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Hadronization, Chemical Equilibrium and Chemical Freeze-Out

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Recent results on baryon production in relativistic heavy ion collisions show that a revision of the chemical freeze-out conditions is necessary. Particularly, there is evidence that chemical freeze-out does not occur at full chemical equilibrium. We present a method to reconstruct original hadronization conditions and show that the newly found points in the $T - \mu_B$ plane are in very good agreement with extrapolations of the lattice QCD critical line.

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The success of the statistical model fits to hadronic multiplicities in heavy ion collisions has convinced many that the so-called chemical freeze-out (the stage of the expansion where inelastic collisions between hadrons cease) occurred at chemical equilibrium. The freeze-out points in the $T-\mu_B$ plane define a curve which was shown not to coincide with the extrapolated pseudo-critical line of QCD in lattice calculation [1] at high μ_B. Thus, in a sketchy summary:

$$\text{critical line} \neq \text{hadronization} \simeq \text{chemical freeze-out} = \text{chemical equilibrium}$$

The essential identity of hadronization and chemical equilibrium stems chiefly from the evidence from elementary collisions [2] (see fig.) and from the fact that if hadronization did not occur at chemical equilibrium, it would be very difficult to achieve it through post-hadronization collisions [3, 4], in any kind of collisions. This argument was also used, in a somewhat different form, in ref. [5].

However, recent new results on $\overline{\mathrm{p}}$ production at $\sqrt{s_{NN}}$ betwen 6 and 17 GeV from NA49 experiment [6] and from ALICE experiment at the LHC [7] at $\sqrt{s_{NN}} = 2760$ GeV have shown a considerable discrepancy with respect to the predictions of the statistical hadronization model [11, 12] in relativistic heavy ion collisions, with an overestimation of model calculations of about 40%. This has led some authors [8, 9, 10] to suppose that post-hadronization rescattering plays a major role in depressing the anti-baryon yield (and, consequently, protons at LHC energy).

Particularly, it was shown in ref. [8] with a hybrid hydro+transport model based on UrQMD code [13] that hadronic collisional stage drives antibaryon ($\overline{\mathrm{p}}$, $\overline{\Lambda}$ and $\overline{\Xi}$) as well as pions out of the originally imposed local chemical equilibrium through the Cooper-Frye prescription. As a consequence, it was shown that statistical hadronization model fits with a common temperature to the measured yields could result in an underestimation of the actual hadronization temperature of about 10 MeV at the top SPS energy of 17 GeV and a lower fit quality in terms of the minimum χ^2.

As far as the actual data is concerned, the inclusion of $\overline{\mathrm{p}}$ at $\sqrt{s_{NN}} = 17.2$ GeV significantly decreases both the temperature and the fit quality compared to the previous analysis [12] within the statistical hadronization model. Likewise, at the LHC the same fit results in a quality lower than expected (see fig.). These are clear indications of a missing ingredient in the modelling of particle production and since the deviation of the data points from the model predictions closely resembles the one observed in the simulated hydro+UrQMD points, we decided to multiply the equilibrium abundances predicted by the statistical hadronization model with the correction factors obtained by dividing the multiplicities after the application of the transport stage to the pure hydrodynamical output (i.e. the statistical model in local equilibrium) by the hydrodynamical ones:

$$correction factor = \frac{hydro + UrQMD}{hydro} \tag{1}$$

for each hadronic species.

The idea behind this procedure is that hadronization, in relativistic heavy ion collisions, occurs at chemical equilibrium and that later hadronic rescatterings drives the system out of it. This picture, has as been mentioned, is borne out by numerous and long-standing observations in elementary collisions, where both strongly stable particles and short lived resonances apparently arise

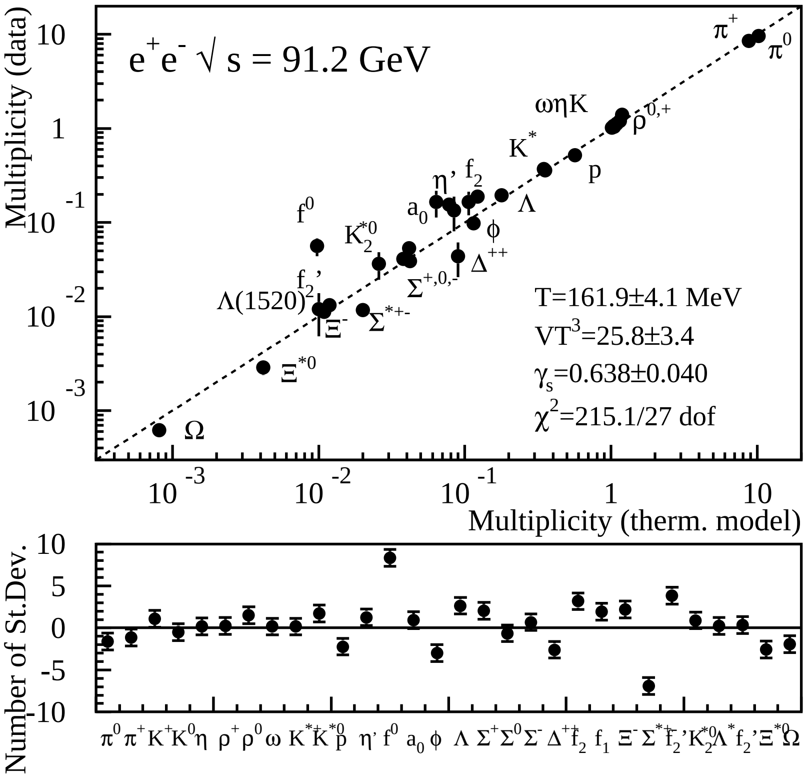

Figure 1: Fit to hadronic multiplicities in e^+e^- collisions at $\sqrt{s} = 91.2$ GeV (from ref. [2]).

from a chemically equilibrated source, with an undersaturation of strange quark phase space [2] (see fig.). The absence of rescattering in elementary collisions is owing to the small size of the emitting source; basically, all particles decouple istantaneously as they are all emitted from a "surface" (see fig.). Conversely, in heavy ion collisions, the larger size of the source entails a distinction between particles which are emitted by the expanding surface (undergoing no collision) and those which are formed within the surface, which have enough time during the expansion to collide with each other. Hence, in this picture, the antibaryon suppression is basically a geometrical effect and for a large surface/volume ratio, like in very collisions, one expects less suppression than for a small surface/volume ratio, that is in very central collisions.

The application of the correction factors at several energies enables to reconstruct the chemical equilibrium points shown in the $T-\mu_B$ plance shown in fig. which nicely follow the extrapolated lattice QCD crossover line at finite μ_B down to an energy of $\sqrt{s_{NN}} = 7.6$ GeV. The statistical model fits with rescattering corrections are in generally better agreement with the data [14] and allow to pin down the primordial chemical equilibrium conditions (*latest chemical equilibrium point*), which occur at a higher temperature compared to previous estimates.

We can then summarize these findings by saying in relativistic heavy ion collisions at high energy:

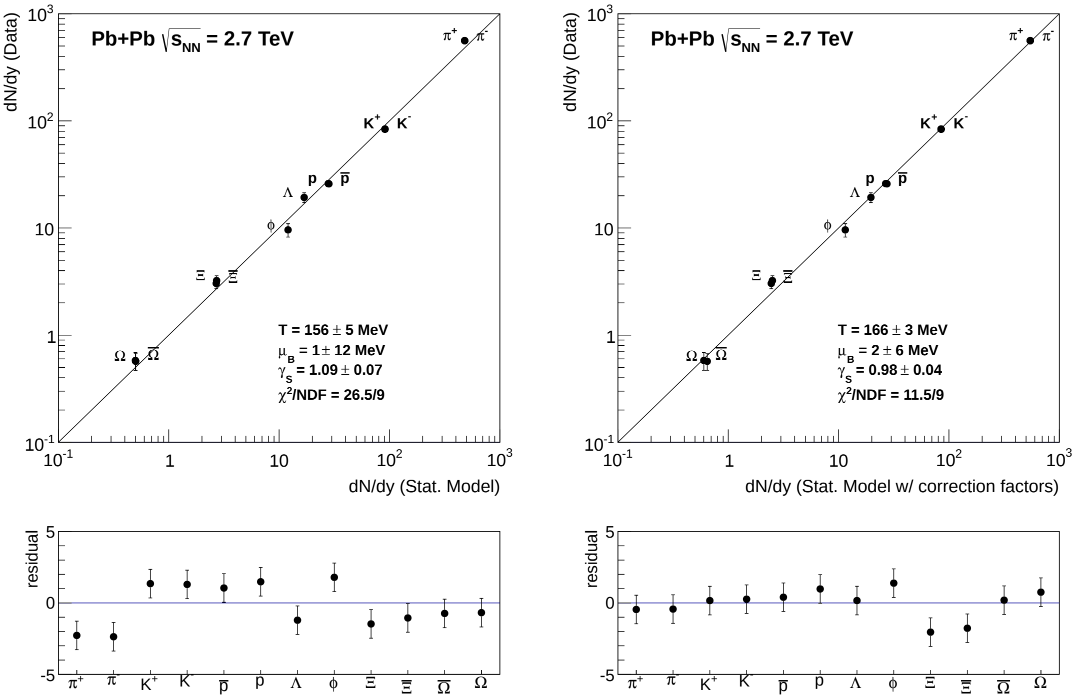

Figure 2: Statistical model fits to preliminary ALICE data for 20% central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.7$ TeV (a) and to the same data but with modification factors from UrQMD applied in the statistical model fits (b) (from ref. [14]).

$$\text{critical line} = \text{hadronization} \simeq \text{chemical equilibrium} \neq \text{chemical freeze-out}$$

unlike previously believed (see beginning of this paper). More investigations are ongoing to explore further consequences of this picture.

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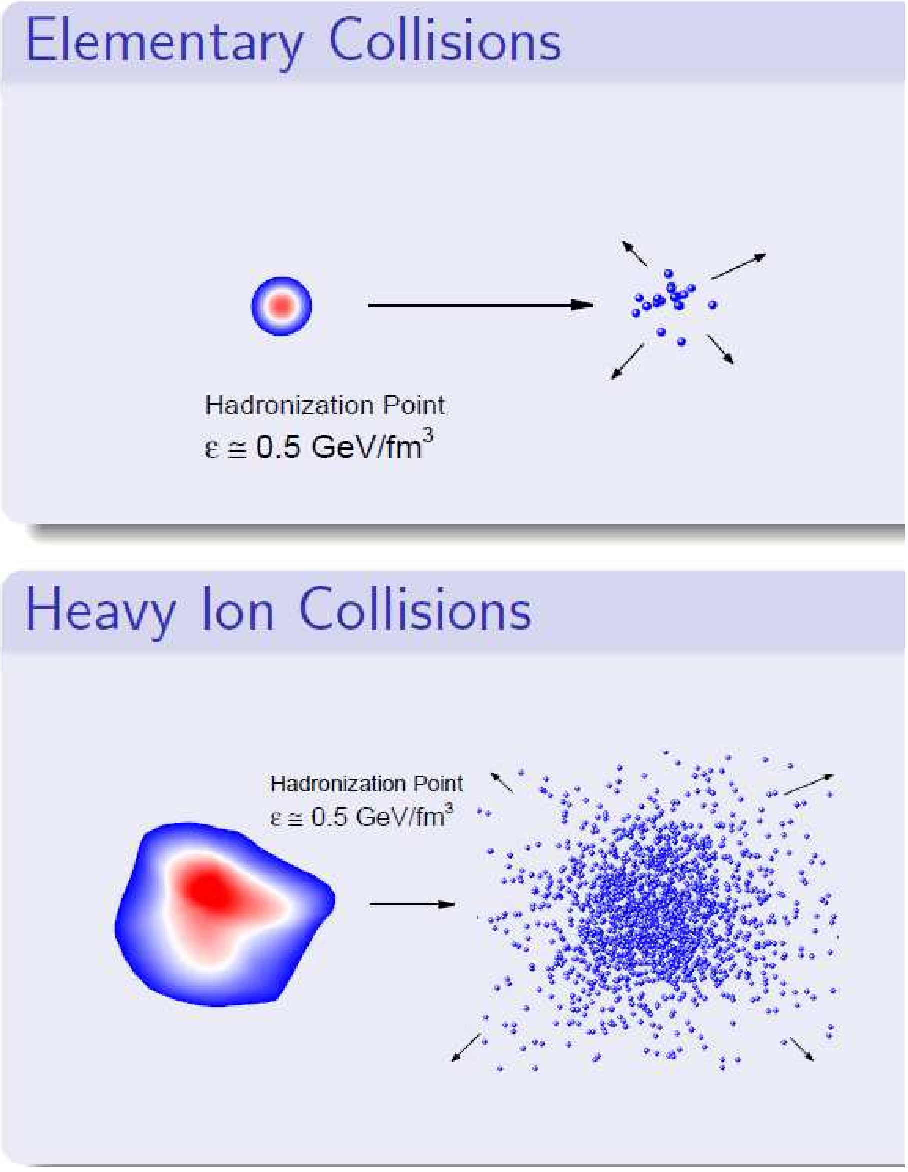

Figure 3: Geometry of elementary and heavy ion collisions.

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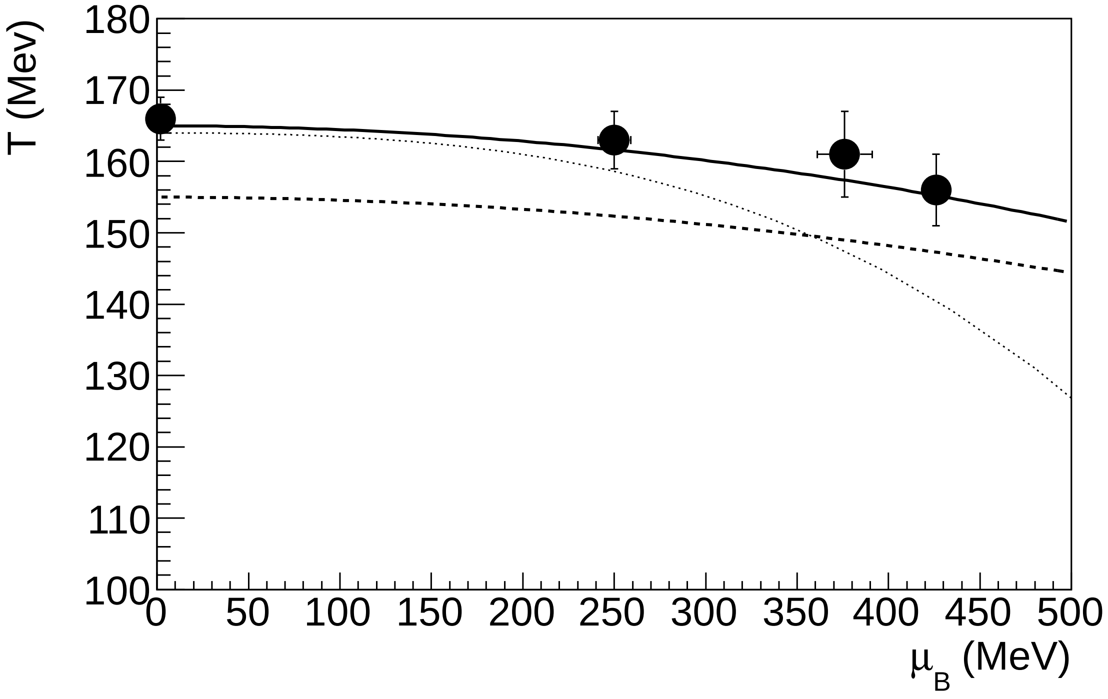

Figure 4: Phase diagram of nuclear matter in the (T,μ_B) plane with predictions from Lattice QCD calculations (solid line: based on strange quark susceptibility χ_S, dashed line: based on chiral condensate $\langle\bar{\Psi}\Psi\rangle$) [1] and from statistical model fits at SPS and RHIC energies (dotted line). The results of the modified statistical model fits of this letter are shown as closed circles (from ref. [14]).

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