2023

Physics analyses at the LHC. — The inclusive search for RPV models of supersymmetry in Run 2 proton-proton collisions at 13 TeV center of mass energy with razor variables using boosted W/Z/Higgs bosons, boosted hadronic or leptonic top quarks or boosted leptonic jets has been completed. Our contribution this year was to extend the scale factor calculations into the fast simulation samples and for the non-isolated leptons in full simulation. The leptons are defined by special object cuts tuned to select electrons and muons originating from leptonic top decays. The analysis is now under internal review by the CMS collaboration and is being prepared for publication.
The search for supersymmetry motivated by the gauge-mediated supersymmetry breaking model – in which low-mass gravitinos are assumed to be the lightest supersymmetric particles (LSP) and neutralinos are the next-to-LSPs – identified in final states with photon, b-tagged jets and missing transverse momentum has been updated for the Run 2 data and simulation that feature improved reconstruction. The results are being collated for the upcoming internal CMS review process in collaboration with the ELTE colleagues.

Detector operation and construction. — During the data collection in 2023, we have carried out performance studies of the pixel detector. High voltage bias scans were performed several times throughout the year in order to monitor the evolution of the silicon bulk due to radiation damage. Radiation damage leads to non-negligible hit detection efficiency loss, especially in layer 1 (the innermost layer) of the pixel detector (seen in Fig. 1). The tracking efficiency impacted by was being monitored throughout the year. We have updated the simulation description of the pixel detector in order to incorporate this effect, which is crucial to retain good agreement between the reconstructed simulation and collision data.

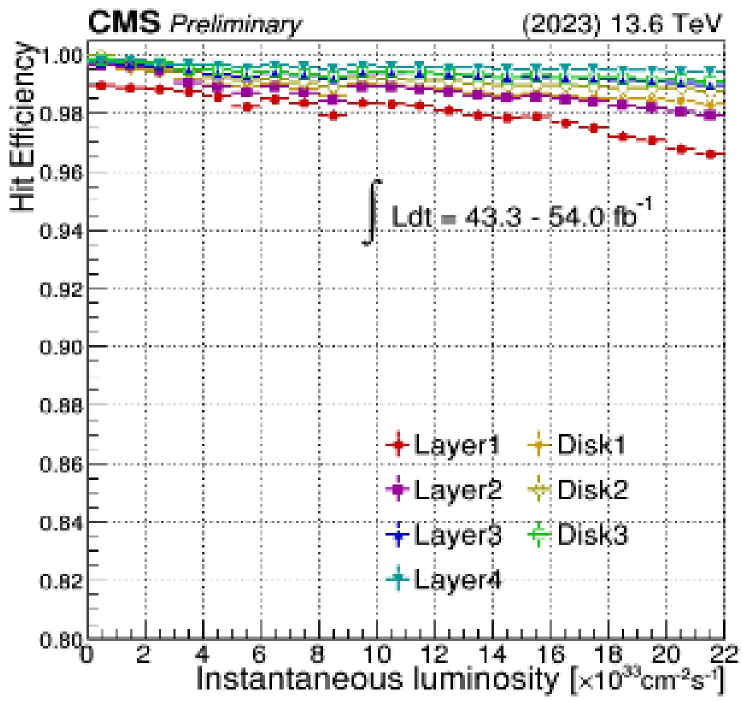

Figure 1: Particle detection efficiency of the CMS pixel detector as function of the instantaneous luminosity at the start of Run 3 [1].

We have also studied the overall readiness of the pixel detector for the Run 3 data-taking period [2].
In the first half of 2023, we finished the preparation of the clean room: installed new air filters and all the equipment needed for the visual inspection of the CMS Phase-2 Outer Tracker hybrid electronics. We have also upgraded the large area scanner with new camera and other optical accessories and rewrote the control software to work under Linux using open source, license free code-base, making it possible to control the scanning process from C++ code and to take into account large variations in the height of the scanned samples. We have designed special sockets to hold the hybrids during the automated optical inspection (Fig. 2). The first sets of the different hybrid electronics (~25 / each type) were produced, tested, and assembled into detector modules in the second half of 2023. The experiences collected during the work with these hybrids suggested that some small modifications in the designs and improvement in the production scheme were still necessary before the mass production of the ~50.000 parts in 2024. They also showed that the testing procedure and the acceptance criteria of the hybrids have to be reviewed and optimized [3].

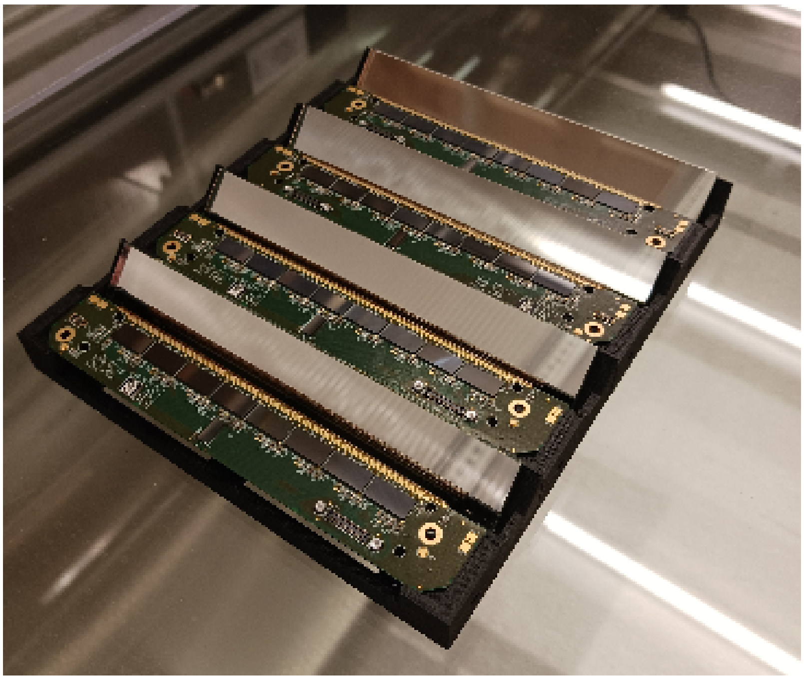

Figure 2: Inspection of CMS Outer Tracker module hybrids with the optical scanner

Superconducting magnet development. — The "SuShi" (Superconducting Shield) septum magnet has been successfully tested at the FREIA facility of the Uppsala Unviersity, Sweden (Fig. 3) [4]. This was the first canted cosine theta-type magnet that was fully impregnated with paraffin wax in a single process. The magnet reached nominal current without training, and did not quench during the entire testing period.

The group completed the design of the combined-function NbTi canted cosine theta prototype magnet of the I.FAST European project. The group engaged in the development of the HTS (high-temperature superconductor) canted cosine theta magnet prototype of the I.FAST project, and developed the basic techniques to manufacture this novel magnet and the necessary infrastructure.

In collaboration with the University of Miskolc, the manufacturing technique of a multilayer NbTi/Cu sheet (eliminating the interleaving Nb diffusion barrier layers) was developed. Preliminary measurements indicate critical current densities similar to earlier products.

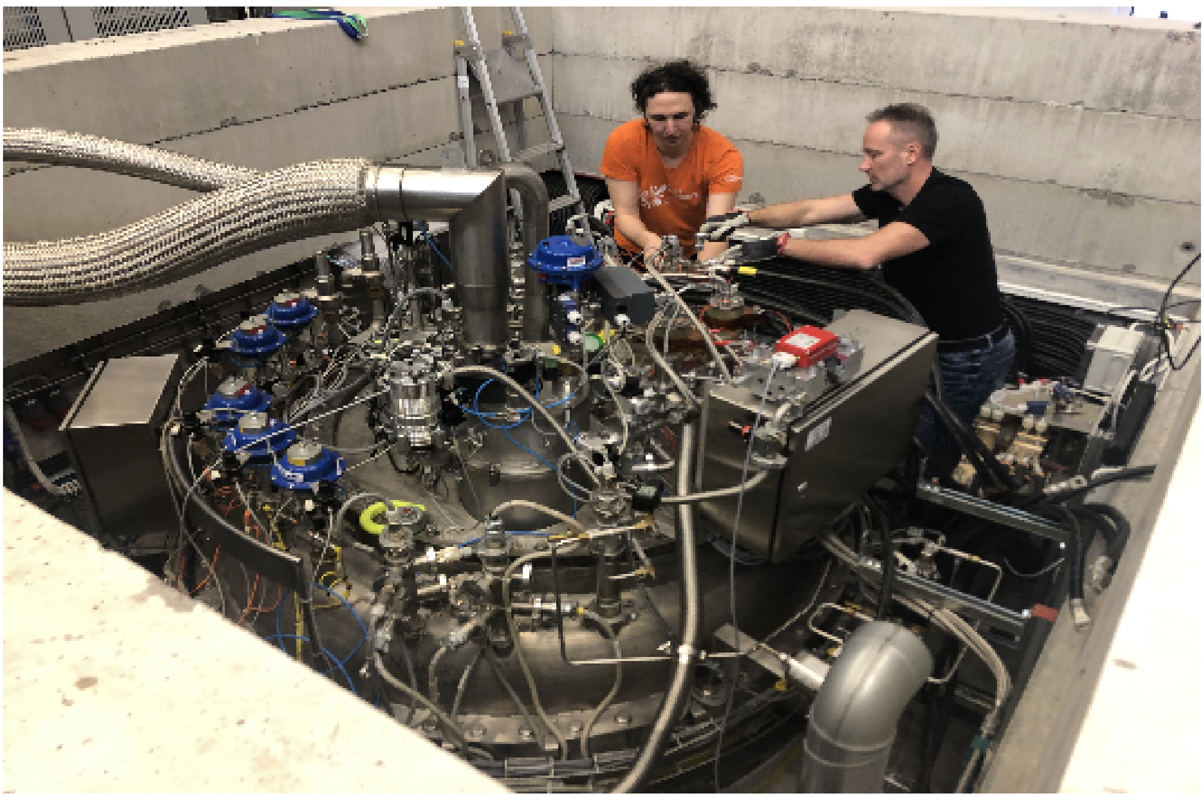

Figure 3: Test of the SuShi septum magnet in the FREIA facility of Uppsala University

References:
[1] http://cds.cern.ch/record/2865842?ln=en
[2] DOI: https://doi.org/10.22323/1.420.0008
[3] DOI: https://doi.org/10.5281/zenodo.8346835
[4] DOI: https://doi.org/10.1109/TASC.2024.3354223

2022

Physics analyses at the LHC. — A search for supersymmetry in proton-proton collisions at 13 TeV center of mass energy motivated by the gauge mediated supersymmetry breaking model in which low-mass gravitinos are assumed to be the lightest supersymmetric particles (LSP) and neutralinos are the nex-to-LSPs is being developed observing final states with photon, b-tagged jets and missing transverse momentum. In the considered simplified models, the neutralinos are either directly produced via electroweak processes or are the decay products of strongly produced gluino pairs. The expected lower exclusion limit in the electroweak model is 1.2 TeV for the neutralino, and in the strong process model, 1.8 – 2.2 TeV for the gluino. The analysis methods are being finalized, in collaboration with ELTE colleagues, for the improved reconstructed Run 2 data and simulation (so called Ultra Legacy datasets [1])

The inclusive search for supersymmetry using razor variables and boosted object identification in zero and one lepton final states are also being updated using the entire Run 2 data. We have contributed to this analysis in 2022 by calculating the electron and muon scale factors that are used to correct for the object reconstruction and cut discrepancies between simulation and collision data.

The searches for new physics in the Run 2 data are near completion, and a significant improvement in sensitivity is only foreseen towards the end of Run 3. While we are preparing to incorporate new data to be measured between 2022 and 2025 into these searches, we have started to set up a precision measurement of the Standard Model in order to further exploit the already available data. We have started to study the Z boson production with two heavy flavor jets, processes that are of interest both as major, often irreducible, backgrounds in the studies of the Higgs boson and as subjects of relatively incomplete studies in the hadronic collider experiments.

Detector operation and construction. — With the start of Run 3 in 2022, we have carried out initial calibrations and performance studies of the pixel detector. High voltage bias scans were performed 14 times and the evolution of the charge collection efficiency as function of the production depth were measured throughout the year in order to monitor the evolution of the silicon bulk due to radiation damage. The pixel detector will suffer a large radiation damage, to the greatest extent in layer 1 (the innermost layer), towards the end of Run 3 and the clusters are expected to be broken. This will lead to a loss in tracking efficiency and performance. To repair these broken clusters, an algorithm has been developed and tested on MC simulation.

The production of the CMS Phase-2 hybrid electronics started at the end of 2022, the testing and the module assembly will start in 2023. The preparation of the infrastructure and the training of the team for the visual inspection of the electronics continued during 2022. We have improved the ESD protection of the clean room and finalized the setup of the workstations, where about 20000 circuits will be inspected with stereo-microscopes in the next three years. We have made several developments concerning the large area optical scanner, which will be also used during the optical testing of the hybrids. We also contributed in the testing of the prototypes and wrote an Inspection Manual.

SuShi septum for the Future Circular Collider (FCC). — In collaboration with CERN, the FCC SuShi septum prototype magnet's winding has been completed (Fig. 1, 2). A method has been developed to impregnate CCT magnets with wax, coping with its ~15% volumentric upon solidification (Fig. 3)

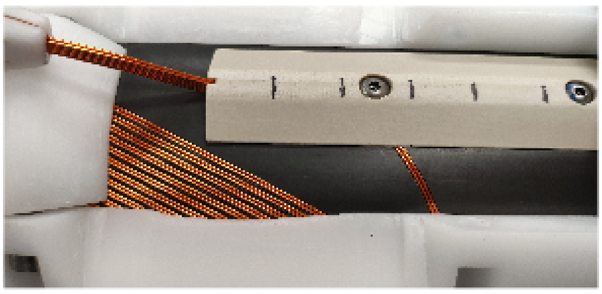

Fig. 1. Winding of the SuShi septum magnet

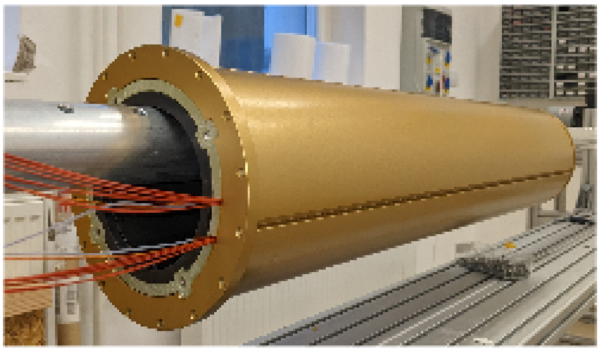

Fig. 2. Winding of the SuShi septum magnet

Hadron therapy. — The group is participating in the HITRI+ project to develop a compact superconducting synchrotron for proton and carton ion treatment of tumors. A new algorithm for optimizing the field quality of curved CCT magnets have been developed [2].
Test winding of a straight CCT former with 2x8 polyester-insulated twisted ropes (each containing 7 superconducting strands) has been carried out at Wigner RCP with the participation of colleagues from INFN Milano, and Ciemat. (Fig. 4). The developed method of wax impregnation was demonstrated to work in this configuration as well.

Fig. 3. Demonstration of the wax impregnation method. A single CCT layer impregnated with wax, without voids.

Fig. 4. Test winding of a straight CCT former for the HITRI+ project.

2021

Search for new physics at the LHC and detector operation. — Searches are ongoing for the production of supersymmetric particles, in collaboration with ELTE colleagues, in particular for scalar top quarks (stops) using the full Run 2 data set. Our latest involvement was in an update of the analysis method developed in our earlier publication [JHEP 03 (2019) 031)]. It now utilizes the latest deep learning techniques in CMS to identify Higgs bosons, W and Z bosons and boosted hadronically decaying top quarks.

We have taken the last turn before the finish line in the preparation of the CMS Tracker detector for Run 3 of the Large Hadron Collider (LHC). We co-lead the organization to refurbish the pixel detector [1]. The components which were designed and produced by our group did not need any rework, but we have repaired two (DOH) control boards that have been exchanged with spare boards. We have played a major role in the recommissioning of the detector after reinsertion and verifying its performance by reestablishing time alignment with cosmic ray measurements and in LHC beam test collisions.

SuShi septum for the Future Circular Collider (FCC). — In collaboration with CERN, the research group is developing a septum magnet prototype for FCC [2], based on a new concept: the application of a passive superconducting shield (SuShi) inside the bore of a superconducting canted cosine theta magnet, to create a field-free channel for the circulating beam, while the extracted beam would be kicked into the high-field domain by an upstream kicker magnet. All components of the magnet have been manufactured and are ready for winding and assembly (Fig. 1).

Figure 1. The hard-anodized aluminum formers and the winding test of the SuShi septum magnet prototype.

Hadron therapy. — The HITRIplus (Heavy Ion Therapy Research Integration Plus) H2020 project started in 2021 with the aim of creating a reference design of a small superconducting synchrotron for hadron therapy, among others. Treatment of tumors using charged particle beams (protons, carbon or other ions) has the advantage compared to X-ray therapy of a much greater contrast of energy deposition between the tumor and the surrounding healthy tissues. However, this treatment method is much less widespread due to the complexity, large size and high construction and operational costs of these machines. The application of high-field superconducting accelerator magnets could very significantly decrease both the footprint and the associated costs of these machines. Our research group has actively participated in the design of a novel, strongly curved magnet prototype, and worked out the optimization algorithm of the magnet winding to achieve the ideal magnetic field pattern. Two such winding geometries are shown in Fig. 2.

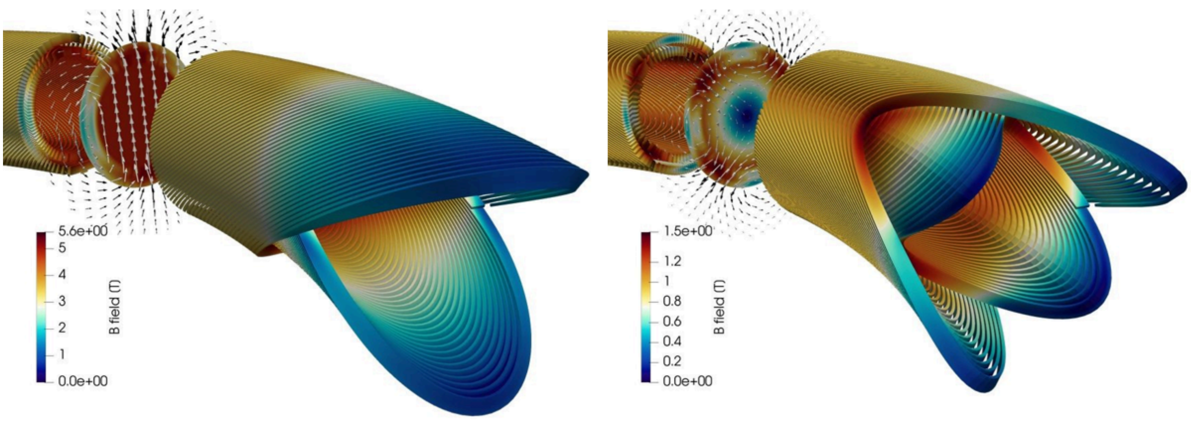

Figure 2. Optimized winding geometries of curved “canted cosine theta” superconducting magnet producing a dipole (bending) and quadrupole (focusing) field.

CMS Tracker Phase 2 upgrade for the High Luminosity LHC. — As preparation for the High Luminosity LHC, the CMS Tracker collaboration is going to replace its entire tracking system during the next long shutdown of the LHC, between 2025 and 2027. The upgraded Outer Tracker will consists of about 13000 silicon detector modules, each of which equipped with up to four different kinds of hybrid electronic components responsible for powering and read-out. In part of the Quality Assurance Plan, the inspection of a third of the hybrids (about 20000 pieces) will be performed at Wigner between 2022 and 2025 as intermediate step of the detector production.

In 2021, several upgrades have been performed to prepare our infrastructure for handling these sensitive components. A humidifier with water-cleaning system and two more air conditioning units have been installed in the clean room and a new system developed for temperature, humidity and air quality monitoring. Our stereo-microscope have been upgraded and two more microscopes installed. The large area optical scanner has also been upgraded with a color camera and with colored LED lighting. Their inclusion to the scanner software is ongoing.

In 2021, during the development and prototyping phase of the hybrids, we have inspected several prototype units in our lab and processed them with the optical scanner. We have helped with the finalization of the inspection checklist and in the development of the production database. The hybrid production project passed the Engineering Design Report at the end of 2021.

2020

Search for new physics at the LHC. — In collaboration with MTA-ELTE CMS Particle and Nuclear Physics Group, we have worked on a new search for supersymmetry in proton-proton collisions at 13 TeV center of mass energy in photon, b-tagged jets and missing transverse momentum final states. This search is motivated by the gauge mediated supersymmetry breaking model in which low-mass gravitinos (superpartner of the hypothetical gravitons) are assumed to be the lightest supersymmetric particles (LSP) and neutralinos are the nex-to-LSPs (NLSP). Two simplified models are considered when the neutralinos are directly produced via electroweak process and when they are decay products of strongly produced gluino pairs. They further decay to a gravitino and either a photon or a Higgs boson. The analysis aims to identify these Higgs bosons through their most dominant decay, to pair of b and anti-b quarks. Current estimates suggest that if the data in the search region agrees with the estimated backgrounds the expected SUSY exclusion on the neutralino mass is at 1.2 TeV in the electroweak model, and on the gluino mass is at 1.8 – 2.2 TeV in the strong process model.

Detector development. — During the construction of the CMS Phase 2 Outer Tracker, all components that make up the semiconductor modules (Figure 1) will go through a thorough testing procedure. As a part of this process, more than 50000 high density circuit boards (called ‘hybrids’, Figure 2), the carriers of the signal processing front-end chips, will have to be inspected functionally and visually before they can be connected to the silicon sensors via wire-bonds. In the beginning of 2020, our group joined the project by volunteering for the optical test of about 20000 hybrids during the production period (2022-2024). The group started out by participating in the prototyping phase, the finalization of the designs and the development of the testing and module building procedures. Performed the visual testing of the latest prototype hybrids and identified issues to be improved by the manufacturer for the production phase.

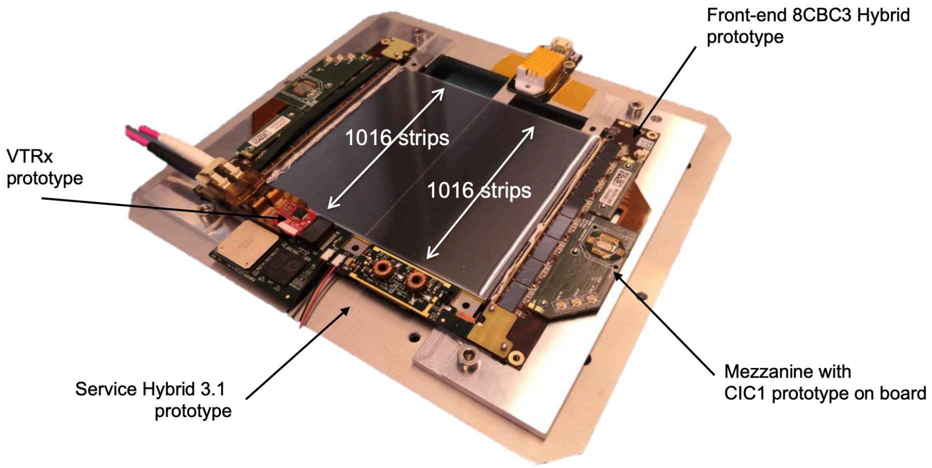

Figure 1. *A Phase 2 Outer Tracker module (https://cds.cern.ch/record/2703569)*

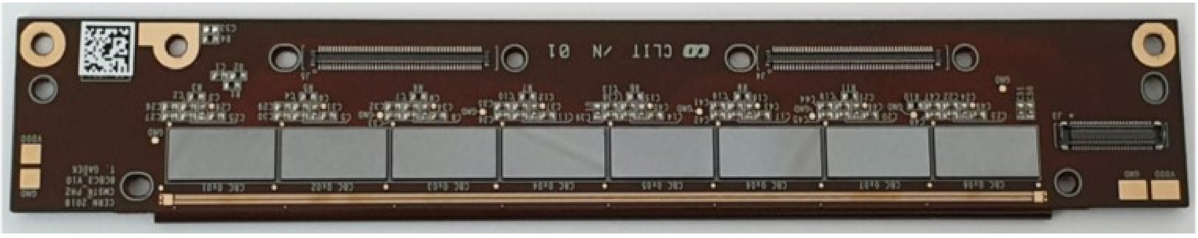

Figure 2. *A hybrid prototype to read out half of a Phase 2 Outer Tracker module with eight read-out chips above the 1016 wire-bond pads where the silicon implants are connected.*

We have started to investigate the feasibility of using the large area optical scanner in the clean room at our department by developing a software for basic measurements and object identification. We also started to upgrade the infrastructure in order to provide proper environment for the hybrid handling.

We have made progress in developing a trigger card for clock and trigger distribution in a data-acquisition system within a uTCA crate that hold the DAQ development boards for Phase 2 Tracker module read-out in order to support the beam tests of Inner and Outer Tracker module prototypes at CERN. The new card is able to read back the state of each DAQ card in the crate and send control commands to them in order to facilitate synchronous data-acquisition and time-stamping.

The refurbishment of the Phase 1 pixel detector is progressing well, on track for the re-installation in CMS this year, and to be ready for data-taking in the beginning of 2022. We have completed the publication of the hardware construction of the detector, and begun the preparation for a **paper to describe its performance in Run 2. We have served in leadership roles within the CMS Tracker project during 2020.**

High field extraction magnet design for accelerators. — The necessary infrastructure for the development of canted cosine theta type magnets was constructed, including a winding machine and vacuum epoxy-impregnation system. The manufacturing and procurement of the SuShi septum magnet prototype have started.

References:

[1] Veszprémi V.: "A Higgs-bozon kutatása: befejezett vagy csak most kezdődik?", Fizikai szemle, 2020 április

[2] CMS Tracker Collaboration [incl. V. Veszprémi], "Beam test performance of prototype silicon detectors for the Outer Tracker for the Phase-2 Upgrade of CMS", 2020 JINST 15 P03014.

[3] D. Barna, M. Novák: Two-dimensional conceptual design of a superconducting iron-free opposite field septum magnet. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 959 (2020), 163521

2019

Search for new physics at the LHC. — We have completed an inclusive search for supersymmetry in proton-proton collisions at 13 TeV center of mass energy using razor variables and boosted object identification in zero and one lepton final states [1]. No signs of new particles have been found; therefore, the results were interpreted as exclusion limits in simplified models of gluino and stop pair production assuming R-parity conservation (Figure 1). The lower limits on the gluino and top squark masses were extended to 2.0 TeV and 1.14 TeV respectively using 35.9 fb^{-1} Run 1 data. This work also earned a PhD for J. Karancsi in the University of Debrecen, under the supervision of V. Veszprémi. The data we have recorded during Run 2, however, has nearly tripled since Run 1. T. Vámi has completed his MSc thesis under the supervision of V. Veszprémi on a study aiming to determine the increase of the sensitivity expected when this new data is included. This was also the first time, when we considered data that was collected with the new Phase-1 pixel detector, in the construction of which we played a major role.

Detector operation. — In 2019, we worked on recomputing all the calibration parameters of the pixel detector for the legacy reconstruction of the data acquired between 2016 and 2018. We contributed to the assessment and bookkeeping of dead areas of the detector during these three years and passing this information to tracking in order to improve charge particle tracking. We also implemented the statistically accurate simulation of the time evolution of the dead areas in order to improve the simulation of the systematic errors in tracking. With this effect, simulation more closely reproduces the efficiency of tracking, b-tagging, and lepton reconstruction seen in data and makes it possible to reduce the systematic uncertainty in physics analyses. We have fulfilled important leadership roles: T. Vámi served as the convenor of CMS Pixel Calibration, Reconstruction, and Simulation group, and V. Veszprémi as the Deputy Project Manager of the CMS Tracker Project.

We have published a major article on the construction of the Phase 1 pixel detector [2]. The article describes our work in the design, the production, and the verification of the read-out electronics with details on the load-balancing technique applied for optimizing the read-out in the high occupancy environment. It also describes our beam test work of the Phase 1 prototype modules, measurement of bad detector components, and efficiency loss measurements.

Detector development. — Several presentations were made on the status of the CHROMIE high-rate test beam telescope to be used for Phase 2 Tracker module testing in the CERN SPS accelerator. Our contribution to the telescope was the design and construction of the read-out electronics, the development of the simulation and reconstruction code, and part of the commissioning. A new beam facility is being put in place in IPHC, Strasbourg, France utilizing a copy of our telescope called CHROMini. We have been working together with the Starsbourg colleagues and CERNTech engineers from Budapest to upgrade the 200 MHz per cm^2 current hit-rate limit of the CHROMini telescope to around 600 MHz per cm2. We have also been developing a data-acquisition, and clock and trigger distribution system within a uTCA crate (Figure 2.) using FPGA cards for reading out both the CHROMIE telescope modules and the CMS Tracker Phase 2 upgrade prototype chips.

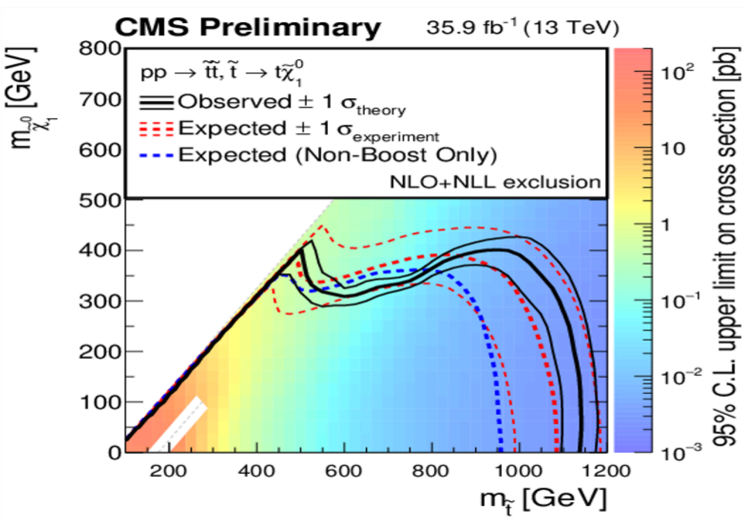

Figure 1. Expected and observed 95% upper limits on the production cross section for pair-produced top squarks decaying to top quarks where the sensitivity increase due to the boosted topology is most prominent [1].

Figure 2. The uTCA crate with two FPGA cards for programming and reading out Phase 2 prototype modules and an FPGA card providing trigger, clock, and control signals via optical link to the secondary crate controller.

High field extraction magnet design for accelerators. — The 3D design of the SuShi septum magnet prototype has nearly been completed. An exploded view of the design is shown in Figure 3.

Future medical superconducting synchrotrons will require very compact solutions for each element of the accelerator. We have proposed a concept to realize a superconducting opposite-field septum magnet for beam extraction, which could reach +/-0.7 T magnetic field in its two adjacent domains with a wall as thin as 4 mm, thereby reducing the required distance to the extraction kicker magnet. The 2-dimensional wire configuration and field pattern are shown in Figure 4.

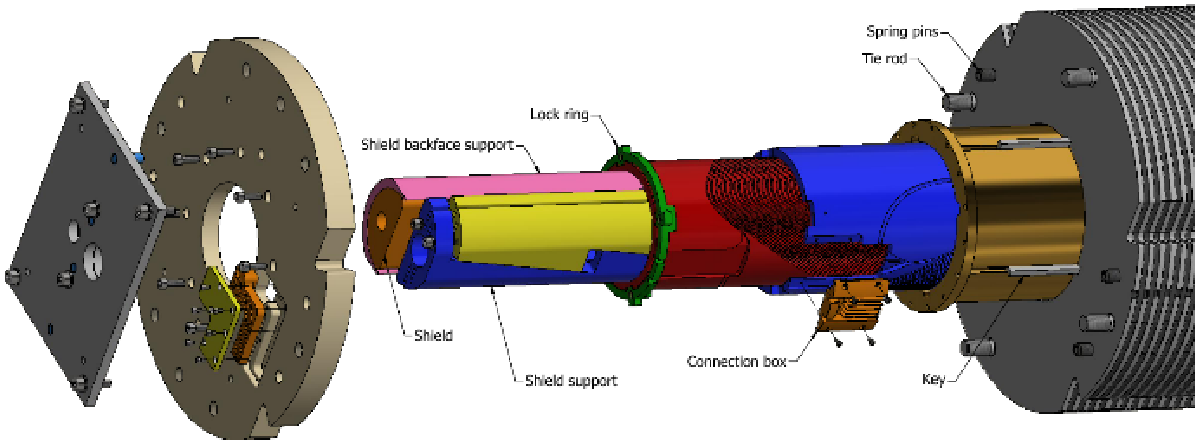

Figure 3. Exploded view of the SuShi septum magnet prototype and the superconducting shield.

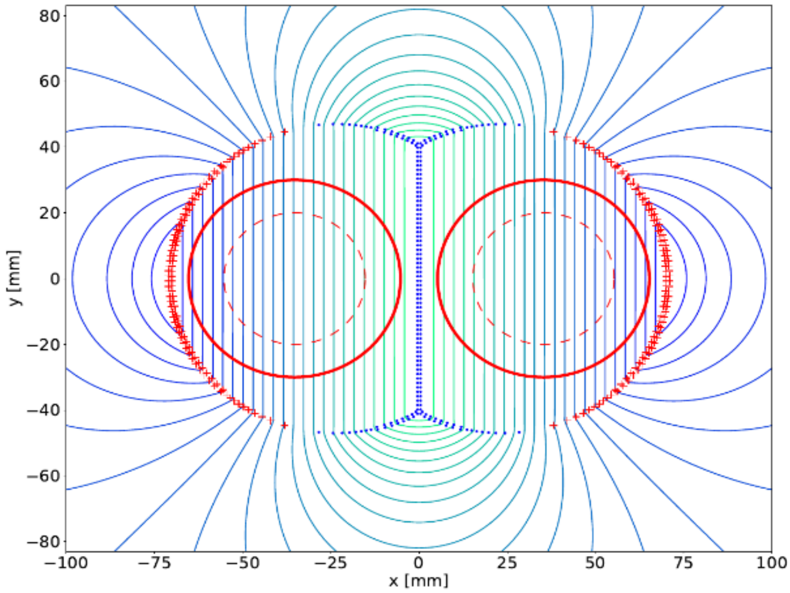

Figure 4. 2D wire configuration and magnetic field pattern of the iron-free superconducting opposite field septum magnet.

2018

Physics analyses and theoretical work. — The group has contributed to bringing an inclusive search for supersymmetry with boosted objects to publication stage using proton-proton collision data that corresponded to an integrated luminosity of 35.9 fb-1, taken prior to 2017. Exclusion limits on the gluino mass were extended to 2 TeV, while on the stop quark mass to 1.14 TeV. Profiting from the opportunity that the LHC has gone into a more than two-year long shutdown, we have started to reprocess the data we took with the new pixel detector in the last two years using improved calibration and detector description models for further analysis in order to approximately double the analysis sensitivity. We provided a member for the Publication Committee of the CMS Experiment at CERN and played an important role in publishing CMS results of low-x QCD studies. We hold leadership positions, a group convenor and a deputy project manager, in the CMS Tracker project.
The stable operation of the T2_HU_Budapest grid site continued in 2018. Our site is used extensively by the entire CMS collaboration including our group for reconstructing collision data in physics analyses. The disk capacity committed to CMS has increased to 1 PB.
We proposed a general concept of bosonic operator orderings and generalized Wick's theorem transforming any ordering into any other one. We pointed out how Planckian scale challenges the validity of the massive body Schrödinger equation.

Work on instrumentation. – The group created a test setup for developing the CMS Phase 2 Upgrade Inner Tracker data-acquisition system, and started to develop firmware in order to calibrate and read out the new sensors that are being designed for the upgraded detector. We have constructed a test-beam telescope to be used for the high rate tests of the new Phase 2 Tracker chips; commissioned the telescope and took the first data using the Phase 2 Outer Tracker chip prototypes at the SPS at CERN.
The SPS Diffuser designed and constructed by our group was successfully installed and tested in the CERN SPS accelerator, and delivered the expected performance in terms of loss reduction. The conceptual design of a high-field extraction septum magnet for the Future Circular Collider was completed, which uses the combination of a superconducting magnet and a passive superconducting shield.

Outreach. – An education program was organized by Wigner RCP at CERN with the leadership of our group: the annual Hungarian Teachers Programme (18-25 August 2018) for 21 physics teachers. For the teachers we organized a meeting on December 8 at Wigner RCP with the lecturers. We also participated in the organization of the annual Hands-on Particle Physics Master-classes on two occasions with 22 high-school students attending each session. We have also participated in the organization of two scientific seminars on particle physics for the Celebration of Hungarian Science on particle physics at the Hungarian Academy of Sciences and at the Roland Eötvös University. In addition to conference talks and university teaching, many popular lectures were given by our group.

2017

Physics analyses and theoretical work. — Our group has measured cross-section limits on supersymmetric processes leading to strongly boosted top quark decays in the data recorded by the CMS detector at the LHC prior to the 2017 installation of the new pixel detector. We have also doubled the recorded collision data using the new pixel detector during 2017. We provided a member for the Publication Committee of the CMS Experiment at CERN and played an important role in publishing CMS results of low-x QCD studies.

The group participated in the ASACUSA experiment at the Antimatter Factory of CERN, which provides a test of the CPT invariance, the theorem stating the equivalence of matter and antimatter, via measuring the transition energies of antiprotons trapped helium atoms using laser spectroscopy. The method leading to the precise determination of the agreement between the proton and antiproton masses earlier was extended to superfluid helium; the data are still in analysis. The first steps were made to use two-photon laser spectroscopy on antiprotonic helium atoms cooled down below 1.7 K in cryogenic low-pressure helium gas.

We wrote and published the first Hungarian textbook of quantum information theory. We proposed the Principle of Least Decoherence and, based on it, improved the widely used theory of semi-classical gravity, which will henceforth not violate the linearity of quantum mechanics.

Work on instrumentation. — The group has successfully commissioned the new pixel detector installed at the CMS experiment in 2017, the control and read-out electronics of which device was developed and manufactured by our group. We have prepared the 3D detector model and the software for the reconstruction of the new data, organized the spatial and temporal alignment of the new detector, and completed the calibration of the reconstruction algorithms. We also verified that the detector performance meets its design requirements.

The stable operation of the T2_HU_Budapest grid site continued in 2017. Our site is used extensively by the entire CMS collaboration including our group for reconstructing collision data in physics analyses. The disk capacity committed to CMS has increased to 900 TB.

We have successfully tested two superconducting shield prototypes for the *Superconducting Shield Septum* project: a high-temperature superconductor and MgB2. The performance of the MgB2 prototype was satisfactory for its application. We have designed and constructed a device called “SPS Diffuser”, which will be installed in the CERN SPS accelerator to decrease the radiation load on the electrostatic septum.

Outreach. – Two education programs were organized by Wigner RCP at CERN with the leadership of our group: the High-School Student Internship Programme (22 May - 2 June 2017) with the participation of 22 students and the Hungarian Teachers Programme (15-21 August 2016) for 21 physics teachers. For the teachers we organized a meeting on November 25 at Wigner RCP in the presence of representatives of the Hungarian Physical Society, the Hungarian CERN Committee and the main sponsor, the Pallas Sthene Domus Innovationis Foundation. We also participated in the organization of the annual Hands-on Particle Physics Master-classes on two occasions with 22 high-school students attending each session. In addition to conference talks and university teaching, many popular lectures were given by our group.