



The QCD Phase Diagram from Statistical Model Analysis

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Abstract

In high multiplicity nucleus-nucleus collisions baryon-antibaryon annihilation and regeneration occur during the final hadronic expansion phase, thus distorting the initial equilibrium multiplicity ratios. We quantify the modifications employing the hybrid UrQMD transport model and apply them to the grand canonical partition functions of the Statistical Hadronization Model (SHM). We analyze minimum bias and central Pb+Pb collision data at SPS and LHC energy. We explain the Pion to Proton ratio puzzle. We also reproduce the deuteron to proton ratio at LHC energy by the SHM, and by UrQMD after attaching a phase space coalescence process. We discuss the resulting (T, μ_B) diagram.

1. Introduction

The boundary between partons and hadrons in the QCD phase diagram can be studied experimentally in relativistic nucleus-nucleus collisions. The collisional system crosses the hadronization domain/line after a preceding phase of hydrodynamic expansion and cooling. Several physics observables assume their asymptotic values at, or in the close vicinity of the hadronization "point" in the (T, μ_B) plane (they "freeze out"), notably the multiplicities of the various hadronic species. We note that no analytic model exists for the process of hadronization because the transition temperature falls well into the nonperturbative domain of QCD. One thus has to turn to QCD inspired models such as the string- or cluster-formation pictures. The latter was formulated by Amati and Veneziano[1], to describe hadron formation in electron-positron annihilation. In it, the primordial DGLAP shower evolution terminates with colour neutralization in local multi-parton singlet clusters which then decay quantum mechanically onto the QCD hadron/resonance spectrum, respecting invariant mass and quantum number conservation. This decay leads to hadron production according to statistical equilibrium via species-wise phase space weights. This highly non-trivial phenomenon has found a twofold confirmation, in a microscopic implementation in the parton-hadron transport model by Ellis and Geiger[2], and in the analysis by Becattini[3] of LEP hadron production multiplicities in e^+e^- annihilation with the statistical hadronization model (SHM) which reported a temperature of 160 MeV. The partition functions of the SHM represent the phase space weights, and the SHM analysis extracts from multiplicity data the temperature prevailing at hadronization, along with the baryochemical potential expressing conservation laws: the parameters of the QCD phase diagram.

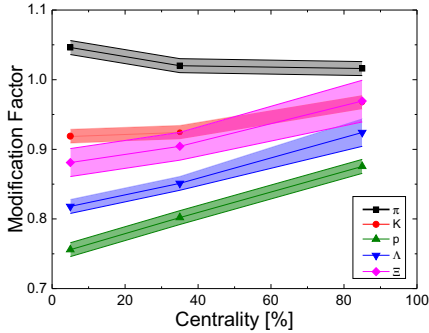


Fig. 1. UrQMD modification factors vs. centrality in Pb+Pb at 2.76 TeV.

No baryonic final state interaction can distort the multiplicity ratios in elementary collisions. However that could be different in high multiplicity central A+A collisions. We have lately demonstrated[4, 5, 6] that post-hadronization baryon-antibaryon annihilation is an important feature of the hadronic expansion phase, which drives the system away from the primordially imprinted hadro-chemical equilibrium. This implies an actual distinction between hadronization and hadrochemical freeze-out. The set of thus-created multiplicities thus develops tensions ("non thermal" ratios), and the deduced temperature changes with sub-selections of considered species[7]. The effects of the "afterburning" stage were taken into account by determining modification factors for the various multiplicities by a hybrid UrQMD transport model calculation that traces the hadron/resonance population from initial Cooper-Frye hadronization to final decoupling. These modification factors are then employed as multipliers of the corresponding grand canonical partition functions in the SHM model, thus reconstructing the "true" hadronization point. We consider the resulting, modified (T, μ_B) values as entries in the QCD phase diagram: the goal of this investigation.

We analyze sets of hadronic multiplicities from the ALICE LHC experiment, for minimum bias and central Pb+Pb collisions at 2.76 TeV, and from NA49 and E-802 for central Pb+Pb/Au+Au collisions at the SPS/AGS energies 17.3, 8.7, 7.6 and 4.75 GeV (see ref. [6] for references). At the AGS energy a sharp drop of the deduced temperature occurs. At the higher energies (lower μ_B) the curve is near flat, in agreement with Lattice QCD predictions ([8, 9]). The temperature at μ_B near zero is found to be 164 ± 3 MeV. We also include the ALICE data for Deuteron production(10) in the SHM analysis finding perfect agreement at the same temperature. Finally, in order to test the agreement between SHM and coalescence model descriptions of such cluster yields we have attached[11] a phase space coalescence mechanism to the UrQMD model and to its hybrid version, addressing both the ALICE p+p and Pb+Pb data for the D/P ratio at 2.76 TeV. This model gives an excellent description over the entire range of midrapidity multiplicity densities.

2. UrQMD afterburning and modification factors in the statistical model

As all details of the employed data and the model calculations have been extensively described in previous publications[5, 6] we restrict here to a brief overview. We studied the afterburner effects with the hybrid UrQMD hadron transport model. The hydro-evolution was stopped, generally speaking, once the energy density (or, alternatively, the temperature) falls below a pre-set critical value in the fluid cell under consideration, then calculating the hypersurface element with a state of the art hypersurface finder. Then the Cooper-Frye equations were sampled in accordance with conservation of charges and energy, and the resulting particle vector information transferred to the cascade part of the UrQMD model. The effect of final state interaction was then quantified by either stopping the calculation directly after hadronization, letting the produced species undergo all their strong decays as if in vacuum, thus establishing a fictitious multiplicity set ideally referring to the hadronization "point". Alternatively, the final afterburner UrQMD stage was attached, and the multiplicities at decoupling generated. For each hadronic species we obtain the ratio of the two respective multiplicities, the so-called modification factor. This factor got finally employed in the SHM analysis. We show in Fig.1 the modification factors for pions, kaons, protons, Lambda and Xi,

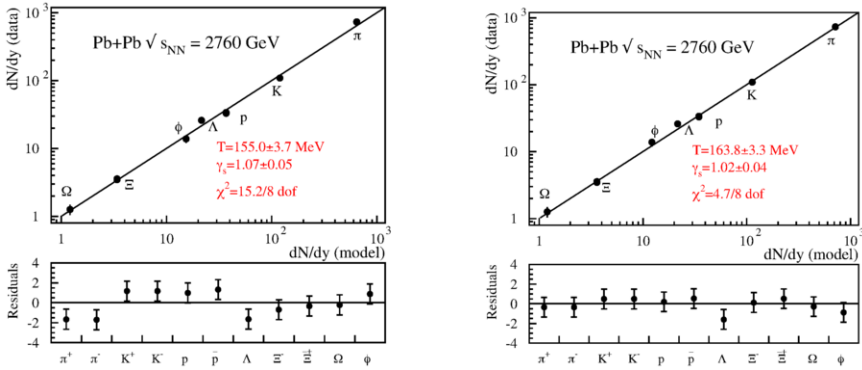


Fig. 2. Stat. model fits to central Pb+Pb data at 2.76TeV (left) and to the same data with UrQMD modification factors(right).

obtained for Pb+Pb collisions at 2.76 TeV, in a selected central, semiperipheral and peripheral centrality window, corresponding to 0 – 10%, 30 – 40% and 80 – 90% cuts in the charged particle midrapidity density distribution. One sees that the mesons remain relatively unaffected by final state effects while the baryons (and the corresponding antibaryons) are subject to annihilation losses. Not surprisingly the effects diminish toward peripheral collisions, due to a shortening of the expansion duration. The seemingly small increase of the central pion yield, of about 5%, does in fact correspond to an extra pion number of about 110, an indeed non-thermal effect which we, consequently, ascribe to baryon- antibaryon annihilation to pions. This explains the pion to proton ratio puzzle[12] of the ALICE data, almost quantitatively.

3. Data analysis

In order to illustrate the effect of the UrQMD modification factors in the SHM analysis we show in Fig.2 the SHM fits to the most central ALICE Pb+Pb data at 2.76 TeV. The left panel shows the standard SHM procedure with $T = 155 \pm 4$ MeV, μ_B being set to zero. The fit underestimates the pions and is of moderate overall quality, with χ^2/dof of about two. With UrQMD modification factors(right panel) we find $T = 164 \pm 3$ MeV, with substantially improved χ^2/dof , of about 0.5. Similar observations were made at the lower energies. The deduced temperature increases with afterburner corrections. Note that at higher μ_B the baryons do outnumber, by far, their anti-partners. Thus annihilation has a much higher fractional impact on the antibaryon multiplicities, there.

4. Deuteron production

Deuterons have been observed systematically in A+A experiments from Bevalac energies up to the LHC. They represent a tool to discuss reaction dynamics, in particular the evolution of the entropy[13]. Light nuclei can not be synthesized at the temperatures/particle densities at hadronization and during the subsequent hadron/resonance expansion period. A rigorous theoretical model is still lacking but one could see their production arise from a very last stage of final state interaction, after the end of all hadronic collision. This is expressed in the qualitative coalescence model. It has been shown by Mrowczynski[14] that the results of the SHM should agree with the coalescence model, which corresponds to the view that light nuclei are formed in proportion to the proton/neutron number density, and the entropy, both fixed at hadronization. We have implemented a phase space coalescence routine at the decoupling stage of UrQMD[11]. The new aspect of this calculation consists in the simultaneous enforcement of closeness in space, and momentum space. We show in Fig.3 the ALICE data[10] for $2D/(P+Pbar)$, equivalent to the commonly discussed D/P

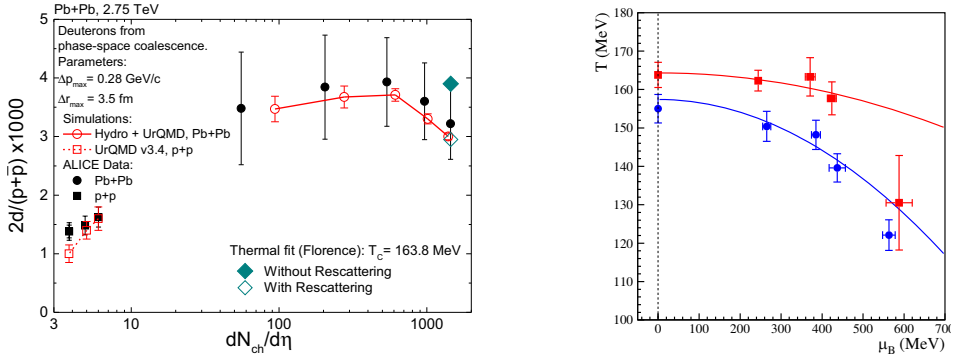


Fig. 3. Left: Fits of UrQMD with phase space coalescence, and of the statistical model to ALICE deuteron to proton ratio data[10] for p+p and Pb+Pb. Right: Reconstructed hadronization points(squares) vs. standard chemical freeze-out points(dots) in the (T, μ_B) plane, with 4 point quadratic fits.

ratio. The figure contains minimum bias data for p+p at various LHC energies and Pb+Pb at 2.76 TeV, plotted vs. midrapidity $dN_{ch}/d\eta$, compared to UrQMD calculations (version 3.4 for p+p and the hybrid version for Pb+Pb), showing perfect overall agreement[11]. The coalescence parameters (space and momentum space radii) are kept constant, throughout. Also included is our SHM result for central Pb+Pb collisions, obtained at $T = 164$ MeV. It agrees both with the data and with the coalescence calculation.

5. The QCD phase diagram

In Fig.3 we show our main result, the estimated QCD pseudo-critical line in the (T, μ_B) plane, as illustrated by 5 points, for LHC, SPS and AGS energy, respectively. The curvature is modest up to about $\mu_B = 400$ MeV; a fit with a quadratic ansatz reveals a curvature coefficient of 0.0048 ± 0.0026 , in qualitative agreement with recent lattice QCD calculations[8, 9]. The temperature at $\mu_B = 0$, deduced from the fit is 164 ± 2 MeV. This is higher than predicted from lattice QCD calculations based on various different observables such as Polyakov loop or higher order fluctuations of conserved quantities[15]. This might be a consequence of the broadness of the parton-hadron transition domain, typical of a cross-over transformation: not all observables must freeze out at the same mean temperature. We also show in Fig.3 the freeze-out points obtained with the standard SHM procedure which fall below the modification-factor corrected results, throughout.

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