Considerations on the suppression of charged particles in high energy heavy ion collisions

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Experimental results related to charged particle suppression obtained at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven for Au-Au (Cu-Cu) collisions and at the Large Hadron Collider (LHC) at CERN for Pb-Pb (Xe-Xe) collisions are compiled in terms of $R_{AA}$, $R_{CP}$ and the ratio of the $p_T$ spectra for each centrality to the pp minimum bias or to the peripheral one, each of them normalised with the corresponding charged particle density $⟨dN_{ch}/dη⟩$, namely $R_{AA}$ and $R_{CP}$, as a function of $(N_{part})$ and $⟨dN_{ch}/dη⟩$. The studies are focused on a $p_T$ range in the region of maximum suppression evidenced in the experiments. The $R_{AA}$ scaling as a function of $(N_{part})$ and $⟨dN_{ch}/dη⟩$ is discussed. The core contribution to $R_{AA}$ is presented. The difference in $R_{AA}$ relative to the difference in particle density per unit of rapidity and unit of overlapping area $(⟨dN/dy⟩/S_L)$ and the Bjorken energy density times the interaction time $(ε_BJ · τ)$ support the model predictions. Considerations on the missing suppression in high charged particle multiplicity events for pp collisions at 7 TeV are presented. $R_{CP}$ for the same systems and energies evidence a linear scaling as a function of $(N_{part})$. While $(1-R_{AA})/(⟨dN/dy⟩)$ shows an exponential decrease with $(⟨dN/dy⟩/S_L)^{1/3}$, $(1-R_{AA})/(⟨dN/dy⟩)$ shows no dependence on $(⟨dN/dy⟩/S_L)^{1/3}$ for $(⟨dN/dy⟩/S_L)^{1/3} ≥ 2.1$ part/fm$^{2/3}$. The $R_{CP}$ and $R_{AA}$, for 4 < $p_T$ < 6 GeV/c, as a function of $√NN$ measured at RHIC in Au-Au collisions and at LHC in Pb-Pb collisions evidence a suppression enhancement from $√NN = 39$ GeV up to 200 GeV, followed by a saturation up to the highest energy of $√NN = 5.02$ TeV in Pb-Pb collisions. The $√NN$ dependences of $R_{AA}^0$ and $(R_{AA})^{π0}$ in the same $p_T$ ranges and for the very central collisions show the same trends. $(1-R_{AA})/(⟨dN/dy⟩/S_L)$ evidences a maximum in the region of $√NN = 62.4$ GeV, followed by a decrease towards LHC energies.

I. INTRODUCTION

Detailed studies of different observables in heavy ion collisions at RHIC [1-6] support theoretical predictions pioneered more than 40 years ago [7-10] that at large densities and temperatures of the fireballs produced at these energies, the matter is deconfined in its basic constituents, quarks and gluons. Obviously, such studies are rather difficult given that the produced fireballs are highly non-homogeneous, have a small size and are highly unstable, their dynamical evolution playing an important role. One of the powerful tools used to diagnose the properties of such a deconfined object is the study of the energy loss of partons traversing the deconfined matter [11]. Within the QCD based models, the energy loss of a parton traversing a piece of deconfined matter is due to collisional or radiative processes. Collisional energy loss due to elastic parton collisions is expected to scale linearly with the path length. Radiative energy loss occurs via inelastic processes where a hard parton radiates a gluon. Soft interactions of partons with the deconfined medium can also induce gluon radiation [12]. Radiative energy loss is expected to grow quadratically with the path length [13]. There are quite a few theoretical approaches for the description of the parton energy loss in expanding deconfined matter [14,23]. However, a proper description of the parton energy loss in the non-equilibrium expanding deconfined matter for the interme-
II. \( R_{AA} (5 < p_T < 8 \text{ GeV/c}) - \langle N_{\text{part}} \rangle \) DEPENDENCE

Usually, the comparisons among different systems and different collision energies in terms of \( R_{AA} \) are done as a function of collision centrality. In Figure 1 the average number of participating nucleons (\( \langle N_{\text{part}} \rangle \)) as a function of centrality obtained within the Glauber Monte Carlo (MC) approach is represented. As can be seen, the difference in \( \langle N_{\text{part}} \rangle \) at a given centrality, for colliding systems with different sizes and incident energies, is increasing from peripheral towards central collisions.

![Figure 1](image)

**FIG. 1.** The average number of participating nucleons \( \langle N_{\text{part}} \rangle \) as a function of centrality for Cu-Cu, Au-Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \), for Xe-Xe at \( \sqrt{s_{NN}} = 5.44 \text{ TeV} \) and for Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ and 5.02 GeV} \).

Therefore, the behaviour of the suppression phenomena evidenced in relativistic heavy ion collisions, with the system size and collision energy, is better to be studied in terms of \( R_{AA} - \langle N_{\text{part}} \rangle \) dependence. At \( \sqrt{s_{NN}} = 200 \text{ GeV} \), the same values of charged particles \( R_{AA} \) as a function of \( \langle N_{\text{part}} \rangle \) for different bins in \( p_T \), for two very different colliding symmetric systems Au-Au and Cu-Cu, were evidenced [29]. A similar scaling was also evidenced for a lower collision energy, i.e. \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \) [33]. Such a dependence was studied for pions and protons, for \( 5 < p_T < 8 \text{ GeV/c} \) and \( 5 < p_T < 6 \text{ GeV/c} \) respectively, in Cu-Cu and Au-Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \), by the STAR Collaboration [36]. A good scaling of \( R_{AA}^{\pi^0} \) as a function of \( \langle N_{\text{part}} \rangle \) for the two systems was evidenced. The PHENIX Collaboration has shown that in Au-Au collisions at \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \) and 200 GeV, the \( R_{AA} \) of \( \pi^0 \) for \( p_T > 6 \text{ GeV/c} \) has the same value as a function of \( \langle N_{\text{part}} \rangle \) [37]. At LHC energies, the CMS Collaboration presented a similar scaling for Xe-Xe at \( \sqrt{s_{NN}} = 5.44 \text{ TeV} \) and Pb-Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) [38] with the remark that \( R_{AA} \) for Xe-Xe was obtained using the \( p_T \) spectrum from minimum bias (MB) pp collisions at \( \sqrt{s} = 5.02 \text{ TeV} \). Suppression studies at LHC energies up to very large \( p_T \) values [39–41], for charged particles, evidence the maximum suppression in the 5-8 GeV/c \( p_T \) range. Although at RHIC energies the measured \( p_T \) range is much smaller than the region where \( R_{AA} \) starts to increase, based on the larger range in \( p_T \) for \( \pi^0 \) [37], one could conclude that the maximum suppression for different centralities is in the same range of \( p_T \), i.e. 5-8 GeV/c. This is the main reason to focus the present considerations on suppression phenomena in this range of transverse momenta. Another aspect worth being considered is the so called core-corona effect [42–53] on the suppression estimate. The contribution to the \( p_T \) spectra in A-A collisions from a nucleon suffering a single collision is similar with the spectra from pp collisions at the same energy. If this is the case, one should first correct the experimental spectra of A-A collisions with the contribution coming from single binary collisions (corona) in order to obtain the spectra of the core and estimate the corresponding \( R_{AA}^{\text{core}} \). The percentage of nucleons that suffer more than a single collision (\( f_{\text{core}} \)) is reported in [29] for Au-Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) and for Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) and 5.02 TeV, respectively, while for Xe-Xe and Cu-Cu collisions is presented in Table I. The values of the overlapping area of the two nuclei and that corresponding to the core contribution, for the two systems,
are also listed. The centrality dependence of the overlapping area, \( S_{\text{var}} \), used in the Bjorken energy density estimate at LHC energies \([25, 26, 34]\), is considered to be given by \( \sim \sqrt{\langle \sigma_N^2 \rangle - \langle \sigma_T^2 \rangle} \) \([55]\), and its estimation and values for the other systems considered in the present study are found in \([29]\). Figure 2 shows the average number of nucleons undergoing single collisions relative to the average number of participating nucleons \( \langle N_{\text{sc}} \rangle / \langle N_{\text{part}} \rangle \) as a function of the average number of wounded nucleons.

TABLE I: The percentage of nucleons that suffer more than a single collision \( (f_{\text{core}}) \), the overlapping surface of the colliding nuclei \( (S_{\text{var}}) \) and the overlapping surface corresponding to the core contribution \( (S_{\text{var}})_{\text{core}} \) for Cu-Cu and Xe-Xe colliding systems and corresponding collision energies and centralities.

| System  | \( \sqrt{s_{NN}} \) (GeV) | Cen. (%) | \( f_{\text{core}} \) | \( S_{\text{var}} \) \( (f_m^2) \) | \( S_{\text{var}} \) \( _{\text{core}} \) \( (f_m^2) \) |
|---------|-----------------|----------|--------------------|-----------------|-----------------|
| Cu-Cu   | 200             | 0-10     | 0.81±0.00          | 67.9±0.5        | 51.8±0.4        |
|         |                 | 10-30    | 0.69±0.00          | 53.4±0.4        | 36.1±0.3        |
|         |                 | 30-50    | 0.55±0.00          | 38.3±0.3        | 23.3±0.2        |
|         |                 | 50-70    | 0.38±0.01          | 24.7±0.2        | 13.2±0.1        |
| Xe-Xe   | 5440            | 0-5      | 0.93±0.00          | 124.1±0.6       | 105.3±0.5       |
|         |                 | 5-10     | 0.89±0.00          | 114.9±0.6       | 91.3±0.5        |
|         |                 | 10-20    | 0.84±0.00          | 100.6±0.5       | 74.9±0.4        |
|         |                 | 20-30    | 0.78±0.00          | 83.7±0.5        | 57.9±0.3        |
|         |                 | 30-40    | 0.72±0.00          | 69.3±0.4        | 44.7±0.2        |
|         |                 | 40-50    | 0.65±0.00          | 57.1±0.3        | 34.2±0.2        |
|         |                 | 50-60    | 0.57±0.00          | 45.9±0.3        | 25.5±0.1        |
|         |                 | 60-70    | 0.47±0.01          | 35.4±0.2        | 18.2±0.1        |
|         |                 | 70-80    | 0.36±0.01          | 24.8±0.2        | 10.9±0.1        |

As expected, \( \langle N_{\text{sc}} \rangle / \langle N_{\text{part}} \rangle \) has large values at low \( \langle N_{\text{part}} \rangle \), the system size and collision energy dependence being rather small. With increasing \( \langle N_{\text{part}} \rangle \) towards very central collisions, although the percentage of nucleons undergoing single collisions decreases, the difference between the various systems becomes significant. Using the latest results obtained at RHIC for Cu-Cu and Au-Au collisions at \( \sqrt{s_{NN}}=200 \text{ GeV} \) \([25, 26, 34]\) and at LHC for Xe-Xe at \( \sqrt{s_{NN}}=5.44 \text{ TeV} \) \([27]\) and Pb-Pb at \( \sqrt{s_{NN}}=2.76 \text{ and 5.02 TeV} \) \([56]\), we obtained the values of \( R_{AA} \) for \( 5 < p_T < 8 \text{ GeV/c} \) presented in Figure 3a. \( R_{AA} \) scales as a function of \( \langle N_{\text{part}} \rangle \) at RHIC \( (\sqrt{s_{NN}}=200 \text{ GeV}) \) and LHC energies, separately, as it was shown in the above mentioned papers. Within the error bars, a slight difference, i.e. a bit larger suppression is observed for central Cu-Cu and Xe-Xe collisions relative to Au-Au and Pb-Pb respectively, at the corresponding \( \langle N_{\text{part}} \rangle \). The highlighted areas corresponding to the experimental values of \( R_{AA} \) represent the systematic uncertainties and the error bars are the statistical uncertainties, for the cases where both were available (Pb-Pb at \( \sqrt{s_{NN}}=2.76 \) and 5.02 TeV, Xe-Xe at \( \sqrt{s_{NN}}=5.44 \text{ TeV} \), Au-Au (PHENIX) and Cu-Cu at \( \sqrt{s_{NN}}=200 \text{ GeV} \)), while in the case of Au-Au (STAR) the error bars represent the square root of statistical and systematic uncertainties added in quadrature. The suppression due to the core of the fireball \( R_{AA}^{\text{core}} \):

\[
R_{AA}^{\text{core}} = \left( \frac{N_{\text{core}}}{N_{\text{bin}}} \right)_{\text{cen,core}} \cdot \left( \frac{d^2N}{dp_T^2} \right)_{\text{pp},MB}
\]

is presented in Figure 3b.

The suppression enhances at peripheral collisions by \( \sim 20-25\% \) and the values for the most central Cu-Cu and
of rapidity and unit of overlapping area \((dN/dy)/S_\perp\) as a function of \(N_{\text{part}}\), is represented. The \(dN/dy\) values were estimated as in \([29, 59]\). In the case of Cu-Cu and Au-Au at \(\sqrt{s_{NN}}=200\ \text{GeV}\), for the same average number of participants and \(dN/dy)/S_\perp\), the suppression has the same value, increasing with \(dN/dy)/S_\perp\) and size of overlapping area. As far as the suppression in central Cu-Cu collisions is the same as in Au-Au collisions at the corresponding \(N_{\text{part}}\), one could conclude that the fireball shape plays a negligible role for the same size of the overlapping area. For \(N_{\text{part}}=200\), the differences in \(dN/dy)/S_\perp\) for Pb-Pb at \(\sqrt{s_{NN}}=2.76, 5.02\ \text{TeV}\) and for Xe-Xe at \(\sqrt{s_{NN}}=5.44\ \text{TeV}\) relative to Au-Au at \(\sqrt{s_{NN}}=200\ \text{GeV}\) are \(5.25\pm0.03, 6.77\pm1,\ 7.89\pm1\) (particles/\(fm^2\)) while the differences in \(1-R_{AA}\) are \(0.10\pm0.03, 0.11\pm0.03\) and \(0.11\pm0.03\). This is a clear evidence of a saturation suppression at LHC energies. For central Au-Au collisions, i.e. \(N_{\text{part}}=350\), the difference in \(dN/dy)/S_\perp\) between Pb-Pb at \(\sqrt{s_{NN}}=2.76\ \text{TeV}\) and Au-Au at \(\sqrt{s_{NN}}=200\ \text{GeV}\) is \(7\pm1\) (particles/\(fm^2\)) while the difference in \(1-R_{AA}\) is \(0.082\pm0.03\). With a parton energy loss in the deconfined medium given by \([22, 60]\):

\[
\frac{dE}{dx} = -k \cdot x \cdot T^3
\]  

where \(k\) is the jet-medium coupling, \(x\) the path length, \(T\) the temperature and with the assumption that \(x^2 \sim S_\perp\) and \(T^3 \sim \langle dN/dy)/S_\perp\rangle\), \(k_{\text{RHIC}} \approx (0.48 \pm 0.03)\cdot k_{\text{RHIC}}\) is obtained. Obviously, the hydrodynamic expansion of the deconfined matter traversed by the parton plays a role in the estimated final suppression. Using the \(\sqrt{dN/dy})/S_\perp\) scaling of the average transverse flow velocity, \(\langle \beta_T\rangle\) reported in Ref. \([29]\), for the geometrical scaling variable corresponding to the particle densities
FIG. 6. The difference between the suppression in Pb-Pb at $\sqrt{s_{NN}}=5.02$ TeV and the suppression in Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV, in Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV, in Au-Au and Cu-Cu at $\sqrt{s_{NN}}=200$ GeV (full symbols). The corresponding differences in particle density per unit of rapidity and unit of overlapping area $(dN/dy)/S_\perp$ (Figure 6a - open symbols) and Bjorken energy density times the interaction time $\epsilon_B \cdot \tau$ (Figure 6b - open symbols) at the corresponding collision energies can be followed using the scales on the right sides.

FIG. 7. $R_{AA}$ as a function of charged particle density per unit of pseudorapidity, $(dN_{ch}/d\eta)$, for the same systems and collision energies as in Figure 6a) experimental values; b) the core contribution to $R_{AA}$ and $(dN_{ch}/d\eta)$.

used before for the $k_{LHC}/k_{RHIC}$ estimation, a ratio $\langle \beta_T \rangle_{LHC}/\langle \beta_T \rangle_{RHIC} \approx 1.09 \pm 0.08$ is obtained. This could be one of the reasons leading to lower values of the jet-medium coupling in Pb-Pb collisions, but not enough to explain the large difference between RHIC and LHC energies. In Figure 6 the difference between the suppression in Pb-Pb at $\sqrt{s_{NN}}=5.02$ TeV and the suppression in Au-Au and Cu-Cu collisions at $\sqrt{s_{NN}}=200$ GeV, Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV and Xe-Xe collisions at $\sqrt{s_{NN}}=5.44$ TeV is represented. The corresponding
differences in particle density per unit of rapidity and unit of overlapping area, \( (dN/dy)/S_L \) (Figure 4) and Bjorken energy density times the interaction time, \( \epsilon_B \cdot \tau \) (Figure 5) are also represented with the corresponding scales on the right side of the figures.

The Bjorken energy density times the interaction time values are estimated based on 61:

\[
\epsilon_B \cdot \tau = \frac{dE_T}{dy} \cdot \frac{1}{S_L}
\]

where \( E_T \) is the total transverse energy and \( S_L \) represents the overlapping area of the colliding nuclei. The total transverse energy per unit of rapidity can be estimated as follows:

- RHIC \( \sqrt{s_{NN}}=200 \) GeV:

\[
\frac{dE_T}{dy} \sim 3 \frac{1}{2} \left( \langle m_T \rangle \frac{dN}{dy} \right)_{\pi^\pm} + 2 \left( \langle m_T \rangle \frac{dN}{dy} \right)_{K^\pm,p,p} \quad (4)
\]

- LHC energies:

\[
\frac{dE_T}{dy} \sim 3 \frac{1}{2} \left( \langle m_T \rangle \frac{dN}{dy} \right)_{\pi^\pm} + 2 \left( \langle m_T \rangle \frac{dN}{dy} \right)_{K^\pm,p,p,\Xi^-} + \left( \langle m_T \rangle \frac{dN}{dy} \right)_{\Lambda,\bar{\Lambda},\Omega^-} \quad (5)
\]

The input data used in the estimation of the Bjorken energy density times the interaction time are reported in 29, 62, 69 and in Table I.

Within the error bars, the suppression in Pb-Pb collisions at \( \sqrt{s_{NN}}=2.76 \) TeV is the same with the one corresponding to \( \sqrt{s_{NN}}=5.02 \) TeV for all values of \( \langle N_{part} \rangle \), although the difference in \( (dN/dy)/S_L \) or in \( \epsilon_B \cdot \tau \) increases from 0.88±0.33 particles/fm\(^2\) to 1.95±0.54 particles/fm\(^2\) and from 0.71±0.32 GeV/fm\(^2\)c to 2.44±0.81 GeV/fm\(^2\)c, respectively, from the low (\( \langle N_{part} \rangle =50 \)) to the highest values of \( \langle N_{part} \rangle \). The difference between the suppression in Pb-Pb at \( \sqrt{s_{NN}}=5.02 \) TeV and Au-Au at \( \sqrt{s_{NN}}=200 \) GeV decreases from about 0.27±0.25 to 0.08±0.02 with \( \langle N_{part} \rangle \) while the differences in \( (dN/dy)/S_L \) and \( \epsilon_B \cdot \tau \) increase from 2.63±0.29 particles/fm\(^2\) and 2.13±0.28 GeV/fm\(^2\)c to 8.9±0.43 particles/fm\(^2\) and 8.2±0.8 GeV/fm\(^2\)c, respectively.

An alternative representation of \( R_{AA} \) could be done as a function of the average charged particle density per unit of pseudorapidity 27. The \( (dN_{ch}/d\eta) \) experimental data for heavy ion collisions are taken from 27, 28, 62, 70, 71. The \( R_{AA} \cdot (dN_{ch}/d\eta) \) dependence is presented in Figure 7a for the same systems and collision energies as in Figure 4. In such a representation, all systems at all energies scale as a function of \( (dN_{ch}/d\eta) \). The same representation in terms of \( R_{AA}^{core} \) and \( (dN_{ch}/d\eta)^{core} \) (Figure 7b) shows a larger deviation between RHIC and LHC energies for \( (dN_{ch}/d\eta) \leq 200 \). Relative to the \( \langle N_{part} \rangle \) dependence, the difference in the shapes of the overlapping areas of different systems for a given \( (dN_{ch}/d\eta) \) is larger, as it can be followed in Figure 8. If we represent \( \epsilon_B \cdot \tau \) or \( (dN/dy)/S_L \), Figure 9a and Figure 9b, respectively, as a function of the charged particle density, a difference between the collision energies is evidenced, which increases with \( (dN_{ch}/d\eta) \). Therefore, with a few contributions playing a role in the observed scaling in \( (dN_{ch}/d\eta) \), it is rather difficult to unravel the importance of each of them. The difference between the two representations is explained by the correlation between \( (dN_{ch}/d\eta) \) and \( \langle N_{part} \rangle \). While the overlapping area is very little dependent on the system size and collision energy for a given \( \langle N_{part} \rangle \), \( (dN_{ch}/d\eta) \) combines the contribution of both, collision energy and system size.

III. WHY \( R_N^{AA} \) ?

\( R_{AA} \), as a measure of the suppression in heavy ion collisions, is based on the estimate of the number of binary collisions \( (N_{bin}) \) within the Glauber MC approach using straight trajectories as a hypothesis, the dependence on the collision energy being introduced by the nucleon-nucleon cross section and the oversimplified assumption that every nucleon-nucleon collision takes place at the same energy, \( \sqrt{s} \), and consequently the same cross section, \( \sigma_{NN} \). In Figure 11 the correlation between the number of binary collisions \( (N_{bin}) \) and \( \langle N_{part} \rangle \) estimated within the standard Glauber MC approach is represented. An alternative approach where the energy and \( \sigma_{NN} \) change after each collision 72 has shown that in Pb-Pb collisions at \( \sqrt{s_{NN}}=2.76 \) TeV, the average number of binary collisions \( (N_{bin}) \) is significantly lower than

![FIG. 8. The same as Figure 7a, with the shapes of the overlapping area \( S_L \) at different values of \( (dN_{ch}/d\eta) \).](attachment:image.png)
the values estimated by the standard Glauber model, the difference increasing towards central collisions. The difference in \( \langle N_{\text{part}} \rangle \) is negligible at peripheral and central collisions, for mid-central collisions being at the level of \( \sim 18\% \).

\( \langle N_{\text{bin}} \rangle \rangle[dN_{ch}/d\eta]^{A−A}/[dN_{ch}/d\eta]^{pp} \rangle \) has to be 1 if only single collisions take place. A very good correlation between \( \langle N_{\text{bin}} \rangle \) estimated within the standard Glauber model and experimental values of \( [dN_{ch}/d\eta]^{A−A}/[dN_{ch}/d\eta]^{pp} \rangle \) is evidenced in Figure 12. However, their ratio as a function of \( \langle N_{\text{part}} \rangle \) shows an increase from close to 1 for the lowest values of \( \langle N_{\text{part}} \rangle \), up to \( (N_{\text{part}}) \sim 150 \), followed by a tendency towards a saturation at \( \sim 3.5 \) for the largest \( \langle N_{\text{part}} \rangle \) values, see Figure 13.

One should remark that all systems at all investigated energies overlap in this representation. In the case of pp collisions, \( (dN_{ch}/d\eta)_{\text{INEL}} \) corresponding to the selection of inelastic collisions, and the parametrisation given in Table 3 have been used.

Based on these, we will also analyse the model independent quantity, namely \( R_{AA}^{N} \), obtained as a ratio of the \( p_T \) spectra in A-A collisions to the one of minimum bias pp collisions at the same energy, each of them normalised to the corresponding charged particle densities, for all the available centralities in A-A collisions, already used in a previous paper for comparing the behaviour of \( p_T \) spectra in pp, p-Pb and Pb-Pb collisions as a function of charged particle multiplicity and centrality, respectively 74:

\[
R_{AA}^{N} = \frac{(d^2N/dp_T^2d\eta)/(dN_{ch}/d\eta))_{cen}}{(d^2N/dp_T^2d\eta)/(dN_{ch}/d\eta))_{pp,MB}} \tag{6}
\]

In Figure 14 \( R_{AA}^{N} \) as a function of \( \langle N_{\text{part}} \rangle \) for the systems discussed in the previous section is presented.

The scaling as a function of the system size for each energy domain, i.e. the highest energy at RHIC and LHC energies remains, the suppression is reduced and the \( \langle N_{\text{part}} \rangle \) dependence is close to a linear one. As it is observed in Figure 15 \( R_{AA}^{N} \) does not show a similar scaling as \( R_{AA} \) as a function of \( [dN_{ch}/d\eta] \) for the two collision energy domains. However, the scaling at LHC...
energies remains, a close to linear dependence being evidenced in this representation as well. The same considerations can be used to estimate the expected suppression, \((1-R_{\text{pp}})<N_{\text{part}}>)\sim S_{\text{pp,HM}}/S_{\text{Pb-Pb}}\langle N_{\text{part}}\rangle=125\geq 0.01 \pm 0.01.\) This could explain why in pp collisions at LHC, in high charged particle multiplicity events, no suppression was observed, although similarities to Pb-Pb collisions at \(\sqrt{s}=2.76\) TeV are observed. Therefore, the hydrodynamics should play a negligible role. For this value of \(\sqrt{\langle N_{\text{ch}}/d\eta \rangle}/S_{\perp}\), \(S_{\text{pp}}^{\perp}=7.43 \pm 0.48\) \text{fm}^2 and \(S_{\text{Pb-Pb}}^{\perp}=70.4\) \text{fm}^2. Assuming the same jet-medium coupling, \((1-R_{\text{pp}})<N_{\text{part}}>)\sim S_{\text{pp,HM}}^{\perp}/S_{\text{Pb-Pb}}\langle N_{\text{part}}\rangle=125\geq 0.01 \pm 0.01.\) This could explain why in pp collisions at LHC, in high charged particle multiplicity events, no suppression was observed, although similarities to Pb-Pb
IV. RELATIVE SUPPRESSION IN TERMS OF $R_{CP}$

For energies where the $p_T$ spectra in pp collisions were not measured, the suppression was studied in terms of $R_{CP}$, i.e. the ratio of charged particle $p_T$ spectra at a given centrality to the $p_T$ spectrum in peripheral collisions, each of them divided by the corresponding average number of the binary collisions:

$$R_{CP} = \frac{\frac{d^2N}{d\eta dp_T}}{\langle N_{ch}^{cen} \rangle} / \frac{\frac{d^2N}{d\eta dp_T}}{\langle N_{ch}^{peripheral} \rangle},$$

(7)

for each centrality in A-A collisions.

For a better comparison of the $R_{CP}$ values as a function of $\langle N_{part} \rangle$, the peripheral centrality of reference was chosen to be the same for all systems and all energies, i.e $\langle N_{part} \rangle$=30. The $R_{CP}$ estimated in this way is represented in Figure 16 for the same systems and energies. The values corresponding to the most central collisions for Au-Au and Pb-Pb are, within the error bars, the same. As for the $R_{AA}$ case, due to the same reasons, using experimental data, we estimated the $R_{CP}^N$:

$$R_{CP}^N = \frac{\frac{d^2N}{d\eta dp_T}}{\langle N_{ch} \rangle} / \frac{\frac{d^2N}{d\eta dp_T}}{\langle N_{ch}^{peripheral} \rangle}$$

(8)

The $R_{CP}^N$ suppression as a function of $\langle N_{part} \rangle$ (Figure 17) is the same at all values of $\langle N_{part} \rangle$ for all the heavy systems, Au-Au, Xe-Xe and Pb-Pb, although the difference in the collision energies is ∼14-27 times higher energy at LHC than at RHIC, between the LHC energies being a factor of ∼2. The linear dependence as a function of $\langle N_{part} \rangle$ follows from the linear dependence observed in $R_{AA}^N$.

V. $(1-R_{AA})/(dN/dy)$ AND $(1-R_{AA}^N)/(dN/dy)$ DEPENDENCE ON $(dN/dy)/S_\perp/^{1/3}$

If we assume that the initial entropy is proportional to the final measured particle density per unit of rapidity and it scales as $T^3$, based on Eq.2 and taking $S_\perp \sim x^2$, a qualitative temperature dependence of the jet-medium coupling can be obtained. As can be seen in Figure 18 $(1-R_{AA})/(dN/dy)$ shows an exponential decrease (hatched line) as a function of $(dN/dy)/S_\perp/^{1/3}$. The line is the result of the fit with the following expression:

$$\frac{1 - R_{AA}}{dN/dy} = e^{a - \beta ((dN/dy)/S_\perp)^{1/3}}$$

(9)

Such a temperature dependence of the jet-medium coupling was considered in [22] in order to reproduce the nuclear modification factors at RHIC and LHC energies.

A similar representation for $R_{AA}^N$ instead of $R_{AA}$ is presented in Figure 19. In this case, $(1-R_{AA})/(dN/dy)$ collisions for other observables were evidenced.
An impact parameter independence of the jet quenching size of the heavy colliding systems and collision energy. The line is the result of the fit with the expression (9).

FIG. 18. \( (1-R_{AA})/\langle dN/dy \rangle \) dependence on \( \langle dN/dy \rangle \langle S_\perp \rangle^{1/3} \). The line is the result of the fit with the expression (9).

FIG. 19. \( (1-R^N_{AA})/\langle dN/dy \rangle \) dependence on \( \langle dN/dy \rangle \langle S_\perp \rangle^{1/3} \).

is constant as a function of \( \langle dN/dy \rangle \langle S_\perp \rangle^{1/3} \), for \( \langle dN/dy \rangle \langle S_\perp \rangle^{1/3} \geq 2.1 \) part/fm\(^2\), independent on the size of the heavy colliding systems and collision energy. An impact parameter independence of the jet quenching parameter was claimed in a series of theoretical estimates 79, 87.

VI. THE \( \sqrt{s_{NN}} \) DEPENDENCE OF \( R_{CP}, R^N_{CP}, R^0_{AA}, (R^N_{AA})^0 \)

As it is well known, within the Beam Energy Scan (BES) program at RHIC, valuable data were obtained relative to the behaviour of different observables in Au-Au collisions starting from \( \sqrt{s_{NN}} = 7.7 \) GeV up to 200 GeV. As far as the \( p_T \) spectra in pp collisions at these energies were not measured, the STAR collaboration studied the \( \sqrt{s_{NN}} \) dependence of \( R_{CP} \) \( [(0-5%)/(60-80%)] \) for Au-Au collisions 78. In order to include as much as possible the lower energies, where the published data are on a lower \( p_T \) range, we had to change the \( p_T \) range from 5 < \( p_T < 8 \) GeV/c, used in previous sections, to 4 < \( p_T < 6 \) GeV/c, for the study of the charged particle suppression dependence on the collision energy. These results, together with the values obtained in Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) and 5.02 TeV, for the most central collisions, are presented in Figure 20a. Following the arguments from the previous section, in Figure 20b \( R^N_{CP} \) as a function of the collision energy is presented. In both plots is evidenced a decrease of \( R_{CP} \) or \( R^N_{CP} \) from \( \sqrt{s_{NN}} = 19.6 \) GeV up to \( \sqrt{s_{NN}} = 200 \) GeV, while the relative ratios of particle densities per unit of rapidity and unit of overlapping area, within the error bars, are constant. Beyond the RHIC energies, \( R_{CP} \) and \( R^N_{CP} \) remain constant. As far as \( R_{AA} \) for charged particles at lower RHIC energies are not reported, in order to confirm the above observations, we used \( R_{AA} \) of \( \pi^0 \) published by the PHENIX collaboration at \( \sqrt{s_{NN}} = 39, 62.4 \) and 200 GeV 37, 79 and by the ALICE Collaboration 80, 81 at LHC energies.

In order to have an estimate on \( R^0_{AA} \) corresponding to 0-10% centrality for the collision energies where it was not published, we applied the procedure described bel-
FIG. 21. a) The same as Figure 20a, fitted with the expression given in Eq.10. b) $R_{AA}$ for $\pi^0$, corresponding to the same range in $p_T$ as a), for experimental values (full symbols) and interpolated/extrapolated results (open symbols) for 0-10% centrality.

The $R_{CP}$ - $\sqrt{s_{NN}}$ dependence (Figure 21a) was fitted with the following expression:

$$R_{CP} \propto a + \frac{b}{s_{NN}} + c \cdot \sqrt{s_{NN}}$$  \hspace{1cm} (10)

with a, b, and c as free parameters, the result being presented in Figure 21a. A similar expression was used in order to fit the measured experimental data of $R_{AA}^{\pi^0}$ - $\sqrt{s_{NN}}$ dependence (Figure 21b), leaving the parameters free. The result was used for estimating $R_{AA}^{\pi^0}$ at the missing collision energies, i.e. 19.6, 27 and 130 GeV (Figure 21b - open symbols). Measured, interpolated and extrapolated $R_{AA}^{\pi^0}$ values as a function of $\sqrt{s_{NN}}$ are presented in Figure 22, for both $p_T$ ranges used in this paper, namely 4-6 GeV/c (open symbols) and 5-8 GeV/c (full symbols).

The $R_{AA}^{\pi^0}$ dependence as a function of $\sqrt{s_{NN}}$ is similar with the one evidenced for $R_{CP}$ corresponding to charged particles presented in Figure 21, i.e. the suppression starts around $\sqrt{s_{NN}}=27$ GeV, increases up to the top RHIC energy and remains constant up to the LHC energies. The ratios relative to $((dN/dy)/S_\perp)^{0-10\%}$ as a function of the collision energy are presented in Figure 23, namely: $(1 - R_{AA}^{\pi^0})/((dN/dy)/S_\perp)^{0-10\%}$ (Figure 23a) and $(1 - R_{AA}^{\pi^0})/((dN/dy)/S_\perp)^{0-10\%}$ (Figure 23b).

These ratios show a maximum around the top RHIC energies, decreasing towards LHC energies, in qualitative agreement with theoretical predictions [21, 24, 82]. To what extent such a trend is due to a transition from a magnetic plasma of light monopoles near critical temperature region [82] to a deconfined matter dominated by quarks and gluons [24] remains an open question. However, a clear transition in the properties of the deconfined matter from RHIC to LHC energies is supported by the experimental trends.

FIG. 23. a) $(1 - R_{AA}^{\pi^0})/((dN/dy)/S_\perp)^{0-10\%}$ as a function of collision energy; b) $(1 - (R_{AA}^{\pi^0})^{0-10\%})/((dN/dy)/S_\perp)^{0-10\%}$ as a function of collision energy (bullets)-left scale and $((dN/dy)/S_\perp)^{0-10\%}$ (stars)-right scales for 0-10% centrality.

VII. CONCLUSIONS

Based on the experimental results obtained at RHIC for Au-Au (Cu-Cu) and at LHC for Pb-Pb (Xe-Xe) collisions, a detailed analysis of the charged particle suppression in the region of transverse momentum corresponding to the maximum suppression is presented. In order to see
to what extent the conclusions based on these studies are not a consequence of the model estimate of the number of binary collisions used in the definition of $R_{AA}$ and $R_{CP}$, model independent ratios of the $p_{T}$ spectra for each centrality to the pp minimum bias or to the peripheral one, each of them normalised with the corresponding charged particle density $\langle dN_{ch}/d\eta \rangle$, namely $R_{AA}^{N}$ and $R_{CP}^{N}$, are presented. While $R_{AA}$ scales as a function of $\langle dN_{ch}/d\eta \rangle$ for the top RHIC and all LHC energies, it scales separately as a function of $\langle N_{part} \rangle$ for RHIC and LHC energies, for all the corresponding measured colliding systems. However, given that $\langle dN_{ch}/d\eta \rangle$ depends on the collision energy and overlapping area of the colliding systems, their relative contribution to suppression is rather difficult to be unraveled. This is the main reason why the considerations on suppression phenomena as a function of collision geometry and collision energy are mainly based on the $\langle N_{part} \rangle$ dependence.

The influence of the corona contribution on experimental $R_{AA}$ is presented. As expected, the main corona contribution is at low values of $\langle N_{part} \rangle$, the core suppression relative to the experimental value being larger.

Based on $(1-R_{AA})$ and $\langle dN/dy \rangle/S_{\perp}$ dependences on $\langle N_{part} \rangle$, one could conclude that a saturation of suppression at LHC energies takes place. At $\langle N_{part} \rangle=350$, corresponding to the most central Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV, if one considers the parton energy loss proportional with the squared path length and charged particle density per unit of overlapping area, a jet-medium coupling approximately two times lower at LHC than at RHIC is obtained. The difference in the hydrodynamic expansion extracted from the $\langle \beta_T \rangle$ scaling as a function of $\sqrt{\langle dN/dy \rangle/S_{\perp}}$, of about 10%, cannot explain the difference observed in the parton-medium coupling constant. Such considerations, applied to the highest charged particle multiplicity measured in pp collisions at 7 TeV could explain why no suppression is evidenced in such events while there are similarities to Pb-Pb with respect to other observables. $R_{AA}^{N}$ as a function of $\langle N_{part} \rangle$ shows similar separate scaling for RHIC and LHC energies, a linear dependence being evidenced at LHC energies. $R_{CP}^{N}$ evidences a very good scaling as a function of $\langle N_{part} \rangle$ for the heavy systems at all collision energies. The ratio $(1-R_{AA})/\langle dN/dy \rangle$ shows an exponential decrease with $\langle dN/dy \rangle/S_{\perp}$ while $(1-R_{AA}^{N})/\langle dN/dy \rangle$ is independent on $\langle dN/dy \rangle/S_{\perp}$ for $\langle dN/dy \rangle/S_{\perp} \geq 2.1$ part/fm$^{2}$/, the value being the same for all the heavy systems and all collision energies. For the most central collisions, $R_{CP}$, $R_{CP}^{N}$ and $R_{AA}^{N}$, $(R_{AA}^{N})^{\pi_{0}}$ for $4< p_{T} < 6$ GeV/c and $5< p_{T} < 8$ GeV/c, measured at RHIC in Au-Au collisions and at LHC in Pb-Pb collisions, evidence, as a function of the collision energy, a suppression enhancement from $\sqrt{s_{NN}}=39$ GeV up to 200 GeV, followed by a saturation up to the highest energy, $\sqrt{s_{NN}}=5.02$ TeV for Pb-Pb collision. $(1-R_{AA}^{N})/\langle dN/dy \rangle$ and $\{1-(R_{AA}^{N})^{\pi_{0}}\}/\langle dN/dy \rangle$ for 0-10% centrality evidence a maximum around the largest RHIC energies, in qualitative agreement with models predictions. This could be considered as a signature of a transition in the deconfined matter properties from the top RHIC energy to LHC energies.

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