Accelerating science and innovation

Societal benefits of European research in particle physics

EDITORS
James Gillies (CERN), Camilla Jakobsson (Swedish research council), Arnaud Marsollier (CNRS/CERN), Vanessa Mexner (Nikhef), Terry O'Connor (STFC)

TEXT
Tim Radford

GRAPHIC DESIGN
Fabienne Marcastel, Eric Mathieu

ILLUSTRATION CREDITS
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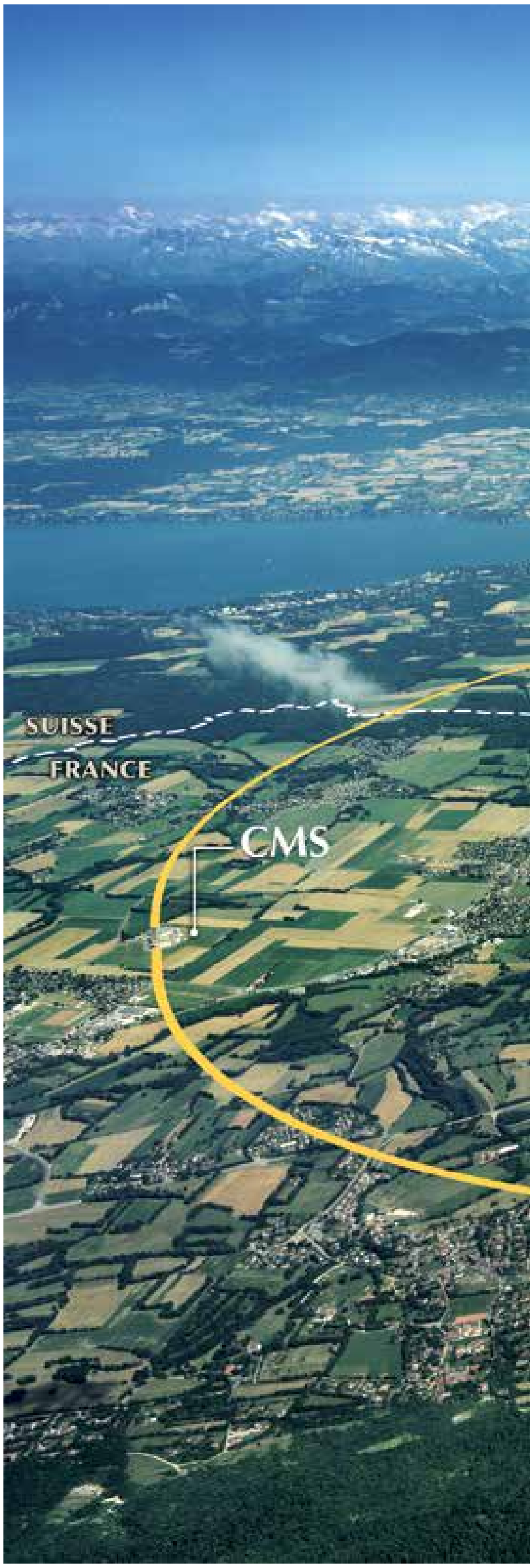
The story so far

Agnieszka Zalewska and Michel Spiro

In the early 1950s, twelve European countries came together to launch a bold new scientific venture, an organization that would propel the continent to the forefront of fundamental research in nuclear physics and provide a place for nations to work peacefully together. Sixty years on, the venture continues to pay off. The CERN laboratory, in close collaboration with European universities and national research institutes, has played a key role in advancing the sum of knowledge about the fundamental constituents of the universe and the ways they interact to form complex structures like stars, planets and human beings. Along the way, the laboratory has pushed forward the limits of technology, delivering innovation and benefits to society in myriad ways. These advances have not gone unnoticed: the Nobel Prize has been awarded to CERN scientists for advances in science, as well as in the technologies that make them possible.



Over the last half century, CERN has played a leading role in building the experimental foundations of what's known as the Standard Model of particle physics – the theory that explains and describes the processes that govern the fundamental particles and their interactions. The basic picture of matter is deceptively simple: just four kinds of particles are needed to account for the diversity of the visible universe. They are called up quarks, down quarks, electrons and electron neutrinos. The quarks stick together to form nucleons: protons and neutrons. Nucleons come together to form atomic nuclei, which, joined by electrons make atoms. Electron neutrinos, so light that their mass has not yet been measured, pervade the universe, travelling at almost the speed of light. For reasons as yet unknown, nature has duplicated this family of particles with two heavier copies. Left to their own devices, these heavier particles revert to members of the lightest family. To complete the picture, particles of a different kind mediate the interactions between the matter particles. It is by studying the behaviour of all these particles in laboratories like CERN that the Standard Model has been established.

In 2012, the ATLAS and CMS experiments at CERN announced the discovery of what looks increasingly like the last ingredient of the Standard Model – the Higgs boson. Proposed

The Large Hadron Collider at CERN: accelerating science and innovation.

in 1964, this particle is linked to the so-called Brout-Englert-Higgs mechanism that endows other fundamental particles with mass. Although completing the Standard Model, the discovery of the Higgs is not an end but a beginning. The Standard Model accounts for the up and down quarks, electrons, electron neutrinos and their heavier cousins, but we know from observation that most of the universe, some 95% of it, is made up of something different, which we call dark matter and dark energy. The Standard Model currently does not account for gravity and the matter dominance in the universe. These are among the challenges at the cutting edge of particle physics research today.

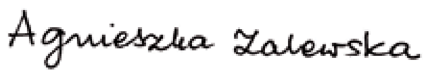
Discovering the Higgs boson required one of humankind's most ambitious scientific projects, the Large Hadron Collider (LHC). Over 10,000 engineers and scientists of more than 100 nationalities have pooled their resources to build and operate the LHC and the particle detectors that observe the collisions it creates. The LHC accelerates a beam of protons to 99.9999991% of the speed of light using superconducting magnets colder than intergalactic space and producing proton-proton collisions up to 600 million times a second. Sophisticated detectors observe these collisions, sifting the data for new physics, while a globally distributed computing grid analyses the data. To do all these things, physicists and engineers, and their industrial partners, have designed new instruments, invented new technologies, and implemented new ways of handling the unprecedented volume of data. It is an illustration of the power of European co-operation, uniting theorists and experimentalists, universities and laboratories, research partnerships and industrial consortia across the continent, and far beyond.

Key to Europe's success is the governance model that CERN's founding fathers established sixty years ago. The CERN Council, over which we have both had the honour to preside, is the body that has steered the development of particle physics in Europe since 1954. It is the body at which CERN's Member States are represented, and it is the body that gave its green light, and continuous support, to the LHC project, which took over two decades from conception to operation. When CERN's Member States, working through Council, give their support to a project, the long term commitment is guaranteed attracting not only research groups in the Member States, but worldwide. This was the case for the LHC, which has evolved to be a truly global facility. The LHC too, is not an end, but a beginning. Dramatic scientific advances inevitably open the horizon to ever more challenging questions, demanding ever more sophisticated instruments. Future accelerator facilities will be designed as global from the start.

With a view to developing a long-term programme for European particle physics, Council adopted a European Strategy for Particle Physics in 2006. Seven years on, and with an important discovery in hand, the global research landscape has developed and it is time to refresh our forward vision. After meticulous consultation with stakeholders from Europe and also around the world, the first updated Strategy was discussed by Council, and then adopted at a special European Strategy Session of Council in Brussels on 30 May 2013.

You can consult the adopted Strategy in full at the end of this brochure. Its main goal is to enhance further the European scientific excellence in particle physics, taking into account the worldwide landscape of this domain of science and its connections with other fields, like astrophysics, cosmology and nuclear physics. In particular, the Strategy underlines Council's continuing support for the LHC, placing an important upgrade to the machine and detectors as the European particle physics community's highest scientific priority.

The remaining chapters of the brochure are dedicated to giving a glimpse of some of the benefits to society that accrue when the nations of Europe pool their resources in the pursuit of fundamental knowledge. The endeavour to advance the knowledge of particle physics builds enduring partnerships that transcend national borders; it demands new technological solutions and it trains a new generation of scientists and engineers. It inspires the young, and opens the wonders of the cosmos to all. In the words of CERN's Director General Rolf Heuer *fundamental science does more than build the sum of human knowledge; it is also the foundation of human wellbeing*.



Agnieszka Zalewska, President of CERN Council 2013-

Michel Spiro, President of CERN Council, 2010-2012

Collaborative research in particle physics

The lesson for Europe: co-operation pays

"The European spirit signifies being conscious of belonging to a cultural family and to have a willingness to serve that community in the spirit of total mutuality, without any hidden motives of hegemony or the selfish exploitation of others." Robert Schuman, 1949

A leader of courage and dignity, Robert Schuman dedicated his life to removing barriers to peaceful cooperation across national borders. His appeal both to friends and former enemies was made in the immediate aftermath of the world's most destructive conflict ever: an era when Europeans both longed for a lasting peace after the horrors of war, but also faced ongoing uncertainty and division across ideological and national boundaries. Science has played a vital role in unifying the European continent by sharing common goals and values of scientific endeavours and demonstrating the effectiveness of working in collaboration with total openness and trust.

Science has continued to break down barriers. More than one third of all scientific papers published in the world involve international collaborations, and today at CERN, scientists, engineers, technicians and others collaborate in a common quest for knowledge. Drawn from more than 600 universities and research institutes from around the world, these searchers for knowledge rely on funding from national governments, the European Union, the private sector and philanthropy – funding provided in explicit recognition of Louis Pasteur's statement that *science knows no country, because knowledge belongs to humanity, and is the torch which illuminates the world*.

The HiLumi LHC design study is set to increase the brightness of the LHC beam by an order of magnitude, with exceptional technological challenges, which extend far beyond Europe to Japan and the US.

CERN was established on this very principle. Following Louis de Broglie's call for the creation of a European laboratory at the 1949 European Cultural Conference, scientists and politicians on both side of the Atlantic, including Edoardo Amaldi, Pierre Auger, Lew Kowarski and Isidor Rabi backed the idea. In 1950 Rabi tabled a UNESCO resolution, unanimously adopted, which called for the *formation and organization of regional centres and laboratories in order to increase and make more fruitful the international collaboration of scientists*. Twelve European nations founded CERN just three years later.

CERN now has 20 Member States, with almost 11,000 users coming from almost 100 states spanning the globe – working together for the common good of humanity in the spirit outlined by the first President of CERN Council, Sir Ben Lockspeiser: *Scientific research lives and flourishes in an atmosphere of freedom - freedom to doubt, freedom to enquire and freedom to discover. These are the conditions under which this new laboratory has been established*.

These conditions make CERN much more than a physics laboratory. It is a hotbed of innovation, a place where the freedom from boundaries inspires technological developments which underpin our modern world – some of which are highlighted elsewhere in this publication including cancer therapy, medical and industrial imaging, radiation processing, electronics, measuring instruments, new manufacturing processes and materials, Information Technology, and the World Wide Web.

At every level, these outcomes of basic research provide a stimulus to national and international economies. The nuclear medicine imaging market is an estimated €10 billion a year, and growing at 10% annually. The World Wide Web, invented more than two decades ago to share information within the collaborations working at CERN's LEP accelerator, is calculated to have stimulated €1.5 trillion in annual commercial traffic. These are huge returns on the estimated €1 billion spent, according to Europe's own TIARA survey, on basic research annually at CERN and the world's other 200 research particle accelerators.

Much of the economic and societal benefits arising from particle physics conducted at CERN and in research institutes and laboratories around Europe derive from the application of particle accelerators, initially developed in the 1920s and 30s to enable physicists to examine the fundamental structure of atomic particles. Accelerators began to generate wealth for industry – and rewards for society - 60 years ago. Worldwide around 20,000 accelerators now produce, sterilise or examine €400 billion worth of goods each year. And that doesn't include the 10,000 accelerators made for medical use in the world's hospitals.

These instruments model proteins for the pharmaceutical industry and explore atomic structures in the design of new materials. They make isotopes for medical scans, irradiate deep tumours, implant ions for high-speed transistors and cure carbon composites to a level of hardness that makes them a substitute for steel. They probe precious works of art, explore archaeological discoveries, clean noxious exhausts, treat nuclear waste, and sterilise food.

These successes have only been possible through scientific cooperation and collaboration, through a unified European continent, and the European Strategy for Particle Physics continues these efforts by achieving a Europe-wide vision of the future of particle physics. But it goes further by confirming Europe's desire to participate in the effort taking place outside of Europe – making clear that research in particle physics will continue to rely on the spirit of collaboration and cooperation enunciated by Schuman, Pasteur and Lockspeiser.

EUROTeV formed a consortium of institutes from Germany, France, Italy, Spain, Sweden, Switzerland and the United Kingdom, to make a design study toward TeV-scale linear colliders.

EuCARD

EuCARD is a network of 37 European laboratories, institutes, universities and industrial partners involved in accelerator sciences and technologies, contributing to the development of world-class infrastructures.

Crystals of lead tungstate for the CMS experiment at CERN. Similar crystals are used in PET scanners.

Medicine and life sciences

The body of knowledge: particles harnessed for health

Particle physics technologies are critical to many essential medical applications. State-of-the-art techniques borrowed from particle accelerators and detectors are increasingly being used in disease prevention, diagnosis, therapy and prognosis.

Physics long ago delivered the X-ray and radiotherapy treatment. But the latest advances in particle physics still offer new ways of detecting diseases, imaging and treating tumours and extending lives.

Better diagnostics, improved imaging

The Crystal Clear Collaboration (CCC) has found a way to scale down the scintillation techniques used in the powerful CMS detector at CERN to develop PET scan instruments that could be used to study brain activity in rats and mice. An initiative from Portugal called ClearPEM exploits the same scintillating crystals to detect breast cancer more effectively. One woman in eight will develop breast cancer: early detection saves lives. The technique promises to be five times as sensitive as conventional X-ray mammography, and to reduce the number of “false positive” finds that so often lead to unnecessary biopsies and to real human distress.

In a separate approach, calorimetry developed for particle detection is being deployed in the battle against pancreatic cancer: the massive detector technology designed to record the energy of 600 million collisions a second has been turned into something that can detect single photons of light in three dimensions and make ultraprecise images of biomarkers in, for example a nascent tumour. So instead of putting a patient in a scanner, doctors can insert a tiny scanner inside the patient. It took 60 scientists, 13 institutes, €6 million and four years to turn the biggest detector in the world into one of the smallest and most precise. The technology delivered by the Endo-TOFPET-US project (an acronym that includes endoscopy, positron emission tomography, ultrasound and the technique called time-of-flight)

Silicon pixel detector technology being readied for CERN's ATLAS experiment.

will be 100 times more sensitive than a whole body PET scanner. CERN is a partner in CERIMED – a European centre for medical imaging bringing together research laboratories, companies and clinical partners – that will take the technology further.

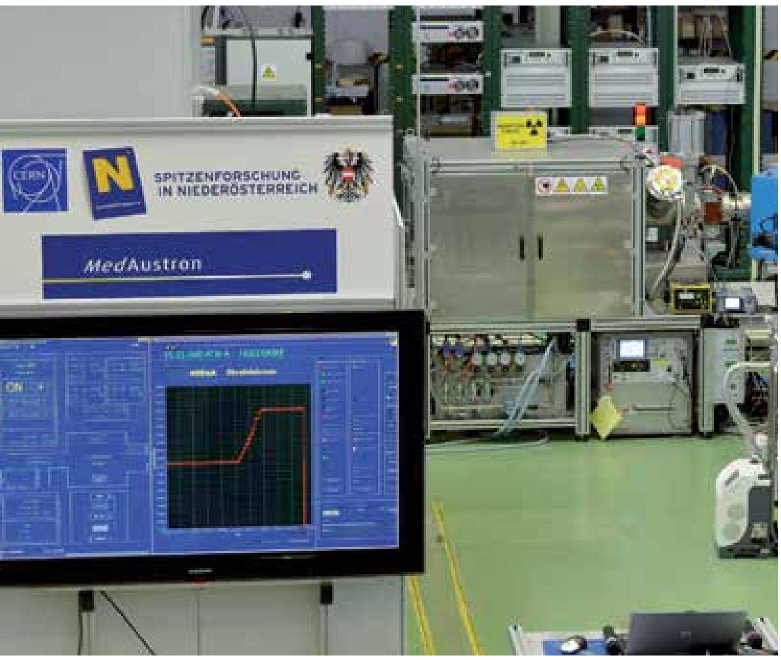
But there are other ways to use the precision dictated by the needs of the LHC experiments. The new detector technologies could help surgeons and clinicians see in ever finer detail and with greater clarity. It could even throw light on some forms of blindness. Think of the human eye as a kind of pixel detector: one collaborator in CERN's ATLAS experiment has turned a system originally designed to look for top quarks into a way of studying how the retina converts signals from photoreceptors and transmits them to the visual cortex. There are 22 or more different types of ganglion nerve cells in the retina that can now be monitored experimentally with a tiny "neurochip" first devised for particle physics. Another team has found a way to exploit colour computerised tomography to reveal three-dimensional structure and resolve images of objects inside objects. The latest generation Medipix3 detector can distinguish elements that normally appear white: it can tell calcium in the bone from iodine by supplying colour based on differing wavelength responses. This LHC detector technology (as it once began) can now characterise pharmaceuticals, and even detect counterfeit drugs. One scanner based on the Medipix advances can even distinguish two or more contrast agents in a patient at once – iodine in the vascular system and barium in the liver, for instance. Since it came on the market from New Zealand in 2009, MARS, the Medipix all resolution system CT scanner has been used to study cancer, heart disease and blood vessel breakdown. The Neurospin project is designed to take magnetic resonance imaging to once-unimaginable precision: the study of the nervous system itself, and beyond that, the cruel neurodegenerative diseases that claim so many lives. It exploits detector technology that grew initially out of CERN and then out of French Atomic Energy Commission expertise.

A leading role in developing particle therapies for cancer

Particle physics research goes beyond simple detection and diagnosis. It is already being harnessed as a form of treatment. In the 1940s, American particle physicist Robert Wilson pointed out that beams of protons could be deployed to treat certain forms of cancer more effectively than the X-rays used in traditional radiotherapy. Over the years, pion, proton and carbon-ion therapies started to be deployed in Europe, at first in accelerator laboratories like PSI in Switzerland and GSI in Germany. In the 1990s, CERN physicist Ugo Amaldi promoted the creation of TERA, a network of centres for hadron therapy. The Proton Ion Medical Machine Study, PIMMS, at CERN produced an accelerator design optimised for hadron therapy, and has since been deployed in two new centres, MedAustron in Austria and CNAO in Italy. In another initiative, scientists working on the antiproton cell experiment, ACE, have investigated the potential use of antiprotons in cancer therapy. The stream of matter in the form of hadrons delivers energy ideally only to the cancerous tissue, damaging the tumour cells' DNA and hitting the tumour at its weakest point. ACE has an even more devastating effect on cancer by targeting antimatter at the cancerous cells, delivering more energy to the tumour. There is an obvious need to co-ordinate research into the new way of destroying once-intractable tumours. ENLIGHT is a consortium of 300 scientists - clinicians, physicists, biologists, engineers – from 20 European nations and four EU-funded projects, including ULICE, the Union of Light Ion Centres in Europe, all working together on particle therapy, to monitor patients, improve techniques, train newcomers, swap data, establish protocols, and try to understand exactly what happens at the molecular level when a hadron stream slams into cancerous growth.

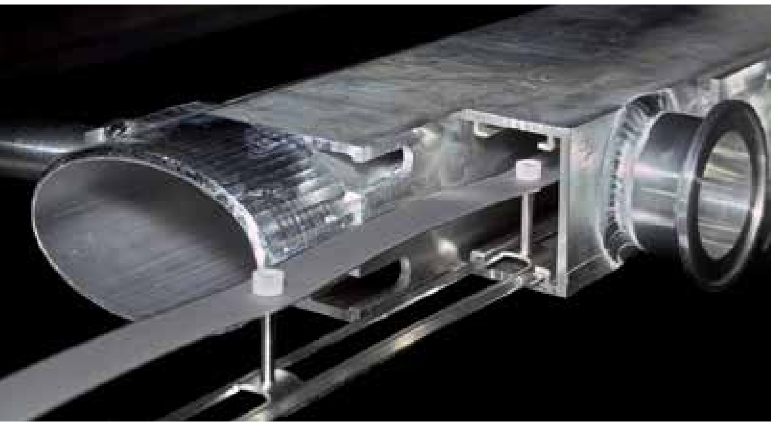
New detector technologies could help surgeons and clinicians see in ever finer detail and with greater clarity

Left: A test facility at CERN for the MedAustron project. Right: The synchrotron at Italy's CNAO facility.



Energy and the environment

Think big: save energy and clean up the planet



Originally developed for fundamental research, accelerators and detectors are used today for a range of applications such as reducing pollution or monitoring the atmosphere and the Earth. High-level technologies developed for physics also increase energy efficiency in other, totally unexpected domains.

Left: Inside the LEP beam pipe. The metal ribbon acts as molecular flypaper.

Right: The same technology is at work inside these solar panels on the roof of Geneva airport.

Clarity, like charity, begins at home and one immediate contribution to better energy management begins with Big Science itself. CERN and other major European laboratories in 2011 committed themselves, through an international workshop at the European Spallation Source in Lund, Sweden, to making the best and most efficient use of the power that drives accelerators: to concentrate on the best ways to deliver and recover energy, to store it, to recycle heat and save water and to demonstrate ways of minimising the organizations' own carbon footprints. But beyond the laboratory sites, particle physicists and engineers have collaborated on new and unexpected ways to turn powerful science into power for the people.

More efficient solar panels

One of these is a technology originally dreamed up to make solar energy conversion far more efficient, perfected at CERN in the service of the Large Electron Positron Collider, and its successor the LHC, which once more found a place in the sun. To maximise acceleration in the collider, engineers had to make the most perfect vacuum on Earth. The solution was a kind of molecular flypaper that traps any particle that bounces onto it, and that now lines the pipes along which hadrons fly at almost the speed of light. Solar collectors, too, make good use of vacuum technology, which provides ultraefficient thermal insulation and delivers 10 times the efficiency of standard rooftop solar panels. Vacuum-sealed solar panels produced by spin-off company SRB energy, now in daily use at Geneva airport, deliver half a kilowatt of power for every square metre of glass. Even under leaden skies and a blanket of snow, the panels have reached temperatures of 80°C.

Towards high-temperature superconductivity

It takes a lot of electricity to drive the superconducting magnets that push particles to colossal energies. Thick copper cables have to carry a huge current: the longer the cable, the greater the electrical resistance and the bigger the drops in voltage – and the greater the risk of interference from high-energy particles once the machine is running at its highest levels. CERN's superconducting cables must be cooled with liquid helium to a couple of degrees above absolute zero: impractical for long distance transmission. So CERN engineers and the Italian company Columbus Superconductors S.p.A. are testing superconducting cables of magnesium diboride that can deliver the same voltage at temperatures 25 degrees above absolute zero: still very cold but achievable at far lower costs. If the technology works at CERN, there could also be huge rewards in efficiency in many other places.

Developing waste-cleaning technologies

Accelerator technology also helps clean up. In Daegu, Korea, a textile factory uses an electron-beam accelerator to remove toxic dyes from wastewater, and in Szczecin, Poland an accelerator blasts sulphur dioxides and oxides of nitrogen from 270,000 cubic metres of flue gas every hour. In trials in Texas, electron beams have purified wastewater, and converted highly infectious sewage sludge into safe-to-handle agricultural fertiliser.

From nuclear waste and water management…

How about using a nuclear reactor and a particle accelerator together to eliminate highly reactive nuclear waste? Beam technology could in theory turn highly-dangerous nuclear products into something less toxic. The TARC experiment at CERN tested the idea in principle almost 20 years ago, and the exploration continues with n-TOF, the neutron time-of-flight experiment. Out of all this grew the project codenamed Guinevere-Myrrha, under test in Europe and Japan.

So at every level, once again, lessons learned at CERN and in other high energy physics experiments are being deployed to make savings and increase efficiencies right through society. A network of specially-designed sensors buried in the Alps detects natural cosmic rays and provides the French power utility EDF with an accurate and up-to-date assessment of snow cover and therefore a guide to the water in the spring and summer melt: efficient water management for hydroelectricity benefits not just the company, and its customers, but ultimately the whole country.

…to better understanding the atmosphere and the Earth.

A more profound understanding of cosmic rays driven by high energy physics has, quite literally, down-to-earth benefits. CLOUD stands for cosmics leaving outdoor droplets. The acronym may seem contrived – but it has united 18 institutes in nine countries and the experiment employs a cloud chamber at CERN to study the possible link between cosmic rays and cloud formation. This in turn could pay off in a better understanding of the dynamics of atmosphere, and of the connection between clouds and climate. So the acronym becomes irresistible.

Three European partnerships exploit cosmic-ray telescopes to provide a kind of tomography scan of active volcanoes such as Etna in Sicily and Soufrière in Guadeloupe, and of underground structures in Switzerland and France. Yet another collaboration monitors neutrinos from subterranean radioactive decay to illuminate the secrets of the planet's interior.

CERN's TARC experiment in the 1990s carried out important preliminary work for using accelerator-driven systems for energy production, nuclear waste management and medical isotope production.

Communication and new technologies

The powerhouse of invention

Web-inventor Tim Berners-Lee with student Nicola Pellow and the world's first Web browser.

Basic research provides an incubator for new ideas. New ideas must be shared, which was why the World Wide Web was invented at CERN. This new communication tool for physicists launched a global information revolution. But that was just a beginning.

Commercial accelerator know-how helps prospectors look for oil, manufacturers make better radial tyres and airport security staff identify suspicious luggage. It hardens metal surfaces to make better automobile ball bearings and artificial hip and knee joints, and it even provides the secure shrinkwrap that preserves packaged food. So it delivers the technology to get up and go - and the packed lunch for the journey. Altogether, the annual commercial output of the world's accelerators, industrial and medical, is valued at up to €500 billion.

Dealing with big data

Research accelerators are designed primarily to deliver information. This data has then to be shared among physicists all around the globe. To handle this dissemination dilemma, CERN's Tim Berners-Lee invented the World Wide Web and changed scholarship, communication and global commerce in ways that could never have been predicted before that moment. The Web's international annual economic value is now estimated at €1.5 trillion. But research generates new challenges, which stimulate new invention, and generate ever more data. To handle this, in 2002, CERN launched the Worldwide LHC Computing Grid by integrating thousands of computers and storage systems, to process the more than 20 petabytes of data generated each year by the LHC experiments. For comparison, neuroscientists calculate the seemingly-inexhaustible information-carrying capacity of the human brain, the most complex organ in all creation, at 2.5 petabytes. CERN is now involved in partnerships and initiatives that will extend pan-European brainpower and global communication in new and still-to-be-explored ways.

Sharing the grid

EGI-InSPIRE is an initiative to create and maintain a pan-European infrastructure for electronic traffic between "grids" of high performance computing centres and high-throughput resources. It will also help integrate the new "clouds" of distributed computing infrastructures made necessary by the information explosion. Another such partnership is HelixNebula, a cloud formation that will address the information problems of three big data-generating organizations. One of these is the geohazard supersite project of the European Space Agency, formed to monitor conditions of potential and actual

A 2010 snapshot of European traffic on the Worldwide LHC Computing Grid.

disaster. Real-time observation on this scale delivers prodigious quantities of data every second that must be sifted for indications of flood, volcanic eruption, earthquake and the slow onset of drought. The demands are great but the benefits for governments, relief agencies, insurance companies, cities and citizens everywhere could, quite literally, be life-saving.

Research generates new challenges and stimulates invention

Another is the European Molecular Biology Laboratory, which is developing a portal for cloud-supported analysis of the rapidly multiplying genome sequences of humans, animals, plants, insects and microbes. Each creature's DNA base pairs may be numbered in billions and biologists everywhere need access to what has become a daily avalanche of information. Once again, in the battle against illness and infection, the payoff could be counted in lives enhanced, lives extended and lives saved. A third HelixNebula case study is CERN's ATLAS experiment, which yields information from 600 million collisions a second. These trigger a substantial proportion of the million grid computing jobs a day from physicists around the world.

All this is primarily in the service of advanced science but once again with life-changing consequences, because such knowledge ultimately directs the way we perceive the world. Grid and Cloud initiatives, like the Web itself, were launched to serve the needs of pure science, but have swiftly been adapted for commerce. In 2010, Cloud and Grid computing was valued at €35 billion. By 2015 it could be €120 billion.

Technological gems

Blue-skies research demands more than just cloud computing: it also imposes immediate practical engineering challenges that can ultimately be adapted for and exploited by the wider world.

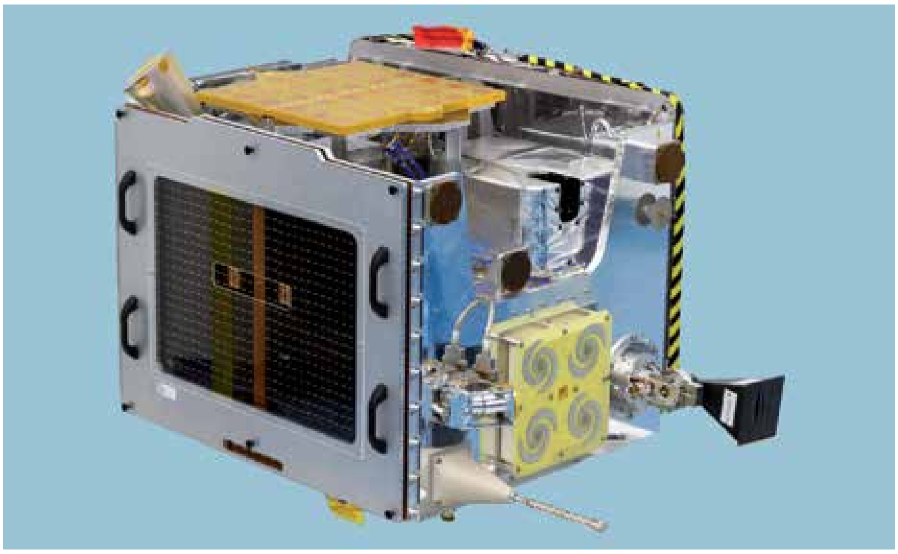
Silicon detectors deep in the heart of particle detectors at the LHC must be kept cool: the challenge is to do that economically. Experiments with liquid carbon dioxide have produced a system that keeps the vertex locator in the LHCb detector stable at -30°C, and the AMS experiment on the space station at 0°C: five prototypes are ready for commercial exploitation. GEM, a gas electron multiplier developed at CERN, has applications in medical imaging, astrophysics, structure analysis and many other fields. One such development could detect the first flames from a forest fire at a distance of a kilometre. This is a hundred times more sensitive than existing ultra-violet sensors: early warning is vital because a forest fire can spread at 100 metres a minute. In 2003, Europe lost half a million hectares of woodland and billions of euros in one long, hot, burning summer. GEM is just one of 40 or so electronics, detector instrumentation, cryogenics, magnet or accelerator technologies from the CERN portfolio, available under license to industry or other laboratories. Each was devised to solve a precise research problem, but any of them could enhance Europe's wider economy in as-yet unforeseen ways.

Gas Elecron Multipliers (GEMs) like these in use at CERN's TOTEM experiment are finding applications in fields as diverse as forest fire detection and medical imaging.

Society and skills

Power to the people

Particle physics has fired up a new generation of school children, informed teachers, stimulated students, ignited enthusiasm throughout Europe and even triggered a high school experiment for low-Earth orbit. It also changed the way we perceive the universe.



Top: TechDemoSat, scheduled for launch in 2013, will have CERN technology, developed by a school in the UK, onboard.

Bottom: The same technology has now been packaged by a company in the Czech republic for educational use in schools.

Particle physics at school

Never speak dismissively of "schoolroom physics". LUCID is an experiment designed for TechDemoSat-1, a British satellite. The acronym stands for Langton Ultimate Cosmic-ray Intensity Detector. Langton is an abbreviation for the Simon Langton Grammar School for Boys in Canterbury, UK, and LUCID is the product of a classroom initiative that began with a school visit to CERN in 2007, when a scientist demonstrated microchips designed to detect particles in the LHC collisions, and also deployed as Medipix, for medical imaging and diagnosis. An enterprising teacher at the Simon Langton school - which despite its name includes girls - encouraged the pupils to compete for an experiment for space-based research.

A training ground for new skills

Fifty students promptly formed their own miniature laboratory, founded the Langton Star Centre and began work on LUCID. The enthusiasm continued long after the Star Centre founders had moved on: working with Rolls Royce, the school's pupils have converted the same technology into a lightweight environmental radiation monitor. In a parallel development, Czech company Jablotron has packaged the Medipix chip for educational use in schools. Particle physics provides a training ground for new skills, a source of excitement for school-children, school-teachers and university students, and a stimulus for postgraduates and post-doctoral researchers. It has perfected dozens of new technologies for commercial exploitation, it uses its unparalleled experience with data to run satellite monitor programmes for the disaster community, and its detector experience has been harnessed in the service of high art and airport security. But it has also inspired the next generation of engineers and physicists, directly as a consequence of deliberate investment in the young. CERN runs high-school teachers programmes, and has state-endorsed programmes for primary schools in France and Switzerland, while the particle physics community runs particle physics masterclasses for high-school students. Discover the Cosmos and the Go-Lab project are new ways of bringing frontier science to schools; there have been remote masterclasses for students from around the continent. The Organization also assembles programmes for physics teachers from Member States and, in at least one case, far beyond. Portugal's science agency and laboratory for experimental physics, have brought together teachers from Brazil, Angola, Mozambique and other Portuguese-speaking countries in order to spread the excitement of science to the wider developing world. CERN co-operates with UNESCO to develop digital libraries and deliver free software to African researchers. CERN has also become a host organization in a series of EU-backed Marie Curie networks and fellowship programmes to introduce young and relatively young researchers to the sophisticated instrumentation for radiation and ion beam therapies for cancer; to advanced accelerator technology; to the use of virtual reality and augmented reality in extreme environments such as nuclear installations, space or the deep ocean; and to a whole series of other techniques. The thrust of such initiatives is to guarantee a supply of people ready for the great technological challenges of the coming decades, and to deliver the intellectual firepower and resourcefulness to confront the as-yet-unknown needs of the crowded, energy-hungry world of tomorrow.

A supply of people ready for the great technological challenges of the coming decades

Around 15,000 particle physicists are engaged in research world-wide: many more have moved on to new challenges in computing, business, finance, healthcare, education,

Participants at the third CERN-UNESCO school on digital libraries in Dakar, Senegal.

communications and the space industries. Others have devised new solutions to complex engineering or technological problems, then adapted these solutions to wider problems and launched their own enterprises. To chose an example almost at random: a simple problem of measurement. To know with high precision the tracks left by particles in high-energy collisions, the researchers need to know exactly where the detectors are, how they are aligned, and if they have moved even fractionally. Nikhef, the Dutch National Institute for Subatomic Physics, developed an alignment system known as Rasnik that can measure to an accuracy of a millionth of a metre. A spin-off company, Sensiflex, has produced a variant that can detect, with exquisite accuracy, any deformation in big engineering structures that might prefigure collapse or subsidence in tunnels, buildings or bridges.

From artist pigments to Ötzi

For many years now applications of high-energy physics have been safeguarding society in once-unimaginable ways. Accelerator mass spectrometry became the archaeologist's tool of choice decades ago for dating fragile or precious objects: among them the Shroud of Turin, and the body of Ötzi the Iceman, a mummified Bronze Age corpse found high in the Alps in 1991. The technique requires only the tiniest fragments of sample tissue. PIXE is a proton-beam detector that doesn't destroy any material at all, yet it can identify the precise mineral or organic components of pigments or alloys and so determine the source of an artist's materials – or identify a forgery.

The most profound reward to society of its investment in particle physics research may have no monetary value at all. The exploration of the sub-microscopic world has illuminated the great mystery of creation. It has helped to change our picture of the universe, and provided a new but still incomplete account of the making of matter and space. That might turn out to be the richest return of all.

The Rasnik alignment system, developed for particle detector alignment, being deployed to monitor deformation in a Rotterdam tunnel.

The European Strategy for Particle Physics

Update 2013

Prepared by the European Strategy Group for Particle Physics for the special European Strategy Session of Council in Brussels on 30 May 2013.

Preamble

Since the adoption of the European Strategy for Particle Physics in 2006, the field has made impressive progress in the pursuit of its core mission, elucidating the laws of nature at the most fundamental level. A giant leap, the discovery of the Higgs boson, has been accompanied by many experimental results confirming the Standard Model beyond the previously explored energy scales. These results raise further questions on the origin of elementary particle masses and on the role of the Higgs boson in the more fundamental theory underlying the Standard Model, which may involve additional particles to be discovered around the TeV scale. Significant progress is being made towards solving long-standing puzzles such as the matter-antimatter asymmetry of the Universe and the nature of the mysterious dark matter. The observation of a new type of neutrino oscillation has opened the way for future investigations of matter-antimatter asymmetry in the neutrino sector. Intriguing prospects are emerging for experiments at the overlap with astroparticle physics and cosmology. Against the backdrop of dramatic developments in our understanding of the science landscape, Europe is updating its Strategy for Particle Physics in order to define the community's direction for the coming years and to prepare for the long-term future of the field.

General issues

a. The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN. *Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.*

b. The scale of the facilities required by particle physics is resulting in the globalisation of the field. *The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.*

High priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c. The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC,* *including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

d. To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

e. There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

f. Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

Other scientific activities essential to the particle physics programme

g. Theory is a strong driver of particle physics and provides essential input to experiments, witness the major role played by theory in the recent discovery of the Higgs boson, from the foundations of the Standard Model to detailed calculations guiding the experimental searches. *Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.*

h. Experiments studying quark flavour physics, investigating dipole moments, searching for charged-lepton flavour violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

i. The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing. *Detector R&D programmes should be supported strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D programme and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*

j. A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.*

k. A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments. *The CERN Laboratory should maintain its capability to perform unique experiments. CERN should continue to work with NuPECC on topics of mutual interest.*

Organizational issues

l. Future major facilities in Europe and elsewhere require collaboration on a global scale. *CERN should be the framework within which to organise a global particle physics accelerator project in Europe, and should also be the leading European partner in global particle physics accelerator projects elsewhere. Possible additional contributions to such projects from CERN's Member and Associate Member States in Europe should be coordinated with CERN.*

m. A Memorandum of Understanding has been signed by CERN and the European Commission, and various cooperative activities are under way. Communication with the European Strategy Forum on Research Infrastructures (ESFRI) has led to agreement on the participation of CERN in the relevant ESFRI Strategy Working Group. The particle physics community has been actively involved in European Union framework programmes. *CERN and the particle physics community should strengthen their relations with the European Commission in order to participate further in the development of the European Research Area.*

Wider impact of particle physics

n. Sharing the excitement of scientific discoveries with the public is part of our duty as researchers. Many groups work enthusiastically in public engagement. They are assisted by a network of communication professionals (EPPCN) and an international outreach group (IPPOG). For example, they helped attract tremendous public attention and interest around the world at the start of the LHC and the discovery of the Higgs boson. *Outreach and communication in particle physics should receive adequate funding and be recognised as a central component of the scientific activity. EPPCN and IPPOG should both report regularly to the Council.*

o. Knowledge and technology developed for particle physics research have made a lasting impact on society. These technologies are also being advanced by others leading to mutual benefits. Knowledge and technology transfer is strongly promoted in most countries. The HEPTech network has been created to coordinate and promote this activity, and to provide benefit to the European industries. *HEPTech should pursue and amplify its efforts and continue reporting regularly to the Council.*

p. Particle physics research requires a wide range of skills and knowledge. Many young physicists, engineers and teachers are trained at CERN, in national laboratories and universities. They subsequently transfer their expertise to society and industry. Education and training in key technologies are also crucial for the needs of the field. *CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop coordinated programmes for education and training.*

Concluding recommendations

q. This is the first update of the European Strategy for Particle Physics. It was prepared by the European Strategy Group based on the scientific input from the Preparatory Group with the participation of representatives of the Candidate for Accession to Membership, the Associate Member States, the Observer States and other organizations. Such periodic updates at intervals of about five years are essential. *Updates should continue to be undertaken according to the principles applied on the present occasion. The organizational framework for the Council Sessions dealing with European Strategy matters and the mechanism for implementation and follow-up of the Strategy should be revisited in the light of the experience gained since 2006.*

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Repres. EU Lab. Directors' Mtg	Dr Ph. Chomaz
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JINR, Dubna	Prof. V. Matveev

COMPOSITION OF PREPARATORY GROUP

MEMBERS	NAME
Strategy Secretariat Members	
Scientific Secretary (Chair)	Prof. T. Nakada
SPC Chair	Prof. F. Zwirner
ECFA Chair	Dr M. Krammer
Repres. EU Lab. Directors' Mtg	Dr Ph. Chomaz
Scientific Secretary Assistant	Prof. E. Tsesmelis
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