The Large Hadron Collider

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The Large Hadron Collider (LHC) [1] is a hadron accelerator and collider that is installed in a 26.7 km long tunnel beneath the Franco-Swiwss border near Geneva at a depth varying from 170 m below the Jura mountains to 45 m below the Leman lake. The tunnel was built by the European Organisation for Nuclear Research (CERN) between 1984 and 1989 to host the former Large Electron Positron collider (LEP). As represented in Figure 1.1 which provides a schematic illustration of the LHC, it is composed of eight arcs and eight straight sections, and two transfer tunnels which connect the LHC to CERN's main injection complex. From the eight possible collision points of the LHC located in the straigth sections of the tunnel, only four are in use and equipped with particle detectors: ALICE [2], ATLAS [3], CMS [4], and LHCb [5].

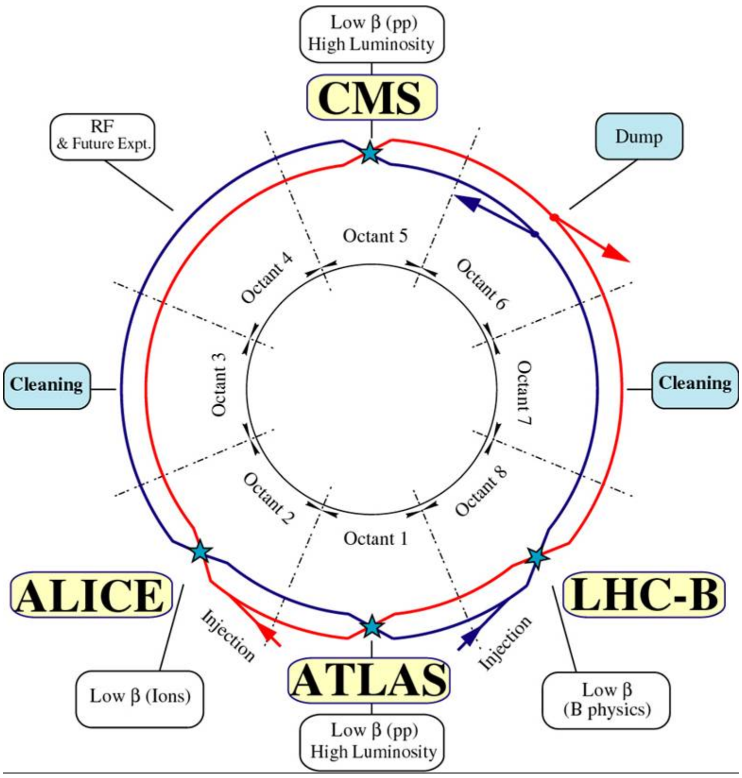

Figure 1.1 – Schematic representation of the Large Hadron Collider complex under the Franco-Swiss border detailling the location of the four experiment (ALICE, ATLAS, CMS, and LHCb) that analyze the produced collision [1].

The construction of the LHC, which concept dates back to 1984, was approved by the CERN Council in December 1994 and started in 1998 with the excavation of the caverns that would hold the experimentation sites. In 2003, the first section of the accelerator was assembled inside the tunnel marking the start of the installation phase of the LHC and its detectors, which would spawn until 2008. On September

10th 2008, the first beam of protons is circulated inside the LHC only to reveal a major technical issue with the superconducting magnets which will shutdown the machine for nearly a year. In November 2009, reparation works are finished just in time for the LHC to produce its first collisions at 2.36 TeV before its Year End Technical Stop (YETS), a yearly technical stop during which maintainance is performed on the machine. In February 2010, the LHC restarts with a physics program with collisions at 7 TeV that will last until February 2013. At that time, the LHC is stopped for two years during the Long Shutdown (LS) in order to perform upgrades to prepare it to run at 14 TeV. On June 3rd 2015, the LHC restarts and sets a new record with an energy in the center of mass reference frame of 13 TeV.

1.1 The Injection Complex

The particles that enter the LHC are first created and accelerated by the injection complex of CERN depicted in Figure 1.2. Protons are extracted from gaseous hydrogen by means of a duoplasmatron, a device that uses a heated filament cathode in conjunction with electric fields to produce electrons that will ionize and break the H_2 gas. The resulting protons have an energy of 100 keV and are injected in the Linac2 linear accelerator.

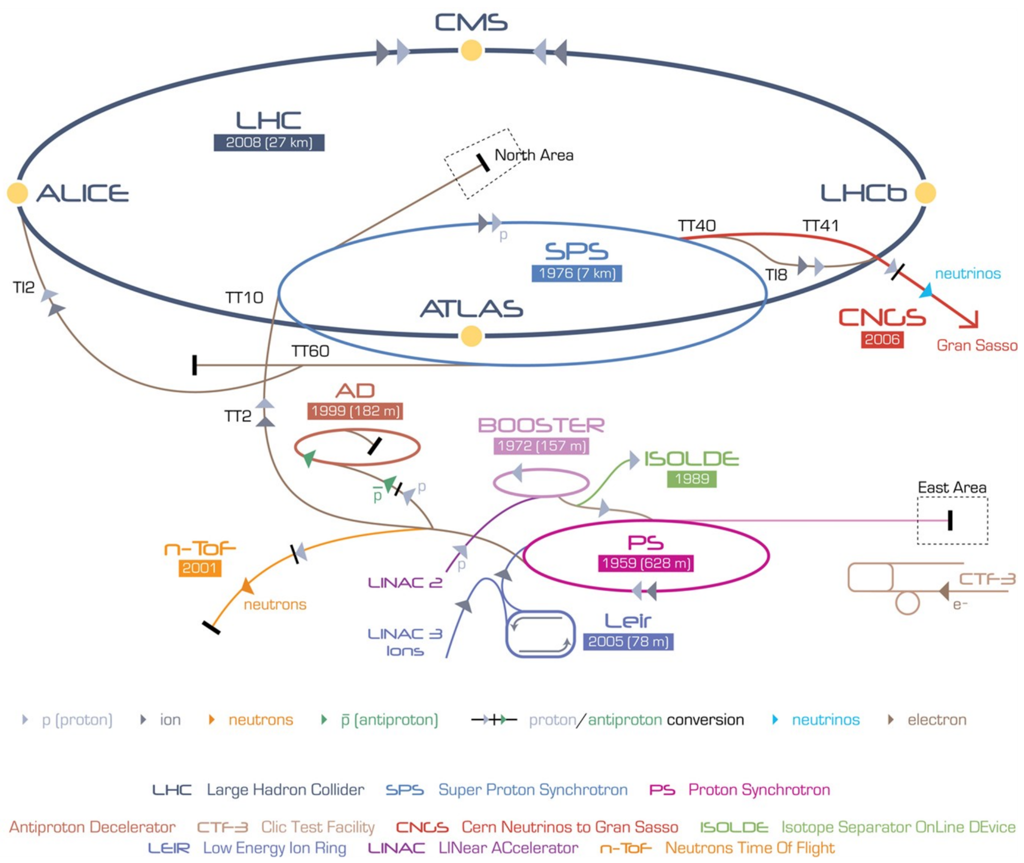

Figure 1.2 – Schematic representation of the LHC's injection chain composed of multiple smaller accelerators [6].

Linac2 uses radiofrequency cavities that produce an electromagnetic field inside the accelerator in order to transfer energy to the charged particles. The oscillations of the field allow to form bunches of particles by regrouping them on the front of the radio wave. The succession of cavities that form Linac2 boosts the incoming protons to an energy of 50 MeV before they enter the Booster.

Following Linac2, three consecutive circular synchrotrons, namelly the Proton Synchrotron Booster (Booster), the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS), accelerate the beams to energies of respectivly 1.4 GeV, 25 GeV, and 450 GeV. Each accelerator is composed of electromagnets that bend the trajectory of the beam and boost it further. From the SPS, the beam is injected in the LHC through two transfer tunnels into two rings where they rotate in opposite directions to be further accellerated until they reach the desired energy. The SPS also provides beam to the North Area were various experiments take place and future technologies can be tested during test beam campaignes frequently organised by CERN.

1.2 LHC Technical Description

Once inside the LHC, particles travel through two beam pipes which are subject to a vacuum of $10^{-}10$ Torr, representing around 3 million molecules per cm^3, which greatly reduces the collisions with the air and allow for longer beam longetivity. The beam pipes do not form a perfect circle as they are composed of eight arcs and eight straigth sections called insertions.

Each arc contain 154 powerfull dipole magnets represented in Figure 1.3 which produce a magnetic field higher than 8 T to bend the beams. The fields are generated by passing high currents through a coil of NbTi superconductor that surrounds the beam pipes cooled by liquid Helium below 2 K. The dipoles use a two-in-one design with a common cooling and housing system for the magnets of the two beam pipes which allows to reduce cost and space, and generate a magnetic flux circulating in opposite direction for the two rings. Due to the low temperature at which the magnets operate, the minimum energy deposition left by particles in the coils needed to trigger a quench, a sudden loss of supercondictivity, is also decreased. A tight control of the beam structure must thus be inforced. Therefore, 49 quadrupole magnets are installed per section in order to focus the beams and reduce horizontal and vertical spread of the particles.

The eight straight sections of the LHC have different usecases and designs: four of them are dedicated to the experiments and provide them with collisions, one contains the radiofrequency cavities to accelerate the beams, two are use to clean the beam, and one to dump the beam. These functions are fulfilled by using various

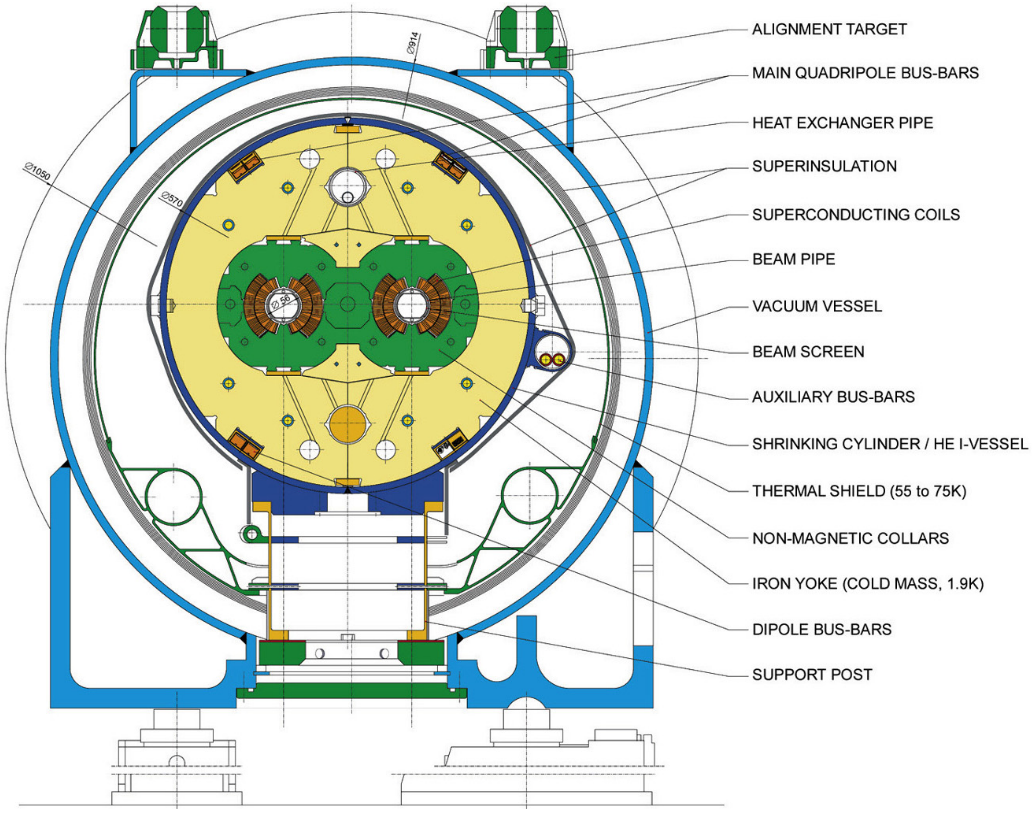

Figure 1.3 – Cross-section of a cryodipole of the LHC representing the two beam pipes equipped with superconducting NiTb coils surrounded by iron cold mass at 1.9 K [1].

magnet designs to bend or deflect the beams. From the four collision sites, two also host the beam injection pipes from the SPS into the LHC. The beam cleaning insertions are used to remove particles with out-of-band momentum by scattering them on collimators. When the integrity of the beam is compromised, fast switching magnets activate at the dump insertion in order to quickly extract the particles from the LHC and redirect it to the dump site: an eight meter long graphite composite block that absorbs the energy of the beam.

1.3 Performance Goals

The beams inside the LHC rings are composed of 2808 bunches each made of approximatly 110 billion protons. They are separated by 25 ns which is the time between two consecutive bunch crossing (BX), yielding a collision frequency of 40 MHz. During a collision, only a small fraction of the protons interract depending on various parameters such as the crossing angle of the beams, collimation of the bunches, etc. To quantify this, the notion of luminosity has to be introduced and is directly related to the frequency of apparition of events in a given interaction process

$$f_{process} = \mathcal{L}\sigma_{process} \ , \tag{1.1}$$

where $f_{process}$ is the number of expected events per second, and $\sigma_{process}$ is the interaction cross-section of the process. For a circular collider, the instantaneous luminosity is defined as

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F, \tag{1.2}$$

where N_b is the number of protons or ions per bunch, n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ is the Lorentz factor, ϵ_n is the beam emittance, β^* is the beta function at the Interaction Point (IP), and F is a function of the crossing angle between the beams at the IP. The ϵ_n and F parameters are related to the structure of the bunches and more specifically to their spatial spreading. These parameters change during the operation of the machine as the number of protons per bunch decreases and the bunches spread out.

The instantenious luminosity can be accumulated over a given period of time in order to obtain the integrated luminosity

$$L = \int \mathcal{L}\, dt, \tag{1.3}$$

which results in the number of events one can expect for a given interaction process

$$N_{process} = L\sigma_{process}. \tag{1.4}$$

Figure 1.5 shows the peak and integrated luminosities delivered by the LHC to its four experiments during 2015. It can be seen in the picture on the left that the highest instantenous luminosity reached during that period is on the order of 5×10^{33} cm^{-2} s^{-1} which is half the nominal luminosity of the current design of the LHC.

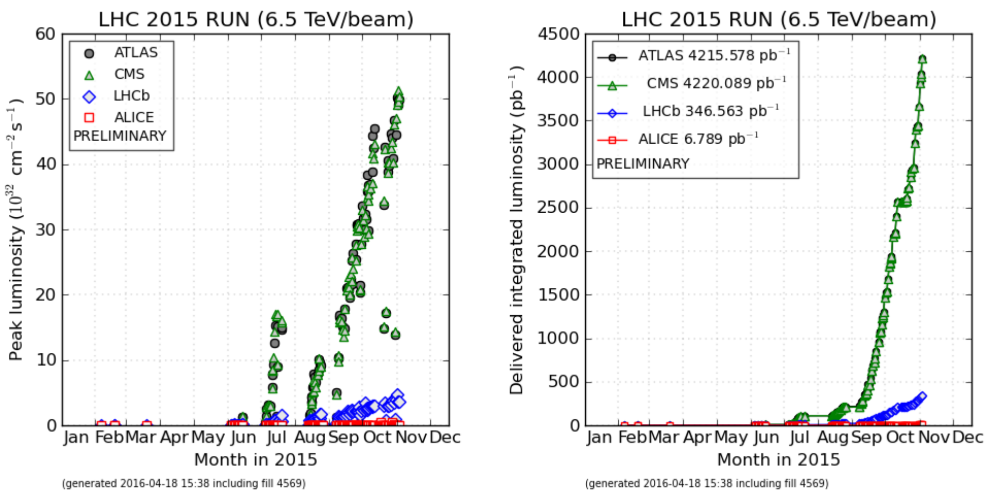

Figure 1.4 – Monthly evolution of the peak delivered luminosity for the four main experiments of the LHC and the corresponding integrated luminosity [7].

1.4 Operations and Schedule

Over the past years, the LHC has been building up in energy but also in luminosity in order to reach its nominal values of 14 TeV and 10^{34} cm^{-2} s^{-1}. Figure 1.5 depicts the schedule of the LHC for the coming years throughout 2037 and the corresponding luminosities: peak on the left axis and integrated on the right axis. It can be seen that several LSs are planned in order to upgrade the LHC and allow the experiments to perform some maintainance and improvments. A noticible increase in peak luminosity happens after LS3 and marks the beginning of the so-called Phase2 operation of the LHC. Such an increase in luminosity will affect the experiments due to the higher number of p-p collisions during each BX which will in turn translated to a higher flux of particles in the detectors. Preparing the LHC and the detectors to function at such high luminosity is a challenge to which physicists and engineers are already providing answers.

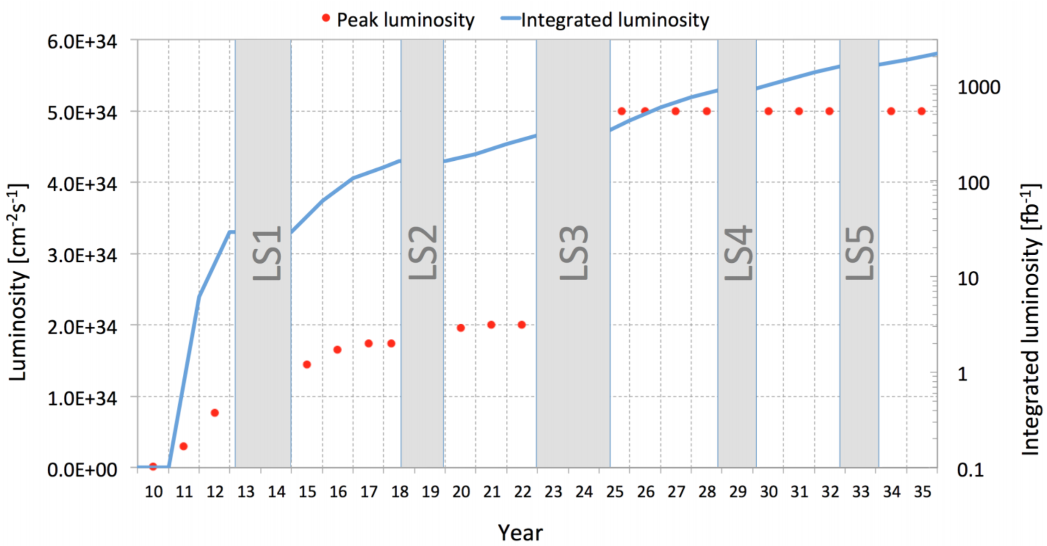

Figure 1.5 – Projected instantaneous and integrated luminosity of the LHC throughout 2037 [CERN].

1.5 Scientific Motivations

The high energy and luminosity at which the LHC operates are the key factors of its success. Reaching new energy levels enables scienctists to discover new hidden sectors of physics as new particles can be created through processes that were previously not able to be produced. Moreover, due to the rarity of these events that lie beyond the standard model, it is import to accumulate a large statistics and thus run the machine at high luminosity.

The discovery of the Brout-Englert-Higgs boson is one of the main goals of the LHC which has already been fulfilled. However, the caracterisation of the particle still requires a great amount of analysis in order to, for example, quantify the coupling constants to fermions on weak bosons. Moreover, it is not excluded that other scalar bosons exist at higher energy as predicted by some theories. In this case, the upgrade of the LHC becomes a necessity to detect the new exotic physics at play.

Not only physics beyond the standard model is being explored by the LHC. Measuring the free parameters of the theory and comparing them to theoretical and previously experimentally obtained values is also an important task which helps validating the models. Reaching new luminosities allows to study rare processes such as the B_S^0 meson decay, $\bar{b}s \rightarrow \mu + \bar{\mu}$, which was first observed at the LHC.

The measurments and observations described here above are done by the detectors which are installed on the LHC using the collisions it provides. From the four experiments the LHC hosts, two of them, namelly ATLAS and CMS, are considered to be generalistic as they are built to detect a wide range of interactions. ALICE and LHCb on the other hand are optimized to study respectivly Pb-Pb interactions at lower energy but which result in a higher density of collisions, and b quark physics to understand the CP violation.