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Thermal model for Pb+Pb collisions at $\sqrt{s}_{NN} = 2.76$ TeV with explicit treatment of hadronic ground states

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Abstract. Various explanations of the anomalous proton to pion ratio at the LHC are discussed. The special emphasis is set on the Cracow thermal model with single freeze-out. This model allows to get a good agreement for both the mean hadron multiplicities and the spectra. Moreover, the values of the fit parameters indicate the possibility of pion Bose condensation in the most central collisions at the LHC. Therefore, a modification of the thermal framework is proposed that explicitly allows for the condensation in the ground state. The generalised model makes a link between equilibrium and non-equilibrium thermal models. It also suggests that the pion condensation may be formed in the central collisions.

1 Introduction

Statistical models are used as the standard tools for the analysis of heavy-ion and elementary (e^+e^-, $p\bar{p}$, etc.) collisions. These models give a very good description of mean multiplicities of many hadron species using only few parameters, for example, see [1–6]. Therefore, it is quite surprising that the new data from the LHC do not agree with the thermal model prediction for proton abundances [9]. Among possible explanations of this problem there are: hadronic re-scattering effects in the final stage [10], incomplete list of hadrons [11, 12], flavor hierarchy at freeze-out [13], and the non-equilibrium hadronization [14, 15], see also [16]. Herein, we will focus on the latter explanation, because, as we have shown before in [7, 8], it offers a plausible description of the transverse momentum spectra of the produced hadrons.

Surprisingly, hydrodynamic models have problems to reproduce the pion spectra at the LHC as well. The low-p_T pion spectra show enhancement by about $25\% - 50\%$ with respect to the predictions of different hydrodynamic models, see the compilation shown by ALICE in Refs. [20, 21]. One can notice that the pions and protons are anti-correlated. If a model explains protons, it typically underestimates pions. On the other hand, if a model explains pions, then it overestimates protons. More recent papers also illustrate this issue [22, 23]. Only in Ref. [24] the pions are described in the satisfactory way, however, no results for the protons are given in this work.

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2 Cracow single-freeze out model

The Cracow single-freeze out model [17–19] allows to solve the problem with the proton/pion ratio and the problem with the pion spectrum [7, 8]. The model includes all well established resonances from the PDG. The masses of resonances and their decays are implemented in the THERMINATOR Monte-Carlo code [25, 26]. The primordial distribution in the local rest frame has the form:

$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_i^{-1} \exp\left(\sqrt{m_i^2 + p^2}/T\right) \pm 1} , \tag{1}$$

where $g_i = 2s_i + 1$ is the degeneracy connected with the spin s_i of the ith particle, p is the particle momentum, m_i - mass, and T is the system temperature. The factor Υ_i is expressed by the numbers of light quarks, N^i_q, antiquarks, $N^i_{\bar{q}}$, strange quarks, N^i_s, strange antiquarks $N^i_{\bar{s}}$; baryon and strange charges of the particle - B_i, S_i, and the corresponding chemical potentials, μ_B and μ_S:

$$\Upsilon_i = \gamma_q^{N^i_q + N^i_{\bar{q}}} \gamma_s^{N^i_s + N^i_{\bar{s}}} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T}\right) . \tag{2}$$

At the LHC the chemical potentials μ_B and μ_S are so small that one can set them zero. However, the introduction of the parameters γ_q and γ_s is equivalent to the appearance of the non-equilibrium chemical potentials $\mu_i/T = \ln \gamma_i$:

$$\Upsilon_i \simeq \gamma_q^{N^i_q + N^i_{\bar{q}}} \gamma_s^{N^i_s + N^i_{\bar{s}}} = \exp\left(\frac{\mu_q \left(N^i_q + N^i_{\bar{q}}\right) + \mu_s \left(N^i_s + N^i_{\bar{s}}\right)}{T}\right) . \tag{3}$$

They are connected with the conservation of the *sum* of the number of quarks and antiquarks during the hadronization process. Similarly, the usual baryon and strange chemical potentials μ_B and μ_S are connected with the conservation of the *difference* of the quark and antiquark numbers. Such an effective quark number conservation may appear due to rapid cooling and hadronization of the fireball. Then the system has no time to equilibrate and the numbers of quarks and antiquarks are larger than the equilibrium values.

We note that, the non-equilibrium model may account for hypothetical heavy particles that decay into multi-pion states [11, 12]. Equation (3) may describe the equilibrium $p + \bar{p}$ annihilation into 3 pions. One can also notice that the Υ_i factor is different for each particle. Some particles are enhanced, while the other are suppressed, compared to the equilibrium case. Therefore, Eq. (3) resembles the modification factors that are obtained in the hadron gas with rescattering effects [10]. Equation (3) obviously separates the strange and non-strange particles. Therefore, it is similar to the model with two separate freeze-outs for strange and non-strange particles proposed in Ref. [13]. A QCD mechanism of gluon condensation may also lead to a similar effect: the creation of low momentum gluons which transform into pions in the condensate [27–29].

We consider two physics scenarios: the equilibrium case (EQ), where $\gamma_q = \gamma_s = 1$, and the full non-equilibrium case (NEQ) with γ_q and γ_s treated as free parameters. The spectra are calculated from the Cooper-Frye formula with the special freeze-out hypersurface:

$$\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(p \cdot u), \qquad t^2 = \tau_f^2 + x^2 + y^2 + z^2, \qquad x^2 + y^2 \leq r^2_{\max} , \tag{4}$$

assuming the Hubble-like flow $u^\mu = x^\mu/\tau_f$.

The system volume, temperature, γ_q, and γ_s are taken from the papers [14, 15] and approximated by the polynomials, for details see [8]. The combination of the freeze-out time, τ_f, and the maximum

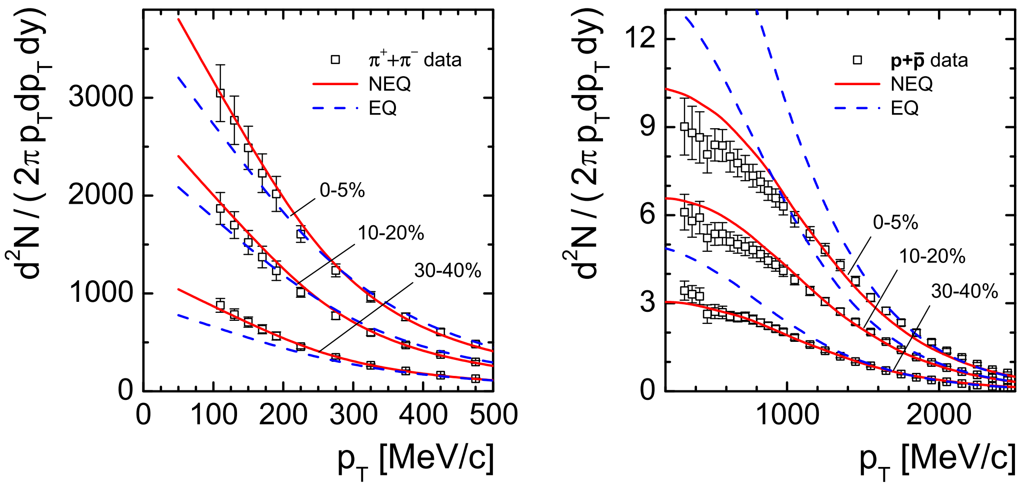

Figure 1. Low p_T spectrum of pions (left) and protons (right) in three centrality windows: 0 – 5%, 10 – 20%, 30 – 40%. The data are from [20]. The solid line shows the fit obtained for pion and kaon spectra, without protons, in the chemical non-equilibrium Cracow model. The dashed line shows the same fit in the equilibrium Cracow model [7, 8].

radius squared, $r^2_{\max}$, gives the system volume per unit rapidity, $V = \pi\tau_f r^2_{\max}$. Therefore, the ratio $r_{\max}/\tau_f$ is the only one additional parameter in the model that determines the shape of the spectra.

The Cracow model allows to fit the spectra of pions and kaons with very good accuracy only in NEQ model, see [7] and also Fig. 1 left. Surprisingly, the proton spectrum comes out right without extra fitting as a bonus, see Fig. 1 right. The increase in the multiplicity of primordial pions due to $\gamma_q^2 > 1$ is compensated by the decrease of volume and temperature in NEQ, see Fig. 2. However, despite of even larger factor for protons, $\gamma_q^3 > 1$, their number is much smaller in NEQ than in EQ. It happens because of decreased contribution from resonance decays, due to lower temperature in NEQ. This effect is much stronger for protons, because they are heavier than pions. The yields are given by the integrals of the corresponding spectra. Therefore, NEQ model is also better for proton to pion ratio.

The same fit gives the very good agreement for the spectra of K^0_S, $K^*(892)^0$, $\phi(1020)$ mesons and a satisfactory agreement for the heavy strange particles from the most central to very peripheral collisions [8]. As we already mentioned in the Introduction, the simultaneous fit of the pion and proton spectra is very difficult, and the difference between EQ and NEQ models drastically increases at low p_T, see Fig. 1. However, even more surprising fact is that the long living $\phi(1020)$ and the very short living $K^*(892)^0$ come out right from the fit done for pions and kaons only [7, 8]. It is a very strong argument either for the absence of the long rescattering phase after the freeze-out or for the effective parametrization of the re-scattering phase by Eq. (3).

3 Pion condensation

There is an upper bound on γ_q and γ_s because of Bose-Einstein condensation, when the singularities appear in the Bose-Einstein distributions of primordial pions and kaons (1). For pions, the value of γ_s

is irrelevant, and we find

$$\gamma_q^{\text{critic}} = \exp\left(\frac{m_{\pi^0}}{2T}\right).$$

The fits to the ratios of hadron abundances yield γ_q which is very close to the critical. It is equivalent to the pion chemical potential

$$\mu_\pi = 2T \ln \gamma_q \simeq 134 \text{ MeV},$$

which is very close to the π^0 mass, $m_{\pi^0} \simeq 134.98$ MeV. It may lead for the condensation of the substantial part of π^0 mesons.

If the chemical potential approaches the mass of a particle, $\mu \to m$, the zero momentum level, $p_0 = 0$, and other low lying quantum states become important. Therefore, one should consider the summation over the low momentum states explicitly. One can show that in the thermodynamic limit, $V \to \infty$, one may keep only the $p_0 = 0$ term and start the integration from zero [30]:

$$N = \frac{g}{\exp\left(\frac{m-\mu}{T}\right) - 1} + V \int_0^\infty \frac{d^3p}{(2\pi)^3} \frac{g}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1} = N_{\text{cond}} + N_{\text{norm}} \tag{5}$$

where N_{cond} is the number of particles in the Bose condensate and N_{norm} is the number of particles in normal states. We have added the condensation term from (5) to the latest version of SHARE [31], because it is the model that was used to obtain our input parameters, V, T, γ_q, γ_s. The obtained non-equilibrium model with the possibility of Bose condensation we call BEC.

The π^0 mesons will condense first, because they are the lightest particles. The π^0 multiplicity is not measured in Pb+Pb collisions at the LHC yet. Therefore we add the estimate for the number of π^0 mesons as $\pi^0 = (\pi^+ + \pi^-)/2$ and fit it together with all other available particle multiplicities. The results are shown in Figs. 2 and 3. We checked that the measured π^0 spectrum [32] agrees with our estimate. The data exist only for the range $p_T \gtrsim 700$ MeV. It gives just about 1/3 of the total expected π^0 multiplicity. Therefore the measurement of the low p_T spectrum of neutral pions is crucially important to judge about the Bose condensation.

One can see that the BEC and NEQ volumes coincide within the errors, while the EQ volume is substantially larger. This is in agreement with the calculations of other authors [14–16] in the EQ and NEQ models. The temperature in EQ is almost constant and is between 150 − 160 MeV, as is expected for the equilibrium. On the other hand the BEC temperature demonstrates an interesting centrality dependance. In most central collisions it is close to the temperature in NEQ, while at very peripheral collisions it approaches the EQ temperature. The γ_q and γ_s parameters also strongly depend on centrality, see Fig. 3. At small centralities the γ_q and γ_s values in BEC are close to those in NEQ, while at high centrality both γ_q and γ_s approach unity. The γ's in BEC are always smaller than in NEQ. It means that the inclusion of the ground state decreases the chemical potential and the number of particles in the condensate. However, the detailed determination of the condensate rate as a function of centrality requires a separate study [33].

4 Conclusions

The non-equilibrium thermal model combined with the single freeze-out scenario explains very well the spectra of light particles. It eliminates the proton anomaly and explains the low-p_T enhancement of pions. This enhancement may be interpreted as a signature of the onset of pion condensation in heavy-ion collisions at the LHC. Since the difference between equilibrium and non-equilibrium models strongly increases at low p_T, it would be interesting to see the measurements of the charged

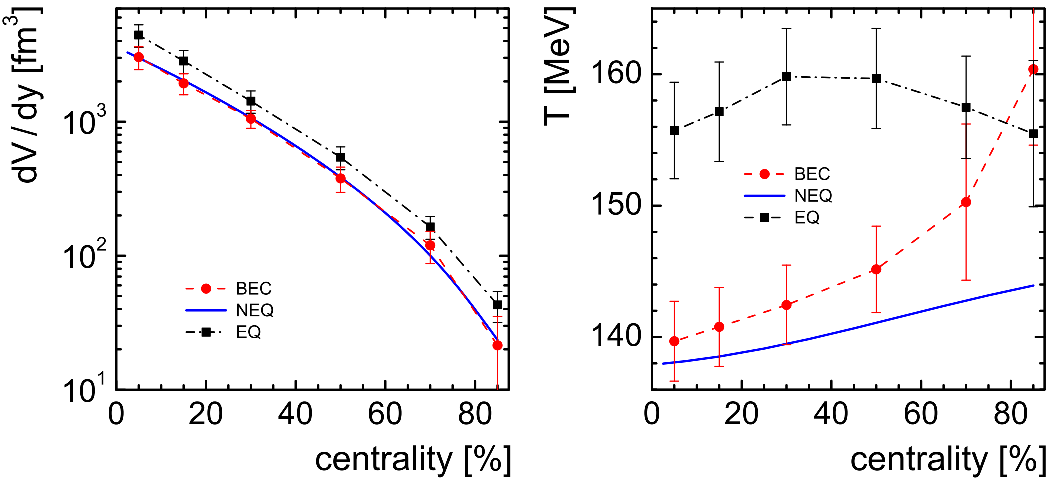

Figure 2. The non-equilibrium parameters from the paper [8], NEQ, are compared to the new fit in SHARE [31] using the equilibrium model, EQ, and the non-equilibrium model with the possibility of Bose condnsation, BEC. The left panel shows the system volume, while the right panel shows the system temperature.

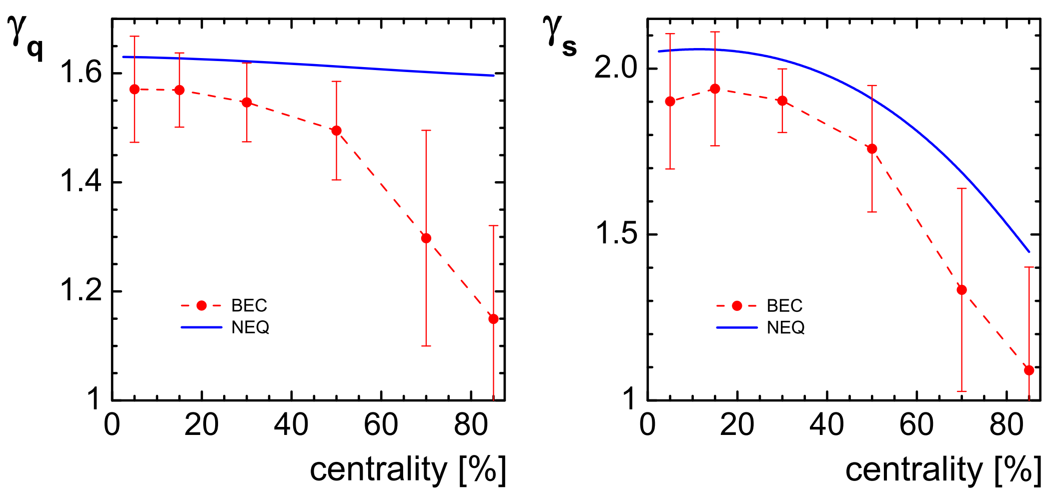

Figure 3. The same as in Fig. 2 for the γ_q and γ_s in NEQ and BEC, while in EQ $\gamma_q = \gamma_s = 1$.

pion spectrum at smaller values of p_T than those available at the moment. The same is even more important for the π^0 meson spectrum, because neutral pions condense first.

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