Closing report on NKFIH OTKA K123815
(2017.09.01. - 2022.08.31.)

The project "Intelligent particle physics: the birth of hadrons" had its main aim in utilizing modern artificial intelligence (AI) methods in interpreting high energy physics experimental data, and to develop their interpretation with respect to a better understanding of the physics behind the hadronization process.

Our research activity in the 5 year period exhaustively concentrated on theoretical work. It can be divided into the following main threads:

1. Application and analysis of AI methods and algorithms.

2. Particle physics approach to hadron and quark matter at high energy density.

3. Statistical approaches on the fundamental and master equation level.

4. Application and further development of extended thermodynamics concepts.

As this chaptering shows, we have continued earlier work as well as started new methods and studied some fundamental questions. The main aim of this research project, to make particle physics phenomenology ''intelligent'' by applying AI methods, is achieved to an extent typical for beginnings and learning of new knowledge: 6 of our 64 indicated publications in this period addresses directly AI development and results (point 1 above). However more effect was realized from this by raising discussion questions and organizing and partcipating in meetings.

Further 31 from our publication list uses methods from particle physics and heavy ion phenomenology, all related to the question of high energy density and hadron binding (point 2). From the rest 13 deal with statistical model development and discussion (point 3), and 14 with extended thermodynamics
(point 4).

This report will follow the above thematic partition instead of the timeline; our activity has been organized more around these research directions than follwowing a foregiven schedule. Since the financial support was applied for and granted to support conference travel acitivity, the international stopping of such activites due to the covid pandemics in 2020-2021 made it necessary to prolongate by one year the originally only for 4 years planned project research. Also some young researchers left the project during this period (Berényi, Homor) and a few rejoined (Pósfay). A senior colleague newly joined for the last two years (Papp). All these changes were in troduced with the kind permission and agreement of the NKFIH office.

1. Application and analysis of AI methods and algorithms

This field had to be learned by us and at the same time we advanced it by raising some fundamental questions. One of our senior researcher, Antal Jakovác, originally working at the Eötvös University, during this period joined the Computationally Challenging Problems department at the Wigner RCP. A younger colleague, Daniel Berényi, obtaining PhD degree drifted to becoming a supervisor of the Graphical Processing Unit Laboratory at Wigner RCP and left our institute during the research period. Two further participants from the hadron phenomenology group (Gábor Bíró and Adithiya Mishra), and an experienced researcher joining the project for the two last years, Gábor Papp from the Eötvös University, worked on detailed numerical simulations of jet evolution and hadronization - with the supervision of Gergely Barnaföldi, an important senior member of this reserach project. The PI, Tamás Biró, ventured a publication together with Antal Jakovác about the fundamental question of entropy reduction by AI learning.

In [3] Berényi established our mathematical background for pattern based learning algorithms, as an entry to the problem of guessing propagators from numerical data points. Another important initiative by Jakovác, Pósfay and Berényi was the paper about "Understanding understanding'' in 2020. This promising but also somewhat philosophical and mathematical approach did not seem to be accomodated easily in the physics community, so no final publication coordinates can be given yet beyond the arxive [28].

Barnaföldi, in cooperation with Mexican colleagues, contributed to the proceedings of Artificial Intelligence for Science, Industry and Society [44], in 2021. This cooperation arose from our research project as a side project of TéT type, but unfortunately the covid 19 pandemic induced non-travel situation and cancellation of several scientific meetings hindranced its pace.

A genuine application of deep learning method for heavy ion collision phenomenology is presented in a publication in Physical Review D in 2022 [54], with the co-authorship of Barnaföldi. Here the elliptic flow coefficient was extracted from data by utilizing deep learning methods.

Another basic research type article occured as a fruit of discussions about the fate of entropy during a machine learning selection process between patterns, published in 2022 [64], authored by Tamás Biró and Antal Jakovác. Here a mathematical proof is given and an interpretation of the AI learning process is established to demonstrate the decrease of entropy during learning. It was guessed all the time, but the details of such a decrease were not explicitly shown.

In [53] Papp et al applied the transfer learning technique with a domain adversary neural network to find the transition point of a 1+1d directed percolation and a 2d site percolation model with a minimal amount of annotated data and found a better reconstruction than in supervised learning models.

Summarizing our activity in directly implementing AI deep learning methods proved to be a worthy beginning. Since it was new for us, its full potential can be developed further in the forthcoming years, well after the closing of this particular supported project.

2. Particle physics approach to hadron and quark matter at high energy density

Birth and behavior of hadrons at extreme high energy density and short time was studied in this program with field theoretical methods.

Chiral effect studies by Jakovác, Kaposvári, Patkós, Berényi and Lévai [1,2], as well as numerical field theory simulations with classical Hamiltonians on lattice [6] by Homor and Jakovác were carried out in the first year. Then bound states were investigated using functional renormalization techniques by Jakovác and Patkós [15]. A book about the emergence of temperature dynamically in field theory, not given as an outside condition, was co-authored by Tamás Biró and Antal Jakovác [25], and appeared in 2019 by Springer. Two-particle states and binding were studied in a particular field theory model of chirality by Jakovác and Patkós in [26] and revisited in 2021 [42]. Fejős and Patkós determined the field dependence of the Yukawa coupling [45], and studied mesonic fluctuation effects on the axial anomaly at finite temperature [51]. The radiation back-reaction in axion electrodynamics was also targeted by Patkós in 2022 [49].

On the other hand statistical approaches based on non-extensive thermodynamics was studied and applied to experimental hadron spectra in several publications. Here a smaller group (Gergely Barnaföldi, Gábor Bíró, Tamás Biró) collected experimental data from LHC and studied single particle energy and transverse momentum spectra, in order to check theoretical ideas about the origin of the Tsallis q parameter beyond the temperature [4,5]. This activity was connected to parton model and jet fragmentation studies, simulations and simulation software development, too [16-18,21,31].

More QCD phenomenology connected works on hadronization and quark-gluon plasma (QGP) equation of state were also published during the project period. Biró and Schram in [14] determined the entropy production during hadronization of a QGP. Scaling propreties in jets were studied by Barnaföldi in [41] and a quantification of an underlying event in pp collisions in [43,48,59]. These are important in understanding small system effects, in particular those occuring as deviations from the canonical approach applied to large systems. A revisiting of the stringy thermal model approach was presented by Tamás Biró in 2022 [61].

Seeking for the physical meaning and origin of the Tsallis parameter, q, statistical and master equation level models and calculations were developed by Tamás Biró, Gábor Bíró and Gergely Barnaföldi where a connection with particle number and temperature variation in systems with finite heat containers could be pointed out as a measure and physical source of non-extensivity.

Related to the hadronization problem is the research of the nuclear equation of state, not only at high temperature, but also at high pressure. Neutron star model calculations were contrasted with data in works by Barnaföldi, Pósfay and Jakovác [7,22,27,29,32,50].

3. Statistical approaches on the fundamental and master equation level

An important theoretical branch of this research about AI method supported investigations of the hadronization process is connected to statistical physics. Interpretations in terms of non-extensive thermodynamics as well as development and application of master equation level approaches have a relevance beyond the particular problem of hadronization and in fact has been probed in further areas of interest, too. We developed the local growth global reset (LGGR) model by Biró and Néda and applied it to wealth and income distribution data in [39,46,52]. That distribution namely is the same as the Tsallis distribution in hadron spectra, in general referred to as Tsallis--Pareto distribution.

More fundamental questions arise by studying energy distributions which are not exponential and/or occur in systems far from thermal equilibrium, even if they come close to an exponential. A fluctuation in the dimensionality of the n-particle phase space, constrained by only the total energy as in the microcanonical approach, leads to an interesting interpretation of the q parameter as a scaled variance, <n(n-1)>/<n>^2. Such distributions can be obtained as stationary solutions to a generalized entropy formula, promoted by Tsallis and others. The underlying (event by event) fluctuations or the fireball evolution in the hadronization process intermitted by re-heating steps back to quark-gluon plasma (QGP) droplets can be modelled by master equations. Combining these two approaches we have studied some fundamental issues, like the entropic distance measure in [11,38,47,60,62]. General issues related to the LGGR model and a nonlinear master equation approach connected to a generalized entropy formula were also studied by Tamás Biró in [13,63].

The entropic distance and a connection to the wealth inequality measure, called Gini index, lead us to construct the quantity gintropy. We have shown its entropic properties and its use in studying fat tail distributions in [11,23,24,36,38,47,60,62]. The study of gintropy and its generalization to f-gintropy is a by-product of investigating generalized entropy formulas for establishing non-Boltzmannian single particle energy distributions occurring as a result of pp and heavy ion collisions at RHIC and more at LHC energies.

4. Application and further development of extended thermodynamics concepts

As already argued in point 3, the extension of thermodynamics to treat finite container effects and non-equilibrium phenomena initiated a number of theoretical investigations on it. Our activity, connected to intelligent particle physics, lead to study dissipative hydrodynamics, in particular the relativistic heat conduction problem. Including these calculations among others, Péter Ván has defended his DSc degree at the Hungarian Academy of Science during the project period.

Heat transfer was adressed in [8,10,30,34,35,40,55,57] by Ván and collaborators. Here an emphasis was given to study deviations from the classical Fourier law - a pendant of considering non-Gaussian fluctuations in non-extensive statistical physics related to hadronization. Also black hole thermodynamics was addressed by us from the thermodynamics viewpoint: a mechanical work term supplement to the Bekenstein--Hawking approach, as well as a use of Rényi entropy resulted in a stabilization of the equation of state. The volume term, associated to the pressure, in this case turned out to be the Rovelli volume, which scales like the spacetime region covered by a totally evaporating black hole (with the fifth power of the size, R^5) [12,37].

Last but not least, due to the pioneering studies by Ván and Abe, our theoretical effort went beyond Newtonian gravity and extended it on the ground of thermodynamical arguments [56,58].

There remain quite a few publications, supported also by this project, which cannot be connected to the original title, but proved to be interesting for our researchers [9,33]. Judging the seeming diversity of topics in the theoretical physics research leaning on a rather narrow objective when planning, we think this is a natural diffusion of research. All the senior (and to good part also the junior) participants were involved also in other publications, where this project was not named in the acknowledgment of funding parts. These are not listed in the accompanying publication list.

Summarizing, we deem this project is closed with success: we have developed new methods, pioneered applications of AI algorithms and met methodological as well as a few fundamental questions in thermodynamics and statistical physics to deal with. We have enjoyed these efforts and thank the NKFIH for supporting our activity.