Attometer physics phenomena: experimental and theoretical studies at the CERN LHC ALICE detector

Final Report for the NK 106119 OTKA project (09/2012 – 08/2016 – 12/2018)

Introduction

The Large Hadron Collider (LHC) started its scientific program by the Fall of 2009 and it has reached its half power by beginning of 2010, which means $\sqrt{s}$ = 7000 GeV = 7 TeV c.m. energy in proton-proton collisions and 2.75 ATeV energy in Pb+Pb heavy ion collisions. During 2010-2011 the Higgs hunter ATLAS and CMS experiments have collected 5-5 fb^{-1} pp collisions (here 1 fb^{-1} means 70 million times million collisions). Because of its special setup and due to the gaseous detector system, the ALICE detector collected 5 pb^{-1} pp collisions and 140 μb^{-1} PbPb collisions. This number means 10 million PbPb collisions, which data sample was enough to extract the charged hadron production spectra in the transverse momentum region of 20-100 GeV/c – values have never been tested in heavy ion collisions. The ALICE Collaboration started to analyze these data and new results appeared by middle of 2012. **Our OTKA project started to accomplish its working plan by September 2012 and the participants of the project contributed to the ALICE Collaboration in the forthcoming 4 years, publishing the results of the accomplished research activities until the end of 2018, using an additional 2 years.**

Until the end of 2012 the LHC worked at the above mentioned half power, performing pp collisions for total of 10 months and pPb/PbPb collisions for 1 month during RUN1. The LHC stopped at December 2012 for 2 years and the facility was improved during the Long Shutdown 1 (LS1) to reach the full power (14 TeV for pp and 5.5 ATeV for PbPb collisions) with an increased luminosity. During LS2 the data collection capability of ALICE had been increased and further detector upgrade projects have been accomplished. The accelerator complex has started it RUN2 program by the beginning of 2015 and run until the end of 2018, when major upgrades will happen during 2 years long LS2 (Long Shutdown 2). We expect the starting of RUN3 by the Fall of 2020, when the “High-Luminosity LHC” will be available with an extreme large luminosity of 100 fb^{-1}/year (or even higher value), which is necessary for studying supersymmetric particle production and the origin of dark matter and dark energy at ATLAS and CMS. The luminosity of RUN2 served already with a unique opportunity for the ALICE experiment to study quark-gluon plasma formation and investigate its details in never before seen regions and observables. For example, it became possible to detect and analyze charged hadron production in the extreme high transverse momentum region of 100-500 GeV/c and investigate the collective phenomena through the properties of charm and bottom hadrons – and heavy quarks in the quark-gluon plasma phase. Thus we could reach the original aim of this project and were able to investigate heavy quark production in the initial state of heavy ion collisions (and energetic proton-proton collisions) in the attometer scale.

These results became available because of a very important Hungarian contribution, namely the upgrade of the DAQ system during LS1: by the end of 2014 all DDL card has been replaced by the DDL-2 system in all ALICE sub-detectors (close to be 500). In parallel an even faster DDL-3 version was started to be developed for the forthcoming LS2, as a foundation of the HI-Lumi LHC facility. This hardware upgrade project was successfully accomplished and the new cards will be installed during 2019 and tested in 2020. The installed and developed DAQ-systems, together with the other detector improvements are the basis of the study of very rear events of high energy particle production. **Since high energy hadrons and heavy hadron production are the key observables to study the attometer scale physics, then these improvements opened the opportunity for attophysics investigations at the ALICE detector system with a strong Hungarian experimental and theoretical presence – which was the main aim of this project.**

Our project is the continuation of the OTKA NK77816 project, which supported the research activities of the Hungarian ALICE group from 2009/05/01 until 2013/04/30. This OTKA NK106119 project financed our research activity in the time period of 2012/09/01 until 2016/08/31. By the end of this project the OTKA NK 120660 was granted and will support the Hungarian ALICE Collaboration between 2016/10/01 and 2020/09/30 under the leadership of dr. Barnaföldi Gergely Gábor. This 12 years of continuous support of NKFIH made possible to from a very strong Hungarian group in the ALICE Collaboration, important hardware/software contributions have been accomplished, and an internationally recognized theoretical and experimental program have been accomplished in the field of high-energy heavy ion collisions. **In the next sections we display the most important results of the time period 2012-2016, supported by the OTKA NK106119 grant. These results were summarized in 60 publications, including 38 refereed papers (with a total impact factor of 160) and 22 publications in conference proceedings. This list includes only a few ALICE Collaboration papers, where our contribution was reasonable and important.**

We are referring to these 60 publications in the next sections by the notation [##] and will not use other references.

A, New theoretical/experimental results in proton-proton and heavy ion collisions at LHC

The study of quark-gluon plasma (QGP) phase has been started at the end of the 70's, right after the acceptance of the theory of quantum chromodynamics (QCD). Theoretical speculations have been ignited by the idea of asymptotic freedom and the existence of weakly interacting quark-gluon plasma state has been suggested. Lattice-QCD calculations have been started to find the characteristic temperature of the confinement-deconfinement phase transition in the 80's. In parallel experimental investigation of this phase transition was planned at available accelerators. In the 90's the CERN SPS experiments at energy $\sqrt{s_{NN}} = 17.3$ GeV, namely the NA49, NA50 and WA98 were closest to the discovery of QGP state. In 2000 U. Heinz claimed the production of a very dense deconfined matter in Pb+Pb collisions at SPS energies, which may be identical with the wanted equilibrium QGP state. This claim was based on the appearance of different QGP signatures suggested earlier in theoretical analysis: strangeness enhancement, charm suppression, and the influence of chiral phase transition on the vector meson masses.

In 2000 the RHIC (Relativistic Heavy Ion Collider) heavy ion program has been started at $\sqrt{s_{NN}} = 130$ and 200 GeV energies and the new data displayed very similar features seen at the SPS energies, supporting the SPS-claim of the QGP formation. Furthermore the experiments in the RHIC energy regions extended the investigated transverse momentum region of the SPS ($p_T \leq 4$ GeV/c) to a much higher value of $p_T \leq 20$ GeV/c. These high momentum data contained lots of information about the produced high energy density region and the interaction between high energy quarks/gluons and the deconfined bulk state. For example, a strong suppression pattern has been recognized in the pion yield in central and semi-central Au+Au collisions. This effect could be connected to the induced energy loss of quark and gluon jets in hot dense matter and became an iconic observable of QGP formation. Perturbative QCD calculations offer the appropriate energy loss formula and parton model was able to incorporate this effect producing theoretical results, which can be directly compared to the experimental data. The measured suppression factor can be used to extract the wanted color charge density of the produced hot dense matter, which was penetrated by the quark or gluon jets.

As the heavy ion program started at LHC it was natural to reinvestigate these RHIC results, comparing the new experimental data from LHC to the previously extracted RHIC data and to the earlier theoretical predictions.

One new theoretical perspective was the recognition of non-additive thermodynamics in strongly interacting systems, especially during quark –gluon plasma formation. This new method has been intensively investigated and the theoretical results were compared to RHIC and LHC data obtained in Au+Au and Pb+Pb collisions. Earlier we separated the thermal region with exponential transverse momentum distributions (in general at $p_T < 3$ GeV/c) and polynomial distributions at higher transverse momentum, which indicated the perturbative nature of QCD. Non-additive thermodynamics connected the two regions and the Tsallis-distribution could extend the validity of collective description for much higher transverse momenta, thus for much higher collision energies. Special thermodynamical and hydrodynamial descriptions remained valid and the collectivity gained a new understanding in heavy ion collisions [1] [2] [13] [30] [31] [35] [46] [47]. This new understanding became extremely useful in high multiplicity proton-proton collisions, where many features were surprisingly similar for heavy ion collisions. This effect was investigated intensively in two-particle correlations for p+p and Pb+Pb collisions theoretically [43], as well as experimentally [5] [7] [10] [18].

The appearance of collectivity was investigated experimentally, when centrality dependence of light hadron production was investigated. New data sets were extracted from p+Pb and Pb+Pb collisions at LHC energies, compared to p+p results and analysed in details to find anomalous phenomena [4] [8] [20] [24] [54].

The bridge between p+p and Pb+Pb collision is the p+Pb reaction. We used different theoretical methods to predict the results in p+Pb collisions at 5 TeV, which was very informative to distinguish between different theoretical models [12]. Fortunately, during RUN2 the experimental data on p+Pb collisions appeared quickly [8] [22] [40], thus we could compare the earlier predictions to the new data, which decreased the number of validated theoretical models [56]. The p+Pb collisions are very important to separate nuclear effects from non-nuclear ones. During our investigations lots of interesting conclusions appeared for pion, kaon and charged particle production. Unfortunately, the proton and antiproton production was not separated yet, thus the difference in Cronin-effect (seen at much lower energies for baryon production) could not be pinned down at LHC energies. Hopefully RUN3 will bring new results in this topic.

The appearance of collectivity can be studied by the investigation of anisotrop flow and its higher harmonics [53]. The investigation of pion and kaon anisotropy flow gives a basic information on the behavior of the bulk material consists of mostly pions and kaons [41] [50]. If we want to know more details on fast processes and early stages of the heavy ion collisions, then we need to include the investigation of heavy quark production and the elliptic flow of charmed hadrons, namely D-mesons [3] [21] [23]. It was very surprising that the heavy quarks will not decouple completely from the light quarks, and they will inherit a similar elliptic flow as the light quarks. Since the observed value of heavy quark energy loss is very close to the value of light quarks, it is a question to the community, why the heavy quarks are interacting soo intensively in the deconfined phase. Beyond the D-meson the J/ψ particle production was also investigated [9] [17], as well as the suppression pattern of the bottom-antibottom pairs (Upsilon) [19]. At this point we do not see the reason of these behavior, charm and bottom hadrons should behave very differently from pions and kaons.

Investigating high multiplicity proton-proton collisions, the anisotropy flow and its higher harmonics indicated collectivity, simply displaying similar behavior as it was seen in Pb+Pb collisions. On the basis of earlier perturbative-QCD calculations, we repeated previous calculations of extra gluon radiation parton-parton collisions. It was interesting to see the appearance of scaling laws in the theoretical calculations of the radiated gluon spectra and the produced hadronic ellipticity [32] [33] [38]. These calculations indicated that collectivity is not completely necessary to explain the experimental data and perfect fluid is not necessary to appear in the heavy ion collisions to understand these collective-like behaviors. More details will bring us a better understanding. We expect that in RUN3 the luminosity will be high enough to study the heavy quark production with higher precision.

Jet production is one of the most interesting developments at LHC, because the yield of high-p_T jets is so large, that many jet properties can be investigated with high statistics, thus with high precision. Differential jet cross section has been extracted in p+p collisions at 2.76 TeV [6] and at 7 TeV [39]. In Pb+Pb collisions we extracted the evolution of the near side jet peak, the modification of its width and its dependence on the passed material [57]. Finally, hadron energy loss was measured and analyzed, serving necessary data for theoretical investigations at LHC energies, especially at 2.76 AGeV c.m. energy in Pb+Pb collisions. These investigations are very important to apply jet energy loss calculations and to extract the parton density in the deconfined phases.

The questions of energy loss, the appearance of the collectivity can be investigated very precisely, if we have a Monte-Carlo based model to describe p+p, p+Pb and Pb+Pb collisions until very high transverse momenta. However, as p_T is increasing, then the hadron yields are decreasing very quickly, thus it is hard to reach the 10 GeV transverse momenta in Monte-Carlo simulations. One possibility is to use GPU-accelerators to run Monte-Carlo codes and/or improving the quality of the code. During the OTKA project we were working together with our Chinese colleagues from Wuhan, where Prof. Xin-Nian Wang wrote the original HIJING-code together with Prof. Miklos Gyulassy in the 90's. With their permission and contribution, the HIJING-code was rewritten in C++, and extended by special features to recognize GPU-accelerators [58]. Now the program is running much faster. It can be used in a multiprocessor environment, which means a large factor improvement in speed.

In parallel with the Monte-Carlo codes we developed very special calculations of strong fields appears in the center of heavy ion collisions. We used some similarities to QED phenomena and applied them in a QCD environment. We used a Wigner function formalism and generated a multicomponent model to describe the time development of these strong fields [29] [44] [45]. The description of time evolution of strong gluon and quark fields led to an interesting application: speculations appeared if a strong chiral magnetic effect (CME) could be created in the heavy ion collisions and could be observed via specific pion fluctuations. At LHC energies the effect has been measured [52] and our calculations displayed the same results – although, according to our calculation, at lower RHIC energies the effect seemed to be much stronger [60]. These calculations and theoretical investigations gave a special knowledge about the nature of strong fields at the attometer scale, which could be used for later investigations.

Finally, we made some progress to describe the strongly interacting hadronic matter at high baryon densities (low temperature, large hadronic chemical potential). The applied method was based on the Functional Renorm Group (FRG) calculations [49]. The main aim was to create a description for the neutron stars to follow their inner structure and detect their influence on gravitational wave formation. Although the initial results were very promising, we need further practice and application to create a success story from these calculations.

We have focused on the presentations of the enlisted theoretical and experimental results. We participated in different conferences (the printed 22 conference proceedings indicate this activity). In parallel we joined to the organization of thematic workshops, for example the series of High-pT Physics at LHC Workshop. We have participated in October 2012 on the 8th High-pT Physics at LHC Workshop (Wuhan) and in November 2012 in the Zimanyi Winter School (Budapest), as well as in every year, since it is continuously organized. The 9th High-pT Workshop was in Nantes in 2014. We organized a very successful "Chinese-Hungarian Workshop on Collectivity" in the summer of 2015 at Lake Balaton, which gave a boost to our progress and we could increase the activity of our collaboration on the HIJING++ program code. In 2013 we organized the WIGNER-111 Memorial Conference, where Wigner-functions were presented in many talks and important contributions were made, which helped later progress in this OTKA project [37].

B, Upgrade activities at the LHC ALICE detector

The ALICE detector is dedicated to identify and study all possible freeze-out hadrons in proton-proton and heavy-ion collisions, thus this detector is the most appropriate to investigate the formation of QGP. The main detector parts of ALICE (Fig.1.), which are responsible for particle identification, namely ITS (Inner Tracking System), TPC (Time Projection Chamber), TOF (Time of Flight), TRD (Transition Radiation Detector) and HMPID (High-Momentum Particle Identification Detector) have been designed well before the RHIC experiments, before the importance of jet physics became evident. The existing detectors are capable of measuring charged particles without identification up to $p_T \leq 50$ GeV/c, but can distinguish pions, kaons and protons up to $p_T \leq 5$ GeV/c. The HMPID detector has a crucial role in this task, extending the particle identification beyond the usual 2GeV/c momentum limit of the TPC-TOF combination.

Beyond 5 GeV/c further efforts are needed for precise separation. Since RHIC results indicate the presence of interesting physical phenomena in the momentum range 5 GeV/c $\leq p_T \leq$ 15 GeV/c, and LHC serves high enough luminosity, the idea of constructing a new detector has been emerged. We planned the VHMPID (Very High Momentum Particle Identification Detector), which is a ring imaging Cherenkov-detector, combined with a high-p_T trigger unit. This unit could have been solved the problem of separation for high momentum charged hadrons.

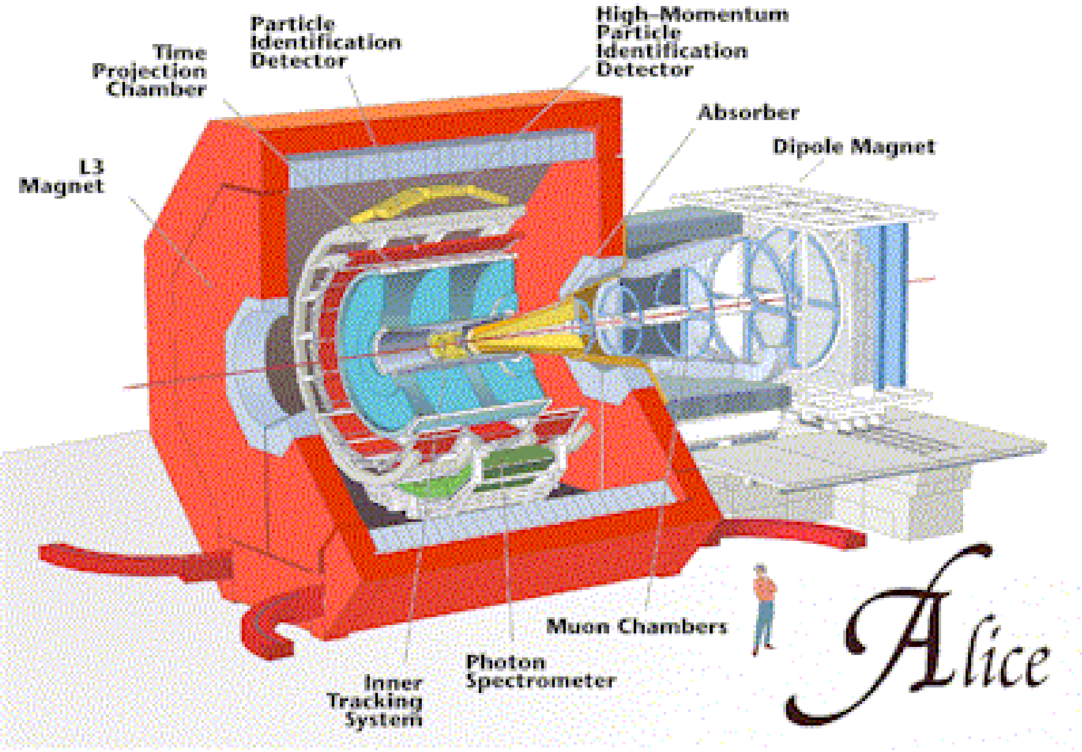

Fig. 1. The ALICE detector

One of our main aim was to construct and install the VHMPID detector during LS2. We made an extended R&D activity on the structure and the applied gas system for VHMPID [11] [14] [15] [26] [27]. All results were summarized in an 80 pages TRD document [25]. Finally, the construction of the VHMPID has been postponed to LS3 in the near future. Instead of this project we have received an invitation to participate in the quality assurance project of the main TPC reconstruction with GEM-based units, which was accomplished very successfully in 2018-19.

Further activities

Our scientific goal was to continue the active Hungarian participation in the ALICE collaboration, with a focus on detection and identification of charged hadrons in wide momentum range, especially in the intermediate and high momentum region. This aim was realized in the following activities, beyond the previously mentioned main activities:

C, We participated in the upgrade activity at the ALICE Central Barrel, focusing on the data acquisition upgrade project. The old DDL system was substituted by the new DDL-2 system in 2013/14, where we had a request for software upgrade. In the meantime, we prepared the software and hardware elements for the DDL-3 upgrade, which will take place during the break in 2019/20, however this development was accomplished earlier, namely by the end of 2018. These activities were organized under the O^2 Upgrade Project, where the active Hungarian participation was expected [28].

D, We continuously participated in the data analysis of the HMPID group. This detector contains Ring Imaging Cherenkov (RICH) counters and it is capable to separate pion and kaon up to 3 GeV/c, kaon and proton up to 5 GeV/c. During last years the HMPID detector has been working with high efficiency. We contributed to the offline activities and data analysis in the p+p and Pb+Pb run. Hungarian ALICE group members contributed to the HMPID data analysis. Unfortunately part of these analysis are not published, even now they are in progress.

E, We continued the operation of the ALICE GRID station at RMKI. We maintained the existing computers and ensure their availability for data analysis and scientific calculations at the TIER-2 level. We extended the GRID to keep 1 % ratio considering the whole ALICE GRID.

Our activity was basic research. The theoretical studies, data analysis and our participation in data collection in ALICE led to important scientific results. Fortunately, the R&D activity at the VHMPID detector brought some direct economic benefit: it was developed a very special detector unit, which was applicable for cosmic muon detection with high reliability. On this basis a muon tomograph was developed and applied for geophysical use, for example the detection of the eruption of vulcanos [16] [34] [48]. Such tomograph has been installed in Japan and there is a strong international interest on its application, e.g. at the Etna mountain in Italy.

Human resource

The Hungarian ALICE Group consists of 25 persons, usually. There are 6 staff member, who are the following persons: Barnaföldi G.G. (group leader), Hamar G., Kőfaragó M., Lévai P., Varga D. and Vértesi R. (deputy). There are IT-engineers in the Group (Dávid E., Kiss T., Tölyhi T.) and other senior colleagues (Boldizsár L, Futó E.). Furthermore, 13-14 persons are graduate students or PhD students, this number was changing yearly.

Epilogue

The time period of 2012-18 was a very successful era of the ALICE Collaboration and the members of the high energy heavy ion community. The ALICE Collaboration published more than 500 papers, Billions of pp and PbPb collisions have been recorded, analyzed and the obtained results had been discussed. These years were the most interesting time period both in high energy particle physics and high energy nuclear physics. The collected information will change the textbooks and will determine a new standard in experimental work. Our group is ready to continue its activities, including new challenges. We hope that our referees will find this report satisfactory and we can finish this project with a good recognition.