Briefing 12

# Large particle accelerators

February 2019

*Ring segment of a particle accelerator*
*© fotonat67 / Adobe Stock*

## Summary

- *Particle accelerators, like other kinds of "very large research infrastructure" (VLRI), make it possible to manage cutting-edge projects and respond to strategic issues: acquiring knowledge, enhancing scientific attractiveness, preparing for technological breakthroughs, scientific diplomacy, etc.*
- *CERN, the European particle physics laboratory, currently operates the biggest circular particle accelerator in the world, the LHC, which achieves the highest energies produced to date.*
- *A decision by the Japanese government is expected shortly on the linear accelerator project, the ILC, proposed since 2012 by this country's scientific community.*
- *Thinking on the future European strategy for particle physics began in 2018 and should be presented in spring 2020. If the Japanese government confirms its interest in ILC, this European strategy must take account of this fact: a possible contribution from Europe, and particularly France, must be assessed in terms of scientific return, cost and industrial benefits.*

Mr. Cédric Villani, MP (National Assembly), First Vice-Chairman

In the course of 2019, several large research infrastructure projects in the field of particle physics will be under consideration in Europe and Asia. Their strategic importance, very high unit cost and different scientific goals justify special attention being paid to them.

### The "standard model" in particle physics

Each atom of matter is made up of a nucleus surrounded by electrons, the nucleus itself being comprised of protons and neutrons.(1) Electrons, protons and neutrons have long been considered the most elementary components of matter. This idea was overturned by the concept of the quark, which appeared in theory in the 1960s and was demonstrated by experiments conducted in the 1970s. Protons and neutrons are now known to be a combination of three quarks, either up or down*(2)*. **The electron and up and down quarks thus constitute the basic building blocks of ordinary matter.** A fourth fundamental particle was first postulated in 1930 and discovered in 1956: the neutrino, an electrically-neutral particle, which fascinates by its very low mass and near-zero interactions with matter.(3) Finally, agreement has been reached on the identification of twelve fundamental particles comprising matter, or "fermions": six quarks(4) and six leptons (electron, muon and tau as well as three types of neutrinos that are respectively associated with them). Particles comprised of quarks, like the proton, are known as "hadrons". Interactions between fermions, also called fundamental forces, are transmitted via the exchange of another type of particles, "bosons".(5) The "standard model"(6) of particle physics is quantum and relativity theory,(7) which categorises all these particles and describes their interactions.(8) Finalised in the 1970s, this model is the fruit of a century of theoretical and experimental research(9) punctuated by numerous Nobel prizes for physics.

### Particle accelerators as a tool for exploring matter

**Particle accelerators have been designed to explore matter via very high energy states** that make it possible to break down particles into their constituent elements (like a locked suitcase that is blown up to find out information on its content) and create new particles (similar to the creation of matter which, according to the now well-accepted Big Bang theory, occurred under conditions of considerable energy). **Their principle is to accelerate certain particles to an extreme speed (close to the speed of light) and then get them to collide.**

Accelerating particles requires three elements:

– an electric field to provide energy;

– a magnetic field to guide trajectory;

– finally, a high vacuum, in order to avoid collisions with residual gas, that would lead to rapid loss of particles.

The first accelerators were developed in the 1930s and are called cyclotrons.(10) Their technology was perfected after the Second World War: if the magnetic field is varied according to the energy of the accelerated particles, their trajectory becomes circular. These accelerators ("synchrotron" type) found a vast range of uses in the form of synchrotrons and colliders.(11) The goal of synchrotrons is no longer so much to explore particle physics as to produce high-intensity and highly-coherent, highly-controlled radiation (generally X-rays) used in diverse fields of study: biology, chemistry, astrophysics and archaeology, etc. Colliders, meanwhile, are still used to explore matter by analysing the products of collisions between particles. **Unequally spread across the globe**, these resources constitute key assets for scientific knowledge and outreach, attracting skills and collaborations.

### The LHC: an emblematic particle physics accelerator

In 1952, **the European Organization for Nuclear Research (CERN)** was created by twelve Member States.(12) In the aftermath of the Second World War, the aim was to re-establish relationships of trust and also to plug the brain drain to the United States and place Europe at the forefront of fundamental physics research, which was limited, at the time, to the scale of the atomic nucleus (i.e. nuclear). Since then, CERN has grown in the subjects it has studied to cover the full range of particle physics, and also in its governance, in that it is managed today by a consortium of twenty-two Member States(13) and welcomes researchers of all nationalities. Based in Geneva, it is a model of very large infrastructure that was made possible only by pooling investments.

**The most famous component of CERN is the Large Hadron Collider or LHC.** One hundred metres underground on the French-Swiss border, with a circumference of 27km and equipped with 9,500 magnets, some superconducting, it makes it possible to accelerate protons to an energy in the order of ten thousand times their energy at rest. Protons race around the LHC at a speed very "close" to the speed of light.[14] To do so, new technologies were developed, particularly specially-created superconducting magnets.(15) Two beams of protons, or other particles as the case may be, are accelerated in opposite directions, before colliding.(16)

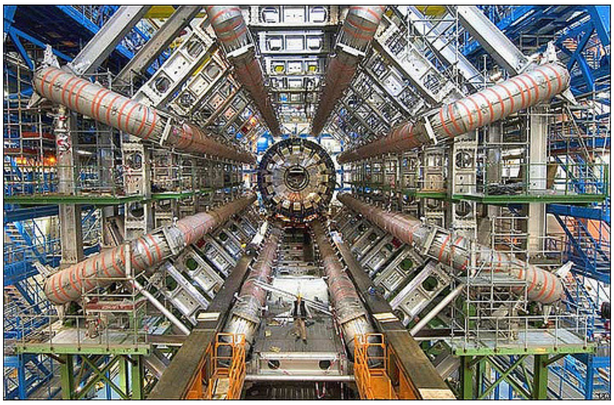

**FIGURE 1. THE ATLAS EXPERIMENT AT THE LHC, WHICH MADE IT POSSIBLE TO DETECT THE HIGGS BOSON (source: CERN)**

Since its commissioning, CERN has made history several times. In science, via the discovery, at the start of the 1980s, **of the W and Z bosons**,(17) leading to the award of the 1984 Nobel prize for physics to Carlo Rubbia and Simon Van der Meer. Then, the detection in 2012 **of the Higgs boson**,(18) which confirmed the standard model and won François Englert and Peter Higgs the 2013 Nobel prize. To detect the trace of the Higgs boson with certainty, it was necessary to cause protons to collide with considerable energy of 6.5TeV(19) and analyse the gigantic masses of data produced by these collisions using powerful statistical tools.(20)

#### CERN's LHC in numbers

The LHC cost approximately €8 billion and took 15 years to build. The first beam of particles was produced in 2008. In 2015, the LHC achieved energy of 13TeV. Every year, it consumes 1.3TWh of electrical energy (origin: France) and has an annual budget of €880 million. These impressive figures compare with France's annual electrical production of 500TWh. On the European scale, this budget is equivalent to the price "of one cappuccino per person" according to Fabiola Gianotti, director of CERN since 2016, who adds that "each Swiss franc or euro invested by its two host countries, Switzerland and France, brings in between two and six, in different forms."(*) CERN has approximately 3,000 permanent employees from every continent, and collaborates with 13,000 scientists of 110 different nationalities, conducting research in the name of hundreds of institutions.

(*) https://www.tdg.ch/savoirs/sciences/cern-besoin-argent-physique-demain/story/15943865

CERN has also had a very strong societal impact via **the creation of the *World Wide Web* (WWW)** in 1989(21) under the leadership of Tim Berners-Lee and his collaborator Roger Cailliau. It was originally a response to researchers' need to exchange a high volume of data simply and instantaneously for international collaborations. CERN published software developed under a public domain license, in accordance with its founding agreement(22) that specifies that all its results must be published and made accessible.

### The Higgs boson

A boson is a particle exchanged between two elementary particles that is the physical manifestation of a force or interaction. In the 1960s, the theories that served as precursors to the standard model failed to explain the mass of the Z and W bosons, representing the weak interaction within atomic nuclei. To overcome this difficulty, Brout and Englert, on the one hand, and Higgs, on the other, proposed in 1964 the existence of a field present all across the Universe and that was hypothesized to be responsible for the mass associated to the particles. The Higgs boson was hypothesized to be the physical manifestation of this field when it is disturbed.

To get a basic idea of the link between the Brout-Englert-Higgs field and the boson, you can imagine an aquarium filled with water. It is difficult to perceive the presence of water by the eye, but if the environment is disturbed (for example by hitting the sides), a wave forms and clearly demonstrates the presence of water. In this analogy, the field is the water and the boson the wave, which makes it possible to provide a mechanism for the generation of the mass of the elementary particles, an essential ingredient of the standard model. The study of its properties offers a unique opportunity, firstly, to research new phenomena and, secondly, to potentially open a window on the beginnings of the Universe.

## Beyond the standard model: new physics

Thanks to the discovery of the Higgs boson, the standard model now appears to be a solid foundation on which particle physics is based. However, according to latest estimates, **the standard model takes account of only 5% of the observable Universe**,(23) the rest consisting of approximately 27% dark matter and 68% dark energy which, at the current time, can be detected only indirectly.(24) This “grey area” requires the development of a theory that is more exhaustive and more fundamental than the standard model, which accordingly appears to be an initial approximation of a description of matter. It is in this search for a new theory that particle accelerators, and their ever higher energies, can give some answers(25) by confirming or disproving certain emerging theories.(26)

## Destination: linear accelerators

**Circular accelerators**, which are actually made out of a succession of a number of straight portions, require deceleration/acceleration cycles; this limits achievable energy, because the braking of a charged particle produces photons via **braking radiation** (in German ***Bremsstrahlung***).(27) This effect is much stronger for electrons, which is why the very high energy collisions in the LHC are collisions between protons. When the LHC’s tunnel housed the **LEP (*Large electron positron ring*)** programme of electron/positron(28) ($e^+/e^-$) collisions, these collisions could only be at lower energy.(29)

To exceed these limitations and transfer very high energies to electrons, **completely linear accelerators** are being developed, avoiding *Bremsstrahlung* in the acceleration phase. This is the principle of the experimental linear electron accelerator built in Hamburg (Germany): **E-XFEL (*European X-ray free-electron laser*)**. At a total cost of €1.2 billion, it makes it possible to accelerate electrons on a single linear branch, up to 17.5GeV over a total length of 3.4km.(30) Imitating the behaviour of a laser, it makes the beam of electrons oscillate in magnetic structures, causing pulsed emissions of very high intensity X-rays. Its excellent results mean linear systems can now be deemed to have been mastered.

## The ILC project in Japan

In 2012, a project was proposed to the Japanese Ministry of Education, Culture, Sport, Science and Technology (MEXT), by an international consortium of researchers.(31)

Prepared since the end of the 1980s, this project concerns the **creation of a large international linear accelerator (International Linear Collider or ILC) enabling $e^+/e^-$ collisions** with very high energy (500GeV, 15km, approx. €8 billion). Its Technical Design Report (TDR)(32) was published in 2013, which makes it the most advanced of the different large linear collider projects worldwide.

In 2016, Japan was considering financing part of the project, provided the total cost was reduced by one third, i.e. a total cost of €5 to 6 billion. This budget compromise accordingly limited **the collider’s energy to 250GeV: insufficient to explore the physics of ultra-high energies, but sufficient to take precision measurements on the Higgs boson via $e^+/e^-$ collisions with much lower background noise than the LHC’s p/p collisions**. N.B. it would still be possible to increase the energy in a subsequent phase by extending the acceleration branches.

The project includes a facility in the Tohoku region in the north-east of the main island of Honshu, still seriously affected by the 2011 earthquake. This earthquake was responsible for the Fukushima nuclear accident. This location raises the question of the impact of a possible earthquake. In view of the costs incurred by the facilities and the energy required, this is a key issue on which advance security and research work has been carried out. Japan would take charge of the civil engineering operations and the production of various high-tech structures in which it has recognised expertise. Other infrastructure (cryomodules, superconducting cavities, etc.) would rely on international financing. **Current discussions concern contributions in kind by Europe and the United State of €1 billion each, and an additional Asian contribution (China, South Korea, India)**.

The ILC's development has also contributed to the progress of parallel projects: the superconducting technology of the X-FEL electron beam's cavities and cryomodules is the direct result of the R&D done for the ILC and developed by European industry. The annual operating budget would amount to an additional €300 million. The ILC's feasibility will particularly depend on the decision by Japan, which could be announced in March 2019,(33) and European countries, which included it on the list of high-priority projects in the 2013-2020 European strategy.(34) The two decisions are closely linked.

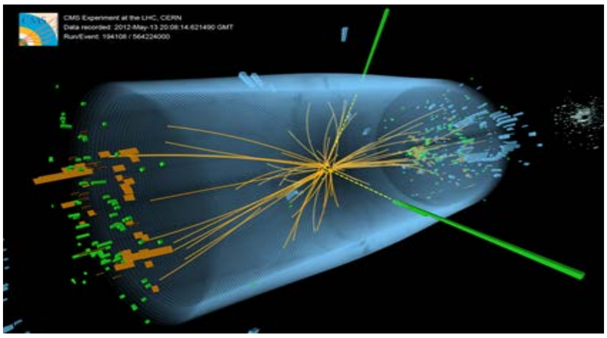

**FIGURE 2. SIMULATION OF A PARTICLE COLLISION IN THE CMS EXPERIMENT AT THE LHC (source: CERN)**

### Other medium- to long-term projects

The decision-making calendars for the Japanese government, on the one hand, and foreign investors, on the other, are not synchronised: though the former needs to make its decision on the ILC public in the first quarter of 2019, preparation of the European strategy, to which CERN contributes, has only just begun and will be made public only in 2020.

At CERN, the LHC is now shut down for building work. It will resume 14TeV activity in 2021-2023 before being shut down again in 2024-2025 and starting, in 2026, the "high luminosity" phase, i.e. with a higher number of collisions in a given time.(35)

CERN is also considering a high-energy circular collider, with the **FCC (Future circular collider) project** near the current site. It will have a circumference of 80 to 100km and could manage energy ten times higher than the LHC, achieving energies in the order of 300GeV for electrons and 150TeV for protons. It would host $e^+/e^-$ collisions from 2040 (at a total cost of €9 billion, including €5 billion to build the tunnel) and proton-proton collisions from around 2055 (at a cost of €15 billion). The Conceptual Design Report (CDR) was published in January 2019.(36)

Other CERN proposals are contained in the **CLIC (Compact Linear Collider)** project: the principle and functioning are similar to the ILC, but with higher energies. The CLIC would make it possible to exceed the energy of 1TeV, i.e. four times what the ILC announced in its currently-envisaged version, and twice what the ILC announced in its original version. This project would benefit from the facilities and know-how of CERN's local teams, accordingly making it possible to keep current particle physics expertise in Europe. However, it is more distant (commissioning certainly after 2050) and still hypothetical.

In China another major project is also being prepared, the **CepC (Circular electron positron Collider)**, possibly followed by the **CppC (Circular proton proton Collider)** project in direct competition with the European FCC.

All these projects(37) must be approached taking account of multiple aspects: scientific issues, attracting talent, technological benefits, financial constraints, scientific and technological diplomacy.

Furthermore, in the medium- and long-term, the paradigm of ever-bigger and more expensive particle accelerators to be more powerful, will undoubtedly be confronted with the emergence of new acceleration technologies currently still in development for limited energies, like very high-intensity lasers.(38) They could make it possible to build far smaller accelerators and find applications in different fields.

*OPECST websites:*
*http://www.assemblee-nationale.fr/commissions/opecst-index.asp*
*http://www.senat.fr/opecst/*

## *Endnotes*

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[1] In the periodic table of elements, drawn up by Mendeleev in 1869, the number of protons (equal to the number of electrons) defines the atom's chemical species.

[2] A proton consists of 2 up quarks and 1 down quark and a neutron 1 up quark and 2 down quarks.

[3] To give an order of magnitude, every square centimetre of our skin is criss-crossed, every second, by approximately one thousand billion ($10^{12}$) neutrinos, without the slightest interaction. At the current time, little is known about the three types of neutrinos (electron, muon and tau). One of the principal discoveries about them is their "oscillation", i.e. their ability to change type during their lifespan. This result made it possible to establish that at least two of them have non-zero mass.

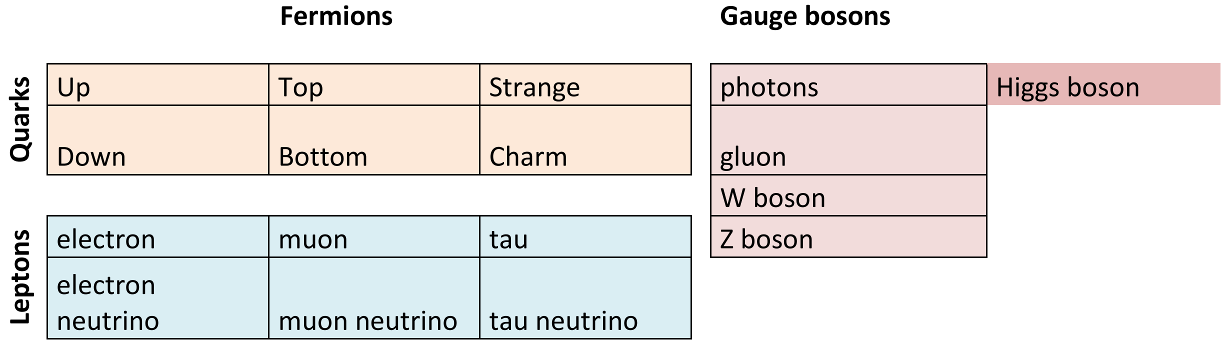
[4] Overall, there are 6 quarks, respectively called up, down, top, bottom, strange, and charm. Only the first two enter into the composition of ordinary matter and more specifically protons and neutrons.

[5] Bosons:

| Fundamental force | Corresponding boson | Characteristics |
|---|---|---|
| **Strong interaction** | Gluon | Acts on quarks to bind protons and neutrons |
| **Electromagnetism** | Photon | Between 2 charged particles |
| **Weak interaction** | W and Z bosons | Electroweak interaction mediators |
| **Gravity** | Graviton | Not yet discovered |

[6]

**THE STANDARD MODEL**



**Fermions**

| | | | |
|---|---|---|---|
| **Quarks** | Up | Top | Strange |
| | Down | Bottom | Charm |
| **Leptons** | electron | muon | tau |
| | electron neutrino | muon neutrino | tau neutrino |

**Gauge bosons**

| | |
|---|---|
| photons | Higgs boson |
| gluon | |
| W boson | |
| Z boson | |

[7] The term "relativistic regime" refers to when speed approaches the speed of light.

[8] Except for gravitation, which is covered by Einstein's theory of general relativity. Combining fundamental particle physics and gravitational theory into a single theory remains one of science's major open problems.

[9] This theory is based on a principle of symmetry, called "gauge principle", which categorises particles into three families of four (two quarks, one lepton, and one neutrino) and also categorises bosons. The principles of symmetry, crucial in fundamental physics, aim both to organise already-known particles, and as applicable predict new ones.

[10] Cyclotrons use a constant-intensity magnetic field combined with a variable electric field that forces the particles to adopt a spiral trajectory.

[11] Approximately 30,000 accelerators are used worldwide, including nearly 15,000 in the medical field (radiotherapy, research, production of radio-isotopes), 12,000 for treatment of materials, and 3,000 in industrial processes.
There are far fewer particle physics research accelerators worldwide:

*Source: IN2P3 (French Institute of Research into the Fundamental Laws of the Universe) (CNRS (National Centre for Scientific Research))*

In addition to CERN/LHC, there is: Fermilab (or *Fermi National Accelerator Laboratory)* in the United States (near Chicago and the previous biggest accelerator in the world before the LHC); in China, the *Institute of High Energy Physics* (IHEP) and the *Beijing Electron Positron Collider* (BEPC) operational since 2005; in Japan, the J-Parc (*Japan Proton Accelerator Research* Complex) and the SuperKEK-B. Finally in Frascati, in Italy, the Dafne synchrotron is also hosting electron/positron collision tests.

[12] The 12 historical CERN Member States: Belgium, Denmark, France, Greece, Italy, Norway, the Netherlands, the Federal Republic of Germany, the United Kingdom, Swede, Switzerland, and Yugoslavia.

[13] CERN then welcomed Austria, Spain, then Portugal, Finland, Poland, the Czechoslovak Republic, Hungary, Bulgaria, Israel, and Romania. The Czech Republic and Slovak Republic became two separate Member States in 1993, after their independence. Yugoslavia quit CERN in 1961. Outside the Member States, many other countries contribute to its activities, in a wide range of forms. Serbia, Cyprus, and Slovenia are Associate Member States in the pre-stage to membership. Turkey, Ukraine, Pakistan, Lithuania, and India are Associate Member States.

[14] Accelerated particles go approximately 10,000 times around the LHC every second, i.e. approximately 300,000km of distance travelled. More precisely, accelerated hadrons reach 99.999999% of the speed of light.

[15] A superconductive material does not put up any resistance against the passage of an electric current and therefore does not dissipate any energy. However, it needs to be cold to function: at the LHC, for example, the superconductive magnets operate at −271.3°C (approximately 1.8 degrees above absolute zero).

[16] At the time of collision, "packets" of $10^{11}$ protons are contained in 20µm (a human hair measures approximately 50 micrometres, i.e. $50\times10^{-6}$ metres, symbolised by 50µm) for a final yield of one billion particle collisions per second.

[17] These bosons are responsible for weak interaction.

[18] Though the field bears the name of three scientists (Robert Brout and François Englert, on the one hand, Peter Higgs, on the other), the current name has remained "Higgs boson" (and is considered unfair in the particle physics community).

[19] 1eV, or electrovolt, corresponds to the kinetic energy acquired by an electron at rest and subjected to a potential difference of 1V: $1\text{eV} = 1.6\times10^{-19}\text{J}$. In absolute terms, this value is very low, and this is why it is often expressed in MeV ($10^6$eV), GeV ($10^9$eV) or TeV ($10^{12}$eV). 1 TeV corresponds to the kinetic energy of a mosquito in flight. Though this energy is considered as "colossal" at the LHC, this is because it is concentrated on particles $10^{12}$ times smaller than a mosquito.

[20] These tools were necessary because collisions of protons, themselves comprised of quarks, produce an enormous number of diverse particles, which create "background noise" in which the target information must be found.

[21] The Internet and Web must not be confused, the latter being only an application of the former, just like messaging or file exchange. The Internet is the global computer network and the Web is the system that allows consultation of pages hosted on the internet via a browser and connection of them to each other via hypertext links.

[22] https://council.web.cern.ch/en/content/convention-establishment-european-organization-nuclear-research

[23] The term "observable Universe" refers to the part of the Universe that can interact with us via electromagnetic radiation.

[24] Dark energy, representing approximately 70% of the Universe's energy, is hypothesized to be responsible for the acceleration of the Universe's expansion. Dark matter, predominant in approx. 30% of matter, appears necessary due to the gravitational anomalies observed in large structures such as galaxies or galaxy clusters. Researchers don't know how to detect them directly but suppose their existence by detecting their indirect effects on structures (for dark matter) and on cosmology (for dark matter and dark energy).

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[25] For example, as they react to gravity, the particles responsible for dark matter are hypothesised to have mass.

[26] For example, supersymmetry is a theory that appeared in the 1970s to attempt to push beyond the standard model. It postulates that supersymmetric particles are associated to each particle of the model, and more particularly, establish "symmetry" between fermions (components of matter) and bosons (force vectors). In addition, supersymmetry supposes the existence of stable particles with properties similar to what would be required to form dark matter. However, no supersymmetric particle has been found so far.

[27] The use of braking radiation constitutes the functional principle of light-emitting synchrotrons, such as the SOLEIL national synchrotron in the Paris region or the ESRF (European Synchrotron Radiation Facility) in Grenoble. After an acceleration phase via the application of radiofrequency fields, the electrons are stored in a storage ring with a circumference of 354m for SOLEIL and 844m for ESRF, where their circular trajectory causes emission of radiation across a wide range of the electromagnetic spectrum (up to energies exceeding several hundred keV for ESRF).

[28] The positron is the antiparticle of the electron: same mass, but opposite electric charge. The positron is therefore positively charged.

[29] The quantity of energy lost determines the wavelength of the radiation emitted (infrared, visible, ultraviolet, X-rays, etc.). This radiation can have applications in many fields: biology, astrophysics, etc.

[30] It is predominantly financed by Germany (more than 50%) and Russia (approx. 25%), with support, ranging from 1% to 3% each, from ten other European countries including France (contribution of €35m in kind, mainly funded by the CEA (French Alternative Energies & Atomic Energy Commission) and CNRS (French National Centre for Scientific Research)).

[31] Since the United States chose to focus on neutrinos in particle physics, Japan occupies a prominent place in this field, behind Europe which however imposes itself via CERN and its ability to produce the Higgs boson.

[32] http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

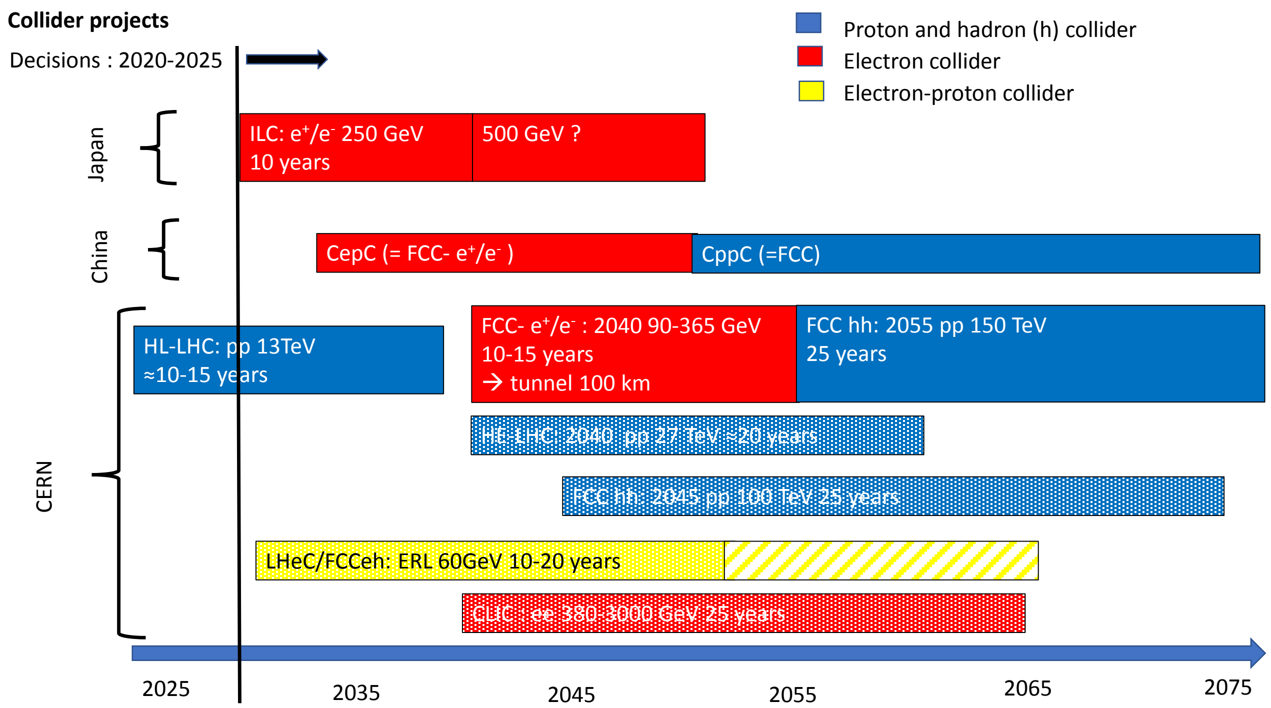
[33] The 83rd meeting of the International Committee for Future Accelerators (ICFA) is to be held in 2019 in Tokyo and will discuss the decisions that will have been evoked by the Japanese government.

[34] https://europeanstrategy.cern/european-strategy-for-particle-physics

[35] The quantity of data, which has already reached 300 petabytes (300 million gigabytes) for the 2015-2018 period, should increase by a factor of 10 during the high-luminosity phase.

[36] Reference: https://fcc-cdr.web.cern.ch/

[37] Summary of different particle accelerator projects ongoing.



*Source: IN2P3 (French National Institute of Nuclear & Particle Physics)* (CNRS)

[38] Hearing by the Office, open to the press, on 14 February 2019, of Mr. Gérard Mourou, director of the applied optics laboratory, professor at École Polytechnique, winner of the 2018 Nobel Prize for Physics, and Mr. Sydney Galès, director of research emeritus, Orsay institute of nuclear physics, former director of GANIL.

## *Experts and scientists consulted*

*M. Thierry d'ALMEIDA, research engineer at CEA (French Alternative Energies & Atomic Energy Commission).*
*Mrs. Ursula BASSLER, deputy director of IN2P3 (French National Institute of Nuclear & Particle Physics) at CNRS (French National Centre for Scientific Research).* Newly-appointed chair of the CERN Board (since January 2019).
*Mr. Gabriel CHARDIN, chairman of the Very Large Research Infrastructure Committee at CNRS (French National Centre for Scientific Research).*
*Mrs. Anne- Isabelle ETIENVRE, director of IRFU (Institute of Research into the Fundamental Laws of the Universe).*
*Mr. Gautier HAMEL de MONTCHENAULT, head of the particle physics department (DPHP) at CEA (French Alternative Energies & Atomic Energy Commission).*
*Mr. François Le DIBERDER, lecturer and researcher at IN2P3 (French National Institute of Nuclear & Particle Physics) and member of the ATLAS experiment at LHC.*
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