THE LARGE HADRON COLLIDER (LHC) AND THE HIGGS BOSON

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1. ABSTRACT

In 1954, twelve Western European countries founded the European Organization for Nuclear Research (CERN). At present, the Large Hadron Collider (LHC) in the CERN (Geneva, Switzerland) is the largest and most powerful particle accelerator in the world. It started to operate on 10th September 2008. The LHC is a so-called strong focusing proton synchrotron. In the LHC, protons are running in opposite directions in the main ring of 27 km circumference, with a planned energy up to 7+7 TeV, and collide in four points of the ring. We discuss the main physical as well as technical parameters of LHC in this paper. Scientific research is being carried out at the LHC along the following: the origin of the mass of elementary particles, Higgs boson, dark matter, origin of the matter-antimatter asymmetry in the present Universe, supersymmetry (SUSY), behaviour of the quark-gluon plasma, Big Bang, as well as the very early state of our Universe. We also discuss the Standard Model briefly, and some open problems in connection with it. Peter W. Higgs et al. predicted a scalar boson, and that boson was found at the LHC in 2012 with a certainty of 4.9 sigma. It means a probability of 99.99994 per cent. Belgium's François B. Englert and Britain's Peter W. Higgs have been awarded the Nobel Prize in physics 2013.

2. THE CERN

In 1954, twelve Western European countries established the CERN (its first name was Centre Européen pour la Recherche Nucléaire, later European Organization for Nuclear Research). Now, it has 20 member and seven observer countries (Figure 1). Hungary joined to the CERN in 1992, and has a contribution to its yearly budget of 0.4 per cent. Nowadays, 2800 employees, 10.500 scientific researchers and 440 students are working at CERN. CERN is situated at the border of France-Switzerland from 9 km North-West to Geneva (village Meyrin, near to Geneva International Airport). The main ring of the LHC crosses that border four times underground (Figure 2).

Figure 1.
Member countries of the CERN

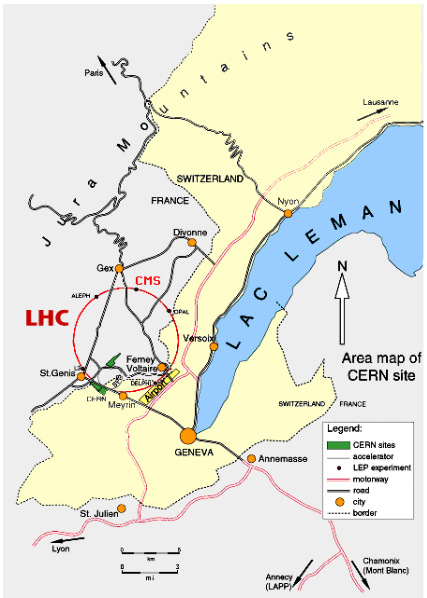


Figure 2.
Site of the CERN and LHC

3. THE LHC

Mottos:

"Electric field is accelerating, magnetic field is bending"

"Let us accelerate faster"

LHC is a very powerful strong-focused proton synchrotron in which protons are running in opposite directions, and collisions occur with a planned energy of 7+7 TeV at 4 places. At those crossover points, four giant particle detectors are placed named as ATLAS, ALICE, CMS, and LHC-b. The design of the LHC started in 1984, and its planning and building took more than 20 years. Operation of the LHC started on 10th September 2008, and it reached the energy of 3.5+3.5 TeV step-by-step, up to 2012.

Proton bunches are accelerated by 8 microwave cavity resonators of 0.4 GHz, with an electric field strength of 5 MV/m in each of them. 2808 proton bunches are running in both directions, each of them contains 1.1×10^{11} protons. At full operation mode (7+7 TeV), proton beams will cross each other in every 25 ns (repetition rate). Therefore, the average crossing frequency of bunches will be 31.6 MHz. It means $\sim600\times10^{6}$ bunches collisions/s, but only ~20 proton-proton collisions/s are taking place directly.

Some important technical and physical data of LHC are as follows:

Length of proton bunches	100 mm
Following distance of bunches	7.48 m
Diameter of bunches on orbit	~2 mm
Diameter of bunches at collision	~16 μm
Beam intensity	560 mA
Beam pipes inside of cryodipoles	56 mm×63 mm
Angle of bunches at collision	1.5^0
Accelerating time up to 3.5 TeV	20 minutes
Lifetime of proton beam	~10 hours
Length of cryodipoles	15 m
Maximum current of cryodipoles	11.85 kA
Maximum magnetic field of cryodipoles	8.36 T
Temperature of cryodipoles	1.9 K
Stored magnetic energy	10 GJ
Circumference of main ring	27 km
Slope of main ring	0.8^0
Frequency of a bunch	11 245 rps
Crossing frequency of the bunches	31.6 MHz
Total energy of proton beams	725 MJ
Planned luminosity	10^{34} cm^{-2}s^{-1}

Superconducting cables build up by elementary wires of 7 μm in diameter, made by an alloy of NbTi. The total mass of magnets takes 6.5×10^4 tons. The shaping of proton bunches uses quadrupole as well sextupole strong focusing magnets. Vacuum system contains 120 tons of liquid He, and 10^4 tons of liquid N_2. It has three parts: (1) insulation for cryomagnets, (2) insulation for distributive system of liquid He, (3) system for beam tubes, where the vacuum is 10^{-8} Pa (it means 7.5×10^{-11} Torr), under operation. Total volume of whole vacuum system is ~6500 m^3. Time of pumping down completely of the vacuum system takes 2-3 weeks. Cryo- and iongetter pumps are used. The LHC main tunnel is 3.0-3.8 m in diameter, and is situated at 50-175 m underground (Jura Mountains).

Some interesting facts in connection with the LHC are as follows:

- at 7 TeV, the kinetic energy of an individual proton is equal to that of a flying mosquito,
- the kinetic energy of a bunch of protons is equal to that of an elephant running a speed of 50 km/h,
- at 7 TeV, velocity of protons is v = 0.999999991c (c = velocity of light in vacuum ≈ 3×10^8 m/s). It means that (c-v) ≈ 3 m/s, only,
- under 10 hours running in the main ring of the LHC, a proton goes ~10^{10} km ≈ 67 AU (AU = Astronomical Unit = average Earth-Sun distance),
- ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) detector contains 7000 tons of iron (it is equal with the mass of Eiffel Tower).

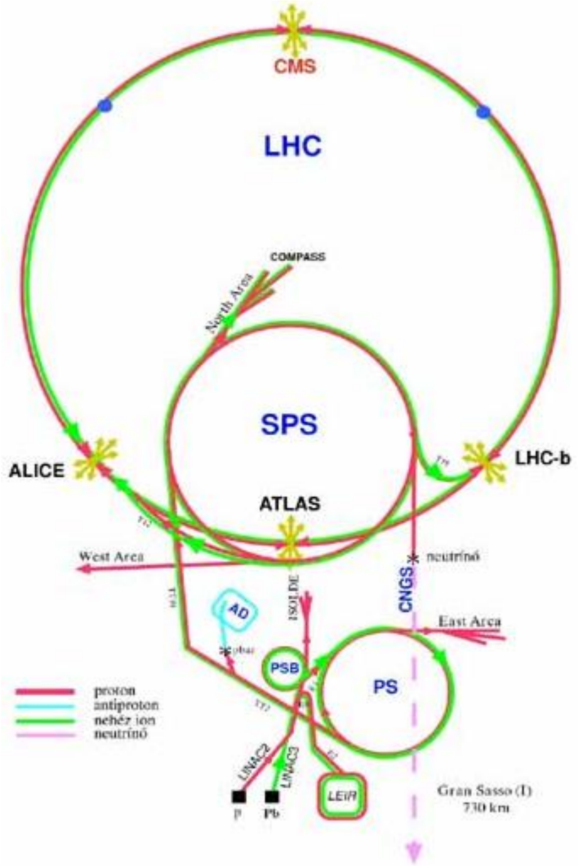


Figure 3.
General layout of the LHC facility

Main parts of the LHC accelerator facility (Figure 3):

P = Duoplasmatron Ion Source (100 keV, 350 mA) → LINAC2 = Linear Accelerator (50 MeV, 180 mA, length = 30 m, v/c = 0.341) → PSB = Proton Synchrotron Booster (1.4 GeV, circumference 70 m, v/c = 0.916) → PS = Proton Synchrotron (25 GeV, circumference 630 m, v/c = 0.9993) → SPS = Super Proton Synchrotron (450 GeV, circumference 7 km, v/c = 0.999997828) → LHC = Main Ring (7 TeV, circumference 27 km, v/c = 0.999999991, Figure 4). The LHC stopped for 20 months in March 2012 because of a planned upgrading project. The accelerator is going to start again in early 2015, at an increased energy of 6.5+6.5 TeV. The LHC people's goal is to reach the final energy of 7+7 TeV.

Data of 10-12 PByte/year are coming directly from the detectors of LHC. A part of those data will be prepared and stored at the Wigner Research Centre for Physics (WRCP) of the Hungarian Academy of Sciences, Budapest/Csillebérc. Network and computers of the WRCP Datacenter (named grid Tier-0) are extreme fast. About 80 per cent of the operation time of the Budapest Tier-0 computers is going to be used for the aim of LHC.

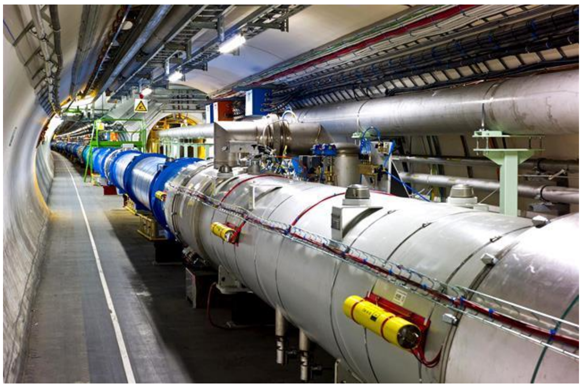


Figure 4.
A part of LHC tunnel of the main ring

4. THE STANDARD MODEL (SM)

Motto:

"Physics is similar to sex: it has practical benefit certainly, but we are not doing for it."

(Richard P. Feynman)

The Standard Model is a very effective form of quantum field theory, which can describe the fundamental particles and forces, as well. SM is in harmony with quantum mechanics and special relativity, and it could predict new particles. The theory describes the electromagnetic, the strong and the weak interactions very well, including the behaviour of elementary particles, too (Figure 5). However, SM cannot describe the gravity (due to the interaction by gravitons or bending of four dimensions Minkowski space-time caused massive matter, respectively geometry?). By the way, origin of the *"quark"* word came from a fiction of "Finnegan's Awake" by James Joyce: *"Three quarks for Muster Mark"*, and theoretical physicist, Murray Gell-Mann gave that funny name to those particles. Moreover, the *"lepton"* word came from the name of an ancient Roman coin, made by Roman Procurator of Judaea, Pontius Pilate ~29 AC (6000 leptons = 1 Roman talent).

Unfortunately, there is some "terra incognita" in the SM as follows:

- From where origins the mass of particles?
- What is the reason of matter-antimatter asymmetry in the present state of our Universe?
- What are the dark matter and the dark energy?
- What is the reason of three (and *only three*) generations of matter?
- Do gravitons exist?
- Why do neutrinos have mass?
- Does supersymmetry (SUSY) exist?

In the next part of this paper, we are going to deal with the Higgs boson and the Higgs mechanism, as well.

5. THE HIGGS BOSON AND THE HIGGS MECHANISM

Mottos:

"Imagination is more important than knowledge"
(Albert Einstein)

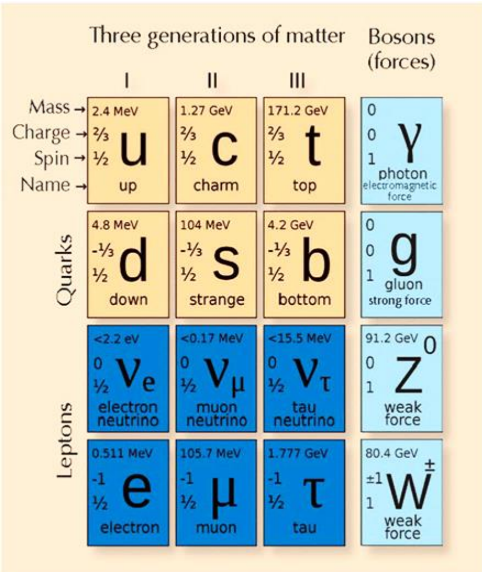
"Wir müssen wissen, wir werden wissen"
(David Hilbert)

In connection with the new boson and mechanism, three very important papers were published by F. Englert and R. Brout [4], and P.W. Higgs [5] [6], in 1964. In those papers, they proposed a scalar field (now it called Higgs field), which fills out our Universe, as well as a mechanism, to explain the origin of the mass of the elementary particles.

At first, Leon Lederman christened that particle as *"Goddamn Particle"* [11]. Now its name is *"God Particle"* or *"Higgs Particle"* (*"Higgs field"* and *"Higgs mechanism"*, as well).

The Higgs particle is an elementary particle initially predicted in 1964 whose discovery was announced at CERN on 4th July 2012. It would explain why some fundamental particles have mass when the symmetries controlling their interactions should require them to be massless and why the weak force has a much shorter range than the electromagnetic force?

In the Standard Model, the Higgs particle is a scalar boson with no spin, no electric charge, and no colour charge, as well. It is very unstable, decaying into other particles (bb_{anti} quarks, $\tau\tau_{anti}$ leptons, W^+W^- and Z^0Z^0 vector bosons [gauge bosons], and rarely $\gamma\gamma$ photon-pair almost immediately (Figure 6). Higgs boson has a mass of 125.3 ± 0.6 GeV/c^2 (it means ~133×mass of proton ≈ 10^{-25} kg). Mass of the Higgs particle was limited between 114 and 141 GeV/c^2 by experiments of LEP/CERN (LEP = Large Electron-Positron Collider), and Tevatron/Fermi National Accelerator Laboratory (Batavia, IL, USA), earlier (the Tevatron was a synchrotron that accelerated protons and antiprotons in a 6.86 km ring to energies of up to 1 TeV.



- **fermions;** spin = ½ , Fermi-Dirac statistics (Pauli-principle), [quarks, leptons]
- **bosons;** spin = 0,1,2, Bose-Einstein statistics [photon, mesons, Higgs]
- **nucleons;** 3 quarks [proton = uud, neutron = udd]
- **mesons;** medium heavy, quark+ antiquark pairs [pions. kaons]
- **barions;** 3 quarks, heavy fermions [nucleons, hyperons]
- **quarks;** [up, down, charm, strange, top, bottom], spin = ½
- **leptons;** light particles, spin = ½, [electron, muon, tau]
- **hadrons;** heavy interaction [barions, nucleons, mesons]
- **hyperons;** [sygma, lambda]
- **graviton;** spin = 2, mass = 0 [theoretical]

Figure 5.
Fermions and bosons in the Standard Model

It was stopped in 2011). The SM predicts a mean lifetime of it about 1.6×10^{-22} s (N. B: the proton should decay with a half-life on the order of 10^{32} years, and our Universe is about 13.75×10^{9} years old).

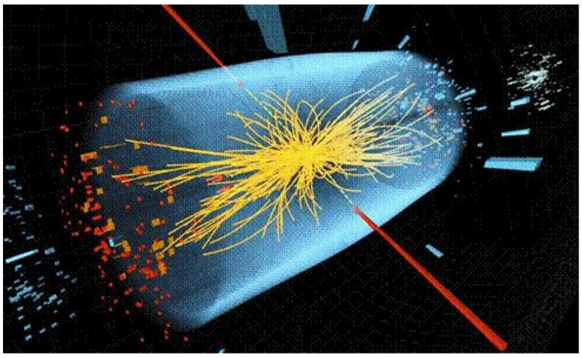


Figure 6.
Decaying of the Higgs boson into two photons

Less than one second after the Big Bang, particles had not yet mass. Later, the mass of different subatomic particles (quarks, leptons etc.) was generated in interaction with the Higgs field which developed about 10^{-12} s after Big Bang. Higgs field can interact with itself, too. The Higgs mechanism is a spontaneous symmetry breaking in the Higgs field. Without Higgs mechanism, every particle would have no mass and move at the velocity of light in vacuum, and atoms, molecules, chemical elements, stars, planets and life would not exist. Higgs field is a scalar quantum field and its quantums are the Higgs scalar bosons, what are bunches (field gets "knot", respectively) in this field. All quantum numbers of the Higgs boson are zero, exactly, and it takes part only in the gravitation interaction. Furthermore, a special property of the Higgs field that its value is not zero in the ground state. In that conception, physical vacuum is a condensation of the Higgs field.

We cannot observe the Higgs particle directly but only its decay products. For example, decay modes of the Higgs are bb_{anti} quarks (60 per cent, detectable with difficulty) or $\gamma\gamma$ photon-pair (0.2 per cent, detectable easily). If the spin of the Higgs particle is zero there is only one kind of Higgs boson and Higgs field, but if its spin is 2 there are five kinds of Higgs boson (H^0, h^0, A^0, H^+, H^-), and two different Higgs fields as well SUSY exist, too. The Standard Model with the Higgs boson is on the Figure 7. Higgs field give mass to the quarks, leptons as well Z^0 and $W^{\pm}$ gauge bosons.

P.W. Higgs said, *"It was in 1972 ...that my life as a boson really began."*

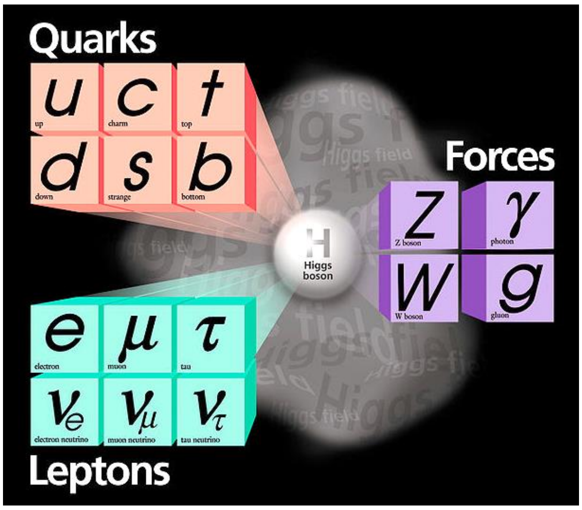


Figure 7.
The SM with the Higgs boson

6. THE NOBEL PRIZE IN PHYSICS 2013

CERN's Director General, Rolf-Dieter Heuer announced the discovery of the Higgs particle on 4th July 2012. He said, *"I think we have it."*

On 8th October 2013, the Nobel Prize in physics was awarded jointly to Belgium's François B. Englert and Britain's Peter W. 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"* (Figure 8).

CERN congratulates F.B. Englert and P.W. Higgs on the award of their Nobel Prize.

Figure 8.
François B. Englert and Peter W. Higgs

However, the researches in connection with it are not over, yet. According to CERN's statement, the detection of the boson is a *very rare event* – it takes cca. 10^{12} proton-proton collisions for each observed event, and we have to clarify exactly, *what kind of Higgs boson* the researchers have discovered at the LHC, indeed. In connection with it, they will have a lot more research to do, of course. They are also interested in using the Higgs to find the key to other "mysteries" mentioned in this paper.

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