Final Summary Report – ALICE OTKA (K135515)
Study of exceptional nuclear effects in heavy ion collisions at the CERN LHC ALICE experiment
2020.10.01 – 2025.12.31

Introduction

The goal of the CERN LHC ALICE collaboration is the study of the Quark-Gluon Plasma (QGP) phase of the early Universe, shortly after the Big Bang. Our OTKA K135515 project aimed to support this international research, both on the theoretical (QCD phenomenology) and detector R&D sides. Our proposed research plan has been successfully done. We fulfilled all our proposed tasks, thanks to the proactive members of the group and the excellent student and early carrier scientists we co-worked with. The delivered work is relevant contribution both to the forthcoming years activities of the CERN LHC ALICE experiment during the LHC's Run-3 period and for the scientific community as well. Below, I will summarize the five major directions of our related activities, results, and achievements of the 2020-2024 period.

The main results of the project

i) Detector R&D, construction, operations and simulations

The Hungarian ALICE Group was deeply involved in various detector buildings, tests, operation, data recording and analysis. Since 2020, detector experts, PosDocs, and PhD students have been trained for ALICE on-site data taking and remote shifts for detector operation during the ALICE Run-3. In 2020, we participated in the remote ALICE shift challenge; our group was the first to build and test a Linux-based Remote Operation Site (ROS) at the Wigner RCP. The ROS was heavily utilized during the pandemic era for remote detector operations and later became a dedicated place for on-call shift and remote discussion room. The required shift credits were fulfilled for the period from 2020 to 2024, including HMPID on-calls. The main shifters were E. Futó, L. Boldizsár, L. Gyulai, Z. Varga, E. Frajna, M. Mazzilli, and R. Vértesi.

The compulsory share, Service Works (SW), is key to detector operation and performance improvement. In parallel with preparing the next generation of heavy-ion experiments at CERN, ALICE3, which includes heavy-hadron studies [28], we also initiated TPC tracking development for Run-3 and beyond within this share. Service works for HMPID were given in 2021, and later we established a new SW for the ALICE Analysis Facility in O2, related to the local Wigner Datacenter (Csillebérc, Budapest, Hungary). The SW shares dedicated to the ALICE Analysis Facility in O2 were allocated as 1 FTE/year, shared between G. Bíró, L. Gyulai, and G.G. Barnaföldi. T. Kiss had 0.5 FTE/yr in DAQ and FoCal SWs, while R. Vértesi and Gy. Bencédi also collected 0.04 FTE/yr through various collaborations.

Our group participated in TPC R&D during the Long Shutdown 2 (LS2), and thus we were involved in the commissioning and cosmic tests of the TPC at CERN, even during the Covid-19 pandemic [76]. We spent several months on TPC setting and tests in late 2020 and early 2021. We summarized the GEM gain study in a separate work [15] and published the ALICE GEM-based TPC Technical Note [5], as well as Á. Gera's MSc thesis: "Reliability of multiwire proportional chambers in field measurements: thermal and mechanical limits" [10]. In parallel, we finalized the HPMID Detector Control System (DCS) description and user guide for shifters, and tested the HPMID DCS layout for Run-3 [14].

The planned upgrade for the Long Shutdown 3 (LS3) aims to enhance the ALICE detector's tracking capabilities, particularly improving heavy-hadron measurements at low momenta, which is crucial for understanding jet-matter interactions. Within this scope, we contributed to the construction of the ITS3 upgrade, in particular by the design of the detector cooling system. For this aim we investigated the applicability of a new material, highly porous carbon foam, as a low-material-budget support and cooling solution. The thermal properties of this novel material had not been previously measured. In collaboration with the Technical University of Budapest, we simulated and measured the thermal parameters of carbon foam samples, then introduced these parameters into the finite element modeling of the ITS3 layers in ANSYS before conducting tests at CERN [66]. The completely new ITS3 will be produced and commissioned during the next planned LHC shutdown and will be connected to the existing read-out and trigger system via the new lpGBT interface. Within the ITS3-WP3 group, we upgraded our local test setup, built around the ITS DAQ Board for testing new ALICE ITS and ITS3 read-out sensors. This setup could help us to work with the ALTAI sensor chip, which is used in the joint Wigner-ELTE University Laboratory project (B. Szigeti & Zs Jólesz). With this setup, we could demonstrate to MSc students the evolution of silicon detector technology, culminating in the latest novel ITS3 MAPS (Monolithic Active Pixel Sensors). As a contribution to testing the new ITS3 MAPS technology, Zs. Jólesz participated in CERN's Summer Student program for 3 months, where she was involved in tracking anomaly searches using machine learning.

The Bergen pCT project represents a knowledge transfer from ALICE's HEP technology to medical physics, particularly hadron therapy. The Bergen University Hospital has recently completed the construction of a new hadron therapy center. The Bergen pCT collaboration is participating in this medical project by introducing a new type of detector, a proton computer tomograph (pCT). Our group contributed to this project from the early beginning, and in this project by participating in beam and cooling tests, indeed using ANSYS simulations to determine the cooling technology for the planned detector. First results were summarized in the pCT technical design report [6,20,21,58]. A Richardson-Lucy-based imaging method resulted in both a 1st TDK prize and another one jointly by the Pro Progressio Foundation and the Hungarian Medical Physics Society at BME, awarded to Á. Sudár. Machine Learning-based numerical methods for pCT tracking have been summarized in [27,73], and two new students, Zs. Jólesz (MSc) and B. Dudás (PhD), are working under the supervision of G. Bíró on developing also a new method using machine learning for tracking, reconstruction, and imaging.

Fig 1: Celebration of the 30th birthday of the ALICE Collaboration, and the presentation of the detailed summary, entitled "The ALICE Experiment: A Journey through QCD" [69].

To commemorate the 30th birthday of the ALICE detector, the Collaboration presented a comprehensive summary, titled "ALICE — a journey to QCD" [69]. In parallel, the concept of the next-generation heavy-ion experiment, ALICE3, was initiated. Our group's main contribution focused on heavy-hadron studies, which were summarized in the ALICE3 Letter of Intent [28]. Following the ALICE Upgrade week in Prague, September 2022, discussions began on the proposed Muon Identification Detector (MID) and aerogel RICH detector groups' possible contributions. Related to the MID, we participated in beam tests at CERN's T10 facility to evaluate the performance of MWPC chamber prototypes. The data analysis is ongoing, including GEANT4 simulations to select the optimal layout presented in the Scoping Document for CERN RRB [79]. Within the RICH detector R&D we learned the silicon photomultiplier (SiPM) technology (V. Peskov).

ii) Analysis of High-momentum Identified hadron and Heavy-flavour Data

The ALICE detector has a uniqueness in particle identification from low to high energy. This is the key for determining the properties of the strongly interacting matter from small to large colliding systems. For this goal, we have analyzed high-momentum identified hadron and heavy-flavour data from the Run-2 and Run-3 data-taking periods during the project. The ALICE heavy-flavour (beauty and charm) production provides information from all stages of hadron collisions and helps in understanding the strong interaction under extreme circumstances, from small to large systems. In the period of 2020-2024 we provided a significant contribution to the ALICE Heavy-Flavor physics working group.

We played a leading role in measuring the b-jet spectra at 5 TeV in pp and pPb collisions [64]. Correlation measurements of charmed D mesons with charged hadrons reveal the heavy-flavour jet structure at intermediate momenta. He was responsible for the D-jet angularity measurements in pp collisions at 5TeV, as well as Ds-jet production, heavy-flavor jet axis differences, and heavy-flavor energy-energy correlators in 13 TeV pp collisions [13,14]. We participated in the coordination of the Heavy Flavor Jets and Correlations Physics Analysis Group from January 2020 to 2022. He was responsible for the progress and quality control of all related data analyses [8]. The production of beauty jets in pp collisions serves as a fundamental test of perturbative QCD, interestingly we observed no significant cold nuclear matter effect within the extended momentum range [40,41]. Our duty was the Pb-Pb data analysis coordination at 5.02 ATeV. Where we measured the radius dependence of charged particle jet suppression [41]. In parallel, simulations on D-h correlations in pp collisions at 5 TeV aimed a detailed understanding of the reaction. These were presented at the ACHT21 conference by E. Frajna [17]. E. Frajna (PhD) and A. Horváth (BSc) worked on NLO and LO simulations of D-Dbar correlations as well. A. Horváth achieved first place at the Scientific Student Conference (OTDK) competition [47,57], and E. Frajna performed an analysis of charm production and fragmentation via azimuthal correlation of D mesons with charged particles [40]. A process-level investigation of D0-D̄0 meson pair formation in jets in PYTHIA8 simulations was also calculated [17]. We also investigated charm production and fragmentation via azimuthal correlations of prompt D mesons with charged particles in pp collisions at 13TeV c.m. energy and found that the correlation has no multiplicity dependence. These results were presented by E. Frajna at QM2022 and R. Vértesi at BEACH2022.

The production of D0 mesons with respect to the underlying event activity is a groundbreaking measurement that links heavy-flavour production to collective phenomena in small collision systems. L. Gyulai (PhD) was responsible for event-activity-dependent measurements of Heavy Flavor in ALICE [7,13]. He worked on the analysis of D0 meson production in dependence on transverse activity RT and calculated trigger-efficiency and feed-down corrections for the raw D0 spectrum. He implemented a novel hybrid track selections for data and Monte Carlo tracks.

The role of the underlying event in charm-baryon enhancement in pp collisions at LHC energies, extending studies to several charmed baryons with and without strangeness content [63,64]. The connection of event shapes to heavy flavour baryon enhancement was published in [44] by Z. Varga (PhD) and A. Misák (MSc). Z. Varga participated in the ALICE measurement of heavy-flavour electron-hadron azimuthal correlations. He estimated the contribution of charm and beauty electrons to the correlations and the resulting correlation peak shapes using PYTHIA8 simulations and FONLL calculations. He also done the ALICE measurement of charm-baryon enhancement and heavy-flavor jet substructures, and also analyzed the jet scaling in Run-2 ALICE data. He was involved in developing the ALICE O2 software framework by: code refactorization, optimization, and implementing new functionalities. He defended his PhD in 2024 and obtained a PostDoc position at Yale University. Meanwhile, he was working together with A. Misák (MSc), R. Vértesi, and a new BSc student L.V. Földvári. These results were presented at the Zimányi Winter Schools 2023 and 2024, V4HEP Bratislava (2023), Budapest, Prague, and Warsaw (2024), ALICE Physics Week (Torino) 2023, PP2024, and ISMD2023 conferences and workshops.

A young Italian postdoc, M. Mazzilli, joined our group in 2023, and in the meantime, she coordinated the Heavy-Flavour Correlation Group in ALICE. She worked with R. Vértesi and L. Gyulai. Recent ALICE results were presented on characterizing the QGP with heavy flavour hadrons with ALICE, and measurements of heavy-flavour-tagged jet substructure and energy-energy correlators at EPS-HEP [59] and BEAUTY2023 [60] conferences. M. Mazzilli left the group in 2024 and obtained a tenure position at the University of Bari, but she remained in contact with our group.

Event shape engineering opened up new domains in Bjorken-x where the contribution of gluons to inclusive hadron production became dominant. Our study is based on flattenicity, a new type of event shapes classifier introduced by A. Ortiz (CERN/UNAM) [1,50]. He joined the project as an expert on event-shape engineering using Run-2 data from ALICE. His work was in collaboration with R. Vértesi and Gy. Bencédi. The latter one was involved in analyzing LHC Run-2 pp data and he was elected chair of the paper committee for a long summary paper [64]. A. Ortiz presented results on multi-parton interactions in pp collisions using charged-particle flattenicity with ALICE at EPS-HEP2023 [56]. Later, Gy. Bencédi finalized this analysis, entitled "Particle production of charged-particle flattenicity in pp collision at 13 TeV". Results were presented at ICHEP24 conference in Prague.

iii) Theoretical Calculations and Simulation Code Development

Our theoretical investigations were related to the properties of phases of strongly interacting matter. For our studies, we further developed the HIJING++ code, incorporating machine-learning-based methods. These methods may serve as solutions for problems with non-linear scaling behaviors. The applied methods were quite successful, aside from phenomenological studies related to high-energy heavy-ion collisions, both for large and small system sizes.

Measurements of jet profiles in high-energy collisions are sensitive probes of QCD parton splitting and showering. Based on an observed scaling behavior of radial jet profiles with charged-hadron multiplicity, R. Vértesi, A. Gémes, and G.G. Barnaföldi proposed that the scaling behavior stems from fundamental statistical properties of jet fragmentation [9]. The multiplicity distributions of events with hard jets show that charged-hadron multiplicity distributions scale with jet momentum, suggesting that the Koba-Nielsen-Olesen (KNO) scaling holds within a jet [23].

In cooperation with the UNAM group, R. Vértesi, Gy. Bencédi, and A. Misák studied underlying-event observables in inelastic proton-proton (pp) collisions at a center-of-mass energy of 13 TeV with identified light and heavy-flavor triggers using the PYTHIA event generator. We found that the underlying event in pion-triggered events shows a stronger effect of color reconnection than events triggered with B-hadrons. We concluded that the observed effect can be attributed to differences in the interactions of gluon and quark jets with the underlying event [41,63,64]. We also studied the production of charged particles associated with high-p_T trigger particles as a function of the relative transverse activity classifier R_T, and proposed a strategy that allows for the modeling and subtraction of the underlying event contribution from the towards and away regions in challenging environments like those characterized by large R_T. We found that the signal in the away region becomes broader with increasing R_T, while its corresponding yield is independent of R_T [46]. R. Vértesi and Sz. Sándor used PYTHIA simulations to provide predictions of different heavy-flavor meson productions, as well as heavy-flavor jets, with respect to the underlying event activity. The yield of heavy quarks was found to be independent of the underlying event at high p_T, while identified quark-jet triggers reveal the dependence of higher-order heavy-flavor production on the underlying event. Results were presented in the TDK works of Sz. Sándor. She awarded a 2nd place at the Eötvös University TDK, as well as in the OTDK national competition.

Heavy-flavour hard probes of strongly interacting matter are our focus by applying event shape classifiers at both theoretical and experimental sides. The observed scaling behavior of radial jet profiles with charged-hadron multiplicity has been intensively investigated by R. Vértesi and Z. Varga. The partonic origin of multiplicity scaling in heavy and light flavor jets was published in [45], and the role of the underlying event in the Λ_c^+ enhancement in high-energy pp collisions was discussed as well [44,46], where A. Misák (MSc) was involved. L. Gyulai, with Sz. Sándor (MSc), worked on the study of heavy flavour production in dependence on R_T with different trigger selections [37]. The main focus is the interaction between semi-hard quarks and gluons with the underlying event in light- and heavy-flavor triggered pp collisions [23]. Following our earlier work on the Tsallis-thermometer, we extended the model for heavy hadron production (R. Vértesi, G. Bíró, L. Gyulai, G.G. Barnaföldi). Applying the non-extensive approach together with the Bjorken model, we were able to measure "How far can we see back in time in high-energy collisions using charm mesons". The results presented the observation earlier relative for light hadrons [77] and identified pions [78], respectively about 5 and 20 times.

B.E. Szigeti (PhD) and G.G. Barnaföldi focused on theoretical investigations of scaling hydrodynamical solutions. They modeled the cold nuclear matter of compact stars and extracted nuclear parameters using the Bayesian method. Thanks to precise measurements by the NICER telescope, we could confirm their model for maximal mass neutron stars [3,4]. This work was presented at the SQM2021 conference and later published as a proceedings contribution in EPJ-WoC2021 [30]. A scaling hydrodynamical solution for the evolution of the Universe was presented in [36]. In the next study we implemented rotation for the scaling hydrodynamical selfgravitating solution for the evolution of the Universe [51]. We also investigated that the rotation of the Universe can resolve the Hubble tension in collaboration with I.F. Barna (HUN-REN Wigner FK) and I. Szapudi (University of Hawaii). The idea was presented at V4HEP 2023 Bratislava and in V4HEP 2024 at Budapest, and it was accepted for publication in [70].

Together with A. Horváth (PhD), a realistic 2 solar-masses Kaluza–Klein compact star's inner structure was modeled. Applying an interaction term for the extra dimensional theory, we could provided solutions for maximal-mass compact star configurations, which led us to provide an observability-criteria of the size of a large-scale extra dimension [67,68]. Results were presented at V4HEP 2023, Bratislava. The effect of strong gravitational fields and Kaluza-Klein extra dimensions on the uncertainty relation was studied in collaboration with A. Wojnar at Complutense University of Madrid, where A. Horváth spend 2 months. A. Wojnar also visited our group during summer 2024. The status of this theoretical work was presented at Zimányi Winter School 2024. The optical interpretation of the above general relativity problems was used modeling mirages for outreach [35,49] and the latter appeared on the cover of AJP (Fig 2).

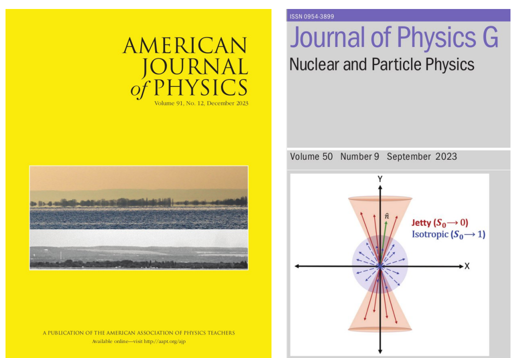

Fig:2: Figs. from publications [49] and [48] were selected as cover page figure on AJP and JPG.

We was working on HIJING++ is the next generation parallel version of the well-known HIJING Monte Carlo event generator for heavy-ion collisions. The tuning of HIJING++ was planned in the project by an IT-student B. Majoros (MSc), who joined the project. After G. Bíró defended his PhD thesis on this topic [2], he started discussing with ALICE O2 the preparation for implementing HIJING++ in AliRoot including an booster-extension by a GPU-based pseudo-random number generation part. M. Németh finished his MSc thesis on this topic. In the HIJING++ development modern, artificial intelligence methods were intensively used:

(a) The tuning of HIJING++ was finished by B. Majoros for pp, p-A, and A-A collisions based on a machine-learning-based parameter optimization method. Preparation of performance plots is ongoing for publication of the code.

(b) The HIJING++ has been tuned and used for testing hadronization algorithm based on machine learning [72]. The developed neural network was built first in PYTHIA 8, in which we could predict hadron production for TeV energy pp collisons, and it worked well for generating identified hadron species and jets from partonic states [18], even adopting QCD-like scaling [33]. Results were presented at Zimányi Winter School 2023, and this project involved a summer student, B. Tanko-Bartalis (University of Oxford, BSc), who learned both the theory of hadronization and machine learning techniques [52,54].

(c) We investigated the applicability of deep neural networks in analyzing heavy-ion collisions [38,39,61,62,75]. Together with N. Mallick, A.N. Mishra, and S. Pasad, we estimated the elliptic flow coefficient in heavy-ion collisions and investigated the scaling of the v_2 parameter [38,39,43].

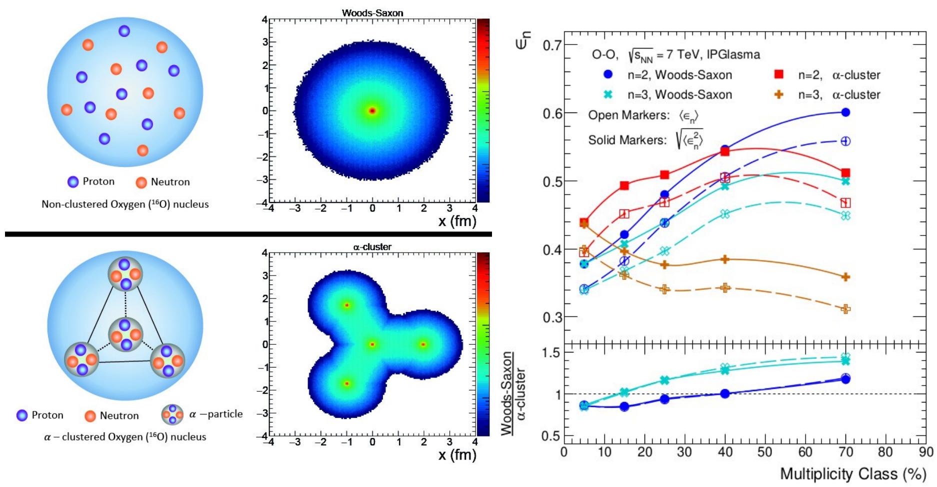

Fig. 3: Effect of the nuclear shape (Woods-Saxon vs alpha cluster model) on the elliptic flow in oxygen-oxygen collisions at LHC energies [31,32].

Within the color string percolation model (CSPM), the jet transport coefficient was calculated for various multiplicity classes at LHC energies [26], and scaling properties were presented from pp to A-A collisions [31,32]. We reported mid-rapidity charged-particle multiplicity, transverse mass, Bjorken energy density, pseudo-rapidity distributions, squared speed of sound, p_T-spectra, kinetic freeze-out parameters, and p_T-differential particle ratios as functions of collision centrality for charged hadron production in planned O-O collisions at the LHC [31,32] . As a continuation of this work, we performed elliptic flow (v_2) studies in Pb-Pb [22] with N. Mallick and S. Prasad (IIT Indore, India), focusing on small colliding systems. We found that the event-plane method used for Pb-Pb collisions was not working anymore, so we applied the n^{th} cumulant technique for oxygen-oxygen collisions [80]. During this study, an interesting feature of oxygen's nuclear structure was observed. We found a significant difference between Woods—Saxon nuclear distribution-based models and alpha-cluster nuclear structure models (Fig 3). We also promoted experimental measurement for this at ALICE and presented these results at several conferences: SQM2024, PP2024. We developed a method to separate perturbative and non-perturbative regimes using correlation techniques and the extended CDF UE definition [11,48] and in hadron spectrta in high-energy proton-proton collisions [11,48,74] together with Guy Paic (ICN UNAM), who spent 1 month at HUN-REN Wigner RCP to study this during summer 2024. JPG has selected one figure of this publication for the cover page (See Fig 2 earlier.).

iv) Novel IT solutions and DAQ R&D for the ALICE O2

The ALICE-related D&R activities in information technology and data acquisition were two folded in the project: on the one hand we provided continuous support for the HUN-REN Wigner-designed CRU2 and RCU by providing firmware upgrades in parallel to the new developments of the ALICE CRU2 technology beyond Run-3. On the other hand, the dedicated, large-scale computing unit Wigner Analysis Facility were developed and set in the production.

Our DAQ upgrade plans for Long Shutdown 3 (LS3) involved implementing the lpGBT technology in the CRU2 cards, and we placed orders for necessary electronics pieces from CERN's EP department. We tested the CRU2 cards at CERN with B. Szigeti and T. Kiss. Later our R&D activity focused on implementing the new CERN lpGBT link interface in Arria 10 GX FPGA, enabling connection to the existing ALICE detector read-out receiver card (CRU). We received the development board from CERN's EP department and built a simulation and test setup, starting actual programming with lpGBT interface implementation and integration into the CRU firmware. The lpGBT link interface was later implemented in the ALICE Common Read-out Units (CRUs) and connected to the Arria 10GX FPGAs of the upgraded CRU prototype, which will be used in ALICE Run-4 (after LS3) detector upgrades and provide possible extensions for FoCal and ALICE3. Tests were conducted at CERN and HUN-REN Wigner using a real VLDB+ test setup, with results presented at TWEPP 2023 by E. Dávid [53]. T. Kiss validated the development in the actual CERN ALICE environment, demonstrating interoperability with existing systems, and this was published in the TWEPP 2023 conference proceedings [71].

The detector developments for the Run-4 upgrade of the ALICE ITS (ITS3) and adding the new RRB-approved FoCal detectors entered a more intensive phase, with our group participating in the CERN common CRU FW development team to support these new sub-detectors. We also took responsibility for R&D on lpGBT-related new hardware components, such as the E-Cal Pads Data Concentrator Boards (Pads DCB) of FoCal, and our expertise was involved in ALICE3 developments, including conceptual design of the front-end and read-out electronics of the ALICE3 RICH detector, which will use lpGBT link technology to interface with the ALICE online system.

In 2020, we set up the first cell element of the Analysis Facility at the Wigner Datacenter. Simulation and optimization of this hardware element for the best performance were started then with 8 racks of about 4000 cores. We performed a data challenge on Run-2 data starting in

2021Q1 with single and 8-core queues. A summary of the benchmark test was given in an ALICE Public Note [19,55]. A year later, 13 cell elements were running with 8-core 2000vcpu and 1.1 PB storage. The MoU between the ALICE Collaboration and the HUN-REN Wigner RCP on the AF was established, and in 2023 we moved the production to the O2 Hyperloop with new 8-core queues. We also invested in a new 100Gbps link between CERN and Wigner AF and the Tier 2 side, which led us to switch to the LHCONE network and to investigate the possibility of using cloud solutions.

v) Operation and Management of the ALICE GRID Tier-2 Center

Our ALICE GRID Tier-2 was operated and improved successfully. We planned and increased the number of Worker Nodes and the volume of the Storage Elements. In late September 2022, we organized the ALICE T1/T2 yearly workshop in Budapest, Hungary, with more than 40 participants to discuss future plans for the ALICE WLCG. Participants visited the ALICE Tier-2 site and the Analysis Facility in the Wigner Datacenter. By 2023, refurbished machines were put into operation after the procurement process. The computing elements of the Wigner_KFKI site have been increased by 20%, and we reached a storage capacity of 1 PB. In 2024, all storage elements of the Tier-2 were moved to Raid 6, which greatly improved the redundancy and safety of the site. G. Bíró presented a site summary in Seoul at the next ALICE T1/T2 Workshop of the ALICE Collaboration. By the end of the project all nodes have been upgraded to the CERN-supported alma9 OS, and we introduced an energy-safe operation taking into account needs and environmental parameters.

Scientific Results and Beyond

Over the period of four years (2020-2024), the OTKA project achieved significant scientific merits, including organizing and participating in numerous international conferences and events, such as the Zimányi Winter School (2020-2024), ACHT2021, LHCP2021, WSCLAB's GPU Day (2020-2024), PP(2020-2024), and V4HEP (2023-2024) ALICE T1/T2 Workshop (2022). The team published a total of about 46 papers in Q1 journals, 10 analysis notes, and 3 CERN Letters of Intent/Scoping Document, and presented their results in over 200 conference talks, posters, and seminars alltogether. Additionally, they engaged in outreach activities (30), including publications in Endglish [49] and in Hungarian in Fizikai Szemle [33] and Nővér [34]. The project also supported the education and training of students, with a total of 14 TDK, 8 BSc, 6 MSc, and 5 PhD students completing their studies (complex exams) or defending their theses during this period. Several students received awards and recognition for their work, including E. Futó's golden diploma at the Karolinka University (Prague), the several top Prize of the TDK and national OTDK (Á Sudár, S. Szende, A. Horváth, Zs. Jólesz), and fellowships such as the DKÖP (B. Dudás, A Horváth) and HUN-REN's mobility grant (A Horváth). The project also hosted prominent guests, including Marco van Leeuwen, the ALICE spokesperson, and Kai Schweda, the ALICE vice-spokesperson, who presented the future of ALICE and visited the team in Budapest. Overall, the project demonstrated a high level of productivity, innovation, and impact in the field of particle physics, with a strong focus on education, outreach, and collaboration.

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