FINAL REPORT for the consortial OTKA grant K 128713
September 2018 - December 2023

Our results are discussed below for the physical and technical aspects of our research as well as our other significant contributions to the Collaboration. We **[cite]** our papers using numbers referring to the included "Publications" list. Our grant supported the participation in the Compact Muon Solenoid (CMS) Collaboration at the Large Hadron Collider (LHC) at CERN. Our group members were responsible for important technical contributions to the experimental hardware, computing, facilities, methodology and certain obligatory 'service' tasks in the Collaboration, and we have conducted and published our research and data analysis within the Collaboration.

CMS has published about 100 peer-reviewed experimental papers every year, and we signed all of these based on our contributions to data collection, hardware development, technical projects, computing facility maintenance, collaboration-wide paper reviews, shifts, service work and leadership responsibilities in the Collaboration. We did not list all our papers, but we restricted the publication list to those where we had a direct, leading/significant role in the data analysis and/or detailed analysis review. Our group constitutes about 1% of the CMS authors. We included a note on few-author papers in the end of the report.

1.) Exclusive pion pair production

Large part of our program consisted of studying various exclusive processes in proton-proton (p+p), ultra-peripheral (UPC) proton-lead (p+Pb) and lead-lead (Pb+Pb) collisions, where only very few (two, four) particles (or jets) are created. In special cases the outgoing beam protons can also be detected. We have published our study of central exclusive $\pi^+\pi^-$ production in p+p collisions at $\sqrt{s}$ = 5.02 and 13 TeV **[13]**, which was the first measurement of this kind at the LHC. Outgoing protons were not detected in this analysis yet. We measured the cross sections as a function of invariant pion pair mass (m_{pair}), transverse momentum (p_T), and rapidity (y). The m_{pair} spectrum is described by a simple model of four interfering resonances, the yields of which are extracted. We also published a presentation at the ICHEP2020 conference on this subject **[25]**.

We analyzed p+p data collected in 2018 at 13 TeV with a special high-β* setup of the LHC, aiming to study the above exclusive production at a level deeper than ever before, trying to uncover the spin structure of the pomeron. Here we required scattered protons detected in the very forward Roman Pot (TOTEM) detectors and another two oppositely charged particles, identified via their energy loss in the CMS tracker as pion, kaon or proton pairs, and a momentum balance of the four particles. A detailed, differential partial wave (spin-parity) analysis of the angular distributions of the decay daughters reveals several f_0 and f_2 resonances. Their helicity amplitudes were precisely measured and compared to vector- and tensor-pomeron models. We have measured the effective meson-pomeron form factors, an essential input to theoretical models. As a by-product, the mass pole and couplings of the f_0(980) are measured more precisely than ever before, along with branching ratios of scalar and tensor resonances. The non-resonant continuum processes are studied in the resonance-free region of the m_{pair} range. Differential cross sections as functions of the azimuthal angle between the protons, squared four-momenta, and m_{pair} are measured in a wide region of scattered proton p_T . A rich structure of interactions related to double pomeron exchange emerged. The parabolic minimum in the distribution of the two-proton azimuthal angle, observed for the first time, can be attributed to additional pomeron exchanges between the protons from the interference of bare and the rescattered amplitudes. After model tuning, various physical quantities related to the pomeron cross section, proton-pomeron and hadron-pomeron form factors, trajectory slopes and intercepts, as well as coefficients of diffractive eigenstates of the proton are determined. After several years of work we have presented these results at conferences (EPS-HEP 2023, ISMD 2023, Low-x 2023) **[48]** and submitted a detailed publication **[37]** to Physical Review D. This result was one of the highlighted achievements of CMS in 2023. On the technical side, we have investigated the strip clusters, details of tracklet and track reconstruction, extraction of strip-level detection efficiencies, precise detector alignment and exclusivity cuts, beam optics, alignment of Roman Pot detectors. We have prepared a publication (pre-approved by CMS and very close to submission) on the innovative technical aspects of this analysis **[45]**, providing a solid ground for central exclusive analyses based on the high-β* data taking period in 2018.

2.) Exclusive ρ-meson, charm and di-jet photoproduction, and light-by-light scattering

We extended our exclusive particle production measurements to other collision systems. We have published our analysis of the exclusive ρ-meson photo-production in UPC p+Pb events at 5 TeV **[4]**. This is the first published result of its kind, and indicate that ion–proton collisions can be used similarly to electron–proton ones, where heavy nuclei act as a quasi-real photon source due to their strong electric field. We have found that the STARLIGHT model overpredicts the data in the high-|t| region.

We have studied the angular correlations of exclusively photo-produced di-jets in UPC Pb+Pb events which provide information about the nuclear gluon structure. This time we were looking for energetic jets in the final state of heavy ion collisions. We measured the second Fourier harmonic of the angular distribution between the sum and difference of the leading and subleading jet p_T vectors as a function of their sum, a first step towards the extraction of the (most fundamental) Wigner-Husimi gluon distributions. The measured second harmonic is found to be positive and rising with the dijet momentum, which cannot be described by *any* of the available models. This is the *first observation* of an exclusive process at such a large momentum transfer - a kinematic domain previously unexplored in hadron colliders. We have published our results in Phys. Rev. Letters **[35]**.

Studying UPC Pb+Pb collisions provide a better understanding of the low Bjorken-x behaviour of strongly interacting matter. During the 2023 Heavy Ion run we collected a large number of UPC events and started studying them in collaboration with the MIT Relativistic Heavy Ion Group. We contribute to tests of various event selection criteria in order to purify the data sample. We studied the track and vertex properties to identify contamination due to background events or reconstruction effects. These new data will be the basis of analysing *exclusive charm* production in UPC events.

We have also worked on the observation of light-by-light scattering in Pb+Pb collisions (rare photon-photon interactions). We optimized the event selection, and produced and processed Monte Carlo (MC) simulations of signal and background events. The related publication is now in preparation.

3.) Particle correlations and femtoscopy

We published our femtoscopic two-particle Bose-Einstein Correlation (BEC) results in p+p collisions at 13 TeV **[12]**, which provide important information on the femtometer scale spatio-temporal structure of particle emission. The measured length of homogeneity is studied as a function of multiplicity and transverse mass (m_T) of the particle pair. We have shown that high-multiplicity *p+p collisions* exhibit scaling patterns observed earlier in *nucleus-nucleus* collisions. A scaling violation at very high multiplicities was observed, which may indicate parton saturation.

We also measured charged-hadron BEC in Pb+Pb collisions and described them using Lévy-type functions. We extracted the source distribution parameters including a correlation strength λ, the Lévy index α, and the Lévy HBT scale parameter R. We found that the source shapes, characterized by α, are neither Cauchy, nor Gaussian. We also found a hydrodynamical scaling of R. Our experimental results are accepted for publication by Phys. Rev. C **[36]**. We performed an event-by-event analysis of the two-particle source function using the EPOS model and found that Lévy-shaped distributions describe the source shape in individual events, and we determined Lévy-parameters of the source. Our phenomenological investigations are also published **[28, 31]**.

Connected to our particle correlation program, we developed a new method to calculate the effects of the strong interaction for Lévy-sources, to be applied in precise measurements where such fine details matter **[16]**. Furthermore, we calculated and published the effect of the fluctuations of the overall Coulomb-field of the surrounding hadron gas on two-particle correlations **[24]**.

4.) Double parton scattering

Precision tests and studies of the Standard Model is one of our research topics **[9]**. In hadron interactions collisions between multiple partons may occur, and related experimental studies are very challenging. We have studied rare, *same-sign* WW pair production looking for evidence of Double Parton Scattering (DPS). We have selected same-sign leptons to look for the same-sign WW final state and used multivariate methods for signal/background discrimination. We have published **[11]** the *first evidence* of the DPS process in this rare channel with a significance of 3.9σ. These measurements are related to the proton structure and helps the development of double-parton distribution functions used to estimate the cross section of these processes.

Our group has also lead the effort to analyse the full CMS Run-2 data set with larger statistics on DPS. We have optimised the Boosted Decision Tree method for the DPS event selection in the same-sign dilepton final state. Using the improved analysis strategy and background estimation we had the *first observation* of same-sign WW pairs via DPS. We published this paper in Phys. Rev. Letters **[34]**, and the results were presented at the LHCP2022 conference, and at CERN on the prestigious LPCC seminar. The achieved significance this time was 6.2σ.

5.) Rapidity gaps and color reconnection studies with jets

We have studied rapidity gaps within jets in p+p collisions. These gaps and their cross section are related to the color reconnection mechanism, and neutral leading clusters of jets trailed by gaps may indicate neutral glueball states. Our analysis of the leading cluster charge distribution of jets in p+p collisions can test hadronisation models and colour reconnection. Since multiple p+p collisions happen at the LHC in each proton bunch crossing (pile-up), we have improved the MC simulation by using realistic pile-up distributions. We unfolded the experimental distributions for detector resolution and efficiency to facilitate model comparisons. We have presented our results on the yearly workshops of the CMS Standard Model Hadronic analysis group and on the Zimanyi Schools. We have prepared a detailed analysis note as a basis for publication **[17]**. We gave a summary talk at the LHCP conference on "Jet measurements in small systems", relevant for in-medium modifications.

6.) Particle tracking methodology

We have developed novel reconstruction techniques for secondary charged particles (decays, photon conversions, nuclear interactions), with the aim to reconstruct photons via electron-positron conversions in the detector material. Instead of classical trajectory building or image transformation, an efficient use of both local and global information is employed while keeping competing choices open. The hits on adjacent tracking layers are clustered first by a mutual nearest neighbor search in the angular distance. The resulting chains of connected hits are the input of cluster analysis algorithms, such as k-medians clustering. This latter alternates between the hit-to-track assignment and the track-fit update steps until convergence. The calculation of the hit-to-track distance and that of the track-fit χ^2 is performed through the global covariance of the measured hits. The clustering is complemented with elements from a Metropolis–Hastings algorithm, optionally adding new track hypotheses or removing unnecessary ones. Models of modern silicon trackers are employed to test the performance of the method. We have published these important methodological developments **[7]**.

7.) Zero Degree and CASTOR Calorimeters, neutrons

Neutrons emitted from the collision point in CMS can be detected by the Zero Degree Calorimeters (ZDC) if they propagate at a shallow angle with respect to the beam, and charged particles very close to the beam can be detected by the very forward CASTOR calorimeter. We improved the simulation, calibration and data analysis of the ZDC, and we have published **[10]** our studies of forward neutrons with the ZDC in p+Pb collisions. We described the calibration method of the detector and demonstrated that the energy deposited in the ZDC has a quasi-discrete distribution featuring separate peaks corresponding to single, double and triple neutron events. We contributed to the installation, commissioning, calibration and decommissioning of the ZDC and participated in the heavy ion **[8]** data taking period (in 2018 and 2023).

We worked on the performance analysis of the ZDC and have published a paper on the subject in JINST **[26]** using p+Pb collisions. We developed a template fitting method which can be used to extract accurate values of the ZDC signals in the presence of collisions preceding our main signal. We have also improved the MC simulation of the ZDC and included the modelling of Cherenkov photons. We have shown that the properties of the measured ZDC signals can be reproduced by this simulation and can be used to match the gains of the ZDC channels. We studied the effect of multiple simultaneous collisions and derived a Fourier deconvolution formula to correct the measured ZDC energy distribution. The corrected spectrum can be used to determine the centrality of p+Pb collisions. We have also participated in the preparation of the new ZDC and Reaction Plane Detector for Run-3, including test beam studies in 2021. We have calibrated the ZDC based on the energy peaks produced by the mono-energetic neutrons originating from the disintegration of the Pb nucleus. We compared the energy measured by the electromagnetic (EM) and hadronic (HAD) sections, distinguished cases in which the neutron started to deposit its energy already in the EM section. In preparation for the 2023 data taking (Pb+Pb), we have participated in the test beam measurements of the ZDC at the CERN SPS, completed the beam test setup and analyzed the beam test data, obtaining relative gain corrections for the EM channels. We worked at CERN during the test beam data taking and completed data recording shifts. We also worked on the cabling of the detector, the trigger system and written data conversion software, using which we examined the signal shapes and deposited charge estimates from the recorded data. We produced channel gain calibration tables, energy resolution and energy calibration of the detector, which was used during the 2023 heavy ion run for the trigger system settings.

We have published a detailed technial paper on the performance of the very forward CASTOR calorimeter as well **[21]**, to which our group contributed as main authors and also by chairing the detailed internal review. This detector offers unique capabilities in an otherwise poorly instrumented pseudorapitity region of the LHC experiments, and have made it possible to publish various unique physics studies.

We recently started a study of forward neutrons and photons in p+p collisions. After detailed recalibration of the ZDC, the data can now be used to extract physical properties of very forward neutral particles. With the 2013 data set, our goals are cross section measurements in p+p collisions and to establish a solid ground for upcoming physics analyses. For calibration purposes, Pb+p and p+Pb data from the same period are also processed.

Most neutrons detected by the ZDC in p+A collisions at the LHC originate from low energy hadronic or electromagnetic interactions, thus we extended our research to related low energy processes in nuclear interactions that provide some outlook compared to the CMS experiment. We have performed a measurements to study a medium-sized nucleus (15C) dropping a neutron when passing through the strong electric field close to the Pb nucleus at a low-energy accelerator. We were able to study this reaction as a function of the impact parameter in the 12-80 fm range, thanks to the improved angular resolution of the detector. The results were presented as a poster at the Nuclear Physics in Astrophysics Conference.

8.) Physics in the forward region

We also studied particle and energy production in the forward region, close to the incoming beam directions. These quantities are not well constrained by models, and are also important for cosmic ray physics. We played a leading role in the analysis and internal review of the publication on the centrality and pseudorapidity (η) dependence of the transverse energy density in p+Pb collisions **[5]**, which was highlighted as a *Suggestion of the Editor of Phys. Rev. C*. This paper has shown that cosmic ray models have difficulties reproducing both the centrality and η-dependence of particle production in p+Pb collisions. We also contributed to a paper on the energy density as a function of η in p+p collisions **[6]**. This result supports limiting fragmentation, the independence of very forward particle production on the energy of the projectile. We have authored and internally reviewed a paper on the multiplicity dependence of the very forward energy in p+p collisions using the CASTOR calorimeter **[2]**. The data exhibit a larger fraction of electromagnetic energy than most models, and disagree with the two recent model tunes (SIBYLL 2.3c and PYTHIA 8 CP5). These cannot explain the famous muon deficit in air shower simulations since the data show that even more energy is spent on the electromagnetic part of the cascade and is lost for hadron production.

9.) Studies of the charge exchange process and cosmic ray showers

One of our goals is to provide a somewhat multidisciplinary approach to LHC physics, where we connect the possible LHC measurements with cosmic ray physics, especially concerning extended atmospheric particle showers. We have therefore collaborated with theoreticians at the Karlsruhe Institute of Technology on the implementation of the charge exchange interaction into event generators inspired by cosmic rays (EPOS, Sibyll, or DPMJET). We use the Cosmic Ray MC (CRMC) package to compare simulated high-energy collisions with and without the above extension. For that reason we have implemented the MC generator for Charge Exchange Reaction (MonCher) into CRMC. This tool makes it possible to compare standard event generators to these extended models and to data in the future. We see that these simulations lead to very different predictions, motivating future π+p or π+ion measurements at the LHC.

We have also conducted feasibility studies of charge exchange and π+p collisions for future LHC runs. We used forward neutron tagging to identify the charge exchange reaction in p+p collisions. We have also studied forward rapidity gaps with cosmic ray event generators. We have studied whether Λ^0 baryons can be misidentified as neutrons. We have concluded that rapidity gaps do not provide sufficient selection power for the charge exchange reaction. One of us organized the Cosmic Ray Simulation Workshop in 2020 where the main focus was to advance the new CORSIKA8 air shower simulation project. The latter will become a cornerstone of research in combining QCD models from accelerator and cosmic ray physics. We have devised an event selection method which is based on neutron tagging with an additional cut on the minimum energy and the energy difference detected in the Hadron Forward calorimeters (HF). With this addition we could increase the purity of the selection while retaining the efficiency. The working point was investigated with bias tests using the multiplicity density and average p_T of charged pions in the tracker acceptance. We have tested various models and found that their predictions scatter in a wide range, while the behaviour of the above mentioned two quantities show similar trends. We aim to motivate an LHC run with oxygen beam in Run-3 for the purpose of solving the so called "muon mystery" - a not understood significant excess of muons in air shower data relative to available models.

We presented our results on the charge exchange process at the Zimányi School in 2021. We have studied the kinematics of p+Pb collisions, examining similar cuts that were used for p+p. We concluded that charge exchange can be selected with higher purity in p+p collisions, because it has a very small relative cross-section and this effect is amplified in p+Pb collisions due to multiple interactions. We took into account the detector resolutions and have published our findings **[27]**.

10.) Luminosity measurement

Precise measurement of the luminosity is essential in a high energy particle collider. The Beam Radiation, Instrumentation and Luminosity (BRIL) system is designed to provide the necessary information for the measurement. The Pixel Cluster Counting (PCC) is part of this system which provides luminosity values using the occupancy of the pixel detector. The precision of the obtained value can be increased with the development of the PCC algorithm. The Beam Position Monitor detectors give us data about the separation of the beams in van der Meer scans. We studied the length scale stability and reliability of the Diode ORbit and Oscillation (DOROS) system using the Beam Gas Imaging (BGI) system during a Van der Meer scan. We play a major role in developing the above algorithms. We have also published a high precision study of the luminosity measurement at CMS in p+p collisions in the data collected in 2015 and 2016 **[22]**. We have contributed both as authors and review committee members.

We have also authored a public note on the luminosity calibration of the p+p collision data taken in 2018 **[3]**. We have designed the trigger menu for special van der Meer scans and other luminosity scans, and we were responsible for validating those trigger tables in the beginning of each data taking run. The new BRIL PLT and BCM1F detectors were installed in CMS and commissioned for the first beam test in 2021. Our method applied on the data quality monitoring (DQM) for the PLT detector using an unsupervised machine learning method (k-means) is implemented online for Run-3 of the LHC **[32]**.

As the precise position of the circulating beams are used for the luminosity calibration, we contributed to the analysis of the recorded Beam Position Monitor data. We improved the analysis software and gave a talk on the XI. International Conference on New Frontiers in Physics about the luminosity measurement at the CMS experiment in Run 2, and its prospects for HL-LHC. A very important part of our activity is the preparation of the Phase-2 upgrade of the BRIL detectors. We had a major contribution to the published Technical Design Report of the BRIL upgrade **[23]** and presented the material at the LHCP2022 conference **[29]**.

The length-scale calibration between the beam position measurements is essential to determine the actual luminosity. We have calculated the final length-scale values for the van der Meer scans conducted in 2017-18. We have worked on the beam particle position correlations in the X-Y direction (perpendicular to the beam). We have analyzed the p+p data measured in 2022, performed two-dimensional fits on the data by sampling the overlap integral in different directions. We have calculated corrections for the various pairings of the scans used in the analysis, and performed simulations to obtain the correction values. Results were presented at the 2023 Zimanyi School. The CMS approval and publication of these results in a journal is expected in 2024.

We have authored a chapter on beam conditions and luminosity in a large summary paper on the recent upgrades of the CMS experiment, accepted by the Journal of Instrumentation **[46]**.

11.) Collaborative analysis review work

In CMS each analysis is reviewed for several months (sometimes years) by an internal committee of 3-4 experts before publication. We have chaired and staffed many such committees as experts, for several publications related to this grant in CMS, for example on strange hadron production in p+p and p+Pb collisions **[14]**, on mixed higher-order flow harmonics **[15]** and hard color singlet exchange in di-jet events **[20]**, b-jet shapes in p+p collisions at 5.02 TeV **[18],** as well as an analysis describing the observation of the forward neutron multiplicity dependence of dimuon acoplanarity in UPC Pb+Pb collisions; strange particle collectivity in p+Pb and Pb+Pb collisions **[33]**, double parton scattering in 4-jet events **[19]**, correlations between multi-particle cumulants and mean p_T, photon-jet angular correlations, azimuthal anisotropy of dijet events in Pb+Pb collisions **[42]**; femtoscopic correlations between strange particles in Pb+Pb collisions; higher moments of the elliptic flow distribution using higher-order cumulants in Pb+Pb collisions **[40]**; charged hadron pseudorapidity distribution in Pb+Pb collisions (featured in the last CERN Courier)

[38]; femtoscopy with strange particles in p+Pb collisions; two-particle correlations in p+p collisions; charged-particle angular correlations in Pb+Pb collisions; jet axis decorrelations with photon-jet events in Pb+Pb and p+p collisions; the first measurement of the forward rapidity gap distribution **[43]** and Υ meson flow in p+Pb collisions **[47]**. We co-authored and also reviewed a summary paper on more than ten years of heavy ion physics results from CMS where submission is imminent, and expected to be a highly cited review **[41]**.

We also regularly conduct institutional reviews of various CMS papers at a later stage of the publication process at our three consortial Institutes (for example, on charge balance functions in heavy ion collisions and their multiplicity and p_T dependence **[39]**).

12.) Responsibilities in the CMS Collaboration

We have also taken collaborative responsibilities in CMS. Members of our team have served as trigger contact persons of the Standard Model Physics (SMP) Analysis Group, and conducted studies of CMS-TOTEM triggers. Another member of our group has convened the Luminosity Physics Object Group, and another one convened the Hadrons and Jets subgroup of the CMS Standard Model Physics Analysis Group. We provide a member for the Standard Model Physics publication committee and one for the Heavy Ion Physics publication committee, and help in the final steps of the publication process in case of dozens of Standard Model and Heavy Ion related papers each year. Two members of our group have been invited to act as GEM (Gaseous Electron Multiplier) Run coordinator and GEM Deputy technical coordinator. We were involved in the coordination of the usage of SMP triggers and also development of Run-3 triggers for SMP. We also filled the position of Deputy Project Leader for the BRIL group; BRIL project manager and OCMS Management Board and Search Committee representative; Level-3 convener of the SMP-VV (vector bosons) subgroup. One of us is a member of the SPS Committee at CERN.

13.) Positioning of the CMS Muon Barrel Detectors

Precise positioning and position monitoring of the CMS muon detectors is essential for most of the CMS publications that involve muons in the final state. Our consortium plays an important role in this technical challenge, our related activities are detailed in this section.

We have performed hundreds of measurements with the CMS Barrel Muon Position Monitor System. We concluded that the displacements of the muon chambers are small enough not to affect physics data analysis, thus it was sufficient to perform a control measurement every few days. The expected radiation dose received by our system have increased, therefore we kept the radiation sensitive components off, and employed them only during the measurements. We were responsible for the maintenance of the Barrel Alignment system during the long LHC shutdown. The separation of the LED operation from the Drift Tube chambers is approved and we worked out the technical details. We have followed the CMS software framework upgrade concerning the position reconstruction software (COCOA). A PhD thesis **[1]** has been successfully defended on the subject of Muon Barrel alignment, in particular, the short and long term deformations influenced by the magnetic field. The temperature and humidity sensors of the carbon fiber structures (MABs) assisting the alignment that were dismantled to ensure access to the barrel muon chambers at the beginning of the second Long Shutdown were re-installed and then tested after installation, following the schedule of closure of the large detector elements (muon rings), as we approached the end of the shutdown. A first measurement with the CMS magnet off, followed by another one at the full 3.8 T magnetic field also took place. After the end of the Long Shutdown, we operated the Barrel Alignment system before/after the ramp-up of the CMS magnet in order to monitor the deformations of the Muon Barrel chambers due to large magnetic forces, and to look for any anomalous mechanical behavior. The MABs assisting the alignment (4 sensors/MAB in 36 MABs) provides relative humidity data in the CMS barrel region for the neighboring Resistive Plate Chamber (RPC) muon detectors using our 144 sensors. The RPC group requests regular measurements with these sensors. The alignment of the muon barrels, the internal alignment of the GEM detector and its temperature monitoring are thus important responsibilities of our group in CMS.

14.) Development of Gaseous Electron Multiplier detectors

We extensively contribute to GEM detector developments. We have successfully calibrated the readout boards of all 164 pieces of GE1/1 chambers (GEM detectors to be installed at the inner side of the endcap disk behind the endcap calorimeters). The reference objects needed for positioning have been glued onto each board. We scanned the surface of the boards and determined the strip electrode positions with respect to the references. We have designed a photogrammetric method in collaboration with the CERN Survey Group, and used it to measure the positions of the references with respect to the chamber frames. Thus, we have a way to obtain the strip positions even after the closure of the chambers. We have also worked on the design and production of the positioning targets of the GE2/1 chambers (these GEM detectors are much larger than GE1/1, they will be installed on the back side of the endcap disk). The conceptual design is complete.

In the second year of our grant we have completed the photogrammetry measurements of single chambers and assembled 72 GEM superchambers. The aim was to determine the relative positions of the chambers within the superchambers. We have also participated in the installation of GE1/1 superchambers on the endcap noses on both ends of the CMS detector. The commissioning of the full GE1/1 system has also been started with our participation. The design of targets for the internal alignment of the GE2/1 chambers is completed and the target production (1152+spares) are ordered. Eight calibration jigs for the scanning of the readout boards of the GE2/1 chambers was designed. The GEM community requested us to develop the CMS Detector Control System integration of the GEM Radiation Monitoring sensors. The task is to collect the data from the front-end electronics and to publish it on the communication system for Distributed/Mixed environments in order to be able to be processed by the WinCC OA project also to be developed by our group. The front-end and publishing is completed.

We also continued scanning of the GE2/1 readout boards. The mechanical design of 8 further different calibration boards and the production of the first 5 boards were also completed. The gluing and measuring tasks related to the first boards has also started. During the first measurement campaign, our group calibrated 25 pieces of GE2/1 readout boards.

In relation to the GEM detector internal alignment, the calibration and gluing jig for all the GE2/1 readout boards were made (8 different types) and we completed the scanning of 48 boards. The plans are drafted for the photogrammetry measurement of the GE2/1 chambers and the measurement campaign started in 2023, when the first GE2/1 chambers were built. The installation of these chambers is planned at the end of 2025. We are designing the scanning and gluing jigs of the ME0 GEM chambers as well as their photogrammetry measurements. These chambers are planned to be installed in CMS in 2026.

Our tasks were also related to GEM temperature monitoring with fiber optical sensors, since this subdetector needs an independent temperature monitoring of the electronics, which will be implemented with fiber optical sensors. ATOMKI purchased the temperature sensors for GE2/1 chambers from internal funds. There is a need to extend the system also for the ME0 GEM, and possibly to GE1/1 chambers, where the future sensors and the system extension is planned to be covered by our new OTKA grant (started in 2024).

We finally completed the alignment scanning of 36 readout boards of the GE2/1 GEM detectors that arrived at CERN in 2023, and preparing for the scanning of the ME0 GEM chambers. The fabrication of the first ME0 gluing and calibration jig is ongoing, and after the validation of this prototype, the remaining 11 jigs will be manufactured. The temperature monitoring of the GEM detector electronics will be done with newly purchased fiber optical sensors which first we need to calibrate in a climatic chamber. We calibrated fibers for 45 GEM chambers. Fiber optical multiplexers will be essential for the readout of these sensors.

In summary, due to our contributions, it is now possible (and also nececssary) to monitor the temperature of the CMS detector system in a rather inaccessible location, while the radiation load/damage in the given geometrical volume varies by several orders of magnitude.

15.) Collaborative service work in CMS

As part of our service task obligations, we have taken a large number of shifts on the CMS experimental site in Cessy (France) as Shift Leader, Technical Shifter and BRIL expert, and we were responsible for the luminosity measurement and monitoring. We have also taken shifts remotely. We are also operating the CMS Tier-2 computer farm at the Wigner Institute.

We started to re-organize the workflow of the calculation and handling of the online beam spot (the volume where protons or ions collide in CMS) for Run-3, in co-operation with the University of Milano-Bicocca and CERN. The aim is to use the calculated online beam spot as a prompt input to the high level trigger, and to reduce redundancies. We have rewritten the software which transmits the online beam spot information during Run-3 for the LHC controls. The new implementation was tested in October 2021. After extensive adjustments, the software is in use during Run-3 operations. We have analyzed pixel high voltage bias scan data, to be used for the compensation of radiation damage. We have worked on the simulation of pixel dynamic inefficiency which shows effects of the instantaneous luminosity. We have updated the pixel cluster shape filter, to be used at a later stage for cleaning seeds and trajectories at various stages of charged particle tracking.

All of our consortial partnets fulfilled service obligations for the CMS Collaboration. As an example, the ATOMKI institute has completed 138% of its fair share of service tasks in 2023.

16.) Conference presentations

We have presented our results in a large number of conference talks and posters, and (co-)organized more than 10 related conferences during our grant, some of which were mentioned in this report. We have presented our results on 18 conferences in the first year and 11 conferences in the second year, and published several conference proceedings. We have also summarized the recent results related to soft QCD from the CMS (and ATLAS) Collaborations at the Moriond 2022 conference **[30]** and results on diffraction and elastic scattering on the LHCP23 conference **[44]**. We have also presented our research and development activities at the 2022 RECFA (Restricted European Committee for Future Accelerators) meeting in Budapest, and received a very positive feedback from the Committee. Some of our conference talks are listed below:

EPS-HEP 2023, Hamburg, Germany,
"Central exclusive production in CMS+TOTEM"
https://indico.desy.de/event/34916/

Low-x 2023, Leros, Greece,
"Nonresonant central exclusive production of charged hadron pairs in proton-proton collisions at 13 TeV in CMS and TOTEM"
https://indico.cern.ch/event/1214186/

EMMI Workshop “Forward physics in ALICE 3”, 2023, Heidelberg, Germany,
"CMS+TOTEM results on central exclusive production (non-resonant processes)"
https://indico.cern.ch/event/1327118/

EDS 2019: 18th Conference on Elastic and Diffractive Scattering, 2019, Qui Nhơn,Viet Nam,
"Recent CMS and CMS-TOTEM results on diffraction and exclusive production" Plenary talk.
https://indico.cern.ch/event/783891/

ICHEP2020: 40th International Conference on High Energy Physics, 2020,

"Central exclusive and diffractive physics measurements at CMS and TOTEM"
http://ichep2020.org/

ICNFP 2022: XI International Conference on New Frontiers in Physics, 2022, Kolymbari, Greece,
"Precision luminosity measurement at the CMS experiment in Run 2 and prospects for HL-LHC"
https://indico.cern.ch/event/1133591/

LHCP2023: The 11th annual conference on Large Hadron Collider Physics, 2023, Belgrade, Serbia,
"Jet measurements in small systems relevant for in medium modifications"
https://lhcp2023.ac.rs/

LHCP2023: The 11th annual conference on Large Hadron Collider Physics, 2023, Belgrade, Serbia,
"Diffraction, elastic scattering at LHC"
https://lhcp2023.ac.rs/

Moriond/QCD2022: 56th Rencontres de Moriond on QCD & High Energy Interactions, 2022, La Thuile, Italy
"Standard Model soft QCD at CMS and ATLAS"
https://moriond.in2p3.fr/2022/QCD/Program.html

EPS-HEP2019: European Physical Society Conference on High Energy Physics, 2019, Ghent, Belgium,
"Probing heavy quark dynamics in PbPb collisions with CMS"
http://eps-hep2019.eu/index.html
Moriond/QCD2019: 54th Rencontres de Moriond 2019: QCD and High Energy Interactions, 2019, La Thuile, Italy
"Heavy ion physics at CMS and ATLAS: hard probes"
https://moriond.in2p3.fr/QCD/2019/MorQCD19Prog.html

XVI Workshop on Particle Correlations and Femtoscopy (WPCF 2023), 2023, Catania, Italy,
"Two-particle Bose-Einstein correlations and their Lévy parameters in PbPb collisions at 5.02 TeV"
https://agenda.infn.it/event/33324/

34th Annual Conference of Academia Europaea, 2023, München, Germany,
"Femtoscopy, or exploring the Big Bang with particle accelerators"
https://dtgeo.eu/conference-34th-annual-conference-of-the-academia-europaea-in-munich/

ACHT 2023: Non-Perturbative Aspects of Nuclear, Particle and Astroparticle Physics, 2023, Leibnitz, Austria,
"Hadron emission distributions with femtoscopy from SPS through RHIC to LHC"
https://indico.cern.ch/event/1238890/

52nd International Symposium on Multiparticle Dynamics (ISMD 2023), Gyöngyös,
"Femtoscopy with Lévy sources from SPS through RHIC to LHC"
https://indico.cern.ch/event/1258038/

LHCPhysics 2023, Belgrade, Serbia,
"Two-particle femtoscopy measurements at the LHC"
https://indico.cern.ch/event/1198609/

The 37th Winter Workshop on Nuclear Dynamics, 2022, Puerto Vallarta, Mexico,
"Event-by-event investigation of the two-particle source function in heavy-ion collisions with EPOS"
https://indico.cern.ch/event/1039540/

11th International Workshop on Multiple Partonic Interactions at the LHC, 2019, Prague, Czech Republic,
"Bose-Einstein correlations of charged hadrons in proton-proton collisions at the CMS experiment"
https://indico.cern.ch/event/816226/

17.) Awards, honours and other achievements

Members of our group have been awarded in relation to their research connected to the grant: several of our students with the ÚNKP grant, M. Csanád with the Order with the Merit of the Republic of Hungary and the ELTE TDK Medal, with the Doctorate of the Hungarian Academy of Sciences (HAS), the Imreh Csanád prize, the Jánossy Lajos prize, the Bolyai plaquette and full professorship at ELTE; G. Pásztor with the Jánossy Lajos Prize. N. Béni and O. Surányi has defended their PhD theses; F. Siklér became a corresponding HAS member. Various members of the group obtained postdoctoral positions at the City University of New York, at the University of Bergen and at JLab. One of our students (P. Major) received the CMS award in 2023, as well as our colleagues from ATOMKI (Z. Szillási and N. Béni) in 2022. Another student in our group (A. Fehérkuti) was admitted to the CERN Summer Student Program in 2022. Two of us served consecutively as the Chair of the Particle Physics Commitee of the HAS.

18.) Education and outreach

Many of our group members regularly teaches physics students at University level (in Budapest, Debrecen and Kolozsvár), even those members working for Research Institutes, since recruitment and education of young talent for our long term experimental projects is of utmost importance. We have also participated in various education and outreach related activities (Researcher's nights, Open Days, MasterClass, etc). We regularly give science outreach talks, educational public talks, scientific seminars at high schools, libraries and on online platforms. We also contribute to life-long education of physics teachers. We (D. H.) published a polular science book titled *"Az elemi részecskék csodás világa"* (ISBN 978-963-604-109-0) and a paper *"Antirészecskék?"* in Fizikai Szemle (2022).

Notes on publications with few and many authors:

We noted that reviewers, commitees and funding agencies tend to associate a higher value to publications with few (or one) author(s) than to large collaboration papers. However, our project proposal was specifically submitted to allow us to participate and conduct research within a large collaboration with more than two thousand authors. Our long-time experience is that it is significantly more difficult and time consuming to produce an experimental publication within a large collaboration, and we ourselves also associate a higher scienfific value/achievement to those. Unique experimental results also represent lasting value and legacy to the community.

Our collaboration papers receive a very detailed scrutiny from expert Physics Analysis Groups, Physics Object Groups and even a Statistics Committee. After completing the data analysis and presenting it multiple times in expert groups, and completing the paper draft and a detailed internal documentation (often hundreds of pages), the Collaboration pre-approves the analysis methods and its details. An Analysis Review Committee (with only a few members) further scrutinizes our work for months or sometimes even years, reaching the point where the CMS Collaboration is ready to formally approve the results for public presentations. This is followed by a Collaboration Wide Review, where the main authors receive usually thousands of comments to each paper draft from the whole Collaboration. After making all these adjustments, the Publication Commitee still improves the papers together with the authors in multiple steps, finished by a Final Reading session, re-reading every word. Only then can a publication be submitted to scientific journals. These papers practically never get rejected by the journals, after such previous scrutiny.

Publishing data analysis and experimental results with one, or few authors based on data collected by our collaboration is explicitely forbidden by our collaboration rules. Along the same rules, all authors have to be indicated on all publications in alphabetical order (there is no first, last, or corresponding author).

We also paid attention to produce few-author publications. Part of those reflect our methodological and technical research, publishing which is allowed by the CMS rules, as well as conference proceedings, where the CMS Conference Commitee honoured members of our group by authorizing them to represent the collaboration on conferences, after a judgement of merit. Our other few-author papers present phemonenological results using already published data. Such few-author publications are listed in our publication list, e.g. **[1], [7-10], [16], [24-32], [44]** and **[48]**.

Some of our research we conducted up to 2023, supported by this grant, is only going to be inevitably published in 2024 (including the acknowledgement to NKFIH and our grant number) due to the long approval process in CMS. We are grateful for the support of NKFIH also in those cases, and therefore we included some of these papers in the publication list as well (**[36-41], [45-46]** and **[47]**).