arXiv:1311.4662v1 [nucl-th] 19 Nov 2013

Confronting LHC data with the statistical hadronization model

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Abstract.
The most recent data from the CERN LHC are compared with calculations within the statistical hadronization model. The parameters temperature und baryon chemical potential are fitted to the data. The best fit yields a temperature of 156 MeV, slightly below the expectation from RHIC data. Proton yields are nearly three standard deviations below this fit and possible reasons are discussed.

1. Introduction

In ultra-relativistic nuclear collisions the phase diagram of strongly interacting matter is studied [1]. One of the interesting questions is about the location of the boundary between hadronic matter and the quark-gluon plasma (QGP). Over the past 20 years the understanding has arisen, that hadron yields can be very successfully compared to a simple statistical model. For central collisions of heavy nuclei (Au or Pb) and energies $E_{lab}/A \geq 5$ GeV, the grand canonical ensemble gives an appropriate representation. The resulting parameters, temperature T and baryon chemical potential μ_b, represent the so-called chemical freeze-out. It was further realized [2] that the very high densities close to the transition temperature, when a QGP hadronizes, and the rapid fall-off of density below the transition temperature lead to rapid equilibration and chemical freeze-out only a few MeV below the transition temperature. The current understanding of the connection between the QCD phase diagram and chemical freeze-out is summarized in [3].

The statistical hadronization model was first successfully applied to data from ultra-relativistic nuclear collisions from the AGS [4] and not much later to first data from the CERN SPS [5]. Both comparisons yielded excellent agreement. Later, a much more complete set of hadron yields was obtained from the SPS experiments, including data from several energies below the maximum energy down to $E_{lab}/A = 20$ GeV. And from the year 2000 on an increasing set of hadron yields from Au+Au collisions at RHIC became available and was compared to statistical model calculations [6]. All data sofar were found to be in very good agreement with the grand canonical statistical model. For a summary see [7].

Inspecting the extracted statistical model parameters as a function of center of mass energy, two characteristic features arose: (i) The baryon chemical potential drops monotonically with

increasing energy and (ii) the temperature initially increases but appears to level off at center of mass energies per colliding nucleon pair of about 20 GeV at a temperature around 160 MeV. This led to a prediction for LHC [8] that chemical freeze-out would occur at $\mu_b = 0.8^{+1.2}_{-0.6}$ MeV and $T = 161 \pm 4$ MeV.

2. LHC data

First results of ALICE at the LHC were discussed in the framework of the statistical hadronization model in [9, 10]. Now a much extended set of published data is available as well as some preliminary data on the production yields of nuclei. A fit of the statistical hadronization model to the data currently available from ALICE at the LHC is shown in Fig. 1. The data point for K^{0*} is not included in the fit. The fit yields a baryon chemical potential of zero and a temperature of 156 MeV with a reduced χ^2 of 2.4. A fit to the preliminary data [10] was significantly worse with $T = 152$ MeV and a reduced $\chi^2 = 4.3$. In Fig. 2 the deviations between fit and data are shown. The proton and antiproton yields are under the model by 18.0 and 19.4 % which, due to the small experimental errors, amounts to a deviation of 2.7 and 2.9 sigma, respectively. The cascade yields, on the other hand, are above the model by about 2 sigma. Otherwise the agreement of data and fit is excellent. The deviation for the K^{0*} meson should be ignored; as a strongly decaying resonance it's yield can be significantly modified after chemical freeze-out.

To demonstrate the sensitivity of the model prediction to the temperature, we also show in Fig. 1 results for a statistical model calculation using $T = 164$ MeV and $\mu_b = 1$ MeV. This higher temperature increases the disagreement for the antiprotons to about 50 % and the yields of nuclei are much overpredicted. Entirely leaving protons out of the fit, the temperature would increase by 2 MeV to $T = 158$ MeV with an otherwise prefect fit with a reduced χ^2 less than one. In that sense one could talk about a proton anomaly, albeit not a very strong one (see above).

3. Comments on the proton anomaly

Already for the RHIC data there is some indication of a low proton yields as compared to the statistical model (see e.g. [10]). But due to bigger uncertainties in removing the contributions from feeding by weak decays - the published hadron yields were obtained without vertex detectors - there are deviations between experiments and no clear picture emerges.

In the following, a few arguments in connection with the close to 3 standard deviation difference of the experimental proton yields from the statistical hadronization model calculations will be made.

The hadron spectrum that enters in the statistical model incorporates all known hadronic states contained in the 2008 compilation by the particle data group [17]. It is clear that this spectrum is still incomplete, there are as of yet undiscovered states. A study was made of the effect of an incomplete hadron spectrum on the K/π ratio [18]. It was based on a Hagedorn resonance gas assumption for states above 3 GeV in mass. This was found to reduce the calculated K/π ratio by about 15 %. While a similar study for the p/π ratio does not yet exist, we would like to argue that it will also reduce the calculated ratio; high mass hadrons will contribute at most one (anti-)proton but multiple pions. In addition, results from lattice QCD predict [19] that numerous additional baryon resonances exist at low masses, partly with high spin and therefore degeneracy. Some of these states have already been found [20]. The effect of an incomplete hadronic spectrum in the statistical hadronization model is to produce relatively too many protons as compared to pions.

Alternatively, it has been argued, that annihilation in the hadronic phase would reduce the number of (anti-)protons [21, 22, 23]. Employing UrQMD to model a hadron gas after hadronization significant reductions in the yields of (anti-)protons and cascades are observed

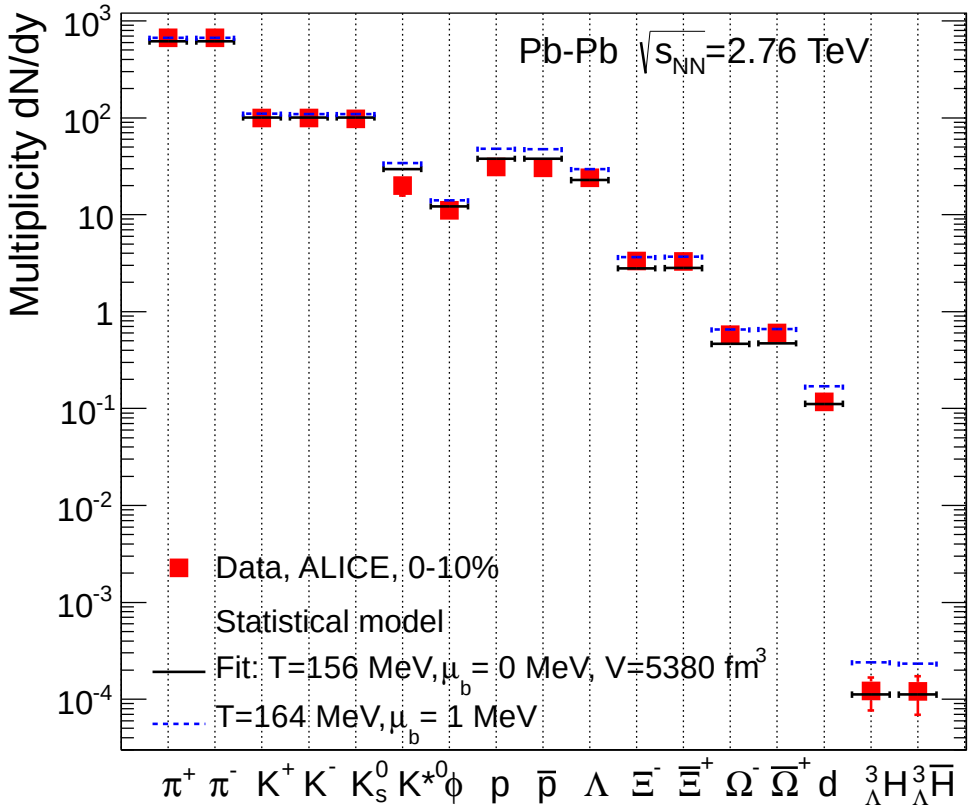

Figure 1. Hadron yields from ALICE at the LHC [11, 12, 13, 14, 15, 16] and fit with the statistical hadronization model. In addition to the fit, yielding T=156 MeV, also results of the model for T = 164 MeV are shown, normalized to the value for π^+. The data point for the K^{0*} is not included in the fit.

for the current LHC energy. This leads to a good description of the observed (anti-)proton yields. However, employing this mechanism, the discrepancy for (anti-)cascades is increased. Also, it has been noted by the authors themselves [22], that in UrQMD detailed balance is not implemented for some of the important annihilation reactions. Already in [24] it was argued, that implementing detailed balance would not lead to a depletion of the antiprotons. The effect of annihilation alone and of then in addition including the back reactions with full detailed balance was studied for full SPS energy [25] (and also AGS energy. There it was shown that the annihilation plus back reaction nearly fully compensate for central collisions reaching the equilibrium value for (anti-)proton yields. In a more recent study for collider energies it was shown [26] that properly taking into account the back reactions reduces the effect of annihilation in the hadronic phase to about one half. Here, (anti-)protons, lambdas, cascades and omegas are equally affected, making the agreement for the last 2 species worse. Another argument why one should not put too much trust in the quantitative changes of hadron yields in the hadronic phase within the UrQMD model is the lifetime of the fireball. From 2-pion Hanbury Brown-Twiss correlations an overall lifetime of the system including QGP phase and hadronization of 10 fm/c is deduced [27] for central PbPb collisions at the LHC. Coupling UrQMD to a hydrodynamics evolution the system, the integral time until thermal freeze-out is significantly longer.

Annihilation in the hadronic phase should affect nuclei as well and it can be seen from Fig. 2

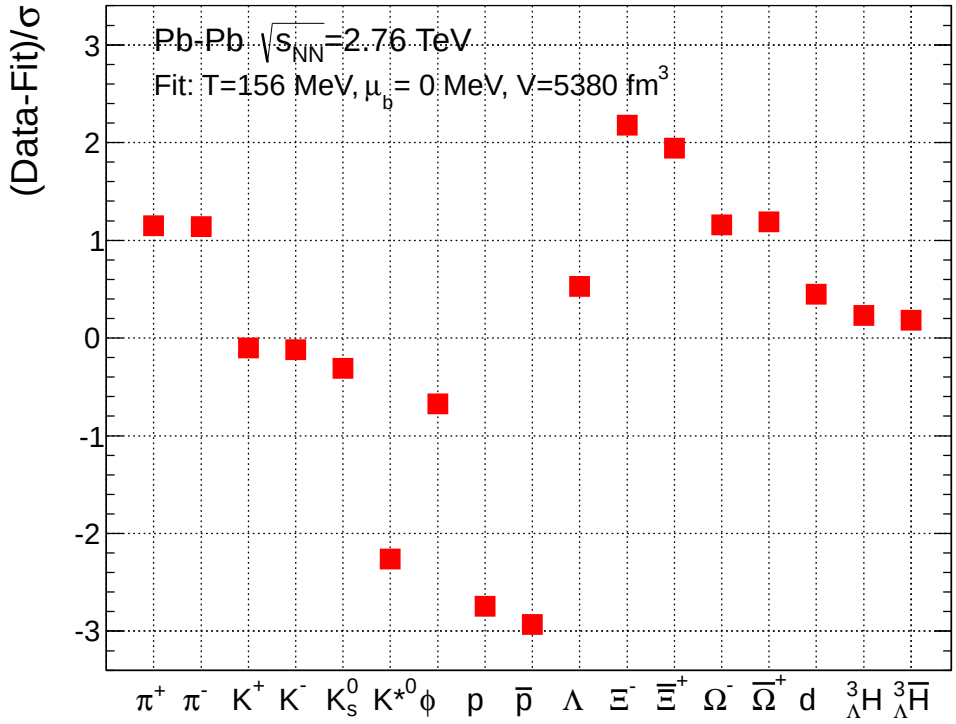

Figure 2. Deviations between thermal fit and data normalized to the error of the data points.

that they are perfectly reproduced without annihilation. One could ask, why (lightly) bound nuclei should also follow the statistical hadronization approach. This is plausible since hadronic reinteractions do not change the entropy per baryon. For much lower energies this argument was already made by Siemens and Kapusta [28] to deduce the entropy per baryon from the yields of light nuclei relative to protons (essentially the d/p ratio). It has been shown [29] that for a system in equilibrium the statistical hadronization and the coalescence approaches agree over many orders of magnitude. In fact, the statistical hadronization approach reproduces very well measured yields of nuclei for central collisions at all energies from AGS up to LHC.

A puzzle is currently the centrality dependence of the proton to pion ratio, which is increasing with centrality for the PHENIX data from RHIC and is decreasing for the ALICE data at the LHC [11]. This opposite trend does not support the annihilation picture of protons in the hadronic phase. If it is a real effect (the current significance is only at the 2 sigma level) it has currently no physics explanation.

A proposal has been made [30, 31] to extend the statistical hadronization model to include out-of-equilibrium features and according new parameters. It is therefore not surprizing that the proton yield can be brought into agreement with such a model calculation. A stringent test for this approach will be the yields of light (anti-)nuclei, since then no additional free parameter is available and they are sensitive to increasing powers of the quark chemical potential. Already the yields of (anti-)hypertriton presented here are in good agreement with the standard statistical hadronization picture employed in this contribution, while they are overpredicted by a factor of 6 in the out-of-equilibrium model of [31].

4. Conclusion

The ALICE data from the LHC pose with their small errors an unprecedented test to the statistical hadronization model. An increasing number of final data has become available over the past year. Excellent agreement with the statistical hadronization model has been achieved with exception of the (anti-)proton yields. Sofar no convincing explanation for this 2.8 sigma deviation is available. Beyond further phenomenological studies, we are looking forward to more data and in particular also to high precision data for the full LHC energy to become available in the next few years.

Acknowledgments

Support by the BMBF Verbundforschung and the Helmholtz Alliance EMMI is gratefully acknowledged.

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