Core-corona interplay in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV

M.Petrovici, I.Berceanu, A.Pop, M.Tărziilă, C.Andrei
National Institute for Physics and Nuclear Engineering - IFIN-HH
Hadron Physics Department
Bucharest - Romania
(Dated: November 14, 2018)

A simple approach based on the separation of wounded nucleons in an A-A collision in two categories, those suffering single collisions - corona and the rest - core, estimated within a Glauber Monte-Carlo model, explains the centrality dependence of the light flavor hadrons production in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. The core contribution does not include any dependence of any process on the fireball shape as a function of the impact parameter. Therefore, the ratios of the $p_T$ distributions to the one corresponding to the minimum bias pp collisions at the same energy, each of them normalised to the corresponding charged particle density, the $\langle p_T \rangle$ and transverse energy per unit of rapidity are reproduced less accurate by such an approach. The results show that at LHC energies the core contribution still plays an important role and it has to be considered in order to evidence the centrality dependence of different observables related to the core properties and dynamics.

PACS numbers: 25.75Ag

At ultra-relativistic energies the initial energy density distribution within the fireball is highly non-homogeneous [1]. This non-homogeneity is directly correlated with the distribution of nucleons suffering a given number of collisions (the thickness of nuclear matter to which a nucleon is exposed) which can be estimated in a simple Monte-Carlo Glauber approach. The non-homogeneous distribution of the initial state has a direct consequence on the fluctuations of different observables and the dynamics of the initial state up to the freeze-out moment. At a given collision energy, the amount of energy transferred into the fireball increases with centrality, i.e. the volume of the overlapping zone, and is correlated with the measured charged particle multiplicity. Therefore, the charged particle multiplicity dependence was extensively studied for many observables. It is mandatory to understand how much of this dependence on centrality or system size is due to the initial high energy density state and its subsequent dynamics and how much is due to a simple interplay between core-corona contributions. Extensive studies of the core-corona separation effects on the centrality dependence of the strangeness production, average transverse momenta, elliptic flow or $p_T$ spectra in heavy-ion collisions at SPS and RHIC energies were done [2][10]. The core-corona interplay estimated by parametrizing the core-mantle contributions such as to reproduce the density of charged particles produced in Au-Au collisions [3] was confirmed by more consistent approaches, based on string density before hadronization within the EPOS model using some global parameters [4] or on quark number density within the UrQMD transport+hydrodynamics hybrid model [5]. Approaches based on separating the participating (wounded) nucleons $N_{\text{part}}$, in two classes, those which scatter only once, coined corona, which would correspond to a minimum-bias pp collision and the rest which contribute to the fireball, called core, both estimated within the geometric Gläuber model, were equally successful in explaining the experimental trends [6][7]. A very good agreement between the percentage of nucleons undergoing single collisions and the percentage taken as a fit parameter in a core-corona scenario was evidenced [8]. Based on this and due to its simplicity, in the present paper we consider the approach from [7] in order to explore to which extent it can explain the centrality dependence of different observables in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV.

The number of participating nucleons and the percentage of wounded nucleons which scatter more than once, $f_{\text{core}}$, were estimated using the Monte-Carlo Glauber approach [11][13]. For the nuclear density profile of the colliding Pb nuclei a Woods-Saxon distribution was used:

$$\rho(r) = \frac{1}{1 + \exp\left(\frac{r-R_A}{a}\right)}$$

with $a=0.546$ fm and $R_A=6.62$ fm. The nucleons of the two Pb nuclei are colliding if the transverse distance between them is smaller than the distance estimated from the inelastic nucleon-nucleon cross section of 64 mb at $\sqrt{s}=2.76$ TeV [11][13]. The correlation between the centrality and impact parameter is taken from [11]. These values, $\langle N_{\text{part}} \rangle$ and the percentage of nucleons suffering more than a single collision are presented in Table I. In Fig.1a the percentage of wounded nucleons which scatter only once, for head-on collisions of two identical nuclei is represented as a function of their mass at two incident energies, i.e. $\sqrt{s_{NN}}=200$ GeV and 2.76 TeV. The percentage of nucleons scattered only once is decreasing with the increasing mass of the colliding nuclei and the centre of mass energy, the value for Pb-Pb collisions at the LHC energy being very small. However, for peripheral and mid-central collisions their contribution becomes important and a good scaling is evidenced as a function
FIG. 1. a) The percentage of wounded nucleons which scatter only once, for head-on collisions of two identical nuclei, as a function of their mass at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV; b) The same percentage as a function of $\langle N_{\text{part}} \rangle$ in Au-Au at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV collisions.

FIG. 2. The estimated light flavor hadrons yields as a function of participants $\langle N_{\text{part}} \rangle$ for Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV: using Eq.(2) - open symbols; experimental values - full symbols [16–19]. To be visible, the open symbols are shifted by 5 units in $\langle N_{\text{part}} \rangle$. A similar decomposition can be done for the double differential $p_T$ distributions. $(dN/dy)^{ppMB}_i$ values for $\pi$, $K$, $p$ were reported in [20]. The values for hyperons and $\phi$ mesons were obtained following the same receipt as the one used by the ALICE Collaboration [18, 19, 21–23] and reported values [24], respectively. Eq.(2) for 0-5% centrality was used to extract the core contribution for each species. The estimated light flavor hadrons yields as a function of the average number of participants $\langle N_{\text{part}} \rangle$ from Eq.(2) and the published experimental values are

TABLE I. Centrality, impact parameter $\langle N_{\text{part}} \rangle$ and the percentage of wounded nucleons with more than one collision estimated for the corresponding centrality, based on the Glauber Monte-Carlo approach, for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV collisions.

| $\text{Cen} (%)$ | $b$ (fm) | $\langle N_{\text{part}} \rangle$ | $f_{\text{core}}$ |
|-----------------|---------|-----------------|-----------------|
| 0 - 5           | 0.00 - 3.50 | 382.5±3.1 | 0.942±0.003 |
| 5 - 10          | 3.50 - 4.95 | 329.4±4.9 | 0.900±0.002 |
| 10 - 20         | 4.95 - 6.98 | 259.9±2.9 | 0.861±0.002 |
| 20 - 30         | 6.98 - 8.55 | 185.4±3.9 | 0.814±0.002 |
| 30 - 40         | 8.55 - 9.88 | 128.1±3.3 | 0.764±0.002 |
| 40 - 50         | 9.88 - 11.04 | 84.2±2.6  | 0.703±0.002 |
| 50 - 60         | 11.04 - 12.09 | 52.1±2.0 | 0.626±0.002 |
| 60 - 70         | 12.09 - 13.05 | 29.5±1.3 | 0.536±0.004 |
| 70 - 80         | 13.05 - 13.97 | 14.9±0.6 | 0.431±0.005 |
| 80 - 90         | 13.97 - 14.96 | 6.3±0.2 | 0.325±0.003 |

$M_{i}^{\text{core}}$ is the multiplicity per core participant. Within a core-corona approach, the yield of a given species $i$, at a given centrality, per unit of rapidity can be written as:

$$\left( \frac{dN}{dy} \right)_{i}^{\text{cen}} = N_{\text{part}}[(1 - f_{\text{core}})M_{i}^{ppMB} + f_{\text{core}}M_{i}^{\text{core}}]$$

where $M_{i}^{ppMB} = \frac{1}{2}(dN/dy)_{i}^{ppMB}$ at the same energy and $M_{i}^{\text{core}}$ is the multiplicity per core participant. The estimated light flavor hadrons yields as a function of participants $\langle N_{\text{part}} \rangle$ from Eq.(2) and the published experimental values are

We start with integrated values, i.e. the yields of light flavor hadrons per unit of rapidity measured in the mid-rapidity region [16–19]. Within a core-corona approach, $\langle N_{\text{part}} \rangle$ and the percentage of wounded nucleons with more than one collision estimated for the corresponding centrality, based on the Glauber Monte-Carlo approach, for Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV collisions.

of the number of participating nucleons for Au-Au and Pb-Pb collisions at the respective energies, as could be followed in Fig.1b.
FIG. 3. The centrality dependent ratios of normalised $p_T$ spectra, measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, to the normalised minimum-bias spectrum at the same energy. The spectra are normalised to the corresponding average charged particle density. Left column (a, b, c): based on $p_T$ spectra measured by the ALICE Collaboration [26, 27]; Middle column (d, e, f): the results using the core-corona scenario; Right column (g, h, i): the ratios of the experimental $p_T$ distributions relative to the ones estimated within the core-corona approach. From top to bottom they correspond to pions, kaons and protons.

presented in Fig.2 by open and full symbols, respectively. As it is observed, the enhancement of light flavor hadrons production with increasing centrality is reproduced rather well by a pure geometrical approach, a superposition of the single nucleon-nucleon (corona) contribution and the contribution due to nucleons which scatter more than once (core) whose relative weights were estimated within the Glauber approach. This approach is also applied for the ratio of double differential cross sections normalised to the charged particle densities, i.e.: 

$$
\frac{(\frac{d^2N}{dydp_T})_{cen}}{(\frac{d^2N}{dydp_T})_{ppMB}}.
$$

The numerator and denominator of the normalised $p_T$ distributions [25] based on $p_T$ spectra measured by the ALICE Collaboration [26, 27] are represented. The results using the core-corona scenario can
be followed in the second column (d,e,f) while the ratios between experimental $p_T$ distributions and the ones estimated within the core-corona approach are shown in the third column (g,h,i). The trends observed in the experiment are qualitatively reproduced. Quantitatively, as could be seen in the last column of Fig.3, there are some differences between the estimates based on the core-corona ansatz and the experimental values. This is the consequence of not including any dependence of different phenomena on the core shape as a function of centrality. At RHIC energies, the PHENIX Collaboration has done detailed studies on the azimuthal dependence of the in-plane/out-of-plane transverse expansion \[28\] and $R_{AA}$ \[29\] for Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV. A clear $N_{\text{part}}$ and azimuthal angle dependence of these two phenomena was evidenced. This is the explanation of the observed deviations in the last column of Fig.3 in the region of $p_T$ where the expansion and suppression have the main contribution to the spectra shapes. Therefore, a deviation from a simple core-corona approach where the core contribution scales only with the number of participants colliding more than once, not including any dependence on the fireball shape, is expected. Being aware of these effects, one can investigate to which extent the $p_T$ dependence on the fireball shape, is expected. As could be noticed, Eq.(4) does not include the contribution of $\Sigma^+, \Sigma^-$ and the corresponding anti-baryons. The estimate of their contribution to the spectra shapes \[17, 18\] can be also estimated. Based on these results and the following approximation for the transverse energy:

$$\frac{dE_T}{dy} \approx 3\left(\frac{dE_T}{dy}\right)_{\pi^+} + 4\left(\frac{dE_T}{dy}\right)_{K^+, p, \Xi^-} + 2\left(\frac{dE_T}{dy}\right)_{\Lambda, \Sigma^-, \Omega^-}$$  \tag{4}$$

\[4\] as a function of $\langle dN_{\text{ch}}/d\eta \rangle$ in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV: a) $\pi^+$, $K^+$ and $p$ \[16\]; b) $\phi$ \[19\], $\Lambda$ and $\Xi^-$. Open symbols - estimated using Eq.(3) and full symbols - experimental values (see the text).
FIG. 5. $\langle \frac{dE_T}{dy} \rangle / \langle N_{\text{part}} \rangle$ as a function of $\langle N_{\text{part}} \rangle$ for Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV: by using Eq.(4) and the core-corona approach for $\frac{dE_T}{dy}$ and $\langle m_T \rangle$ - open circles; the results obtained using the experimental values (see the text) - red triangles; $\langle \frac{dE_T}{dy} \rangle$ values from Ref. [32] - green squares. To be visible, the red triangles are shifted by 5 units in $\langle N_{\text{part}} \rangle$.

not yet available, we decided to not include the contribution of Σ baryons in the present study. The results are presented in Fig.5 by open circles. The $\frac{dE_T}{dy}$ values estimated within the core-corona approach follow the trend obtained using in Eq.(4) the experimental values - red triangles. This estimate is in a very good agreement with the $\langle \frac{dE_T}{dy} \rangle$ values from Ref. [32] - green squares. In Fig.6 the ratio $\langle \frac{dE_T}{dy} \rangle / \langle \frac{dN_{ch}}{dy} \rangle$ as a function of $\langle N_{\text{part}} \rangle$ is represented. The ratio obtained based on the core-corona estimate - open symbols agrees with the experimental values within the error bars. This shows that in such a representation the $\langle N_{\text{part}} \rangle$ dependence of $\langle \frac{dE_T}{dy} \rangle$ and $\langle \frac{dN_{ch}}{dy} \rangle$ has a similar trend due to the interplay between core and corona contributions, therefore it cancels in the ratio.

In conclusion, the centrality dependence of the light flavor hadrons yields at mid-rapidity is well reproduced by a simple core-corona assumption where the corona represents the percentage of the wounded nucleons which scatter only once and the core represents the rest of wounded nucleons at a given collision centrality. The difference between the experimental ratio of normalised $p_T$ distributions to the average charged particle densities for Pb-Pb and minimum bias pp collisions at the same energy, the average transverse momenta and the transverse energy at mid-rapidity, as a function of centrality and the estimates using the core-corona approach can be attributed to the core shape dependence of different phenomena, like flow and suppression, which depends on the collision geometry and is not included in the present approach. The broad distribution of $N_{\text{part}}$ for a given experimentally selected centrality is also not considered in the present estimates. The results show that the corona contribution plays an important role also at energies available at the Large Hadron Collider and it has to be separated in order to evidence the centrality dependence of different observables related to the core properties and dynamics.

This work was carried out within the 44/05.10.2011 and 2/03.01.2012 projects sponsored by Ministry of Research and Inovation via CNCSI and IFA coordinating agencies.

[1] H.J.Dresher et al., Phys.Rev.C 65 (2002) 054902
[2] F.Becattini et al., Phys.Rev.C 69 (2004) 024905
[3] P.Bozek, Acta Phys. Pol. B36 (2005) 3071
[4] K.Werner, Phys.Rev.Lett. 98 (2007) 152301
[5] J.Steinheimer and M.Bleichner, Phys.Rev.C 84 (2011) 024905
[6] F.Becattini, J.Manninen, J.Phys.G 35 (2008) 104013, Phys.Lett.B 673 (2009) 19
[7] J.Aichelin, K.Werner, Phys.Rev.C 79 (2009) 064907, J.Phys.G 37 (2010) 094006, Phys.Rev.C 82 (2010) 034906
[8] P.Bozek, Phys.Rev.C 79 (2009) 054901
[9] C.Schreiber, K.Werner, J.Aichelin, Phys.Atom.Nucl. 75 (2012) 640
[10] M.Gemard and J.Aichelin, Astron.Nachr. 335 (2014) 660
[11] R.J.Glauber, Phys.Rev. 100 (1955) 242
[12] V.Franco and R.J.Glauber, Phys.Rev. 142 (1966) 119
[13] M.L.Miller et al., Ann.Rev.Nucl.Part.Sci. 57 (2007) 205
[14] ALICE ColI., Phys.Rev.C 88 (2013) 044909
[15] ALICE ColI., Phys.Rev.Lett. 106 (2011) 032301
[16] ALICE ColI., Phys.Rev.C 88 (2013) 044910
[17] ALICE Coll., Phys.Rev.Lett. 111 (2013) 222301
[18] ALICE Coll., Phys.Lett.B 728 (2014) 216
[19] ALICE Coll., Phys.Rev.C 91 (2015) 024609
[20] ALICE Coll., Eur.Phys.J. C75 (2015) 226
[21] ALICE Coll., Eur.Phys.J. C71 (2011) 1594
[22] ALICE Coll., Phys.Rev.Lett. 105 (2010) 252301
[23] ALICE Coll., Phys.Lett.B 712 (2012) 309
[24] ALICE Coll., arXiv:nucl-ex/1702.00555v1
[25] M.Petrovici et al., AIP Conf.Proc., in press
[26] ALICE Coll., Phys.Lett.B 736 (2014) 196
[27] ALICE Coll., Phys.Rev.C 93 (2016) 034913
[28] PHENIX Coll., J.Phys.Conf.Series 270 (2011) 012041
[29] PHENIX Coll., Phys.Rev.C 80 (2009) 054907
[30] CMS Coll., JHEP 05 (2011) 064
[31] A.Bylinkin and A.Rostrovitsev, arXiv:hep-ph/1008.0332
[32] ALICE Coll., Phys.Rev.C 94 (2016) 034903
[33] P.Huhn, ALICE Coll., Poster Quark Matter 2017