# Final scientific report

**K109703 and K109803 consortial projects**
**"Hungary in the CMS experiment of the Large Hadron Collider"**

## Introduction

Our research spanned a very wide spectrum of high-energy experimental physics activities, ranging from detector design, construction, calibration, operations, to development of analysis methods, data processing, and finally physics analysis, comparison to theory, and publication of results.

The contributions of the four Hungarian groups (MTA Wigner RCP, MTA Atomki, University of Debrecen, Eötvös University) to the extremely rich physics harvest of the CMS Collaboration (660 papers) are detailed below. Due to space limitations, we can only flash a selection of the most important results and achievements, accompanied by the relevant citations.

## Detectors and computing

**Silicon tracker** During the first shutdown period of the LHC, we have completed the analysis of the collected data [1], and prepared the calibration of the CMS tracker detector for the coming higher luminosity regime. Our group carried out the time alignment of the CMS pixel detector and the calibration of its local reconstruction. We further monitored the performance of the local reconstruction of the pixel and strip detectors. We participated in the alignment of the tracker, first with cosmic rays and then with LHC collisions, and participated in the study of track reconstruction [2].

Studies on the effect of irradiation accumulated in the pixel detector during Run 1 were done [3], as well as, measurements of its efficiency in a high-radiation environment. We developed a method in order to simulate the efficiency loss mechanism at high collision rates [4, 5]. We studied the properties of a prototype detector (pixel pilot blade) that has been installed during the long shutdown.

During the 2016 data-taking, our group has monitored the radiation damage induced changes in the performance of the CMS pixel detector [6]. We determined the collision pile-up dependent efficiency of the pixel detector in 2016, which is a major determining factor for the CMS luminosity measurement used in all physics analyses [8]. By identifying nuclear interactions inside the pixel detector, we participated in the position measurement of various mechanical components of the detector and beam pipe.

**New pixel detector** Our group played a major role in the commissioning of the data acquisition system of the updated detector in 2017, in the construction of the modelling of the new detector in the CMS software framework, and in the preparation of the local

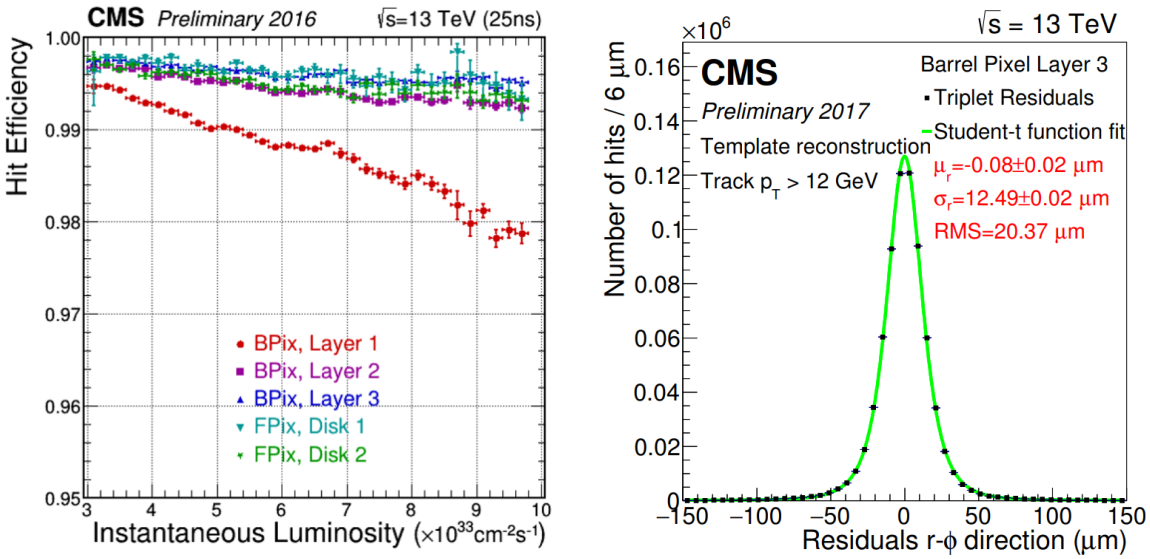


Figure 1: Left: Hit efficiency as a function of instantaneous luminosity in the pixel detector [6]. Right: Measurement of hit residuals in the new pixel detector [7].

reconstruction for the new detector. We have successfully completed the tasks related to the design, production, and installation, and have led the fabrication of the control and readout electronics. The test of the components have been carried out in Wigner RCP, while the final assembly happened at the University of Zürich.

We have performed the timing scan of modules, and grouped the channel such that the detector operates without data loss in 2017. The software developments related to the simulation, calibration, and reconstruction of the new detector was led by us [7, 9]. We have joined the conceptual design of the phase-2 detector which will take data in the high-luminosity LHC runs [10], expected after 2025.

**Extension of the muon system** We were invited in the endcap muon upgrade project. We were involved in setting up of the new cathode strip chamber factory at CERN Prevessin site and have participated in the manufacturing and testing of the 72, new ME4/2 chambers. After full installation and commissioning of the new chambers were ready for the forthcoming LHC run.

**Position monitoring system for barrel muon detectors** The barrel position monitoring system provides regular data for detector alignment. During the first long shutdown of the LHC, we have further improved its accuracy and reliability. The built-in components were fabricated in the Wigner RCP workshop. Some cameras and all modules for the alignment of the CMS barrel were recalibrated. More than a thousand measurements have been taken covering two dozen of magnetic cycles. A new, fast algorithm has been developed for data evaluation providing position differences with respect to any earlier measurement within 24 hours.

**Position monitoring system for forward muon detectors** During the second long shutdown of LHC a new muon detector GE1/1 will be installed on both sides of the endcap, to be built with gas electron multiplier (GEM) technology and having sub-millimeter

resolution. Its alignment system will use fiber Bragg grating (FBG) sensors [11]. The R&D work included the design of the readout board scanning table, the board-image analysis, the finite-element calculations of the sensor mechanics, the first glue tests of the sensor brackets and the optical fibers. The sensor has been tested and some of the system elements have been produced. We have constructed and started operating a high precision scanning table measuring the geometry of the readout boards. Similar tasks for the future GEM-based GE2/1 and M0 chambers have been studied.

**Fiber optic sensors** The continuous monitoring of the temperature and relative humidity at the CMS tracker detector is vital. We were involved in the analysis of the measured data, including the validation of the long-term stability of the calibration and the development of algorithms.

We were also involved in the development of a new kind of optical hygrometers based on long period grating (LPG) technology giving much higher sensitivity [12, 13, 14]. We implemented the newly installed fiber optic sensors during the first long shutdown to the detector control system, and have analyzed their data. Presently about 300 sensors measure temperature, humidity [15] and strain. We carried out four radiation-hardness tests of LPG thermometers using the high intensity Co-60 gamma photon source of MTA Atomki. We confirmed that these sensors are effective and reliable.

**Forward detectors** We have worked on the commissioning and calibration of the Zero Degree Calorimeter (ZDC) during 2016 pPb data-taking. The ZDC is capable to detect neutrons and photons in the very forward, and can be used in heavy ion and proton-nucleus physics for centrality classification and selection of ultra-peripheral collisions.

**New timing layer** The Debrecen group has joined the Barrel Timing Layer project. In the phase-2 upgrade of the muon detectors the aim is to design and develop a thin scintillator and SiPM readout layer to determine the emission time of charged particles with 30-40 ps precision. The test of high voltage modules of barrel muon chambers has already started.

**Computing** Our T2_HU_Budapest grid computing site provided the pledged amount of computing and storage resources to the CMS experiment, meaning an increase of 600 CPU cores 400 TB disk storage in the past four years. Upgrades were also carried out in the power and networking infrastructure to ensure the continued stable operation of our computing center, giving us the third position among 54 CMS T2 sites in the site availability ranking. We also took part in the central shifts overseeing the global operation of CMS computing.

# Physics

**New method for tracking of charged particles at high multiplicities** We have developed a novel combination of established data analysis techniques for reconstructing charged particles in very high multiplicity collisions [16]. It uses all information available while keeping competing choices open as long as possible. Suitable track candidates are

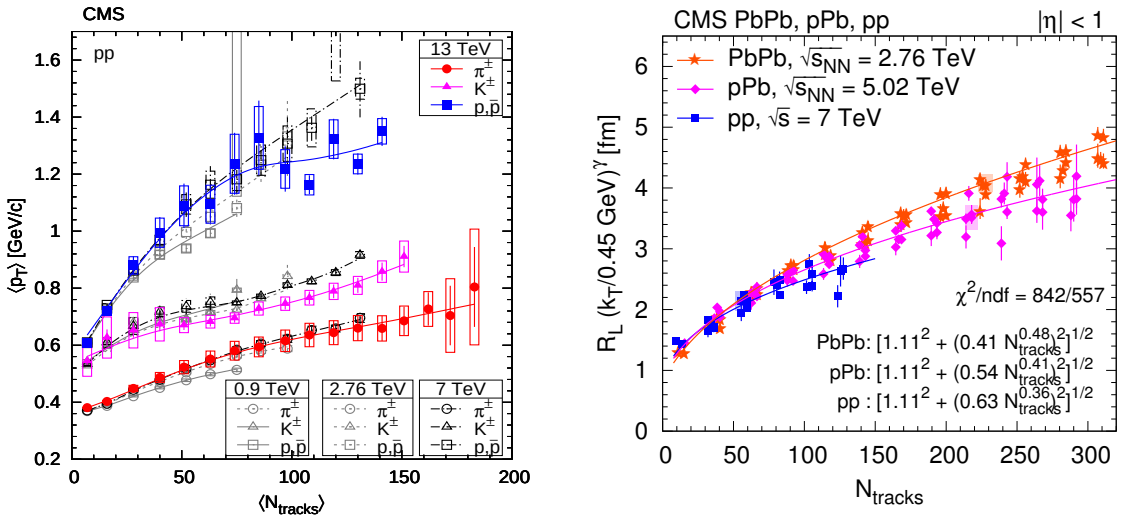


Figure 2: Left: Multiplicity dependence of average transverse momentum for charged pions, kaons, and protons in pp collisions [17]. Right: Multiplicity dependence of extent of the pion emitting source in various collision systems [18].

selected by transforming measured hits to a track parameter space with help of templates. The highly connected network of track candidates and their corresponding hits is cut into very many subgraphs by removing a few of its vulnerable components, edges and nodes. Finally the hits distributed among the candidates by exploring a deterministic decision tree. A depth-limited search is performed maximizing the number of hits on tracks, and also the sum of track-fit quality measures.

**Spectra of hadrons, and of identified particles** Our group has measured the spectra of charged pions, kaons and protons – identified through their energy loss in the tracker – in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ and compared them with pp at different collision energies (0.9, 2.76 and 7 TeV). We showed that particle production is strongly correlated with event multiplicity in all collision types, rather than with the center-of-mass energy or collision system. The data supports the assumption that the characteristics of particle production are constrained by the amount of initial parton energy that is available in any given collision [19, 20].

We have measured the pseudorapidity distribution ($\mathrm{d}N/\mathrm{d}\eta$) of charged hadrons in 13 TeV inelastic pp collisions. The data taking was performed without magnetic field, under special conditions, analyzed with a newly developed tracking algorithm. While the predictions of both Pythia8 and EPOS LHC event generators agree with the measured values at mid-rapidity, the measured distribution in the full range is better described by the latter [21]. The center-of-mass energy dependence of $\mathrm{d}N/\mathrm{d}\eta$ matches well the extrapolations based on lower energy data. These results were the first published results based on 13 TeV LHC data. They provide new constraints for the improvement of perturbative and nonperturbative QCD aspects of hadronic event generators [22].

We have measured the transverse momentum spectra of identified charged hadrons in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ [17]. The $p_{\mathrm{T}}$ spectra and integrated yields are compared to lower center-of-mass energy pp results and to Monte Carlo simulations. The average $p_{\mathrm{T}}$ increases with particle mass and the charged-particle multiplicity of the event.

A comparison with lower energy data shows only a moderate dependence of the average $p_{\mathrm{T}}$ on the center-of-mass energy. The Pythia8 CUETP8M1 event generator reproduces most features of the measured distributions, but EPOS LHC also gives a satisfactory description of several aspects.

**Quantum correlations of identified particles** We have measured short-range two-particle correlation functions of identified hadrons in pp, pPb, and peripheral PbPb collisions. The extracted radii of the particle emitting source (via Bose–Einstein correlations) are in the range 1-5 fm, reaching highest values for very high multiplicity pPb and PbPb collisions. The pp and pPb source is elongated in the beam direction, while in the peripheral PbPb case the source is symmetric. The dependence of the radii on the multiplicity and $k_{\mathrm{T}}$ factorizes and appears to be less sensitive to the type of the collision system and center-of-mass energy. The observed similarities may point to a common critical hadron density reached in the collisions [18, 23].

**Suppression at high $p_{\mathrm{T}}$, probes of nPDFs** Our group has measured charged particle spectra in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ in a wide transverse momentum range. The measured forward-backward asymmetry at $p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$ shows an enhancement in the Pb beam direction that is in qualitative agreement with nuclear shadowing expectations. The measured nuclear modification factor shows an enhancement at high $p_{\mathrm{T}}$ that is larger than expected from next-to-leading order perturbative QCD predictions which include anti-shadowing effects in the nuclear parton distribution functions (nPDF) in this kinematic range [24, 25].

We have developed a common event selection for the analysis of dijets in pPb collisions that was used later for other measurements as well. The dijet momentum imbalance shows no indication of jet quenching in pPb collisions, allowing the study of nPDFs with jets. The dijet pseudorapidity shows a shift away from theory expectation for pp collisions but it is consistent with predictions including the EPS09 nPDF set [26].

We have measured the spectra of charged particles at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ using PbPb and pp data [27]. The corresponding nuclear modification factor $R_{\mathrm{AA}}$ in the 5% most central collisions shows a maximal suppression by a factor of 7-8 in the $p_{\mathrm{T}}$ region of 69 GeV. This dip is followed by an increase and approaches unity in the vicinity of $p_{\mathrm{T}} = 200\,\mathrm{GeV}$. The $R_{\mathrm{AA}}$ is compared to theoretical predictions and earlier experimental results at lower collision energies. The newly measured pp spectrum is combined with the above mentioned pPb spectrum to construct its nuclear modification factor. For $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, it exhibits weak momentum dependence and shows a moderate enhancement above unity.

**Z bosons in nuclear collisions, probes of nuclear nPDFs** We have finalized the publication of the combined muon and electron channel results of Z boson production in PbPb and pp collisions. The results show that Z bosons are not modified by the hot and dense QCD medium: their production scales with the number of binary nucleon-nucleon collisions [29, 30]. Our group has performed the measurement of Z boson cross sections in pPb collisions. The inclusive cross section measured in the muon decay channel is consistent with binary collision scaling. The differential cross section as a function of rapidity and the forward-backward ratio shows hints of nuclear effects. The pPb collision data shows great potential for constraining the nPDF uncertainties by adding new data

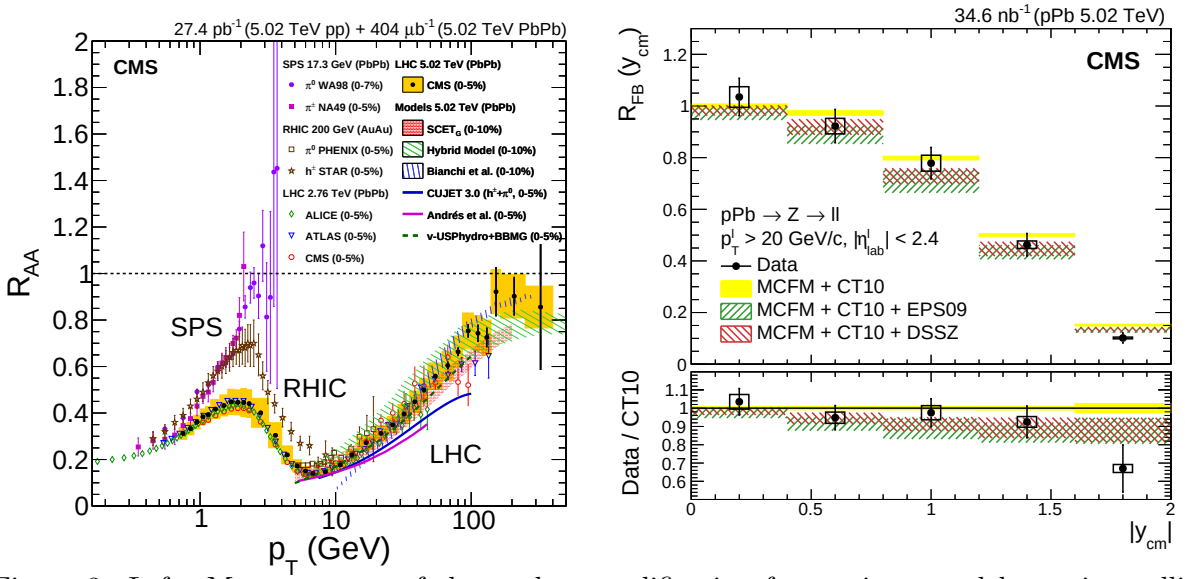


Figure 3: Left: Measurements of the nuclear modification factors in central heavy-ion collisions [27]. Right: Forward-backward asymmetry distribution of the Z bosons in pPb collisions compared to the predictions of MC generators [28].

points in a previously unexplored region of phase space [31, 32]. We have measured the Z boson production in pPb collisions also in the electron decay channel. The combined differential cross section shows better agreement with presence of nuclear effects. The combination of W boson, charged particle and jet measurements in pPb collisions provide constraints for nuclear parton distribution functions [28, 33].

We have measured the production of Z-jet pairs for the first time in pp and central PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [34]. A moderate shift in the jet $p_{\mathrm{T}}$ over Z boson $p_{\mathrm{T}}$ ratio is seen in central PbPb collisions with respect to the ratio found using pp data, in agreement with expected jet quenching effects. The results show that the recoiling jet stays back-to-back with the Z boson in the azimuthal direction, but there are less recoiling jets found in PbPb collisions compared to pp collisions, indicating the energy loss of the hard partons.

**Properties of the Higgs boson** We participated in discussions of the studies on the newly discovered Higgs boson and have shown that its properties indeed correspond to the predictions of the standard model. These result were presented at international conferences [35, 36, 37] and in a book [38].

**Search for supersymmetry** Our group participated in the completion of searches for supersymmetric particles in 8 TeV proton-proton collisions. We were looking for possible signatures of gluino-pair production and decays to top squarks where b-jets, a lepton, multiple light flavor jets, and missing transverse momentum were present. No excess was observed during these searches [39] and the results were interpreted as exclusion limits.

We participated in the preparation of summary publications on the search for supersymmetric particles, based on data 8 TeV pp data. Five mutually exclusive searches for supersymmetry were based on events in which b jets and four W bosons are produced [40]. The combined results yield confidence level limits for the gluino and bottom-

squark masses, they are excluded below 1280 and 570 GeV, respectively. Another search focussed on final states with an electron or muon and missing transverse energy [41]. No significant deviation of the transverse mass distribution of the charged lepton-neutrino system from the standard model prediction is found. Mass exclusion limits of up to 3.28 TeV for a W-boson with the same couplings as that of the standard model W-boson are determined.

# Leadership within the Collaboration; outreach

As a recognition of our work within the Collaboration our research group provided a convener for the Forward and Small-x QCD Group (G Veres); a coordinator for the Tracker Detector Performance Group (V Veszprémi); a coordinator for the Standard Model Group (G Pásztor); two subgroup leaders for the Heavy Ions Group (K Krajczár, AJ Zsigmond); two subgroup leaders for the Pixel subgroups (J Karancsi, T Vámi); and two members for the Publication Committee (D Horváth [also as English language editor], F Siklér). We participated in the internal discussion, cross-check, and preparation of more than 60 CMS publications as group or subgroup leaders, chairs or members of analysis review committees, and as participants of institutional reviews.

In recognition of their work two of us received the Academy Prize of the Hungarian Academy of Sciences (F Siklér, G Veres), and we have a winner in the Lendület (Momentum) Programme of the Academy (G Pásztor). A member got the CMS Achievement award twice (K Krajczár). With their CMS work, our students won first and second prizes at nationwide students' research competition (O Surányi, D Englert). Group members got a DSc (F Siklér), two PhD (AJ Zsigmond, A Makovec) and several MSc or BSc degrees.

In the past years we have pursued various educational activities in Hungary: among others the Hungarian Teachers' Program, Physics Bus led by Wigner RCP; the Physicists' Days and Researchers' Night at MTA Atomki. The aim was to raise the interest of high school students in natural sciences, and especially in physics [42]. In the MTA Atomki visitor center a new CMS Center was established.

# References


[1] J. Karancsi for the CMS Collaboration, "Operational Experience with the CMS Pixel Detector," JINST **10** (2015) C05016, arXiv:1411.4185 [physics.ins-det].

[2] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker," JINST **9** (2014) P10009, arXiv:1405.6569 [physics.ins-det].

[3] V. Veszprémi for the CMS Collaboration, "Radiation experience with the CMS pixel detector," JINST **10** (2015) C04039, arXiv:1411.5990 [physics.ins-det].

[4] M. Bartók for the CMS Collaboration, "Simulation of the Dynamic Inefficiency of the CMS Pixel Detector," JINST **10** (2015) C05006, arXiv:1411.6770 [physics.ins-det].

[5] T. Vámi for the CMS Collaboration, "Calibration of the CMS Pixel Detector at the Large Hadron Collider," Nucl. Part. Phys. Proc. **273-275** (2016) 2527–2529, arXiv:1506.05046 [physics.ins-det].

[6] J. Karancsi for the CMS Collaboration, "Operational experience with the CMS pixel detector in LHC Run II," JINST **11** (2016) C12057.

[7] V. Veszprémi for the CMS Collaboration, "Performance verification of the CMS Phase-1 Upgrade Pixel detector," in 11th International Conference on Position Sensitive Detectors (PSD11) Milton Keynes, UK, September 3-8, 2017. 2017. arXiv:1710.03842 [physics.ins-det].

[8] CMS Collaboration, "CMS Luminosity Measurement for the 2015 Data Taking Period,". https://cds.cern.ch/record/2138682/files/LUM-15-001-pas.pdf. CMS-PAS-LUM-15-001.

[9] CMS Tracker Collaboration, "Test Beam Performance Measurements for the Phase I Upgrade of the CMS Pixel Detector," JINST **12** (2017) P05022, arXiv:1706.00222 [physics.ins-det].

[10] CMS Collaboration, "P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC," JINST **12** (2017) P06018.

[11] A. Colaleo, A. Safonov, A. Sharma, and M. Tytgat, "CMS Technical Design Report for the Muon Endcap GEM Upgrade," Tech. Rep. CERN-LHCC-2015-012. CMS-TDR-013, 2015. https://cds.cern.ch/record/2021453.

[12] G. Berruti, M. Consales, A. Borriello, M. Giordano, S. Buontempo, A. Makovec, G. Breglio, P. Petagna, and A. Cusano, "A Comparative Study of Radiation-Tolerant Fiber Optic Sensors for Relative Humidity Monitoring in High-Radiation Environments at CERN," IEEE Photonics Journal **6** (2014) 1–15.

[13] M. Consales, G. Berruti, A. Borriello, M. Giordano, S. Buontempo, G. Breglio, A. Makovec, P. Petagna, and A. Cusano, "Nanoscale TiO2-coated LPGs as radiation-tolerant humidity sensors for high-energy physics applications," Optics Letters **39** (2014) 4128–4131.

[14] A. Makovec, G. Berruti, M. Consales, M. Giordano, P. Petagna, S. Buontempo, G. Breglio, Z. Szillasi, N. Beni, and A. Cusano, "Radiation hard polyimide-coated FBG optical sensors for relative humidity monitoring in the CMS experiment at CERN," JINST **9** (2014) C03040.

[15] G. M. Berruti, P. Petagna, S. Buontempo, A. Makovec, Z. Szillasi, N. Beni, M. Consales, and A. Cusano, "One year of FBG-based thermo-hygrometers in operation in the CMS experiment at CERN," JINST **11** (2016) P03007.

[16] F. Siklér, "Combination of various data analysis techniques for efficient track reconstruction in very high multiplicity events," EPJ Web Conf. **150** (2017) 00011.

[17] CMS Collaboration, "Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s} = 13$ TeV," arXiv:1706.10194 [hep-ex]. submitted to Phys. Rev. D.

[18] CMS Collaboration, "Femtoscopy with identified charged hadrons in pp, pPb, and peripheral PbPb collisions at LHC energies,". https://cds.cern.ch/record/1703272/files/HIN-14-013-pas.pdf. CMS-PAS-HIN-14-013.

[19] CMS Collaboration, "Study of the production of charged pions, kaons, and protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," Eur. Phys. J. C **74** (2014) 2847, arXiv:1307.3442 [hep-ex].

[20] F. Siklér for the CMS Collaboration, "Identified particles in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with the CMS detector," Nucl. Phys. A **926** (2014) 128–135.

[21] CMS Collaboration, "Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s} = 13$ TeV," Phys. Lett. B **751** (2015) 143–163, arXiv:1507.05915 [hep-ex].

[22] F. Siklér for the CMS Collaboration, "First 13 TeV results from CMS," EPJ Web Conf. **120** (2016) 09001.

[23] F. Siklér for the CMS Collaboration, "Femtoscopy with identified hadrons in pp, pPb, and peripheral PbPb collisions in CMS," 2014. arXiv:1411.6609 [hep-ex]. Proceedings of the WPCF 2014 workshop, Gyöngyös, Hungary.

[24] CMS Collaboration, "Charged particle nuclear modification factor and pseudorapidity asymmetry in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with CMS,". https://cds.cern.ch/record/1625865/files/HIN-12-017-pas.pdf. CMS-PAS-HIN-12-017.

[25] K. Krajczár for the CMS Collaboration, "Transverse momentum and pseudorapidity dependence of charged particle production and nuclear modification factor in protonlead collisions at $\sqrt{s_{NN}} = 5.02$ TeV with CMS," Nucl. Phys. A **932** (2014) 174–178.

[26] CMS Collaboration, "Studies of dijet transverse momentum balance and pseudorapidity distributions in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV," Eur. Phys. J. C **74** (2014) 2951, arXiv:1401.4433 [nucl-ex].

[27] CMS Collaboration, "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{N\,N}}} = 5.02$ TeV," JHEP **04** (2017) 039, arXiv:1611.01664 [nucl-ex].

[28] CMS Collaboration, "Study of Z boson production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," Phys. Lett. B **759** (2016) 36–57, arXiv:1512.06461 [hep-ex].

[29] A.J. Zsigmond for the CMS Collaboration, "Electroweak bosons in heavy ion collisions in CMS," Nucl. Phys. A **926** (2014) 34–40.

[30] CMS Collaboration, "Study of Z production in PbPb and pp collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in the dimuon and dielectron decay channels," JHEP **03** (2015) 022, arXiv:1410.4825 [nucl-ex].

[31] A.J. Zsigmond for the CMS Collaboration, "Study of Z boson production in pp, pPb and PbPb collisions in CMS," J. Phys. Conf. Ser. **612** (2015) 012011.

[32] CMS Collaboration, "Study of Z boson production in the muon decay channel in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,". https://cds.cern.ch/record/1703012/files/HIN-14-003-pas.pdf. CMS-PAS-HIN-14-003.

[33] A.J. Zsigmond for the CMS Collaboration, "CMS results on electroweak probes from LHC Run 1," Nucl. Part. Phys. Proc. **276-278** (2016) 237–240.

[34] CMS Collaboration, "Study of Jet Quenching with $Z$ + jet Correlations in Pb-Pb and $pp$ Collisions at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$," Phys. Rev. Lett. **119** (2017) 082301, arXiv:1702.01060 [nucl-ex].

[35] D. Horváth, "Twenty years of searching for the Higgs boson: Exclusion at LEP, discovery at LHC," Mod. Phys. Lett. A **29** (2014) 1430004, arXiv:1402.6103 [hep-ex].

[36] D. Horváth, "Broken Symmetries and the Higgs Boson," EPJ Web Conf. **78** (2014) 01003.

[37] CMS Collaboration, "Search for the Higgs Boson: a Statistical Adventure of Exclusion and Discovery," J. Phys. Conf. Ser. **510** (2014) 012001, arXiv:1310.6839 [hep-ex].

[38] D. Horváth, A Higgs-bozon. Typotex, Budapest, 2014.

[39] CMS Collaboration, "Search for supersymmetry in pp collisions at $\sqrt{s}$=8 TeV in events with a single lepton, large jet multiplicity, and multiple b jets," Phys. Lett. B **733** (2014) 328–353, arXiv:1311.4937 [hep-ex].

[40] CMS Collaboration, "Searches for supersymmetry based on events with b jets and four W bosons in pp collisions at 8 TeV," Phys. Lett. B **745** (2015) 5–28, arXiv:1412.4109 [hep-ex].

[41] CMS Collaboration, "Search for physics beyond the standard model in final states with a lepton and missing transverse energy in proton-proton collisions at $\sqrt{s} = 8$ TeV," Phys. Rev. D **91** (2015) 092005, arXiv:1408.2745 [hep-ex].

[42] E. Oláh *et al.*, "Particle physics education in Hungary," Nucl. Part. Phys. Proc. **273-275** (2016) 2569–2571.