Addendum1: Current status and prospects of Particle Physics in Poland

1.The LHC programme: high energy frontier

1.1.ALICE

The Polish groups participate in the ALICE experiment since the very beginning, being one of the founders of the Collaboration. The main motivation behind the modern investigations of heavy-ion collisions is the study of the quark-gluon plasma, the QGP, which is a special state of matter with the chiral symmetry restored. In the QGP quarks and gluons are no longer confined into hadrons. The QGP presumably was the dominating state of matter in the Universe during the early stages of its evolution after the Big Bang. The expansion of the QGP and its subsequent cooling resulted in formation of the matter consisting of hadrons which we observe today.
Polish physicists, at present about 25 scientists and several PhD and Diploma students[1] actively participate in the project. Detector-wise, Polish groups are responsible for the simulation and calibration of the main tracker of ALICE, the Time Projection Chamber (TPC), the high granularity Photon Spectrometer (PHOS) and for the development of the diffractive detector AD (Alice Diffractive). They are also responsible on the Quality Assurance (QA) at the whole experiment level and in the Event Visualisation effort. In physics analysis Polish physicists are involved in the studies of particle correlations, both, small-angle and forward-backward, in research of the diffractive processes, in the analysis of the high-p_T jets, and in studies of the electromagnetic probes, in particular the direct photons. Polish groups actively participate in the experiment upgrade program. This covers the upgrade and development of the ALICE software as well as the service tasks during the deinstallation/installation of the hardware components. The upgrade activity covers the time interval 2019-2021. The involvement in physics analysis extends for the entire period of ALICE experiment till the end of time.
The activity of the Polish groups in ALICE is financed by the Ministry of Science and Higher Education and by grants from the National Science Centre (2017-2019)

1.2. ATLAS experiment at the LHC

The Polish groups involved in the ATLAS[2] experiment have been participating actively in taking and analysing the data collected during the last decade of LHC operations.

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[1] from the Henryk Niewodniczanski Institute of Nuclear Physics in Cracow (IFJ PAN), National Centre for Nuclear Research (NCBJ) in Warsaw and the Warsaw University of Technology, and recently, the AGH University of Science and Technology in Cracow

[2]r Cracow: Henryk Niewodniczański Institute of Nuclear Physics of Polish Academy of Sciences IFJ PAN, Faculty of Physics and Applied Informatics of AGH Uniiversity of Technology IFiIS AGH, Jagiellonian University UJ,

Experimental studies performed with the participation of Polish physicists within the ATLAS experiment cover a wide spectrum of problems: from verification of the Standard Model (SM), through precise measurements in the strong and electroweak SM sectors, diffractive physics studies, a search for phenomena beyond SM (BSM), to exploration of the high-density QCD matter created in nuclear collisions. These efforts will be continued from 2021 and afterwards with the data collected in LHC Run-3 and at HL-LHC. The continuously increased LHC/HL-LHC luminosity will allow performing searches with an increased statistical sensitivity to new physics phenomena and new particles as well as to studies of rare production and decay processes. The large statistics data to be recorded in the HL-LHC era will substantially extend the mass reach in BSM searches and significantly increase the precision of the SM measurements, in particular the determination of Higgs couplings.

The Polish groups are responsible for maintenance and operation of key components of the ATLAS detector, including: power supply system of the Semiconductor Tracker, Gas System and Detector Control System of the Transition Radiation Tracker and the ALFA detector. These activities will be continued until the end of Run3, i.e., end of 2023. Strong involvement in the optimisation of the High Level Trigger (HLT) will be continued as well. The major activity will be devoted to the Phase I Upgrade to be completed for the Run3. The Polish groups play a leading role in the upgrade of the HLT core framework. Towards the end of Run 3 additional effort will be devoted to the adaptations of the HeavyIon specific trigger algorithms.

The work is continued on the Phase II Upgrade of the ATLAS Detector, which is a major hardware project foreseen for the coming years, to be completed by the end of 2026. The Polish teams contribute to upgrades of two detector subsystems: the Inner Tracker (ITk) and the Trigger and Data Acquisition (TDAQ) for the for the Phase-II Upgrade. In the Inner Tracker (ITk) projects, the areas of strong engagement of the Polish teams are: front-end ASICs for the readout of silicon strips detectors, high-voltage and low-voltage power supply system for the silicon strip detectors and for the front-end electronics, respectively, and the cooling system for the ITk. In particular, the team is responsible for development of custom-designed radiation tolerant DC-DC converters for the low-voltage power supply system and highly specialised components of the cooling system. In the TDAQ system, the Polish teams contribute to the development of hardware and firmware for so-called jFEX and L1Topo modules for the Phase-I upgrade and to the development of hardware and firmware for jFEX and L0Topo modules for the Phase-II upgrade.

1.3.CMS experiment at the LHC

The Polish institutes in CMS are from **Warsaw** (since 1990; known as Warsaw Group[3]) and from Cracow[4], which joined CMS in 2018. The Warsaw Group contributions to CMS apparatus are related to Level-1 trigger activities. **Warsaw group** build:

- The PACT (Pattern Comparator Trigger), which was Level-1 muon sub-trigger based on comparison of RPC hits. The PACT was operated as a muon trigger component since the beginning of Run-1 until Phase-I upgrade in 2015/2016. After that, although not involved in trigger decision, PACT trigger boards and Trigger crates are still kept functional, since they are a part of RPC signal transmission and readout system. The part of that system will be maintained until the end of LHC Phase-I (2023). The PACT system consists of 84 custom trigger boards, set of splitting boards, sorters and readout boards. It is hosted in 12+2 VME crates in electronic underground cavern.
- The RPC control and data transmission system. It is designed for configuration and monitoring of RPC detector and to transmit RPC data. The system, maintained by Warsaw Group was build and designed in cooperation with Finish groups, with later contribution from Italy. The system scale is about 1500 custom boards located in CMS detector cavern. It is to be maintained until the end of Phase-I.
- OMTF (Overlap Muon Track Finder) trigge, the successor of Polish PACT trigger activities. It is the main Level-1 muon trigger in the CMS barrel-endcap overlap area covering pseudorapidity range $0.83 < \left|\eta\right| < 1.24$. This region was given a selected partition in the muon trigger due to overlap peculiarities: data from three different types of detectors, non-homogenous magnetic field and complicated geometry. The Warsaw group designed trigger algorithm and implemented it in 12 boards (Poland funded 10 boards) in 2 uTCA crates, located in CMS underground electronic cavern. The system will be operated until the end of Phase-I.

The Warsaw group is participating in design of a muon trigger for LHC Phase-II.
The non-hardware related scientific activities of Warsaw Group are:

- Higgs studies in decay channel with tau leptons in final state, including embedding of simulated tau decays in Z muonic decays, cross-checks of backgrounds and various tau-reconstruction studies as well as studies based on machine learning techniques.
- Search for heavy long-lived charged particle, in particular development of time-of-flight methods with muon chambers.
- Other fields: forward physics, heavy ions and vector boson scattering. Warsaw contributed also to online and offline CMS software and data analysis.

The **Cracow institutes** interests are focused on forward physics (Cracow-IET is a member of TOTEM and CT-PPS collaboration), especially on data analysis, and (Cracow-AGH) in

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[3] Warsaw: Institute of Experimental Physics, University of Warsaw, National Centre of Nuclear Research, Institute of Electronics Systems Warsaw University of Technology (associated institution of CMS)

[4] Cracow: Faculties of Physics and Applied Computer Science (associate institution of CMS), and of Computer Science, Electronics and Telecommunications, AGH University of Technology

electronic design of front-end data processing for CMS High Granularity Calorimeter project.
The basic funding supporting participation of Polish groups in CMS experiment (including the maintenance of the detectors) is provided by Polish Ministry of Science and Higher Education while funding for additional equipment upgrades (Phase I) and particular analyses by National Science Centre.

2. Flavour physics

2.1.The LHCb experiment at the LHC

Polish groups[5] joined LHCb Collaboration in 1999 and actively contributed in many areas including detector prototyping and construction, simulation of the detector response and optimisation of the detector subsystems, development of trigger algorithms and physics analysis tools. The main contribution to detector subsystems concerned Outer Tracker, Vertex Locator and High Level Trigger.
Polish groups are active in LHCb Upgrade being involved in Upstream Tracker, RICH detectors and Vertex Locator. The groups participate also in central software development for the upgraded detector. The work includes track and vertex reconstruction, low level detector reconstruction and simulation and development of tools for distributed computing environment. Poland provides substantial computing resources used by the whole LHCb Collaboration.
The importance of indirect measurements, such as those carried out in the LHCb experiment, has increased significantly. In recent years, a wide program of searching for New Physics (NP) in the b- and c-hadrons yielded a number of interesting measurements which results differ from the predictions of the Standard Model in the range of 3 or 4 standard deviations. The pattern of these anomalies seems to be consistent with some extensions of the Standard Model. The priority of the Polish LHCb groups is to continue the NP searches in beauty and charm sectors using large statistics of data expected to come in years 2020-2026. In particular:

- Polish groups will continue participation in searches for rare decays of b- and c-hadrons, and those with lepton number or lepton flavour violation decays. In particular the angular distributions of four body decay of $B\to K^*\mu\mu$ is a good probe for effects from new heavy particles which can enter loop diagrams and modify the SM predictions. The study of CP symmetry violation, the measurement of gamma angle of CMK matrix is also a place where the NP can be searched for.

5 Warsaw:National Centre of Nuclear Research, Cracow: Faculty of Physics and Applied Informatics, AGH Uniiversity of Technology, H Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences

- The LHCb experiment has the world's largest sample of charm hadrons and is ideally suited for charm studies. Studies in the charm sector start reaching a precision allowing for sensitive tests of the SM studies in unique rapidity range. Polish groups are searching for NP in radiative decays of charmed mesons and in rare decays of charmed baryons.
- A number of valuable SM measurements are conducted concerning CP and CPT symmetries. The QCD measurements for the unique on LHC rapidity range is also important part for coming years.

Polish groups had accumulated a lot of know-how and expertise related to the detector physics. This experience is going to be used for design and construction of the future upgrades of the LHCb spectrometer. The activity of the Polish groups in LHCb is financed by the Ministry of Science and Higher Education as well as by grants from the National Science Centre for the individual physics analyses project

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2.2.The Belle II experiment at the SuperKEKB

The Belle II experiment at the SuperKEKB e^+e^- collider, with a designed luminosity of $8\times10^{35}cm^{-2}s^{-1}$, is being carried out by an international collaboration with a substantial European contribution. The Polish involvement includes at present 12 researchers and students from the Cracow Institute of Nuclear Physics PAS. The team , exploiting a long experience of working in the experimental environment of B-factories (since 1994) actively participates in the project. The main focus is on designing, installation and running of the Belle II vertex detector (VXD) with contributions to the readout system of the silicon vertex detector, power supply of the pixel detector, and the on- and off-line software development.

Belle II aims at searches for physics beyond the Standard Model (SM) at the intensity frontier.   In the physics program a special emphasis is put on studies of processes with difficult experimental signatures that can hardly be accomplished at hadronic machines, such as inclusive and semi-inclusive measurements of *B* meson decays, or *B* decays with large missing energies. Of special interest are comprehensive studies of (semi)taonic *B* decays, where measurements of exclusive $b\rightarrow c\tau\nu$ transitions, pioneered by the Cracow group, show puzzling tensions with the SM predictions.

The commissioning of the accelerator and the spectrometer, consisting of all subsystems except VXD (replaced by detectors dedicated to measure radiation from the accelerator) started in February 2018. During this period the accelerator reached the peak luminosity of $0.5\times10^{34}cm^{-2}s^{-1}$ and the experiment collected ~500 pb^{-1} of data. In March 2019 the physics running will start with the full detector, and will continue till summer 2020. It is foreseen to run in average 9 months per year until 2025 when Belle II will accumulate the integrated luminosity of $50ab^{-1}$ which is the current goal. The more detailed information on readiness and expected challenges of the experiment can be found in [1].

Participation of the Polish group in Belle II is supported by MNiSW, and by the program "Japan and Europe Network for Neutrino and Intensity Frontier Experimental Research" (Jennifer), funded by European Commission under Grant Agreement n.644294

as a part of the Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020).   A continuation of the Jennifer program , Jennifer II, was approved from 2019.
[1] The Belle II experiment at SuperKEKB: input to the European Particle Physics Strategy (update 2018 - 2020)

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3. ILC and other future higgs factories

Since more than 20 years major HEP groups at Polish research institutes and universities have been involved in a broad spectrum of activities related to future e+e-collider projects. Here we focus on the development of the technology and detector design, as well as the physics case studies for the experiments at the e+e-colliders.
Main activities in this field are carried out at the AGH University of Science and Technology in Cracow, the Henryk Niewodniczanski Institute of Nuclear Physics in Cracow (IFJ PAN), University of Silesia (US) in Katowice and University of Warsaw (UW), with the estimated total involvement of about 6 senior, 6 post-doc and 5 students (FTE).
Polish physicists are involved in the development of the International Large Detector (ILD) project for the International Large Collider, detector and physics studies for the future Compact Linear Collider (CLIC) at CERN, establishing physics goals for the FCC-ee collider and in the studies on the dedicated instrumentation for the very forward region of future e+e-experiments within the FCAL collaboration.
Hardware activities of Cracow groups focus on the design of the BeamCal and LumiCal detector for ILC and CLIC, and on the R&D on the monolithic SOI detectors for vertexing and tracking. Design of the LumiCal is a challenge, as the detector has to be very compact and equipped with an ultra-low power readout electronics while providing high granularity, stability and precision of the measurement in high background environment. Physicists from AGH and IFJ PAN are in particular responsible for the design of the new readout ASIC for LumiCal - FLAME (FcaL Asic for Multiplane rEadout), design of the readout sensors, laser alignment and data acquisition system for the beam calorimeters. They also participate in prototype beam tests and test data analysis, and contribute to the construction of the new prototype of Compact Multilayer FCAL Detector (within the AIDA-2020 project). The new concept of monolithic SOI sensor for tracking detectors offers analogue charge measurement with precise timing information, high granularity and ultra-low power consumption (within the E-JADE project)..
Studies of the physics case for the future e^+e^- colliders range from the theoretical calculations of the Standard Model and “new physics” processes, to phenomenological analysis of the physics potential of e^+e^- experiments and the physics case studies based on full Monte Carlo simulations. Recent activities focused on improving precision of theoretical calculations for electro-weak processes e^+e^- colliders, heavy flavour physics, top-quark physics and searches for beyond the Standard Model processes. In particular, Polish physicists contributed recently to the estimate of the top-quark mass determination precision at CLIC, sensitivity of CLIC to the FCNC top-quark decays and prospects for discovering dark matter particles in future e^+e^- colliders within the so called Inert Doublet Model (IDM).

The activities described above are financed from the European projects (AIDA-2020, E-JADE), dedicated grants received from the National Science Centre, Poland, and from the budget funds of the institutes involved. The total funding is estimated to about 120 k€/year.
If the decision concerning the ILC or CLIC construction is positive, the Polish groups have both the expertise and the potential to participate in the ILC/CLIC consortium and in the detector construction provided the necessary funding is supported.

4. QCD and Heavy Ion physics

NA61 experiment at CERN SPS

The main activity of the Polish research community in the field of QCD/Nucleus-Nucleus is currently focused on the NA61/SHINE programme at the CERN SPS. NinePolish research institutions[6] form the national consortium which as the whole contributes to the NA61/SHINE at the level of ~30% in terms of human resources, funding and task responsibilities of the collaboration.The total number of the researchers involved is 54 (36 senior physicists, 18 PhD/MSc) plus 3-4 FTE engineers/technicians.
Taking into account the high attraction capability of the NA61/SHINE activities in the Polish academic community one can assume that in 2020-2025 the number of the researchers, engineers and students involved will exceed 60.
It is important to stress that the beam momentum range provided to NA61/SHINE by the SPS and the H2 beam line is highly important for the heavy ion, neutrino and cosmic ray communities. Based on the success of the currently running program and motivated by new physics needs NA61/SHINE intends to continue measurements with hadron and ion beams during the period 2021-2024. The objectives include: (i) measurements of charm hadron production in Pb+Pb collisions for heavy ion physics, (ii) measurements of nuclear fragmentation cross sections for cosmic ray physics, (iii) measurements of hadron production in hadron-induced reactions for neutrino physics.
The new and extended experimental programme for 2020-2025 require upgrades of the NA61/SHINE detector and DAQ that shall increase the data taking rate to about 1 kHz. These are: (i) construction of a new Vertex Detector, (ii) replacement of the TPC read-out electronics, (iii) construction of a new trigger and data acquisition system, (iv) upgrade of the Projectile Spectator Detector.
Furthermore, the construction of new Time-of-Flight detectors would be highly desirable for potential future measurements of hadron production in C+C and Mg+Mg collisions which are expected to be needed to understand the onset of fireball phenomenon.The intense activity towards the detector upgrade will be carried during the LS2 period

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[6] Jan Kochanowski University in Kielce, National Center for Nuclear Research, Jagiellonian University, AGH-University of Science and Technology, University of Silesia, University of Warsaw, University of Wroclaw, Warsaw University of Technology, H. Niewodniczanski Institute of Nuclear Physics of Polish Academy of Sciences.

2019-2020. Members of the Polish consortium will coordinate the upgrade operation and take the responsibility in all major subsystems' upgrade.
It is reasonable to assume that the current annual funding at the level of 350 kCHF from the Ministry of Science and National Science Centre will be maintained in 2020-2025.
Polish institutions will continue to offer the advanced training facility of NA61/SHINE to the undergraduate and graduate students in physics, as well as to the technical students in the framework of technical diplomas and dedicated internships.
It should be noted as well the growing involvement of Polish research community — four institutions, in the lower energy NICA (JINR Dubna) research programme. Experiments on high energy nucleus-nucleus collisions at NICA should commence in 2023 and will be complementary to the NA61/SHINE data.

Compass experiment at the CERN SPS

The COMPASS Collaboration of about 250 members of 24 institutions runs a modern fixed target experiment[7] at a secondary M2 beam of the Super Proton Synchrotron at CERN. The experiment studies hadron structure and spectroscopy with muon and hadron beams of high intensity: nucleon spin structure in semi-inclusive deep inelastic scattering and in Drell-Yan process, measurement of the nucleon generalised parton distributions via deeply virtual Compton scattering (and meson production), search for new hadronic states and of their production mechanism and chiral dynamics in the Primakoff process.
A Polish group of 13 members from the University of Warsaw, Warsaw University of Technology and National Centre for Nuclear Research is governed by a consortium of the above three institutions. The group is involved in hardware construction, maintenance, software developments and physics analysis, from the very beginning of the Collaboration in the late 1990-ties.
The upgraded COMPASS spectrometer [8]with new elements will form a skeleton of the future QCD Facility run by the new, enlarged collaboration.

4.Neutrino Physics and Dark Matter Searches experiments

In 2000[9] physicists from eight research institutions formed the **Polish Neutrino Group** and started to work together in the ICARUS project, a time projection chamber filled with the

7 The COMPASS detector is a multipurpose universal two-stage spectrometer with magnets, tracking, calorimetry, particle identification (large RICH) and various targets: liquid (also polarised) and solid

8 The proposed Facility's programme is described in the Letter of Intent (arXiv:1808.00848v3) to be submitted to the CERN management by end of December 2019; it will be followed by the proposal due at the end of 2019

9 Polish participation in neutrino physics has started 1970s with the BEBC bubble chamber exposed to the neutrino beam and the CDHSW experiment at CERN, followed by involvement in the IMB, Super-Kamiokande (SK) and GALLEX experiments.

liquid argon (LAr). In 2006 six of those institutions joined the T2K experiment and later on, participated also in the formation of the Hyper-Kamiokande (HK) proto-collaboration. Recently, two more institutions expressed interest to join HK project. Smaller groups are involved in several other experiments and projects as well.

At present the Polish neutrino community consists of about 43 FTE's including 16 PhD and MSc students. There is a close collaboration between experimentalists, theorists and engineers. Since 2000, many PhD and diploma theses and on neutrino physics have been defended and 3 postdoctoral degrees (habilitation) have been obtained (two more expected soon). At present, the strongest involvement of the Polish neutrino physicists is in the T2K experiment (about 27 FTE's, incl. 10 students). That number is expected to grow to above 30 in the close future. Since 2006 the Polish group has been involved in the construction of the near detector ND280 , developing of the track reconstruction algorithms, external background simulation and production of MC simulations. Recently, the Polish group took over the responsibility for the operation and calibration of the FGD sub-detector (part of the ND280).

The data analyses performed in Poland concern neutrino interaction models (development of the neutrino event generator NuWro and contribution to the NEUT generator), cross section measurements in the ND280, background studies, ND280 systematic error estimation and preparation of the ND280 input for the oscillation analyses. The funds for the participation in the T2K coming from Polish and European sources are secured up to 2022.

All the aforementioned activities will be continued in the planned phase II of T2K expected 2021-2026., the Polish group participates also in the upgrade of the ND280, namely in the development of the mechanical constructions and test module design for micromegas detectors and tests of the detector prototypes on particle beams. The funds for those activities are being secured.

Polish T2K group plans to get more involved in the Water-Cherenkov-related activities, starting with the calibration studies in the SK and possibly development of the reconstruction algorithms and oscillation analysis. Experience gained with the SK will benefit in the future when the HK experiment will start to take data with the beam (including proposed intermediate Water Cherenkov detector E61). Some members are also highly involved in the work concerning the read-out electronics for the HK and E61. The level of funding needed for the participation in the HK construction is still under consideration.

Although all the institutions constituting Polish Neutrino Group are interested in the HK project, there is also some interest in the neutrino short and long baseline experiments (SBN, DUNE) in the US, both based on LAr detectors. The possible involvement may include detector development , simulations and reconstruction work, benefitting from the experience gained in the ICARUS experiment and from current activities in the detector prototype work at the CERN Neutrino Platform.

Two smaller groupsare involved in three non-accelerator neutrino experiments: GERDA/LEGEND, Borexino and KM3NeT. Polish National Science Centre provides funds through dedicated grants for the research carried out by the groups:

- **GERDA/LEGEND**[10] Polish participation consists of 7 members (4.5 FTE's, incl. 2 students). Since the collaboration formation in 2004 the main responsibilities were related to background reduction with appropriate screening techniques to select radio-pure materials as well as to development of the LAr and to development of pulse shape discrimination methods. Presently, the GERDA experiment is close to achieve its design goals and in 2020 will be turned into LEGEND with larger active mass in order to search for neutrino-less double beta decay.
- **Borexino** Polish group[11] was deeply involved in the background reduction in this experiment during its construction phase and presently it focuses mostly on the data analysis and development of software methods for identification and rejection of the background events. The group consists of 3 scientists (1.2 FTE's).
- **KM3NeT** The group[12] consists of 4 FTE's (incl. 1 student) and is expected to grow to 7 in the future. They are interested in the atmospheric neutrino and cosmic ray measurements, as well as the searches for the Dark Matter induced neutrinos (including sensitivity studies). Presently, they are working on the development of reconstruction tools based on machine learning and simulation of the cosmic rays underwater.
    - **Darkside**, is an experiment looking for the Dark Matter in the direct way, in which a group of Polish physicists[13] is involved. In parallel with operations of the 50 kg prototype, the DarkSide-20k is being constructed (20 tons of active LAr mass). The strong potential for the LAr technology allows to push the sensitivity for WIMP detection several orders of magnitude beyond current levels. The Polish group focuses on the problems related to reduction of background which is crucial for direct Dark Matter searches. The Polish group consists of 6 members (4 FTE's, incl. 3 students).

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[10] Jagiellonian University, Cracow

[11] Jagiellonian University, Cracow

[12] National Centre for Nuclear Research, Warsaw

[13] From Jagiellonian University, Cracow

5. Research in instrumentation: electronics, detector and accelerator physics

Groups of physicists and engineers from several Polish research institutes and universities[A] contribute to key accelerator research areas with teams of experts involved in many accelerator projects all over Europe. These are accelerators for research as well as for medical and industrial applications. Several Polish institutions participate in EU projects the objective of which is the integration of national and international accelerator R&D facilities. Participation in key accelerator projects confirms the substantial expertise in such areas as sources and injectors, RF structures and systems, superconducting and conventional magnet systems, cryogenics, alignment and stabilisation, diagnostics and instrumentation, electronics and software. Well trained groups of Polish engineers and technicians have demonstrated their experience during the installation and upgrades of the LHC machine, installation of the XFEL as well as at present works at ESS. Thanks to their skills they are of great help in any accelerator construction, repairing or upgrade work.

Recently, there is an important progress in creation of national centres of accelerator physics: The Cyclotron Centre Bronowice (CCB) at the Institute of Nuclear Physics not only provides regular treatments for patients with tumours, using two gantries, which allow for the whole body treatments, and the separate line for the eye melanoma cases but also provides the proton beam for research groups as well as for institutions and commercial organisations, open for transnational access. Solaris, the National Synchrotron Centre at the Jagiellonian University started recently serving experiments at two beam lines, the other two are under construction. The National Centre for Nuclear Research (NCBJ Warsaw-Świerk), which produces for years small accelerators for medical and industrial applications, contributed significantly to the construction of the LINAC 4, the new injector for CERN accelerator complex. NCBJ just starts to construct POLFEL the first Polish free electron laser with the linac design based on the XFEL concept.

R&D in superconductive materials and various SC products developed in Poland significantly in the last years. Many small and medium size teams, including also industrial partners have developed a close collaboration, kind of a national network, open also for international contacts. Wide range of projects is presented at bi-annual Superconductivity and Particle Accelerators conference (SPAS) which 4th edition was

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SPAS'2018[B] as well as at regular working meetings: Low and High Temperature Superconductors Workshop[C].

Research Infrastructures.

The infrastructures for accelerator R&D in Poland are growing. Those for detector and readout electronics are reported elsewhere. The Polish e-infrastructure for science is in good shape and is used effectively for HEPAP experiments. In particular, the Polish Tier2 resources are reliable and permanently growing. The infrastructures for *sensu stricto* accelerator physics are distributed among research institutes and technical universities. The above mentioned close collaboration of Polish groups also improve rules to easy the trans-institutional access to these facilities. To the well-established facilities e.g. of the Wroclaw University of Technology or at NCNR- Warsaw- Świerk some new are added, e.g., the substantial modernisation of the cryogenic research infrastructure in the INP.

Detector R&D

The R&D activities related to detector development are carried out by Polish groups within the EU programmes AIDA-2020 – Advanced European Infrastructures for Detectors at Accelerators and E-JADE – The Europe-Japan Accelerator Development Exchange Programme, as well as within the CERN based programs RD50 – Radiation hard semiconductor devices for very high luminosity colliders and RD51 – Development of Micro-Pattern Gas Detectors Technologies.

The major areas of activity are silicon strip and pixel detectors, various gaseous detectors, radiation resistant readout ASICs (Application Specific Integrated Circuits) and trigger electronic systems based on the FPGA (Field Programmable Gate Array) technologies. The Polish groups involved in these R&D activities have at disposal modern infrastructures including well equipped electronics and detector labs as well as software for ASIC design and FPGA based system developments and thermo-mechanical design and simulations.

The HEP detector technologies have been successfully used for the development of X-ray imaging detectors and this activity will be continued in collaboration with other groups outside the HEP community.

Industry involvement and Technology Transfer.

CERN was the first research related, high-tech market statutorily available to Polish industry and industrial research institutes. The important stimulating events were the Industrial Exhibitions Poland @CERN which are going to be continued under active involvement of Polish ILO industry liaison officer. Recently, besides CERN, the close contact with industry are maintained for ESS, ITER, ESA and other Big Science institutions. There are regularly organised meetings between Big Science Organizations

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[B] https://spas.ifj.edu.pl/

[C] https://indico.ifj.edu.pl/event/222/

and industry as for example Big Science Partner and Industry Day[D] on 30.11.2018 organised at INP by Polish ILO for ESS and Polish ILO for CERN and ITER, or Fly Me to Mars[E] event in 2017 organized at WPT. Recently a platform Big Science HUB was launching at WPT in Wroclaw.

Industrial participation in the development and construction of large research infrastructure, especially in HEP laboratories, is always combined with technology transfer to the companies via prototyping, experts' visits, know-how communication and all forms of direct contacts.

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6. Particle Physics theory

Theoretical high energy physics research in Poland focuses on the following topics: (i) investigating extensions of the Standard Model (SM) and testing them against experimental data, (ii) performing precision calculations within the SM, with special attention to processes where signals of new physics could occur, (iii) studying QCD dynamics in bound states and in high-energy multipartonic processes, (iv) preparing Monte Carlo (MC) simulation codes for direct use by the experimental collaborations, (v) studying strongly interacting matter at high temperatures and densities, (vi) analyzing theoretical aspects of quantum field theories and string theory. The main research centres are located in Kraków, Warszawa and Wrocław, sizeable ones in Kielce and Łódź, while smaller groups are active in Białystok, Szczecin and Zielona Góra. The overall number of theoretical high energy physicists in Poland includes around 100 researchers at permanent and/or post-doc positions, and around 50 PhD students.

Short descriptions of the topics (i)-(vi) are given below. The SM studies in (ii)-(iv), apart from providing knowledge of the SM itself, are crucial in searches for Beyond-SM (BSM) effects in observables dominated by the SM contributions, as well as for estimates of the relevant experimental backgrounds.

(i) BSM studies that aim at investigating complete models require including constraints from accelerator experiments, astrophysical observations, dark matter detection, neutrino mixing, and low-energy precision experiments. Additional requirements that are often imposed include the hierarchy problem, resolving flavour physics puzzles, succesful baryogenesis, proper description of perturbations during the cosmological inflation, etc. Usually, only a subset of the above constraints is taken into account. For instance, noticeable effort is devoted to extended Higgs sector models that provide acceptable dark matter freeze-out and correct electroweak baryogenesis at the same time. Their common property is existence of new particles that are within reach either for the upgraded LHC or for the planned e^+e^- colliders (ILC, CLIC, FCC-ee). Another path is supersymmetric models with $\mathcal{O}(1 TeV)$ higgsinos as dark matter candidates, offering partial explanations

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D https://indico.ifj.edu.pl/event/219/

E http://www.flymetomars.space/

to observed tensions in anomalous magnetic moments of the leptons and several B-meson decays, which is of relevance for Belle II and LHCb. Neutrino physics studies cover both the Dirac and Majorana mass scenarios, often requiring extra discrete of continuous symmetries, and allowing for new sources of CP violation. A model-independent approach to BSM physics is carried out within the Standard Model Effective Field Theory (SMEFT) where Wilson coefficients of non-redundant higher-dimension operators (e.g., the so-called Warsaw basis) paremeterise effects of heavy particles on physics around the electroweak scale and below.
(ii) Multi-loop perturbative calculations within the SM are being performed for the purpose of precision electroweak measurements at the future e^+e^- colliders, as well as for measurements of rare B-meson decays at LHCb and Belle II. They often involve thousands of Feynman diagrams that are evaluated using various techniques, including algebraic reduction, differential equations and Mellin-Barnes representations. In the case of differential spectra with cuts, when phase-space integration is an issue, development of devoted MC codes is necessary (see below).
(iii) Phenomenological investigations of QCD dynamics span from structure functions and particle density functions including higher twists, parton saturation, diffraction to multiparticle production, correlations and geometrical scaling. Effective models of QCD confinement, based on chiral symmetry, are being constructed and applied to studies of the QCD phase diagram, particle spectroscopy in light and heavy-light sectors, calculations of parton distributions, generalized and nonforward distributions, form factors and transition form factors at low-energy scales. Lattice and light-front approaches to QCD bound-state dynamics, studies of ground state formation in non-perturbative relativistic QCD, planar expansion and various dimensional reductions are also being investigated.
(iv) Polish research groups have a long and well-known tradition in preparing (or participating in preparation) of widely used MC simulation programs, both for hadronic and e^+e^- colliders. Examples of such codes are PHOTOS, TAUOLA, HDECAY, CARLOMAT, HERWIG, KORALZ, KrkMC, EKHARA, PHOKARA, BHLUMI, BHWIDE, etc. Their names are sufficient to find the corresponding publications in the INSPIRE database. They implement results of complex perturbative calculations in a fully differential manner, often include effects of multiple photon radiation, parton showers, or effects of low-energy hadronization. They are essential for signal modelling, background estimation, as well as total luminosity measurements via normalisation to precisely calculated electromagnetic processes. Further development of such codes should and will follow the needs of future colliders.
(v) As far as the strongly interacting matter at high temperatures and densities is concerned, activities of the Polish theory community include application of relativistic hydrodynamics for phenomenological description of heavy-ion collisions at RHIC and LHC. They combine the language of quantum field theory, relativistic kinetic theory, and holography. Another recent

Issues of interest are heavy quarks propagating in turbulent quark-gluon plasma, in which case the Fokker-Planck transport equation is being used. Temperature oscillations and sound waves in hadronic matter are investigated on the basis of LHC heavy-ion collision data on transverse momenta distributions.

(vi) Examples of Polish expertise in the hep-th domain include analyses of Donaldson-Thomas invariants, torus knots and lattice paths at the classical and quantum level, studies of kappa-deformations of the Poincaré algebra, conformal defects in supergravity, or appearance of infinite-dimensional symmetry groups in N=8 supergravity.

A large part of Polish theoretical high-energy physics research is carried out in collaboration with foreign institutions, often within well-established international teams. Some of these teams are led by physicists from Poland.
