios are represented in Fig.4 by blue stars and full blue squares, respectively. As it should be, based on the argument above, for very peripheral collisions, the charged particle pseudorapidity densities at 2.76 TeV and the ones at 19.6 GeV and 200 GeV multiplied by the corresponding scaling factors are the same within the experimental uncertainties. Towards higher centralities the difference between the 2.76 TeV data and the scaled 200 and 19.6 GeV results is increasing.

In Fig.5 are presented the average number of collisions suffered by a wounded nucleon $< N_{coll} >$ in Au+Au collisions at 19.6 and 200 GeV and in Pb+Pb at 2.76 TeV as a function...
Figure 4. The charged particle pseudorapidity density at 19.6 GeV (dark stars), 200 GeV (dark full squares) and 2.76 TeV (black dots \( |\eta| < 0.5 \) [24], open black squares \( 0.5 < |\eta| < 1.5 \), blue full triangles \( 1.5 < |\eta| < 2.5 \) [7]). These values scaled by the ratios of charged particle pseudorapidity density in p+p collision at 2.76 TeV relative to 19.6 GeV and 200 GeV are represented by blue stars and full blue squares, respectively. The results of a further scaling of 19.6 and 200 GeV data by the ratio of the average number of collisions suffered by the wounded nucleons at 2.76 TeV and the corresponding values at 19.6 and 200 GeV as a function of \( N_{\text{part}} \) are represented by full green and red squares, respectively. Hatched zones correspond to the experimental uncertainties.

Figure 5. The average number of collisions suffered by a wounded nucleon in Au+Au collisions at 19.6 and 200 GeV and in Pb+Pb at 2.76 TeV as a function of \( N_{\text{part}} \), blue, red and black full dots, respectively. The inelastic nucleon-nucleon cross section used in Glauber Monte Carlo calculation were taken from [35], see Fig.6.
Figure 6. Inelastic cross section as a function of collision energy [35]

experimental uncertainties. A rather good agreement between the scaled centrality dependence of normalized charged particle pseudorapidity density at 19.6 and 200 GeV and recent results obtained at 2.76 TeV could be observed. The scaling is based on the ratio of charged particle pseudorapidity density in inelastic p+p collisions and the average number of collisions suffered by wounded nucleons at a given centrality at the corresponding energies.

4. Conclusions

The extrapolation of the fits based on normalized averaged total charged particles produced in $e^+ e^-$ collisions up to $\sqrt{s} \sim 90$ GeV at LHC energy overestimate the experimental results obtained in Pb+Pb central collisions at 2.76 TeV. The ratio between the results of the fits using the same parametrization for A + A relative to $e^+ e^-$ shows an average difference of about 10%, a slight decrease of the ratio from 0.925 at $\sqrt{s_{NN}} \sim 20$ GeV to 0.865 at $\sqrt{s_{NN}} \sim 2.76$ TeV being observed.

The normalized charged particle pseudorapidity density as a function of centrality manifests a change from a constant behaviour at SPS and AGS energies through a slight increase with the centrality at RHIC energies to a significant centrality dependence at 2.76 LHC energy. An energy scaling of the centrality dependence of mid-rapidity charged particles pseudorapidity density, based on the ratio of charged particle pseudorapidity density in inelastic p+p collisions and the average number of collisions suffered by wounded nucleons at a given centrality at the corresponding energies is proposed and shown to be valid within the experimental uncertainties.

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