High energy experiments at CERN

Hunting for New Particles

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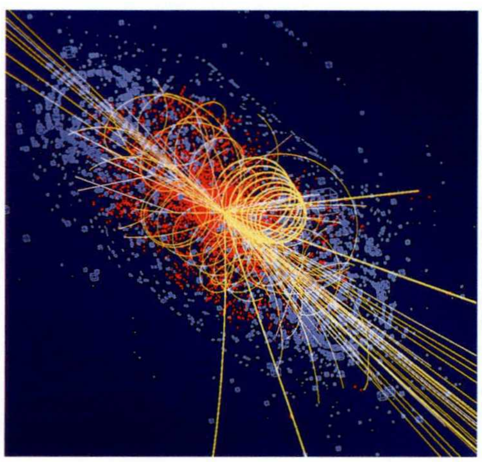
CERN, the European Organisation for Nuclear Research, is the world's largest particle physics laboratory. Located near Geneva as a common project of twelve European countries, it is celebrating its 50th anniversary this year

Over this half-century the number of CERN member states has risen to twenty. Most of the newcomers are former Eastern Europe countries, among which Poland was the first to join CERN on 1 July 1991. This early access undoubtedly reflected a long, successful tradition of Polish physicists' participation in CERN experiments, starting in the early sixties with the first visits of individual particle physicists from Kraków and Warszawa. Since then, a growing number of Polish physicists, both experimentalists and theoreticians from Warszawa (Warsaw University, Institute for Nuclear Studies, Warsaw Technical University), Wrocław (Technical University) and Kraków (INP, University, AGH), have participated in the fascinating hunt for new particles in order to understand their properties and interactions, and through them, the structure and origin of matter. Experimental groups from the Henryk Niewodniczański Institute of Nuclear Physics (INP) of the Polish Academy of Sciences participated in several leading experiments at CERN, making considerable contributions both to the construction of the experimental equipment and to the physical measurements themselves. Let us now concentrate on some highlights of this long, successful story.

High energy accelerators

Research at CERN is centered around its complex of accelerators. Protons and antiprotons, electrons and positrons, plus heavy ions are accelerated to higher and higher energies, reaching new frontiers in particle beam energy and quality. With what purpose? In order to collide these ordinary particles and to produce new, as-yet unknown particles which are too rare and short-lived to be observed elsewhere, e.g. in the collisions of cosmic rays. The greater the energy of the particles accelerated, the heavier the new particles that can be produced. These precious particles bring new insight into the early stages of the Universe and reveal new symmetries of Nature.

Each of CERN's accelerators has its page in the history of particle, nuclear or atomic physics. Let us mention two of them, at the recent high-energy frontier. The first one, dismantled in 2001, was the LEP - the world's largest electron-positron collider. It was situated in an underground tunnel 27 km in circumference and generated collision energies of up to 209 GeV. A second accelerator, the Large Hadron Collider (LHC), succeeding the LEP in the same tunnel, is now under construction and should start operations in 2007. The LHC will produce the highest achievable energy of 14 TeV in proton collisions and the immense total energy of about 1140 TeV in lead ions collisions. With its thousands of superconductive magnets,



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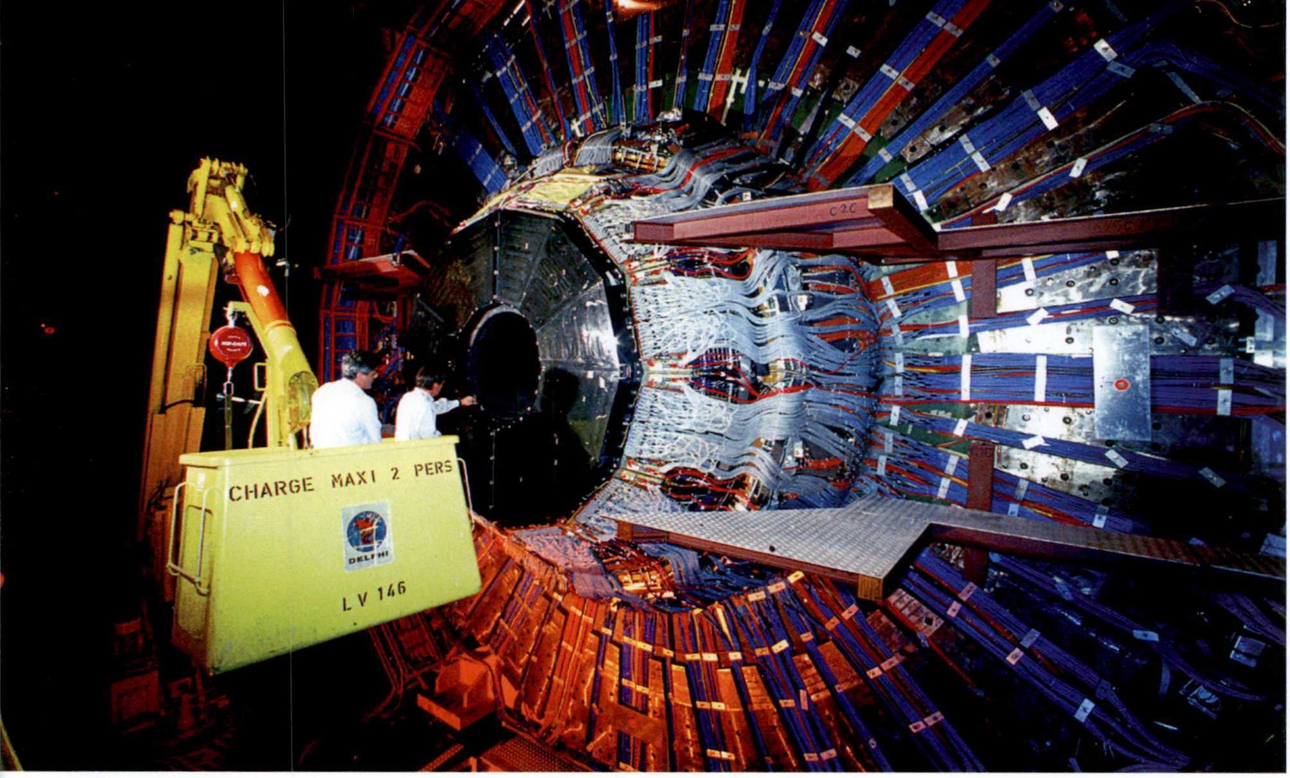
Simulation of a Higgs decay into four isolated muons in the CMS detector at the Large Hadron Collider at CERN. The lines denote particles produced by the collision of a pair of ultra-high energy protons. Energy deposits of the particles in the detector are shown in blue



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Inspection of the forward part of the DELPHI detector

the LHC collider will be the world's largest cryogenic installation.

Physics adventure

It all started with studies of many ordinary hadrons (i.e. protons, neutrons and other particles built up from two or three light quarks) produced in collisions of equally ordinary hadrons. Kinematical and dynamical correlations between these particles became the INP physicists' specialty.

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After the discovery of the charm quark in 1974, foreseen by the newly formulated theory of elementary particles and their interactions known as the Standard Model (SM), studies of particles containing this quark became very important. The CERN experiments NA11 and NA32 were among the leading ones in this field. Due to innovative apparatus, the first observations of some charmed particles and accurate measurements of their lifetimes were performed - something that was not at all trivial since charm particles live between 10^{-13} and 10^{-12} second, depending on their species.

Bosons Z and W, mediating in the weak interactions of elementary matter particles, were discovered at CERN in the early eighties. Three months of data-taking on Z in the fall of 1989 were sufficient for the four LEP experiments to make the observation, fundamental not only for particle physics but also for astrophysics and cosmology, that there are only three families of elementary particles of matter. This experimental observation is still one of the biggest puzzles for theory. The following eleven years of measurements at LEP brought tests of the Standard Model performed with unprecedented precision. One of the experiments was DELPHI, which strongly involved the INP Kraków group and an apparatus especially suited for precise measurements of particles containing the heavy charm and beauty quarks.

Other interesting studies concern accelerated heavy ions. According to theoretical predictions, quark-gluon plasma should be produced for a very short time and in a very small volume, with sufficient energy.

Quark-gluon plasma, present just after the Big Bang and possibly inside neutron stars, is only accessible on Earth in ultra high energy heavy ions collisions.

For more than one decade, up to 2002, CERN provided physicists with the most energetic beams of heavy ions. Several experiments have been searching for different signatures of quark-gluon plasma, and some indications of it were observed at CERN a few years ago. One of the leading experiments was NA49, in which INP physicists were strongly involved. They will continue this fascinating study at the much higher LHC energy with the ALICE experiment.

High energy experiments at CERN

Neutrinos, ghostly particles that interact only weakly, have been a subject of study at CERN for more than three decades. The first accelerator-based neutrino beam was produced at CERN and was used in the great discovery of long-sought-after neutrino interactions, mediated by the Z boson. Polish physicists are now participating in another great neutrino adventure: a neutrino beam produced at CERN will be sent to the Italian underground laboratory in Gran Sasso, at a distance of 730 km from CERN. ICARUS,

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Aerial view of CERN with the red contour of the LEP/LHC tunnel

one of the two experiments designed for this beam, is being carried out with Polish participation.

Research at CERN will center on the LHC accelerator in the near future. INP teams are participating in three of the four LHC experiments: ATLAS, ALICE and LHCb. The ATLAS experiment (like CMS, the fourth LHC experiment), will search for new, as-yet unknown particles, too heavy or too rare to have been observed earlier. The most "wanted" of these is the Higgs boson, the only missing elementary particle foreseen by the Standard Model. Finding or discarding Higgs particle is of extreme importance because according to theory other particles acquire mass due to its existence. Observing other particles that are not allowed by the SM, revealing a new symmetry of Nature, is another big goal of ATLAS and CMS.

Particle detectors

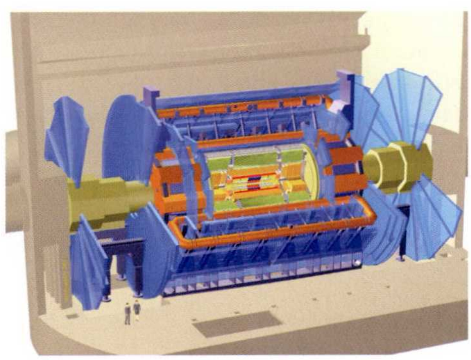
To detect the passage of particles, or to measure their properties, one explores how they interact with the detector materials: gases, liquids or solids. Tracking detectors are used to reconstruct the topology of events, and to measure particles' deflection in a magnetic field, which could be translated into their momenta. Detectors of this kind have been produced or designed by INP teams composed of physicists, engineers and technicians. Of particular interest and difficulty are detectors that measure the cone of Cerenkov light emitted along particle paths, enabling particle masses to be identified. An INP team was much involved in their construction for the DELPHI spectrometer.

Large spectrometers

Recording the interaction of particles and the products of such interaction, reconstructing and analyzing them require the use of special apparatus called "spectrometers." Modern spectrometers, like the ATLAS one, can reach the dimensions of large buildings: 20 x 20 x 40 m^3. These huge devices include construction materials, but they mainly consist of detectors saturated with readout electronics, to record small signals left behind by passing particles.

Readout electronics

Modern detectors are equipped with readout electronics, which provide end data in digital form - input for further analyses. The signals left behind by particles are usually very small; in extreme cases they could be just single electrons. These need to be amplified, filtered and digitized - all of this has to be



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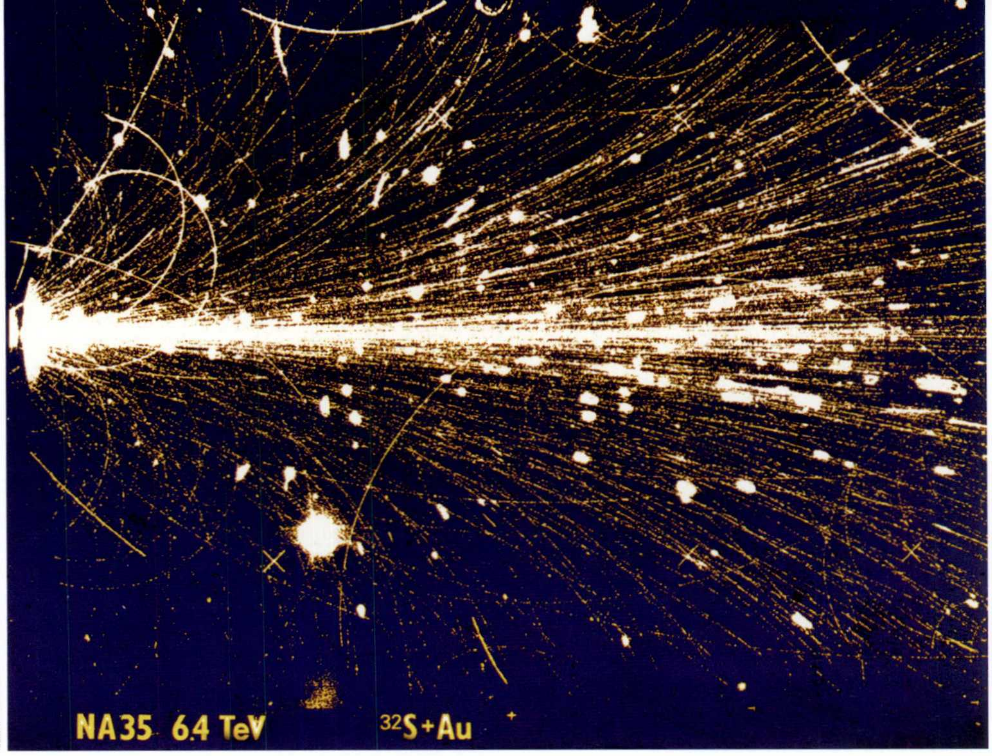
Virtual reality image of the ATLAS detector



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A sulphur ion at 6400 GeV strikes a nucleus in a gold target. The resultant particle shower is recorded in a streamer chamber

done very fast, and the electronics has to be low-power and small-volume. The combination of analogue inputs and digital outputs is nontrivial and requires particular design skills. Although these stringent requirements are not easy to satisfy, Polish designers have nonetheless been able to design sophisticated VLSI chips and complex large boards, and Polish companies produce good electronic units.

Quark-gluon plasma, present just after the Big Bang, is only accessible on Earth in ultra high energy heavy ions collisions

Computing

When hunting for new particles and new physics phenomena, one collects enormous amounts of information, which has to be filtered to find "gold plated" events. At the LHC, these might occur only once per ten billion interactions.

Some analysis can be carried out in real time ("on-line") using dedicated processors, so that interesting events are not lost. Still, a huge amount of data has to be recorded for later ("off-line") analysis – and all of this has to be available to all the participants of the huge experiments, spread over many continents. Connecting all of this into one common structure facilitating the sharing of data and resources is not easy – special software ("middleware") is developed to enable the construction of computing "grids." Kraków physicists and computer scientists are taking active part in these developments, and the Kraków local cluster of processors was one of the first to be integrated into the world-wide computing grid for physics.

Creative environment

World wide international collaborations, involving hundreds or even more than a thousand physicists, perform experiments at the CERN accelerators. Experiments usually last about a decade and are preceded by a comparably long period of designing and constructing the experimental apparatus. The complexity of the accelerators and measuring equipment and the vast amounts of data collected demand that pioneering industrial technologies be applied, e.g. in superconductivity, cryogenics, vacuum technology, electronics or telecommunications.

The most impressive example of a by-product of CERN's activity is the World-Wide Web, invented at CERN in 1990 in order to facilitate communication within large-scale collaborative projects.

These high-tech and innovative aspects of CERN make it attractive not only for physicists but also for high-caliber engineers and technicians. And, last but not least – when discussing physics in the CERN cafeteria, it is not an unusual occurrence to pass by one or two Nobel Prize winners. ■

Further reading:

Gerard`t Hooft (1996). *In Search of the Ultimate Building Blocks.* Cambridge: Cambridge University Press.

Martinus Veltman (2003). *Facts and Mysteries in Elementary Particle Physics.* Singapore: World Scientific Publishing Company.

http://www.cern.ch