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Review of the Doctoral Thesis by Rahul Ramachandran Nair entitled „A study of the imprints of thermalisation on charged particle emission using light-front variables in ultrarelativistic heavy-ion collisions"

The Thesis is aimed to study the possible presence of a thermalised medium in heavy-ion collisions at RHIC and LHC energies using the framework of light front variables. A rigorous test of the idea involving the light front variables, proposed in the late 70s, at the largest possible centre of mass energies today using the modern-day event generators such as UrQMD, EPOS and HIJING, together with ALICE experimental data from LHC to demonstrate that a thermalised medium does exist in these collisions, forms the core subject of this thesis.

The Thesis is composed of seven chapters and exhaustive list of references containing 143 items.

In the first chapter of this thesis, the author describes how the dissertation is organised introducing the remaining chapters. The main content of each of those chapters is mentioned briefly in it.

The second chapter is titled "Quark-Gluon Plasma and Heavy Ion Collisions". In this chapter, the idea of a deconfined state of matter and the attempts to study it before and after the advent of QCD is given. The discovery of asymptotic freedom in QCD, leading to the possibility of a deconfined Quark Gluon Plasma state and the possibility of producing such a system in the laboratory using heavy-ion collisions are discussed. The basic geometry and thermodynamics of the medium in such collisions are given. The idea of particles in the phase space of heavy-ion collisions getting thermalised via interactions is introduced and some of the current efforts to study this effect are briefly discussed. The Boltzmann distribution as a maximum entropy distribution is reviewed and an introduction towards the light-front-variable-based scheme in connection with the Boltzmann distributions to study the thermalisation is given to conclude this chapter. This chapter is well written. It is concise, contains well-selected information on QCD, QGP and heavy-ion collisions. It also introduces the concept of temperature in nuclear collisions and the notion of thermalisation.

The third chapter of the thesis describes the light front variable based scheme in a very detailed manner. It starts with the section on Dirac's paper on forms of relativistic dynamics and discusses how the light front form was first introduced. The light front combination of coordinates forms a mass-shell hyperboloid on which the components of momentum (p_0-p_3, p_T) define a horospherical coordinate system. The corresponding hyperboloid in the velocity space is the realization of the Lobachevsky space with constant negative curvature. The Lobachevsky geometry, its connection with the light front combination and its significance in the relativistic nuclear collisions are explained in this chapter. The invariant form of light front variable together with its properties are introduced in detail. The basic scheme followed in this study to demonstrate the existence of a thermalised group of particles in heavy-ion collisions at RHIC and LHC energies is very carefully formulated. The Author succeeds in convincingly presenting the basic features of the procedure he is going to use in his analysis.

In the fourth chapter of the thesis, a description of the UrQMD, EPOS and HIJING models are given. The proposed light front analysis is done for particles from simulated Au-Au collisions using UrQMD and EPOS models of heavy-ion collisions at a centre of mass energy of 200 GeV. A similar analysis is done for particles from simulated Pb-Pb collisions using HIJING heavy-ion collision model at a centre of mass energy of 2.76 TeV. The HIJING analysis is shown to be repeated with kinematic cuts applied to the particles to know the feasibility of this study using ALICE data from LHC. The chapter concludes with the summary of these studies and the conclusion that the light front scheme works in the phenomenological level at RHIC and LHC energies. It is shown in this chapter that irrespective of the mass of the particle and the centre of mass-energy, the author could always find a critical value of light front variable ζ-tilde which gives a constant temperature, within errors, from his fits to the kinematic distributions (polar angle, a square of transverse momentum and light front variable distributions) assuming a Boltzmannain form for the energy distribution. A comparison of the temperatures obtained from these models for various species of particles is also given. The chapter concludes by showing the intentions to perform the light front analysis with LHC data.

The fifth chapter of the thesis is devoted to the description of the ALICE experimental setup at LHC. The sub-detectors and working principle of the main detectors used in the analysis are discussed in a detailed manner in this chapter. The Author demonstrates here in deep knowledge of the numerous detectors constituting the ALICE experimental complex.

The sixth chapter starts with the description of the steps involved in the light front analysis of ALICE data. In the subsequent section, each of these steps is explained in some details. The data selection, event selection, track selection, particle identification, estimation of correction factors, and the treatment of the systematic errors are all described followed the presentation of light front analysis for pions, kaons and protons for various centralities. It also presents the light front analysis over raw deuterons assuming a flat correction factor for these particles in the kinematic region under consideration. The section titled "A Comprehensive View of the analysis and Conclusions" starts with the review of the entire analysis procedure. It is shown that the light front analysis is feasible with ALICE data despite the kinematic restrictions. The author shows that he could always find a constant value of the light front variable which divides the phase space into two. It is shown that among these two groups, one set of particles can be described by a Boltzmannian form of energy distribution using the fit results. A comparative study of the temperature thus obtained is presented for various particle species and centrality of the collision. From these studies, it is concluded that a thermalised group of particles do exist at the collisions at ALICE. The light front analysis of deuterons is shown to give a smaller temperature compared to that of protons. From this, it is concluded that the observed deuterons are formed after the protons got thermalised and later participating in coalescence mechanism with the neutrons. It is the central chapter of the Thesis. I had a real pleasure reading it.

The seventh chapter, which is the final chapter of this Thesis, gives a concise summary of the whole of this study and reviews the conclusions reached during various stages of this work.

Moving to the evaluation of the dissertation, one should say that it represents a very professionally executed detailed a study of thermalisation of various particle species emitted in high energy heavy-ion collisions. The dissertation is very well written with great care for precision and clarity. The author demonstrates accuracy in assessing results, caring for details and caution in drawing conclusions. The fits of Boltzmannian ζ, pt and cos(theta) distributions to the data are of notable statistical significance. The Author shows that the average temperature systematically increases with the mass from about 100 MeV for pions to 200 MeV for kaons and about 300 for protons and antiprotons. Only the deuterons behave differently exhibiting a temperature of about 120 MeV. The qualitative explanation of this observation suggests that those observed in the final state are produced via coalescence in the later stage of the expansion when the system sufficiently cooled down. The deuterons produced at earlier stages are disrupted due to their low binding energy. The centrality dependence of the average temperature is not strong, except for protons and antiprotons. Also, the charge dependence of the temperature was studied. The richness of the obtained information is remarkable. The obtained results are new and conclusive. The experimental findings presented in the dissertation supported with event-generator computations one allow to successfully conclude that the group of particles selected using the light-front scheme exhibits Boltzmannian behaviour supporting thus the thermalisation hypothesis. This also implies that the thermodynamic computations carried out for this group of particles become compelling.

The Author has done enormous work and presented his results in legible and attractive way. I have no objections or critical comments about the manuscript, except for a few typos that are not worth mentioning. Instead, I would like to encourage the Author to continue this study both from the experimental and theoretical side. As for the experimental analysis, it would be very important to perform a similar study for the tritium, helium3 and helium4 nuclei in the same ALICE experiment to explore the Boltzmann temperature dependence on the mass of light nuclei other than deuteron, the latter being the special case because of the small binding energy. This would require major extensions of GEANT to handle the necessary corrections, which is not easy, but certainly worth the effort. From the theoretical point of view, understanding the relationship between the horospheric coordinate system, the eminently geometrical construct, and the physics of high-energy collisions is an extremely fascinating issue.

Concluding, in my opinion, Mr Rahul Nair's Thesis meets all the requirements for doctoral dissertations and deserves the **highest grade with distinction**. I am asking, therefore, for the admission of the Author to the further stages of the doctoral procedure and the public defence of his PhD Thesis.

V. Greiner