Challenges and opportunities for the HL-LHC [1] at CERN [2]

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Introduction to the article

by Marc GOOSSENS, MSc Engineering Physics,
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Developed in the early 1970s, the standard model of particle physics explains and accurately predicts a large number of fundamental phenomena at the smaller spatial scales currently accessible to experiments, but it is incomplete and leaves a number of questions unanswered :

- Where does **the mass of the particles** come from, some of them being relatively heavy while others have none? While there is no a priori reason why elementary particles should not come in a ladder of mass values, few things could be more interesting than a theory predicting exactly such values. The discovery of Higgs' boson at CERN in 2012 brings a beginning of an answer, but much work remains to be done to measure its properties.
- The **force of gravity** does not enter into the Standard Model that unifies the other fundamental forces, although some versions of this model add the graviton (which has never been observed up to now) ; nevertheless, classical General Relativity and standard Quantum Field Theory are mutually incompatible. Could we explain and resolve what is perceived as an anomaly?
- During the Big Bang, matter and antimatter must have been produced in equal amounts, but from what we have been able to observe so far, our Universe is made up entirely of matter.

This article describes the most recent phase of the history of our search for an understanding of the foundations of Nature at its smallest scales. For those who are not versed in the physics of elementary particles, the following table summarizes the main names and categories.

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[1] **H**igh **L**uminosity **L**arge **H**adron **C**ollider

[2] **C**entre **E**uropéen pour la **R**echerche **N**ucléaire (today : « European Organization for Nuclear Research »)

[3] Reviewed by the author

BOSONS (particles with integer spin)			FERMIONS (particles with semi-integer spin)	
Higgs' boson	Gauge bosons	HADRONS (« heavy » particles)		LEPTONS (« light » particles)
	Photon, W^+, W°, Z, gluon	MESONS	BARYONS	Electron, muon and tau, plus their neutrinos
		Pions, kaons, …	Proton, neutron	

These particles are classified as **fermions** and **bosons.** The three fundamental interactions known to be mediated by gauge bosons are electromagnetism (by photon), the weak interaction (radioactivity, by Ws & Z), and the strong interaction (within the nucleus, by gluons).

Quarks cannot exist on their own (one says "de-confined") at "normal" energies (that's why they don't appear in the table), but they form **hadrons**. The hadrons that contain an odd number of quarks are called **baryons** (mainly the **proton** and the **neutron**), and those that contain an even number of quarks are called **mesons** (very unstable particles, with a life of only a few hundredths of a microsecond).

Fundamentally speaking, the elementary particles as we know now are the six quarks, the six leptons, the gauge bosons and the Higgs' boson ; hadrons are made up of quarks.

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*"You know, the problem is, we know how to build **detectors** for lepton collisions but we do not know how to build lepton **colliders**. And we know how to build hadron **colliders**, but we do not know how to build **detectors** for them".*

Carlo Rubbia looked at his audience sideways, slightly smiling, his eyes moving across fast at the people in front row, but focusing for a long instant on mine, the way he normally did when he knew he was saying something deeply intelligent and was pleased to witness that his listener had instantly grasped his thoughts.

Carlo Rubbia, Nobel Prize winner, and to become CERN Director General in 1989, had just started his keynote in Castiglione della Pescaia {4}, the Italian posh resort on the Maremma coast. Eight months had elapsed since the author had returned from the United States and a few months since he had first met him in person in his office at CERN.

What Carlo Rubbia meant, of course, was the radiation loss in circular **electron-positron colliders**, and the "dirty" collisions which characterize collisions in **hadron colliders**, the opposite "*bêtes noires*" of every experimental particle physicist. Let us start to explain why, by recalling some elementary accelerator and particle physics.

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[4] Castiglione della Pescaia, Grosseto, Italy. Third Pisa Meeting: Frontier Detectors for Frontier Physics (2-7 June 1986)

Up to 1970's, most of the efforts to probe deeper and deeper into the innermost constituents of matter relied on accelerating particles and having them impact **fixed targets**. Since :

$$p = \frac{h}{\lambda}$$

where 'p' is a particle (scalar) linear momentum, 'λ' its (quantum mechanical) wavelength and 'h' is Planck's constant, higher energies (= higher momentum) in a beam allowed for higher spatial resolution (going to lower and lower λ) in probing the inner structure of the nucleus first, and of its inner constituents later.

By the 1970's we had gained firm evidence of the dynamic internal structure of protons and neutrons, proving their bound structure with quarks and gluons confined within them. New particles had been observed as well, but, because of linear momentum conservation, most of the energy in the incoming beam gets scattered away when a beam is focused on a fixed target and is not available to create interesting new stuff.

The *"Colombo's egg"* idea is obviously that of accelerating beams of particles flying in opposite directions and making them collide head on. Then, or at least it could be thought at first {5}, all of the energy in the beams is available to create new bounded states, typically fast decaying into previously known particles, from exotic kaons to more ordinary muons or plainly mundane electrons.

The first such "colliders" were electron-positron (e- e+) circular accelerators, one of them having been ADONE, at Frascati National Laboratory in the rolling hills around the Eternal City. The idea requires the use of particles with a high cross-section for inelastic scattering, which could be easily produced: electrons and positrons were the natural first candidates.

One advantage of e^--e^+ colliders comes from the fact that, to all known extent, the electron is a truly "elementary" particle, which fully annihilate with a positron, resulting into very "clean" decay channels, with relatively few traces, fairly easy to identify and reconstruct with appropriate visualizing software in the detector where the collision occurs. **But there is a problem**.

A fundamental principle of physics has to be recalled. It states that any charged particle that is accelerated or decelerated by an electromagnetic field along a circular orbit emits a synchrotron radiation, which causes an energy loss of the particle. Calculating this loss of energy for a charged particle having to follow a circular orbit at a relativistic speed is not a simple matter and leads to a complex formula according to which this loss of energy is $1.6 * 10^{13}$ times greater for an electron than for a proton of the same energy (this is of course due to their difference of mass).

But, making use of protons, instead of electrons, provided for its own challenges. The first was the very low inelastic cross section for proton-proton collisions at the energy levels available at that time . Making protons collide with antiprotons make for a higher cross section, but how to focus properly in a beam the antiprotons, which need first to be produced by a fixed target beam? Rubbia led the effort to convert the just commissioned Super Proton Synchrotron (SPS) at CERN into **a hadron collider**, making good use of antiproton beams stochastic cooling {6}, the newly developed technology brainchild of the late Simon van der Meer, who would share the Nobel Prize with him two years later.

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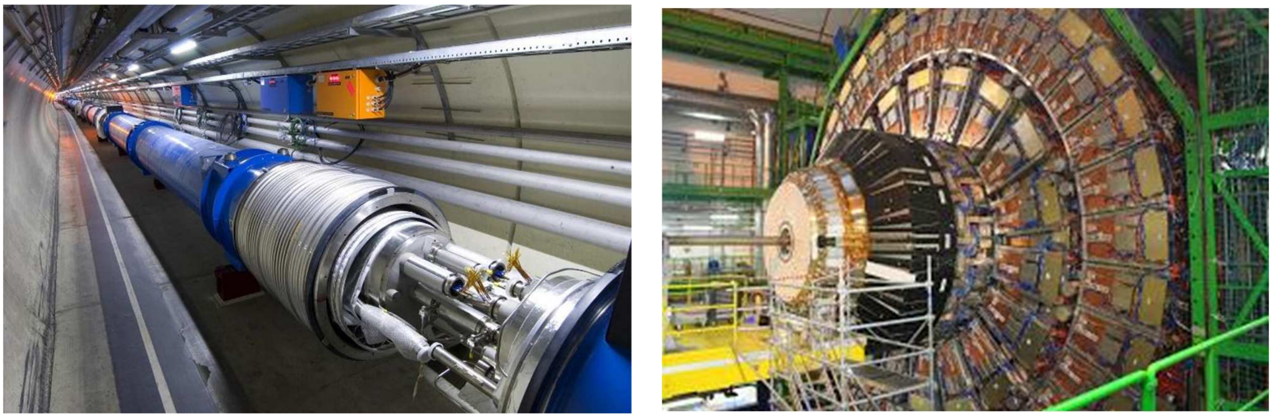
[5] Please refer to the short discussion about the nucleon Form Factor later in the present article.

[6] Stochastic cooling involves sending signals the short way (along its diameter) across an accumulation ring, where antiprotons can be better focused in a well-collimated beam. To all practical effects, the antiprotons get "cooled" in phase space.



Photos of the LHC (the photo at the right was taken by the author)

Work was also needed however on the side of the detectors necessary to study the results of the collisions. Under Rubbia's leadership, who basically created the model for today's large, multinational "collaborations" to propose, build and operate large detectors, the UA-1 detector announced in early 1983, with UA-2 quickly following to confirm, the discovery of the W's and the Z, the carriers of the weak force, proving the theory of electroweak interactions right.

While it is much easier to accelerate protons and antiprotons, because of the synchrotron radiation problem for e^--e^+ colliders, proton-antiproton collisions result in extremely complex events, precisely because of their composite structure : already at the energies attained by the SPS, but all the more so in today's LHC, collisions actually occur between the individual quarks and gluons confined within each colliding nucleon. This is also why the LHC relies on colliding beams of protons : at such high energies (LHC operates at over 7 TeV per beam), one really has quark and gluon collisions rather than protons on protons (or antiprotons, of course). This introduces a further complication : within a bounded nucleon state, the individual quark (and gluon) energies are distributed across several values as described by the appropriate Form Factor function {7} : therefore, for a hadron collider, the centre-of-mass energy in the colliding beams is actually not entirely available to create new states. As a rule of thumb, one has an order of magnitude reduction : in other words, the LHC, with its about 14 TeV of centre-of-mass beam energy, explores "the TeV range", rather than the "ten TeV range".

Building a TeV-range linear "à la SLAC {8}" e^--e^+ collider remains a concept worth thinking about, leveraging one-future-day technology, for instance, plasma wakefield technology {9}, to produce the needed immense accelerating gradients. Ditto for the dream of a muon circular collider, for which the 200 mass ratio with the electron would make the e^--e^+ synchrotron radiation problem much less severe, while keeping the "clean" collisions characteristic of lepton accelerators. But, for the foreseeable future, Rubbia's aphorism still holds true.

Clearly, the larger the orbit radius, the less is the particle loss, but the dependence on the orbit radius is only linear, while the dependence on the mass ratio between electrons and protons appears to be raised to the fourth power. Therefore, going to larger radii for an electron-positron scales horrendously with the

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[7] In elementary particle physics, a **form factor** is a function that describes the energy and momentum of the composite particle constituents (in the case of the proton : it's 3 valence quarks and its 'sea' of quarks-antiquarks, plus the gluons) without including all of the underlying physics.

[8] The Stanford Linear Accelerator Collider.

[9] Laser-wakefield acceleration (LWFA) is a method for producing high-energy electron beams using the accelerating field structure produced in the wake of a high-power, ultrashort pulsed laser propagating through low density plasma.

available-budget and civil engineering challenges : the 27 km circumference of the CERN tunnel, now hosting the LHC and originally drilled partly under the Jura massif to host the then Large Electron Positron collider (LEP), was the maximum that budgets and rock formation reasonably allowed at the time, but could only allow beams of electrons and positrons of a little more than 100 GeV per beam, therefore providing a little more than 200 GeV in the centre-of-mass.

LEP started operations at about 45 GeV per beam, providing enough energy in the centre-of-mass for meaningful Z spectroscopy (the rest mass of the Z being about 91 GeV, ndr). LEP-upgrade eventually reached a total of 209 GeV in the centre of mass. Incidentally, LEP detectors had “hinted” at Higgs boson decays in the last about two years of operation, but with confidence levels of less than 3 sigma. This author, EU Delegate in the CERN Council between 2000 and 2003, remembers all too well the anguishing decision that the then Director General Luciano Maiani, whom he had the immense pleasure of working with closely in those years, proposed to the Council to courageously take : close down LEP as planned, forego the hope that the fledgling evidence for the Higgs could materialize during his term, start the construction of the LHC in the LEP tunnel, and leave it to the “next generation” to finally claim the landmark discovery.

And rightly so, well-deserved fame came again to CERN nine years later, when the then spokesperson for the ATLAS Collaboration and presently CERN Director General Fabiola Giannotti, her voice vibrant with tangible emotion, and the then Director General Rolf Heuer, beaming with joy besides her, announced during a packed press conference that ATLAS and CMS (the largest multi-purpose LHC detectors) had observed a particular decay mode in p-p collisions at the LHC (incontrovertible signature of a Higgs having been produced, n.d.r.) with slightly better than 5 sigma confidence. This confirmed also that the decision to wrap up LEP operations, not to extend its life further, but to proceed with installing the LHC magnets, RF cavities and detectors in the LEP tunnel, had been the right one : the Higgs boson discovered at the LHC is not the one for which there was fledging evidence in 2000, as it is ten GeV heavier and therefore completely out of the LEP energy range.

Since then, no breakthrough new physics has come out of the LHC or from anywhere else, for that matter. Very recently {10}, flavour anomalies in rare B-meson decays (into muons and electrons, respectively) seemed to indicate some exciting new physics, breaking the so-called lepton universality which is foreseen by the ubiquitous Standard Model. But more accurate analysis by the LHCb collaboration showed that there had been an underestimation of hadronic backgrounds to electrons. Nor have we seen, for now, any evidence of the much touted **“dark matter”** that velocity dispersion curves in the star motion in galaxies, and galaxies’ motion in cluster, seem to indicate “must be there” to account for this motion if one wish to preserve standard Newtonian mechanics / classical General Relativity.

While dreams for TeV-range linear e^--e^+ or circular muon colliders continue to grace the nights of experimental elementary particle physicists, and (in the eyes of the author, slightly budget-optimistic) plans for a new circular collider in the 100 km class for CERN, using the present LHC as its last-stage injector {11}, which would allow for even higher energies at present accelerator technology, are being actively discussed, people at CERN are hardly resting on their laurels.

During its foreseen Long Shutdown 3 in 2026-2029, the LHC is due to experience its largest upgrade ever, bringing higher luminosity and to reach a ten-fold increase in the event rate during collisions.

We have seen how proton collisions at the energies at which the LHC operates are really parton (collective name for quark and gluons) collisions, and we also explained how the energy distribution in individual collisions varies to an extent, according to each proton Form Factor function. And that’s where increasing the production rate of events in collisions comes to (partial) rescue for centre-of-mass energy. Higher

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[10] Preliminary results announced in 2021 by the LHCb collaboration at CERN.

[11] The way the former PS and SPS now do for the LHC.

collision rates, aka higher “luminosity”, involving even better focused “denser” beams, result, in very simple terms, in making extremely rare events a bit more frequent. Therefore, exotic new particles, or “interesting” new physics hidden in equally rare decay modes of known particles, might still lie within the reach of the present day LHC’s energy, when collisions at higher luminosity could provide more rare events and better statistics.

While the work on its focusing magnets and other improvements needed in its accelerating cavities look well within reach, the main challenges lie with the very large upgrading of the detectors (ATLAS and CMS first of all, but also ALICE and LHCb), which would be required to withstand the larger radiation damage and their data acquisition, trigger systems and the distributed computing analysis later will need to be also overhauled to cope with the over tenfold rate increase.

But that will be the subject of a future article!