Systematic investigation of the strongly interacting matter from SPS through RHIC to LHC energies

Project closing report for NKFIH grant FK123842–FK123959

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# 1 Introduction

The quest of physics for understanding the fundamental properties of matter is as fervent today as it ever was. The strong interaction—described by Quantum Chromodynamics (QCD)—is responsible for confining quarks in hadrons, as well as for most of the mass of hadrons and hence of the visible part of our Universe. A forefront of contemporary particle physics is to unveil the rich phase structure of QCD. It turned out that at small baryochemical potentials, strongly interacting matter has two thermodynamical phases: "ordinary" hadronic matter and Quark-Gluon Plasma (QGP). In the first microseconds of the existence of our Universe, space is thought to have been filled by QGP. In the last 50 years, heavy ion accelerators and experiments were constructed, starting from the Berkeley Bevalac through BNL AGS, CERN SPS, BNL RHIC, and CERN LHC, in order to discover the QGP. The existence of the strongly coupled QGP (sQGP) is now an established fact. However, the quest for the detailed structure of QCD phase diagram is just as intriguing if not tantalizing as was the rush for the QGP. New facilities (FAIR, NICA, J-PARC HI) and new programs at RHIC and at SPS are initiated for characterizing the phases of QCD, by systematically varying the size and collision energy of the nuclei. In this project we joined this effort by performing various measurements in NA61, STAR, PHENIX and CMS, as well as phenomenological and theoretical calculations to contribute to this effort. Our participation in multiple conferences with many senior and junior colleagues resulted in a large number of proceedings publications, some in refereed journals. Unfortunately many of our conferences in 2020 and 2021 were cancelled (in particular the conference most important to us, the normally annual Workshop on Particle Correlations and Femtoscopy, WPCF).

# 2 Results

Our research covered by the project was a synergy of experimental data analysis (mostly Bose-Einstein correlations), phenomenology (mostly hydrodynamical approaches of describing the strongly interacting matter), as well as close-to-hardware experimental methods (detector development). Correspondingly, our results span various topics from femtoscopy and flow through fluctuations to critical phenomena and analytic hydrodynamics, including "exotic" results related to an Aharonov-Bohm-like effect and general relativity with spin-polarized light-ion beams. We detail all of these in this section, in separate subsections.

## 2.1 Femtoscopy measurements

We performed a detailed PHENIX measurement of the two-particle Bose-Einstein correlation strength, as a function of transverse mass (from 228 to 871 $\mathrm{MeV}/\mathrm{c}^2$), in $\sqrt{s_{NN}}$=200 GeV Au+Au collisions. We found the data to be describable with correlation functions calculated from Lévy sources. The Lévy exponent alpha was found to have a weak transverse mass dependence, and take values around $1.1-1.2$, far from the usual Gaussian case of $\alpha$=2, as well as the conjectured region below 0.5 to appear at the critical point. We found a significant decrease of the intercept parameter $\lambda$ at low values of the transverse mass, not inconsistent with predictions based on an in-medium modified $\eta'$ mass. We found the source scale parameter $R$ to depend on transverse mass as predicted for Gaussian radii by hydro, noting that there were no predictions from Lévy source scale parameters. Surprisingly, we also found an unpredicted, empirical new scaling variable $\hat{R}$ to appear. Its clear linear scaling with $m_T$ is still to be explained. The final data were published in [1].

As planned, we worked in the PHENIX experiment towards measuring the excitation function of the Lévy exponent and the Lévy parameters of the hadron emitting source in heavy ion collisions. We achieved preliminary for several new results, related to the centrality and collision energy dependence of Lévy-femtoscopic correlations, as well as multi-particle correlations, and multi-dimensional correlations – all of these are extensions of the first PHENIX paper on this subject, mentioned in last year's report. In particular, we measured the threepion femtoscopic correlations in 0-30$\%$ centrality Au+Au collisions, and found that pion production is compatible with the chaotic (thermal) production and the core-halo model. Members of our group published several papers in proceedings volumes about the new (preliminary) results, in the fully peer-reviewed, impact factor journal Universe, Acta Physica Polonica B Proceedings Supplement and others [2–11]. Our centrality dependent analysis is finalized, and the paper is currently under preparation and review within PHENIX, with Sándor Lökös leading the Paper Preparation Group. It will include interesting new results about the centrality dependence of the $\eta'$ in-medium mass modification. It is expected to be submitted for publication and to arXiv in the next months.

We also achieved new results about kaon Lévy HBT, which show that the stability index $\alpha$ of kaons is comparable to that of pions, which requires a new understanding of the origin of Lévy distributed sources in heavy ion physics: if anomalous diffusion would have caused them, then kaon exponents would have been smaller (i.e., kaon sources would have a longer tail), due to their smaller scattering cross-section. New simulations and phenomenological calculations are currently underway. The preliminary results have been presented at Quark Matter 2022 and will furthermore be presented at the most important relevant conference, WPCF 2022.

As PHENIX is not participating in the Beam Energy Scan II program, we joined also the STAR experiment, and obtained the first preliminary results [12], indicating that correlation functions from Lévy-shaped sources are compatible with the larger statistics dataset of the STAR experiment. Further results on kaon Lévy HBT radii were obtained and presented at Quark Matter 2022. These will also be presetend at WPCF 2022.

A non-Gaussian HBT analysis of 0.7-9 TeV pp, pPb and PbPb data at CMS was performed, finished and published [13]. The extracted radii of the particle emitting source (via Bose-Einstein correlations) are in the range 1-5 fm, reaching highest values for very high multiplicity pPb and PbPb collisions. The pp and pPb source is elongated in the beam direction, while in the peripheral PbPb case the source is symmetric. The dependence of the radii on the multiplicity and $m_T$ factorizes and appears to be less sensitive to the type of the collision system and center-of-mass energy. The observed similarities may point to a common critical hadron density reached in the collisions. We also obtained results on HBT in 13 TeV pp collisions [14], and they yielded interesting results in the sense that pp collisions at this energy show phenomena similar to ion-ion collisions (such as signs of transverse flow), and at very high multiplicities, saturation-like phenomena were observed.

Furthermore, a multiparticle correlation analysis of 5.02 TeV PbPb data in CMS was performed, and the first results were presented on a poster at the CMS Week. Subsequently this analysis was approved preliminary and a CMS report was published online [15]. The corresponding paper, detailing the two-particle results is currently under review in CMS and is expected to be sent to publication and uploaded to arXiv during the summer. In this analysis the geometrical interpretation of the Lévy $R$ parameter was confirmed by investigating its dependence on initial collision system size. Furthermore, a linear dependence of $1/R^2$ with the transverse mass ($m_T$) was found, consistent with a hydrodynamic scaling even in the case of Lévy sources. We also estimated that the Hubble constant of the QGP created in 5.02 TeV PbPb collisions is between 0.12 c/fm and 0.18 c/fm. We found the $\alpha$ parameter to have little, if any, $m_T$ dependence and to range between 1.6 and 2, increasing with centrality. Altogether, these results implied that the hadron emitting source in 5.02 TeV PbPb collisions can be described by Lévy distributions in a statistically acceptable manner.

In NA61/SHINE, identified pion pair correlations were measured in Be+Be and Ar+Sc collisions, and were found to be compatible with previous, hadron-hadron correlations. Our femtoscopic results indicate that there might be an important difference between the $\lambda(m_T)$ distribution going from SPS to RHIC, and this was suggested to be connected to the onset of partial UA(1) symmetry restoration. Proceedings papers were published on this topic [16–19]. A regular journal publication is currently under review within NA61, and is expected to be submitted for publication during the summer.

Finally, let us note that our group also investigated Lévy-femtoscopy in e+e- correlations, with the reanalysis of published data, in a proceedings publication [20].

### 2.2 Phenomenology of femtoscopy

In terms of phenomenological investigations of Lévy femtoscopy, we published papers [21,22] about the Coulomb effect in femtoscopy, this became important in our measurements detailed above as well; in particular, this calculation was utilized in PHENIX, STAR, CMS and NA61 measurements as well. We worked on further calculations related to the Coulomb-interaction [23], and this calculation showed that in case of femtoscopic measurements in the Longitudinally Comoving Frame, a new type of Coulomb-treatment is necessary, in particular the source radius tensor $R^{\mu,\nu}$ has to be boosted to the Pair Comoving Frame. We utilized this important finding in subsequent experimental analyses.

We developed a new method to calculate the effects of the strong interaction in case of Lévy sources [24]. In the same work, we found that the effect of strong interaction on pion-pion correlations is non negligible when it comes to recent precise measurements. Hence for an adequate description of the measured correlation functions, the effects of the strong interaction may have to be taken into account.

We also started to investigate the shape of the femtoscopic correlations in simulations, and the first results indicate that at high collision energies, resonances and rescattering may be contributing for the departure from Gaussian shapes [25,26]. These works provide important background when understanding and interpreting the shape and strength of femtoscopic correlations.

We furthermore calculated the effect of the random field produced by the final state hadrons on the particularly investigated boson pair in femtoscopic calculations [27]. These results shown that this "Aharonov-Bohm-like" effect may also be important when explaining the pair momentum dependence of Bose-Einstein correlation strength.

Related to forward femtoscopy, we connected Lévy distributions and imaging techniques applicable in femtoscopy to the field of proton-proton elastic scattering. It was rather surprising that the technique that members of our group have developed for femtoscopy, namely the systematic investigation of the deviation from the Lévy shape with the help of a complete orthonormal set of Lévy polynomials found much more significant applications in elastic collisions of protons at high energies as compared to the investigation of the Bose-Einstein correlations in high energy multi-particle production processes. This is due to the pronounced dip-bump (diffractive interference) structure in elastic collisions, which indicates a significant deviation from the Lévy-like diffractive cone, and a strong first-order non-Lévy behavior, while in the Bose-Einstein correlation functions in multiparticle production processes, the first-order corrections to the Lévy shape are found to be vanishing within the experimental errors in the PHENIX Au+Au data sets that we have investigated. In elastic proton-proton collisions, the Lévy series expansion technique led to a statistically significant signal on proton hollowness. Another unexpected outcome of this line of investigations was the discovery of a statistically significant signal of Odderon exchange from the scaling analysis of elastic proton-proton and proton-antiproton scattering data. This observation of Odderon exchange at LHC energies was confirmed and its statistical significance has been enhanced with the help of a real extended Bialas-Bzdak model. [28–37]

### 2.3 Results on hydrodynamics and flow

As part of our research in hydrodynamics and transport properties, we used a hydrodynamic solution to simultaneously describe RHIC and LHC data on pseudorapidity distributions. We drew consequences on the initial state, in particular the initial energy density. Our results indicated, that a Quark Gluon Plasma droplet may also be formed in LHC p+p collisions. The results were published in [38,39].

In addition to this, we found accelerating solutions of perturbative hydrodynamics, describing deviations from Hubble-flow. We calculated observebles from this new solution, and found small deviations from calculations based on Hubble-flow. [40]

We also investigated rotating solutions to describe the observed polarized baryon production, and this resulted in the first analytic calculation on this hot topic [41]. Our results will help to disentangle various sources of baryon polarization: fluid vorticity, temperature gradient and accelerating flow. It will furthermore help in understanding the discrepancies between numerical hydrodynamic calculations and polarization measurements.

A subsequent result was made possible by the observation that Hubble-flow is an ideal testing ground for bulk viscous hydrodynamics, since shear viscosity (and in some cases heat conductivity as well) cancels. We found several different classes of solutions for different assumptions on bulk viscosity. [42–44]. This we think is an extremely important results, as it moves the field of viscous hydrodynamics in the domain of analytic hydrodynamics, and will help understanding many viscous phenomena. The new solutions with bulk viscosity furthermore generalize the analytic solutions of relativistic hydrodynamics for an arbitrary temperature dependent speed of sound, shear and bulk viscosity, heat conduction and fluctuating initial temperature profiles. The obtained solutions are causal and not only stable but also asymptotically perfect. In connection to this, we extended the available hydro models to describe rotation and arbitrary equations of state. Results were published in Refs. [39, 45, 46].

Utilizing new hydrodynamic solutions, we also investigated evolution of the fireball in heavy ion collisions [47, 48]. These results provide an analytic tool to understand the relation between measurements and the lifetime of the fireball, as well as the initial energy density. They furthermore include a generalization of the Bjorken solution and the corresponding energy density estimate to accelerating velocity fields, hence a correct, exact energy density estimate could have been made for accelerating perfect flows.

We also investigated the scaling properties of small and large collision systems, and found that the quantification of these scaling patterns predict multiplicities and pseudorapidity densities, and may be important in studying a broad array of observables at RHIC and the LHC. A relevant paper including members of our group was published with the help of this grant [49].

In terms of the applicability of hydrodynamics in small collision systems, members of our team participated in the journal publication of important PHENIX papers [50–53]. These papers investigated p+Au, d+Au, $^3$He+Au and p+Al collisions, and found that the hadron production in all of these can be described by hydrodynamics, especially near midrapidity. These results got quite a bit of attention, and members of our team subsequently presented these results at four international conferences (for example in Moriond and at the ICNFP in Crete), and corresponding proceedings papers were published [54, 55] Let us also mention that we worked on papers about higher-order nonlinear flow coefficients as well as strange particle collectivity and azimuthal anisotropy of jet quenching, some of them under consideration for publication as of now [56–58]

## 2.4 Close-to-hardware experimental developments

In accordance with the research workplan, the new Forward-TPC system for the NA61 experiment at CERN has been completed, comissioned, and was deployed. It is based on a new working principle, which we named the *tandem-TPC concept*, useful for off-time particle rejection in a high rate environment. The conceptualization, design and construction of the detector and its infrastructure, was also performed by our group in close collaboration with the University of Colorado (Boulder) group in NA61. The Boulder group was responsible for the engineering design, field cage construction, and machining of shaped parts. Our group was responsible for the amplification wireplane as well as the readout electronics and the reconstruction software, with the coordination of the Co-PI of the present grant. The tracking and off-time rejection performance of the system turned out to be excellent, and corresponding detector paper [59] was published (the co-PI of the grant is corresponding author).

Significant progress was made towards extending the $p_T$ coverage of midrapidity single particle spectra in p+p and p+Pb collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ energy. The acceptance corrected charged particle spectra show that reaching the 4 GeV/c goal in $p_T$ is quite possible together with PID, and eventual centrality differentiation in p+Pb with the LMPD detector, constructed by our group is also feasible. Results to be publication ready after the present grant period.

Also in accordance with the research workplan, we gave significant support for the data taking of the NA61 experiment at CERN. Our group was responsible for the Data Acquisition (DAQ) system, developed by us, moreover for our mentioned newly developed Time Projection Chambers (Forward-TPC system). Our efforts helped to complete the full physics data taking program of the NA61 experiment, up to the period of LS2.

In the CMS experiment, we worked on the performance analysis of the Zero Degree Calorimeters [60], and participated in the internal preparation and review process of analyses related to b jet shapes [61] and hard color-singlet exchange in dijet events [62], an analysis describing the observation of the forward neutron multiplicity dependence of dimuon acoplanarity in ultraperipheral PbPb collisions [63], another analysis about forward energy as a function of track multiplicity [64], as well as one about double-parton scattering in four-jet events among pp collisions [65]

In accordance with the research plan, we actively participated in the design and implementation phase of the new TDAQ system of the NA61 experiment for after LS2, and in the development of its reconstruction software. For our continued gaseous detector R&D activities related to NA61, we also designed and built a new kind of gas micro-flow meter device for low flow regions, which is not accessible via industrial solutions. It is extensively used in our testbench lab applications.

## 2.5 Spin polarized light-ion beams and field theory

As an application of spin-polarized light-ion beams, an experimental setting was proposed in our paper [66] for detecting general relativistic effects in so called ”frozen spin” storage rings, foreseen for Electric Dipole Moment (EDM) experiments, similar to the g-2 experiments. This seems to open up a surprising possibility to apply spin-polarized beam physics, high energy particle detector technologies, as well as light-ion physics to experimentally address general relativistic effects caused by the gravitational field of the Earth.

A concrete proposal article for such new kind of general relativity (GR) experiment using spin polarized light-ion beams was published by us [67]. It was pointed out that such experiment seems feasible with large magnetic moment anomaly (g-2) particles. The most significant systematic background source was studied, namely the conical shape imperfection of the magnetic bending field. By a renowned beam physicist R.Talman (Cornell) it was argued that in order to cancel such background, a differential measurement could be done, with two kind of beam particles, such as with proton-helion3 combination. We published a systematic error cancelation study for such scenario [68]. These results were presented on the ECFA satellite topical workshop “Towards Storage Ring Electric Dipole Moment Measurements”, designated for future EDM experiment planning.

Further, field theory related works were also published by us in [69, 70].

## 2.6 Further results with the NA61/SHINE experiment

We published several papers with the NA61/SHINE collaboration.

In particular, the papers [71–75] were on proton-nucleus collisions. These aim at providing reference data for the long baseline neutrino beam experiments (in particular for T2K), in terms of meson production. Also, they provide cross section measurements for meson-nucleus collisions, a very relevant input for long baseline neutrino experiments, and for the AUGER community, as well as for heavy-ion physics.

The paper [76] was published about exclusion analysis of a pentaquark state.

About strangeness enhancement studies as a function of system size and collision energy [77–79] were published. On two-particle correlations, the paper [80] was published, and on multiplicity fluctuations the result [81] was released. The publications [82–84] are particle yield and spectra measurement data releases.

The contribution of our group to these papers were mainly hardware related (DAQ, Trigger, reconstruction software).

## 2.7 Results related to the RHIC Beam Energy Scan II

In the STAR collaboration, with the dawn of the Beam Energy Scan II project, we investigated the beam energy dependence of correlations and fluctuations to look for effects related to the QCD critical point. We also participated in a flow and interferometry analysis (as appointed internal reviewer) at 4.5 GeV [85], as well as several fluctuation papers, measuring net-lambda and net-proton fluctuations and (anti-)deuteron production [86–88]. These results indicate non-monotonic phenomena observable in the Beam Energy Scan range. We hope to complete several similar analyses by the end of the grant period, including the pion-pion and kaon-kaon femtoscopy analyses with Lévy sources. Let us also mention that the PI of this grant was selected to be the HEP data archival manager for STAR.

Let us note finally that we participated in maintaining and calibrating the Event Plane Detector in STAR, which will make several further future papers possible. In particular, we measured charged particle pseudorapidities via and unfolding method with STAR, and this results was presented at Quark Matter 2022, and will be also presented at the upcoming Workshop on Particle Corelations and Femtoscopy. Very interestingly this preliminary result is in contradiction to earlier PHOBOS results, and represents incidentally the only method to measure $dN_{ch}/d\eta$ at several energies belonging to the Beam Energy Scan program.

# 3 Important conference appearances

The above results were also presented at several important conferences, which generated inspiring discussions. The most important conference related to the field of femtoscopy is the Workshop on Particle Correlations and Femtoscopy (WPCF). The most important conference of the broader research topic is International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (Quark Matter). Members of our group and our results were well represented at both of these meetings. In particular, let us note that our group in these years gave $10-15\%$ of all presentations at the WPCF series. This shows that indeed this grant from NKFIH/NRDI helped us make an internationally very much visible and recognized contribution to femtoscopy. Broken down to years, appearances at these meetings are detailed below (with hyperlinks to the conference webpages):

- XIII WPCF in 2018 (eight talks)
- XIV WPCF in 2019 (nine talks)
- the upcoming XV WPCF in 2022 (six talks)
- Quark Matter 2018 (three posters)
- Quark Matter 2019 (one poster)
- Quark Matter 2022 (six posters)

and in addition, we gave multiple talks and presented multiple posters at (in some cases several instances of) the following conference series: Initial Stages, Strange Quark Matter, Winter Workshop on Nuclear Dynamics, Critical Point and the Onset of Deconfinement, International Conference on New Frontiers in Physics, International Workshop on Multiple Partonic Interactions at the LHC, as well as many more workshops, seminars and smaller national conferences (ISSP Erice, Zimányi School, International Femtoscopy Days, Indian Summer School, Hungarian Nuclear Physics Meeting, etc). Several proceedings papers also appeared in these subjects, as indicated in the attached publication list.

Further important conference appearances occurred on Spin 2018 (1 talk), on Simplicity III in 2019 at the Perimeter Institute (1 invited talk), and at the ECFA satellite workshop on spin physics (1 talk), plus several (of the order of 10) invited seminars at various institutes in Europe.

# 4 Publication statistics

In the above section we described our results. These can be summarized as follows

- 15 regular few-author phenomenology/theory publications in peer-reviewed, indexed journals
- 18 few-author proceedings papers in phenomenology/theory topics
- 18 proceedings papers (partly in peer-reviewed, indexed journals) in the name of CMS, NA61/SHINE, PHENIX, STAR and TOTEM
- 36 many-author experimental papers with direct contributions from our group

- $>500$ many-author experimental papers with indirect contributions from our group
- Two books
- One outreach paper

## 5 Organized conferences

We also organized multiple international conferences and meetings, listed below with a link to the web-page of the given event (where a member of our group was the chair of the event):

- Zimányi Winter School 2017
- Zimányi Winter School 2018
- Zimányi Winter School 2019
- Zimányi Winter School 2020
- Zimányi Winter School 2021
- Day of Femtoscopy 2017
- Day of Femtoscopy 2018
- Day of Femtoscopy 2019
- Day of Femtoscopy 2020
- Day of Femtoscopy 2021

## 6 Education and outreach

We supervised many students during the project years, and several student research (TDK) papers and theses of various levels emerged from these activities. Below we list them and other outreach activities.

- 11 (O)TDK (student research competition) papers: Bálint Kurgyis (2017/18), Péter Maller (2018/19), Roland Pintér (2018/19), Barnabás Pórfy (2018/19), Bálint Kurgyis (2018/19), Barnabás Pórfy (2019/20), Bálint Kurgyis (2019/20), Barnabás Pórfy (2020/21), Balázs Kórodi (2020/21), László Kovács (2021/22), Balázs Kórodi (2021/22), also listed at `http://csanad.web.elte.hu/teaching#students`
- 18 BSc & MSc theses: János Báskay (2017/18), Gábor Kasza (2017/18), Péter Maller (2017/18), Bálint Kurgyis (2018/19), Roland Pintér (2018/19), Bálint Szűcs (2018/19), István Zsigmond (2018/19), Barnabás Pórfy (2019/20), István Szanyi (2019/20), Balázs Kórodi (2020/21), Okolo Collins Chukwuebuka (2020/21), Mátyás Molnár (2021/22), Laura Bognár (2021/22), Réka Szabó (2021/22), Barnabás Pórfy (2021/22), also listed at `http://csanad.web.elte.hu/teaching#students`
- 2 Pro Scienta prizes: Dániel Kincses and Bálint Kurgyis
- PhD finsihed: Sándor Lökös (2021), 3 ongoing: Dániel Kincses (to defend in 2022), Gábor Kasza (to defend in 2023), István Szanyi (to defend in 2024)
- DSc (doctor of the Academy of the Hungarian Academy of Sciences) 2021 Maté Csanád
- Two educational books [89, 90]
- Outreach article on GR experiment with spin polarized light-ion beams [91]

- Numerous outreach appearances in the media (National Geographic, 24.hu, index.hu, Szertár, origo.hu, ELTE webpages, many of them listed at `http://csanad.web.elte.hu/research`)
- More than 30 outreach talks in high schools and university events (e.g. Researchers' Night), out of these the ones by the PI listed at `http://csanad.web.elte.hu/talks#popular`

# 7 Summary

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