CERN Science bridging cultures

CERN
Science bridging cultures

Edited by Marilena Streit-Bianchi

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"Pushing particles near to the speed of light" Justino António Cardoso 2015, Indian Ink (front)
"Geneva Switzerland" Justino António Cardoso 2015, colour Indian Ink (back)

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In memory of Dr. Karl-Peter Streit, a physicist who was a member of the University of Heidelberg and assistant to Prof. Volker Soergel. He participated in the experiments WA2, WA42 and WA46, studying the characteristics of hyperons. In 1983 the collaboration WA62, for which he was spokesman, demonstrated the existence of the charmed strange baryon A^+ (csu) at 2.46 GeV/c^2 and in 1984 of the charmed doubly strange baryon T^0 (csu) at 2.74 GeV/c^2. After working in industry he joined the group of Prof. Allan Clark at the Department of Nuclear and Corpuscular Physics of the University of Geneva working on the aspect of radiation hardness of the silicon pixel detector for future upgrades of the ATLAS tracker (insertable B-Layer (IBL) and High Luminosity - LHC (HL-LHC)). He was for many years member of the User Community of CERN.

CERN was his professional and intellectual home from science to culture and humanity.

Marilena Streit-Bianchi and Rolf Heuer

Preface

I know from my own long experience that CERN has been, and remains, a place where knowledge, technical competence and understanding find a welcoming home. It has been so since the Organization's foundation in the 1950s and will continue to be for as long as CERN exists. This is because those who work at CERN in research and operations are motivated by the desire to advance the frontier of our understanding of the fundamental forces of nature, regardless of where they come from, or of any cultural preconceptions they may have.

This book gives a glimpse of CERN's activities and highlights various lesser-known facets of the Laboratory: facets that are nevertheless essential to carry out research in High Energy Physics. CERN is not only a prime example of excellence in research, technology and innovation, but also a genuine melting pot of diversity of competencies, and of humanity.

Science and art have creativity and open-ended enquiry as a common denominator. This book shows how these two worlds, once clearly united but now perceived as separate, remain, in fact, manifestations of that same spirit of human enquiry. It shows how artists of different cultural backgrounds perceive CERN and the work carried out there*. The graphic work of Justino António Cardoso brings an unmistakable and unique African touch.

To conclude I would like to add that this book, in its various language versions, has been made possible thanks to the benevolent work of all contributors who, on top of their daily scientific or artistic work have taken the time to participate in this endeavour.

I take the opportunity to warmly thank:

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Marilena Streit-Bianchi

* Davide Angheleddu (Italy), Justino António Cardoso (Mozambique), Margarita Cimadevila (Spain), Angelo Falciano(Italy), Michael Hoch (Austria), Karen Panman (The Netherlands), Islam Mahmoud Sweity (Palestine).

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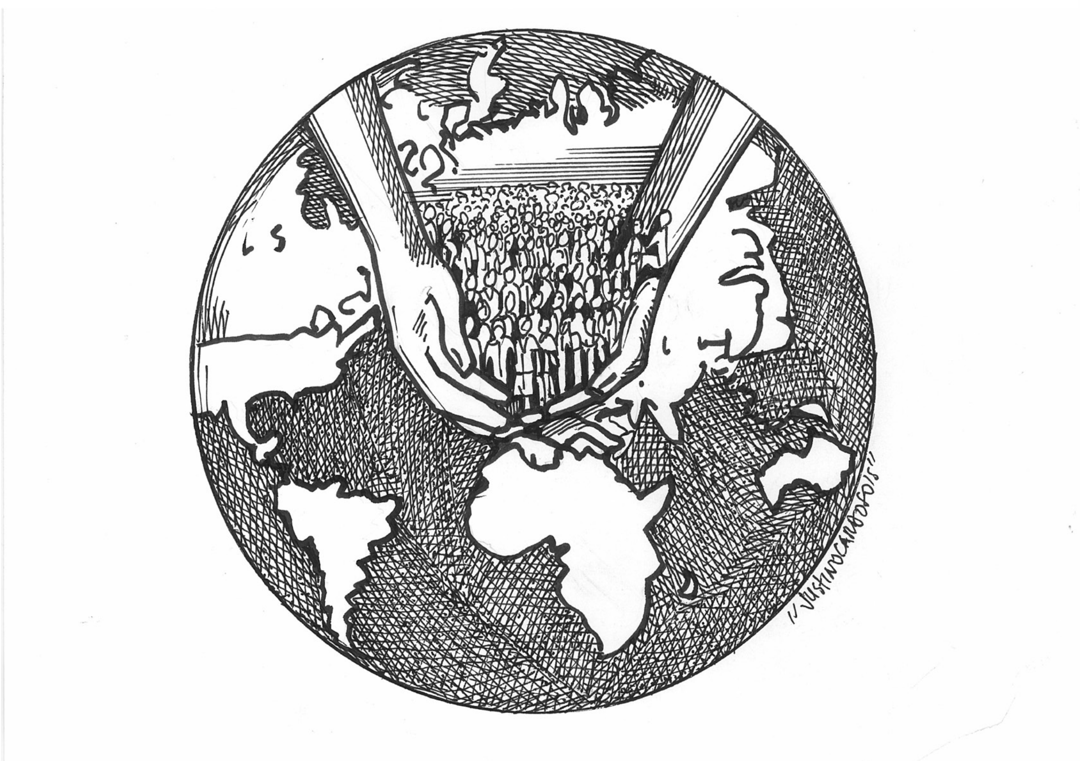
the largest particle physics laboratory in the world
is a leading Organization in creating knowledge



“The evolution of our Universe” Justino António Cardoso *2015, Indian Ink*

The evolution of our Universe, leading to life on Earth, has taken billions of years. LHC physicists are studying what happened in the 10^{-12} seconds after the Big Bang. Hydrogen and helium atoms were produced about 380,000 years after.

CERN, the European Particle Physics Laboratory

Marilena Streit-Bianchi

CERN, the European Organization for Nuclear Research, is the largest particle physics laboratory in the world and a longstanding European example of excellence in research, education and knowledge transfer. The Laboratory was founded in 1954 on the Swiss side of the Franco-Swiss border near Geneva. The aim was to create a world-class physics research centre to stem the brain drain to the United States of America and federate Europe around a research project that could not be carried out by a single nation. The group of visionary scientists and diplomats that founded CERN also wanted to foster understanding between people regardless of their nationality, political or religious beliefs.

CERN today is very international especially in research collaborations with over 600 institutes and universities all around the world using the CERN facilities.

CERN is a world-renowned centre of excellence, which has contributed major discoveries in the field of particle physics and continues to be a leading organization in creating knowledge.

Its role and importance for the education and training of physicists, engineers, computer scientists and technicians is continuously growing. Around a thousand young people each year receive qualifications for work carried out at CERN.

Over the years, the positive outcomes of knowledge acquisition and transfer have proved substantial and the Laboratory is a source of continuous technological development.

At CERN, results obtained from fundamental research are published, freely exchanged and made available to the world. Since the beginning, CERN scientists have developed a very natural concept of information sharing, which has involved researchers, engineers, technicians and students. As a result, everybody is able to exercise and fulfil their curiosity by interacting with people of many different origins, fields and areas of expertise.

The Laboratory’s gigantic infrastructures and free team spirit of learning and sharing come as a great discovery to any newcomer. In the big collaborations, the management and coordination roles are key to the success of the scientific endeavour.

The impact on many fields of the knowledge acquired in big and small technical and research projects is well documented. CERN has a long tradition in fostering relations with industry to develop the innovative technologies needed for the construction of accelerators and detectors. Today, having institutionalized Technology and Knowledge Transfer and having increased efforts to ensure more rapid and effective impact, CERN is playing an even more proactive role in transferring innovations from fundamental research to society.

“How to extend the Standard Model?” Justino António Cardoso *2015, Indian Ink*

CERN, science for peace

Emmanuel Tsesmelis

At the end of the Second World War, European science was no longer in a leading position. Following the example of other international organizations, a number of visionary scientists and diplomats proposed creating a European nuclear physics laboratory. Such a laboratory would not only unite European scientists but would also allow them to share the increasing costs of nuclear physics facilities. French physicist Louis de Broglie put forward the first official proposal for the creation of a European laboratory at the European Cultural Conference, which opened in Lausanne on 9 December 1949. A further push came at the fifth UNESCO General Conference, held in Florence in June 1950, where American physicist and Nobel laureate Isidor Rabi tabled a resolution authorizing UNESCO to "assist and encourage the formation of regional research laboratories in order to increase international scientific collaboration…".

At the sixth session of the CERN Council, which took place in Paris from 29 June - 1 July 1953, the CERN Convention establishing the Organization was signed, subject to ratification, by 12 states. The convention was gradually ratified by the 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, and Yugoslavia. On 29 September 1954, CERN - the European Organization for Nuclear Research - officially came into being.

The CERN Convention has stood the test of time for more than 60 years. It provides the means to allow the Organization to adapt to a changing political environment, and to new scientific and technological challenges. The Convention is testimony to the wisdom and foresight of CERN's founding fathers, on a par with their vision of rebuilding peace in Europe by establishing a unique focal point that would foster scientific collaboration on an unprecedented scale, between nations that had fought a war against each other only a few years earlier.

Ever since, CERN has helped build mutual confidence and trust across borders. During the Cold War years, CERN, in 1968, was the first organization to conclude an agreement with the Soviet Union, establishing a cooperation with the large national laboratory at the **I**nstitute for **H**igh **E**nergy **P**hysics (IHEP) at Protvino near Serpukhov. In 1956, the international laboratory called **J**oint **I**nstitute for **N**uclear **R**esearch (JINR) was founded at Dubna northeast of Moscow following the CERN model for the 'Warsaw Pact states' behind the Iron Curtain. The cooperation between JINR and CERN provided one of the rare bridges for cooperation between physicists from the West and East during the Cold War. It played a particularly important role in the cooperation between scientists from West Germany and East Germany, since at that time it was the only possibility for scientists of the two parts of Germany to work together. The cooperation between JINR and CERN has been strengthened over the past decades and has led to a reciprocal agreement that sees CERN becoming an Observer of JINR and JINR becoming an Observer of the CERN Council. Another example is the cooperation between CERN and the People's Republic of China. It began in the 1970s, initially in accelerator technology and in theoretical physics, and was soon followed by participation in CERN's experimental physics programme. Building on International Cooperation Agreements signed with the People's Republic of China in the 1990s, universities from the People's Republic of China now participate in four LHC experiments (ALICE, ATLAS, CMS and LHCb), in the LHC Computing Grid and in the CLIC study. CERN has also developed a cooperation with Palestine. After the An-Najah National University signed an Expression of Interest with ATLAS, Palestine has taken a major step towards consolidating its collaboration with CERN by signing an International Cooperation Agreement in December 2015. Following this, a number of initiatives have been launched in Palestine, including Masterclasses, a Physics School at the Arab American University in Jenin and participation of Palestinian teachers in the special High-School Teacher programme dedicated to SESAME, the **S**ynchrotron-light for **E**xperimental **S**cience and **A**pplications in the **M**iddle **E**ast. Finally, CERN has served as a model for other successful science organizations, most recently for SESAME.

Today, the LHC is CERN's flagship scientific project and has launched a new era of research and discovery in particle physics. Experiments at the LHC have provided the breakthrough observation of the Higgs boson, validating the **B**rout-**E**nglert-**H**iggs (BEH) mechanism, and being one of the most significant discoveries in the history of fundamental physics. Expectations from the LHC are great, and revolutionary perspectives in the understanding of the microcosm and a change to our view of the early Universe are being probed.

CERN and its large-scale science projects like the LHC require large and sustained infrastructure and also global collaboration over a long time scale. The large international collaborations of the LHC provide an environment where people learn to work and share together and also provide the opportunity to recognise differences, accept them and learn from them by respecting diversity. CERN is also an example of unifying efforts in so many different fields of competences. Engineers, technicians and administrators are working on the common endeavour of making equipment of cutting-edge technology and providing the services and support needed for the research infrastructure and ancillary systems. Building research infrastructure of such complexity as the LHC requires engineers, technicians and administrators for areas as diverse as civil engineering, installation, magnets, radiofrequency systems, vacuum, cryogenics, electricity, health and safety, radiation protection, legal services, fire brigade, logistics, finance, purchasing and human resources management. They represent the large majority of the CERN staff, which in 2017 numbered about 2500 people. Moreover, about 1000 contractors from external companies provide services that are not part of the core competence of CERN and that could be outsourced.

Results from the LHC and its upgrades will guide the way in particle physics for the years ahead and CERN, as host to the LHC, is in a unique position to contribute to further understanding in particle physics in the long term. In view of this, CERN is exploring two different and challenging avenues to prepare its future – CLIC (**C**ompact **Li**near **C**ollider) and the FCC (**F**uture **C**ircular **C**ollider) study.

All this is happening as facilities for high-energy physics (as for other branches of science) are becoming larger and more expensive. Funding for the field is not increasing in many countries and the timescale for projects is becoming longer, both factors resulting in fewer facilities being realised. Particle physics will need to adapt to this evolving situation. This leads to the need for more coordination and more collaboration on a global scale. Expertise in particle physics needs to be maintained in all regions, ensuring long-term stability and support throughout. It is necessary to engage all countries with established particle physics communities and to integrate the emerging communities in other countries. The funding agencies should in their turn provide a global view. Planning and execution of high-energy physics projects today require world-wide partnerships for global, regional and national projects, namely for the whole particle physics programme. Particle physics must adapt to this evolving reality by fostering greater coordination and collaboration on a global scale.

CERN builds on a long tradition of global engagement in our scientific work. The Organization has formal relations with **N**on-**M**ember **S**tates (NMS) via bilateral **I**nternational **C**ooperation **A**greements (ICAs), currently in force with about 50 countries. Out of a total of about 13,000 users at CERN, the participation of NMS users is now almost 40% -- the majority of the NMS users are researchers from the US and the Russian Federation working on the LHC. The overall NMS participation in the non-LHC research programme is currently about 20%. Financial resources for research programmes, notably maintenance and operation costs for the LHC experiments, are shared between the Member States, the Associate Members and the NMS. In addition, there is increasing interest in collaboration on accelerator R&D, such as for high-field magnets and accelerating structures, and related technologies, focusing on the LHC's upgrades and also on the FCC and CLIC studies. The number of states involved in such activities is already growing beyond the restricted circle of NMS that contributed to the LHC accelerator's construction.

The increasingly global interest in CERN also translates into an increasing demand for CERN's education and training programmes - falling within CERN's mission of helping build capacity in countries that are developing their particle physics communities.

The scientific achievements of CERN over the years have gone hand-in-hand with CERN's policy of increased global networking and scientific, technological and educational collaboration with world-wide partners. In view of this, in 2010, Council approved the most radical shift of paradigm of CERN's membership policy to date, embedded in a new policy of geographical enlargement that opened full Membership to non-European states, irrespective of their geographical location. At the same time, Council introduced the new instrument of Associate Membership to facilitate the accession of new members, including emerging countries outside Europe, which might not command sufficient resources to sustain full Membership in the immediate future.

Today, CERN has 22 Member States[1], eight Associate Member States[2] and six Observers[3]. Israel became CERN's 21st Member State in 2014 while Romania joined as the 22nd Member State in 2016. Cyprus, Serbia and Slovenia are presently Associate Members in the pre-stage to Membership, while India, Lithuania, Pakistan, Turkey and Ukraine are Associate Members. Brazil and Croatia have also applied for Associate Membership. At a time when CERN is attracting new Member States and Associate Member States , developments in formal relations with other non-Members States , e.g. through the conclusion of new International Cooperation Agreements (ICAs), continues. Today, around 50 ICAs are in force with a diverse and wide geographical spread and scientific contacts have also been established with many others[4].

The geographical enlargement policy of 2010 offers important opportunities for the future of the Organization. Now, CERN has developed it into a strategy, presented to the Council in March 2016, to ensure that geographical enlargement consolidates the institutional base and thus reinforces the long-term scientific aspirations of CERN. Enlargement is not an aim in and of itself. Rather, the focus is on strengthening relations with countries that can bring scientific and technological expertise to CERN and can, in turn, benefit from a closer engagement, while also helping to nurture and build capacity in countries with developing particle physics communities. It is essential that Membership and Associate Membership are beneficial to particle physics in individual countries, and that governments continue to invest in the growth of national communities. At the same time, enlargement should not hinder the operational efficiency of the laboratory.

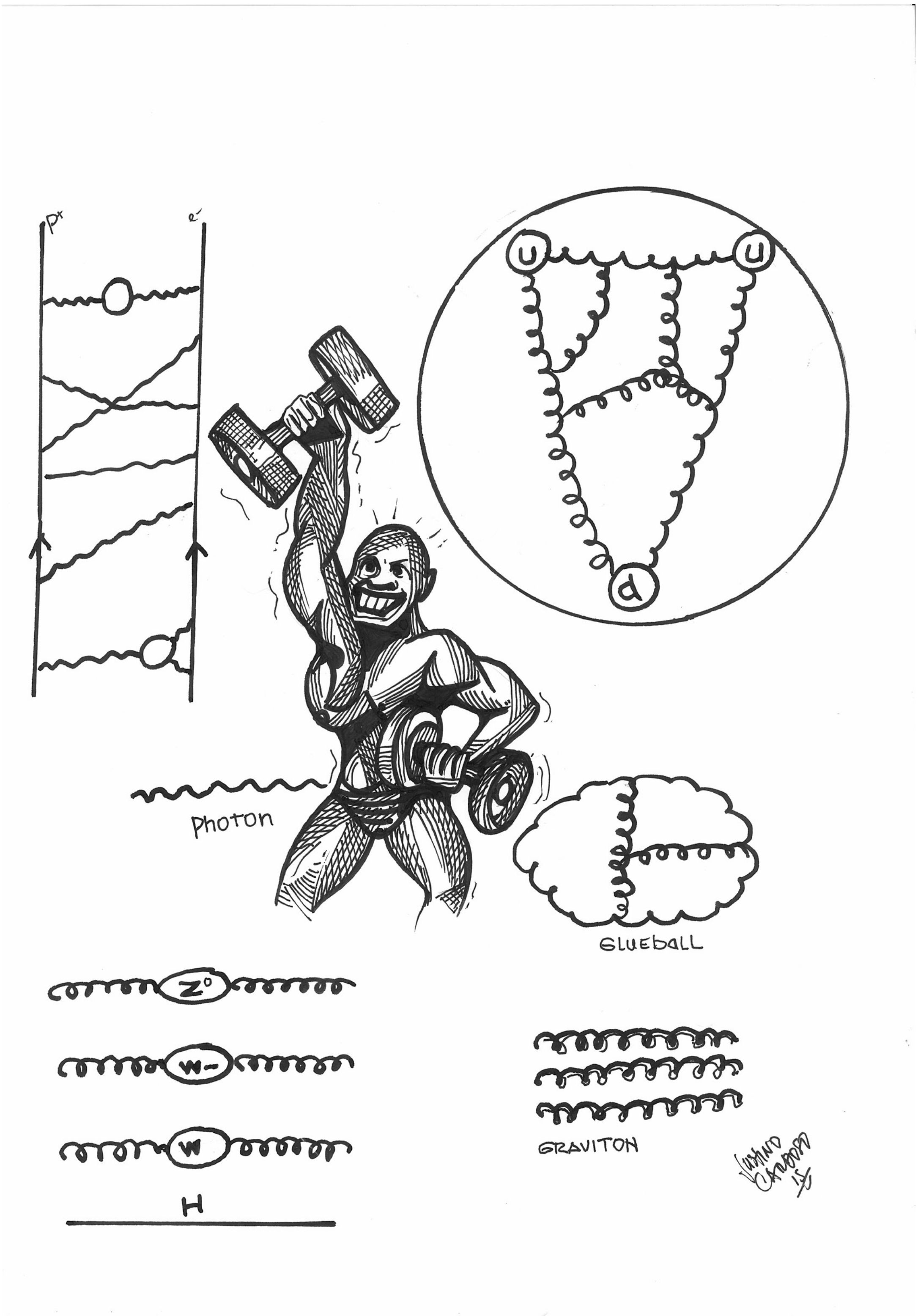
In conclusion, looking ahead, CERN's engagement with the international particle physics community is clearly oriented towards continuing with the objectives as set out in the CERN Convention and in the geographical enlargement policy, mindful that investigating the unification of the fundamental forces of nature requires uniting our efforts for science on a global scale for the benefit of the discipline in the long term.

[1] Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland, and United Kingdom.

[2] Cyprus, Serbia and Slovenia are Associate Member States in the pre-stage to Membership. India, Lithuania, Pakistan, Turkey and Ukraine are Associate Member States.

[3] Japan, Russian Federation, United States of America, European Union, JINR and UNESCO.

[4] http://international-relations.web.cern.ch/stakeholder-relations/Associate-Non-Member-State-Relations
Non-Member States, Territories and Regions Collaborating with CERN : Albania, Algeria, Argentina, Armenia, Australia, Azerbaijan, Bangladesh, Belarus, Bolivia, Brazil, Canada, Chile, China, Colombia, Costa Rica, Croatia, Cuba, Ecuador, Egypt, Estonia, Georgia, Ghana, Hong Kong, Iceland, Indonesia, Iran, Ireland, Jordan, Kazakhstan, Korea, Latvia, Lebanon, Madagascar, Malaysia, Malta, Mexico, Mongolia, Montenegro, Morocco, Mozambique, Nepal, New Zealand, Oman, Palestine, Peru, Philippines, Qatar, Rwanda, Saudi Arabia, Singapore, South Africa, Sri Lanka, Taiwan, Thailand, The Former Yugoslav Republic of Macedonia, Tunisia, United Arab Emirates, Uzbekistan, Vietnam.



“The forces” Justino António Cardoso *2015, Indian Ink*

There are four known fundamental forces. The strong force binds the quarks together and is carried by gluons. The electromagnetic force binds electrons to nuclei in atoms and atoms into molecules, it is carried by photons. The weak force underlies radioactivity and is carried by intermediate vector bosons W^+*,* W^- *and Z. Gravitation is the attractive force that makes objects fall, binds matter in planets and stars and holds the stars in the galaxies and it is thought to be carried by yet-to-be-discovered gravitons.*

Standard Model and searches for new fundamental physics

John Ellis

Where do we come from?

"Where do we come from? What are we? Where are we going?" These are, timeless, universal questions that people have been asking for thousands of years. Famously, they were posed in a well-known painting by Paul Gauguin created in 1897, the year of the first discovery of an elementary particle, the electron. Particle physicists interpret Gauguin's second question as "What are we made of?" and have an answer called the Standard Model, which describes all the visible matter in the Universe. The culminating success of the Standard Model was the discovery in experiments at CERN's Large Hadron Collider (LHC) of the Higgs boson, the last particle expected in the Standard Model. Its discovery also gives insights into what happened in the early history of the Universe and raises questions about its possible future, thereby addressing Gauguin's other two questions.

But the Standard Model is incomplete. For example, it does not explain the origin of the matter in the Universe, and it does not explain the mysterious dark matter that enabled galaxies to form and still holds them together. Experiments are continuing at the LHC to address these questions, but particle physicists are also debating what might be the next steps in the universal quest articulated by Gauguin. The collisions made at the LHC and similar machines recreate processes that occurred very early in the history of the Universe, and collisions at higher energies than the LHC would enable us to look further back in time. Therefore, one option is to build a more powerful version of the LHC in a larger circular tunnel. The LHC collides protons (hydrogen nuclei) at energies up to about 14,000 times their equivalent rest-mass energy, and such a higher-energy circular accelerator might be able to make collisions at 100,000 times the proton rest-mass energy. These collisions might finally reveal the origin of the dark matter filling the Universe.Another possibility might be to collide electrons with their antiparticles. Such collisions would be at more modest energies, but they could in principle provide much more precise information about the particles they produce, such as the Higgs boson. Such high-precision studies would help us understand better what roles it had in the early history of the Universe, and could provide indirect hints what new physics might lie beyond the Standard Model.

The next step in particle physics will be a truly global challenge, requiring the development of many new technologies, the training of many engineers and scientists, significant financial resources and broad political support. The technologies required will range from civil engineering through cryogenics, material science and electronics to informatics. Many of these technologies, will have applications beyond answering Gauguin's questions. Now is the time to think together how to meet this challenge to human curiosity.

The Standard Model and the new searches

Particle physics has provided us with a theory, called the Standard Model, which describes successfully all the visible matter in the Universe. However, in parallel, astrophysicists and cosmologists have shown that the Universe contains much more than meets the eye, or even the astronomers' telescopes. In the 1930s the Swiss astronomer Fritz Zwicky discovered that galaxies in the nearby Coma cluster are being moved around by a much stronger gravitational field than could be generated by the visible matter in the cluster. He suggested that this extra gravitational field must be due to additional, invisible "dark matter" that does not emit light.

This radical idea was slow in gaining acceptance, but crucial extra evidence came in the 1970s from measurements by the American Astronomer Vera Rubin and others of the motions of stars in different galaxies. Unlike the solar system, in which planets that are further from the Sun move more slowly, in accordance with Kepler's laws, it was found that stars that are more distant from the centres of galaxies move much faster than expected on the basis of the gravity due to the visible matter, at speeds similar to those of stars closer in. These observations show that there must be extra, invisible dark matter surrounding galaxies, many times more than what we see. Many subsequent observations have supported the dark matter hypothesis.

However, it came as a great surprise in the late 1990s and early 2000s when astronomers discovered that, in addition to the dark matter clumped in galaxies and clusters, there must be some additional distribution of energy throughout the "empty" space between them. This so-called "dark energy" is causing the Universe to expand at an accelerating pace, unlike ordinary and dark matter, whose gravitational attraction would cause the expansion of the Universe to slow down. Overall, the density of dark energy must be about 3 times larger than that of matter.

What might the dark matter be composed of? A popular idea is that it might be some unknown type of massive, weakly-interacting particle. The Standard Model does not contain any possible candidates, but many extensions of the Standard Model do. A common suggestion is that the dark matter particle might weigh between 100 and 1000 times the mass of the proton, which could place its production within reach of the **L**arge **H**adron **C**ollider (LHC) at CERN. Experiments at the LHC have been looking for collisions in which a large amount of energy is carried away by invisible dark matter particles, without any luck so far. Searches at the LHC are continuing at higher energies, but the discovery of dark matter may require some future higher-energy collider. Alternatively, experiments are looking directly in astrophysics for dark matter, for example the AMS (**A**lpha **M**agnetic **S**pectrometer) experiment on the International Space Station is looking for particles that might have been produced by dark matter particles annihilating in interstellar space. the AMS control room is hosted by CERN.

And what of dark energy? The possibility of its appearance was first suggested by Einstein in 1917, as what he called the cosmological constant. All theories of fundamental physics predict possible contributions to the density of dark energy, for example via the Higgs boson in the Standard Model, so its presence should not have come as a surprise. However, these theories typically predict much more dark energy than the amount discovered by astronomers. The puzzle is rather why the density of dark energy is so small. Studies of the Higgs boson at the LHC and future colliders may cast some light on this dark puzzle. One possibility is that dark energy is being mimicked by a new particle whose mass depends on the local density of matter: such a "chameleon" particle would be very difficult to detect experimentally, like its colour-changing lizard namesake!

“Strings propagate through space and interact” Justino António Cardoso *2015, Indian Ink*

Many theoretical phyicists think that, at the most fundamental level, elementary particles may be pieces of vibrating strings, and are trying to construct models of matter based on this idea. (caption from John Ellis)

“The search is open” Justino António Cardoso 2015, *Indian Ink*

Accelerators: how and why

Lucio Rossi

Accelerate, v. move or cause to move more quickly (OED). Since the time of the manifesto of Futurism in 1909, acceleration has been one of the marks of contemporary time. Particle accelerators, invented in the 20th century, are a typical product of that period when barriers were broken and new frontiers of knowledge were exceeded.

Rutherford first understood that atomic structure can be unveiled by bombarding it with nuclear particles, opening the route toward particle accelerators. In his famous 1927 opening talk as President of the Royal Society he said: "The advance of science depends to a large extent on the development of new technical methods and their application […] From the purely scientific point of view interest is mainly centred on the application of these high potentials to vacuum tubes in order to obtain a copious supply of high-speed electrons and high-speed atoms [...] This would open up an extraordinarily interesting field of investigation which could not fail to give us information of great value, not only in the constitution of atomic nuclei but in many other directions". It is today easy to recognize how good a prophet he was!

Brief description of an accelerator

Accelerators can be divided into two main configurations:

a) *Linacs – Linear Accelerators*, in which a linear array of RF cavities provides the multiple acceleration. More cavities mean higher energy. However the size and cost of the accelerators increase accordingly.

b) *Circular accelerators*, in which the beam passes through the same cavities millions of times, until the maximum energy is attained. In such machines, like the LHC, the cavity region is very short, a few tens of meters out of the 27 km overall length, while the magnetic part is vastly longer.

A particle accelerator features four main components:

a) A vacuum chamber, from which molecules and atoms are evacuated leaving a vacuum at the level of 10^{-7} to 10^{-11} mbar (almost a million billion times fewer molecules per unit volume than in atmospheric air at sea level)

b) An electric field that accelerates the particles (which are electrically charged).

c) A magnetic field that bends the particles' trajectories (a dipole field, generated by a two-pole magnet)

d) Various types of magnetic field including quadrupoles (four-pole magnets) that focus the particle beam, ensuring that particles do not go astray and hit the vacuum pipe.

In an accelerator, tiny subatomic particles are assembled in a cloud forming a long thin line called a particle beam. The beam is usually not continuous: the particles are grouped in bunches. The accelerated particle beam can be used to bombard a fixed target, usually a thin foil, a gas chamber, a thick solid or a liquid. In the 1960s, Bruno Touschek proposed and built the first particle collider, AdA in Frascati, Italy. At AdA, a particle beam was accelerated and then smashed against another particle beam travelling in the opposite direction. Since then, almost all record-breaking accelerators have been mainly used in collider mode.

Electric fields give speed (momentum) to the particles: usually these fields are in the form of electromagnetic waves, with frequency in the range from radio/TV waves to microwaves. These are all called radiofrequency (RF) fields, since initially 10-200 MHz frequency were used. However in modern accelerators frequencies of tens of GHz (well into the microwave range) are actually employed. These electromagnetic waves are trapped in a metallic "empty" box, called an RF cavity, very much as an acoustic wave is trapped in an organ pipe. Each time the beam passes through the cavity each particle receives a kick, provided that it enters at the right phase, very much like surfers propelled forward as long as they remain on the crest of the wave. A cavity can deliver a voltage of

1-10 MV (which in energy we call 1-10 MeV). To reach Gigalectronvolt (GeV) or Teraelectronvolt (TeV: the energy of the LHC), the beam must pass through a cavity thousands or even millions of times.

Magnetic fields are necessary to guide the particles. The most abundant magnets are dipoles, in which a uniform magnetic field bends particles' trajectories into a curved orbit. An array of dipoles keep the particles on a circular track. The more powerful the dipole magnet, the higher the centripetal force (sometimes called Lorentz force) on the particles, and the higher the energy attained by the particles. In a circular accelerator the particle energy is given by a simple relation (in a relativistic approximation): $E_{beam} = 0.3\ BR$, where B is the magnetic field value and R is radius of the circle followed by the particles. . With the LHC magnet parameters of 8.3 tesla fields and a 2.8 km radius, one arrives at an energy of 7 TeV for each beam, equivalent to an acceleration provided by a voltage of 7 million million Volts! However the LHC RF cavities only provide about 10 MV, so the beam has to pass through them millions of times to reach the maximum energy. Thanks to the bending power of its 1232 dipoles, each one 15 m long and filling a total of 18 km of the 27 km long LHC tunnel the particles are kept on track as they are accelerated.

Magnetic fields also have the job of stabilizing the beam against any small deviations from its ideal trajectory. Just as car drivers keep their vehicles on the road by continuous subtle adjustments of the steering wheel, so in an accelerator, magnets called quadrupoles (with four poles) in between the dipoles compensate for the inevitable imperfections of the trajectory. Without quadrupoles, any machine, linear or circular, could not work because the beam would rapidly diverge and hit the vacuum chamber. In the LHC the beam envelope is about 1 mm, thanks to its 400 quadrupoles. So, the beam in LHC is a series of cylindrical bunches, 1 mm in diameter and around 20-30 cm long, spaced by 7.5 m, or 25 nanoseconds in time. About 2800 bunches fill each of the two 27 km long counter-circulating rings.

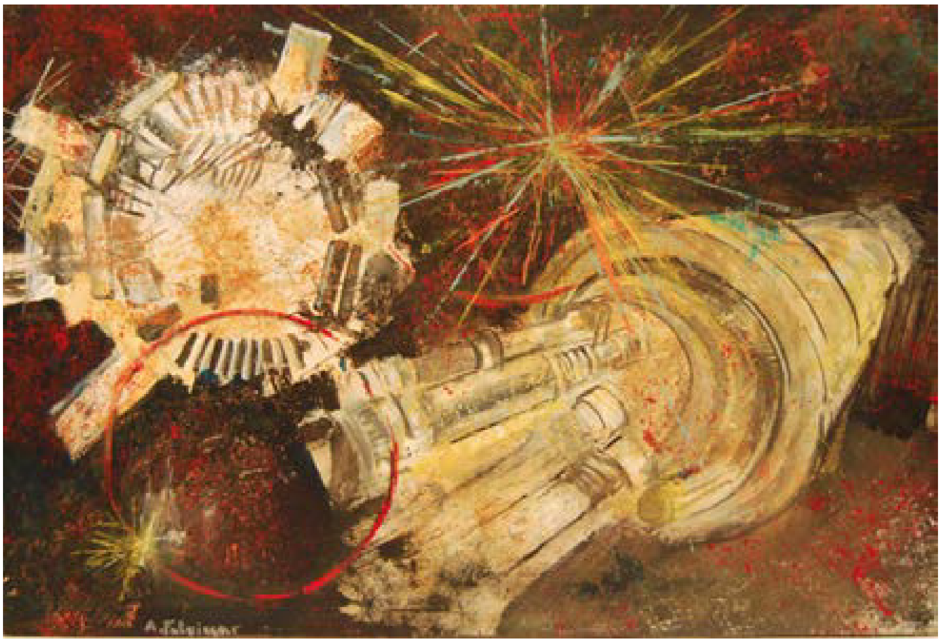
There are many other types of magnets from sextupoles (six-poles) up to dodecapoles (12-poles), each type curing a specific instability.

The LHC chain

The LHC is the largest and final stage of a chain of accelerators. It all starts when hydrogen molecules, extracted in form of gas from a bottle, are ionized by means of an electric discharge to form a plasma, a gas of charged particles such as is to be found in stars like the Sun. Then the positively charged hydrogen nuclei, called protons, are separated from electrons by means of static fields, forming a beam that is then accelerated to 50 MeV by a Linac about 30 m long. The beam is then fed into a circular accelerator, a 150 m long synchrotron called the Booster, which accelerates the beam up to 1400 MeV (1.4 GeV). The beam is then guided into the 600 m circumference Proton Synchrotron (PS). The oldest of the CERN accelerators, the PS was inaugurated in 1959. It accelerates the proton beam up to 25 GeV. The particles are then injected into the 7 km long Super Proton Synchrotron, SPS[5], which pushes them up to 450 GeV. Finally, the protons are injected into the LHC: two beams are formed and made to rotate in opposite directions and then accelerated up to 7000 GeV, or 7 TeV, which is liberated in head-on collision at 14 TeV energy in the centre of mass.

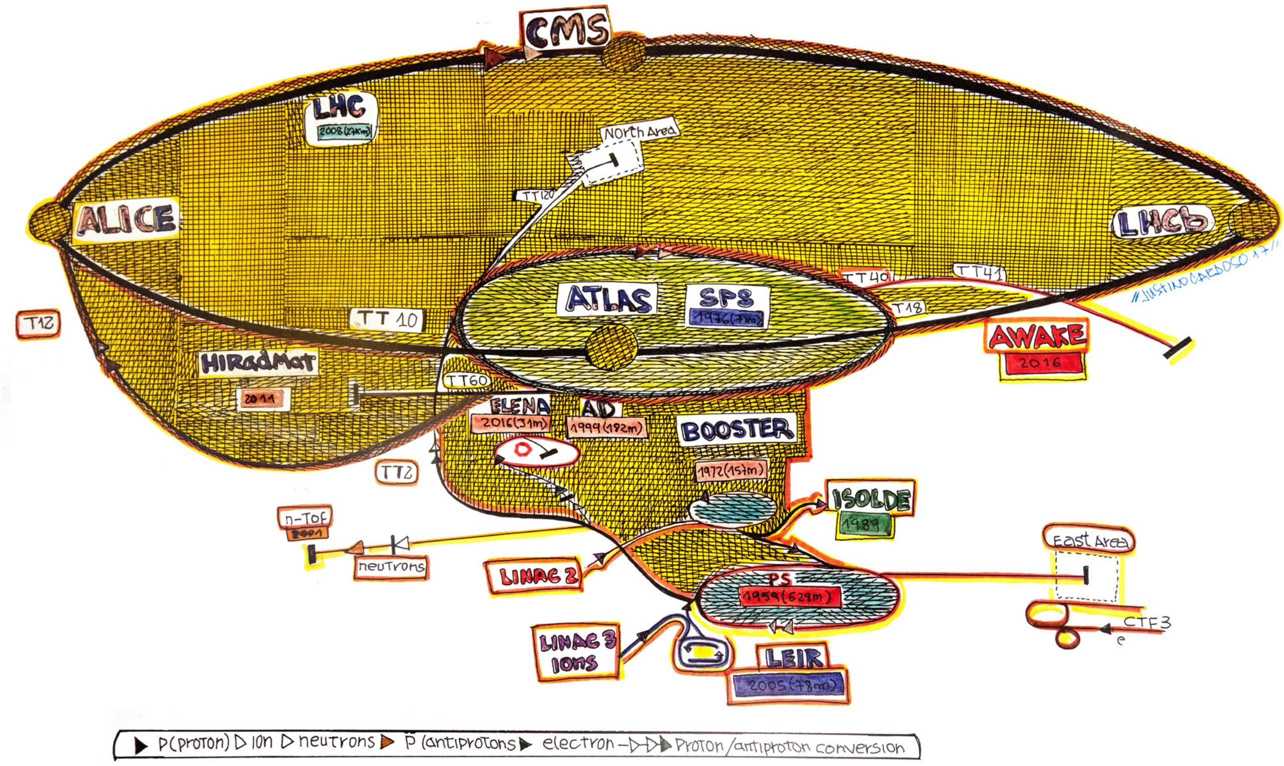
The whole chain is more than 40 km long, of which 27 km are taken up by the LHC. The first machines are at ground level. The SPS is in a 40 m deep tunnel. The two injection tunnels, TI2 and TI8, connecting SPS with LHC, each more than 3 km long, bring the proton beam from 40 m to 100 m underground. Each single piece of the complex machine is a marvel and the tens of thousands of pieces of complex equipment all have to work together to bring the protons from the hydrogen bottle to collide in the LHC experiments at 14 TeV and generate new particles including the famous Higgs boson!

[6] The SPS was transformed for a short period into a proton-antiproton collider, allowing the discovery at CERN of the Z and W bosons, in 1983 and for which the Nobel Prize in 1984 was awarded to Carlo Rubbia and Simon van der Meer.



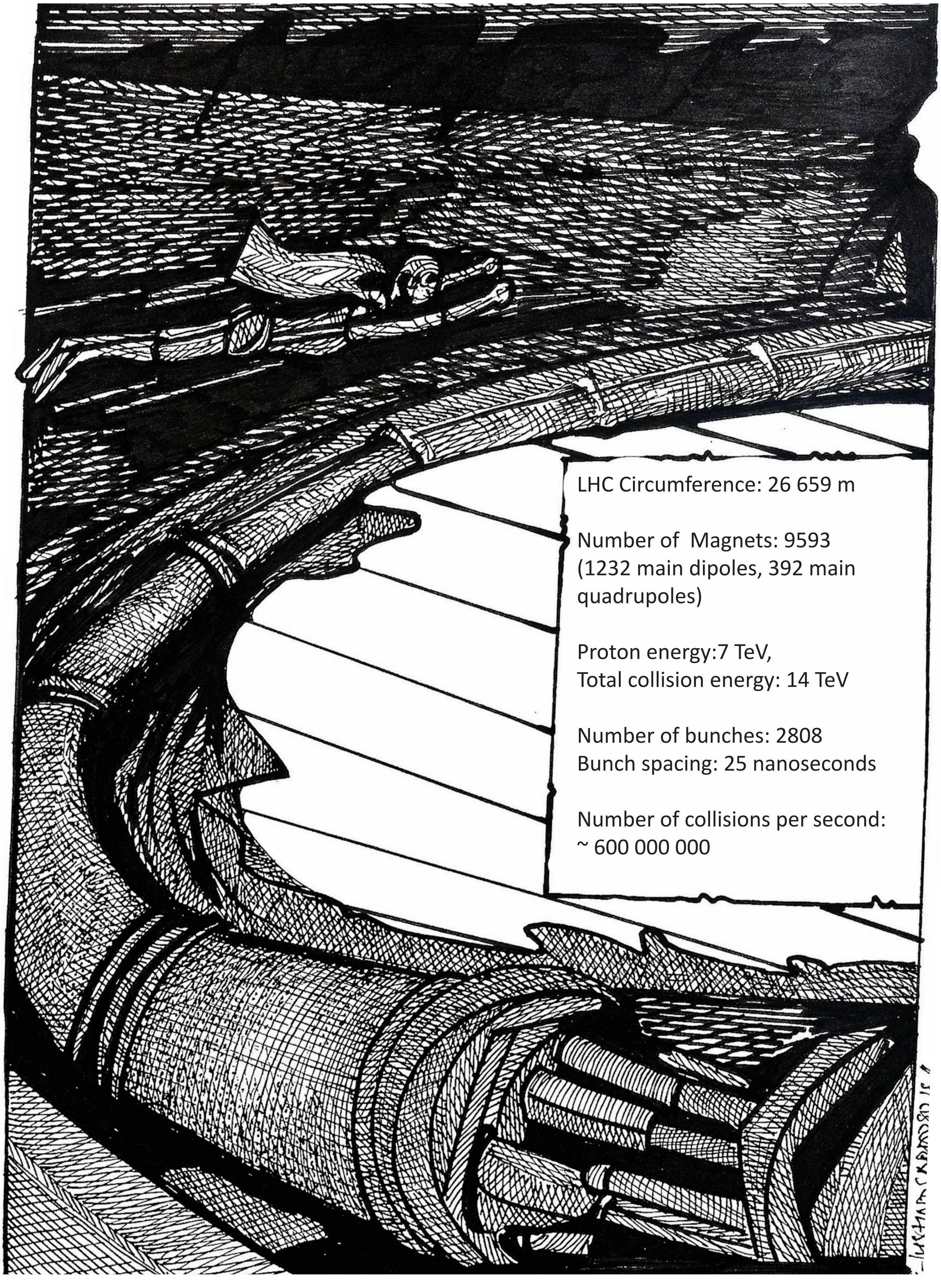
“Congetture circolari” Angelo Falciano 2011, *Acrylic on masonite*

In the accelerator a race of particles: going from the known to the unknown.

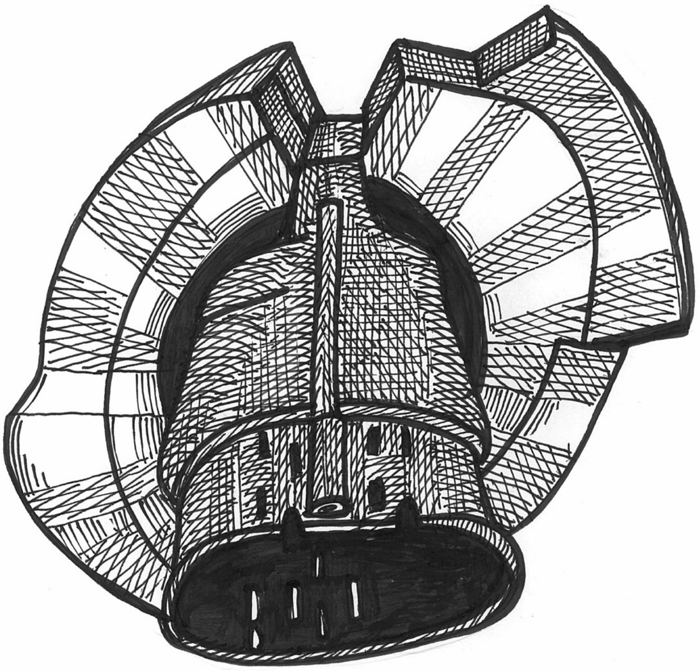


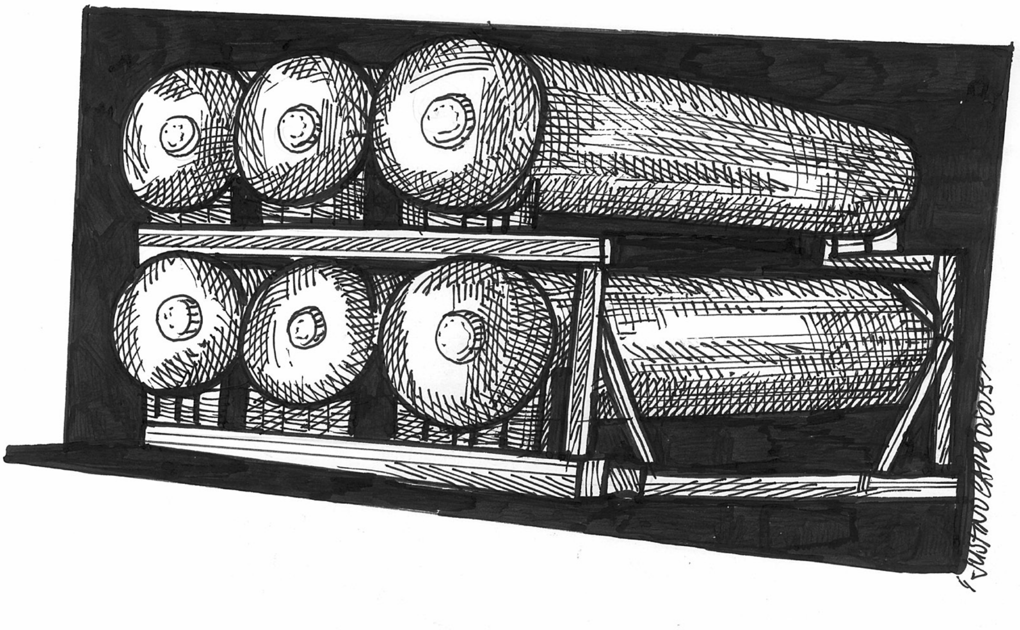
“CERN’s accelerator complex” Justino António Cardoso 2015, *colour Indian Ink*
(from OPEN-PHO-CHART-2013-001-1, Photograph: Marcastel, Fabienne)

The LHC chain includes Linac2, the PSB (PS Booster), the PS (proton synchrotron) and the SPS (Super PS) that is connected to the LHC via the long TI2 and TI8 transfer tunnels.



“Energetic protons in a circular collider” Justino António Cardoso 2015, *Indian Ink*





“Superconducting coils of an LHC magnet and vacuum beam pipe” Justino António Cardoso 2015, *Indian Ink*

“Tanks of liquid helium to cool LHC” Justino António Cardoso 2015, *Indian Ink*

An enabling technology: superconductivity

The quest for higher and higher energy cannot be satisfied only by making things bigger: there is a limit to the size of an accelerator. One way to limit size is to increase the magnetic field, since higher field equates to higher energy. Thanks to the fact that in a superconductor the electric resistance is zero, superconducting cables allow enormous current without any energy dissipation, and higher current equates to higher field. In the LHC we feed our magnets with currents of 12,000 A without generating any heat in the coil. Thanks to this, the LHC magnets are five times more powerful than the magnets of accelerators using conventional technology. The superconducting heart of the LHC is its 300,000 km of one-millimetre thick superconducting wire, a composite made up of a matrix of very pure copper in which thousands of fine filaments of precious niobium-titanium, Nb-Ti, alloy give rise to superconductivity: there are 2100 million km of superconducting filaments in the LHC magnets, enough to go to the Sun and back seven times!

This wonder comes at the cost of an extreme technological challenge: the superconducting Nb-Ti alloy used for LHC requires the astonishingly low temperature of -271 °C, a temperature colder than outer space, which is reached thanks to superfluid helium. The LHC is the world's largest cryogenic facility, and its enormous fridges consume about 50 MW. This is not a small figure. However, an LHC without superconductivity, with classical magnet technology would have required a 100-120 km ring, with electrical consumption of about 1000 MW, the power delivered by a fairly good size nuclear plant. Superconductivity has without a doubt been a good investment, from technological, economic and environmental points of view!

Modern physics at work

1-Relativity

An interesting feature of accelerators is the macroscopic manifestation of strange modern physics effects. The fact that we push particles very close to the speed of light means that we see things foreseen by Einstein at macroscopic scales. Particles approaching the speed of light in CERN accelerators accelerate less and less the quicker they go. Their speed saturates at the velocity of light and instead they start to increase in mass, or precisely speaking: momentum. We detect this effect very easily, because if we did not take the necessary countermeasures we would lose the particles. As their mass increases, they would shift out of orbit because speed, mass and field are finely synchronised. This rapidly became apparent to the inventor of the first circular accelerators, Ernest O Lawrence, as soon as he started building cyclotrons in the 1930s. Another interesting effect is the fact that when unstable, short lived, particles are accelerated, their lifetime is extended, exactly as Einstein predicted in the theory of special relativity, published during his *Annus mirabilis* 1905.

2- Microscopes and Quantum Mechanics

Accelerators can be regarded as super-microscopes that allow us to peer into the world of the infinitesimally small. The resolution of a microscope, all technical limits and imperfections put aside, is limited by diffraction effects of the wavelength of the light employed. That is the reason that microscopes using visible light are limited to about 500 nanometers (nm). However, if we employ X-rays, electromagnetic waves of same nature as light but with much shorter wavelengths of 0.1-1 nm, we can visualize atoms, which are about that size. Quantum mechanics teaches us that particles behave like waves with wavelength $\lambda=hc/E$, where h is called the Planck constant, c is the speed of light and E the particle's energy. The higher the energy of the particle, the smaller its associated wavelength. By accelerating particles to 7 TeV, the LHC achieves a wavelength of 10^{-19} m, i.e. one billionth of the 0.1 nm accessible to electron microscopes. The LHC experiments investigate distance scales much smaller than atoms and atomic nuclei, shedding light on distances ten thousand times smaller than the proton itself! Because of this, the LHC brings us to the universe in its infancy, when it was no bigger than that, at about one thousandth of a billionth of a second after the Big Bang!

What future for HEP accelerators

Accelerators are not used only for **H**igh **E**nergy **P**hysics (HEP), thousands of accelerators are in use for industry and medicine and hundreds are used for applied researches, mainly synchrotron light sources. Only a few tens of accelerators are used for basic particle and nuclear research. However, particle physics is undoubtedly the main technological driver for innovation in the accelerator domain.

So, what is next step after the LHC? First there is the **H**igh **L**uminosity **LHC**, HL-LHC. This project, based on new superconducting magnets approximately 50% more powerful than those in use today at the LHC, is a new configuration of the LHC that will greatly increase the number of collisions. It will be rather like turning up the light in a dimly lit room, allowing us to see much better and discover details that would be otherwise hidden in the dark. HL-LHC, now under construction, will be installed in 2024-25 and then will run up to almost 2040.

In the meantime, a large network of laboratories and Institutions from all over the world is collaborating with CERN to study the new machines that will define the post-LHC/HL-LHC accelerator era.

Two giant projects are currently under consideration:

1. *An electron-antielectron linear collider*: two projects are competing in this area. One is called the **I**nternational **L**inear **C**ollider, ILC, and would be a 30 km long machine based on superconducting cavities, the other is called the **C**ompact **Li**near **C**ollider, CLIC, and is based on resistive RF cavities of high frequency (12 GHz), with millimetre beam aperture and nanometre alignment accuracy over its 50 km tunnel length. While ILC is limited to 0.5-1 TeV, CLIC could reach 3 TeV in the centre-of-mass, however with a very high electrical consumption (600 MW (no superconductivity!)
2. *A **F**uture **C**ircular **C**ollider* (FCC), based on a circular ring of 100 km, Here, by using powerful superconducting magnets, twice as powerful as the LHC magnets, proton-proton collisions at 100 TeV energy in the centre-of-mass can be envisaged. Reaching this unprecedented energy heavily depends on the development of new superconducting technology for accelerator magnets. FCC magnets must be double the strength of the LHC ones. Magnet technology development for the FCC has just started, building on HL-LHC results, the first step beyond LHC.

Which of these two projects will win the race? It's too early to say.

To prepare the next update of the European Strategy for Particle Physics for 2020, a process involving all main European Laboratories, CERN has launched a complete study of the FCC with 100 km tunnel including the assessment of the geology and civil engineering with the formidable problem of passing under Lake Geneva and various mountain chains. The end of this decade is the ideal time for decision-making, since the results of LHC Run 2 (2015-2018) will by then be available and it is not too early to prepare for the next generation of accelerators to come after 2040, since these projects have twenty year development cycles. Meanwhile we hope that the new technology currently being developed for the High Luminosity LHC will soon find practical applications, for example in the medical and renewable energy sectors.

"A look into the future" Justino António Cardoso 2015, *Indian Ink*

“Quarks” Margarita Cimadevila 2006, *Acrylic mixed technique on canvas*
www.cimadevila.tk/

In the traditional quark model, the strongly interacting particles (hadrons) aggregate in groups of twos and threes either from quark-antiquark pairs (mesons) or three quarks (baryons). Particles which cannot be classified within this scheme are called exotic four-quark and five-quark particles. In 2016 the LHCb experiment confirmed the 2015 discovery that quarks can combine into groups of five.

“Simon van der Meer and Carlo Rubbia celebrate their awarding of the Nobel Prize in 1984 with a toast at CERN” (CERN-PHOTO-8410523)
The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and Simon van der Meer “for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction”

“François Englert and Peter Higgs at CERN in 2012” Islam Mahmoud Sweity 2014, *Charcoal drawing (from a photo by Maximilian Brice/ CERN).*
The Nobel Prize in Physics 2013 was awarded to François Englert and Peter Higgs “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”

The physicists and the experiments

Ana Maria Henriques Correia and João Martins Correia

The little story that we are telling you is about CERN with its gigantic accelerators and huge detectors of particles, and how that infrastructure - unique in the world - brings ideas to practice in other fields of science while producing challenging engineering that is applied to daily life. Starting with the experiments at CERN's LHC; the biggest particle accelerator, which essentially collides particles at very (very!) high energy to break and fuse them together releasing the original bricks of matter. Using sophisticated machines and detectors, CERN recreates processes that occurred very early in the history of the Universe:

ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) and **CMS** (**C**ompact **M**uon **S**olenoid) are the two biggest of the four major experiments at the LHC. These are general-purpose particle physics experiments, which are designed to exploit the full discovery potential that the LHC provides. ATLAS is the largest volume detector ever constructed for a particle collider, a cylinder with dimensions 46 m long by 25 m in diameter, and weighing 7,000 tons, similar to the weight of the Eiffel Tower. ATLAS and sits inside a cavern 100m underground. By comparison the CMS detector is "only" 21 metres long and 15 metres in diameter. It is built around a huge solenoid magnet that generates a field of 4 tesla, about 100,000 times the magnetic field of the Earth. The field is confined by a steel yoke that forms the bulk of the detector's 14,000-tonne weight, twice that of the Eiffel Tower! The detectors themselves are many-layered instruments designed to detect some of the tiniest yet most energetic particles ever created on Earth. They consist of different subsystems wrapped concentrically in layers around the collision point to record the trajectory, momentum and energy of particles, allowing them to be individually identified and measured. Huge magnet systems bend the paths of the charged particles so that their momenta can be measured as precisely as possible.

Before being made to collide, the particle beams are stored in packets inside the 27 km LHC ring and accelerated to speeds approaching 99.999999% that of light. Then, from time to time, the trajectories of the particles are bent so the beams collide at the centre of the ATLAS and CMS detectors. When this happens some of the energy of the collision is turned into mass and previously unobserved, short-lived particles - which could give clues about how Nature behaves at a fundamental level - fly out in all directions into the detector. Over a billion particle interactions take place at the centre of the detectors every second, a data rate equivalent to 20 simultaneous telephone conversations held by every person on the Earth. Only one in a million collisions are flagged as potentially interesting and recorded for further study. On 4 July 2012, ATLAS and CMS were able to announce the discovery of the Higgs Boson at a rest mass energy of 126.5 GeV at a 4.9 sigma confidence level. Now, the LHC experiments are further analysing the properties and characteristics of the Higgs boson, exploring higher energy territories and Proton-Lead collision events. The Higgs bosons exist for less than a thousand of a billionth of a billionth of a second before decaying into lighter particles. But can exotic long-lived particles be found? These particles would rarely interact with ordinary matter and their existence would constitute a sign for physics beyond the Standard Model.

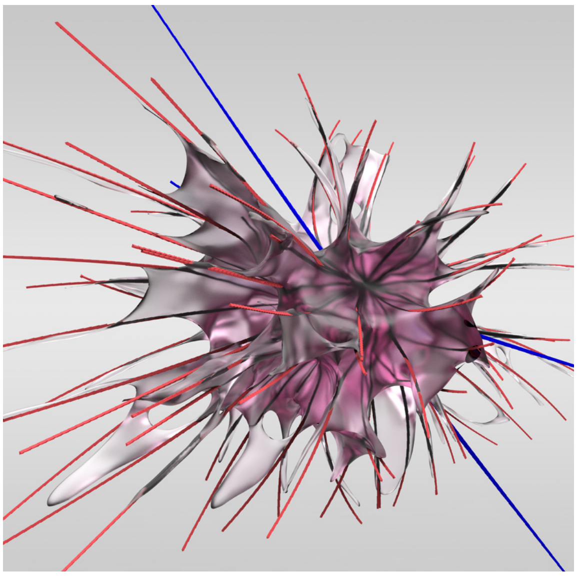
Of the other LHC experiments, **LHCb *(*L**arge **H**adron **C**ollider **b**eauty***)*** is studying what happened in the first seconds after the Big Bang when antimatter disappeared leaving only matter to build us, the world we live in and the Universe that surrounds us. Unsuspected by many of us, our world and every day existence is in fact a tremendous cosmic mystery! When antimatter and matter come into contact the result is dramatic. In the blink of an eye they both vanish, destroying one another and leaving behind a flash of energy. This explosive relationship raises some intriguing questions. For example, if matter and antimatter were created in equal quantities during the Big Bang, why do we find ourselves living in a Universe made only of matter? Could some unknown mechanism have stepped in to prevent matter and antimatter completely annihilating each other? LHCb has been set up to study the slight asymmetries between matter and antimatter using particles known as beauty

"ATLAS Remeshed-Higgs Boson" Davide Angheleddu 2016, *Glass fibres and acrylic fibres , 1.5 m L*

3 D Representation of candidate Higgs Boson kindly provided by ATLAS experiment. The Higgs Boson materialises as 2 muons and 2 electrons represented in blue. The sculpture is made in 3 steps:
1) from the simulation received using a remeshing computer graphic process, a remeshing algorithm is applied to the data to build a virtual model sculpture.
2) with laser sintering, a high precision nylon model is produced.
3) using the standard old lost-wax casting process, the final sculpture can be made with the selected material.

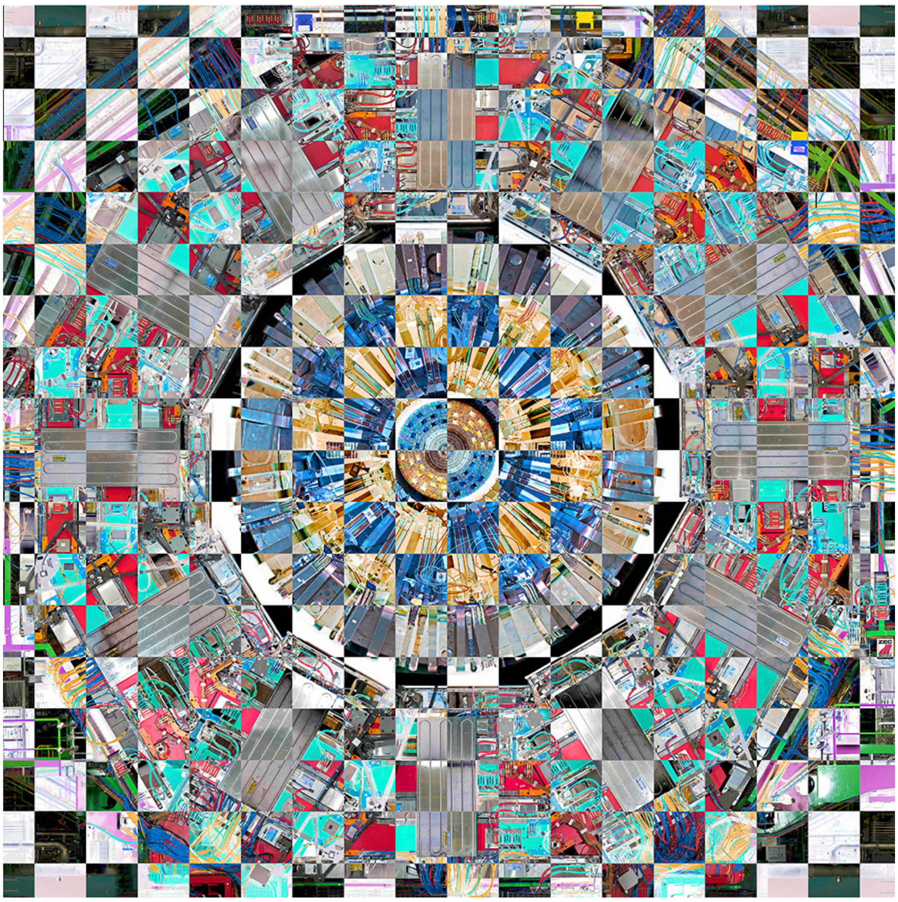
Presented in July 2016 at the exhibition "Extreme. In search of particles", designed and produced by the Museo Nazionale della Scienza e della Tecnologia Leonardo da Vinci in Milan, in partnership with CERN and INFN.

The sculpture and video showing the remeshing process has been presented at the Grunwald Art Gallery, Indiana University, Bloomington November 2016.



"ATLAS Remeshed-Higgs Boson"
Davide Angheleddu 2015
photoprint

www.davideangheleddu.weebly.com



“Matter-Anti-Matter, symmetry 4” Michael Hoch, 2012 *photo collage on Alu Dibond, 100 x 100 cm,* based on the CMS (Compact Muon Solenoid) detector.

CMS, a general-purpose LHC particle physics experiment, is the size of a six storey office building containing sensors that in some cases are no larger than the width of a human hair.

At the EPS-HEP 2017 Conference in Venice, Michael Hoch, art@CMS founder, received the 2017 Outreach prize from the High Energy and Particle Physics Division of the European Physical Society “for initiatives highlighting the conceptual and physical beauty of high-energy physics, and the inspirational qualities that are common to both Art and Science.” The committee acknowledged “Michael Hoch’s exceptional talent in bringing scientific thoughts to the mind of the general public.”

art@CMS is an educational and engagement programme of the CMS experiment at CERN’s Large Hadron Collider. It is a collaboration between the scientific High Energy Physics community, artists and art communities, Museums, art teachers and science teachers. The project began as an attempt to build bridges between the arts and sciences whilst projecting the voice and work of CMS and CERN to a broader audience.

It is comprised of two complementary modules:

- The art@CMS exhibitions with the aim to create a dialogue between the HEP science community and art communities produce and present art works of collaborating artists and facilitate group and individual exhibitions worldwide.

- SciArt Workshops (Science&Art@School): is an interdisciplinary workshop designed to introduce school, college and university art and science students to the scientific world of particle physics and fundamental research through artistic enquiry and cross disciplinary approach.

Acting as an ideas factory, art@CMS is built on a platform of learning and sharing.

https://artcms.web.cern.ch

quarks. Although absent from the Universe today, beauty quarks were common in the aftermath of the Big Bang and are generated in their billions inside LHCb along with their antimatter counterparts, anti-beauty quarks. By studying the slight difference in decay between the beauty quark and its antiparticle with unprecedented precision, LHCb is shedding light on one of the Universe's most fundamental mysteries. LHCb recently reported the observation of Ξcc^{++} (Xicc^{++}) a new particle containing two charm quarks and one up quark. The mass of the newly identified particle, a doubly heavy baryon, is about 3621 MeV, which is almost four times heavier than the proton.

ALICE ***(A L***arge **I**on **C**ollider **E**xperiment), another large LHC experiment is investigating the existence and properties of the melting of protons and neutrons when they liberate their constituent quarks and gluons under extreme conditions of temperature and density. This substance is called quark-gluon plasma, and among ALICE's goals is to understand how it is formed. Ordinary matter is made of atoms, each of which consists of a nucleus surrounded by a cloud of electrons. Nuclei are then made of protons and neutrons, which in turn are made of quarks. Quarks are bound together into protons and neutrons by a force known as the strong interaction, mediated by the exchange of particles called gluons. No quark, or gluon, has ever been observed in isolation: the quarks, as well as the gluons, seem to be bound permanently together and locked inside composite particles, such as protons and neutrons. This is known as confinement. Although much of the physics of the strong interaction is well understood, two very basic issues remain unresolved: the origin of confinement and the mechanism of the generation of mass. Protons and neutrons are known to be made of three quarks, but by adding together the masses of the three quarks one gets only about 1% of the proton or neutron mass. Where does the remaining 99% come from?

The current theory of the strong interaction, called quantum chromodynamics, predicts that at very high temperatures and very high densities, quarks and gluons should no longer be confined inside composite particles. Instead they should exist freely in a new state of matter: quark-gluon plasma. Such a transition should occur when the temperature exceeds a critical value estimated to be about 100,000 times hotter than the core of the Sun! Such temperatures have not existed in Nature since the birth of the Universe . By inducing head-on collisions of heavy nuclei such as the nuclei of lead atoms accelerated by the LHC to a speed close that of light, scientists are able to obtain – albeit in a tiny volume about the size of a nucleus, and for a fleetingly short instant – a drop of such primordial matter and observe it as it reverts to ordinary matter through expansion and cooling. ALICE physicists can then explore deep into the physics of confinement, to probe the generation of mass in strong interactions, and to get a glimpse of how matter behaved immediately after the Big Bang.

Furthermore, when protons meet head on in the LHC, the collisions provide a micro-laboratory to investigate many phenomena, including the protons themselves. This is the physics that the **TOTEM**, (**TOT**al cross section, **E**lastic scattering and diffraction dissociation **M**easurement at the LHC), experiment is especially designed to explore. By making precise measurements on particles that emerge from collisions very close to the direction of the LHC beams — the so-called forward direction - TOTEM probes physics that is not easily accessible to other LHC experiments. Among a range of studies, TOTEM is measuring the total probability, or cross-section, for proton–proton interactions. In a sense, this is a measure of the overall size that a proton presents as a target. The experiment is also investigating scattering phenomena analogous to the diffraction of light.

About twenty more different experimental facilities and projects benefit from the accelerated protons and CERN's technological expertise and innovation. These call on, for example, CERN's longstanding tradition in neutrino physics. CERN now hosts R&D facilities on detectors for future neutrino experiments around the world.

For many years, CERN has also pursued research on antimatter at the Antiproton Decelerator, **AD**, facility. Recently, an **E**xtra **L**ow **En**ergy **A**ntiproton, **ELENA**, ring was inaugurated to decelerate antiprotons delivered by the AD facility at 5.3 MeV to just 100KeV. Thanks to ELENA, physicists will not only be able to produce and trap antimatter atoms but also to study more accurately the funda-

mental properties and interactions of anti-hydrogen, antiprotonic helium and anti-hydrogen ions in free or in bound states in the quest to learn whether in a world fully made of antimatter would be 100% equal to our world, just like a mirror image.
In the North Hall of the SPS accelerator, the **NA64** experiment is searching for visible and invisible decays of dark photons, a hypothetical elementary particle, proposed as an electromagnetic force carrier for dark matter, using electrons beams. Meanwhile **CAST**, the **C**ERN **A**xion **S**olar **T**elescope. is trying to detect axions or chameleons, theoretical particles, which if they exist could be responsible for dark matter and dark energy. Together, these make up around 95% of the universe, and axions or chameleons could originate from the 16 million-degree plasma in the Sun's core.

"Chameleon a hypothetical scalar particle" Justino António Cardoso 2015, *Indian Ink*

Chameleon particles were proposed in 2003 by Justin Khoury and Amanda Weltman.

A quite different branch of research, smaller but noneltheless important, is carried out at the ISOLDE isotope mass separator, where about 50 experiments per year are performed. **ISOLDE** is a unique facility that produces on-line a panoply of radioactive nuclei using energetic protons from the CERN Booster accelerator colliding with and breaking apart target materials. In this way, ISOLDE plays the role of the stars, delivering exotic radioactive nuclei to researchers studying nuclear and atomic physics, solid states physics, materials and life sciences. ISOLDE has been recently upgraded in energy, post-accelerating the radioactive nuclei, exciting and recreating the reaction conditions of their synthesis in stars. One of CERN's oldest facilities, ISOLDE remains at the forefront of fundamental nuclear research and applications of unique radioactive nuclear techniques. Particularly dedicated to the optimization of cancer radiodiagnostics and therapy, the capabilities of ISOLDE are being extended with the construction of the **CERN-MEDICIS** facility. This is happening within the concept of the MEDICIS-PROMED collaboration, which will train a new generation of entrepreneurial scientists, bridging disciplines across fundamental research institutions, private companies and hospitals. This in turn will lead to the rapid application of new types of equipment in companies and to new radiopharmaceutical drugs used for cancer treatment in hospitals. This will be done using radioactive ion beams that have never been used to produce dedicated medical batches for radiopharmaceuticals. In 2017 the facility produced radioisotopes for medical research for the first time.

Last but not least, the experiment **CLOUD** (**C**osmics **L**eaving **Ou**tdoor **D**roplets) studies how cosmic rays, charged particles that bombard the Earth's atmosphere from outer space, may influence cloud cover either through the formation of new aerosols, tiny particles suspended in the air that can grow to form seeds for cloud droplets, or by directly affecting clouds themselves. Clouds exert a strong influence on the Earth's energy balance; changes of only a few per cent have an important effect on the climate. However, despite its importance for climate, aerosol formation is poorly understood. Measuring the underlying microphysics in controlled laboratory conditions is important for a better understanding of atmospheric aerosols and is the key to unravelling the possible connection between cosmic rays and clouds. The Proton Synchrotron provides an artificial source of cosmic rays that simulates natural atmospheric conditions from ground level to the stratosphere. A beam of particles is passed through the cloud chamber and its effects on aerosol production or on liquid or ice clouds inside the chamber are recorded and analysed.

Another sign of CERN's global use and utility is the LHC's computing infrastructure. Ever since the LHC's first colisions, data has been produced at the unprecedented rate of tens of petabytes per year (1pB = 1,000,000,000,000,000 Bytes, or about two thousand 500 GB PC hard-drives). This presented a major challenge, solved by deploying a grid-based computer network infrastructure connecting 140 computing centres in 35 countries by 2012. The resulting Worldwide LHC Computing Grid, WLCG, is the world's largest distributed computing grid today, comprising over 170 computing facilities in a worldwide network spanning 42 countries. The main mission of the WLCG project is to provide global computing resources to store, distribute and analyse the many Petabytes of data generated by the LHC. In 2017 12.3 petabytes were stored in just one month. But, the activities of the grid extend to many public projects including Civil Protection, Earth Sciences, Computational Chemistry, and Life Sciences providing computing for medical data management and analysis.

The only way to realize such challenging projects, with the required intellectual and financial resources, and to maximize scientific output is through large international collaborations with many thousands of people. The flagship of this approach is the universal nature of the experiments at the LHC, which have attracted participants of over 100 nationalities from all continents including Africa. Large project funds come in the form of investments from the funding agencies of participating countries. In, ATLAS and CMS, the largest experiments, contributions also come from CERN and some resources come from individual universities

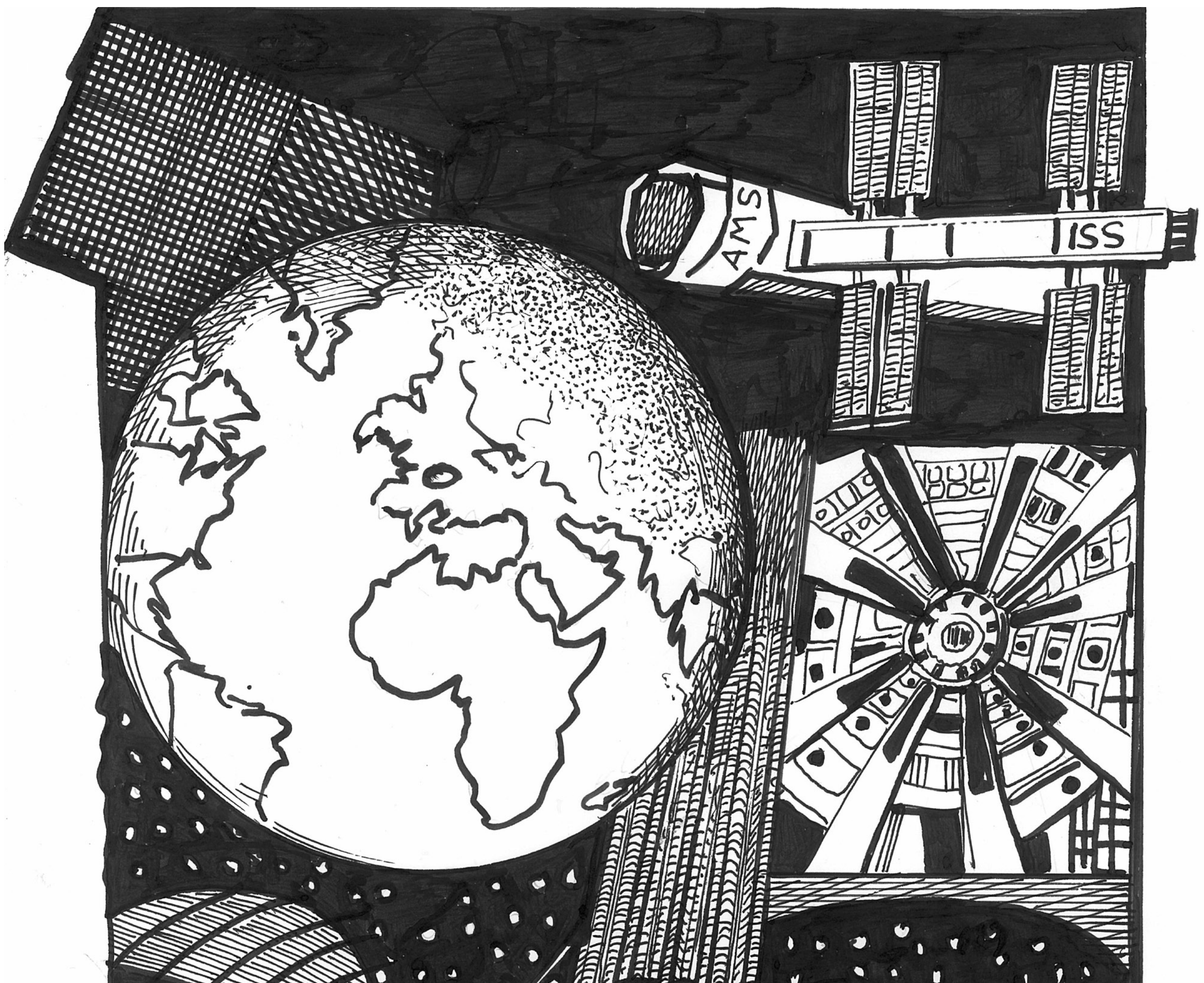
To make this work, ATLAS and CMS select their leadership with an organizational structure allowing teams to self-manage, and members to be directly involved in decision-making processes.

Scientists usually work in small groups, choosing the research areas and data that interest them most. Any output from the collaboration is shared by all members and is subject to rigorous review and fact-checking processes before results are made public. The success of the collaboration is, therefore, bound by individual commitment to physics and the prospect of exciting new results that can only be achieved with a complete and coherent collaborative effort of scientists, countless engineers, technicians and administrative staff.

While being a unique world of knowledge, diversity and complementarity contributing to academic development, education and outreach of the state of the art of science and technology, CERN is already looking to the future. While continually exploring ways to best use its existing research facilities, CERN is also leading the exploration of strategic concepts for future high-energy physics facilities. The Laboratory is also investigating future opportunities to diversify its research portfolio through the Physics Beyond Colliders Study Group. All this is necessary, since the Standard Model of particle physics cannot explain several observations, such as: evidence for dark matter, the prevalence of matter over antimatter and neutrino masses.

In the words of CERN Director general, Fabiola Gianotti, speaking in January 2017: *"We know there is new physics, we don't know where it is in terms of energy scale and/or couplings, but we need to be as broad as possible in our exploratory approach as scientific diversity is a must, by exploiting the unique capabilities of CERN's accelerator complex and infrastructure, being complementary to other efforts in the world and optimizing the resources of the field globally."*

Creativity and innovation are needed to develop the physics cases, meet the required accelerator parameters and realize unprecedented experiments. The significant leadtime of approximately twenty years for the design and construction of a large-scale accelerator calls for a coordinated effort. The goal is to ensure the seamless continuation of the world's particle physics programme after the LHC era. The LHC at CERN with its High Luminosity upgrade is the world's primary instrument for exploring the energy frontier in physics until at least 2035. This defines the time window for preparing a post-LHC high-energy physics research infrastructure.



"Accelerators and detectors to understand the Universe" Justino António Cardoso 2015, *Indian Ink*

CERN and Information Technology

Frédéric Hemmer

A look at the past

The history of computing at CERN goes back nearly to the very beginning of the Organization. The proposal to purchase an electronic computer was discussed as early as the 3rd meeting of the CERN Scientific Policy Committee in November 1955, chaired by a certain Werner Heisenberg, pioneer of quantum mechanics. The first computer installed at CERN was the Ferranti Mercury, which took two years to be built by Ferranti engineers. It was installed in summer 1958 and occupied the entire computer room. It had a clock cycle of 60 microseconds. Today's CPU (**C**entral **P**rocessing **U**nit) cores are hundreds of thousands of times faster!

The next significant step in CERN's computing history was the acquisition of the IBM 709, installed in 1961. This was still a vacuum tube machine, and was the first computer featuring FORTRAN (**For**mula **Tran**slation) as a programming language. The 709 was later upgraded to its transistorized version, the 7090. During the same period, mini computers started to appear, generally connected directly to the equipment in experimental halls, recording data onto tapes that were brought to the computer centre for analysis. By the end of the 60s, over 50 minis were scattered around the site.
It is remarkable to think that already at that time there were attempts to connect the central computers to the experimental zones through home grown network systems, intended to replace what was fondly referred to as the bicycle on-line method of transporting tapes to the computer centre for priority processing in order to obtain quick feedback to the experiments.

The same period saw the installation of the first CDC ((**C**ontrol **D**ata **C**orporation) machines, which took a long time to be commissioned, largely due to the lack of stable operating system. The beginning of the 70s was marked by the installation of the first time-sharing mainframe, the CDC 7600. Over the next 15 years, the 7600 was upgraded to various models of Cybers, while IBM systems (370/168, 3081, 3050, ES9000, etc.) were purchased or leased to complement the computing capacity needed for the experiments. A Cray XMP supercomputer eventually replaced the CDC machines in 1988. From 1982 onwards, the **D**igital **E**quipment **C**orporation (DEC), which had installed 100s of PDPs (**P**rogrammed **D**ata **P**rocessor) and VAXs (**V**irtual **A**dress e**X**tension) around the site, made its entrance to the CERN computer centre with central VAX-based services.

The beginning of the 90s saw the appearance of RISC work stations from Apollo, DEC, HP, SGI, SUN and others. These replaced the mainframes a few years later, as they offered orders of magnitude better price performance, not only for processor speed, but perhaps even more importantly, for disk storage. Slowly but surely, the number of computers in the CERN computer centre grew from a few 10s in the 70s to several hundred at the end of the 90s.

At the same time, Intel-based personal computer processing speeds became fast enough (200 MHz in 1997) to consider them for physics data processing, and commodity computing eventually took over the whole computer centre, which now consists of over 14 000 servers, 200 000 CPU cores and 200 PB on tape.

Towards the present

Computer networks

CERN started to develop computer communications as early as the 60s, developing several systems (FOCUS, OMNET, CERNET) before adopting the Ethernet industry standard that equips every office, accelerator and detector today, and running the TCP/IP protocol.

Over the years, the evolution of external networking has been a real game changer. At the beginning of the 80s, transfers were at the level of Kbps and only interconnected a handful of sites. In the 90s, capacities of several 100s of Mbps became available, and CERN even became the largest Internet exchange point in Europe, carrying 80% of the European Internet capacity. Nowadays, **H**igh **E**nergy **P**hysics (HEP) institutes are typically connected at gigabit per second speeds to CERN with some sites at multiple 100 gigabits per second. Computer network capacity is essential for the High Energy Physics community to work with CERN, or from CERN, without needing a physical presence. The LHC data is replicated worldwide 24x7 in other data centres so that there is always an up to date copy available.

The Web

It is of course impossible to talk about computing at CERN without mentioning the Web. Beyond Tim Berners-Lee's vision, it is the need of thousands of HEP scientists spread across the world, combined with the emergence of new technologies such as fast global internetworking with TCP/IP, and the advent of graphics workstations and later Macs & PCs accessible by everybody, that made the World Wide Web a global revolution.

The Grid

The Worldwide LHC Computing Grid (WLCG) is the largest scientific endeavour dedicated to sharing computing resources worldwide. The project began at the beginning of the century from initial ideas and implementations at Argonne and University of California Santa Cruz, with significant contributions from the European Commission and HEP institutes all over the world. It then grew in a robust and resilient distributed system scattered over 170 sites, making half a million cores and 500 petabytes of data available for LHC analysis, all interconnected with high speed links running at multi Gbps.

The WLCG now routinely processes half a million jobs simultaneously: quite an improvement compared to the single calculation that the Ferranti could swallow almost 60 years ago.

Data Preservation

The challenge over the last 50 years or so has been to be able to handle and process the data produced by accelerators and experiments. But what happens when the experiments end and the detectors are dismantled? Will data stay forever on tape? Are the 1960 FORTRAN programs still able to run and understand these data? Will people still understand what the program was doing and what assumptions the author took? This is where Data Preservation comes into play, and it remains for HEP an unsolved challenge. In my opinion, it is actually a much bigger, and highly underestimated problem going way beyond the realms of HEP. Are you sure you can still watch the movies of your kids taken on a digital camera 10 years ago? Are you still able to read the media they were stored on? Can you still read Word documents written in the mid-90s? Can you even still find them?

Open Access (Publications, Data & Code)

CERN is committed to Open Access, as it reflects values that have been enshrined in the Organization's Convention for more than sixty years and is becoming increasingly important for the CERN Member States, the European Commission and other institutional partners across the world. For over twenty years, most of CERN's physics publications have been made immediately and openly accessible online, in the form of CERN preprints, before publication in journals. This is generally known as Green Open Access.

Gold Open Access journals make peer-reviewed articles available to readers free of charge. Such journals are generally financed by a publishing fee for each article, known as the Article Processing Charge (APC). Up until 2013, the CERN Scientific Information Service covered such fees for certain journals centrally. Thanks to partnerships with most of the major publishing houses, articles by the LHC collaborations on experimental results have systematically been published as Gold Open Access since 2010. CERN authors are expected to publish all their results in Gold Open Access journals.

Several CERN technologies are being developed with open access in mind. Invenio is an open source software library management package benefitting from international contributions from collaborating institutes. Invenio is typically used for digital libraries. CERN, with co-funding from the European Commission, has also long invested in a free Open Data repository for use beyond the high-energy physics community: Zenodo.

Working with Industry: CERN openlab

The CERN openlab is a unique public-private partnership that accelerates the development of cutting-edge solutions for the worldwide LHC community and wider scientific research. Through CERN openlab, CERN collaborates with leading ICT companies and research institutes.

CERN openlab was created in 2001 and enters its sixth three-year phase in 2018. As in its fifth phase, It will continue to tackle ambitious challenges covering the most critical foreseeable needs of IT infrastructures in domains such as data acquisition, computing platforms, data storage architectures, compute provisioning and management, networks and communication, and data analytics. Within this framework, CERN provides access to its complex IT infrastructure and its engineering experience, in some cases even extended to collaborating institutes worldwide. Testing in CERN's demanding environment provides the ICT industry partners with valuable feedback on their products while allowing CERN to assess the merits of new technologies in their early stages of development for possible future use. This framework also offers a neutral ground for carrying out advanced R&D with more than one company.

Education

The CERN School of Computing lasts for two weeks every year and is a summer university providing a series of lectures and hands-on exercises, with an official CSC Diploma upon successful completion of the CSC exam (and often ECTS (**E**uropean **C**redits **T**ransfer **S**ystem)). It is open to postgraduate students and research workers, working at CERN or at external institutes, with a few years of experience in elementary particle physics, in computing or in related fields.

The participants come from worldwide laboratories and universities, even outside the particle physics community, generally attracted by the advanced topics that are taught. Attendance ranges from 60 to 80 students, with typically of 15 to 30 nationalities represented. Over the last 10 years, people of 60 nationalities have taken part. About 80% of the students come from European countries.

A look into the future

With the LHC's computing well on track, the WLCG collaboration is looking further into the future, already focusing on the two phases of upgrades planned for the LHC. The first phase (2019–2020) will see major upgrades of the ALICE and LHCb experiments, as well as increased luminosity of the LHC. The second phase, the **H**igh **L**uminosity **LHC** project (HL-LHC) currently scheduled for 2024–2025, will upgrade the LHC to a much higher luminosity and increase the precision of the substantially improved ATLAS and CMS detectors.

The requirements for data and computing will grow dramatically over this time, with rates of 500 PB/year expected for the HL-LHC. The needs for processing are expected to increase more than 10 times over and above what technology evolution is expected to provide. These are all significant and exciting challenges. It is clear that the LHC's computing will continue to evolve, and that in 10 years things will look very different, while retaining the features that enable and empower global collaboration.

On a longer-term perspective, computer specialists, physicists and engineers have also already started to work in close collaboration to assess the needs both in terms of power and of network for the ***F***uture **C**ircular **C**ollider (FCC) project. Such a large-scale project also requires specific managerial, financial and administrative planning. The solutions in many of the technical areas, computing included, from the installation controls to the data analysis solutions, are still to be developed.

Knowledge and technology transfer
Giovanni Anelli

To pursue its ambitious research goals, CERN has constantly to develop advanced instrumentation and innovative technological solutions, mainly in fields related to particle detectors, accelerator technologies and IT. These include many fields such as, for example, microelectronics, superconductivity, cryogenics, advanced materials.

These technologies, and most importantly the knowledge behind them, are key assets of the Organization, and it is of paramount importance that society at large is able to benefit from them.

For many years, CERN has been actively investigating possible applications of its innovation in fields other than High-Energy Physics, and has developed different tools to transfer its know-how and expertise to companies and other research institutions. Some examples of these tools are the CERN Open Hardware license, partnerships with industry, licenses, service and consultancy agreements, and a network of Business Incubation Centres in CERN's member states, to assist start-up companies adopting CERN technologies.

Knowledge transfer to industry also happens through procurement of high-tech components and through mobility of people: many students and young researchers who have worked at CERN at the beginning of their careers move to industry, profiting from the wealth of knowledge that they have acquired while working for the organization.

A strong relationhip with industry is vital for the Organization. CERN needs industry for its advanced instrumentation, and at the same time it helps industry developing new products and services, by being at the same time a customer and a provider of technologies and know-how.

Running the largest research infrastructure in the field of HEP, CERN has unique requirements and develops unique technologies. There are many examples of how the knowledge generated at CERN has impacted society, in fields as varied as advanced medical imaging, cancer treatment, dosimetry, aerospace applications, energy generation, data storage and data analysis.

On the following page is an example of a recent practical application in preclinical trial in hospitals: ClearPEM.

"A clinical application: ClearPEM"Justino António Cardoso 2015, *Indian Ink*

ClearPEM

João Varela

ClearPEM is a high spatial resolution (1.4 mm) and high specificity Positron Emission Mammography scanner developed by the Crystal Clear Collaboration at CERN to detect breast cancer lesions. It uses an imaging technique based in a positron-emitting radioisotope marked with a molecule that binds to cancer cells, which is injected in the blood flow. As the tracer concentrates in cancer lesions it is possible to reconstruct an image of its spatial distribution inside the body by detecting photon pairs that result from the annihilation of the positrons with electrons in the matter of the human body. The positron is the antiparticle of the electron and therefore when the two come close they annihilate creating two energetic photons emitted in opposite but random directions. In positron emission tomography, commonly known as PET, many of these events are recorded by external photon detectors allowing their emission directions to be reconstructed, and by using sophisticated algorithms to create a 3D image of the tumour. Almost one century after the discovery of antimatter, PET has emerged as a spectacular practical application of this weird form of matter.

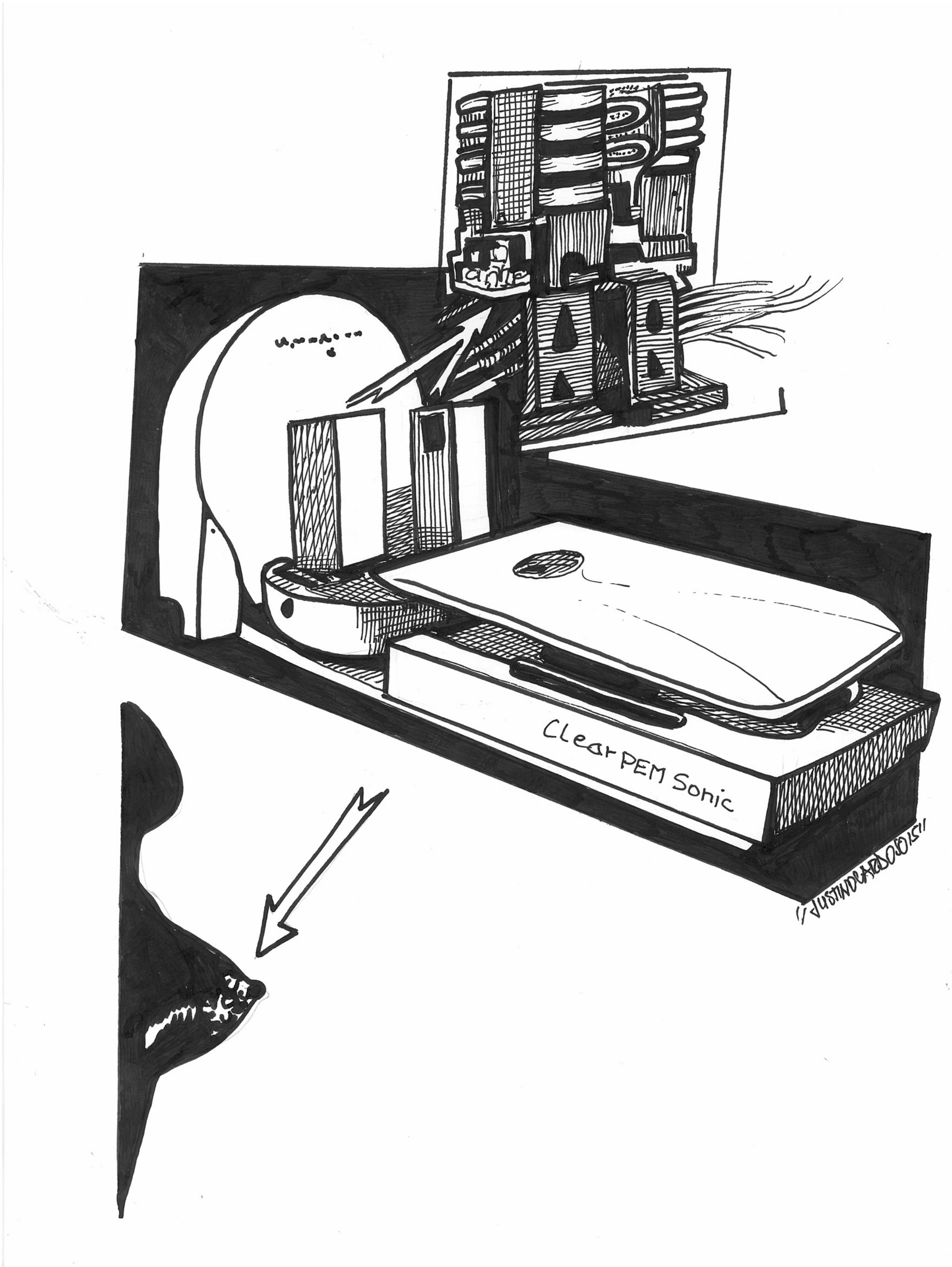
The ClearPEM scanner is the result of longstanding developments carried out on crystal detectors, photosensors and readout electronics for the CMS experiment at the LHC. A large photon detector known as ECAL (**E**lectromagnetic **Cal**orimeter) using about 80 thousand lead tungstate crystals, was built by the CMS collaboration and has been in operation since 2009 to measure photons produced in the proton collisions at the LHC with high precision. Photon pairs were expected to result from the decay of a new hypothetic particle, the Higgs boson, which was indeed discovered in 2012 through the observation of two-photon events among other signals. There is, nevertheless, a big difference between photons from Higgs decay and photons from positron-electron annihilation: they are one hundred thousand times more energetic! One important consequence is that the photon detector could be much smaller than the ECAL making it suitable for breast scanning

The knowledge and understanding acquired by the physicists prompted the creation of a consortium for using the new technologies in this important practical application. It allowed the conception and building of an instrumentation that comprises detector heads made of 6144 LYSO lutetium-based crystals of dimension of 2x2x20 mm to detect the photons emitted by the radioisotope accumulated in the lesion. For the first time, silicon photo-sensors developed for ECAL, avalanche photo-diodes (APD), have been used in a PET scanner to read the scintillating light generated in the crystals instead of traditional photo-multipliers. Associated with a new dedicated microchip, the APDs allowed very compact detector heads, that could be placed closely around the breast, to be built.

The system has high detection sensitivity allowing not only the location of the lesion(s) to be determined, but also their metabolic activity and therefore a more accurate evaluation of the extent of the disease and a better definition between benign and malignant lesions can be made. This is, of course, a determinant factor for the following treatment planning of the disease and patient outcome.

Two ClearPEM machines have been built. One is now installed at the University Hospital of Coimbra (ICNAS, **I**nstituto de **C**iências **N**ucleares **A**plicadas à **S**aude) and another is in operation at San Gerardo Hospital in Monza. The performance of the machines has been validated for patients with breast cancer diagnosed by the standard procedures and exams and following treatment. Comparison between images of the same patients produced by commercial PET scanners and by ClearPEM have shown the advantages of the high spatial resolution achieved by the latter. In a laboratory where physicists are studying the origin of our universe, trying to understand the asymmetry between matter and antimatter and to unveil the mystery of dark matter, a project like ClearPEM has stimulated our imagination.

This example illustrates how fundamental research in particle physics leads naturally to important breakthroughs in terms of innovation and technology transfer to the benefit of our daily lives.



"An innovative Technology" Justino António Cardoso 2015, *Indian Ink*

ClearPEM is a new type high resolution positron emission mammography scanner developed by the Crystal Clear Collaboration at CERN to detect breast cancer lesions. It is a practical application of different types of technological developments made for the CMS experiment at LHC.

ARTSCI at CERN

Arthur I. Miller

CERN is a world leader in research into the arcane world of elementary particles. It is also a prime site for the burgeoning field of artsci, in which artists and scientists work together to produce new ways of representing the universe in which we live. This began around 2000 when the London artist Ken McMullen brought a coterie of established european artists to CERN. The artists visited CERN for brief periods then returned to their studios to work on ideas inspired by conversations with CERN scientists. The resulting show, *Signatures of the Invisible*, included paintings and sculptures. It opened in 2001 at London's Atlantis Gallery to great acclaim, and went on to appear in Stockholm, Lisbon, Paris and the MOMA PS1 in New York, to name a few.

In the ensuing years, CERN continued to be in the news. In 2009, Dan Brown's blockbuster novel, *Angels and Demons*, awash with secret societies, symbolism and the unique addition of an antimatter bomb manufactured at CERN, was partly set there. CERN made it abundantly clear that both the story and the bomb were pure fiction. Shortly afterwards, Robert Harris based his thriller Fear Index on a scientist that had previously worked at CERN.

But in terms of advancing art at CERN, the most important event of 2009 was the arrival of Ariane Koek, a London producer of cultural programmes at the BBC, who kickstarted an arts residency programme. She called it *Collide@CERN* (Collide at CERN), funded in part by Ars Electronica, based in Linz, Austria.

The artist in residence was chosen in a formal competition to spend two months in residence at CERN and a month at Ars Electronica to develop a work inspired by CERN. This differed from McMullen's programme in which artists spent several brief periods of time at CERN but did their work in their own studios. At CERN the chosen artist paired off with a scientist by 'speed dating', the idea being to meet as many scientists as possible, each of whom would explain their work to the artist. Today this programme is run by the Spanish art critic and curator Monica Bello. The problem here is that the scientist is too often uncomfortable with the world of the artist and vice versa, more seriously the artist knows very little science.

Of the artists who have passed through the programme I would like to focus on the Japanese data visualisation artist Ryoji Ikeda. Data visualisation artists use algorithms to mine huge caches of data and represent it aesthetically. Like scientists they search for patterns because patterns in data are the DNA of nature. Data is CERN's business, its life-blood, and Ikeda lives and breathes in that world. His installations use real time computer programming to depict a huge amount of data with scintillating dots of light in variegated patterns with a hypnotic sound track. They are literally breathtaking, catching the excitement of data from the sub-microscopic world collected by mammoth detectors.

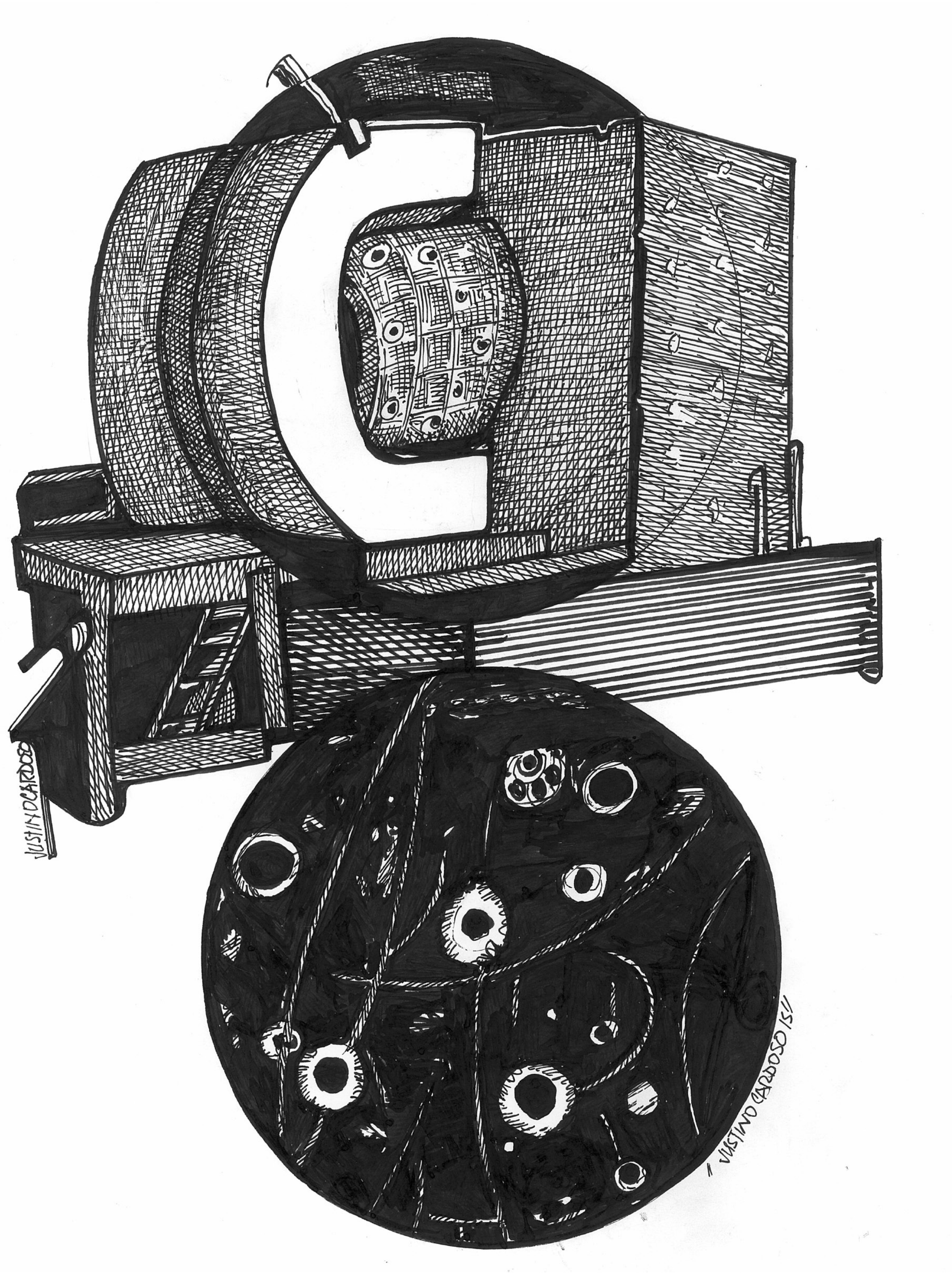
CERN has the cachet to attract top-rate artists who in my opinion should be invited and paid for their services with the understanding that they produce a work for display on site. Imagine that - an art gallery at CERN. Since research at CERN strives to make the invisible visible, artists who specialise in abstraction should be preferred, such as the established English artist Keith Tyson, winner of the prestigious 2002 Turner Prize. His work – paintings and sculptures - encompasses generative systems and embraces the complexity and interconnectedness of existence. So it is not surprising that the CERN Theory Group was much impressed with him when he paid CERN a visit. CERN's scientists are elite and should deal with top ranked artists who should be free to come and go as they please.

In my book *Colliding Worlds: How Cutting-Edge Science Has Redefined Contemporary Art**
I discuss the Collide@CERN programme in some detail. On the basis of over one hundred interviews with 21st century artists, it emerged that art, science and technology as we know them are disappearing, fusing into what I call a third culture, a new avant-garde. Its citizens are a new breed of artist - artist, scientist and technologist rolled into one. These hybrid creatures are to be found in

the exciting and much discussed field of art generated by artificial intelligence (AI). CERN should consider inviting this new breed of artist.

* for more information: www.arthurimiller.com/ and www.collidingworlds.org/ or a.miller@ucl.ac.uk

“Strings at the horizon of a black hole” Karen Panman 2014, *Painted pottery and plastic strings,*



“Gargamelle and the neutral currents” Justino António Cardoso 2015, *Indian Ink*

In July 1973, a groundbreaking discovery was announced in CERN's Main Auditorium by André Lagarrigue and his colleagues from the Gargamelle group. At the CERN proton synchrotron, PS, they had found evidence for neutral currents in Gargamelle bubble chamber pictures. The discovery confirmed the electroweak theory. Gargamelle, whose body now reposes in the Microcosm garden, was a huge bubble chamber weighing around 1000 tonnes, filled with 18 tonnes of liquid freon.

"The gravitation law I know" Justino António Cardoso 2015, *Indian Ink*

In 1687 Isaac Newton published in "Principia" the law of universal gravitation. Gravity is the weakest of the four fundamental interactions of nature. Extra dimensions could explain why gravity is so weak. With the Theory of Everything, physicists are on the quest for the unification of all the fundamental interactions of nature: gravitation, the strong interaction, the weak interaction, and electromagnetism.

Science, policy and society

Rolf Heuer

Progress is a complex beast, but one thing is for certain: it relies on the basic characteristic of human curiosity. Without that the human race we would still be in the Great Rift Valley. With it, we've mastered our world, are exploring others, have put ourselves in a position to contemplate the nature of our Universe, and we've made the lives of ordinary people unimaginably better.

Today, we live in an age where curiosity-driven science touches almost every aspect of our lives, yet science has been growing apart from society and culture for decades. This matters, because people are being called upon more and more to make science based decisions, and if the scientific community does not help equip them to do so, we as scientists are failing in our duty. If we scientists stay cloistered in our ivory towers, then we're simply not doing our job. This is one important responsibility of science: to help people make rational choices in their everyday lives.

For people such as me, working in publicly funded science, there is also a moral obligation to engage the public. At CERN, we do fundamental science. Our main deliverable is knowledge about the universe. Along the way, CERN scientists and engineers develop technologies that range from the World Wide Web to detectors for medical scanners, and from ultra-high vacuum techniques that have applications in solar energy collection to particle accelerators for cancer therapy. But it is knowledge that we're here for, and in my experience, the knowledge we deliver satisfies a basic human need to learn. Fundamental science feeds the mind. And let me just add, that the public who fund us have the right to know what we are doing, and to know that we are investing their money well.

At CERN, these responsibilities are taken seriously: we have leveraged the start-up of the world's most powerful particle accelerator, the Large Hadron Collider (LHC), to raise our profile and engage with broad range of audiences. From primary school children to decision makers, from artists to world religions we have started conversations that are making a difference.

This forms my first key message: it is vital, today more than ever, that science engages with society since we're all dependent on science, our future is dependent on science, and science has a moral obligation to engage.

My second key message is that it is equally vital that science be carried out not in isolation but in collaboration. This was recognised in Europe after the Second World War by a small group of visionary scientists and visionary diplomats who combined science and education to create a resonance that would change forever the way cross-border science is done. On the 29th of September 1954, that resonance became CERN, and a blueprint for long-term, international collaboration in science was established.

CERN's founding fathers created a stable system for the public sector to sustain basic science. Since then, the world has seen economic highs and lows, but basic science has always been performed at CERN. If all basic science could be done on the CERN model: international, collaborative and open, with a stable public sector funding structure, our progress would be assured. And the world might become a little more recession proof than it is today.

CERN is a European organization, founded on principles of fairness to its members, and openness to the world. Accordingly, its governance model gives a fair voice to all member states, large and small. Its funding model allows member states to contribute according to their means. And its research model welcomes scientists from around the world who are able to contribute positively to the laboratory's research programmes. Through these basic principles, CERN provides a model of stability for cross-border collaboration in Europe, for coordinated European engagement with the rest of the world, and a blueprint for leadership in the field of particle physics. The result is that today, CERN is undisputedly the hub of a global community of scientists advancing the frontiers of knowledge. It is a shining example of what people can do when they work together.

Today, we have to deploy this model more broadly. Science is becoming more and more global, and particle physics is in the vanguard of this development. It was, therefore, quite natural that in 2010 CERN went beyond the boundaries of Europe, opening up the possibility of membership or associate membership to all states, independent of their geographical location.

Consequently, the CERN ideal of peace and understanding among nations, mediated through the universal language of science is visible around the globe. Along with that comes the joy of shared human curiosity, and the practical benefits of education, innovation and collaboration.

An institution like CERN can play a vital role in education. Let's start with the youngest of our stakeholders. Surveys of industry regularly show that there is a shortfall of science and engineering graduates. How do we address the problem? In my opinion: by enthusing the very young. When we surveyed local opinion of CERN in the Geneva region in 2009, the results came as no surprise. Our neighbours recognised the local economic impact of having a large intergovernmental organization on their doorstep, but they were wary of us. So we asked them how they'd like us to become better neighbours. Among the themes that emerged was bringing science into primary school classrooms.

We worked with the educational authorities in France and the Swiss Canton of Geneva, as well as with Geneva University, to design a research project for children. Simply put, classes get a sealed box, and by using scientific reasoning, helped along the way by a few clues, they have to work out what's inside without peeking. The project has been presented at conferences, translated into other languages, and deployed as far away as Mexico. It's too early to tell whether this will encourage more youngsters to turn to science, providing a supply of skilled people for industry, but even if all it does is encourage children not to lose their sense of curiosity, it will have been worthwhile.

Turning now to policy, to decision makers, here is my third key message: it is vital for the scientific community to better engage with political circles.

How many times have we seen politicians making the wrong decision as a result of bad scientific reasoning? With issues as important as climate change demanding urgent action, it is vital that those we entrust with making the decisions are able to evaluate the science well. That's why CERN has asked for and been granted permanent observer status at the UN where we have promoted an important message for the politicians: it's your job, as custodians of the public purse, to maintain a healthy basic science base. This, in fact, is precisely what Europe achieved over 60 years ago in founding CERN, and since then seven other world-leading European intergovernmental research organizations.

Working to ensure a scientifically literate governing class, and a healthy flow of science and engineering graduates may be seen as clear objectives for CERN, but what about other groups? The arts? Major world religions? During my mandate as Director-General of CERN, we launched an artist residency programme that has already seen some remarkable interactions between two apparently opposite ends of the cultural spectrum. What we're finding is that artists and scientists have a lot in common. They are both curious about the world they live in, and they are both highly creative. For example, when the Mozambican artist Justino Cardoso produced the works in this volume it was on his first visit outside Africa. He had never had any contact with physics or physicists before coming to CERN, and the collision of artistic and scientific creativity has produced some remarkable results, as I'm sure you'll agree.

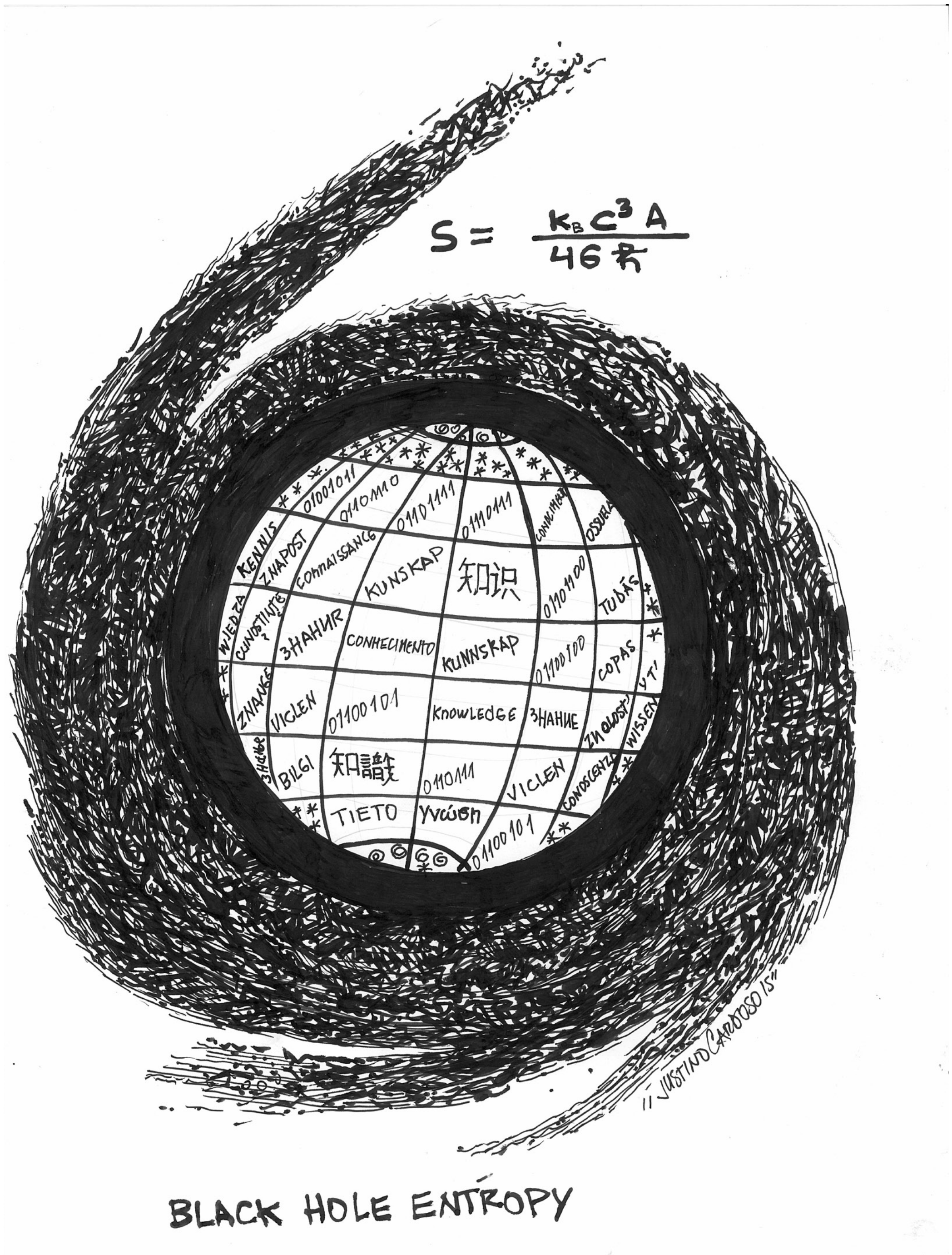
Engaging with the arts enables CERN to reach audiences that we would not otherwise be able to. When we stage a dance performance inspired by science at CERN, we bring in people who would not normally dream of setting foot inside a physics lab, and when we held a comedy night, to cite a slightly different point on the artistic scale, over half the audience told us they'd never been to CERN before. But they're likely to come again.

And here is my fourth key message: for science and for art you need an open atmosphere in society.

We need freedom and trust to perform, to think and to express. Both science and art need these things. Tim Berners-Lee, for instance, had the freedom and trust to develop something. That freedom was given to him by the institute he worked for, and what he did was every bit as creative as a work of art. He could have developed anything. What he did develop was the World Wide Web.

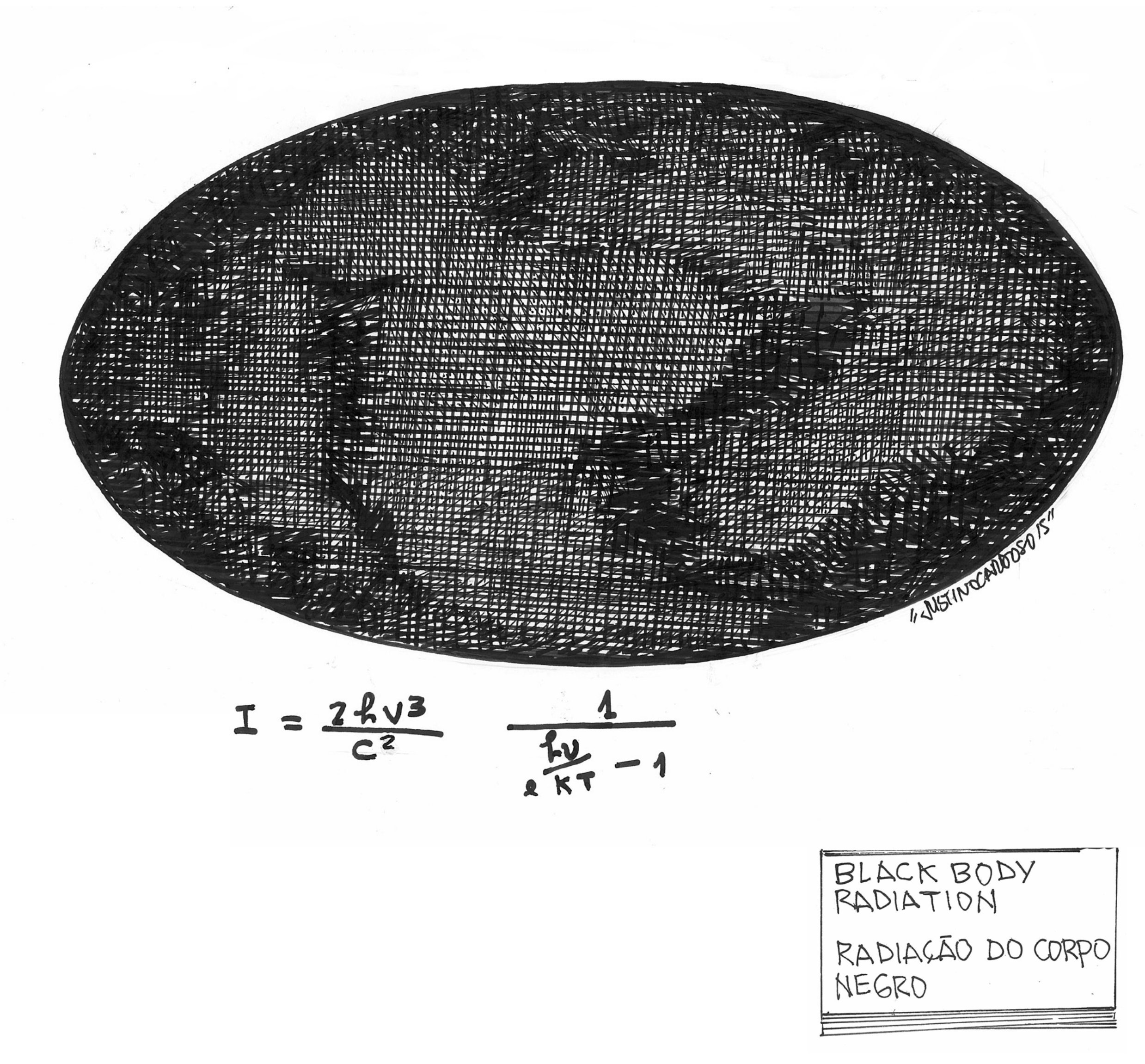
To conclude: science has a responsibility to bring itself to the mainstream of popular culture, to engage in and shape public debate about major issues that are science based. It has the responsibility to make itself accountable, particularly if it is public funded. And it has a duty to work to the highest possible ethical standards. Science underpins almost every aspect of modern life, be it economic, social, cultural or humanitarian, and it is blind to race, gender, language and religion.

In short, science represents the best in humanity.



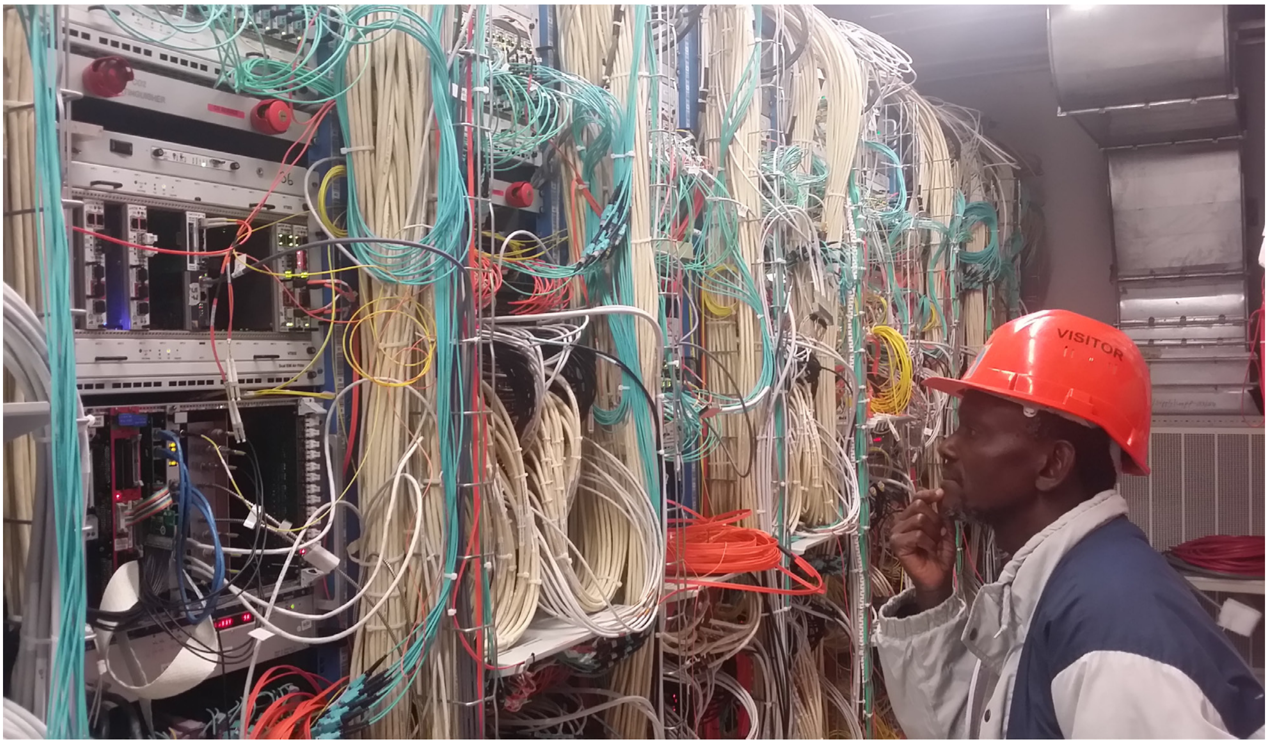
“Knowledge and black holes” Justino António Cardoso 2015, *Indian Ink*

According to physicists’ current understanding of black holes, information is lost when matter falls into a black hole. But is there some way this lost knowledge can be recovered? (caption from John Ellis)



"Cosmic microwave background" Justino António Cardoso 2015, *Indian Ink*

The Universe is filled with a microwave background emitted when the Universe was very young: irregularities in this radiation map the origins of the structures in the Universe.(caption from John Ellis)



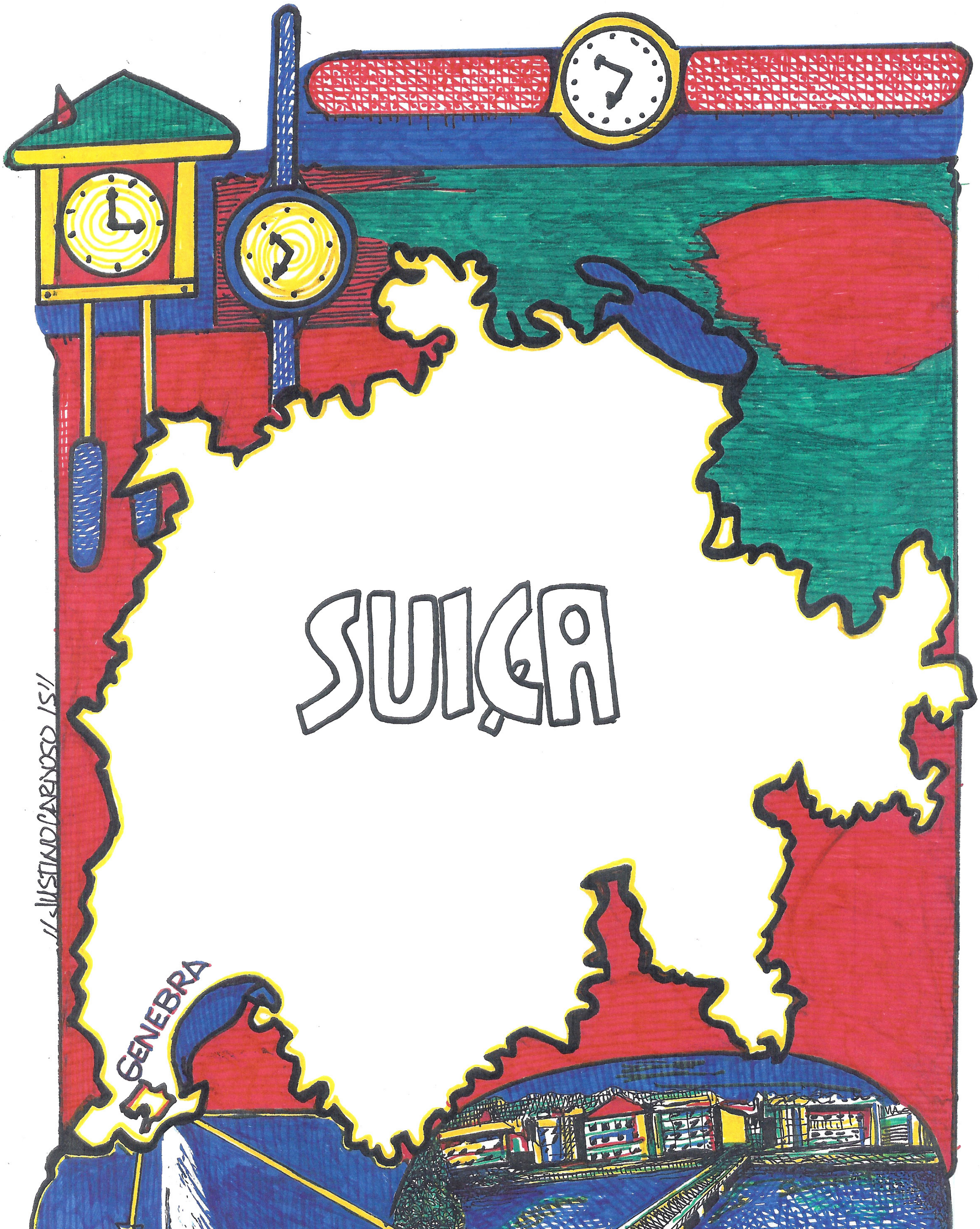
Justino António Cardoso visiting the CMS experiment (photo : José Carlos Rasteiro Da Silva)

Justino António Cardoso at CERN with Sergio Bertolucci and Marilena Streit-Bianchi
(Photo: Bettina Hamoudi)

Justino António Cardoso at CERN with John Ellis (Photo: Marilena Streit-Bianchi)

Justino António Cardoso at CERN with João Penedones Fernandes (Photo Marilena Streit-Bianchi)

Justino António Cardoso at CERN. On his right, Jack Steinberger, Nobel Prize in Physics 1988 with Leon Lederman and Melvin Schwartz, and on his left, Jean Michel Laurent physicist of the CAST collaboration (Photo Marilena Streit-Bianchi)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