HELSINKI INSTITUTE OF PHYSICS

Annual Report 2020

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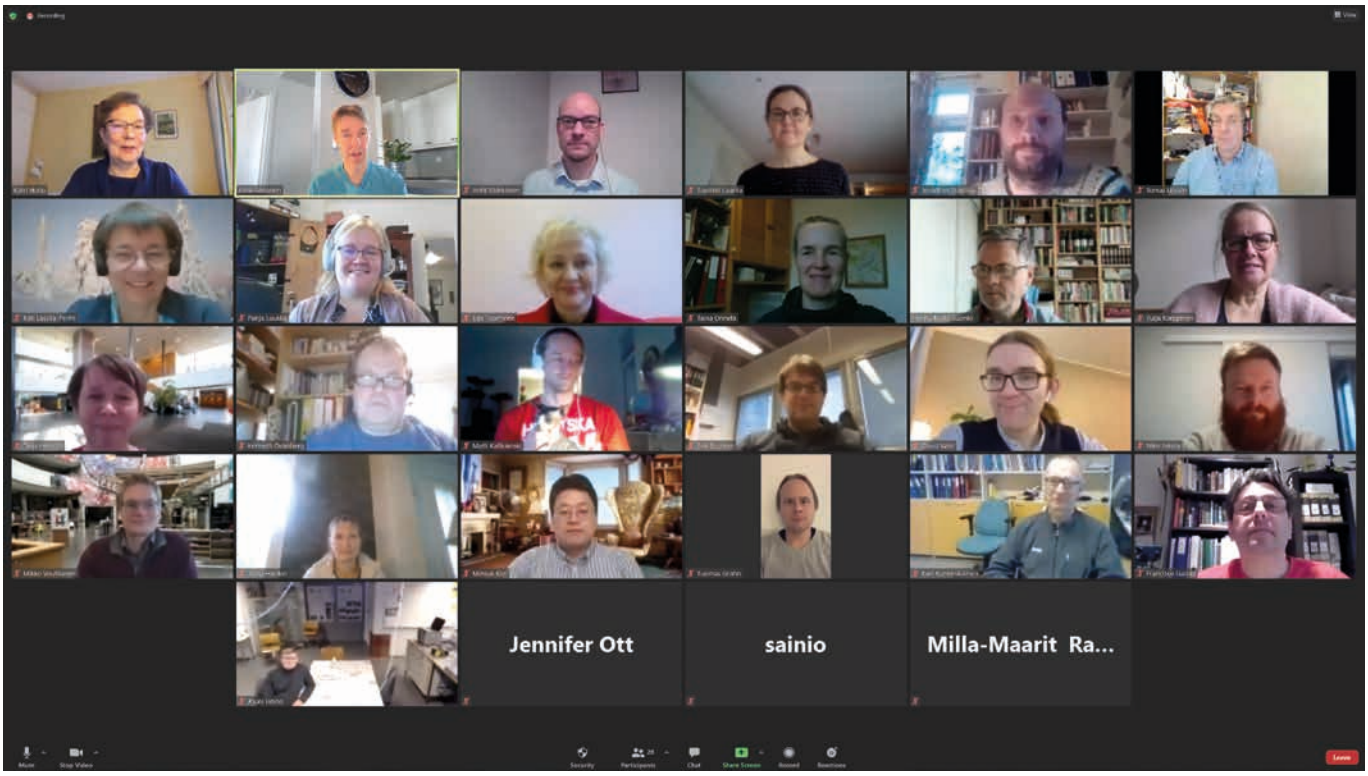

HIP remote staff meeting in December. *Credit: J. Aaltonen.*

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KATRI HUITU
Helsinki Institute of Physics director

PREFACE

The Helsinki Institute of Physics (HIP) is a joint research institute of the Universities of Helsinki, Jyväskylä and Tampere, Aalto University, and Lappeenranta-Lahti University of Technology LUT. The Radiation and Nuclear Safety Authority has been an interim member of HIP since 2018. The University of Helsinki is the host organisation of HIP. HIP addresses fundamental science questions from quarks to Cosmos, as well as technologies from semiconductors to medical applications and climate research. It serves as a national institute for Finnish physics and related technology research and development at international accelerator laboratories. By mandate of the Finnish Ministry of Education and Culture, HIP is responsible for the Finnish research collaboration with the European Organization for Nuclear Research (CERN) and the Facility for Antiproton and Ion Research (FAIR GmbH), which is under construction in Darmstadt.

In 2020, the research activities of HIP consisted of four research programmes: 1) the Theory Programme; 2) the CMS Programme including the CMS and TOTEM experiments; 3) the Nuclear Matter Programme including involvements in the ALICE experiment, ISOLDE, and the FAIR facility; and 4) the Technology Programme, with nine applied research projects in three thematic areas. In addition, there were three independent research projects: CLOUD; Education and Open Data; and Euclid. The Detector Laboratory served as a general facility for the Institute.

During the year 2020, special circumstances due to the COVID-19 pandemic were implemented from March 16, and as a consequence most meetings, conferences, and travel, as well as teaching, were conducted by videoconferencing methods. The digital means developed vastly during the year.

The annual meeting of the Scientific Advisory Board (SAB) in August was also held remotely. The SAB found that HIP research projects continued to be successful and high level by international standards and that HIP continues to do an excellent job in education and outreach. The SAB were concerned about the budget, as the funding contribution from the Ministry of Education and Culture will be significantly reduced for 2021–2024. With appreciation the SAB commented on the strong commitment from the member universities, as they are compensating for the reduction from the Ministry.

The renewed Theory Programme had four projects. The Theoretical Cosmology project has driven strong collaboration between Helsinki and Jyväskylä, and the Tampere based Designer Topological Matter project has involved collaboration with Aalto University. Exceptionally, two of the projects are continuations of the very successful High Energy Phenomenology as well as QCD and Strongly Interacting Gauge Theory projects.

The Large Hadron Collider (LHC) experiments – ALICE, CMS, and TOTEM – have been analysing data from Run 2 and at the same time upgrading their detectors during the Long Shutdown 2, which lasts until 2022. Contrary to many other laboratories in Europe and elsewhere, the Detector Laboratory could help in testing the novel detectors. The evidence for an ”Odderon” in the TOTEM data was published. Concerning FAIR, the Phase-0 experiments have been active, and several in-kind projects are in progress.

The three thematic areas of the Technology Programme were Systems, Materials, and Radiation Safety. All of these had wide coverage from the member universities. Although most projects could proceed rather normally via digital platforms, the Accelerator Technology: Modules, Systems and Manufacturing project was harshly affected, as it was leading a Business Finland application, and the companies approached were affected by the pandemic.

Another HIP operation suffering from the restricted working conditions was the Detector Laboratory, which had to limit the number of people that could work in the laboratory at the same time. Although during the COVID-19-year, HIP managed to participate in the Researcher's night in November, and the Detector Laboratory was visited by the national broadcasting company's TV programme ”Puoli seitsemän” with prime-time live coverage.

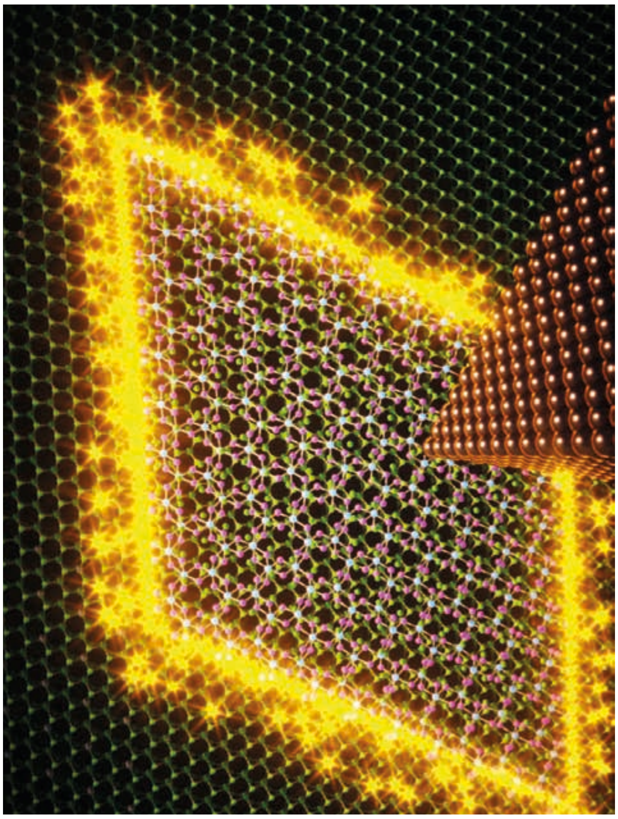
The CMS project leader, Assistant Professor Mikko Voutilainen, was promoted to an Associate Professor position at the University of Helsinki. The FAIR project leader, Tuomas Grahn, started as an Assistant Professor at the University of Jyväskylä, where the project leader of the ALICE project, Sami Räsänen, also started as a University Lecturer. Dr. Matti Kalliokoski started as a Staff Scientist in the Detector Laboratory.

Several documents regulating HIP operations were updated and supplemented during the year. In addition, the HIP long-term strategy document was accepted after the launch of the European Particle Physics Update 2020.

HIGHLIGHTS OF RESEARCH RESULTS

Theory Programme

The physics research in the HIP Theory Programme spans distance scales from elementary particles up to the whole universe, under four research projects. The highlights of the research in 2020 include the following.



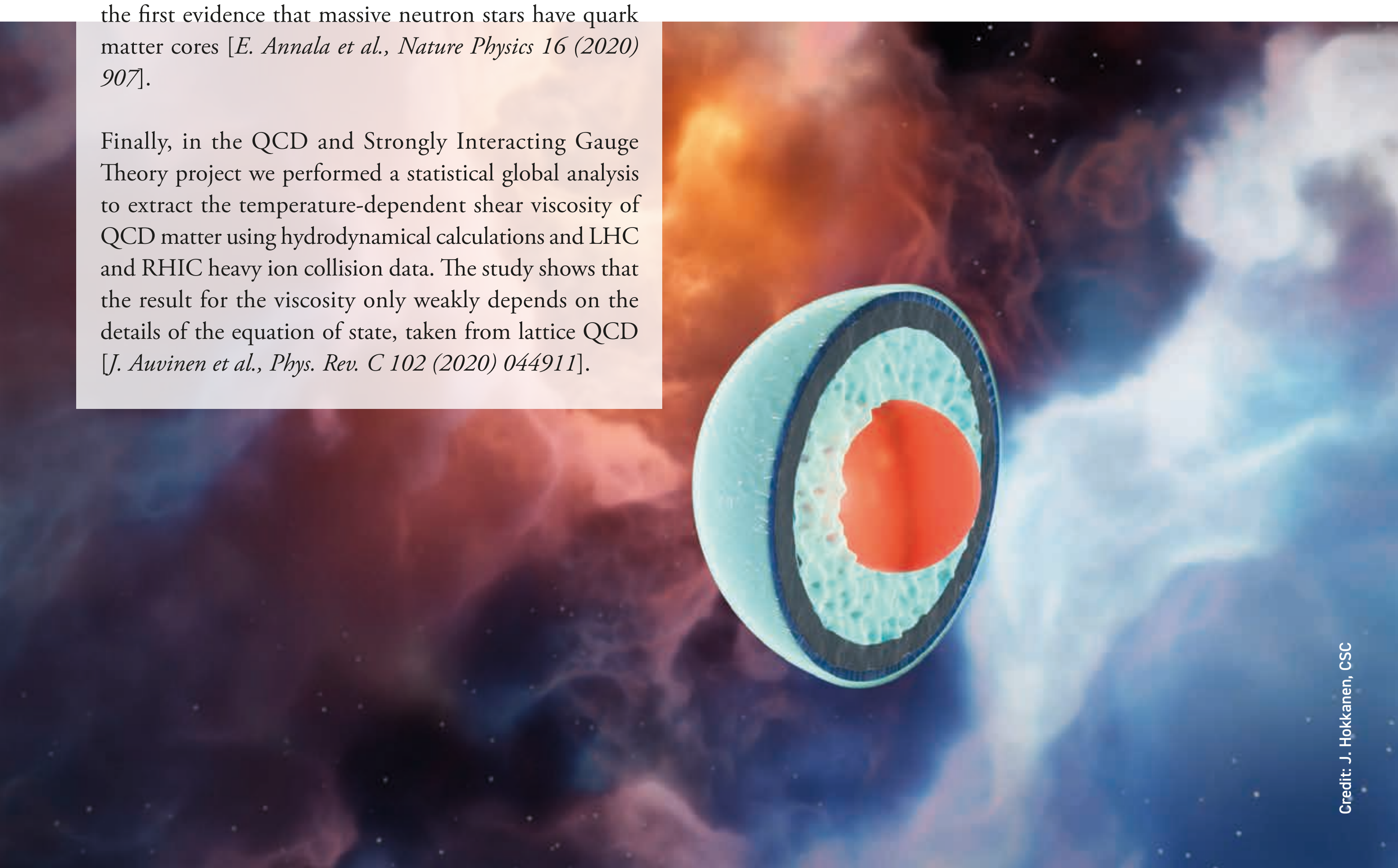
Credit: A. Tokarev, Ella Maru Studio

In the Theoretical Cosmology project, we showed that, contrary to expectations, the electroweak baryogenesis is only smoothly suppressed for wall velocities exceeding the sound of speed. This makes baryogenesis efficient also for strong detonations, allowing for simultaneous production of observable gravitational waves [*J. M. Cline, K. Kainulainen, Phys. Rev. D 101 (2020) 063525*].

The scientists in the Designer Topological Matter project, in collaboration with experimental groups at Aalto University, realised a system with two-dimensional topological superconductivity and chiral Majorana states, one of the major goals of quantum condensed matter physics [*S. Kezilebieke et al., Nature 588 (2020) 424*].

The High Energy Phenomenology project personnel found the first evidence that massive neutron stars have quark matter cores [*E. Annala et al., Nature Physics 16 (2020) 907*].

Finally, in the QCD and Strongly Interacting Gauge Theory project we performed a statistical global analysis to extract the temperature-dependent shear viscosity of QCD matter using hydrodynamical calculations and LHC and RHIC heavy ion collision data. The study shows that the result for the viscosity only weakly depends on the details of the equation of state, taken from lattice QCD [*J. Auvinen et al., Phys. Rev. C 102 (2020) 044911*].



Credit: J. Hokkanen, CSC

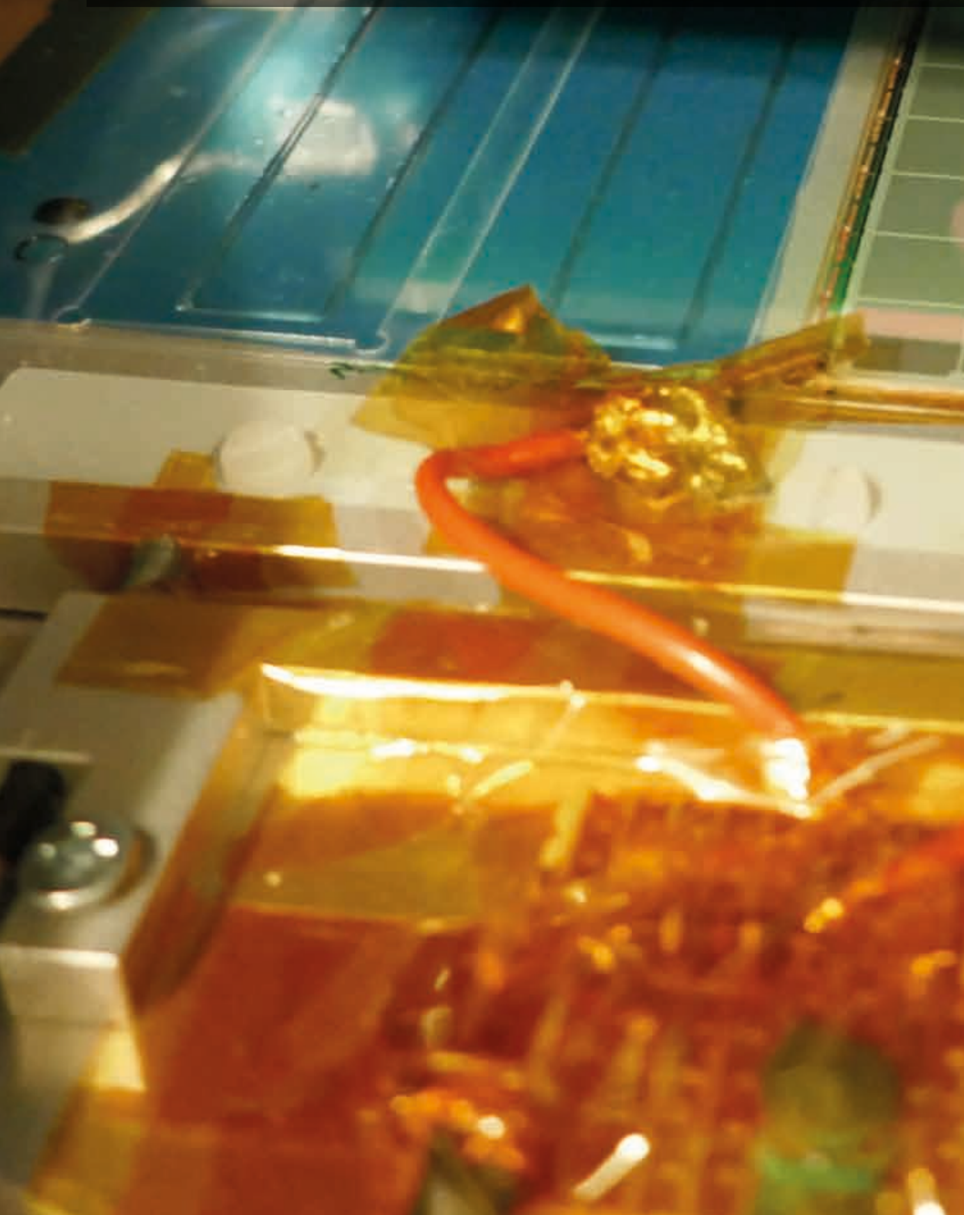
CMS Programme

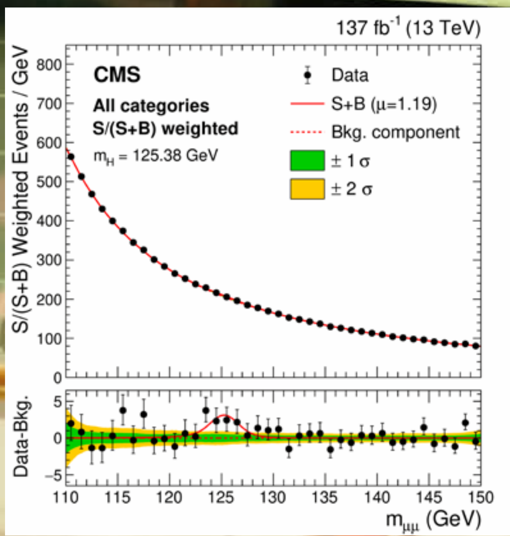
CMS is a general-purpose experiment at CERN's Large Hadron Collider (LHC). The overall CMS highlights were the evidence for the Higgs boson coupling to second generation leptons ($H \to \mu\mu$) and reaching the 1000th physics paper milestone.

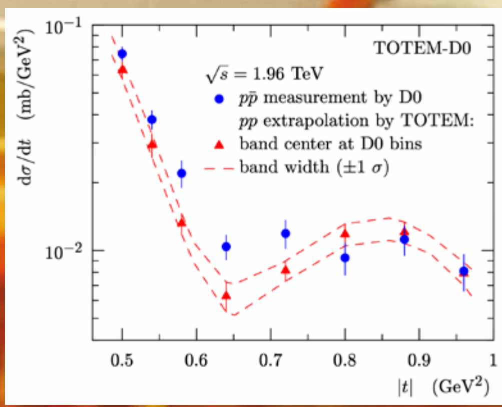
HIP contributed to *new physics searches* (Higgs bosons and supersymmetry), *precision physics with jets* (top quark mass and strong coupling) and *vector boson scattering*. The focus for 2020 was on completing the legacy reconstruction and calibration of the full Run 2 data set. M. Voutilainen, H. Kirschenmann, and M. Kim were appointed conveners of the LHC Electroweak Working Group Jets & EW Bosons subgroup, the CMS Jet and Missing Energy group, and the Jet Energy Resolution and Corrections group, respectively.

HIP completed the quality assurance of the flip-chip bonded modules for the refurbishment of the innermost layer of the pixel detector. For the new Minimum Ionizing Particle Timing Detector Endcap Timing Layer, HIP took a leading role in the testing of the novel detectors, as the Helsinki Detector Laboratory was one of the first laboratories to open for detector studies after the COVID-19 lockdowns. The muon GE1/1 station with HIP contributions to the electronics and data acquisition system was the first CMS Phase-2 upgrade detector to be installed.

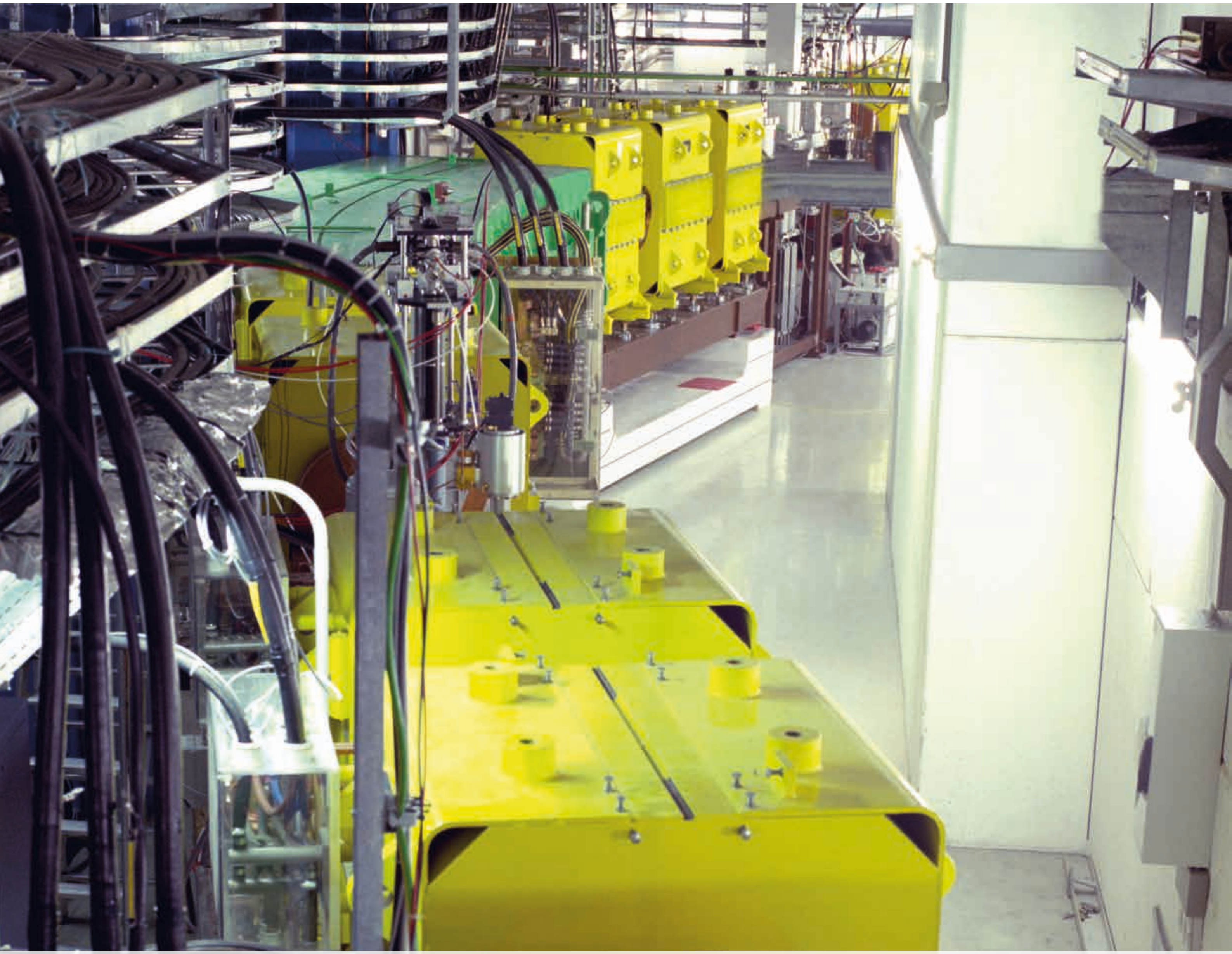
TOTEM is a forward physics experiment at the LHC. The TOTEM highlight was the preprint together with the D0 experiment on the comparison of the 1.96 TeV elastic proton-proton (pp) and proton-antiproton differential cross-section ($d\sigma_{el}/dt$), providing *evidence for t-channel exchange of a C-odd colourless gluonic compound*, an "Odderon". This represents the observation of Odderon exchange, when combined with the published TOTEM measurement of a decreasing ρ value in pp elastic scattering at the LHC.







Credit: A. Zschau, GSI Helmholtzzentrum für Schwerionenforschung



Nuclear Matter Programme

The COVID-19 situation had a major influence on the Nuclear Matter Programme, where all projects operate abroad, either at CERN or at FAIR. Fortunately, analysis work and dissemination of results has continued, resulting in high impact publications.

At ISOLDE, HIP-affiliated scientists were involved in a study of the evolution of octupole deformation in radium nuclei using Coulomb excitation technique. The work was published in *Physical Review Letters*. Another example from ISOLDE shed light on the role of the proton $d_{3/2}$ shell in the region where the shape coexistence phenomenon is prominent. These data were published in *Physical Review C*.

The ALICE project has produced many publications, as usual. One of the highlights was a detailed study on interactions among baryons containing strange quarks, published in *Nature*.

Despite the travel restrictions due to the global crisis, a few experiments with Finnish researchers could be performed at FAIR with remote participation.

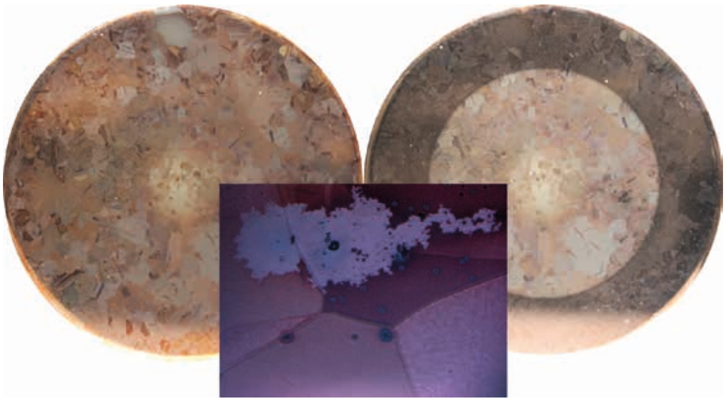
Technology Programme

The Technology Programme aims to integrate HIP projects that have significant technology development, transfer, and pre-commercialisation activities into the same programme. In addition, the research activities performed within the programme are designed to seek synergies with big science initiatives at large. The programme is structured into three thematic areas – systems, materials, and radiation safety – each consisting of several small projects. Several projects have been successful in raising external funding for the R&D work, thus strengthening the impact of the programme. In 2020, several projects finished, including the Finnish BIC, as a result of re-focussing of the programme activities for the coming years.

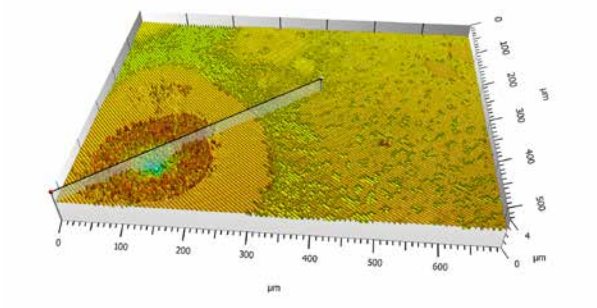
Within the detector system development activities, the capability of the PANDA system was expanded to include coincident alpha, beta, and gamma-ray spectroscopy. This system analyses the radioactivity collected onto air filters from the environment in a collection network in Finland.

The materials projects have generated significant breakthroughs in the understanding of conditioning of Cu in high field systems such as RF accelerating structures. In addition, they have shown that short-range order is manifested in high entropy alloys in a way that significant attention has to be given to composition fluctuations at the atomic level already in low-level irradiated materials.

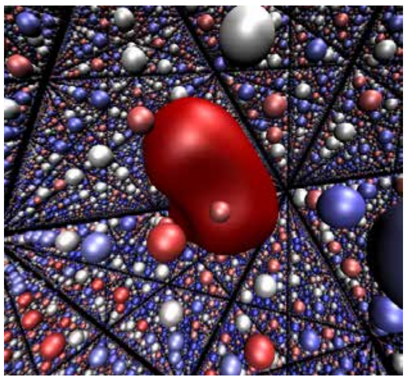
An important highlight in technology development is the construction of two different prototype warning detectors for improved emergency management (in the context of the joint STUK-HIP DEFACTO project) that enable autonomous radiation monitoring and fast deployment. Several CERN-related co-innovation project proposals were set up and one of them, led by Tampere University, received funding from Business Finland.



Credit: A. Saressalo



Credit: I. Kassamakov



Credit: I. Makkonen

THEORY PROGRAMME

The HIP Theory Programme was renewed in 2020, with the start of four fixed-term theory projects: 1) Theoretical Cosmology (leader Sami Nurmi, University of Jyväskylä); 2) High Energy Phenomenology in the LHC Era (leader Aleksi Vuorinen, University of Helsinki); 3) QCD and Strongly Interacting Gauge Theory (leader Tuomas Lappi, University of Jyväskylä); and 4) Designer Topological Matter (leader Teemu Ojanen, Tampere University).

KARI RUMMUKAINEN
Theory Programme director

Theoretical Cosmology

SAMI NURMI
Theoretical Cosmology project leader

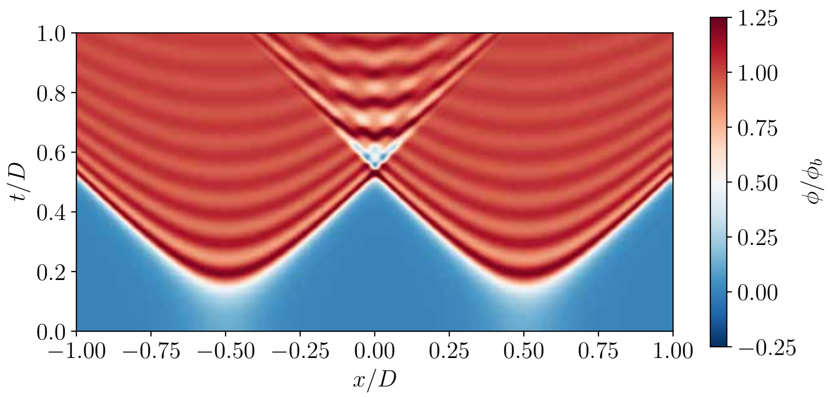
We study the origin and evolution of the universe and connections between cosmology and particle physics. Our key topics are inflation, dark matter, phase transitions and out-of-equilibrium quantum physics, large scale structures, and gravitational waves. We apply a complementary range of methods to test theoretical models against the data from cosmological and collider surveys. With this information, we make new progress in understanding fundamental properties of matter and gravity. We belong to the LISA Gravitational Wave Survey Consortium and the LISA Astrophysics and Cosmology Working Groups.

The microscopic mechanism of inflation remains unclear. We work broadly to investigate various aspects of inflation in theoretically motivated particle physics setups. This year we made new developments to resolve questions linked to gravitational couplings and quantum corrections in Higgs inflation, and showed that the Higgs field may source primordial perturbations even if it does not directly affect the dynamics of inflation. Inflation can source primordial black holes (PBHs) which affect a wide range of cosmological observables. For the first time, we computed PBH abundance using the full non-linear probability distribution of seed fluctuations derived from a numerical simulation of stochastic ultra slow-roll inflation.

Dark matter (DM) is most naturally explained by yet unobserved, new massive particles. We developed a new framework for fast and accurate computation of DM abundance in setups where annihilations occur near resonances and standard methods are either inaccurate or slow. DM may have important links to primordial physics. We discovered a novel mechanism for DM production from curvature-induced symmetry breaking during inflation. We also investigated how PBHs constrain thermal relic DM candidates and identified a novel observationally testable signal from DM annihilations around nearby PBHs.

We investigate gravitational wave (GW) signals from primordial processes and structure formation. This year we obtained improved resolution of the GW spectrum from collisions of vacuum bubbles, investigated the signal from self-ordering dynamics after a phase transition, and reviewed the prospects for phase transition signals at high frequencies. We have run simulation of two-step phase transitions, studied phase transitions in strongly interacting systems using holographic methods, and showed that electroweak baryogenesis is only smoothly suppressed for large wall velocities, associated with observable GWs. We work extensively to study GW signals from supermassive black holes. This year we have run the locally developed KETJU code to resolve black hole dynamics in the centres of massive galaxies, and simulated dwarf galaxy mergers.

The time evolution of two vacuum bubbles in a first-order phase transition, leading to production of gravitational waves. *Credit: D. Cutting.*



Artist's illustration of the structure of a neutron star with a sizable quark matter core (orange sphere in the middle). *Credit: J. Hokkanen, CSC.*

High Energy Phenomenology in the LHC Era

ALEKSI VUORINEN
High Energy Phenomenology in the LHC Era project leader

During the strange and unprecedented year that was 2020, the High Energy Phenomenology (HEP) project continued performing cutting-edge research on a wide variety of problems in contemporary theoretical high energy physics. With neutron star mergers and, more widely, the physics of dense QCD matter continuing to be the centre of international attention due to recent observational advances in neutron-star physics, the focus of the project has remained on these important topics. Simultaneously we have, however, broadened our research towards topics such as attempts to constrain the parameter spaces of different dark-matter models through the COSINUS experiment and to study the dynamics of bubble nucleation in a possible first-order electroweak phase transition in the early universe. In the coming years, we expect to both continue these lines of work and further expand our research spectrum.

In the field of neutron star physics, E. Annala and A. Vuorinen from the HEP project and their international collaborators, including the expatriate Finns A. Kurkela (Stavanger University) and J. Nättilä (Flatiron Institute), published an article in *Nature Physics* that gained extensive publicity both in Finland and internationally. In this work, the group presented the first-ever evidence for the existence of quark matter cores in massive neutron stars, elevating this scenario from an exotic possibility to a likely one. The new insights originated from a novel parameterisation of the neutron-star-matter equation of state, allowing for model-independent constraints using robust theoretical results and astrophysical observations. According to the article, quark matter is bound to reside in the cores of the most massive stable neutron stars unless two very specific conditions are met, i.e., the speed of sound in dense QCD matter almost reaches the speed of light and the high-density deconfinement transition is of strongly first-order type.

A highlight within our holography research was the publication of an article in *Physical Review Letters* by N. Jokela, J. Tarrío, A. Vuorinen, and international collaborators, including M. Järvinen (APCTP, Pohang), on the behaviour of different transport coefficients of dense quark matter. By utilising the so-called improved holographic QCD (IHQCD) framework, they were able to derive the first-ever non-perturbative predictions for four important transport quantities: the shear and bulk viscosities and the electrical and thermal conductivities. Accurate knowledge of their behaviour as functions of density and temperature will be a critical ingredient in realistic hydrodynamic simulations of supernovae explosions and neutron star mergers.

TUOMAS LAPPI
QCD and Strongly Interacting Gauge Theory project leader

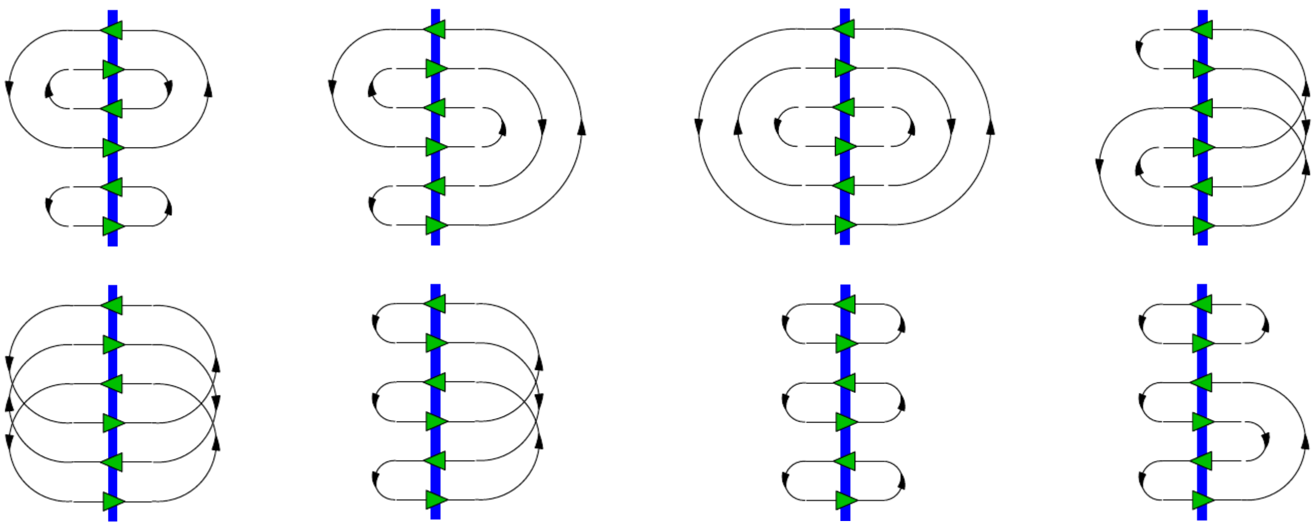
QCD and Strongly Interacting Gauge Theory

Our work revolves around different aspects of QCD at high energy and density. In addition to the phenomenology of high-energy nuclear collisions at the LHC and RHIC, we are involved with physics studies for planned colliders such as the EIC and FCC. We use weak coupling QCD renormalization group equations to understand the partonic structure of hadrons and nuclei. We then use this information to understand and model the formation of thermalized quark gluon plasma in heavy ion collisions and model its subsequent evolution using relativistic hydrodynamics.

The DGLAP equations describe the scale dependence of proton and nuclear parton distributions (PDFs), and our group specialises in particular in nuclear PDFs. In 2020, we showed how the nuclear PDFs and LHC data for W/Z production can be used to improve the Glauber modelling of nuclear collisions. Our EPS09 nuclear PDFs reached the 1000 citation benchmark. The BK and JIMWLK evolution equations, in turn, describe the energy dependence of QCD cross sections at high energy. In 2020, we published the first fit of electron-proton collision data from the HERA collider using the BK formalism at next-to-leading order in perturbation theory, and continued developing the theory to include massive quarks. We have also studied many aspects of exclusive photon-nucleus processes, such as ultraperipheral photon-mediated processes at the LHC, both in order to eventually include them in PDF fits, and to explore the transverse spatial distribution of gluons inside nucleons and nuclei. We also participated in preparing for the next major version release of the general purpose PYTHIA event generator in 2021, focussing in particular on modelling hard diffractive photoproduction events.

To describe the formation of quark gluon plasma, we use two complementary QCD approaches. In the Colour Glass Condensate picture, the early stage of a heavy ion collision is described in terms of a strong classical gluon field. We have continued to study the dynamics of the infrared sector of overoccupied gluonic systems far from equilibrium, in particular by calculating the heavy quark diffusion coefficient in overoccupied gluon plasma. We also model the initial stages of heavy ion collisions starting from perturbative quark and gluon scattering, and use a saturation conjecture to control multiparticle production. These initial conditions are then used in our event-by-event hydrodynamical studies of heavy ion collisions. In the past year, we used this setup to improve the determination of the temperature-dependent QCD matter shear viscosity by a statistical global analysis.

Diagrammatical representations of 6-point Wilson line operators, needed for the calculation of the finite number of colours – corrections to the next-to-leading order Balitsky-Kovchegov (BK) equation *[Phys. Rev. D 102 (2020) 074027]. © American Physical Society.*



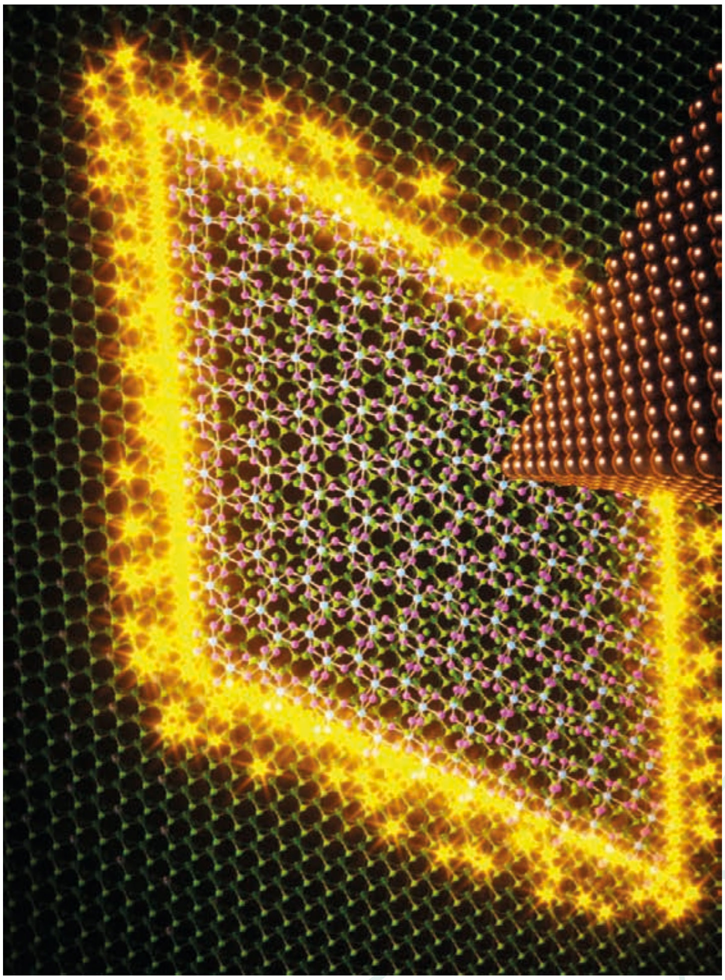
Designer Topological Matter

TEEMU OJANEN
Designer Topological Matter project leader

We study condensed matter systems with exotic collective quantum behaviour, such as topological materials. Our work ranges from theoretical prediction of novel phases of matter to modelling experiments and studying complex systems with numerical approaches. We also aim to design novel quantum materials which allow access to the physics of emergent quantum particles beyond the presently known elementary particles. Besides the fundamental interest, our research has potential to stimulate future quantum technologies.

In a breakthrough work published in *Nature*, we collaborated with experimentalists at Aalto University to realise two-dimensional topological superconductivity and chiral Majorana states. An experimental realisation of topological superconductivity has been one of the grand goals of quantum condensed matter physics for over a decade. The driving force behind these efforts is the desire to access the exotic Majorana quasiparticles in these systems. Despite a large number of theoretical proposals to guide the experimental efforts, the conclusive evidence on Majorana states has remained elusive. In the work published in *Nature*, we designed a van der Waals layer structure where an atomically thin ferromagnet was grown on top of layered superconductor $NbSe_2$. Combining magnetism, spin-orbit physics and superconductivity, this structure satisfies all the necessary requirements needed for topological superconductivity. The experimentally observed signatures of topological superconductivity were in excellent agreement with the predictions of our theoretical model. While not completely conclusive, our work provides some of the most compelling evidence of topological superconductivity to date.

Since the discovery of the quantum Hall effect, it has been known that the topologically non-trivial electronic spectrum protects the system from the disorder and unideal features that are ubiquitous in real-world systems. In our recent work, we have characterized the remarkable robustness of topological states on random lattices. In particular, we have proved that topological states can persist in highly irregular percolation-type random geometries down to the theoretical lower limit provided by the percolation threshold. Our results shed new light on the theory of Anderson localisation and pave the way to topological states in random fractals.



Topological superconductivity in a ferromagnet-superconductor van der Waals structure. The Majorana edge mode (golden sparkles) surrounding the magnetic island constitutes smoking-gun evidence on the topological superconducting phase *[Nature 588 (2020) 424]. Credit: A. Tokarev, Ella Maru Studio.*

CMS PROGRAMME

The HIP CMS programme is responsible for co-ordinating Finnish participation in the CMS and TOTEM experiments at the Large Hadron Collider (LHC). The Compact Muon Solenoid (CMS) is a general-purpose experiment covering precision measurements of particles and interactions, the origin of electroweak symmetry breaking (Higgs bosons), and the search for signatures of new physics. TOTEM is a dedicated forward physics experiment, located at the same LHC interaction point as CMS, focussing on elastic scattering, total cross section, and diffractive and exclusive processes. The programme is divided into four projects: 1) the CMS Experiment project, responsible for physics analysis and operations; 2) the CMS Upgrade project, responsible for the detector upgrade contributions; 3) the Tier-2 Operations project; and 4) the TOTEM project. The Finnish groups in CMS are: HIP (currently 15 authors); the Department of Physics at the University of Helsinki (5 authors); and Lappeenranta-Lahti University of Technology (3 authors). TOTEM currently has 8 HIP authors, of which 6 are also affiliated with the Department of Physics at the University of Helsinki.

KENNETH ÖSTERBERG
CMS Programme director

MIKKO VOUTILAINEN
CMS Experiment project leader

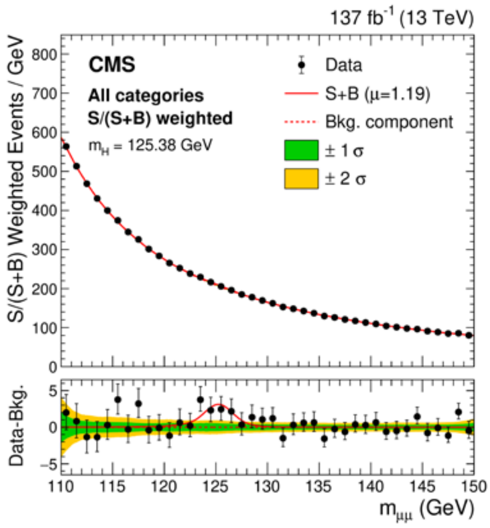
CMS Experiment

Introduction and Highlights

The LHC is in a unique position to explore electroweak symmetry breaking and the origins of the universe. The CMS Experiment project is focussed on analysis of the LHC data, in particular on new physics searches (charged Higgs bosons, SUSY), precision measurements with jets (m_t, α_s), and measurements of vector boson scattering (VBS) processes. These are supported by a strong involvement in detector operations on jet energy corrections (JEC), in the Level-1 trigger, and in the alignment, calibration and database (AlCaDB) group. We also develop machine learning (ML) applications in high energy physics (HEP).

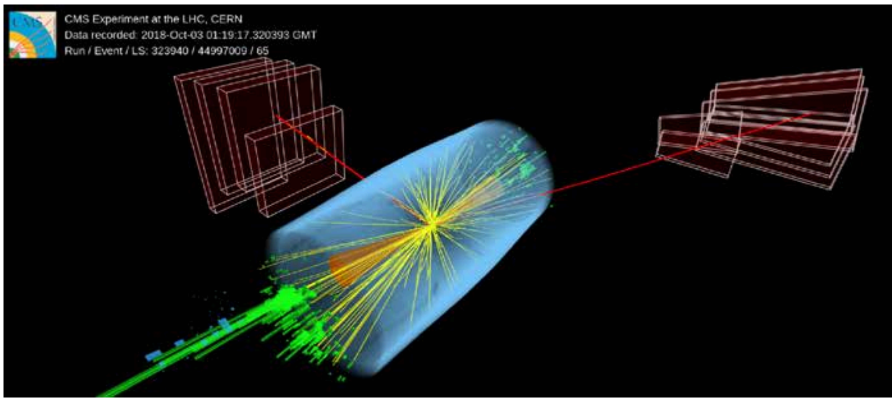
The focus of 2020 was on completing the legacy reconstruction and calibration of the full Run 2 data set, in preparation for precision analyses and the Run 3 start-up, which has been delayed due to COVID-19. Both searches and measurements focussed on systematic improvements, with MSc theses on tau triggering by A. Autio, improved modelling of JEC uncertainties by M. Myllymäki, and Z+jet/dijet ratio by B. Schillinger. Three more MSc theses are in preparation on ML techniques and b-jet JEC.

HIP continued its strong scientific leadership at CERN: T. Lampén convened the CMS AlCaDB group; K. Lassila-Perini co-ordinated the CMS Data Preservation and Open Access project; and M. Voutilainen, H. Kirschenmann, and M. Kim took up new convenerships of the LHC Electroweak Working Group Jets & EW Bosons subgroup, the CMS Jet and Missing Energy (JetMET) group, and the CMS Jet Energy Resolution and Corrections (JERC) group, respectively, after having convened the CMS Top Mass & Properties and SMP Hadronic Final States groups. Overall, the CMS highlights of the year were the evidence for the Higgs boson coupling to second generation leptons (H → $\mu\mu$) and reaching the milestone of the 1000th physics paper.



The muon-antimuon ($\mu^+\mu^-$) mass distribution for the weighted combination of events selected in the CMS Higgs to $\mu^+\mu^-$ analysis. The lower panel shows the residuals after background subtraction, with the best fit of a Standard Model Higgs boson signal contribution indicated by the red line. © *Journal of High Energy Physics, Springer Nature Switzerland AG.*

Screenshot of the video celebrating that the CMS Collaboration had issued 1000 physics papers in June 2020, later during 2020 another milestone of publishing 1000 physics papers was reached.
© CMS Collaboration, CERN.



A CMS event in which a candidate Higgs boson produced via vector boson fusion (VBF) decays into a pair of muons, indicated by the solid red lines. The two forward VBF-jet candidates are depicted by orange cones.
© CMS Collaboration, CERN.

Detector Operations and Machine Learning

The AlCaDB group completed the legacy re-reconstruction of the last Run 2 data, and the JEC team with seven contributors from HIP provided first calibrations for the 2017 and 2018 data, with a strong focus on implementing new techniques to improve systematic uncertainties for the final combination of the full 2016–18 data set. The ML team focussed on W boson polarization tagging, quark-gluon discrimination, and ML-based JEC.

Precision Measurements

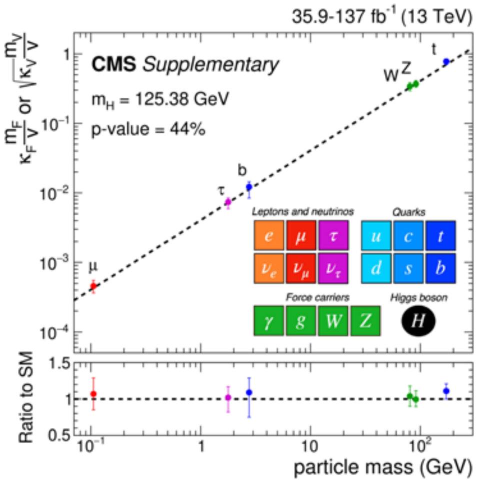
Measurements of the top quark mass m_t, the inclusive jet cross section, and the gluon jet production continued to improve internally, with the overall goal of measuring the proton structure, the strong coupling α_s, and m_t in exploration of SM vacuum stability and physics up to the Planck scale. A preprint by H. Siikonen provided a possible explanation for the anomalous m_t measured by D0. The MSc thesis by B. Schillinger explored systematic uncertainty cancellations with Z+jet/dijet production ratio measurement.

New Physics Searches

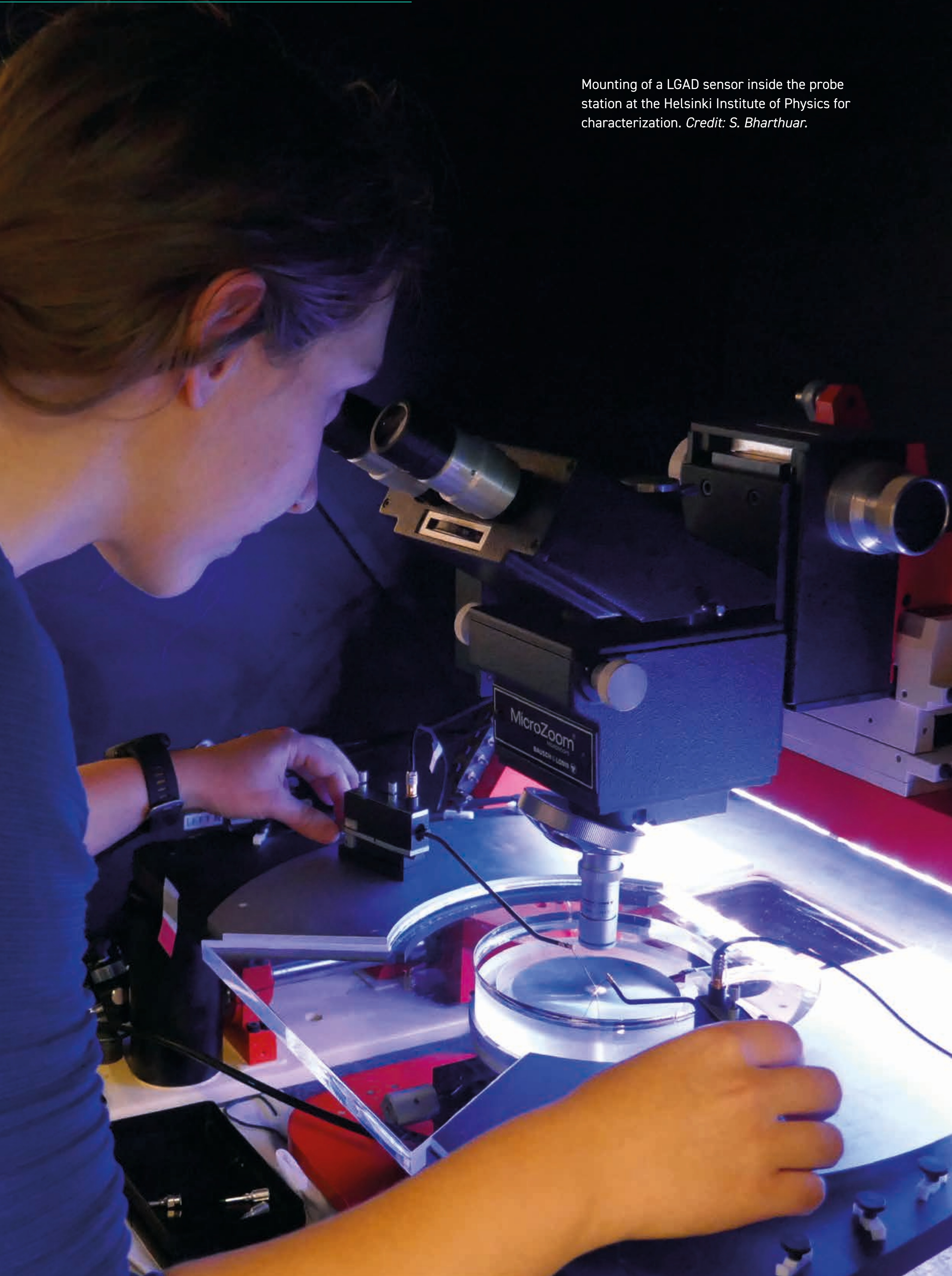
Searches for charged Higgs bosons continued on the full Run 2 data set in the $\tau\nu_\tau$ and WH final states, which access parameter space that is so far poorly constrained by other searches. The SUSY search for gluino pair production decaying to $t\bar{t}t\bar{t}$ is approaching its completion on the full Run 2 data set. These channels allow exploration of electroweak symmetry breaking, in search for physics beyond the Standard Model and candidates for dark matter.

Vector Boson Scattering

The HIP team made preparations for measurement of VBS in the all-hadronic final state and organised a workshop for the VBSCan COST network in Helsinki, before all HEP conferences and workshops moved online.



The best-fit estimates for the reduced Higgs coupling modifiers extracted for fermions and weak bosons from the CMS Higgs measurements compared to their corresponding prediction from the Standard Model (SM). The green points are the coupling modifiers for vector bosons, while the red, magenta, and blue points are the coupling modifiers for muons, taus, and quarks of the third generation, respectively. The lower panel shows the ratios of the measured coupling modifier values to their SM predictions. *© CMS Collaboration, CERN.*



Mounting of a LGAD sensor inside the probe station at the Helsinki Institute of Physics for characterization. *Credit: S. Bharthuar.*

CMS Upgrade

The most extensive upgrade of the LHC will take place during the years 2025–2027. As a result, the instantaneous luminosity will significantly increase and consequently, the detector systems need to be upgraded to allow high-quality physics data taking in high luminosity conditions.

During 2019–2021, the CMS pixel detector will go through an intermediate upgrade to improve its performance for Run 3 starting in spring 2022. In this upgrade, the innermost layer of the pixel detector (L1) will be replaced with modules carrying an upgraded readout chip. The module production started in July 2019 at Advacam Ltd in Finland. The CMS Upgrade project was responsible for the quality assurance of the pixel detector bare modules after the flip-chip bonding, similarly to the Phase-1 pixel detector upgrade. In October 2020, the full L1 was moved to CERN and the commissioning of the upgraded detector began. After the final cabling and upgrade of the high-voltage system in early 2021, the detector will be cooled down and the final system testing completed before the first beams at the LHC in autumn 2021.

In the Phase-2 upgrade of the CMS detector, Finland will participate in the upgrade of the Tracker pixel detector and in the building of the new Minimum Ionizing Particle Timing Detector Endcap Timing Layer (MTD-ETL). In the CMS MTD-ETL detector construction project several pre-production runs with different commercial detector producers have been achieved during 2020, despite the global COVID-19 situation. In 2020, the CMS Upgrade project had a significant role in the testing of the novel detectors, as the Helsinki Detector Laboratory was one of the first laboratories to open for detector studies after lockdowns in several countries.

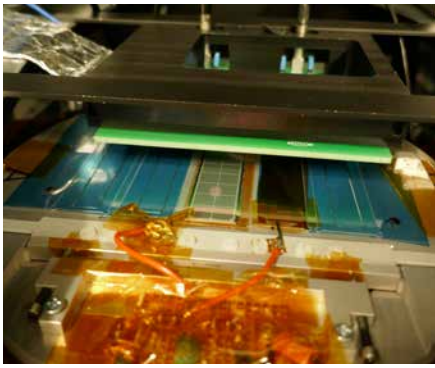
In 2020, the CMS Upgrade project was able to test the functionality of the new AC-coupled pixel detectors at the Finnish Radiation and Nuclear Safety Authority (STUK), utilising alumina as a field insulator. The tests were successful, and we can conclude that the concept has significant potential for the applications requiring small pixel size and excellent radiation hardness.

During 2020, the CMS Upgrade project also continued the collaboration with STUK, Aalto University, and Lappeenranta-Lahti University of Technology (LUT) in developing a multispectral imaging detector for medical imaging and beam characterization within an Academy of Finland project.

In 2020, the CMS group at Lappeenranta-Lahti University of Technology (LUT), led by Professor T. Tuuva, finished the construction of the electronics and data acquisition system for the CMS muon GE1/1 station. The GE1/1 station is the first of the Phase-2 upgrade detectors, which has been installed in the experiment.

During 2020, P. Luukka continued as the CMS Collaboration Board Secretary (L0 position) and is also continuing as a member of the CMS management team.

PANJA-RIINA LUUKKA
CMS Upgrade project leader



A pixel module for the refurbishment of the innermost layer of the CMS pixel detector mounted inside the probe station at the Helsinki Institute of Physics for quality control. *Credit: J. Ott.*

The CMS GEM based muon GE1/1 station being installed in the CMS cavern. © *CERN.*

TOMAS LINDÉN
Tier-2 Operations project leader

Tier-2 Operations

CMS analysis and simulation jobs were run on the HIP Tier-2 site during the LS2 with good availability ensured by the collaboration between HIP, CSC (IT Center for Science Ltd), and the NeIC Nordic DataGrid Facility. The CMS Site Readiness Status average OK fraction was 85%. T. Lindén represented HIP in the NeIC Nordic LHC Computing Grid steering committee. F. Kivelä worked in the project during the summer. There were 18 GGUS tickets (17 in 2019) concerning HIP.

CMS jobs were run on the Linux clusters Kale (5096 cores from 2015) and Alcyone (840 cores from 2011). The ARC middleware on Kale was upgraded from v5 to v6. Issues with the Lustre file system affected the usability of Kale in the second half of 2020. The dCache services at CSC were stable. The ARGUS service was decommissioned. The BDII and Frontier services were reinstalled on CentOS 7 and 8, respectively.

The Finnish Computing Competence Infrastructure (FCCI) was added to the Academy of Finland infrastructure roadmap. The CHEP 2019 Conference contribution on an ARM cluster for CMS was published in EPJ Web of Conferences.

PhEDEx moved 1516 TB of production data (9697 TB in 2019) and 188 TB of test data (183 TB in 2019) to HIP; and 1540 TB of production data (2479 TB in 2019) and 139 TB of test data (164 TB in 2019) were moved from HIP to elsewhere. In total, HIP's PhEDEx moved 3383 TB data (12522 TB in 2019). In November, PhEDEx was replaced by RUCIO, which moved 53 TB of data to HIP and 12 TB from HIP. A total of 0.98 million CMS grid jobs (1.12 million in 2019) using 24.5 MHS06 CPU hours (27.0 in 2019) were run with an average CPU efficiency of 47.5% (49.8% in 2019).

KENNETH ÖSTERBERG
TOTEM project leader

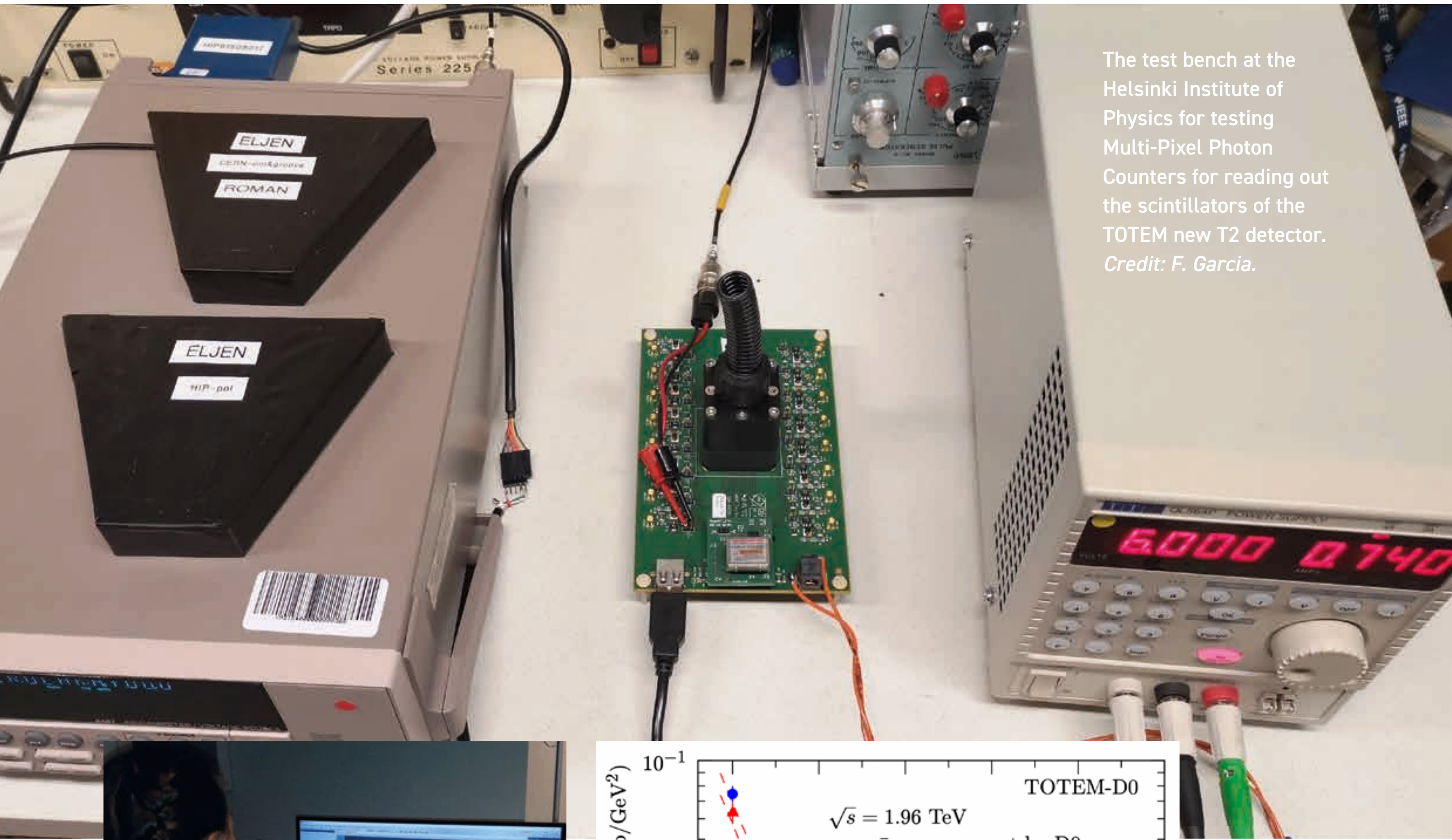
TOTEM

The TOTEM project is responsible for the Finnish TOTEM and CMS forward physics contributions. In 2020, the group consisted of Professor K. Österberg, Professor Emeritus H. Saarikko, scientist F. Garcia, post-doc L. Forthomme, PhD student F. Oljemark and MSc students A. Molander and M.-M. Rantanen. The focus in 2020 was on physics analysis and publications, as well as Run 3 preparations. The group members co-ordinated the TOTEM physics (K. Österberg) and CMS Proton Precision Spectrometer (PPS) test beam (F. Garcia) activities.

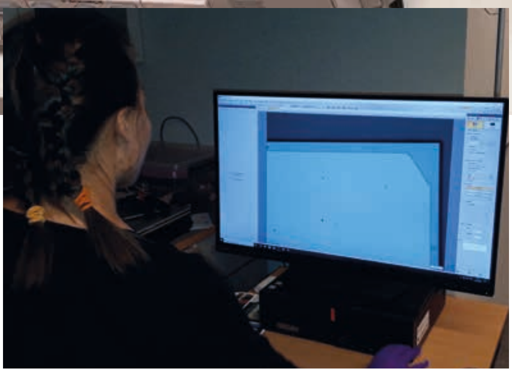
In 2020, the TOTEM and D0 experiments made a comparison of the 1.96 TeV elastic proton-proton (pp) and proton-antiproton differential cross section ($d\sigma_{el}/dt$) in the region of the pp diffractive minimum and secondary maximum, providing evidence for t-channel exchange of a C-odd colourless gluonic compound, an "Odderon", in elastic scattering. This represents the observation of Odderon exchange, when combined with the already published TOTEM measurement of the decreasing ρ value, the real-to-imaginary hadronic elastic amplitude at momentum transfer squared t = 0, in pp elastic scattering at the LHC.

During 2020, F. Oljemark successfully defended his PhD thesis on the TOTEM measurement of single diffraction and K. Österberg was actively involved in the TOTEM Odderon and glueball studies. Regarding PPS, in 2020 CMS and TOTEM made public the first LHC results of the exclusive diphoton search at high masses using measured protons (L. Forthomme). In addition, the development of a dedicated high-level trigger combining central CMS and PPS information for low mass SUSY searches with tagged protons was started to increase the CMS sensitivity to such searches in Run 3 (A. Molander, L. Forthomme).

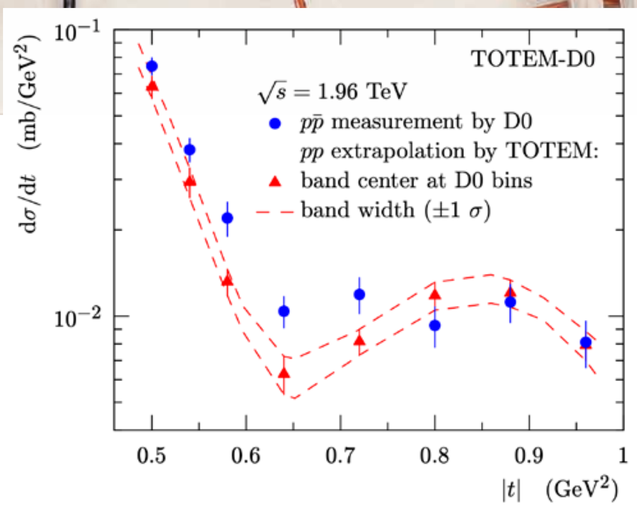
A prototype scintillator for the TOTEM new T2 detector. *Credit: F. Garcia.*



The test bench at the Helsinki Institute of Physics for testing Multi-Pixel Photon Counters for reading out the scintillators of the TOTEM new T2 detector. *Credit: F. Garcia.*



The optical quality inspection of the metallization of a diamond time-of-flight sensor for the upgrade of the CMS Proton Precision Spectrometer at the Helsinki Institute of Physics. *Credit: K. Österberg.*



The comparison between the D0 proton-antiproton elastic measurement at 1.96 TeV and the TOTEM extrapolated proton-proton elastic cross section at the same energy using the measurements at 2.76, 7, 8, and 13 TeV. The difference between the cross sections is evidence for the t-channel exchange of a C-odd colourless gluonic compound, an "Odderon", in elastic scattering. © *TOTEM and D0 Collaborations.*

For the Run 3 PPS time-of-flight (TOF) detector, HIP plays a key role for the diamond sensor purchase, metallization, and quality assurance (M.-M. Rantanen, P. Koponen, K. Österberg), as well as for the TOF detector software (L. Forthomme). A performance study of the Run 2 PPS TOF sensors, using test-beam data taken with large HIP participation (L. Forthomme, F. Garcia, R. Turpeinen), is summarised in a CMS note providing vital information for the Run 3 detector design. F. Garcia, who is responsible for the scintillators of the TOTEM new T2 (nT2), has prepared for their production and quality assurance in Helsinki. The nT2 will be used for a 14 TeV total cross section measurement in an upcoming dedicated special run. In view of the longer-term future, HIP is involved in an expression-of-interest of a high luminosity PPS upgrade. ●

NUCLEAR MATTER PROGRAMME

The Nuclear Matter Programme involves the participation of Finnish teams at CERN in studies of two aspects of nuclear and hadronic matter. These are cold exotic matter with the extreme composition of its proton and neutron numbers on the one hand, and dense matter created in relativistic heavy ion collisions on the other. Exotic nuclei are studied at the ISOLDE facility while the study of quark gluon plasma and related phenomena takes place at ALICE. The Nuclear Matter Programme has also continued co-ordinating the Finnish participation in the planning and construction of the FAIR project in Darmstadt. The Finnish involvement in FAIR includes participation in the construction of the Super-FRS facility and in the NUSTAR Collaboration for nuclear structure, reaction, and astrophysics studies.

ARI JOKINEN
Nuclear Matter Programme director

SAMI RÄSÄNEN
ALICE project leader

ALICE

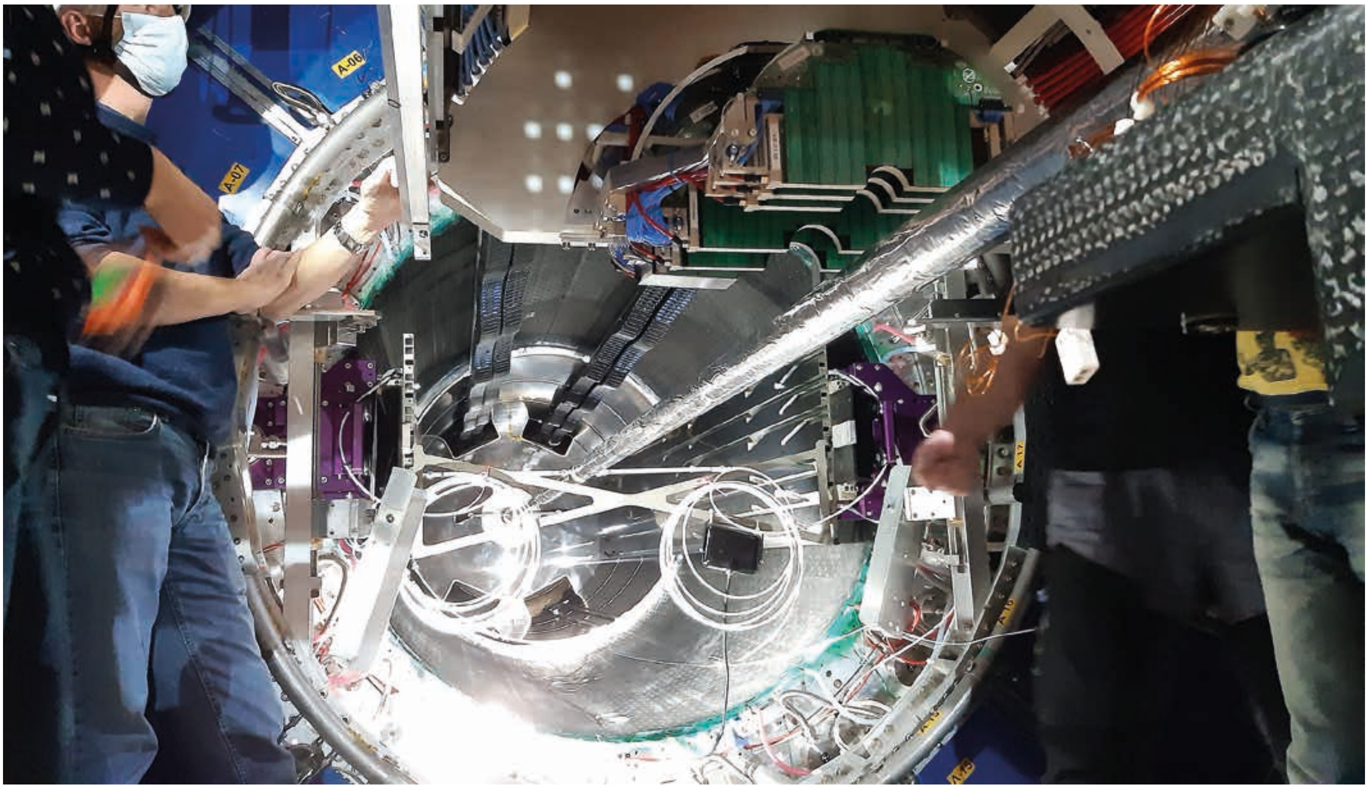
ALICE (A Large Ion Collider Experiment) at the CERN Large Hadron Collider (LHC) investigates matter at extreme temperatures and densities. In such conditions that prevailed in the early universe, matter is expected to undergo a deconfined phase transition to quark gluon plasma (QGP). In QGP, quarks and gluons are no longer confined inside baryons but can move freely inside matter. A small droplet of QGP is created in relativistic heavy ion collisions providing an opportunity to study this cosmological phase transition in the laboratory.

The primary goal of ALICE is to make detailed measurements on the QGP in lead-lead collisions, e.g., map out the transport properties of the strongly interacting matter. In proton-proton and proton-lead collisions, ALICE seeks limits for quark gluon plasma creation and explores novel phenomena in QCD. One of the highlights of ALICE, published by Nature Physics [*Nature 588 (2020) 232*], was a detailed study on interactions among baryons containing strange quarks.

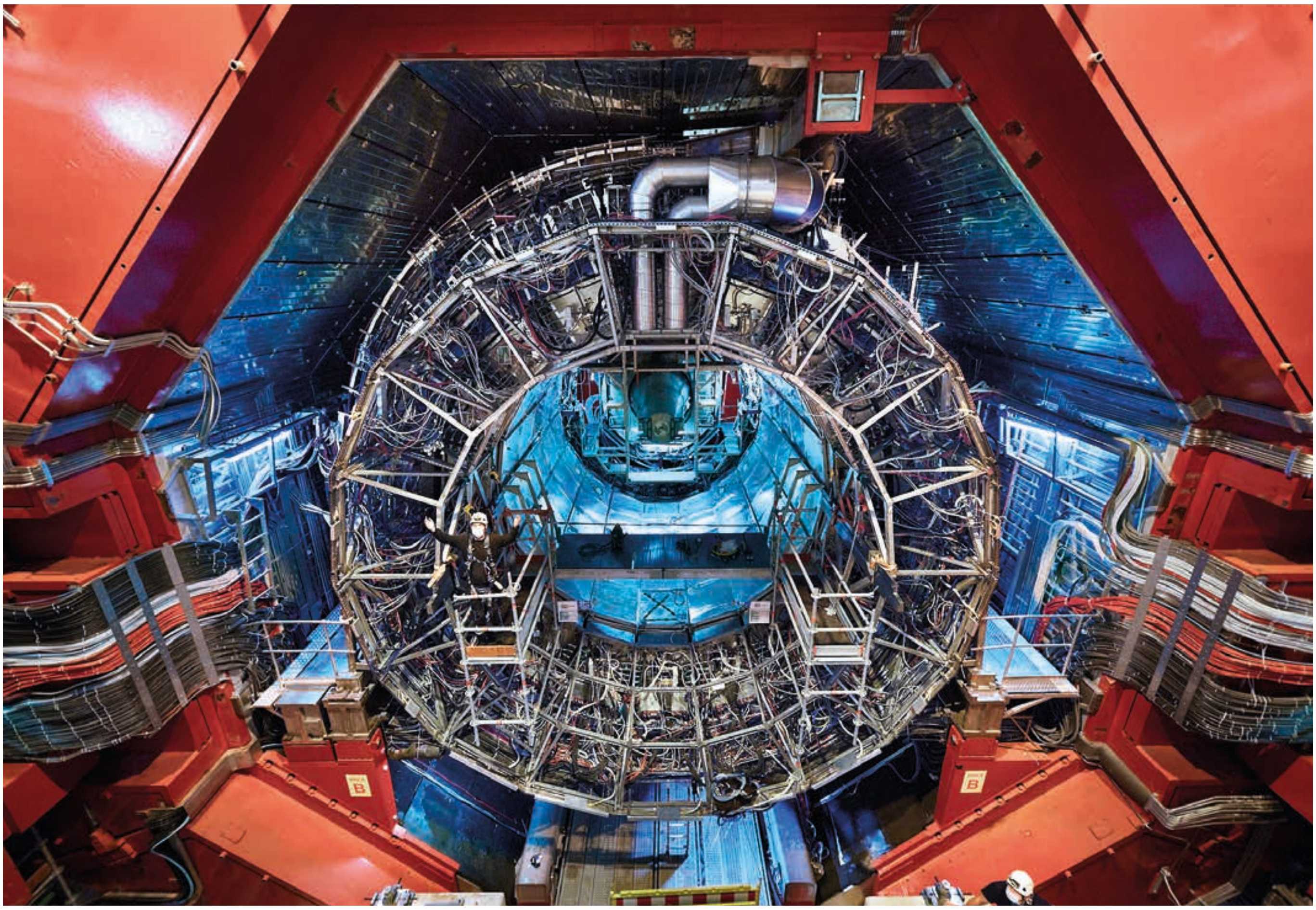
Our research group is involved both in the development and operation of the experimental setup and in the physics analysis. The latter work concentrates mostly on the studies of collective flow phenomena and jets. We studied high harmonic flow modes to gain information on viscosities, both shear and bulk, of the QGP [*J. High Energy Phys. 05 (2020) 085*]. We also studied jet transverse structure, both in p-p and p-Pb collisions, to constrain the cold nuclear effects [*ALICE Collaboration, arXiv: 2011.05898*]. Our next goal is to perform Bayesian analysis of transport properties based on extensive data-theory comparisons.

The year 2020 marked the middle of the Long Shutdown 2 (LS2) of the LHC. ALICE is using LS2 to implement a significant upgrade of the detector systems to cope with the increased luminosity and interaction rate after the restart of the LHC expected in 2022. In particular, ALICE is introducing three new detectors [*Nucl. Instr. Meth. A 958 (2020) 162116*] including the Fast Interaction Trigger (FIT). FIT involves 19 institutions from 9 countries with the University of Jyväskylä holding the leadership from the start of the project. FIT consists of 3 subsystems arranged into 5 detector arrays. The first one – an array of fast Cherenkov modules – was installed in December. The remaining subsystems are due for installation over the next 5 months.

In June, the first PhD thesis fully devoted to FIT [*M. Slupecki, JYU dissertations, URN: ISBN:978-951-39-8186-0*] was defended by M. Slupecki. M. Slupecki continues as a post-doc in the group. He moved full-time to CERN to continue his contribution to the construction, installation, commissioning, and soon operation of FIT.



Installation of a FIT detector array at the ALICE experimental hall. *Credit: W. H. Trzaska.*



JANNE PAKARINEN
ISOLDE project leader

ISOLDE

Due to the COVID-19 pandemic, our ISOLDE operations were mainly focussed on analysis of earlier data obtained at ISOLDE.

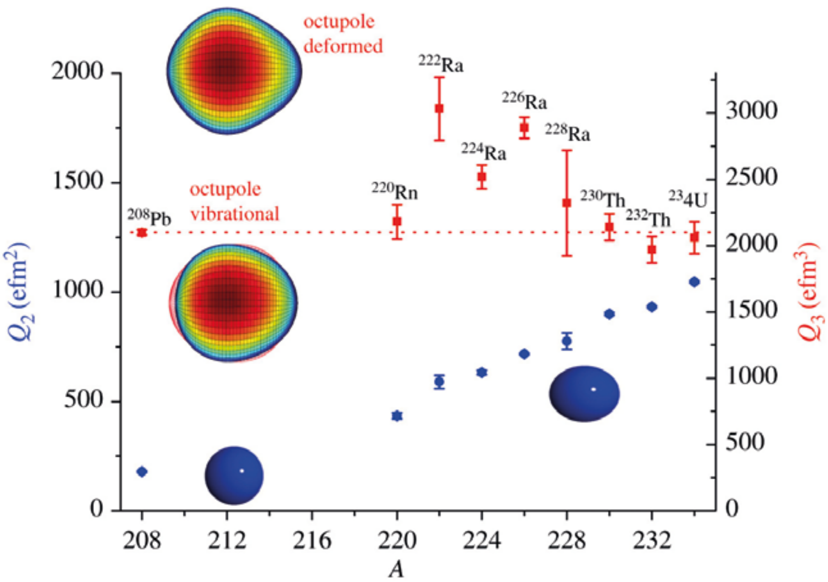
The physics highlight of the year continues to be the studies of pear-shaped nuclei. HIP-affiliated researchers J. Ojala and V. Virtanen were part of an international team lead by P. Butler from the University of Liverpool, UK. Exploiting post-accelerated radium beams only available at the ISOLDE facility, CERN, they investigated the evolution of octupole deformation in radium nuclei using Coulomb excitation technique. The observed pattern of E3 matrix elements for different nuclear transitions is explained by describing ^{222}Ra as pear-shaped with stable octupole deformation, while ^{228}Ra behaves like an octupole vibrator. This work was published in *Physical Review Letters*.

Another highlight of 2020 was the publication of the first experimental physics result using the SPEDE spectrometer developed in collaboration between the University of Jyväskylä and the University of Liverpool. The discovery of a new alpha-emitting state by M. Stryjczyk et al. enabled us to fix the location of several excited states in the ^{186}Tl nucleus. Overall, these findings shed light on the role of the proton $d_{3/2}$ shell in the region where the shape coexistence phenomenon is most prominent. These data were published in *Physical Review C* and the experiment is likely to produce a few other publications.

Despite the COVID-19 pandemic, K. Phan from Tampere University could participate in the HIP-funded summer training for one month at CERN, in which he developed analysis tools to help the treatment of experimental data obtained at the ISOLDE decay station.

Future Plans

The ISOLDE users community has been steadily growing in the last 15 years and the demand for beam time outnumbers the current production capabilities. Thus, the ISOLDE Collaboration has initiated the EPIC project (Exploiting the Potential of ISOLDE at CERN) to take full advantage of the recent upgrades at CERN, driven by the LHC Injectors Upgrade. The second ISOLDE – EPIC Workshop took place on a virtual platform in November. Ambitious plans on how the ISOLDE facility could expand in the future were presented. These include a new building for the so-called low-energy branch of ISOLDE, with several new target stations and front-ends.



P. A. Butler, 2020 Pear-shaped atomic nuclei, Proc. R. Soc. A. 476: 2020.0202.

FAIR
(Facility for Antiproton and Ion Research in Europe GmbH) Operations

TUOMAS GRAHN
FAIR
project leader

The FAIR Phase-0 experimental programme continued successfully in 2020 with a focus on super-heavy element studies and research carried out with high-energy beams delivered by the SIS18 synchrotron. While the COVID-19 pandemic hampered the experimental programme for most of the year, high quality data were collected, and more than half of the scheduled experiments were performed. Civil construction of FAIR in Darmstadt is currently on schedule; however minor delays due to the pandemic may be foreseen.

Phase-0 Programme and HIP FAIR Operations

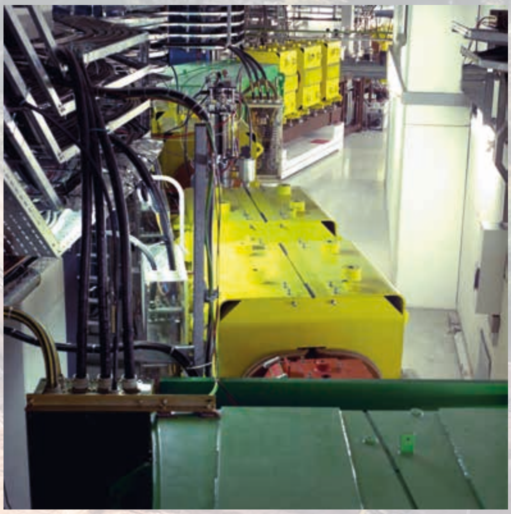
HIP researchers participated in several experiments during the 2020 Phase-1 campaign. The main emphasis was given to studies related to astrophysical nucleosynthesis processes. This was done through measurements of atomic masses, radioactive beta-decay half-lives, and spectroscopy of excited states in atomic nuclei. Since the isotopes of interest are very far from their stable counterparts, they have to be produced with relativistic heavy-ion beams in projectile fragmentation reactions. The unique instrumentation for such studies is the Fragment Separator (FRS), which will later be superseded by the Superconducting Fragment Separator (Super-FRS) of FAIR. The HIP efforts concentrated mainly on the regions of the nuclear chart below ^{100}Sn and around neutron number $N = 126$. These regions represent two current topics in nuclear physics, addressing the structure of so-called self-conjugate ($N = Z$) nuclei and measuring nuclear data relevant for *r*-process nucleosynthesis ($N = 126$).

Despite the global crisis, experiments proceeded and were productive. Online monitoring was carried out partly remotely, allowing international participants to help with the data taking. Currently, the data analysis is ongoing.

The FAIR Phase-0 programme continues beyond 2020 and proposals for future experiments were evaluated by the FAIR programme advisory committee. The accepted experiments include a strong contribution from HIP researchers.

FAIR Accelerator and Spectrometer Components

Design and construction of the beam diagnostic and identification detectors of Super-FRS advanced. Engineering and R&D efforts were dedicated for the readout electronics development of the GEM-TPC detector and its integration to the beamline of Super-FRS. Furthermore, SEM-grid beam-profile detector conceptual design was reviewed. The design and construction of the Super-FRS radioactive component safety transport container was initiated with an industrial partner in Germany.



The magnets and beamline of FRS.
Credit: A. Zschau, GSI Helmholtzzentrum für Schwerionenforschung.

TECHNOLOGY PROGRAMME

The Technology Programme aims to integrate HIP projects that have significant technology development, transfer, and pre-commercialisation activities into the same programme. In addition, the research activities performed within the programme are designed to seek synergies with big science initiatives at large. The programme is structured into three thematic areas – systems, materials, and radiation safety – each consisting of several small projects. Several projects have been successful in raising external funding for the R&D work, thus strengthening the impact of the programme.

FILIP TUOMISTO
Technology Programme director

Systems

MARKUS AICHELER
Accelerator Technology: Module, Structures and Manufacturing (MSM) project leader

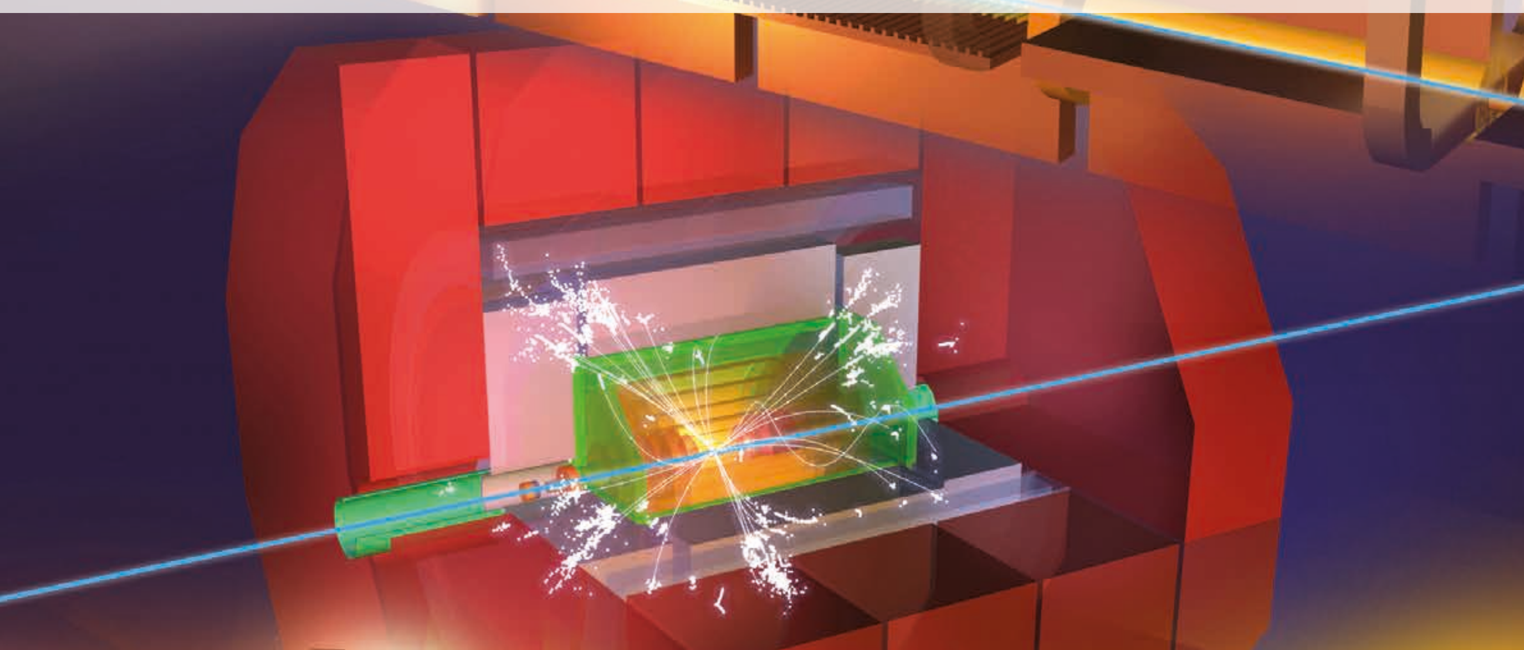
Accelerator Technology: Module, Structures and Manufacturing (MSM)

The Accelerator Technology: Module, Structures and Manufacturing (MSM) project collaborates strongly with various groups and projects at CERN, including the Compact LInear Collider (CLIC) study at CERN that is developing a two-beam technology for a future multi-TeV electron positron collider, as well as with the Beam Instrumentation Group.

The focus of the HIP contribution was on: a) R&D for CLIC RF structures manufacturing and the re-engineering of the so-called CLIC module (the smallest modular entity containing all sub-systems of the accelerator); b) an R&D activity on a cooling system for Beam Instrumentation in close collaboration with the BI group at CERN; c) taking part in CompactLight (an EU project on the design of future normal conducting FELs); d) developing a Business Finland co-innovation related to hybrid manufacturing in Finland for Detectors and Accelerators at CERN to be submitted in March 2021 within the FAME eco-system; and e) the completion and the publishing of a CDR for the ”Electrons in the SPS” project at CERN.

The work is executed in close collaboration with the CERN CLIC accelerating structures group of Dr. W. Wünsch and the CLIC module team of Dr. S. Döbert (co-led by Dr. M. Aicheler), and several Finnish industrial and academic partners. In 2020, the project was led by Dr. M. Aicheler at CERN, plus two PhD students (A. Holmström and J. Väinölä) based in Helsinki.

More details can be found at: https://www.hip.fi/accelerator-technology/m-s-m/



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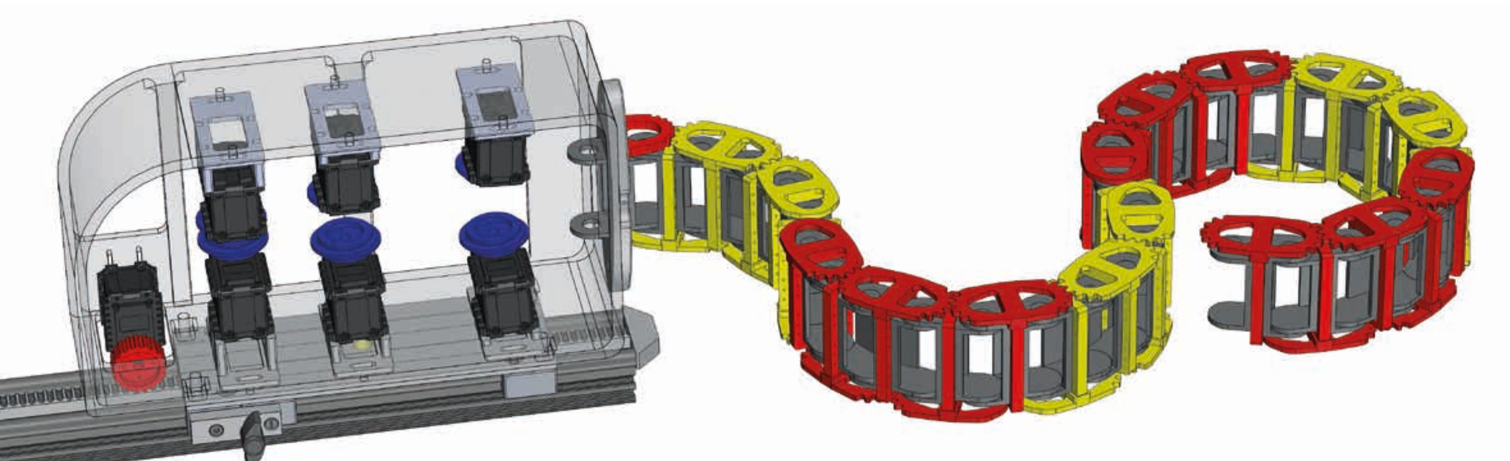
Robotics and AI for Monitoring and Intervention (ROBOT)

The ROBOT project of HIP's Technology Programme aims to utilise robotics and AI for assistance in monitoring and intervention of CERN's accelerator infrastructure. Tele-operated robots and their perception are under development for:

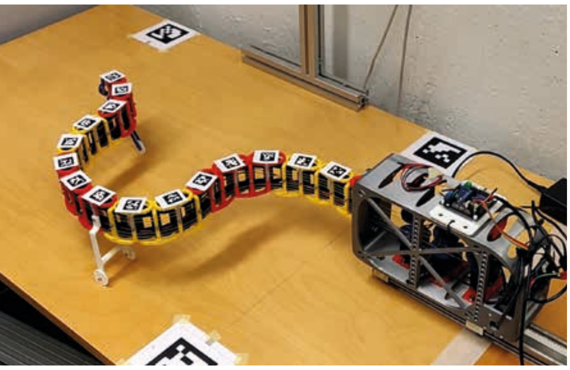
1. *Design of a continuum robot for inspection of the ALICE detector.* Assembly, maintenance, and inspection of the ALICE detector is done mostly manually but can benefit from robot-assisted tools for better views or for assisted assembly. As the detector is complex in shape and has narrow access, a small continuum robot is under development. The first prototype design (35 x 62 x 940 mm) is tendon-driven by seven motors and can achieve planar motion with high curvature. Limitations to this design (e.g., size, control accuracy) are being designed and realised in a second prototype. This work is part of D. Mohamadi's PhD studies and in collaboration with CERN's Experimental Physics Department.

2. *AI assisted tele-operation: vision-based grasp pose estimation.* In robot tele-operation, machine and deep learning can assist the user in difficult remote tasks such as robot object grasping. An object grasp pose estimation model can be trained with (simulated) data to achieve a robust grasp estimator that can handle the difficult conditions in the real world (e.g., a noisy, poorly lit tunnel environment). A robot grasping model is being developed that can handle dozens of industrial parts typical in (robotic) maintenance interventions. The training of the model utilises only simulation and generates training data from CAD models of industrial parts. This work is/has been done as part of two MSc theses (S. Ahmad, graduated; K. Osanda), and is relevant for CERN's robotics group that carries out remote interventions.

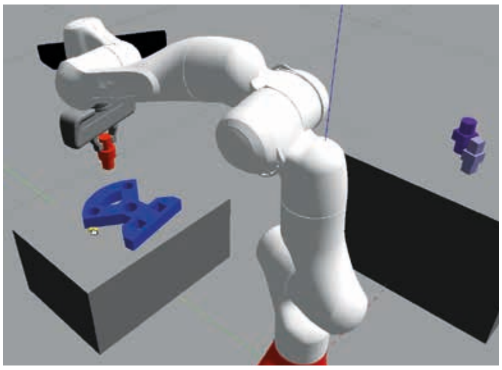
ROEL PIETERS
Robotics and AI for Monitoring and Intervention (ROBOT) project leader



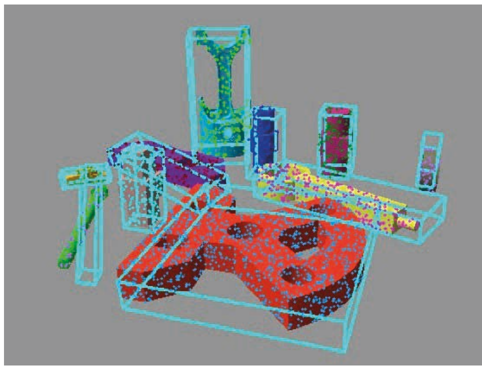
CAD design of continuum robot arm for ALICE inspection. *Credit: Cognitive Robotics group, Tampere University.*



Prototype of continuum robot arm for ALICE inspection. *Credit: Cognitive Robotics group, Tampere University.*



Simulation of robot grasping (with Franka Emika Panda robot) for a peg-in-hole manipulation task. *Credit: Cognitive Robotics group, Tampere University.*



3D pose estimation of simulated objects, to aid in robot grasping. *Credit: Cognitive Robotics group, Tampere University.*

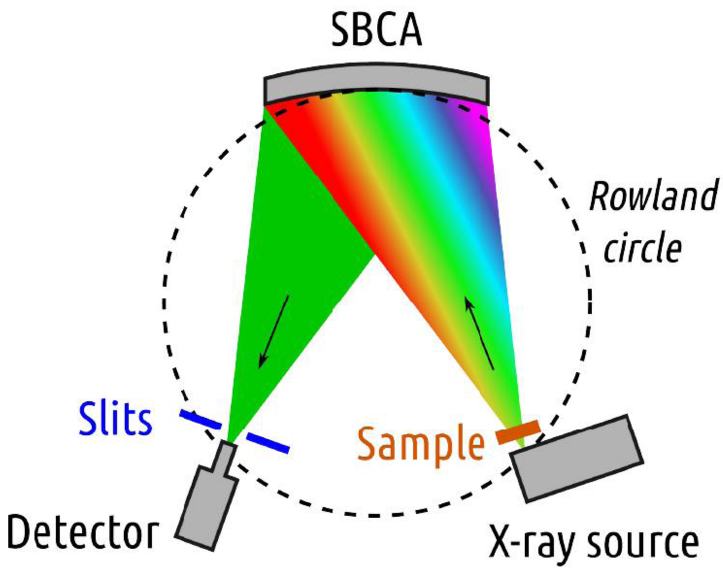
RENÉ BÈS
GAMMA
project leader

Diagnostics: Novel Gamma-Ray Spectroscopy for Radioactive Materials Testing (GAMMA)

Securing sufficient and environmentally sustainable electricity production is one of the main challenges for the future. Among electricity sources, fission and fusion reactors do not suffer from intermittencies observed in solar or wind resources and allow an efficient and flexible basis for the highly demanding electricity network. However, they require materials that resist extreme radiation environments.

Maintaining those material properties under irradiation is only possible by perfectly harnessing their behaviour and by developing new materials with finely tuned properties, including improved radiation resistance and easy reprocessing, and a reduced amount of resources and nuclear waste to manage will be required. An efficient way to characterize those material properties is via X-ray Absorption Spectroscopy (XAS) and Positron Annihilation Lifetime Spectroscopy (PALS). Those non-destructive and complementary characterization techniques are not usually applied to highly radioactive materials due to scarce access to the dedicated facilities, and the high cost and technical limitation arising when dealing with strongly radioactive materials. Thanks to recent technological developments in radiation detection and X-ray optics, the GAMMA project has developed new XAS and PALS devices that allow studying highly radioactive materials at the laboratory scale, unlocking access to their microscopic structure behaviour.

Within the project, we specially designed a PALS setup optimised to study nuclear fuels and currently entering operation at JRC Karlsruhe (Germany). A laboratory XAS setup has also been designed in order to study in situ materials under irradiation and will enter into operation in 2021.



R. Bès et al., X-ray absorption spectroscopy at laboratory scale: towards new actinide research opportunities XAFS 2018 (Krakow, Poland).

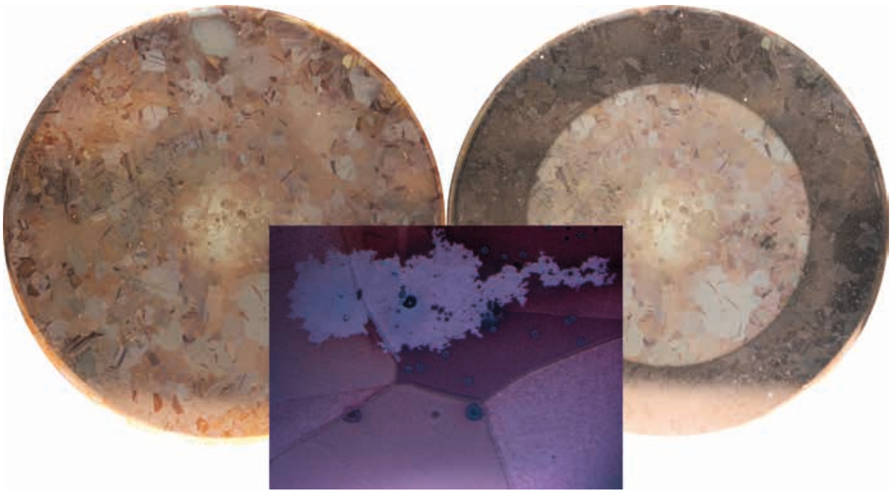
Materials

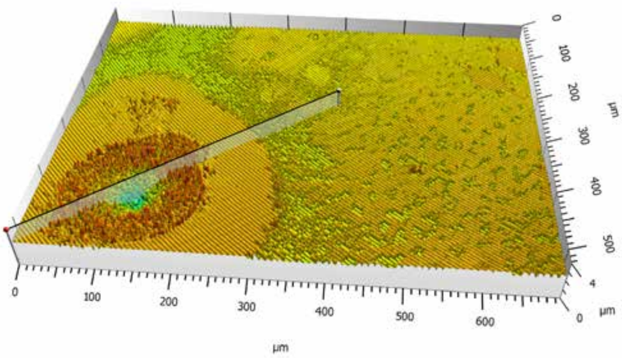
FLYURA DJURABEKOVA
Accelerator Technology: Materials (MAT) project leader

Acclerator Technology: Materials (MAT)

The project Acclerator Technology: Materials (MAT) focusses on developing a theoretical understanding of vacuum arcing onset with a strong experimental component in the research. In collaboration with Xi'an Jiaotong University, we were able to understand the processes developing near the anode surface. While the consensus on the active role of the cathode material in plasma is generally achieved, the experiment shows the bright light connecting both electrodes even if they are separated by a few millimetres. The lateral extent of the light suggests a significant role of the anode material. By combining our theoretical approach with experiments, we were able to show that the contribution of the anode material is not significant and plays only a secondary role in the appearance of the light in the gap between the electrodes. However, it is present in the vapour above the anode due to anode sputtering by ions from the quickly expanding cathode plasma.

In the HU Accelerator Laboratory, we have also performed dc-discharge experiments with high repetition rates (a few kHz) to imitate the condition of the CLIC RF accelerating structure. The study showed that the breakdown probability correlates with the length of idle time between the electric pulses. To understand the effect of the idle time, which allows contaminating particles always present even in high vacuum influence the surface, an in situ cleaning procedure utilising oxygen and argon plasma was implemented. The plasma treatment was shown to reduce the number of impurities on the electrode surfaces and to improve the breakdown resistance of pristine samples, but not to significantly affect the overall performance of the surface, corroborating our hypothesis of activation of undersurface mechanical processes.





Top: The cathode surface after oxygen plasma cleaning. The large image shows the comparison of the surface images before and after (see bright spot in the middle) the plasma cleaning. The inset shows that the cleaning is not even, but rather in spots. *Credit: A. Saressalo.*

Bottom: Image of the cathode surface obtained with optical profilometer. The roughness of the surface induced by plasma cleaning does not correlate with the probability of the appearance of vacuum arcing (a large spot at bottom left). *Credit: I. Kassamakov.*

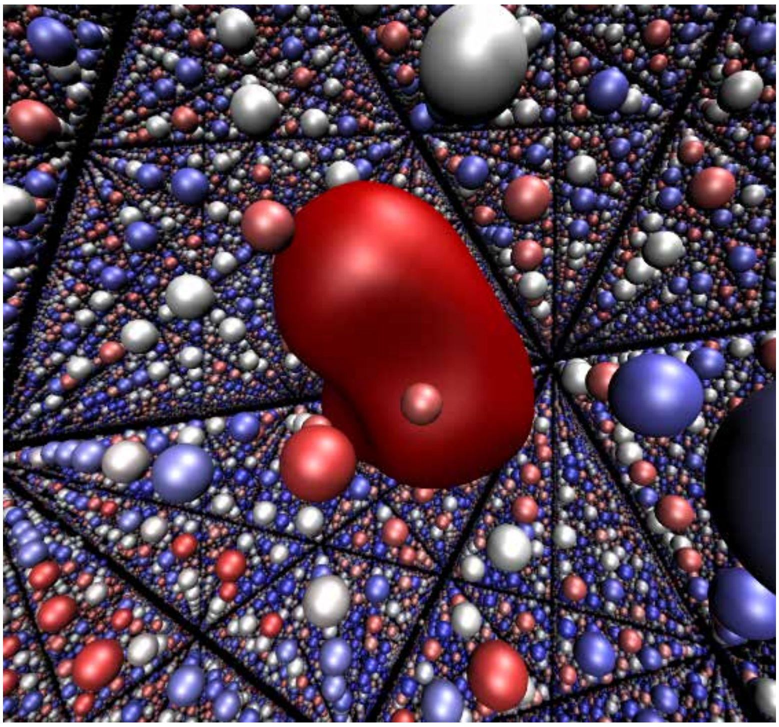
ILJA MAKKONEN
Materials for Big Science Installations (BIGS) project leader

Materials for Big Science Installations (BIGS)

The development and characterization of new materials for extreme environments is at the core of the technological needs of Big Science. Choosing and developing materials for next-generation facilities is critical for cost and environmental efficiency. This HIP Technology project has focussed on two classes of materials, the high-entropy alloys (HEAs), a novel metallic alloy, that can be tailored to suit multiple potential applications, and tungsten, an important plasma-facing material to be used in future fusion reactors.

HEAs are a relatively new class of metallic alloys that contain five or more elements in nearly equivalent ratios. HEAs differ significantly from conventional alloys, such as steel-based Fe-C alloys, cupronickels, and bronze, where there are one or two main elements with other alloying elements clearly in the minority. Global interest towards HEAs is due to the exceptional properties of these alloys, such as unique corrosion or abrasion resistance, radiation hardness, or performance at extreme (either low or high) temperatures. Even though the HEAs are a hot topic globally, a fundamental understanding of these types of materials from the atomic scale to macroscale is currently lacking.

The project's research has had two aspects: experimental characterization using especially the positron annihilation technique, and first-principles calculations of the metals and metallic alloys, as well as defects and defect clusters inside. In 2020, the main focus of the project was on the experimental studies of the effect of carbon on irradiation-induced defects and their annealing properties in a prototypical HEA alloy, the so-called Cantor alloy (fcc FeCrMnNiCo), but we have also started work on another refractory alloy (bcc MoNbTaVW).



Credit: I. Makkonen

Radiation Safety

Radiation Metrology for Medical Applications (RADMED)

The increasing frequency of computed tomography (CT) medical imaging calls for efficient patient exposure optimisation. This optimisation aims at the lowest patient dose possible, with the constraint that the required diagnostic information must be obtained from the acquired CT image.

The aim of the Multispectral Photon Counting for Medical Imaging and Beam Characterization (MPMIB) project, funded by the RADDESS programme of the Academy of Finland, is to develop a next-generation medical imaging system capable of spectral imaging. Our approach is to employ a real-time detection system based on single photon counting with silicon and Cadmium Telluride (CdTe) semiconductor pixel sensors, using readout electronics developed for high-energy physics experiments.

In 2020, we successfully tested silicon and CdTe pixel sensors bonded to a high-energy physics integrated readout circuit. Different X-ray spectra at the secondary standard laboratory of the Finnish Radiation and Nuclear Safety Authority STUK were used to study the energy and radiation intensity dependence of the detectors. Additionally, the suitability of a silicon pixel detector for radiation therapy quality control purposes was studied with a Co-60 therapy source, with the detector immersed in a water tank.

The project partners are the Helsinki Institute of Physics, Aalto University, Lappeenranta-Lahti University of Technology, and the Finnish Radiation and Nuclear Safety Authority STUK. The project receives funding from the Academy of Finland (RADDESS programme).

TEEMU SIISKONEN
Radiation Metrology for Medical Applications (RADMED) project leader

Group picture from a meeting regarding the development of a multispectral imaging detector for medical imaging and beam characterization within an Academy of Finland project of the RADDESS programme. *Credit: J. Aaltonen.*

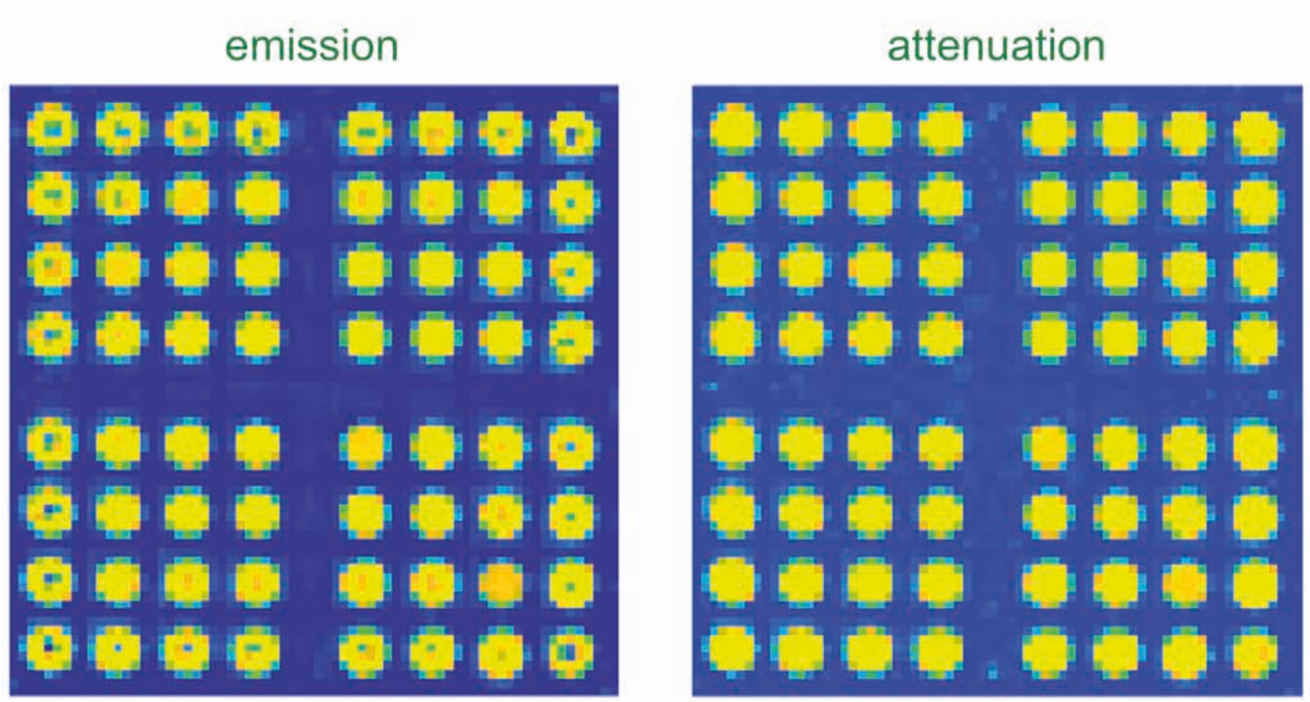


Image reconstruction of the Cs-137 emission (left) and the gamma-ray attenuation (right) for a SVEA-64 spent nuclear fuel assembly. The PGET spatial resolution is good enough to reveal the non-uniform distribution of Cs-137 inside the 10 mm diameter fuel rods, the result of diffusion of Cs-137. The attenuation image shows a uniform intra-rod distribution, indicating that, as expected, the spent fuel is homogeneous across the rod. *Credit: R. Virta (HIP and STUK).*

PETER DENDOOVEN
Radiation Safety Research & Development (RADAR) project leader

Radiation Safety Research and Development (RADAR)

GOSSER II (the Geological Safeguards and Security R&D project, 2019–2022, co-ordinated by the Finnish Radiation and Nuclear Safety Authority STUK) aims to create a safeguards approach for spent nuclear fuel disposal in a geological repository. In this context, we are developing two complementary methods for the characterization of spent nuclear fuel: Passive Gamma Emission Tomography (PGET) gives information on the presence of fission products whereas Passive Neutron Albedo Reactivity (PNAR) confirms the presence of fissile material. The PGET image reconstruction method developed in 2019 was applied to the data taken at Finnish nuclear power plants from 2017 to 2020. We concluded that the method is well-suited for nuclear safeguards verification of BWR fuel assemblies prior to geological disposal, whereas some further work is needed for VVER-440 assemblies. The analysis of the PNAR data from the first test in 2019 demonstrates the ability to detect the presence of fissile material in a repeatable manner in a reasonable amount of time as well as differences in multiplication between partially and fully spent fuel assemblies.

In the STUK-HIP joint project DEFACTO (Detector for fallout and air concentration monitoring), early warning detectors for improved emergency management are being developed. The detectors aim to improve upon the present ones by distinguishing airborne radioactivity, fallout components and radioactive contamination of the detector box. Two different prototype detectors were constructed and characterized, confirming that the set requirements are met. The detectors enable autonomous radiation monitoring and fast deployment. This is achieved with an integrated LTE modem, GNSS receiver, and battery.

Radiation Detection for Safety, Security and Safeguards (RADSAFE)

The main goals of the projects carried out within the RADSAFE project are to bring state-of-the-art radiation detection technologies and multi-parameter data-acquisition techniques to routine use in safety, security, and safeguards (3S) applications. Many technological solutions which have been developed for forefront research can be directly transferred to 3S applications, improving the sensitivity and reliability of radiation measurements. These solutions can ultimately improve the health and security of society as a whole. The projects are carried out in close collaboration with STUK and the University of Jyväskylä.

In 2020, the capability of the PANDA (Particles and Non-Destructive Analysis) system used in the analysis of radioactivity collected onto air filters from the environment in a collection network across Finland was expanded. PANDA is now capable of coincident alpha, beta, and gamma-ray spectroscopy and the first results were published [*Nucl. Instrum. Meth. A 984 (2020) 164637*].

Further significant progress has been made in the development and implementation of multi-parameter (coincidence) data-acquisition techniques and use of list mode data in various facilities at STUK. Solutions based on modern digital electronics have been implemented and will be phased into broader operational use in routine analysis at STUK.

Finally, work in the sub-project to develop an application-specific detector for full-body counting resulted in the development of an extensive GEANT4 simulation package. The package includes both male and female ICRP computational phantoms and simulations have been benchmarked with data from real-world measurements. A publication related to this work is in preparation.

P. Kivimäki

PAUL GREENLEES
Radiation Detection for Safety, Security and Safeguards (RADSAFE) project leader

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Finnish Business Incubation Center of CERN Technologies (BIC)

The CERN Business Incubation Network aims to improve commercialisation, and therefore, social utilisation, of CERN-related technologies in each member state. The FBC (Finnish Business Incubation Center of CERN Technologies), the CERN BIC in Finland, was established in 2015. The FBC has been operated under the Technology Programme at HIP.

During 2020, the opportunities to organise FBC operations have been discussed with multiple partners nationally and a network type of governance for FBC has been proposed.

The project, as part of the Technology Programme, has also supported a number of other R&D&I activities nationally and these have included during 2020, for example, support for Business Finland applications in partner universities, Challenge Based Innovation programmes and industrial partner engagements on various occasions.

SAKU MÄKINEN
BIC project leader

OTHER PROJECTS

MARKKU KULMALA
CLOUD
project leader

CLOUD

Background

Indirect observations and theoretical studies have suggested that galactic cosmic rays (GCR) may have influenced the Earth's cloud cover and climate, possibly by affecting the properties of aerosol particles. These tiny particles, floating in the atmosphere, influence the Earth's climate system via two mechanisms. First, they can directly reflect or absorb solar radiation, and second, they can act as seeds for the formation of cloud droplets or ice crystals and thereby affect the lifetime and precipitation of clouds. Measuring the underlying microphysics in controlled laboratory conditions is a key to understanding the dynamical behaviour of aerosol particles and cloud droplets, including the formation and growth processes of aerosols particles, cloud droplet activation, and ice nucleation. The CLOUD (Cosmics Leaving OUtdoor Droplets) experiment at CERN is one of the most advanced laboratory setups for studying these processes. The experiment aims to find the possible pathways of these phenomena and to evaluate their significance in the atmosphere by using the CERN proton synchrotron to vary the levels of GCR. The CLOUD Collaboration comprises 21 institutes, with a strong Finnish contribution.

Reconstruction and Improvement of the CLOUD Facility

In 2020 and 2021, the 60-year-old East Hall building, where the CLOUD chamber is located, is going through a major renovation. Therefore, the CLOUD facility will also be upgraded by increasing the size of the experimental area, renewing its control and meeting room, and building a chemical laboratory and an aerosol flow tube.

Data Analysis, Education, and Reporting of Results

Two CLOUD students are conducting their PhD in the Doctoral Programme of Atmospheric Sciences at the University of Helsinki. In 2020 they participated in two workshops, one winter school and in the bi-weekly CLOUD meetings all year long.

This year, 8 peer-reviewed papers were published. Briefly, *Dada et al. (2020)* established a protocol on how to calculate growth and formation rate of aerosol particles from chamber experiments. *He et al. (2020)* studied the collision rate of iodic acid in which an ion-induced nucleation mechanism helps to stabilise the cluster against evaporation. *Stolzenburg et al. (2020)* presented precise growth-rate measurements of uncharged sulphuric acid particles. *Simon et al. (2020)* studied new-particle formation from alpha-pinene and showed that a decrease in temperature results in a reduced yield of highly oxygenated organic molecules (HOM). *Heinritzi et al. (2020)* showed that isoprene reduces the yield of HOM dimers and particle formation rates. *Yan et al. (2020)* found that NO_x suppresses initial particle growth from biogenic precursors. *Wang et al. (2020a)* confirmed that oxidation products of urban aromatic gases can contribute to the initial growth of newly formed particles. Finally, *Wang et al. (2020b, Nature)* revealed that against expectations nitric acid can grow particles, possibly explaining the rapid growth of particles in megacities.

The 70 participants in the combined INAR Winter School and CLOUD Data Workshop (February 2020) organised by the University of Helsinki, in Hyytiälä Finland. Hyytiälä is the place where ambient new particle formations have been monitored for more than 25 years. *Credit: J. Aalto.*

HANNU KURKI-SUONIO
Euclid project leader

Euclid

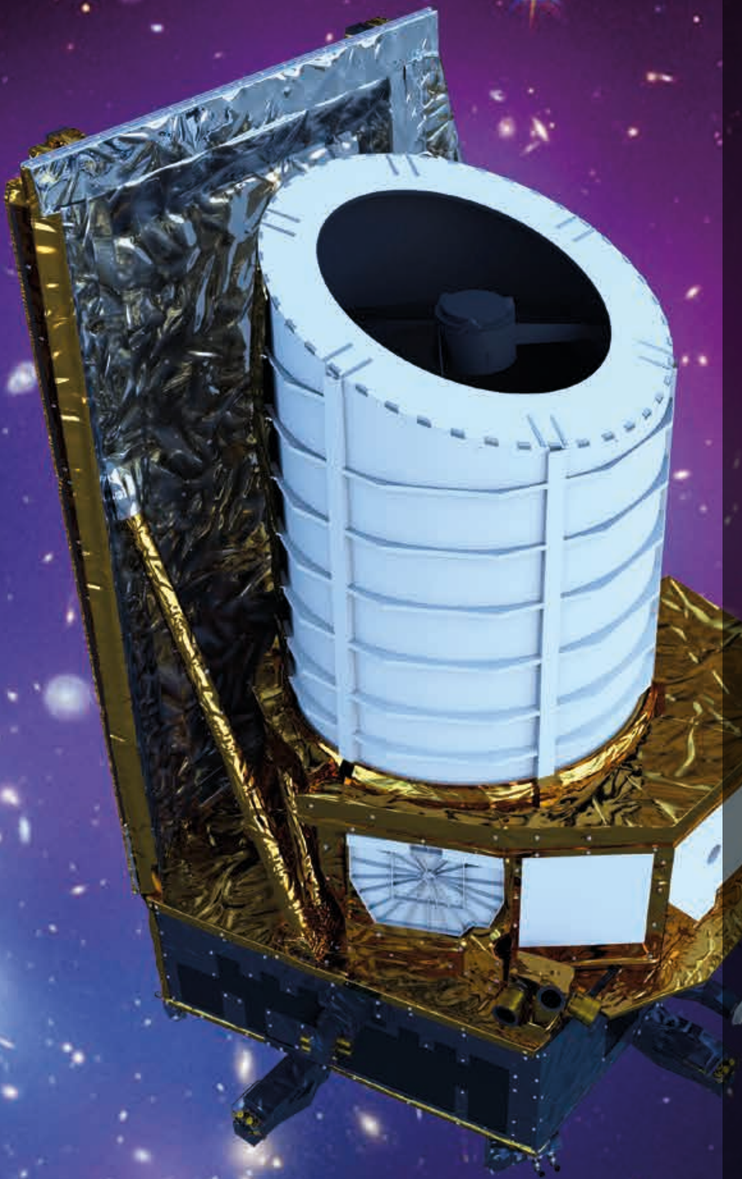
Euclid is a cosmology mission of the European Space Agency. Euclid will study the "Dark Energy Question" – why is the expansion of the universe accelerating, and what is the nature of dark energy? To this goal, Euclid will be surveying over a third of the sky, obtaining images of over a billion galaxies and tens of millions of galactic spectra. The Euclid Consortium will use these observations to determine the 3-dimensional distribution of galaxies and dark matter in the universe, compare their statistics to cosmological models, and thus constrain the law of gravity and the dark energy equation of state.

Euclid complements the previous cosmology mission, Planck, in improving our understanding of the universe, its structure, composition, origin, and governing forces; Planck concentrated on the early universe and Euclid will concentrate on its later evolution. Our involvement in the Planck Collaboration ended in 2020 with the publication of the final Planck results (15 publications), which agree with the standard model of cosmology, the LambdaCDM model, and determined its parameters to high accuracy.

The Euclid satellite is nearing completion. The two instruments, NISP (Near Infrared Spectrometer and Photometer) and VIS (imager at visible wavelengths), were integrated to the wide-field telescope in 2020 and this satellite payload is now being tested. Euclid will be launched near the end of 2022 and will make observations for 6 years.

The analysis of Euclid data is divided among nine Euclid Science Data Centers (SDC). We operate one of them, SDC-FI, on virtual machines at the national CSC Kajaani Data Center. In 2020 we participated in the Euclid SDC Science Challenges 7 and 8 where the current version of the Euclid data analysis pipeline was tested. Science Challenge 8 will continue in 2021 and will, for the first time, involve the full pipeline from simulated images to final data products. We participated in the development and validation of the code to produce simulated NISP data, and in the production of the simulated VIS data.

We have the main responsibility in Euclid for validating the code to estimate one of the main cosmology products of Euclid, the 2-point correlation function of the distribution of galaxies. We also develop the code together with an international team within Euclid. For this code, we achieved a major maturity milestone in 2020. In the Euclid Theory Working Group we prepared forecasts for the constraining power of Euclid on early universe models.



Artist's impression of the Euclid spacecraft. *Credit: ESA/ATG medialab (spacecraft); NASA, ESA, CXC, C. Ma, H. Ebeling, and E. Barrett (University of Hawaii/IfA) et al., and STScI (background).*

Education and Open Data

KATRI LASSILA-PERINI
Education and Open Data project leader

The Education and Open Data project covers and connects two activities: the Finnish high-school visit programme at CERN, and the preservation of CMS experiment data and preparing open access to them. The project is led by K. Lassila-Perini, who also acts as the Data Preservation and Open Access co-ordinator of the CMS experiment.

High School Visits

In 2020, 5 high-school groups from Finland were able to make a three-day visit to CERN before the outbreak of the pandemic. The visits are preceded by extensive studies in schools, preparing for an intensive lecture and visit programme at CERN. The programme is partly subsidised by the Finnish National Agency for Education, and co-ordinated by the national CERN high-school network. The feedback from these visits is excellent, the direct contact with the researchers and their enthusiasm is greatly appreciated, and the visits encourage students to join various scientific branches. The participating schools are looking forward to the continuation of the visits.

CMS Data Preservation and Open Data Releases

The CMS Data Preservation and Open Access group manages the actions needed for data and knowledge preservation of the experiment. Data is regularly released for public use, and the two releases in 2020 completed the open data for the standard proton-proton collisions from 2011 and brought the first heavy-ion collisions, taken in 2010 and 2011, to the public domain. The CMS Open Data are increasingly in use, for scientific studies and in education, and a successful CMS Open Data workshop was organised in autumn. A CERN Open Data policy was drafted this year, and it was endorsed by all LHC experiments and announced in December. This was facilitated with the positive experience gained with the public CMS data.

Open Data Training

The project organises two-day training sessions for teachers for using open data in schools with the help of ”jupyter notebooks” and common python libraries. The situation did not allow for such training in 2020. However, the time was well spent in preparing new material, also covering topics beyond particle physics, in which the data can be accessed and analysed with the same tools and methods. A user guide was prepared to facilitate the ease of use of the material. Use of open data in real teaching situations was also piloted by P. Veteli, who finalised his Master’s Thesis on the topic at the University of Helsinki. This work was made possible by a subsidy to promote science studies in high school by the Finnish National Agency for Education.

DETECTOR LABORATORY

EIJA TUOMINEN
Detector Laboratory chief engineer

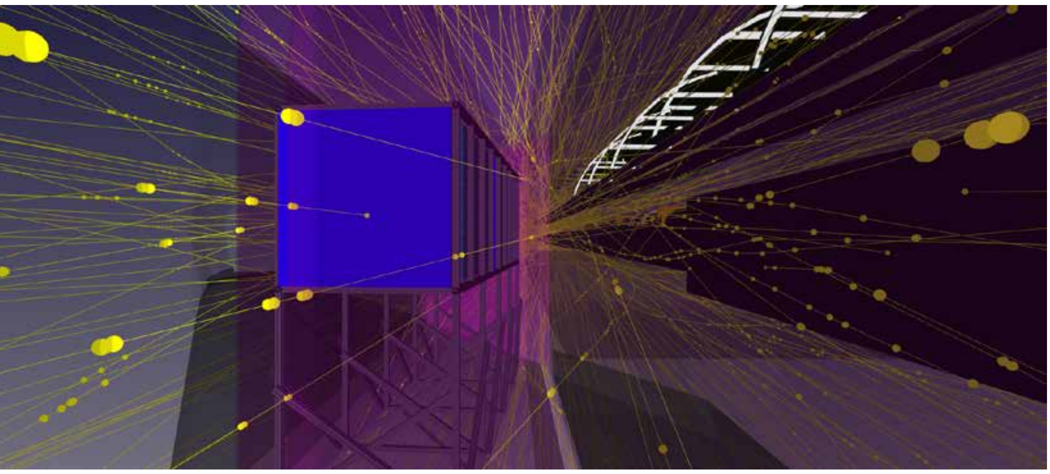
The Helsinki Detector Laboratory is a national permanent infrastructure specialised in the **instrumentation** of particle and nuclear physics. It is a joint laboratory between the Helsinki Institute of Physics (HIP) and the UH Department of Physics, especially the Division of Particle and Astrophysics (PAP). The Laboratory provides premises, equipment, expertise and technical support for research projects that develop semiconductor, gas-filled, and scintillator detector technologies.

The Detector Laboratory provides reliable instruments for **large international physics experiments**. In 2020, despite the severe limitations set by the COVID-19 pandemic, the Laboratory successfully participated in the instrumentation of the CMS, TOTEM, and MoEDAL experiments at CERN, and the NUSTAR experiment at FAIR. In addition, activities of radiation safety by the Finnish Radiation and Nuclear Safety Authority STUK and activities of medical imaging funded by the Academy of Finland were present in the Laboratory.

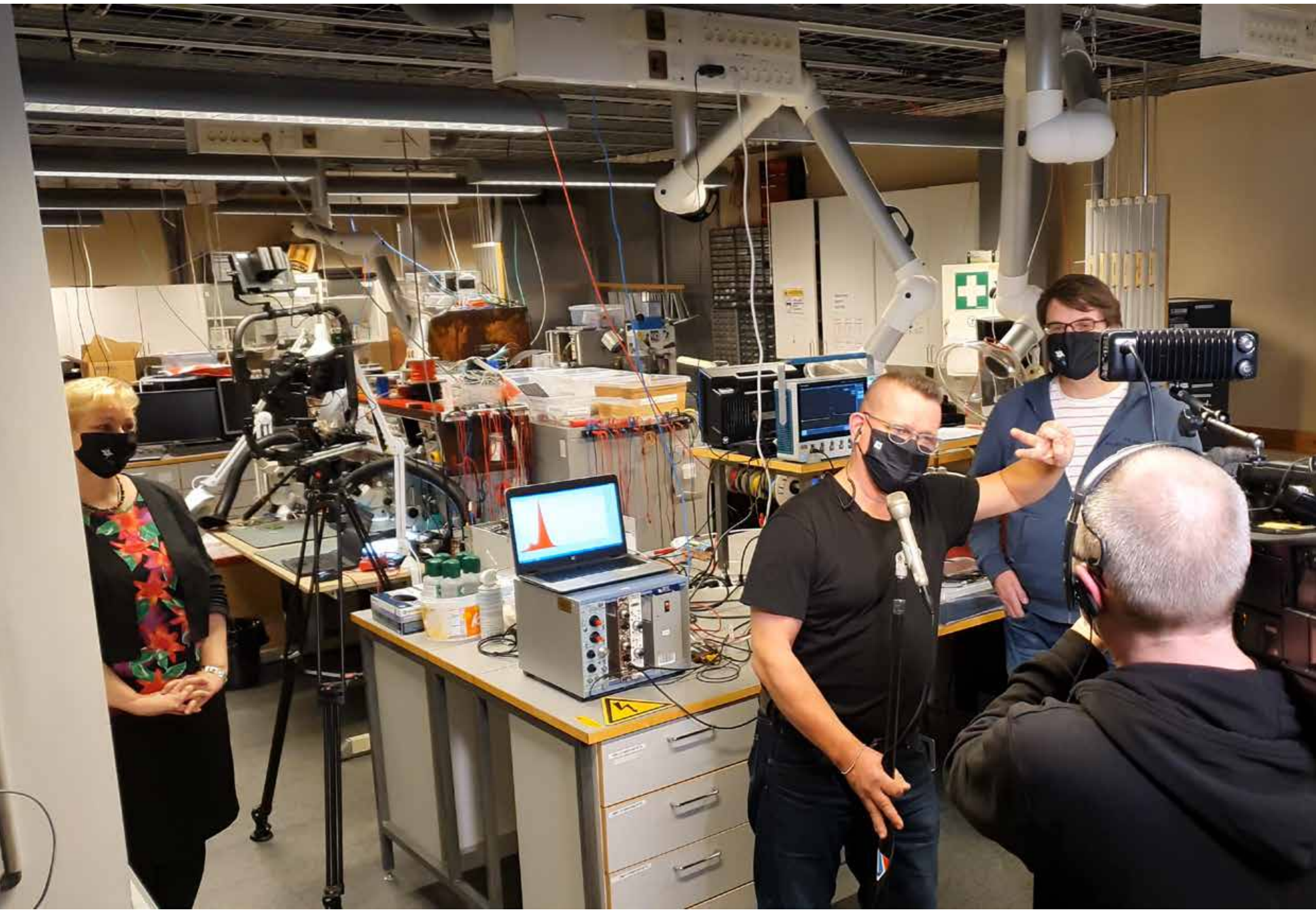
The Detector Laboratory has a wide network of **national collaboration** for sharing expertise, equipment and infrastructure. In 2020, the Laboratory worked closely with the laboratories of the UH Faculty of Science and with the instrumentation laboratories and physics departments from other Finnish universities, such as the Aalto University Nanofabrication Centre and the Jyväskylä University Accelerator Laboratory. In addition, the Laboratory collaborated with Finnish industry, especially with small- and medium-size companies and start-ups.

Guaranteeing the future expertise in the instrumentation via research-based **education** is important in the Laboratory. In 2020, the Laboratory hosted a course on semiconductor detectors and a laboratory course on instrumentation for the Master's Programme for Particle Physics and Astrophysical Sciences (PARAS). The Laboratory personnel also supervised doctoral, master, and bachelor students in their thesis works. Here, the Laboratory worked closely with the Doctoral Programme in Particle Physics and Universe Sciences (PAPU).

In 2020, despite the severe limitations due to COVID-19, special effort was devoted to **societal interaction** to ignite interest in physics especially among children and youth. In summer 2020, the Laboratory had two high-school students as the first-ever remote-working summer trainees. In November, the Laboratory participated actively in EU Researchers' Night by producing videos and animations on the internet, hosting an interactive zoom-event from the Laboratory, and welcoming a team from YLE (the Finnish public service media company) for online broadcast.



Geant4-simulation of MoEDAL-MAPP detector in UGC1 gallery at 100 meters from the IP8 with neutron background from 14 TeV pp-collisions. *Credit: M. Kalliokoski.*



YLE Puoli Seitsemän broadcasting live from the Detector Laboratory during EU Researchers' Night 2020. *Credit: J. Aaltonen.*

Artist Collective Honkasalo-Niemi-Virtanen at the Detector Laboratory clean room videographing for their artwork "Atomic". *Credit: J. Aaltonen.*

JOINT ACTIVITIES

© Linda Tammisto, University of Helsinki

ANTTI VÄIHKÖNEN
Research coordinator

HIP is a joint institute of five universities with the University of Helsinki as the host. The Finnish Radiation and Nuclear Safety Authority (STUK) became an interim member of HIP for 2018–2019 followed by a continuation for 2020–2022. Due to its core mission, many of the research activities of HIP take place at CERN and FAIR. The distributed nature of HIP brings its own flavour and challenges.

The year 2020 was defined by the COVID-19 pandemic. The personnel of HIP felt the extra burden and conducting research, especially experimental and laboratory work, became more difficult. At the same time, the full immersion in remote mode reduced the significance of geography. Everyone at HIP was equally far away from everyone else. In addition, the forced learning and implementing of new tools and habits provided invaluable means to reduce travel and to tackle future sustainability challenges.

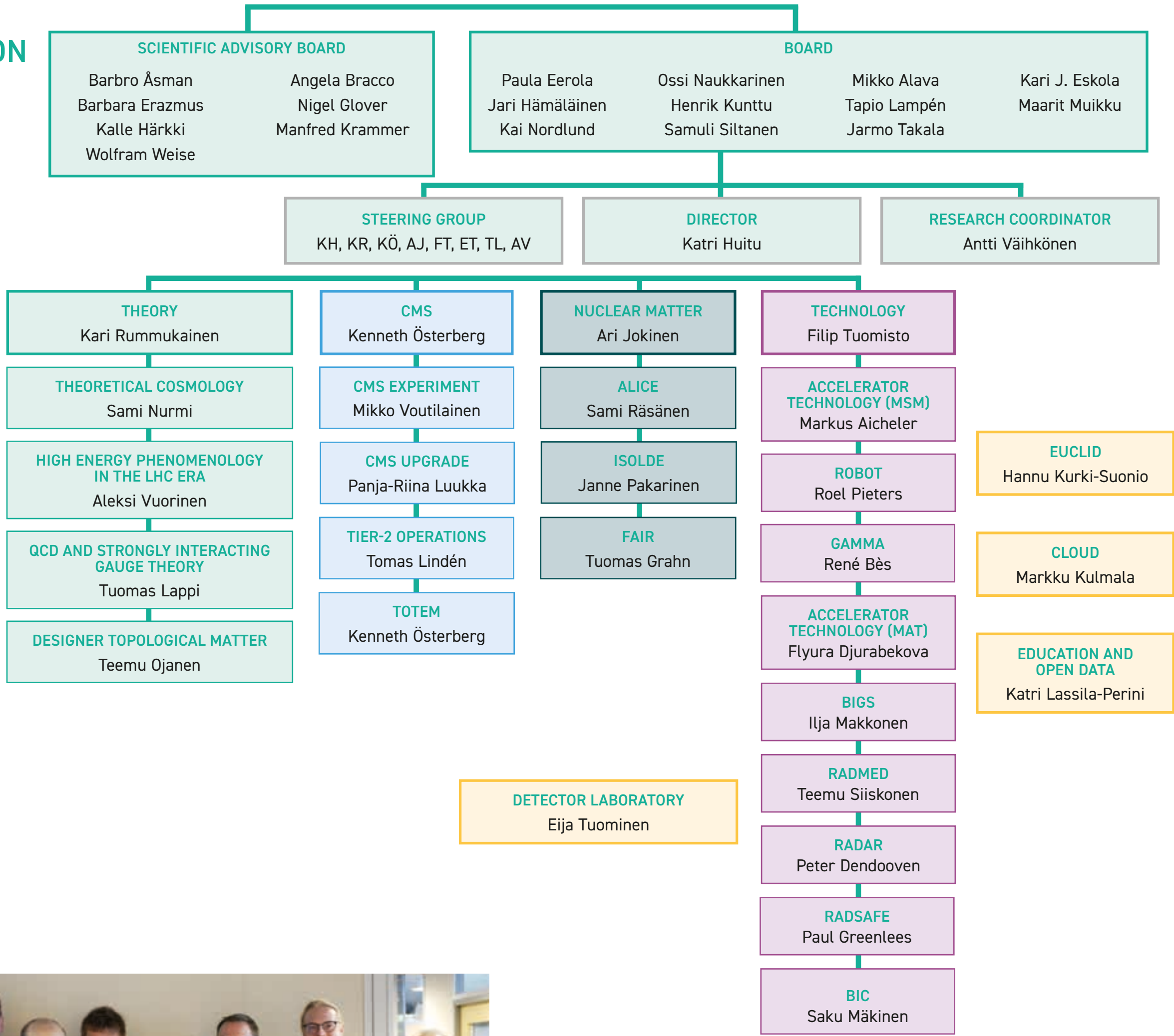
There were also financial worries as the government cut the earmarked direct funding for HIP by 26% for 2021–2024, despite meetings with key ministers and other efforts by HIP and its stakeholders. In order to prevent significant reduction of HIP activities, the member universities decided to increase their joint funding by the corresponding amount and, thus, they are keeping the HIP base funding at its previous level for the coming years.

The publication output of HIP continued very strongly with about 330 peer-reviewed publications in 2020. The scientific production of HIP is generally of high quality, as was stated by the Scientific Advisory Board, and verified in the research evaluation of the University of Helsinki in 2019. HIP publications are mostly in the two highest national JUFO categories and practically all, about 95% of them, are open publications.

The doctoral education of physics students continues to be one of the main tasks of the Institute. In addition, a fair number of undergraduate students have joined the research groups. Many of them are continuing as doctoral students in Institute projects. During the period 2016–2020, 49 doctoral degrees and 59 Master's degrees have been earned in HIP research projects. Although the CERN BootCamp was cancelled, the HIP summer student programme at CERN and ESRF continued in 2020. Due to COVID-19 restrictions the trainees mostly worked remotely.

ORGANIZATION AND PERSONNEL

ORGANIZATION



The Board: Kari J. Eskola, Kai Nordlund, Tapio Lampén, Mikko Alava, Paula Eerola, Erkki Lähderanta (substitute member), Samuli Siltanen, Maarit Muikku, Ari Jokinen (substitute member).

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D. Cutting, scientist
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E. Schiappacasse, adj. scientist
E. Tomberg, adj. scientist
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O. Koskivaara, grad. student
N. Lahén, grad. student
L. Laulumaa, grad. student
J. Leskinen, grad. student
M. Mannerkoski, grad. student
L. Niemi, grad. student
J.-M. Ojanperä, grad. student
S. Raatikainen, grad. student
P. Rahkila, grad. student
L. Tenhu, grad. student
N. Venkatesan, grad. student

High Energy Phenomenology in the LHC Era

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O. Lebedev, prof., adj. senior scientist
N. Jokela, senior scientist
E. Keski-Vakkuri, adj. senior scientist
M. Sainio, adj. senior scientist
K. Tuominen, adj. senior scientist
M. Heikinheimo, scientist
O. Henriksson, scientist
P. Schicho, scientist
J. Tarrío, scientist
V. Keus, adj. scientist
R. Paatelainen, adj. scientist
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J. Hirvonen, grad. student
L. Niemi, grad. student
J. Remes, grad. student
A. Stendahl, grad. student
S. Säppi, grad. student
J. Österman, grad. student

QCD and Strongly Interacting Gauge Theory

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H. Mäntysaari, scientist
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P. Guerrero Rodriguez, adj. scientist
I. Helenius, adj. scientist
G. Inghirami, adj. scientist
M. Li, adj. scientist
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H. Hänninen, grad. student
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J. Penttala, grad. student
A. Ramnath, grad. student
J. Suorsa, grad. student

Designer Topological Matter

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L. Yang, adj. scientist
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I. Sahlberg, grad. student

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CMS Experiment

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S. Laurila, adj. scientist
J. Pekkanen, adj. scientist
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J. Heikkilä, grad. student
K. Kallonen, grad. student
M. Lotti, grad. student
L. Martikainen, grad. student
M. Myllymäki, grad. student
H. Siikonen, grad. student
A. Autio, student
A. Pirttikoski, student
B. Schillinger, student

CMS Upgrade

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V. Litichevskyi, scientist
S. Barthuar, grad. student
M. Bezak, grad. student
M. Golovleva, grad. student
A. Gädda, grad. student
S. Kirschenmann, grad. student
L. Martikainen, grad. student
J. Ott, grad. student
J. Tikkanen, grad. student
I. Ninca, student
M.-M. Rantanen, student

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F. Kivelä, research assistant

TOTEM

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F. García, lab. engineer
F. Oljemark, grad. student
A. Molander, student
M.-M. Rantanen, student

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H. Rytkönen, grad. student
O. Saarimäki, grad. student
M. Slupecki, grad. student

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R. de Groote, adj. scientist
W. Gins, adj. scientist
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H. Penttilä, adj. senior scientist
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M. Luoma, grad. student

Technology Programme

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Systems

Accelerator Technology: Module, Structures and Manufacturing (MSM)
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K. Österberg, prof., adj. senior scientist
A. Holmström, grad. student
A. Solodko, grad. student (at CERN)
J. Väinölä, grad. student
O. Willman, student

Robotics and AI for Monitoring and Intervention (ROBOT)
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E. Rahtu, ass. prof., adj. scientist
D. Mohamadi, adj. scientist

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A. Karjalainen, grad. student

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Radiation Safety

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J. Tikkanen, grad. student

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T. Hildén, scientist (at STUK)
M. Muikku, scientist (at STUK)
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R. Pöllänen, scientist (at STUK)
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H. Jutila, grad. student
O. Neuvonen, grad. student

Finnish Business Incubation Center of CERN Technologies (BIC)

S. Mäkinen, prof., proj. leader
P. Kauttu, grad. student

Other projects

CLOUD

M. Kulmala, prof., Academician, proj. leader
J. Duplissy, senior scientist

Euclid

H. Kurki-Suonio, docent, proj. leader
E. Keihänen, senior scientist
J. Väliviita, senior scientist
A.-S. Suur-Uski, scientist
G. Gozaliasl, adj. scientist
C. Kirkpatrick, adj. scientist
K. Kiiveri, grad. student
S. Kivistö, grad. student
V. Lindholm, grad. student
S. Tuomisto, grad. student
A. Viitanen, grad. student

Education and Open Data

K. Lassila-Perini, Dr., proj. leader (at CERN)
P. Veteli, grad. student

Detector Laboratory

E. Tuominen, chief engineer
I. Kassamakov, docent, lab. engineer
M. Kalliokoski, staff scientist
F. García, lab. engineer
J. Heino, lab. engineer
P. Koponen, lab. engineer
R. Turpeinen, lab. technician

Administration and Support

K. Huitu, prof., director
A. Väihkönen, research coordinator
J. Aaltonen, lab. engineer

University Services administration team including:
T. Laurila, admin. manager
H. Kinnunen, controller
T. Hardén, service coordinator
E. Veranen, HR coordinator
T. Heikkilä, secretary
T. Karppinen, secretary (at CERN)
T. Onnela, secretary (at CERN)

HIP SEMINARS

21 January P. Saffin (Nottingham)
Integrating the path integral

28 January S. Vihonen (Guangzhou)
China and the quest for the lepton flavour

11 February C. Rosen (Imperial College, London)
Supersymmetric deformations and spatially modulated masses

20 February S. Kawai (Sungkyunkwan University, Suwon, South Korea)
eV-scale sterile neutrinos from an extra dimension

25 February A. Krikun (NORDITA)
Non-metallic ground states from holography: features and observables

25 February A. Ferrari (Uppsala)
Higgs boson pair production at the LHC: experimental overview

27 February LISA day
M. Hewitson (AEI, Hannover)
– **The status and design of the LISA mission**
M. Hindmarsh (Sussex and Helsinki)
– **LISA science**
A. Petiteau (APC, Paris)
– **Challenges of LISA data analysis**
E. Tuominen (HIP, Helsinki)
– **Helsinki Detector Laboratory in the instrumentation of international physics experiments**
E. Keihänen (Helsinki)
– **Planck and Euclid**
J. Huovelin (Helsinki)
– **Activities for ongoing and planned space science missions at the University of Helsinki**
T. Savolainen (Aalto)
– **Horizon-scale imaging of supermassive black holes**
P. Johansson (Helsinki)
– **Simulating black hole dynamics and gravitational wave emission in galactic-scale simulations**
D. Weir (Helsinki)
– **Detecting first-order phase transitions at the electroweak scale with LISA**

3 March C. Hoyos (Oviedo)
Scattering length from holographic duality

28 April E. Annala (Helsinki) (online)
Neutron stars and quark matter

5 May R. Gonzalez Suarez (Uppsala) (online)
Long live the Large Hadron Collider

12 May C. Herzog (King's College, London) (online)
Graphene and boundary conformal field theory

19 May R. Pöttgen (Lund) (online)
Light in the dark – opening a new window to the dark sector

26 May N. Schlusser (Darmstadt) (online)
Jet momentum broadening from the lattice

2 June J. Remes (Helsinki) (online)
V-QCD and neutron stars

9 June V. Sanz (Sussex and Valencia/CSIC) (online)
Theoretical interpretation of non resonant searches

1 September A. Cherman (Minneapolis) (online)
Higgs-confinement phase transitions with fundamental matter

8 September J. Havukainen (Helsinki) (online)
Machine learning at the LHC

22 September M. Piai (Coleg y Gwyddoniaeth, Abertawe, Cymru) (online)
Higgs compositeness and beyond the Standard Model physics

29 September H. Waltari (Southampton) (online)
Exploring neutrino physics through sneutrinos

20 October N. Jokela (Helsinki) (online)
Holographic confinement confronts lattice Yang-Mills theory

3 November J. Kastikainen (Helsinki, Paris) (online)
Holographic F-functions in ABJM theory with flavor on the 3-sphere

24 November S. Säppi (ECT*, Trento) (online)
Thermal pQCD and the progress towards the NNNLO pressure at zero temperature

1 December M. Järvinen (APCTP, Pohang, South Korea) (online)
Holographic neutron stars and transport in dense QCD

8 December J. Kost (Sussex) (online)
Deciphering the archaeological record: cosmological imprints of non-minimal dark sectors

15 December F. Bigazzi (INFN, Florence) (online)
Dark holograms and gravitational waves

VISITORS

Theory Programme

Theoretical Cosmology

A. Rantala (Germany) 8.–10.1.
U. Steinwandel (Germany) 8.–10.1.
P. Saffin (UK) 20.–21.1.
D. Cutting (UK) 3.–28.2.
D. Karamitros (Poland) 10.–15.2.
N. Venkatesan (Finland) 19.–21.2.
P. Auclair (France) 24.–28.2.
D. Steer (France) 25.–28.2.
A. Petiteau (France) 26.–28.2.
M. Hewitson (Germany) 27.–28.2.
V. De Romeri (Spain) 4.–6.3.

High Energy Phenomenology in the LHC Era

M. Rahimi (Iran) 1.1.–31.5.
C. Rosen (UK) 11.–12.2.
C. Heissenberg (Sweden) 12.–15.2.
S. Kawai (South Korea) 12.–29.2.
A. Krikun (Sweden) 24.–25.2.
C. Hoyos (Spain) 1.–6.3.
D. Gutiez (Spain) 4.10.–2.12.

QCD and Strongly Interacting Gauge Theory

D. Rischke (Germany) 14.–24.2.

CONFERENCE PARTICIPATION, TALKS AND VISITS BY PERSONNEL

Theory Programme

Theoretical Cosmology

University of Jyväskylä,
24 January, Jyväskylä, Finland (colloquium talk by D. Weir)

Tufts University,
2–3 March, Medford, MA, USA (talk by D. Weir)

Flatiron Institute,
4–6 March, New York, NY, USA (D. Weir)

University of Southern Denmark,
6 April, Odense, Denmark (online)
(remote talk by D. Weir)

Instituto de Fisica Gleb Wataghin, Universidade Estadual de Campinas,
29 April, Campinas, São Paulo, Brazil (online)
(remote colloquium talk by S. Räsänen)

Newton 1665 On-Line Seminar,
7 May (remote talk by K. Kainulainen)

Institute for Nuclear Research,
29 May, Moscow, Russia (online)
(remote seminar talk by J. Rubio)

Teleparallel Gravity Workshop 2020,
15–19 June, University of Tartu, Tartu, Estonia (online)
(S. Raatikainen, remote talk by S. Räsänen)

Quantum Gravity Meets Dark Energy Workshop,
19–23 June (online) (remote talk by J. Rubio)

13th MoEDAL Collaboration Meeting,
1 July (online) (remote talk by O. Gould)

INFN,
2 July, Rome, Italy (online) (remote talk by E. Schiappacasse)

Heidelberg University,
9 July, Heidelberg, Germany (online)
(remote talk by D. Weir)

Anomalies 2020,
11–13 September, IIT, Hyderabad, India (online)
(remote talk by M. Hindmarsh)

MAOL (Matemaattisten Aineiden Opettajien Liitto),
3 October (online) (remote talk by K. Kainulainen)

Tokyo Institute of Technology,
7 October, Tokyo, Japan (online)
(remote talk by E. Schiappacasse)

Institute for Nuclear Research,
12 October, Moscow, Russia (online)
(remote seminar talk by E. Schiappacasse)

Zooming in on Axions in the Early Universe,
22–26 October, CERN, Geneva, Switzerland (online)
(S. Räsänen)

PBH and Stochastic Inflation Workshop,
9–10 November (online) (S. Raatikainen, S. Räsänen)

APC, Paris Diderot University,
24 November, Paris, France (online)
(remote seminar talk by D. Cutting)

High Energy Phenomenology in the LHC Era

Summer Seminar Series: Applications of Gauge Topology, Holography and String Models to QCD,
18 June, Simons Center, Stony Brook, NY, USA (online)
(invited remote talk by N. Jokela)

Universidade Estadual de Campinas,
24 June, Campinas, São Paulo, Brazil (online)
(invited remote seminar by A. Vuorinen)

Workshop "Compact Stars and QCD",
21 August, International Centre for Theoretical Sciences, Bengaluru, India (online)
(invited remote talk by A. Vuorinen)

Brookhaven National Laboratory,
2 October, Upton, NY, USA (online)
(invited remote seminar by A. Vuorinen)

Workshop "Frontiers of Holographic Duality-2",
12–30 October, Steklov Mathematical Institute, Moscow, Russia (online) (invited remote talk by N. Jokela)

University of Southampton,
15 October, Southampton, UK (online)
(invited remote seminar by A. Vuorinen)

Workshop "Hot Problems of Strong Interactions",
10 November, Kurchatov Institute, Moscow, Russia (online)
(invited remote talk by A. Vuorinen)

Kavli IPMU, University of Tokyo,
25 November, Kashiwa, Japan (online)
(remote talk by P. Schicho)

Research visit,
1–3 December, Lappeenranta, Finland (P. Schicho)

QCD and Strongly Interacting Gauge Theory

Spaatind 2020 – Nordic Conference on Particle Physics,
2–7 January, Skeikampen, Norway (talk by T. Lappi, J. Penttala)

Frontiers in Nuclear and Hadronic Physics 2020,
24 February – 6 March, The Galileo Galilei Institute, Florence, Italy (P. Guerrero Rodríguez, H. Hirvonen, J. Penttala)

The 1st EIC Yellow Report Workshop,
19–21 March, Temple University, Philadelphia, PA, USA (online) (I. Helenius, remote talks by T. Lappi, remote talk by H. Mäntysaari)

PYTHIA Collaboration Meeting,
20–24 April (online) (remote talk by I. Helenius)

The 2nd EIC Yellow Report Workshop,
20–23 May, Pavia, Italy (online) (T. Lappi)

Hard Probes 2020: International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions,
31 May – 5 June, Austin, TX, USA (online) (remote talk by K. J. Eskola, remote talk by H. Hänninen, remote talk by M. Kuha, T. Lappi, remote talk by M. Li, T. Löytäinen, H. Mäntysaari, H. Paukkunen, J. Penttala, remote talk by A. Ramnath)

ICHEP2020 – 40th International Conference on High Energy Physics,
28 July – 6 August, Prague, Czech Republic (online)
(remote talk by H. Mäntysaari, J. Penttala)

The 3rd EIC Yellow Report Workshop,
16–18 September, CUA, Washington DC, USA (online)
(T. Lappi)

2020 Fall Meeting of the APS Division of Nuclear Physics,
29 October – 1 November (online)
(remote talk by H. Mäntysaari)

The 4th EIC Yellow Report Workshop,
19–21 November, LBL, Berkeley, CA, USA (online)
(remote talk by T. Lappi)

Snowmass Report 2021 EF07 Group Meeting,
23 November (online) (remote talk by I. Helenius)

CMS Programme

CMS Experiment

Spaatind 2020 – Nordic Conference on Particle Physics,
2–7 January, Skeikampen, Norway
(P. Eerola, J. Havukainen, M. Kim, H. Kirschenmann, S. Laurila, M. Lotti)

CMS Data Analysis School,
13–17 January, Fermilab, Batavia, IL, USA
(H. Kirschenmann)

ML4Jets Workshop,
15–17 January, New York, NY, USA (K. Kallonen)

CMS Week,
3–7 February, CERN, Geneva, Switzerland
(H. Kirschenmann, plenary talk by T. Lampén, J. Tuominiemi)

SMP-HAD Workshop,
10–11 February, CERN, Geneva, Switzerland
(H. Kirschenmann, talk by L. Martikainen)

PARTICLEFACE 2020: Working Group Meeting and Management Committee Meeting,
11–13 February, Cracow, Poland (talk by M. Voutilainen)

VBSCan@Helsinki,
19–21 February, Helsinki, Finland
(J. Havukainen, K. Kallonen, H. Kirschenmann, T. Lampén, M. Voutilainen)

PREFIT20: Precision Effective Field Theory School,
1–13 March, DESY, Hamburg, Germany (K. Kallonen)

CMS Week,
30 March – 3 April, CERN, Geneva, Switzerland
(talk by H. Kirschenmann)

Virtual IPPOG Meeting,
7–9 May (online) (S. Lehti)

HIP Scientific Advisory Board Meeting,
17–18 August (online) (remote talk by M. Voutilainen)

QCD@LHC-X,
31 August – 3 September (online) (invited remote plenary talk by M. Voutilainen)

Particle Physics Day 2020,
5 November (online) (K. Kallonen, remote talk by M. Kim, session chaired by H. Kirschenmann, L. Martikainen, M. Myllymäki, H. Siikonen, E. Tuominen, J. Tuominiemi, M. Voutilainen)

20th IPPOG Meeting,
2–4 December (online) (S. Lehti)

CMS TOP Group Workshop 2020,
7–9 December (online) (remote presentation by M. Kim, M. Myllymäki, H. Siikonen, M. Voutilainen)

CMS Upgrade

CMS Timing Days,
30–31 January, CERN, Geneva, Switzerland (J. Ott)

CMS Week,
3–7 February, CERN, Geneva, Switzerland
(P. Luukka, J. Ott)

CMS Endcap Timing Layer Module Workshop,
10–12 February, Turin, Italy (J. Ott)

15th ”Trento” Workshop on Advanced Silicon Radiation Detectors (TREDI),
17–19 February, Vienna, Austria (talk by J. Ott)

EDIT-2020 School for Detector and Instrumentation Technologies,
17–28 February, DESY, Hamburg, Germany (S. Bharthuar)

36th RD50 Workshop,
3–5 June (online) (S. Bharthuar, E. Brücken, J. Ott, E. Tuominen)

HIP Scientific Advisory Board Meeting,
17–18 August (online) (remote talk by P. Luukka)

The 13th Inverted CERN School of Computing (iCSC 2020),
28 September – 2 October (online)
(M. Golovleva, S. Kirschenmann)

FMS-LLP Workshop,
1 October (online) (remote talk by E. Brücken)

29th International Workshop on Vertex Detectors,
5–8 October (online) (remote talk by S. Bharthuar, E. Brücken)

RD51 Collaboration Meeting and the Topical Workshop on ”New Horizons in TPCs”,
5–9 October (online) (E. Brücken)

2020 Virtual IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS-MIC),
31 October – 7 November (online)
(S. Bharthuar, S. Kirschenmann)

Particle Physics Day 2020,
5 November (online) (E. Brücken)

MATRENA Seminar 2020,
11 November (online) (remote talks by S. Kirschenmann and J. Tikkanen)

37th RD50 Workshop,
18–20 November (online) (S. Bharthuar, E. Brücken, remote talk by M. Golovleva, J. Ott, E. Tuominen)

Seminar – Quality Assurance and Reliability Testing for Silicon Trackers in HEP,
27 November (online) (S. Bharthuar, M. Bezak, E. Brücken, M. Golovleva, A. Gädda, P. Luukka, J. Ott)

Tier-2 Operations

HTCondor Workshop,
21–25 September (online) (T. Lindén)

HEPiX Autumn 2020 Workshop,
12–16 October (online) (T. Lindén)

LHC Soft Skills Workshop: Science Communication,
4 November (online) (T. Lindén)

Particle Physics Day 2020,
5 November (online) (T. Lindén)

HSF WLCG Virtual Workshop,
19–24 November (online) (T. Lindén)

Fusion Power Associates 41st Annual Meeting,
16–17 December (online) (T. Lindén)

TOTEM

PPS and TOTEM Upgrade Meeting,
23–24 January, CERN, Geneva, Switzerland
(talks by L. Forthomme and F. Garcia, K. Österberg)

8th Beam Telescopes and Test Beam Workshop (BTTB2020),
27–31 January, Tbilisi, Georgia (talk by L. Forthomme)

CMS PPS General Meeting,
4 February, CERN, Geneva, Switzerland
(L. Forthomme, talk by F. Garcia)

TOTEM Collaboration and LHCC Referees Meeting,
17–20 February, CERN, Geneva, Switzerland
(L. Forthomme, talk by F. Oljemark, talks and chairing by K. Österberg)

LHC Students Poster Session,
19 February, CERN, Geneva, Switzerland (F. Oljemark)

LHCC Referees Meeting,
3 June (online) (remote talk by K. Österberg)

CMS PPS General Meeting,
16 June (online) (L. Forthomme, remote talk by F. Garcia, K. Österberg)

CMS Exotica General Meeting,
6 July (online) (remote talk by L. Forthomme)

RD51 Electronics Workgroup,
6 August (online) (remote talk by F. Garcia)

HIP Scientific Advisory Board Meeting,
17–18 August (online) (remote talk by K. Österberg)

TOTEM Collaboration and LHCC Referees Meeting,
1–2 September (online) (remote talk by F. Oljemark, remote talks and chairing by K. Österberg)

CMS PPS General Meeting,
15 September (online) (L. Forthomme, remote talk by F. Garcia, M.-M. Rantanen, K. Österberg)

LHC EW Precision Sub-Group Meeting,
7 October (online) (remote talk by L. Forthomme)

Particle Physics Day 2020,
5 November (online) (remote talk by L. Forthomme, F. Oljemark, K. Österberg)

TOTEM Collaboration and LHCC Referees Meeting,
16–17 November (online) (remote talks by L. Forthomme and F. Oljemark, remote talks and chairing by K. Österberg)

CMS PPS General Meeting,
1 December (online) (remote talks by L. Forthomme and F. Garcia, M.-M. Rantanen, K. Österberg)

Super-FRS Tracking Detector Workshop,
15 December (online) (remote talk by F. Garcia)

Nuclear Matter Programme

ALICE

LHCC Review,
18 February, 31 August, CERN, Geneva, Switzerland (online) (remote talk by W. Trzaska)

JETSCAPE Collaboration Workshop,
16–20 March, University of Tennessee, Knoxville, TN, USA (online) (remote talk by O. Saarimäki)

ICHEP2020 – 40th International Conference on High Energy Physics,
28 July – 6 August, Prague, Czech Republic (online)
(H. Rytkönen, remote talks by M. Slupecki)

NUCLEUS 2020 – LXX International Conference on Nuclear Physics and Elementary Particle Physics,
12–17 October, St. Petersburg, Russia (online)
(remote talk by J. Parkkila, remote talk by M. Slupecki, remote plenary talk by W. Trzaska)

NuPECC Mini-Workshop,
15 October, Jyväskylä, Finland (online)
(remote talk by S. Räsänen)

Heavy Ion Meeting (HIM) 2020-10 – Relativistic Heavy Ion Collisions: Playgrounds for the QCD Matter Studies,
29–30 October, APCTP, Pohang, South Korea (online)
(remote talk by D. J. Kim)

Particle Physics Day 2020,
5 November, Helsinki, Finland (online)
(remote talk by D. J. Kim)

ISOLDE

Nuclear Physics Seminar,
9 January, Jyväskylä, Finland (talk by A. Illana Sison)

63rd INTC Meeting,
5–6 February, CERN, Geneva, Switzerland (I. Moore)

87th ISOLDE Collaboration Committee Meeting,
20 February (online) (J. Pakarinen)

88th ISOLDE Collaboration Committee Meeting,
23 June (online) (J. Pakarinen)

64th INTC Meeting,
24–25 June (online) (remote talk by A. Illana Sison, I. Moore)

ISOLDE Solenoidal Spectrometer Workshop 2020,
20–21 July (online) (A. Illana Sison, J. Pakarinen)

HIP-SAB Meeting,
17–18 August (online) (remote talk by T. Grahn, remote talk by A. Jokinen, remote talk by J. Pakarinen)

65th INTC Meeting,
3–4 November (online) (I. Moore)

89th ISOLDE Collaboration Committee Meeting,
5 November (online) (J. Pakarinen)

IDS Collaboration Meeting,
16 November (online) (remote talk by A. Illana Sison, J. Pakarinen)

ISOLDE – EPIC Workshop,
24–25 November (online) (A. Illana Sison, I. Moore, J. Pakarinen, P. Ruotsalainen, J. Äystö)

ISOLDE Workshop and Users Meeting 2020,
26–27 November (online) (A. Illana Sison, I. Moore, J. Pakarinen, J. Äystö)

FAIR

NUSTAR Annual Meeting 2020,
25 February – 1 March, Darmstadt, Germany (T. Grahn, A. Jokinen, A. Kankainen, M. Luoma, I. Moore, J. Äystö)

NUSTAR Week 2020,
28 September – 1 October (online) (T. Eronen, T. Grahn, A. Jokinen, A. Kankainen, M. Luoma, I. Moore)

Super-FRS Experiment Collaboration Meeting,
26–27 October (online) (F. Garcia, T. Grahn, A. Jokinen, remote talk by A. Kankainen, M. Luoma, J. Äystö)

Technology Programme

Materials

Accelerator Technology: Materials (MAT)

International Workshop "Radiation Effects of Materials and Devices" (REMD-2020),
13–15 January, Harbin, China (F. Djurabekova)

RF Development Meeting,
15 July, CERN, Geneva, Switzerland (online) (remote talk by A. Saressalo)

Mini MeVArc 2020 Workshop,
9 December, CERN, Geneva, Switzerland (online) (remote talk by A. Saressalo)

Radiation Safety

Radiation Safety Research and Development (RADAR)

INMM 61st Annual Meeting,
12–16 July (online) (P. Dendooven, R. Virta (STUK))

2020 Virtual IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS-MIC),
31 October – 7 November (online) (P. Dendooven, R. Virta (STUK))

ESARDA 42nd Annual Meeting,
16–19 November (online) (remote talk by P. Dendooven, R. Virta (STUK))

LUT Seminar on Computational Engineering,
8 December (online) (remote talk by R. Virta (STUK))

Inverse Days 2020,
14–18 December (online) (remote talk by R. Virta (STUK))

Other projects

Euclid

Euclid LE3 Meeting,
3–5 January, Paris, France (talk by E. Keihänen)

Liverpool John Moores University,
13–17 January, Liverpool, UK (C. Kirkpatrick)

Galaxy & AGN Evolution in Euclid: Type 1 and 2 AGN,
22–24 January, Pisa, Italy (talk by A. Viitanen)

Euclid Joint SWGs+LE3 Meeting,
3–6 February, Paris, France (talk by E. Keihänen, H. Kurki-Suonio, A. Viitanen)

Euclid OU-EXT Meeting,
9–11 March, Groningen, the Netherlands (K. Kiiveri)

BeyondPlanck 5th Consortium Meeting,
27–28 April (online) (remote talk by E. Keihänen, remote talk by A.-S. Suur-Uski)

Euclid SC7 End Meeting,
29 April (online) (V. Lindholm)

Euclid Consortium Meeting,
4–8 May (online) (H. Kurki-Suonio, A. Viitanen, J. Väliviita)

Euclid SC8 Kick-Off Meeting,
13–14 May (online) (K. Kiiveri, V. Lindholm)

Euclid Theory Working Group Meeting,
7–8 June and 1 July, Trieste, Italy (online) (remote talk by J. Väliviita)

Euclid September SC Meeting,
8–9 September (online) (H. Kurki-Suonio, V. Lindholm)

BeyondPlanck Release Conference,
18–20 November (online) (remote talk by E. Keihänen, H. Kurki-Suonio, V. Lindholm, remote talk by A.-S. Suur-Uski, J. Väliviita)

BeyondPlanck Tutorial,
23–24 November (online) (V. Lindholm, remote talk by A.-S. Suur-Uski, J. Väliviita)

CMB Systematics and Calibration Focus Workshop,
30 November – 2 December, Kavli IPMU, Kashiwa, Japan (online) (remote talk by E. Keihänen)

Euclid December SC Meeting,
16–17 December (online) (H. Kurki-Suonio, V. Lindholm)

Education and Open Data

ICHEP2020 – 40th International Conference on High Energy Physics,
28 July – 6 August, Prague, Czech Republic (online) (remote talk by P. Veteli)

CMS Open Data Workshop for Theorists,
30 September – 2 October, Fermilab LHC Physics Center, Batavia, IL, USA (online) (remote talk by K. Lassila-Perini)

Detector Laboratory

GENERA (Gender Equality Network in Physics in the European Research Area) General Assembly Meeting,
22–23 April, Rome, Italy (online) (E. Tuominen)

CERN RD50 Workshop,
3–5 June (online) (E. Tuominen)

13th MoEDal Collaboration Meeting,
1–3 July (online) (M. Kalliokoski)

GENERA General Assembly Meeting,
14–15 September, Madrid, Spain (online) (E. Tuominen)

2020 Virtual IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS-MIC),
31 October – 7 November (online) (remote talk by M. Kalliokoski)

FPS Particle Physics Day,
5 November (online) (E. Tuominen)

CERN RD50 Workshop,
18–20 November, Zagreb, Croatia (online) (E. Tuominen)

14th MoEDal Collaboration Meeting,
15–17 December (online) (M. Kalliokoski)

PUBLICATIONS

Theory Programme

Theoretical Cosmology

K. Ala-Mattinen and K. Kainulainen,
Precision calculations of dark matter relic abundance,
J. Cosmol. Astropart. Phys. 09 (2020) 040

J. Rubio in J. P. Beltrán Almeida et al.,
Chiral gravitational waves and primordial black holes in UV-protected Natural Inflation,
J. Cosmol. Astropart. Phys. 11 (2020) 009

T. Koivisto in J. Beltrán Jiménez et al.,
The coupling of matter and spacetime geometry,
Class. Quantum Grav. 37 (2020) 195013

J. Rubio in N. Bernal et al.,
Boosting ultraviolet freeze-in in NO models,
J. Cosmol. Astropart. Phys. 06 (2020) 047

J. Rubio in N. Bernal et al.,
UV freeze-in in Starobinsky inflation,
J. Cosmol. Astropart. Phys. 10 (2020) 021

D. Bettoni and J. Rubio,
Hubble-induced phase transitions: Walls are not forever,
J. Cosmol. Astropart. Phys. 01 (2020) 002

O. Gould in R. Bruce et al.,
New physics searches with heavy-ion collisions at the CERN Large Hadron Collider,
J. Phys. G: Nucl. Part. Phys. 47 (2020) 060501

M. Hindmarsh, K. Rummukainen, and D. J. Weir in C. Caprini et al.,
Detecting gravitational waves from cosmological phase transitions with LISA: an update,
J. Cosmol. Astropart. Phys. 03 (2020) 024

J. M. Cline and K. Kainulainen,
Electroweak baryogenesis at high bubble wall velocities,
Phys. Rev. D 101 (2020) 063525

D. Cutting, M. Hindmarsh, and D. J. Weir,
Vorticity, kinetic energy, and suppressed gravitational-wave production in strong first-order phase transitions,
Phys. Rev. Lett. 125 (2020) 021302

V.-M. Enckell, K. Enqvist, S. Räsänen, and L.-P. Wahlman,
Higgs-R^2 inflation – full slow-roll study at tree-level,
J. Cosmol. Astropart. Phys. 01 (2020) 041

K. Enqvist et al.,
Constraints on decaying dark matter from weak lensing and cluster counts,
J. Cosmol. Astropart. Phys. 04 (2020) 015

K. Enqvist et al.,
Structure formation with two periods of inflation: beyond PLaIn ΛCDM,
J. Cosmol. Astropart. Phys. 10 (2020) 053

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HELSINKI INSTITUTE OF PHYSICS

Helsinki office
P.O. Box 64 (Gustaf Hällströmin katu 2)
FI-00014 University of Helsinki, Finland

CERN office
CERN/EP
CH-1211 Geneva 23, Switzerland

www.hip.fi