Centrality dependence of hadronization and chemical freeze-out conditions in heavy ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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We present an analysis of hadronic multiplicities measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of the collision centrality within the statistical hadronization model. Evidence is found of a dependence of the chemical freeze-out temperature as a function of centrality, with a slow rise from central to peripheral collisions, which we interpret as an effect of post-hadronization inelastic scatterings. Using correction factors calculated by means of a simulation based on the UrQMD model, we are able to obtain a significant improvement in the statistical model fit quality and to reconstruct the primordial chemical equilibrium configuration. This is characterized by a nearly constant temperature of about 164 MeV which we interpret as the actual hadronization temperature.

I. INTRODUCTION

The determination of the critical temperature of QCD is one of the principal goals of relativistic nucleus-nucleus (AA) collision physics. This temperature has been calculated in lattice QCD \cite{1-3} to be about 160 MeV, at a baryon-chemical potential $\mu_B \approx 0$, a situation characteristic of heavy ion collisions at top RHIC and LHC energies. At very low $\mu_B$ the phase transition from hadronic matter to Quark-Gluon Plasma (QGP) has been found to be a continuous one (a cross-over), so that the value of the (pseudo-) critical temperature depends somewhat on the specific observable under consideration \cite{1, 2}.

It has been conjectured for quite some time \cite{4} that the experimentally measured hadronic multiplicities, or multiplicity ratios do, in fact, represent such an observable: they depend on the temperature prevailing at, or near QCD hadronization. It has been proposed to use fluctuation of conserved charges to determine it \cite{5, 6} as these can be directly calculated in lattice QCD. However, multiplicities are first moments and, as such, are more robust observables against spurious effects. Indeed, a statistical ansatz is able to reproduce the measured hadronic yields, both in elementary \cite{7} and in relativistic nucleus-nucleus collisions \cite{8}. This has led to the formulation of the Statistical Hadronization Model (SHM) which, in a nutshell, assumes that hadrons are emitted from the fireball source at (almost) full chemical equilibrium. The reason of such a success, unexpected in elementary collisions, as well as the identity of the fitted temperature in all kinds of collisions, has been debated for a long time (see refs. \cite{9, 10} for a summary). In practice, one can take advantage of this phenomenon to obtain the position of the parton-hadron coexistence line of QCD matter in the $(T, \mu_B)$ plane.

The temperature determined by fitting the hadronic multiplicities with the SHM is actually the one at which hadrons/resonances cease inelastic interaction, the so-called “chemical freeze-out” temperature. In principle this may differ from the QCD transition temperature if hadrons, after their formation, keep interacting inelastically. This is, clearly, not the case in elementary $e^+e^-$ annihilation to hadrons but it could become relevant in the high multiplicity final state of AA collisions. Different reactions could then freeze-out at different times, in inverse order of inelastic cross section, so that this stage of the fireball source expansion, dubbed as “afterburning”, would generally imply deviations from full chemical equilibrium of the hadronic species \cite{11}. In the standard SHM analysis such effects were assumed to be negligibly small, and that, therefore, the temperature and baryon-chemical potential yielded an ideal snapshot of the fireball dynamical trajectory, at or near QCD hadronization.

An unexpected recent outcome from LHC has been the relatively low $p/\pi$ ratio measured by the ALICE experiment in central Pb+Pb collisions \cite{12} at $\sqrt{s_{NN}}=2.76$ TeV, with respect to the expectation from the SHM \cite{13}. A similar result was obtained earlier by the SPS experiment NA49 \cite{14} which reported sizeably low $\bar{p}$ and $\bar{\Lambda}$ yields compared to SHM predictions \cite{15}. This has been interpreted \cite{16, 17} as an evidence of post-hadronization baryon-antibaryon annihilation. An alternative explanation has been put forward in ref. \cite{18}. Note that annihilation cross sections do not fade away with dropping temperature, unlike inelastic transmutations. In ref. \cite{20} we proposed a picture of hadron production in relativistic A+A collisions based on the idea of the hadronization process leading to chemical
equilibrium of its outcome, followed by a stage of afterburning driving some hadronic species (notably baryons and antibaryons) out of chemical equilibrium before freeze-out. We determined these effects by employing the hybrid version of the microscopic transport model UrQMD \cite{22}, obtaining modification factors due to afterburning which were then employed in the subsequent data analysis. We thus reconstructed the primordial chemical equilibrium, up to a point where multi-hadron collisions could become important, and showed, for central collisions at various energies, a resulting rise of the deduced temperatures, and significantly improved SHM fit quality. This bears out the idea of a primordial chemical equilibrium as an intrinsic feature of hadronization.

In the present paper we extend our analysis, changing the topic from central collisions at various energies, to consideration of the centrality dependence of hadron multiplicities at fixed energy. Whereas, in central collisions, the final hadronic expansion stage causes substantial antibaryon and (at higher energies) baryon annihilation/regeneration, these effects should diminish toward more peripheral collisions because of the reduced overall multiplicity (see discussion in sect. \text{II}). Thus, if our hypothesis is correct that the QCD hadronization process generates an equilibrium hadron/resonance yield distribution, at some constant temperature $T$, the afterburning effects should lead to a larger modification in central than in peripheral collisions. As baryon attenuation leads to lower apparent freeze-out temperatures derived from the standard SHM analysis, we would expect this temperature to rise, mildly, from central toward peripheral collisions.

These expectations have been borne out by a detailed hydrodynamical investigation \cite{23} of the final stages of AA collisions. Interestingly, it was pointed out in ref. \cite{23} that, if afterburning played some role, the chemical freeze-out temperature $T_{\text{chem}}$, fitted within the SHM should exhibit a non-trivial behaviour, with a rise from central to peripheral collisions. Indeed, this effect is clearly observed for the kinetic freeze-out temperature, the temperature at which hadrons cease their elastic interactions. On the other hand, at the highest RHIC energy, no significant dependence of $T_{\text{chem}}$ on centrality was seen \cite{23–25}, indicating that chemical composition are much less affected than spectra by the afterburning stage. In fact, the STAR experiment has found a dependence of $T_{\text{chem}}$ on centrality at lower energy \cite{23}, but the slope of the function is reversed if the strangeness neutrality is enforced. It should also be kept in mind that at low energy the use of midrapidity densities may give rise to spurious effects such as an artificial enhancement of the strange particles, so that this observed dependence is difficult to interpret at this time.

Recently, the ALICE experiment at the LHC has provided \cite{27} a set of high precision measurements of hadronic species midrapidity multiplicities, as a function of centrality in Pb+Pb collisions at $\sqrt{s_{NN}}= 2.76$ TeV. The improved accuracy and the increased total multiplicity with respect to RHIC energy, should allow to highlight a dependence of $T_{\text{chem}}$ on centrality. It is precisely the goal of this paper to test the centrality dependence of the chemical freeze-out temperature. This should settle the much debated “proton anomalies”, and provide further evidence for the constancy of the primordial hadronization temperature, to be identified with the pseudo-critical QCD temperature. To this end we first analyze the ALICE data with the standard SHM method. Then, by employing modification factors for all hadronic species, and all centralities, obtained from the hadronic transport model UrQMD, we shall show that significant modification of the primordial abundances occurs in central collisions, in agreement with the findings in refs. \cite{16, 21}, reducing towards more peripheral collisions and mostly affecting the baryon-antibaryon species, via annihilation and regeneration. With the modification factors in place in a second SHM analysis we shall arrive at a uniform temperature of $164\pm3$ MeV.

\section{II. THE FREEZE-OUT PROCESS}

We can understand the effect of multiplicity on chemical freeze-out in relativistic heavy ion collisions with simple arguments. In an expanding system of interacting particles freeze-out occurs when the mean scattering time $\tau_{\text{scatt}}$ exceeds the mean collision time $\tau_{\text{exp}}$:

\begin{equation}
\tau_{\text{scatt}} = \frac{1}{n \sigma \langle v \rangle} > \tau_{\text{exp}} = \frac{1}{\partial \cdot \vec{u}}
\end{equation}

where $\vec{u}$ is the hydrodynamical velocity field and $\langle v \rangle$ is the mean velocity of particles. If the cross-section $\sigma$ is the inelastic one, the freeze-out is called chemical, whereas if it includes elastic processes, the freeze-out is called kinetic. Chemical freeze-out of course precedes the kinetic as the inelastic cross section is smaller than the total.

We can obtain a gross approximation of the expansion time with the ratio $V/V$ where $V(t)$ is the volume of the fireball at the time $t$. For a fireball which is spherical in shape with a radius $R$, this is $R/3\dot{R}$ and if the radius increases at approximately the mean particle velocity $\langle v \rangle$, we have the condition:

\begin{equation}
\frac{1}{n \sigma \langle v \rangle} > \frac{R}{3 \langle v \rangle} \implies \frac{1}{n \sigma} > \frac{R}{3}
\end{equation}
For a given number of particles $N$ within the volume, this inequality yields the radius at which freeze-out occurs as a function of $N$ and of the average cross-section:

$$R_{fo} = \sqrt{\frac{N \sigma}{4\pi}}$$  \hspace{1cm} (3)

and the density at which freeze-out occurs, which decreases with $N$ according to:

$$n_{fo} = \frac{N}{3\pi R_{fo}^3} = 3\sqrt{\frac{4\pi}{N}} \frac{1}{\sigma^{3/2}}$$  \hspace{1cm} (4)

Of course, it should be kept in mind these estimates (3) and (4) are crude, but they tell us that the freeze-out radius, for each particle, approximately scales with the square root of the number of scattering centers a particle can interact with and the related cross section. For a low multiplicity hadronic system, it may happen that the above value exceeds the density of hadrons when they are formed, that is at hadronization. This simply signals that hadrons decouple right after their formation without reinteracting, what happens in elementary collisions, at the intrinsic hadronization density scale which is dictated by QCD. For relativistic heavy ion collisions, conversely, the multiplicity can grow to large numbers so that there could be enough time for hadronic reinteraction and freeze-out occurs later. For instance, for the typical value of $N = 1000$, in most central collisions, and $\sigma = 30 \text{mb} = 3 \text{fm}^2$ one has $R_{fo} \approx 15 \text{fm}$, which is in the right ballpark (for kinetic freeze-out) taking into account the drastic approximations made; the density at freeze-out turns out to be $n_{fo} \approx 0.06 \text{ fm}^{-3}$ which is lower than the typical hadronization density of about $0.5 \text{ fm}^{-3}$.

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FIG. 1: (Color online) Ratio between antiproton and negative pion yields in relativistic heavy ion collisions as a function of centrality at different energies.

The above equations also imply that, if hadronization occurs at a universal temperature $T_h$ \cite{9, 10} which is the pseudo-critical QCD temperature, the effective average temperature of the chemical freeze-out should increase in peripheral collisions if equilibrium is approximately maintained in the hadronic reinteraction stage. The strength of this effect depends, according to \cite{11}, on the function $n_{fo}(T)$ and it is, as expected, larger for the kinetic than chemical freeze-out simply because the total cross section is larger than the inelastic one. In general, since the hadronic density
strongly depends on the temperature, the dependence of $T_{chem}$ on $N_c$ hence on centrality, is mild. To highlight it, one needs a large lever arm in terms of multiplicity and higher energies are more favourable in this respect, as has been mentioned in the Introduction.

\[ \sqrt{s_{NN}} (\text{GeV}) \quad \bar{p}/\pi^- (\text{AA}) \quad \bar{p}/\pi^- (\text{pp}) \quad \Xi^+/\pi^- (\text{AA}) \quad \Xi^+/\pi^- (\text{pp}) \]

| $\sqrt{s_{NN}}$ (GeV) | $\bar{p}/\pi^-$ (AA) | $\bar{p}/\pi^-$ (pp) | $\Xi^+/\pi^-$ (AA) | $\Xi^+/\pi^-$ (pp) |
|------------------------|-----------------------|-----------------------|---------------------|---------------------|
| 17.2                   | 0.0067 ± 0.0062 [28]  | 0.0165 ± 0.0005 [29]  | (1.12 ± 0.17) $10^{-3}$ [28] | (3.9 ± 0.4) $10^{-4}$ [29] |
| 200                    | 0.082 ± 0.012 [30]    | 0.080 ± 0.009 [31]    | (6.6 ± 0.79) $10^{-3}$ [30] | (2.0 ± 0.7) $10^{-3}$ [31] |
| 2750                   | 0.045 ± 0.005 [27]    | -                     | (4.7 ± 0.5) $10^{-3}$ [27] | -                   |
| 7000                   | -                     | -                     | -                   | (3.25 ± 0.32) $10^{-3}$ [32] |

TABLE I: Ratios $\bar{p}/\pi^-$ and $\Xi^+/\pi^-$ in pp and AA collisions at different energies. The ratio $\Xi^+/\pi^-$ in pp is always less than in AA at the same $\sqrt{s_{NN}}$.

FIG. 2: (Color online) Ratio between $\Xi^+$ and negative pion yields in relativistic heavy ion collisions as a function of centrality at different energies. At the largest energy (a), a structure can be clearly seen. We interpret the bump in mid-peripheral events as the combination of two effects: increased baryon annihilation owing to larger multiplicity at LHC and the corona effect in very peripheral. Also shown the prediction of corona-less UrQMD calculations normalized to the most central bin.

Before moving to the data analysis, it should be pointed out that there is evidence of afterburning in the data itself. In fig. 1 we show the behaviour of $\bar{p}/\pi^-$ ratio as a function of centrality at different centre-of-mass energies. In all three cases, the ratio slightly, yet significantly (taking into account that errors are visibly correlated) increases from central to peripheral collisions, in agreement with the expectation of a larger anti-baryon annihilation in more central events. Note that, at the LHC energy, this effect cannot by any means be explained by a genuine decrease of baryon-chemical potential at freeze-out in peripheral collisions because all particle/antiparticle ratios are consistent with $\mu_B \approx 0$ at all centralities. A possible mundane explanation to be considered is a core-corona superposition if the ratio $\bar{p}/\pi^-$ was larger in pp than central AA at the same energy (see table I). However, this is ruled out by the stunning centrality behaviour of the ratio $\Xi^+/\pi^-$, shown in fig. 2. Unlike at RHIC, this ratio surprisingly increases
from central towards peripheral collisions, then drops according to the expectations of the core-corona model \cite{33} as its value is indeed much lower in pp than in AA collisions (see table I) at all energies.

The rise of the $\Xi/\pi$ ratio is the result of the larger relative absorption of $\Xi$ and the larger relative production of pions in the most central collisions. Altogether, the centrality dependence of these particle ratios confirm the expected dependence of chemical freeze-out on particle multiplicity.

### III. DATA ANALYSIS

We have analyzed the multiplicities measured by the ALICE experiment at $\sqrt{s_{NN}} = 2.76$ TeV \cite{27} to determine the chemical freeze-out parameters with fits to the usual SHM (described in ref. \cite{10}) predictions and to the same formulae corrected for the modification factors, defined as the ratios between the particle yields with afterburning and the same yields without it. The modification factors have been estimated with a hybrid version of the code UrQMD \cite{22} implementing afterburning after a hadron generation according to local thermodynamical equilibrium prescription (Cooper-Frye formula). Therefore, the estimated factors are the outcome of a full simulation of the heavy ion collision process.

#### A. Data interpolation

The midrapidity densities of hyperons \cite{27} are provided by the ALICE experiment with a centrality binning different from that of p, K and $\pi$ (10 centrality classes for the latter, 7 for $\Lambda$’s and 5 for $\Omega$ and $\Xi$’s). Thus, we have interpolated the yields of hyperons to obtain their values in the same centrality bins as for the protons, pions and kaons. As interpolation function we chose a 6th degree polynomial for $\Lambda$’s and a 4th degree polynomial for $\Omega$’s and $\Xi$’s. In order to make a proper comparison with the data, we calculated the integral mean value within each bin:

$$N([c_i, c_{i+1}]) = a_0 + a_1(c_{i+1}^2 - c_i^2)/2(c_{i+1} - c_i) + a_2(c_{i+1}^3 - c_i^3)/3(c_{i+1} - c_i) + \cdots$$

where $c_i$ are the centrality limits of each bin. We have determined the coefficients $a_i$ by making a $\chi^2$ fit to the data in the various centrality bins. Since the experimental errors among different centrality bins are apparently correlated, we have formed a non-diagonal covariance matrix $C$ in the $\chi^2$:

$$\chi^2 = \sum_{\text{bins}} (\text{Theo}_i - \text{Meas}_i)C_{ij}^{-1}(\text{Theo}_j - \text{Meas}_j)$$

assuming a constant correlation coefficient $\rho = 0.5$. Once the parameters $a_i$ of the interpolating function were obtained, we have been able to estimate the yields of the hyperons along with their error in the same bins of proton, pions and kaons (see table II) up to the 70-80% bin. Since the data from ref. \cite{27} show that the yields of particle and anti-particles are compatible within errors, we have interpolated the sum $\Omega + \bar{\Omega}$ to reduce the statistical uncertainty in the interpolation.
FIG. 3: (Color online) Modification factors (see text for definition) for $\pi^+$, proton, and $\Xi^-$ as a function of centrality at $\sqrt{s_{NN}} = 2.76$ TeV calculated with UrQMD. The error bars are statistical.

B. Calculation of modification factors

To quantify the effects of the hadronic phase (afterburning) on the particle ratios we employ the Ultra relativistic Quantum Molecular Dynamics model (UrQMD) in its current version \cite{22}. The hadronic transport part of the model is based on an effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x^\nu, p^\nu) = C_i,$$

which describes the time evolution of the distribution functions $f_i(x^\nu, p^\nu)$ for particle species $i$, including the full collision term on the right hand side. The interactions of hadrons in the current version is limited to binary elastic and $2 \to n$ inelastic scatterings, including resonance creations and decays, string excitations and particle-antiparticle annihilations. The cross sections and branching ratios for the corresponding interactions are taken from experimental measurements, where available, and detailed balance relations.

The modification factors, required for our analysis, are extracted by running the fluid dynamics mode of the UrQMD hybrid model, as discussed in ref. \cite{17}, for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and the centralities defined by the ALICE experiment.

We then analyze the particle multiplicities of stable hadrons either at the end of the fluid dynamical phase, or after the hadronic rescattering phase of the nuclear collision. The transition point from the fluid dynamical phase to the hadronic transport part occur in successive transverse slices, of thickness 0.2 fm, whenever all fluid cells of that slice fall below a critical energy density, that is six times the nuclear ground state density $\epsilon \approx 850$ MeV/fm$^3$ (in accordance with measures particle yields \cite{17}), which is then the maximal energy density at which particles are generated. For the hydrodynamical stage of the UrQMD simulation we have applied an EoS that follows from combining a hadronic phase with an effective mean field quark model, see ref. \cite{34}. In the UrQMD hybrid model hadrons of species $i$ are produced by sampling the particle distributions defined by the Cooper-Frye prescription on a pre-defined hypersurface.
\[ E \frac{dN}{d^3p} = g_i \int_{\sigma} f_i(x, p) \, p^\mu \, d\sigma_\mu \] (6)

Serving as an input, the local temperature, the chemical potentials and the flow velocity \( u_\mu \) enter the particle distribution function \( f_i \), i.e., all the particles, at the end of the fluid dynamical phase, are produced according to local chemical equilibrium. We therefore obtain the particle yield \( N_i \) either at the latest chemical equilibrium point (LCEP, see ref. [21]) \( N^CE_i \) or after the chemical and kinetic freeze out \( N^FO_i \). The modification factor \( F^*_i \) of particle species \( i \) is then simply defined as \( F^*_i = N^FO_i / N^CE_i \). Note that the modification factors have been determined by turning off weak decays but performing all strong decays, in accord with the yields quoted by the ALICE experiment. It should also be stressed that in this procedure the UrQMD average midrapidity particle multiplicities, generated at the end of the hydrodynamical stage (after the Cooper-Frye procedure) do, indeed, exhibit a common temperature of 158.2±2.2 MeV if we fit them with the statistical model, as shown in table III. Therefore, our calculated modification factors are close to those which would result from a calculation at the actually determined latest chemical equilibrium temperature of about 164 MeV in the data analysis (see sect. IV).

| Temperature   | \( \mu_B \) | \( \chi^2/\text{dof} \) |
|---------------|-------------|--------------------------|
| 158.2 ± 2.2 MeV | 0 (fixed)   | 2.52/8                   |
| Particle      | Calculated  | Fitted with SHM          |
| \( \pi^+ \)   | 528±37      | 542.4                    |
| \( \pi^- \)   | 529±37      | 542.4                    |
| \( K^+ \)     | 100.0±7.7   | 95.63                    |
| \( K^- \)     | 101.0±7.7   | 95.63                    |
| \( p \)       | 33.7±2.4    | 33.31                    |
| \( \bar{p} \) | 30.9±2.2    | 33.31                    |
| \( \Lambda \) | 18.9±1.6    | 18.45                    |
| \( \Xi^- \)   | 2.79±0.19   | 2.744                    |
| \( \Xi^+ \)   | 2.79±0.19   | 2.744                    |
| \( \Omega+\bar{\Omega} \) | 0.94±0.15  | 0.9498                  |

TABLE III: Comparison between calculated, at the end of hydrodynamical stage, and fitted midrapidity densities of particle species in most central Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. The relative errors on calculated multiplicities are the same as the experimental measurements at the same centrality. The \( \gamma_S \) parameter has been fixed to 1. The overall normalization is arbitrary.

The modification factors for \( \pi^+ \), proton, and \( \Xi^- \) are shown in fig. 3 as a function of the collision centrality. Note that the modification factors get closer to 1 for peripheral collisions.

At this point it is important to discuss the importance of multiparticle (= \( N \) body with \( N > 2 \)) reactions and their effect on the modification factors defined above. As has been pointed out in earlier studies [35], the \( N\pi \rightarrow p + \bar{p} \) (with \( N \) being 4 or 5) reaction can be responsible for the regeneration of protons and antiprotons in the hadronic phase. Since the implementation of these multiparticle properties in a microscopic solution of the transport equation eq. 4 is very difficult we have to make a quantitative estimate on the importance of this back reaction. In ref. [17] we estimated that the multi-pion fusion process, at the investigated beam energy, should only account for less than 10% regeneration of protons. This result agrees well with a recent study by Pan and Pratt [19], at the same beam energy and explicitly including detailed balance, which finds that even if a larger LCEP temperature of 170 MeV is chosen, only about 20% of all annihilated protons can be regenerated. Consequently we can assume that neglecting the back reaction implies a small quantitative uncertainty in the modifications factors and does not basically alter our findings.

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1 We note in passing that the average Cooper-Frye temperature in ref. [17] was obtained by calculating an average of the temperatures in the various hydro cells weighted with pion yields and it is therefore not directly comparable with the temperature determined by fitting particle multiplicities.
IV. RESULTS

The SHM, the relevant formulae for the calculation of midrapidity yields and the fit procedure in relativistic heavy ion collisions at very high energy have been described in detail elsewhere [25]. Here we just note that at such a large energy, the rapidity distributions are wide enough to enable a determination of the thermodynamical parameters of the most central fireball, as it was possible at \( \sqrt{s_{NN}} > 100 \) GeV. Furthermore, the antiparticle/particle ratios measured at \( \sqrt{s_{NN}} = 2.76 \) TeV are consistent with 1 at all centralities, hence we have set all chemical potentials to zero and the free parameters of the fit are 2 or 3: temperature, normalization and, optionally, \( \gamma_S \).

![FIG. 4: (Color online) Temperature as a function of the impact parameter \( b \) (central values corresponding to centralities measured by ALICE). Black dots: chemical freeze-out temperature. Red dots: LCEP (see text) temperature obtained by including UrQMD modification factors.](image)

As a first step, we have fitted the measured multiplicities to the basic version of the SHM with \( \gamma_S = 1 \) (see table IV). For the most central collisions, we confirm previous findings [21] as well as recent analysis by different groups [36] with a \( \chi^2/dof \approx 17/8 \) and an overestimation of proton yields by about 2\( \sigma \) along with an underestimation of pion yield by 1.4\( \sigma \) (see table V) which seems to be a common feature of SHM fits to high energies [8]. For the mid-peripheral bins, the fit quality is significantly worse, with a \( \chi^2/dof \approx 31/7 \) and larger discrepancies for both pions and protons, as well as for \( \Xi \). It has been shown that in peripheral bins [21, 23] the corona of single NN collisions makes strange particle yields lower than expected from a source at full chemical equilibrium. Therefore, we introduce \( \gamma_S \) as a free parameter to take the effect of corona into account. This, as expected, improves the fit quality (see table V) considerably in the most peripheral bin where corona effect is more important. In other bins, it improves the fit, although not enough to make it statistically significant.

It should be noted that the chemical freeze-out temperature, in both versions with and without \( \gamma_S \), is larger in mid-peripheral bin than in central (see fig. 3) collisions. To assess the significance of the difference one should take into account that the errors on fit parameters are strongly correlated, as it is apparent from fig. 4 because so are the errors on particle multiplicities measured in the different centrality bins. The increase of temperature toward peripheral bins is observed for the first time and it is in qualitative agreement with the idea of an afterburning stage, which, if present, has to depend on the total multiplicity as discussed in sect. II. Thus, the more central the collision, the longer the time spent into the colliding hadronic stage and the larger the shift from hadronization temperature.
The results of the fit including corrections for afterburning are shown in the third column of table IV. The theoretical yields are calculated multiplying the output from SHM (after strong and electromagnetic decays) by the modification factors defined in the previous section. Therefore, the fitted thermodynamical parameters (essentially temperature) supposedly pertain to the source at its latest state of chemical equilibrium, i.e. LCEP, before hadronic collisions set in. In a more refined calculation, one would use the thus determined LCEP conditions to compute modification factors with isothermal Cooper-Frye transition at that temperature and refit the LCEP temperature until the procedure converges. Nevertheless, already in the present calculation, the fitted temperature at hydro-UrQMD transition (158.2 MeV, see sect. [13]) is close to the final fitted value of 164 MeV, showing that we are not far from full self-consistency. The improved calculations are already in progress [37].

As it can be see from fig. 6, the fit quality improves throughout after the implementation of afterburning corrections. The fitted temperature rises by several MeV’s, as shown in fig. 4 in agreement with our previous findings [21]. Furthermore, the LCEP temperature is less centrality dependent than the plain chemical freeze-out temperature, which bears out the idea of a universal (at fixed baryon density) hadronization temperature [9, 10]. This is best seen in fig. 5 where we show the difference between the corrected temperature and the plain SHM fitted one.

TABLE IV: Results of the fits to the SHM for different centralities at $\sqrt{s_{NN}} = 2.76$ TeV. First and second column: results of the traditional fit to SHM with $\gamma_S$ and with $\gamma_S$ fixed to 1. Third and fourth column: same, but with afterburning corrections to the theoretical yields.
Table V: Comparison between measured and fitted midrapidity densities of particle species in most central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In the plain SHM fits, either with or without $\gamma_S$, there is an overestimation of proton and an underestimation of pion yields. The modification factors predicted by UrQMD improve the agreement between data and model for those particles. Also shown the predicted midrapidity density of deuterons assuming they are formed at hadronization according to SHM, and (for the afterburning case) that they are later suppressed with the square of the modification factor calculated for protons.

| Particle | Measurement | Plain SHM fit $\gamma_S = 1$ | Plain SHM $\gamma_S = 1$ | SHM+afterburning $\gamma_S = 1$ | SHM+afterburning $\gamma_S = 1$ |
|----------|-------------|-------------------------------|---------------------------|-------------------------------|-------------------------------|
| $\pi^+$  | 733 ± 54    | 659.2                         | 645.7                     | 694.2                         | 683.2                         |
| $\pi^-$  | 732 ± 52    | 659.2                         | 645.7                     | 694.2                         | 683.2                         |
| $K^+$    | 109.0 ± 9.0 | 116.0                         | 121.2                     | 112.1                         | 116.8                         |
| $K^-$    | 109.0 ± 9.0 | 116.0                         | 121.2                     | 112.1                         | 116.8                         |
| $p$      | 34.0 ± 3.0  | 39.69                         | 36.64                     | 38.62                         | 35.93                         |
| $\bar{p}$ | 33.0 ± 3.0  | 39.69                         | 36.64                     | 38.62                         | 35.93                         |
| $\Lambda$ | 26.1 ± 2.8  | 21.90                         | 21.55                     | 22.77                         | 22.39                         |
| $\Xi^-$  | 3.57 ± 0.27 | 3.246                         | 3.427                     | 3.239                         | 3.384                         |
| $\Xi^+$  | 3.47 ± 0.26 | 3.246                         | 3.427                     | 3.239                         | 3.384                         |
| $\Omega$ | 1.26 ± 0.22 | 1.112                         | 1.237                     | 1.327                         | 1.444                         |
| $D$      | 0.115       | 0.115                         |                          |                               |                               |

FIG. 5: Difference between the corrected temperature and the chemical freeze-out temperature as a function of the impact parameter $b$ (central values corresponding to centralities measured by ALICE). The error bar has been estimated by taking a 100% correlation between the errors on $T$ in the two fits.

not presently able to understand in detail. Both effects will be the subject of further investigation.
V. CONCLUSIONS

To summarize, we have demonstrated that in the high multiplicity environment of relativistic heavy ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV the inelastic collisions play a significant role in modifying the primordial hadronic yields from hadronization. The amount of inelastic rescattering is expected to depend on multiplicity, hence on centrality. This effect is clearly seen in the centrality dependence of specific particle ratios measured by the ALICE experiment and especially $\Xi/\pi$ which - for the first time - is observed to increase towards peripheral collisions before dropping. In the framework of the statistical hadronization model, this phenomenon implies a slight dependence of the chemical freeze-out temperature as a function of centrality, which is actually observed. Once suitable correction factors, estimated through the transport model UrQMD, are introduced, primordial particle multiplicities turn out to be in better agreement with a chemically equilibrated source at a nearly constant temperature of about 164 MeV. The difference between the chemical freeze-out temperature and the reconstructed latest chemical equilibrium temperature, arguably coinciding with the hadronization temperature, decreases smoothly from central to peripheral collisions, as expected in this picture. Further calculations of modification factors are in preparation to investigate the remaining small structures seen in the behaviour of temperature as a function of centrality. These findings are in excellent agreement with the concept of a universal statistical hadronization occurring at the pseudo-critical QCD temperature.

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References

[1] T. Bhattacharya, M. I. Buchoff, N. H. Christ, H.-T. Ding, R. Gupta, C. Jung, F. Karsch and Z. Lin et al., arXiv:1402.5175 [hep-lat] and references therein.

[2] G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011); S. Borsanyi, G. Endrodi, Z. Fodor, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, JHEP 1208, 053 (2012).

[3] P. Oea, L. Cosmai, M. D’Elia, A. Papa and F. Sanfilippo, Phys. Rev. D 85, 094512 (2012).

[4] R. Stock, Phys. Lett. B 456, 277 (1999).

[5] F. Karsch, Central Eur. J. Phys. 10, 1234 (2012); A. Bazavov et al., Phys. Rev. Lett. 109, 192302 (2012); S. Mukherjee and M. Wagner, PoS CPOD 2013, 039 (2013).

[6] P. Alba, W. Alberico, R. Bellwied, M. Bluhm, V. M. Sarti, M. Nahrgang and C. Ratti, arXiv:1403.4903; S. Borsanyi, Z. Fodor, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, arXiv:1403.4576.

[7] F. Becattini, J. Phys. G 23, 1933 (1997) and references therein.

[8] J. Cleymans, H. Satz, Z. Phys. C 57, 135 (1993); P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B 365, 1 (1996); F. Becattini, M. Gazdzicki and J. Sollfrank, Eur. Phys. J. C 5, 153 (1998); P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B 518, 41 (2001); A. Baran, W. Broniowski and W. Florkowski, Acta Phys. Polon. B 35, 779 (2004); W. Florkowski, W. Broniowski and M. Michalec, Acta Phys. Polon. B 33, 761 (2002); J. Cleymans, B. Kampfer, M. Kaneta, S. Wheaton and N. Xu, Phys. Rev. C 71, 054901 (2005); F. Becattini, M. Gazdzicki, A. Keranen, J. Manninen and R. Stock, Phys. Rev. C 69, 024905 (2004).

[9] H. Satz, Int. J. Mod. Phys. E 21, 1230006 (2012) and references therein.

[10] F. Becattini, arXiv:0901.3643 [hep-ph] and references therein.

[11] S. A. Bass and A. Dumitru, Phys. Rev. C 61, 064909 (2000).

[12] L. Milano, ALICE Coll., Nucl. Phys. A 904-905 (2013) 53ic; B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 88, 044910 (2013).

[13] A. Andronic, P. Braun-Munzinger and J. Stachel, arXiv:0707.4076 [nucl-th]; A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A904-905 2013, 535c (2013).

[14] T. Anticic et al. [NA49 Collaboration], Phys. Rev. C 83, 014901 (2011).

[15] F. Becattini, J. Manninen and M. Gazdzicki, Phys. Rev. C 73, 044905 (2006).

[16] F. Becattini, M. Bleicher, T. Kollegger, M. Mitrovski, T. Schuster and R. Stock, Phys. Rev. C 85, 044921 (2012).

[17] J. Steinheimer, J. Aichelin and M. Bleicher, Phys. Rev. Lett. 110, 042501 (2013).

[18] R. Stock, F. Becattini, M. Bleicher, T. Kollegger, T. Schuster and J. Steinheimer, PoS CPOD 2013, 011 (2013).

[19] Y. Pan and S. Pratt, arXiv:1210.1577 [nucl-th] and references therein.

[20] M. Petran, J. Letessier, V. Petracek and J. Rafelski, Phys. Rev. C 88, 034907 (2013).

[21] F. Becattini, M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, Phys. Rev. Lett. 111, 082302 (2013).

[22] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998); M. Bleicher et al., J. Phys. G 25, 1859 (1999); H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stöcker, Phys. Rev. C 78, 044901 (2008); H. Petersen, M. Bleicher, S. A. Bass and H. Stocker, arXiv:0805.0567 [hep-ph].

[23] U. Heinz and G. Kestin, PoS CPOD 2006, 038 (2006).

[24] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92 (2004) 112301; J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 98 (2007) 062301.

[25] J. Manninen and F. Becattini, Phys. Rev. C 78, 054901 (2008).

[26] S. Das [STAR Collaboration], Nucl. Phys. A904-905 2013, 891c (2013).

[27] B. B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 728, 216 (2014); B. B. Abelev et al. [ALICE Collaboration], Phys. Rev. Lett. 111, 222301 (2013); B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 88, 044910 (2013).

[28] T. Anticic et al. [NA49 Collaboration], Phys. Rev. C 86 (2012) 054903; T. Anticic et al. [NA49 Collaboration], Phys. Rev. C 83 (2011) 044901. NA49 data compilation, https://edms.cern.ch/file/1075059/4/na49compil20130801.pdf.

[29] T. Anticic et al. [NA49 Collaboration], Eur. Phys. J. C 65, (2010) 9; C. Alt et al. [NA49 Collaboration], Eur. Phys. J. C 45 (2006) 343; NA49 data compilation, https://edms.cern.ch/file/1075059/4/na49compil20130801.pdf.

[30] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 79 (2009) 034909; J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 98 (2007) 062301.

[31] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 79 (2009) 034909; B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 75 (2007) 064901.

[32] B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 717, 162 (2012); B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 712, 309 (2012).

[33] F. Becattini and J. Manninen, J. Phys. G 35, 104013 (2008); F. Becattini and J. Manninen, Phys. Lett. B 673, 19 (2009).

[34] J. Steinheimer, S. Schramm and H. Stöcker, Phys. Rev. C 84, 045208 (2011).

[35] R. Rapp and E. V. Shuryak, Phys. Rev. Lett. 86, 2980 (2001).
[36] J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, \texttt{arXiv:1311.4662} [nucl-th].
[37] F. Becattini, M. Bleicher, E. Grossi, J. Steinheimer, R. Stock, in progress.