# Research report on the consortial NKFIH/OTKA projects K 104260 and K 104292

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# General evaluation

The project "Particles and intense fields" aimed at reaching advances in the description of hadronization in high-energy accelerator experiments on the basis of studying both the statistical and thermodynamical aspects of ensembles of long-range correlated particle systems with fluctuating number of particles and energy, and the coupling and interaction of such systems with intense fields. We have organized our efforts around three main ideas and research subgroups accordingly: i) at the Wigner RCP Heavy Ion Group we utilized the expertise present in theoretical model making for hydro- and thermodynamical aspects of relativistic, strongly correlated matter, applying the novel non-extensive statistical approach; ii) at the Wigner RCP Theoretical Solid State and Optics Group we counted on decades long experience in the mathematical handling of strong field and particle systems, also relevant for the extreme light infrastructure (ELI) still to be completed in Szeged, Hungary, iii) and also the Nonperturbative Field Theory Research Group at the Department of Atomic Physics of the Eotvos University, Budapest, having collected serious knowledge on functional renormalization and field theoretical phase transition and symmetry breaking issues.

Our research was very successful in each of the above described areas, resulting altogether in about 80 publications in various professional journals. All of these publications were being made open access by archiving a content-identical copy of each on the arxiv.org. Beyond the successful advances inside the subgroups of this consortial research we have put emphasis onto the close collaboration, too. From the organization of common discussions at the beginning, named Wigner–Eotvos Education Circle, through our strong involvement in organizing and presenting fresh results at the yearly ACHT (Austrian-Croatian-Hungarian Triangle) meetings, and completing with the Nonperturbative Seminar Series, held at the Eotvos University we have initiated various fori for the exchange of ideas and oppinions closely related to our research goals involved in this project.

As a result also quite a few common publications originated in these discussions. Alone a common article with the project leader heavy-ion group and the coherent optics group could not be finalized in this initial research period of four years, since the distance between the methods and mathematical techniques in this case was the largest in the project consortium. However, some fundamental ideas to begin with are included in a review article, co-authored by the consortial subproject leaders Biro and Jakovac, and appearing at the end of the reported research period.

## Particular achievments

We started our research on statistical models of hadronization with the idea of applying non-extensive statistical physics formulas to experimental data. Beyond this, since the non-extensive approach has been being debated for long by some particle physicists, we were interested in understanding the origin of non-extensive effects in heavy-ion and elementary pp collisions at high energies. The cut power-law shaped functions to the experimental transverse momentum distributions have been fitted for long, albeit without any attempt for a physical interpretation of the fit parameters. The folklore was that "QCD explains everything", and some opinions went so far, that the power-law tailed shape would stem from propagators. Based on our studies, this is not the only contribution.

During our researches in the supported period we understood that the leading order corrections due to finiteness of the environment, statistically acting as a heat reservoir, causes the particular distribution of temperature fluctuations which are compatible with the observed Tsallis-Pareto distribution in the single hadron energy. More closely we have derived a formula, first for ideal gases, then more generally - solely based on Einstein's formula for the connection between the occupied phase space and entropy. Our formula interprets the temperature, $T$, and the Tsallis parameter, $q$, in a unified treatment. In the retrospective view of our results it has been revealed that any deviation of $q$ from the classical Boltzmann-Gibbs value, 1, is due to an interplay between the finite heat capacity and the variance of the average kinetic energy event by event. We have further investigated fits to experimental data, figuring out whether a radial flow can be present in *pp* collisions and how would a valence quark number scaling possibly appear in the observed hadron spectra. Indeed we have discovered first in the world that meson and baryon yields in the Tsallis-Pareto fit gather on unified curves when using the local kinetic energy variable, $m_T - m$, on RHIC spectra and these two curves unify if counting the valence quark content. Analyzing identified hadron spectra in a wide energy range from SPS to LHC we uncovered a QCD-like energy scaling of the Tsallis-Pareto parameters $q$ and $T$. We have started to develop a new parton fragmentation parametrization, based on these results. Unfortunately, however, we are not yet able to exclude concurring interpretations, here further research is necessary.

Having learned that the seeming temperature in spectra, with non-exponential tail better viewed as average kinetic energy per degree of freedom, is connected to the distribution of the number of hadrons produced in elementary collision events, we turned to a more dynamical view of the statistical hadronization. On the one hand we investigated classical field dynamics, and found that it is able to produce a radiation with energy quantum distribution reminding to temperature and flow effects (akin but not identical to the Unruh temperature caused by accelerating a monochromatic source), and on the other hand we analysed dynamical models leading to stationary states without fulfilling a detailed balance condition. These more recent works revealed applications to other phenomena in complex system statistics, like scientific citation distributions, income distribution, degree distribution characterizing network connectivity, still including models of hadron number distribution.

Related to the Unruh-like effects, but also triggered by an inner logic of understanding the emergence of temperature in dynamical field theory, an analysis of local energy density fluctuations has been performed on a numerically simulated, classical lattice field theory simulation. Here also the Tsallis-Pareto distribution dominated this distribution for a very long time, not converging to the commonly assumed exponential in the local energy content. For the non-interacting case, as a baseline comparison, of course the exponential distribution has been recovered. During the study of the appearence of nontrivial (non-Gaussian) renormalization fixed points in field theories we have established the existence of such points in fermionic field theories without boson fields.

Searching for the physical mechanism(s) behind non-extensive effects in strongly interacting field theory we have focused our attention lately to the non-particle like spectral functions, signalling of-mass-shell quantum effects. By doing so we have clarified that in producing a quark-gluon plasma in hadronic collisions and producing a much higher number of hadrons in the final state as collided such effects must cause a washing out of the sharp temperature value, unlike so far assumed in theoretical approaches to thermal and lattice field theory. Whether such a mechanism, causing non-Gaussian temperature distribution, would correspond to the yield of non-Poissonian number of hadrons distribution, as our paralel statistical studies may suggest, is a question postponed to future research along these lines. A suspicion, based on looking for mathematical techniques to reconstruct non-hermitic Hamiltonians from non-Poissonian, especially negative binomial, coherent states in quantum optics, can be already formulated, but it needs some years of further theoretical investigations yet.

This last mentioned problem is related to the question of defining a useful and usable phase operator for the quantum states, especially in the presense of intense fields, when the observed degree of freedom is part of an open system. We have achieved important intial progress also in this field, as the attended publication list witnesses this statement.

# Education and Qualification Upgrades

Several of our young rsearchers have passed qualifying exams and obtained higher educational or scientific degrees.

Károly Ürmössy reached the PhD degree qualification in 2013 at the Eotvos University. He received two offers for postdoc and finally has chosen to join to a Chinese Research Institute as postdoc. Nevertheless - with the special permission of the chairman of the Physics Jury at OTKA - he continued collaborating with our group on the research topic of non-extensive statistical approaches to the parton fragmentation.

Miklós Horváth has obtained PhD degree with "summa cum laude" qualification at the Eotvos University in 2016. He received his first postdoc offer from Central China University, Wuhan, China.

Zsuzsa Szendi, Péter Pósfay, Szilvia Karsai and Gábor Bíró were granted physics MSc degrees and were succesfully promoted to become students of the Physics PhD School at the Eotvos University. Ádám Takács successfully surpassed the exams for obtaining the BSc degree and continues his studies as physics major.