The Henryk Niewodniczański
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

dr hab. Paweł Brückman de Renstrom, prof. IFJ PAN
Instytut Fizyki Jądrowej PAN
ul. Radzikowskiego 152
32-342 Kraków

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Referee report on the doctoral thesis by Rahul Ramachandran Nair: „A study of the imprints of thermalisation on charged particle emission using light front variables in ultrarelativistic heavy-ion collisions"

Mr Rahul Ramachandran Nair submitted for review his doctoral thesis entitled „A study of the imprints of thermalisation on charged particle emission using light front variables in ultrarelativistic heavy-ion collisions" which, in its main part, presents analysis of experimental data collected by the ALICE experiment with the goal of detecting signatures of thermalisation of the strongly interacting medium created in relativistic heavy ion collisions at the LHC.

The main purpose of the ALICE spectrometer is to study in detail properties of hot, deconfined state of strongly interacting matter – the quark gluon plasma (QGP). If asymptotically free partons are given enough time to interact they are expected to reach the maximum entropy state, i.e. undergo thermalisation. Thus, energy spectrum of such ensemble should be described by the Boltzmann distribution ($\sim e^{-E/kT}$). As a consequence, hadrons produced in the process of QGP cooling down should reflect similar energy dependence. Additionally, products of thermalisation should be emitted with spherical symmetry. It is expected, that low energy part of the hadronic spectrum emerging from ultrarelativistic heavy ion (HI) collisions would satisfy the above conditions.

Study of inclusive spectra in such collisions may appear more convenient in transformed coordinate systems. This was first suggested by Dirac in 1949 in his paper on *Forms in Relativistic Dynamics* where, among others, he proposed the "front form" where relativistic on-shell hadrons emerging from the interaction point are conveniently described in the curved sub-space of the front. Such description allows to study their momentum and energy spectra as well as the angular distributions. The approach was adopted in the presented thesis after a publication by Garsevanishvili and collaborators from 2003.

The submitted thesis, written in English, on 130 pages features seven chapters, two appendices, rich bibliography of almost 150 items and an abstract, both in Polish and English version.

Chapter 1 contains an introduction and provides the main motivation and goals of the thesis. It introduces QGP as a distinct phase of matter, manifestation of deconfinement as predicted by the QCD. It argues that Lobachevsky geometry underlying the light front variables are particularly suitable to search for thermalisation signatures in QGP, which in turn is a key stage of the Universe evolution that we can reproduce and study experimentally.

Chapter 2 provides a quick overview of physics of QGP from a historical angle. From its role in Universe evolution, through early concepts and models, the reader is introduced to QCD and modern description of QGP dynamics and HI collisions. Basic geometrical notions, the Glauber Model and Bjorken scenario of HI collisions are discussed. Finally, the temperature of hot strongly interacting matter, elliptic flow and thermalisation leading to Boltzmannian energy spectrum indicating thermodynamic equilibrium is discussed in detail.

Chapter 3 is entirely devoted to discussion of the light front (LF) variables in the relativistic HI collisions after the paper of Garsevanishvili. It starts with the general discussion of Dirac concepts. Then, an entire big section gives an overview of Lobachevsky geometry in view of using its particular realisation of horospherical coordinate system on the mass-shell hyperboloid in the velocity space. The remainder of the chapter gives a detailed discussion of LF variable ξ (or its logarithm ζ) used in the analyses presented thereafter. The procedure of fitting the ζ, p^2_T and $\cos\theta$ distributions to the functional shape predicted assuming Boltzmann energy spectrum is detailed as well. The actual choice of the ζ region for which the spectrum appears thermalized plays a central role. The ζ cut is first determined based on the quality of the fit to its distribution and subsequently applied to construct the p^2_T, and $\cos\theta$ distributions. The latter are then fitted to their functional predictions. Each fit yields a temperature which parameterizes the fitted Boltzmann distribution. The ζ cut is optionally modified until temperatures obtained from fits to the tree variables are consistent within uncertainties. Analogous procedure is defined for the case when additional bounds on p_T and pseudorapidity η are imposed due to experimental acceptance limitations.

Chapter 4 presents analysis of kinematic spectra of various hadron species emerging from different event generators using LF variables defined earlier. The UrQMD and EPOS are used to generate events at $\sqrt{s}$=200 GeV (RHIC), while the HIJING event generator is used to generate events at $\sqrt{s}$=2.76 TeV (LHC). In all cases, extraction of Boltzmann temperature with ζ, p_T and $\cos\theta$ distributions follow the scheme given in Chapter 3. For UrQMD, temperatures are extracted for $\pi^{\pm}$, $K^{\pm}$, p, η^0, Λ^0, $\Sigma(1192)$ and $\Xi(1317)$, while for EPOS and HIJING for $\pi^{\pm}$, $K^{\pm}$ and p only. Additionally, the analysis of HIJING events at $\sqrt{s}$=2.76 TeV was repeated with experimental-like kinematical cuts on the final state hadrons. Results are summarised in the last section demonstrating consistent measurement of pion temperature (~100 MeV) and that imposed additional kinematical cuts do not significantly affect resulting temperatures, the latter being an important prerequisite for the analysis of ALICE experimental data.

Chapter 5 presents the ALICE experimental setup, starting from the CERN accelerator complex and then describing ALICE spectrometer subsystems one-by-one. A separate section is devoted to particle identification using specific energy loss measured in the ALICE main tracking device, the TPC. Discussion of centrality estimation using energy deposited in the VZERO calorimeter is also of importance for the analysis performed.

Chapter 6 guides the reader through the analysis performed on ALICE data. After describing general data preparation and quality requirement, trigger and basic selection cuts, more detailed discussion is devoted to particle identification with TPC dE/dx and the related MC-derived correction factors which account for selection and identification efficiency and contamination from wrongly identified particles. A separate section lists systematic uncertainties considered in the analysis. Boltzmannian temperature is extracted using the procedure validated on generated data, with the addition of splitting data in centrality bins and considering particles and antiparticles separately. Results are obtained for $\pi^{\pm}$, $K^{\pm}$ and p as well as deuterons. Again, temperatures fitted for pions are independent of the charge and centrality and consistent with the one obtained from HIJING generator. For the heavier species divergences are larger, and temperatures observed in data are generally higher than those from HIJING. Author concludes that the temperature fitted for deuteron lower than the one for protons may indicate late coalescence of cooled down protons and neutrons into deuterons.

Chapter 7 contains summary and conclusions.

The thesis contains interesting results and is written in a particularly personal style. The author has not avoided editorial mistakes and explanations are not comprehensive in some places. Feature-rich Figures 2.3 and 2.4 are only mentioned on page 8 while deserving at least basic explanation. In description of the Bjorken scenario on page 13, right after discussion of collider physics the reader is presented with formula 2.10 which refers to fixed target collisions and this without a slightest warning. The expression for p_z is given three times (Eqs.: 3.38, 3.47, 3.50) and once (3.47) with a sign typo. Eq. 3.43 should have $p(\max)$ rather than $p_z(\max)$ in the integration limit. In Equations 3.47 and 3.48 I'd expect a tilde over ξ. I'm quoting these particular flaws as the formulae in question are central for the presented analysis. In Tables 4.1 through 6.11 presenting results of temperature fit the quoted χ^2/ndf are suspiciously low (particularly for fits to ζ). Is there a plausible explanation? Do these values play any role in the choice of the threshold ζ? In fact, the essential procedure of converging on the ζ range, and hence the fitted temperature could be better documented. The reader finds a statement about the iterative procedure where the threshold value is adjusted until temperatures obtained from fits to the three considered variables become consistent within uncertainties. What that means e.g. for fits binned in centrality, remains unexplained. The fact that for UrQMD, temperatures are extracted for $\pi^\pm$, $K^\pm$, p, η^0, Λ^0, $\Sigma(1192)$ and $\Xi(1317)$, while for EPOS and HIJING for $\pi^\pm$, $K^\pm$ and p only is not commented. Chapter 5 contains quite detailed, but rather randomly chosen pieces of information. The selection of those relevant for the analysis could be done more carefully. Section title "Inner Transition System" should probably read "Inner Tracking System". The Bethe-Bloch formula 5.2 has a problem with dimensions under the logarithm and on page 71 it is not explained how $\sigma(dE/dx)$ used for particle separation is obtained. Are Tables 4.3 and 6.1 meant to be the same? If yes, why the lower bound on pion p_T used in the HIJING analysis is zero? Also, a short justification of the applied cuts would be appropriate. Upper limits are presumably driven by the dE/dx identification, but the lower ones remain mysterious. I have trouble understanding the procedure of spectra correction based on MC estimated efficiencies ε_i and misidentification factors m_i. I suspect that in Formula 6.3 the numerator means *number of particles other than i wrongly identified as species i* while the denominator should read *number of particles reconstructed as species i*. Still, Formula 6.4 presents an oversimplification of the problem, as it implicitly assumes that particle compositions are perfectly modelled in the MC. I'd rather expect an inversion of the efficiency matrix, instead. Chapter 6 contains a discussion of experimental systematic uncertainties. Tables 6.2 through 6.4 list "systematic errors for distributions" in percent. Are these uncorrelated fractional uncertainties on per-bin content? It is not clear how they are defined, hence how they affect the measurement. Also, uncertainties due to efficiency ε_i and contamination m_i do not seem to be covered at all. Is the impact of kinematic cuts (p_T, η) assumed negligible? Finally, Appendices A and B seem little informative for an external reader.

On the purely editorial side, references are edited inconsistently using different conventions and some are not even referred to in the text (e.g.: [137], [138], [139]).

At the general level, I would appreciate a more pedagogical explanation of the benefits stemming from the use of *light front* approach in a collider experiment. It is clear that a spherically symmetrical emission with Boltzmannian energy spectrum is an expected signature of thermalisation. These are the assumptions behind integrals 3.40, 3.43 and 3.44. For a given $\sqrt{s}$ and m^2, ξ, E, p^2_T and p_z are not independent. Would the direct study of energy spectra and angular distributions lead to the same conclusions? Is there a particular interpretation of the cut on ζ? Could it be replaced by just considering particles with energies below certain cut-off? In my opinion, the section on Lobachevsky geometry (starting p. 22) while interesting per se, appears a bit over the top and does not help the reader understand the subsequent discussion.

In conclusion, despite the above-mentioned remarks, I consider the thesis addressing relevant questions of modern physics with an interesting approach. I find it meets all the formal and customary requirements for doctoral dissertations and as such I recommend it for further steps of the public defence procedure.

Paweł Brückman de Renstrom