

Collider Physics an Experimental Introduction

To cite this article: Carmine Elvezio Pagliarone 2011 *J. Phys.: Conf. Ser.* **287** 012005

View the [article online](#) for updates and enhancements.

Related content

- [High-energy particle accelerators](#)
M C Crowley-Milling
- [Trends in high energy particle accelerators](#)
S Tazzari and M Ferrario
- [Spin-polarized charged particle beams](#)
S R Mane, Yu M Shatunov and K Yokoya



IOP | ebooks™

Bringing you innovative digital publishing with leading voices
to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of
every title for free.

Collider Physics an Experimental Introduction

Journal of Physics: Conference Series

Carminc Elvezio Pagliarone¹

Università di Cassino & INFN Trieste, Italy

E-mail: pagliarone@fnal.gov

Abstract. This paper reviews shortly a small part of the contents of a set of lectures, presented at the XIV International School of Particles and Fields in Morelia, state of Michoacán, Mexico, during November 2010. The main goal of those lectures was to introduce students to some of the basic ideas and tools required for experimental and phenomenological analysis of collider data. In particular, after an introduction to the scientific motivations, that drives the construction of powerful accelerator complexes, and the need of reaching high center of mass energies and luminosities, some basic concept about collider particle detectors will be discussed. A status about the present running colliders and collider experiments as well as future plans and research and development is also given.

1. Introduction

The need of understanding the nature and its laws in the sub-nuclear domain has always been the driving force behind the development of particle accelerators and particle detectors and related techniques. Particle physics experiments, at the highest possible energies, with their unique ability to explore the uncharted territory at the energy frontier have been providing and will provide exciting opportunities for great scientific advances. In the past four decades, hadron colliders such as the Intersecting Storage Rings (ISR, CERN), that on January 27th 1971 delivered the first pp collision [1], the Tevatron Collider, the Fermilab $p\bar{p}$ machine, and at the present the Large Hadron Collider (LHC, CERN) have held the high-energy frontier resulting in the discovery of the W and Z-bosons [2], the top quark [3, 4, 5], together with other particles and other important measurements. Very important test about the Standard Model of Particle Physics (SM) have been performed using lepton colliders such as the Large Electron Positron (LEP) at CERN, the Positron Electron Project (PEP) at SLAC (the first e^+e^- linear collider in the history) and the Hadron Electron Ring Accelerator (HERA) an ep collider at DESY. Other collider facilities, specifically, designed to produce a large number of B mesons, the so-called B-factories, such as the PEP-II at SLAC or KEKB at KEK in Japan have been used to intensively and widely studying the CP violation. In the next years, LHC will provide, excellent chances to discover the Higgs boson and new physics at the TeV scale, while the Tevatron collider experiments will end collecting data by September 2011, continuing the process of analyzing the collected data for other years, contributing to the process of searching for new physics.

¹ To whom any correspondence should be addressed.

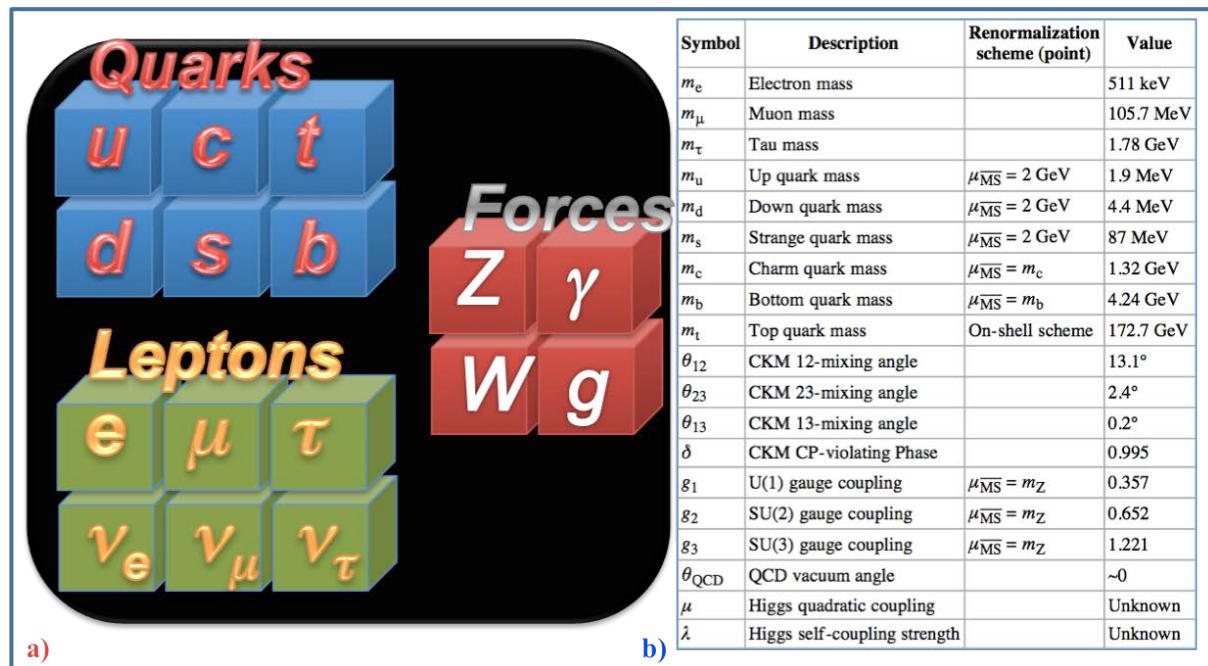


Figure 1: a) The “Periodic Table” of Particle Physics; b) list of the Standard Model free parameters and their values, as measured up today [6].

2. The Physics challenge

The Standard Model of Particle Physics represents the simplest and most economical theory, which is able to describe jointly weak and electromagnetic interactions. At present it continues to survive all experimental tests, providing a remarkably successful description of known phenomena; some precision observable tests it at 10^{-3} (see Fig. 1.a and Fig. 1.b) [7]. In spite of that, there are plenty of aspects that we do not understand yet and that may suggest the SM to be most likely, a low energy effective theory of spin-1/2 matter fermions interacting via spin-1 gauge bosons. As matter of fact, the SM leaves many important questions unanswered. It is also widely acknowledged that, from the theoretical standpoint, the SM must be part of a larger theory, “beyond” the SM (BSM), which is yet to be experimentally “confirmed”. Within the kinematic regime and the viable physical signatures, which have been possible to explore so far, none, of the ample spectrum of particles, predicted by models beyond the SM [8], as well as the Higgs boson, that is a key building block of the SM, has been found so far. Most of these particles may have, depending on the theoretical scenario under consideration, production cross-sections that lies well below the most common QCD production cross sections, as shown in Fig. 2.a and in the case of LHC in Fig. 8.a. The basic formula for evaluating the cross section and kinematic distributions for a $2 \rightarrow N$ scattering process is the following:

$$d\sigma = \frac{1}{2s} \left(\prod_{i=1}^N \frac{d^3 p_i}{(2\pi)^3} \frac{1}{2E_i} \right) \cdot (2\pi)^4 \delta^4(p_A + p_B - \sum p_i) \cdot |M(p_A, p_B \rightarrow \{p_i\})|^2 \quad [1]$$

where M is the invariant matrix element, also know as scattering amplitude, and $p_i = (E_i, \vec{p}_i)$ are the 4-momenta of the final-state particles. Note that M contains the entire information specific for the process under consideration, information such as coupling constant dependence and so on, whereas all other ingredients are simply kinematic factors common for any $2 \rightarrow N$ process. Equation [1] is written in the center of mass (cms) frame of the colliding particles, it is in fact invariant under boosts parallel to the collision axis. This feature is important when we consider, in particular, hadron collisions. If the colliding beams are unpolarized, one needs to average the quantity $|M|^2$ over all possible initial-states

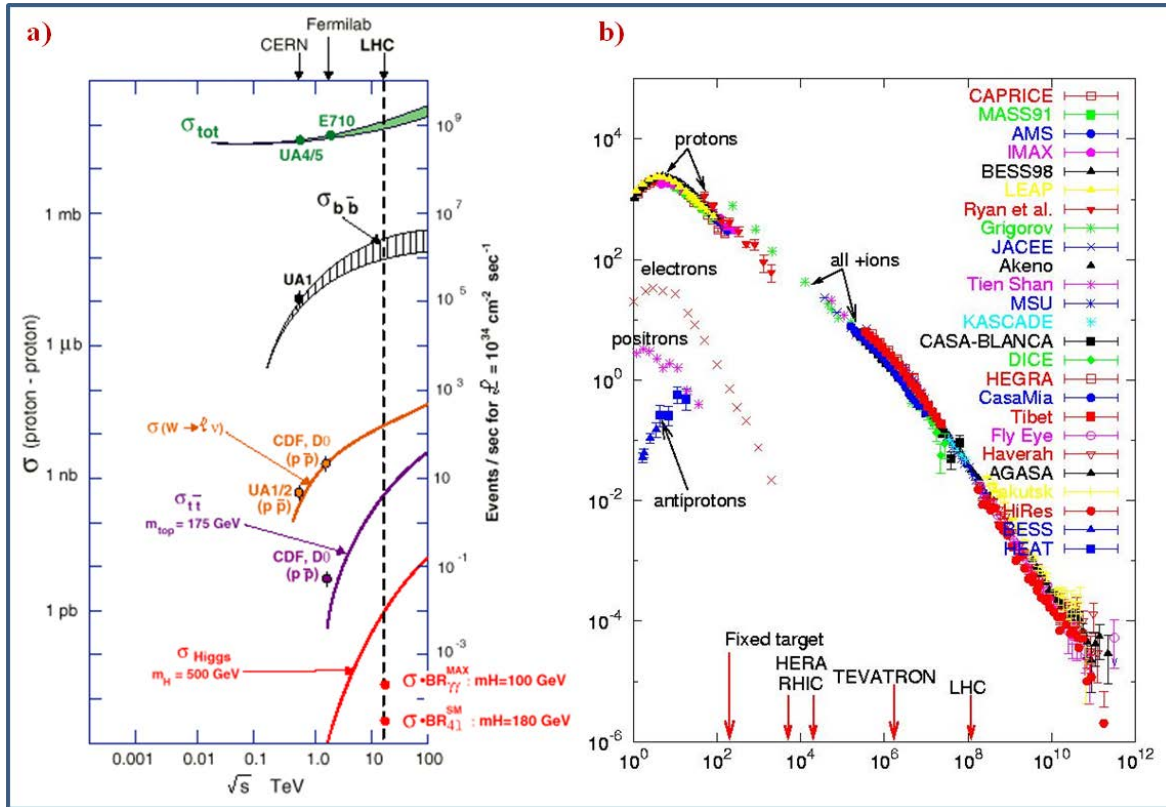


Figure 2: a) pp and $p\bar{p}$ cross-sections as a function of the center of mass energy $\sqrt{s}$ [9]; b) global view of the full measured cosmic ray spectrum as performed by several different experiments [10].

polarizations. If the beams are polarized (this was the case of the Stanford Linear Collider, SLC, and may be implemented at the ILC), an appropriately weighted average should be computed instead. In addition, if the final-state particles have spin, $|M|^2$ should typically be summed over all possible spin states, since no collider detector is capable of detecting spins of individual particles. (Exception occurs when the final-state particles decay promptly, in which case the angular distribution of their decay products may carry information about their polarization state.) The appropriately averaged and/or summed squared scattering amplitude will be denoted by $|M|^2$. A summary of the cross sections, for the most important SM processes and not, in the case of pp and $p\bar{p}$ collisions, as a function of $\sqrt{s}$, is given in Fig. 2.a and in Fig. 8.a for the LHC case. The total scattering cross section $\sigma_{Tot} \approx 0.1 \text{ bn}$ is completely dominated by low- $p_\perp$ pure QCD scattering, and depends only weakly (logarithmically) on the center of mass energy ($\sqrt{s}$). The inclusive cross section for b-quark production is 2÷3 orders of magnitude lower, reflecting the effective $p_\perp$ cutoff provided by the b-quark mass. The strongest electroweak processes, inclusive W and Z production, have cross-sections of order 10÷100 nb; in other words, there is one electroweak boson produced per 1÷10 million of pure QCD events. Of course, the Data Acquisition System (DAQ) of each experiment does not collect the vast majority of these purely QCD events, as they are not relevant for most of the searches for physics beyond the SM or for the SM Higgs searches or for other specific SM channels under investigation. For this reason is common to use specific “trigger” systems (triggers), that may be hardware or software or both of them, with single or multiple trigger levels, able to select, with high efficiency and large background rejection, those events that match specific final state topologies. Even if triggers are necessary, they anyhow introduce

unavoidable bias. Generally speaking, experiments running on hadron colliders are more sensitive to the need of having more complex trigger systems.

3. Particle Accelerators

When J. J. Thomson discovered the electron, he did not call the instrument, he was using, an accelerator, but in reality it was an accelerator as electron was accelerated between two electrodes to which he had applied a difference in electric potential. He manipulated the resulting beam with electric and magnetic fields to determine the ratio between the charge and the mass of the so-called cathode rays (q_e/m_e). Thomson achieved his discovery by studying the properties of the beam itself not its impact on a target or on another beam, as we do today. Accelerators have, since that time, become indispensable in the quest to understand Nature at smaller and smaller scales. And although they are much bigger and far more complex, they still operate on much the same physical principles as Thomson's device. It took another half century, however, before accelerators became entrenched as the key tools in the search for subatomic particles. The energies and techniques have changed, but the scientific methods have not. These machines, often little known, in the world outside particle physics, are extensively used for general industrial use (~1500 machines for sterilization, imaging, etc.), ion implantation and surface implantation (~6000 machines for controlled semiconductor doping, change of surface properties, etc.), radioisotope production (~200 machines for cancer treatment, imaging organs for medical use, etc.), radiotherapy (~4500 machines for cancer treatment with X-rays, protons, neutrons and ions) and research (~1200 machines for producing synchrotron light for biomedical, physics, chemistry, biology, material research) [11].

3.1. The Cosmic Accelerator

Before starting to describe as a collider work we want to remind that the most energetic collisions, available for experimental analysis, do not occur in the particle colliders rather they are produced during the collision of cosmic ray primaries (CRs) with nuclei in the Earth atmosphere [12]. The spectrum of those particles has been measured, extensively, over more than ten orders of magnitude in energy ($E < 10^{11}$) and about 30 orders of magnitude in flux. Figure 2.b shows a global view of the full measured cosmic ray spectrum as performed by several different experiments [13]. It is believed that most CR primaries are accelerated in shock fronts, surrounding celestial bodies [14]. The basic requirement, for such acceleration mechanisms to work, is that there must be a sufficiently strong magnetic field B extending over a sufficient length L giving rise to a sufficiently large energy CR primaries. In this scenario, the neutral primaries would have to be produced when charged particles collide with the matter, but these would require even higher energies for the charged particles than what is commonly observed on the Earth. It is possible, in principle, to use high energy cosmic rays to make studies similar to the one we do using particle colliders. Of course these studies are performed but, because of the very low particle flux, the number of events, expected, is very small even if we construct very large surface detectors. In many cases, anyhow, the study of Ultra High-energy Cosmic Rays (UHCs) is very useful and complementary to the study performed using particle colliders [15].

3.2. Colliding beams and the Energy frontier

Colliders are only the last product of the evolution of devices built in order to perform violent collisions of particles on other particles. Earlier version used accelerated beams impinging on fixed targets. The focus is on colliding beam machines (colliders) because they provide the highest center of mass energies. As matter of fact if $p_\mu(j) = (E_j, \vec{p}_j)$, with $j=1,2$, are the 4-momenta of the two colliding particles of mass m_1 and m_2 we have that the center of mass energy, during the collisions is:

$$E_{CM} = (p_\mu(1) + p_\mu(2)) = (p^\mu(1) + p^\mu(2)) = \sqrt{m_1^2 + m_2^2 + 2E_1E_2 + 2\vec{p}_1\vec{p}_2} \approx \sqrt{4E_1E_2} \quad [2]$$

In the case of a fixed target experiment, in the laboratory frame, assuming that the particle 1 is the fixed target particle of mass m_t and the particle 2 is the colliding beam of mass m_b with a beam

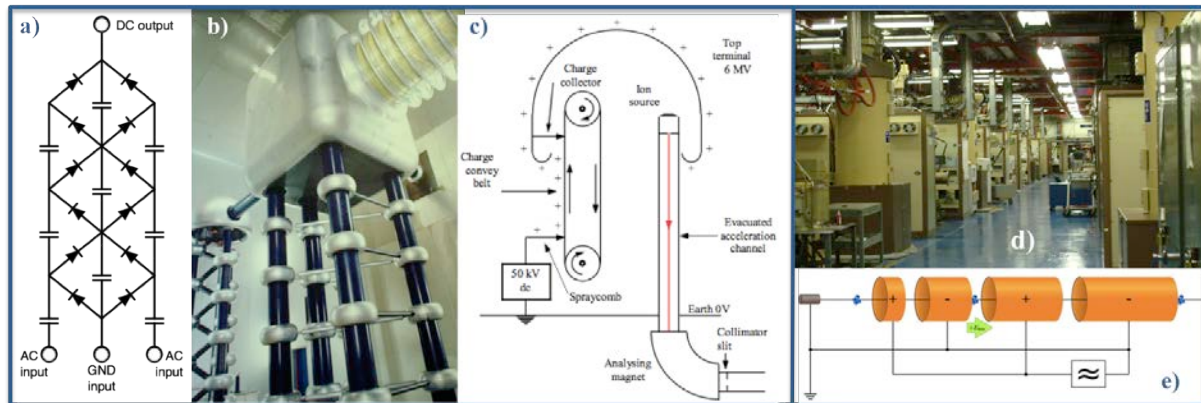


Figure 3: a) Schematic view of a Cockcroft-Walton generator; b) the Fermilab Cockcroft-Walton accelerator [16]; c) a schematic view of a generic Van de Graaff generator with an accelerator inside; d) the Fermilab Linac Klystrons and Klystron modulators; e) schematic description of the linac working principle [16].

energy of E_B , we have: $p_\mu(1) = (m_T, 0)$ and $p_\mu(B) = (E_B, \vec{p}_B)$, then, for a fixed target collision, the center of mass energy will be lower:

$$E_{CM} = \sqrt{m_T + m_B + 2m_T E_B} \approx \sqrt{2m_T E_B} \quad [3]$$

R. Widerow laid down, for the first time in the history of physics, the concept of a particle collider in a German patent that was registered in 1943 but not published until 1952. It proposed storing beams and allowing them to collide repeatedly so to obtain a high energy in the center of mass. This result has been achieved, after several years of fixed target experiments, only the 27 January 1971, 40 years ago, when two beams of protons collided for the first time in the CERN Intersecting Storage Rings (ISR) [1]. It was the world's first hadron collider, and ran from 1971 to 1984, achieving the maximum center of mass energy of 62 GeV. From its initial startup, the collider itself had the capability to produce particles like the J/ψ and the ψ , as well as to observe jets; however, the particle detector experiments were not configured to observe events with large momentum transverse to the beamline, leaving these discoveries to be made at other experiments in the mid-1970s. Nevertheless, the construction of the ISR involved many advances in accelerator physics, including the first use of stochastic cooling, and it held the record for luminosity at a hadron collider until surpassed by the Fermilab Tevatron collider in 2004.

In order to achieve very high-energy collisions a set of different kinds of particle accelerators is needed. Each specific accelerator operate to step-up the beam energy up to some level and deliver the beam to the next machine until the beam will not reach the energy needed to be injected into the collider. Later on we will give an example of this, describing how the two presently running colliders, the Tevatron collider and the Large Hadron Collider work.

Cockcroft-Walton and Van de Graaff Accelerators

Common to all accelerators is the use of electric fields for the acceleration of charged particles; however, the manner in which the fields are applied varies widely. The most straightforward type of accelerators results from the application of a potential difference between two terminals. To obtain more than about 200 kV of accelerating voltage, it is necessary to use one or more stages of voltage-doubling circuits. J. D. Cockcroft and E. T. S. Walton built the first of such a device in 1932. Cockcroft-Walton accelerators are still widely used nowadays as injectors for much larger accelerators (see Fig. 3.a and Fig. 3.b). Another kind, pioneered at beginning of 1929 by R. J. Van de Graaff is the Van de Graaff accelerator, in which a high potential difference is built up and maintained on a smooth conducting surface by the continuous transfer of positive static charges from a moving belt to the

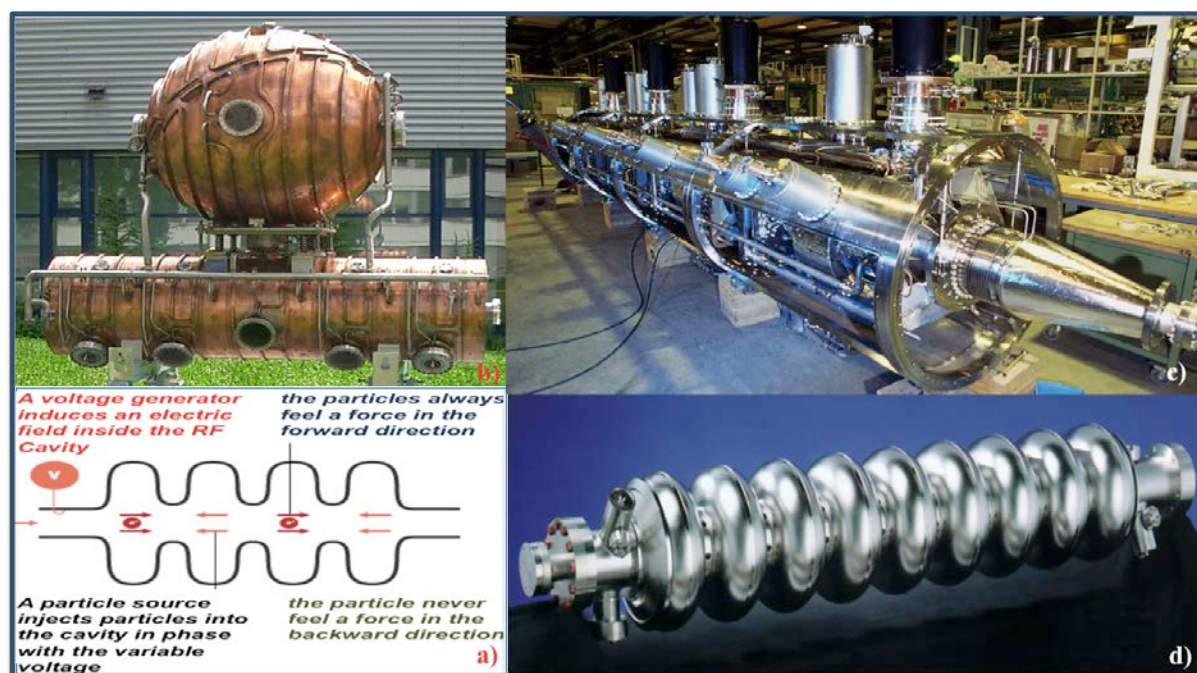


Figure 4: a) Schematic description of the acceleration process inside a RF cavity; the particles feel, always, a force in the forward direction; b) detail of a LEP RF cavity [17]; c) a LHC Four-cavity module during the assembly [18]; d) ILC 1.3 GHz nine-cell superconducting RF cavity [19]. These niobium cavities are supposed to operate at an accelerating gradient of 31.5 MV/m.

surface (see Fig 3.c). The limitation of these types of accelerators arises from the maximum practical potential difference that can be held by the charged surfaces.

Linear Accelerator

In a linear accelerator (Linac), an ion is injected into an accelerating tube containing a number of electrodes. A high-frequency alternating voltage, from an oscillator, is applied between groups of electrodes. An ion traveling down the tube will be accelerated in the gap between the electrodes if the voltage is in the proper phase. The distance between electrodes increases along the length of the tube so that the particle stays in phase with the voltage (see Fig. 3.d and Fig. 3.e). R. Wideroe built the first linear accelerator in 1928. Since that time, a sizable number of linear accelerators, also called linacs, have come into operation, both for electron and proton acceleration, as well as several heavy-ion linacs. In the next sections we will discuss the evolution of linacs with the use of superconducting Radio Frequencies (RF) cavities (SCRf).

Cyclotron

The best known and one of the most successful devices for acceleration of ions to millions of electron volts is the cyclotron, which was invented by E. O. Lawrence in 1929. The first working model produced 80 keV protons in 1930. A cyclotron, as well as a linac, uses multiple acceleration by a RF electrical field. However, the ions in a cyclotron are constrained by a magnetic field to move in a spiral path. The ions are injected at the center of the magnet between two semicircular electrodes called dees. As the particle spirals outward it gets accelerated each time it crosses the gap between the dees. The time it takes a particle to complete an orbit is constant, since the distance it travels increases at the same rate as its velocity, allowing it to stay in phase with the RF. As relativistic energies are approached, this condition breaks down, limiting cyclotrons in energy. However, cyclotrons are still in use all over the world for nuclear science studies, radioisotope production, and medical therapy.

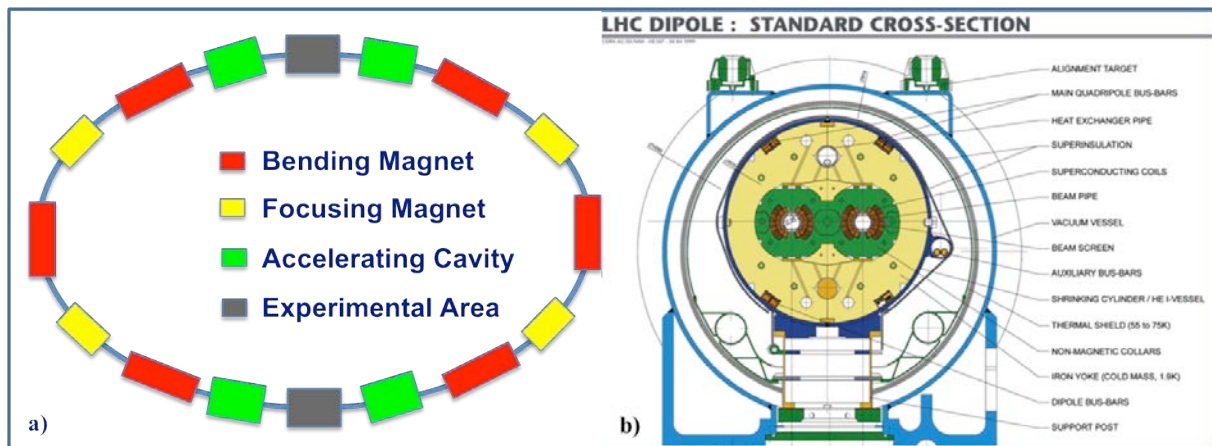


Figure 5: a) A schematic view of a generic circular collider; b) cutaway of a LHC dipole [18]. Two opposite sign dipolar fields are used to make the proton bunches circulating in opposite directions.

Synchrotron

The synchrotron was developed to overcome the energy limitations of cyclotrons imposed by special relativity. In a synchrotron, the radius of the orbit is kept constant by a magnetic field that increases with time as the momentum of a particle increases. The acceleration is provided by a RF oscillator that supplies an energy increment every time the particle beams cross an accelerating gap.

Main collider components

In a circular accelerator, particles circulate in a vacuum tube and are manipulated using electromagnetic devices: dipole magnets keep the particles in their nearly circular orbits, quadrupole magnets focus the beam, and accelerating cavities are electromagnetic resonators that accelerate particles and then keep them at a constant energy by compensating the Larmor energy losses, described in the next section. Fig. 4.a gives a schematic description of the acceleration process inside a RF cavity, where the particles feel, always, a force in the forward direction. In Fig. 4.b, Fig. 4.c and Fig. 4.d we show a LEP RF cavities, a LHC SCRF cavity and an example of a 1.3 GHz nine-cell SCRF cavity for the International Linear Collider (ILC). The LHC and ILC colliders will be described in some detail later. A schematic description of a generic circular collider is given in Fig. 5.a together with a cutaway of a LHC dipole (see Fig 5.b).

3.3. The Luminosity Frontier

Luminosity of a high-energy collider is a key parameter that is second, in importance, only to the collider energy reach. Luminosity measures the flux of particles capable of creating a reaction of interest. The reaction rate (R), that is the number of events produced in a collision per unit time, is directly proportional to the luminosity and is given by the following equation:

$$R_X(t) = \sigma(AB \rightarrow X + \sum_j Y_j; E) L(t) \quad [4]$$

where $\sigma(AB \rightarrow X; E)$ is defined to be the total X particle production cross section. Though the units for the cross section are conventionally taken as cm^2 , these units are too big in order to be used for sub-atomic particle scattering, and thus more suitable units, called a barn, are introduced as follow: $1 \text{ cm}^2 = 10^{24} \text{ barn} = 10^{27} \text{ mb} = 10^{36} \text{ pb} = 10^{39} \text{ fb} = 10^{42} \text{ ab}$. It may also be convenient to use these units for the luminosity accordingly like $1 \text{ cm}^{-2} \text{ s}^{-1} = 10^{-33} \text{ nb}^{-1} \text{ s}^{-1}$. If we call N , the total number of event produced in a collider, for a given process, after an “effective” running time T , we will have:

$$N_X = \sigma(AB \rightarrow X + \sum_j Y_j; E) \int_0^T L(t) dt \quad [5]$$

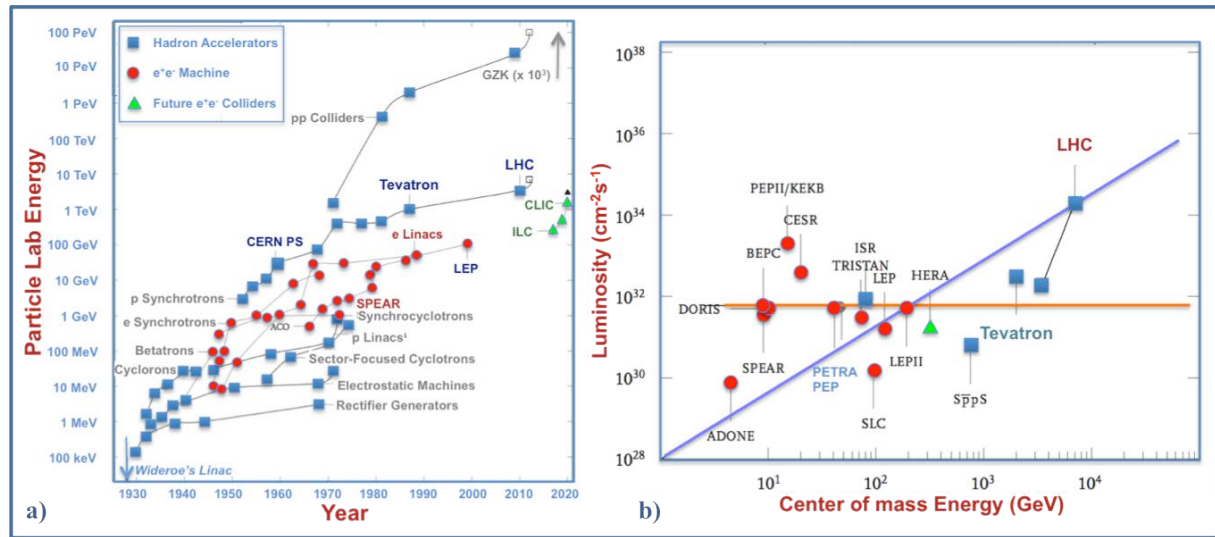


Figure 6: a) Livingston plot showing the historical exponential growth with time in the energy reach from Wideröe's Linac to the GZK limit (solid symbols are for existing machines, open symbols are for nonexistent machines); b) Panofsky plot showing the collider luminosity versus $\sqrt{s}$ [20].

For a given integrated luminosity the number of events observed in an experiment is:

$$N_{obs} = \sigma(AB \rightarrow X + \sum_j Y_j; \sqrt{s}) \times \epsilon_{Detection} \times \int_0^T L dt + N_{Background} \quad [6]$$

where $\epsilon_{Detection}$ is the probability that a signal event will be observed in a given detector and depends from the overall detector and trigger efficiency and acceptance and $N_{Background}$ is the number of events produced from other processes that got counted incorrectly between the signal events. At colliders, the luminosity depends on both the beam intensities and the beam densities and it is generally defined as 4-dimensional overlap integral of two colliding bunches in space and time and in the ultrarelativistic limit given by:

$$L = f_c \int \int \int \int_{-\infty}^{+\infty} \rho^A(x, y, s + ct) \rho^B(x, y, s + ct) 2c dt ds dx dy \quad [7]$$

where ρ^A and ρ^B are the particle distributions within the bunches. Note that the relative velocity of the colliding bunches in laboratory space is $2c$ and $f_c = c/b$ is the collision frequency with b the distance between successive bunches in the beam, as shown below.

If we assume a Gaussian distributions for ρ^A and ρ^B and, for simplification, we also assume

$$\dots \left(\begin{array}{c} \bullet \bullet \bullet \bullet \\ \bullet \bullet \bullet \bullet \\ \bullet \bullet \bullet \bullet \end{array} \right) \xrightarrow[t = 1/f]{} \left(\begin{array}{c} \bullet \bullet \bullet \bullet \\ \bullet \bullet \bullet \bullet \\ \bullet \bullet \bullet \bullet \end{array} \right) \dots$$

identical *rms* beam parameters for both beams and we also allow the beams to collide not head-on but at a small crossing angle where $2\theta \ll 1$ we may write:

$$L = \frac{f_c N_A N_B}{4\pi \sigma_x^* \sigma_y^*} S \quad [8]$$

where σ_x^* and σ_y^* are the *rms* beam radii, at collision point. The beam radii before and after the interaction point are expressed as follow:

$$\sigma_j = \sigma_j^* \sqrt{1 + \left(\frac{s}{\beta_j^*} \right)^2}, \quad j = x, y \quad [9]$$

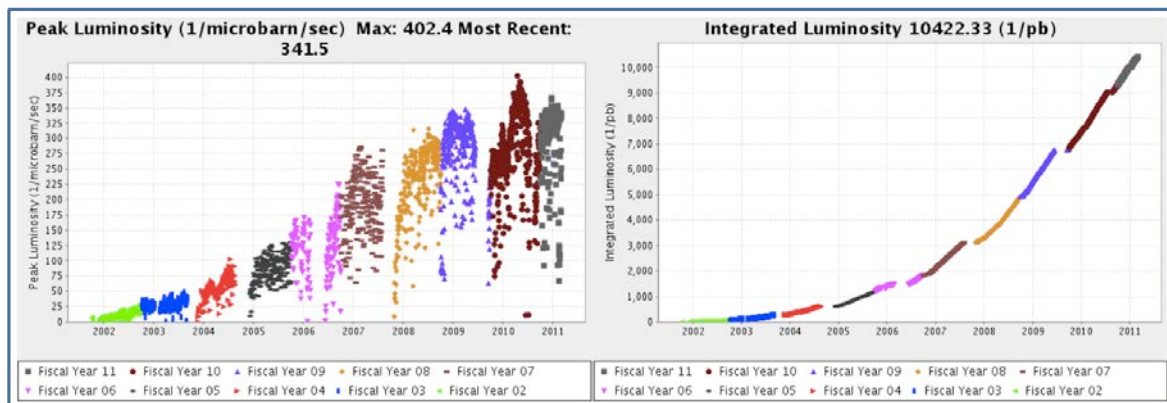


Figure 7: a) Tevatron collider peak luminosity as a function of time; the growth in machine performances is clearly visible [21]; b) Tevatron integrated luminosity as a function of time [21].

The luminosity suppression factor S describes the increase of effective interaction area due to the divergence from the formula and to the crossing angle between the beams. Equation 8 can be recast in terms of emittances and amplitude functions as

$$L = f \frac{n_1 n_2}{\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}} \quad [10]$$

Then, in order to achieve high luminosities, all one has to do is make high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible. M. Stanley Livingston, that was the first student of Ernest Lawrence to build the first cyclotrons, plotted the laboratory energy versus calendar year. The Livingston chart shows, in a very striking way, how the succession of new ideas and new technologies has relentlessly pushed up accelerator beam energies over five decades at the rate of over one and a half orders of magnitude per decade (see Fig. 6.a). One repeatedly sees a new idea, which rapidly increases the available beam energy, but only to be surpassed by yet another new idea. Meanwhile the first idea continues into saturation and possibly into quasi oblivion. Figure 6.b shows the Panofsky plot, which gives collider luminosity versus center of mass energy. In Fig. 7.a and in Fig. 7.b are plotted the Tevatron collider peak and integrated luminosities. As it is possible to see, colliders are very complex and sophisticated machine that in order to be brought to the edge need time, upgrades and continues tuning of their performances.

3.4. Synchrotron radiation energy losses

Charged particles emit light when accelerated. These energy losses are often a large problem when designing a very high-energy accelerator and represent an important limiting factor in the maximum attainable energy. An accelerated charged particle emits photons according to the Larmor law:

$$P = -\frac{2}{3} \frac{e^2}{m^2 c^3} \left(\frac{dp_\mu}{d\tau} \frac{dp^\mu}{d\tau} \right) \quad [11]$$

where p_μ is the charged particle's 4-momentum. For a given applied force the radiated power depends inversely on the square of the mass of the particle involved. Consequently these effects are larger in the case of electron beams. In a linear accelerator the motion is one-dimensional consequently:

$$P = \frac{2}{3} \frac{e^2}{m^2 c^3} \left(\frac{dE}{dx} \right)^2 \quad [12]$$

showing that for linear motion the power radiated depends only on the external forces which determine the rate of change of particle energy with distance. The ratio of power radiated to power supplied by the external sources (i.e. a RF cavity) is expressed by following formula:

$$G = \frac{P}{dE/dx} = \frac{2}{3} \frac{e^2}{m^2 c^3} \frac{1}{v} \frac{dE}{dx} \rightarrow \frac{2}{3} \frac{(e^2/mc^2)}{mc^2} \frac{dE}{dx} \quad [13]$$

This equation shows that the radiation loss will be unimportant unless the gain in energy is of the order $mc^2 = 0.511$ MeV in a distance of $e^2/mc^2 = 2.82 \cdot 10^{-15}$ m, that means of the order of $2 \cdot 10^{14}$ MeV/m. In a linear collider such as ILC, assuming a design cavity gradient of about 31.5 MV/m the expected synchrotron radiation energy losses can be considered negligible. The situation changes drastically in the case of a circular accelerator. The radiated power in this case becomes:

$$P = \frac{2}{3} \frac{e^2}{m^2 c^3} \gamma^2 \omega^2 |p|^2 = \frac{2}{3} \frac{e^2 c}{\rho^2} \beta^4 \gamma^4 \quad [14]$$

where $\omega = (c\beta/\rho)$ and ρ is the accelerator radius. The energy loss, per evolution, can be then written as follow:

$$\delta E = \frac{2\pi\rho}{c\beta} P = \frac{4\pi}{3} \frac{e^2}{\rho} \beta^3 \gamma^4 \quad [15]$$

that becomes, in the case of an ultrarelativistic accelerator ($\beta \approx 1$), as follow:

$$\delta E(\text{MeV}) = 8.85 \cdot 10^{-2} \frac{E^4(\text{GeV})}{\rho(\text{m})} \quad [16]$$

the radiated power for a circular accelerators can be then expressed as follow:

$$P[\text{W}] = 10^6 \cdot \delta E(\text{MeV}) \cdot J(\text{A}) \quad [17]$$

If synchrotron radiation is problem when designing a very high-energy accelerator, however, it is an excellent probe of the surface structures of matter and a tool in producing modern microelectronics. As should be expected, synchrotron radiation plays a major role in the design and optimization of the e^+e^- colliders. While vacuum stability and electron clouds can be of concern in the positron rings, synchrotron radiation along with the restoration of longitudinal momentum by the RF system have the positive effect of generating very small transverse beam sizes and small momentum spread. Further reduction of beam size at the interaction points using standard beam optics techniques and successfully contending with high beam currents has led to record luminosities in these rings, far exceeding those of hadron colliders. To maximize integrated luminosity the beam can be “topped off” by injecting new particles without removing existing ones – a feature difficult to imitate in hadron colliders.

3.5. Hadron and Lepton Colliders

The different experimental conditions and, particularly, the different interacting projectiles of hadron and lepton colliders will generally lead to different sensitivities for specific processes at the energy scale under consideration, so the two types of colliders are also complementary to a certain extent and there are advantages to operating both types of machines. This complementarity also applies to the types of lepton colliders e^+e^- and $\mu^+\mu^-$, but a lesser extent. Protons are composite particles, made of “partons” of quark and gluons. The quarks and gluons are the fundamental degrees of freedom to participate in strong reactions at high energies according to QCD. The proton is much heavier than the electron. These lead to important differences between a hadron collider and an e^+e^- and $\mu^+\mu^-$ collider. Due to the heavier mass of the proton, hadron colliders can provide much higher center of mass energies in head-on collisions. Lepton colliders can provide on the other hand precise measurements and perform studies using polarized beams. We do not want here to use, anyhow, the common point of view according to which the hadron collider are discovery machines and lepton colliders provides only precise measurements as particles like J/ψ , Y , the jets, the gluons, etc. have been for example discovered in e^+e^- colliders and, on the other hand, a hadron collider like Tevatron performed and is performing the most precise measurement of M_W mass. A summary of most relevant collider parameters of past, present and future machines both for lepton-lepton, hadron-hadron and e-p colliders can be found here [12].

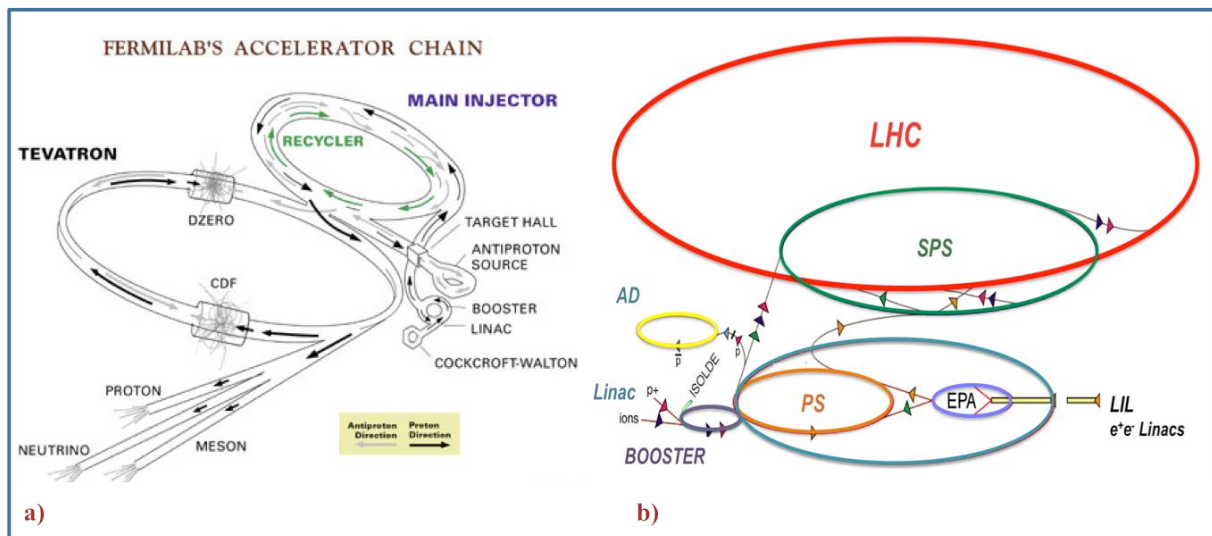


Figure 8: a) Fermilab Tevatron Collider complex [22]; b) the CERN Large Hadron Collider [18].

3.5.1. The Fermilab Tevatron Collider

In order to offer a more detailed description of how a collider works we will describe, with more details, the Tevatron collider and accelerator complex. The Tevatron is a circular particle accelerator at the Fermi National Accelerator Laboratory (FNAL) close to Batavia, Illinois (USA). The Tevatron Collider has been built in order to accelerate beams of protons and anti-protons and make them collide at center of mass energy of 1.80, during the Run I (1992-1996) and 1.98 TeV, during the Run II (2001-2011). Around 2:30 a.m. on October 13, 1985, scientists, working in the Collider Detector at Fermilab experiment (CDF-II), observed the Tevatron collider's first antiproton-proton collision. The collision's center-of-mass energy was of 1.6 TeV, three times higher than the previous world record set by the Super Proton Synchrotron collider (SPS) at CERN. Over the next 20 years, a steady stream of improvements to the accelerator complex and the collider detectors, some big and some small, kept the Tevatron at the leading edge of particle physics. Researchers with the CDF-II and DØ collaborations continue to exploit the growing Tevatron luminosity, which is now 400 times the 1985 design goal, and have produced a magnificent collection of scientific results. During this initial operating period, called Run I, the top quark was discovered in 1995 [3, 4, 5]. After an upgrade period of almost 5 years, the Tevatron resumed operations in early 2001, at a higher energy of $\sqrt{s} = 1.96$ TeV and higher intensities. The Tevatron has continued to operate at this higher capacity during what is called Run II and is scheduled to be turned off by the end of September 2011, as announced on January 10, 2011. Achieving energy of 980 GeV for each beam requires several acceleration steps, which can be seen in Fig. 8.a. These steps are described in the following sections.

Cockcroft-Walton

The starting point, in the accelerator chain, begins with the Cockcroft-Walton, which is an accelerator that provides a continuous beam of H^- ions at 750 keV. These ions come from the Proton Source, which contains pure hydrogen gas. The hydrogen gas is placed in an electric field, which strips the hydrogen atoms of an electron to become H^+ . These protons (H^+) are then attracted to a cesium anode where they attach and acquire two electrons to become H^- , which is then repelled, by the anode. The Cockcroft-Walton then accelerates these H^- ions to 750 keV.

Linac

A Linear Accelerator, called Linac accepts H^- ions from the Cockcroft-Walton at 750 keV. These ions are accelerated by AC electric fields between successive drift tubes of increasing length. This field is

varied at high frequency such that when exiting a drift tube some of these negative ions will see an electric field pointing in the opposite direction of their velocity in each gap region, which increases their energy. The ions which arrive out of phase with the RF system will be decelerated, and not make it through the entire Linac. The result of this is a beam consisting of bunched H^- ions in the Linac. These bunches are accelerated to an energy of 400 MeV by the Linac. At the end of this 130 m accelerator the H^- ions pass through a thin carbon foil where the electrons are stripped away from H^- leaving H^+ (protons).

Booster

The Booster is the first of several synchrotrons, in the accelerator chain, which accelerates 400 MeV bunches of protons from the Linac to an energy of 8 GeV. This is done in 16,000 revolutions where each revolution is about 475m. This is on average an increase of 475 keV per revolution.

Main Injector

The Main Injector is another synchrotron, with a circumference of approximately 3 km, and serves multiple purposes in the accelerator chain. It accelerates 8 GeV protons and anti-protons to 150 GeV for injection into the Tevatron ring. The MI also accelerates 8 GeV protons to 120 GeV, after which they are sent to and collided with a nickel alloy target producing antiprotons through the interaction $p + Ni \rightarrow p + \bar{p} + p + Ni$, with an efficiency of $\sim 20 \times 10^{-6}$. Thus, it takes about 1 million protons to produce 20 antiprotons, due to the low efficiency, which must be selected among the resultant particles. This is done using a lithium lens and pulsing dipole magnet; only negatively charged particles with the mass of a proton will be bent at the angle necessary to continue in the accelerator. The antiprotons are stochastically cooled before they are sent to the Accumulator where they are stored and cooled further.

Debuncher, Accumulator, and Recycler

After the anti-protons are created and filtered out they enter the Debuncher in bunches which tend to have a large energy spread. The debuncher stochastically cools this beam translating the large energy spread into a large time spread such that the anti-protons have a more uniform energy distribution. Anti-protons are sent from the debuncher to the Accumulator roughly every 1.2 s. The accumulator is an 8 GeV storage ring that is used to collect successive injections of anti-protons from the debuncher. After the accumulator has collected a sufficient amount of anti-protons they will be transferred to the Recycler which is an 8 GeV storage ring made of permanent magnets. Anti-protons will be transferred from the recycler to the main injector before they are put into the Tevatron.

Tevatron Collider

The Tevatron Collider is a superconducting synchrotron with a circumference of 6.3 km that accelerates both protons and antiprotons from 150 GeV to their final energy of 980 GeV. The two beams are steered in opposite directions in the same beam-pipe by a set of niobium-titanium superconducting magnets; these 774 dipole magnets, 240 quadrupole magnets with a maximum magnetic field of 4.2 T, and dozens of other types of magnets are cryogenically cooled by liquid helium at a temperature of 4.2 K. Electrostatic separators keep the beams from colliding except at two points along the ring – these points are where the detectors, CDF-II and DØ, are located (see Fig. 13.a and Fig. 13.b). Within these detectors, the beams are focused using quadrupole magnets; the width of each bunch is reduced to approximately 35 μm , although the length increases to 30 cm during the focusing. The beams are then crossed to induce collisions at the center of each detector, at a collision rate of approximately 1.7 MHz. The peak luminosity reached by this collider is $4.02 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ the 16th of April 2010 (see Fig. 7.a). Both CDF-II and DØ will be collecting data until the Tevatron collider will be shut down. The total amount of data collected so far is shown in Fig. 7.b.

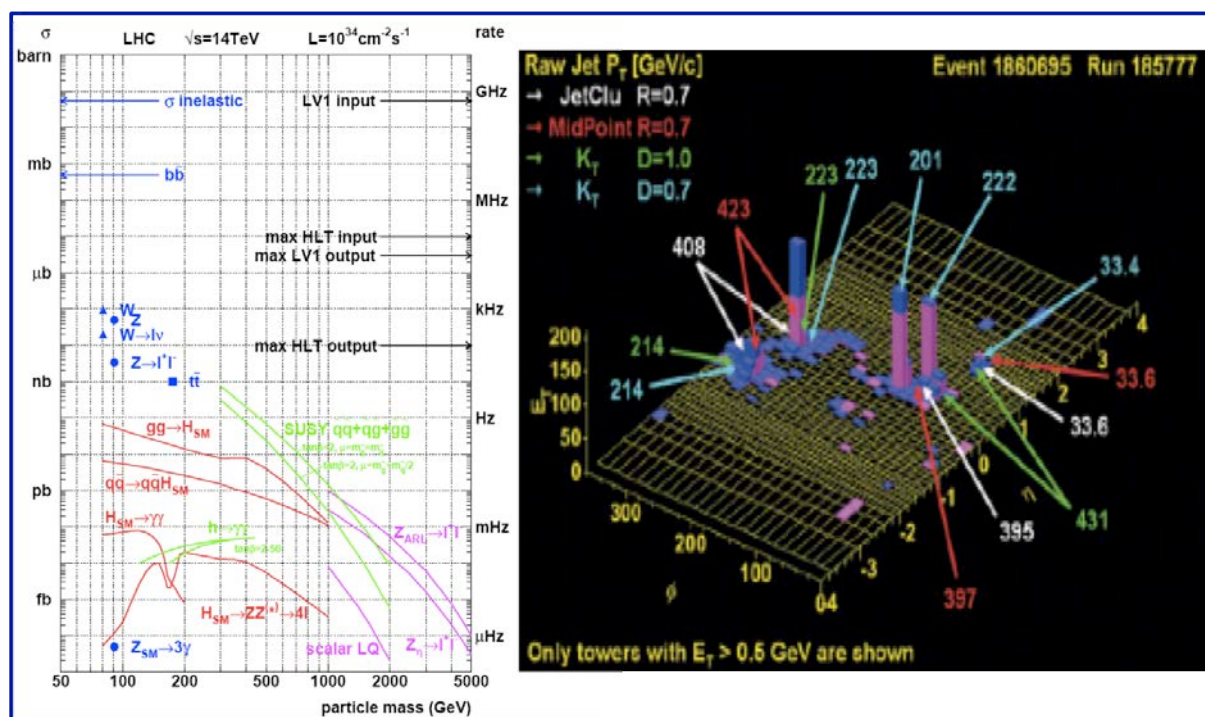


Figure 9: a) Expected production cross-section and rate for several physics processes, assuming a cms energy of $\sqrt{s} = 14 \text{ TeV}$ and a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-2}$; b) A CDF-II QCD candidate event [23].

3.5.2. The CERN Large Hadron Collider

The Large Hadron Collider (LHC), starting from December 2009, is the world's largest and highest-energy particle accelerator complex presently taking data. The collider physical reach for a design luminosity of $\sqrt{s}=14\text{ TeV}$ is reported in Fig. 9.a [24]. LHC has been built by the European Organization for Nuclear Research (CERN), and lies underneath the Franco-Swiss border near Geneva, Switzerland. The collider is contained in a circular tunnel, with a circumference of 27 kilometers, at a depth ranging from 50 to 175 meters underground. The 3.8 m diameter, concrete-lined tunnel, constructed between 1983 and 1988, was formerly used to house the Large Electron-Positron Collider (LEP). The collider tunnel contains two adjacent parallel beam pipes, each containing a proton beam; beam pipes travel in opposite directions around the ring and they intersect at four points. Some 1,232 dipole magnets keep the beams on their circular path, while an additional 392 quadrupole magnets are used to keep the beams focused, in order to maximize the chances of interaction between the particles in the four intersection points, where the two beams will cross. In total, over 1,600 superconducting magnets are installed, with most weighing over 27 tons. Approximately 96 tons of liquid helium is needed to keep the magnets at their operating temperature of 1.9 K, making the LHC the largest cryogenic facility in the world at liquid helium temperature.

The Accelerator complex

The CERN accelerator complex is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy. A schematic overview of the Large Hadron collider accelerator complex is given in Fig. 8.b. The design, LHC center of mass energy is $\sqrt{s} = 14 \text{ TeV}$. At the present, the CERN hadron collider is running at the lower energy of $\sqrt{s} = 7 \text{ TeV}$, reached March 30th 2010, after a previous run at 2.36 TeV. The proton acceleration chain can be summarized as follows:

- Protons are produced by H atoms, stripping off the orbiting electrons (H^+), and sent to a linac that brings their energies up to 50 MeV;
- Protons are then injected into a Proton Synchrotron Booster (PSB) that accelerates them to energy of 1.4 GeV;
- The beam is then fed to the Proton Synchrotron (PS) where it is accelerated to 25 GeV;
- Protons are then sent into the Super Proton Synchrotron (SPS) where they reach energy of 450 GeV.

At this point p can be, finally, injected into the Large Hadron Collider. As this accelerator collides protons with protons, the particles are injected into two different accelerator lines; one accelerates beams clockwise the other anticlockwise by using an opposite sign dipole fields.

The beam time structure

Protons circulate in well defined bunches. As we saw, the bunch structure is a direct consequence of RF acceleration scheme. In the LHC, under nominal operating conditions, each proton beam has 2808 bunches, each bunch containing about 10^{11} protons. The bunch size is not constant around the accelerator, as circulating, it gets squeezed and expanded. When they are far from the collision points, bunches of particles measure a few centimeters long and a millimeter wide. However, as they approach the collision points, they are squeezed to about $16\ \mu\text{m}$ in order to get a higher probability of having a proton colliding another proton. Increasing the number of bunches is one of the ways to increase luminosity in a machine. The LHC has opted for a bunch spacing of 25 ns (about 7 m), which introduces many technical challenges. A beam might circulate for 10 hours, travelling more that 10 billion kilometers; a proton, in the LHC, makes 11 245 circuits per second.

The main accelerator components

In an accelerator, particles circulate in a vacuum tube and are manipulated using electromagnetic devices: dipole magnets keep the particles in their nearly circular orbits, quadrupole magnets focus the beam, and accelerating cavities are electromagnetic resonators that accelerate particles and then keep them at a constant energy by compensating the Larmor energy losses.

- The Vacuum systems: the internal pressure at the LHC is 10^{-13} atm (ultrahigh vacuum), because we want to avoid collisions with gas molecules. There is $\sim 6500\ \text{m}^3$ of pumped volume in the LHC that is like pumping down a cathedral.
- Magnets: there is a large variety of magnets in the LHC, including dipoles (see Fig. 5.b), quadrupoles, sextupoles, octupoles, decapoles, etc. for a total number of about 9300 magnets. Each type of magnet contributes to optimizing a particle's trajectory. Most of the correction magnets are embedded in the cold mass of the main dipoles and quadrupoles. The LHC magnets either have a twin aperture (for example, the main dipoles), or a single aperture (for example, some of the insertion quadrupoles). Insertion quadrupoles are special magnets used to focus the beam down to the smallest possible size at the collision points, thereby maximizing the chances of two protons smashing head-on into each other. The biggest magnets are the 1232 dipoles.
- RF Cavities: the main role of the LHC cavities is to keep the 2808 proton bunches tightly bunched to ensure high luminosity at the collision points and consequently, maximize the number of collisions. They also deliver radiofrequency power to the beam during acceleration to the top energy.

Superconducting cavities with small energy losses and large stored energy are the best solution. The LHC uses eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz (see Fig. 4.c). Cavities operate at 4.5 K (the LHC magnets will use super-fluid helium at 1.8 K). For the LHC they are grouped in fours in cryomodules, with two cryomodules per beam, and installed in a long straight section of the machine where the transverse inter-beam distance has been increased from the normal 195 mm to 420 mm. The precision level of LHC machine is so extreme that phenomenon like tides in the ocean can alter its activities. At the new Moon and when the Moon is

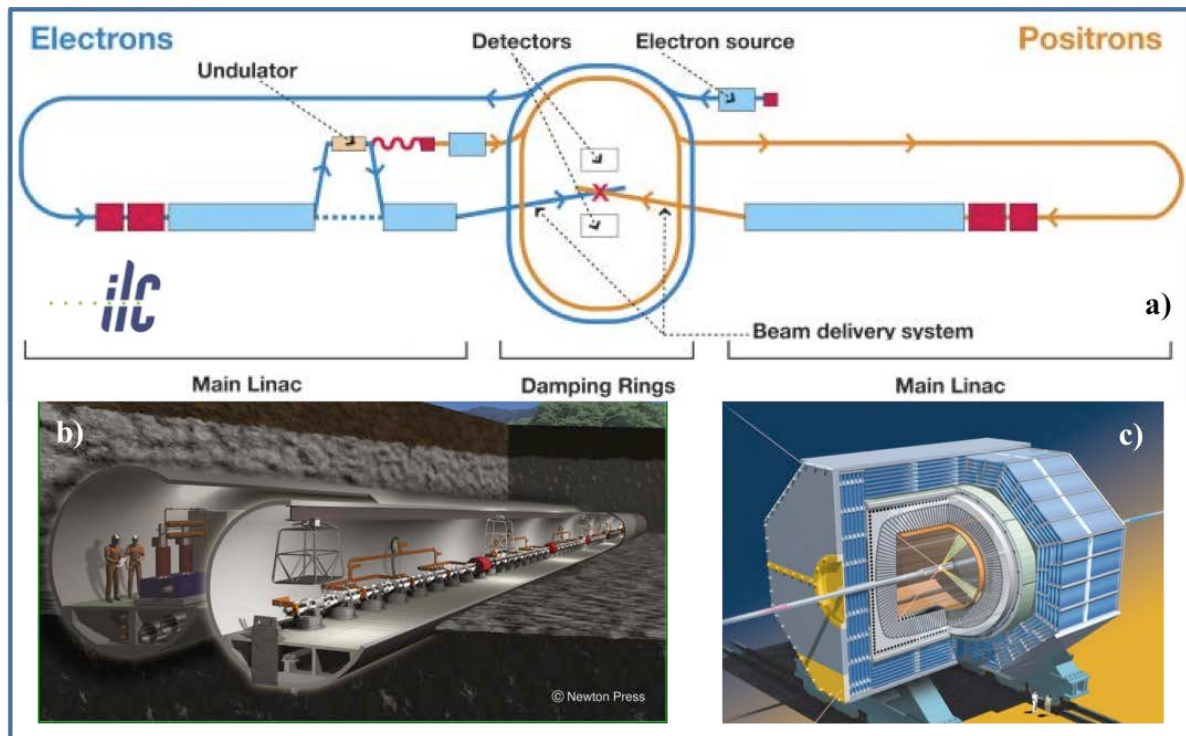


Figure 10: a) ILC general layout [19]; b) schematic view of the serving tunnel containing the klystrons and the modulators [19]; c) a schematic drawing of a possible ILC detector [19, 25].

full, the Earth's crust rises by some 25 cm in the Geneva area under the effect of these 'ground tides'. This movement causes a variation of 1 mm in the circumference of the LHC.

The LHC dipoles

The dipoles of the LHC represented the most important technological challenge for the LHC design. In a proton accelerator like the LHC, the maximum energy that can be achieved is directly proportional to the strength of the dipole field, given a specific acceleration circumference. At the LHC the dipole magnets are superconducting and able to provide the very high field of 8.3 T over their length. No practical solution could have been designed using 'warm' magnets instead of superconducting ones. The LHC dipoles are realized using niobium-titanium (NbTi) multiwire cables, which become superconducting below a temperature of 10 K.

The LHC Cryogenic System

LHC superconducting magnets sit in a 1.9 K bath of superfluid helium at atmospheric pressure. This bath has been cooled by low-pressure liquid helium flowing in heat-exchanger tubes threaded along the string of magnets. The reliability and effectiveness of this sophisticated cryoloop are key factors in achieving the required magnet performance. Liquid helium is used because it can keep things cool over long distances. In all, LHC cryogenics needed 4×10^4 leak-tight pipe junctions, and 96 t of helium have been required by the LHC machine to keep the magnets at their operating temperature. 60% of the helium is in the magnet cold masses while the remaining 40% is shared between the distribution system and the refrigerators. Eight refrigerators operating at 18 kW and 4.5 K have been used to cool down the LHC machine (36 800 t of mass) in about 2 weeks. There were three main phases: first cool down to 4.5 K, second filling with liquid helium of the magnet cold masses and at last the final cool down to 1.9 K.

A layout of the Compact Solenoid Detector (CMS) and of the ATLAS experiment is given in Fig. 13.c. and Fig. 13.d. A candidate event produced by a pp collision at LHC is given, for the ATLAS detector in Fig. 9.b.

3.6. Future Colliders

Here we want to summarize some of the R&Ds under consideration of the scientific community. Present design activity emphasizes a lepton collider as the next major HEP project following initial results from the LHC. Synchrotron radiation precludes a higher energy successor to LEP. Three alternatives are noted in this section: two approaches to an electron-positron linear collider, the International Linear Collider and the Compact Linear Collider (CLIC) and a muon ring collider. We will discuss shortly also the possibility of realizing a Very Large Hadron Collider.

3.6.1. The International Linear Collider

At present the highest energy accelerators are all circular colliders, but it is likely that limits have been reached in respect of compensating for synchrotron radiation losses for electron accelerators, and the next generation will probably be linear accelerators 10 times the current length. An example of such a next generation electron accelerator could be the ~40 km long International Linear Collider. The maximal center of mass energy is designed to be $\sqrt{s} = 500 \text{ GeV}$, and a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with a possible upgrade to 1 TeV, where physics runs must be possible for every energy above $\sqrt{s} = 200 \text{ GeV}$ and some luminosity for calibration runs is needed at $\sqrt{s} = 91 \text{ GeV}$ [25]. For mass measurements threshold scans are required so that it must be possible to change the beam energy fast in small steps. The total luminosity is required to be around 500 fb^{-1} within the first four years and about 1000 fb^{-1} during the first phase of operation. For the electron beam, polarization with a degree of larger than $\pm 80\%$ is mandatory. For the positron beam, a polarization of more than $\pm 50\%$ is useful which should be relatively easy to achieve with the undulator positron source in the present ILC design. To reduce systematic uncertainties, the polarization direction has to be switchable on the train-by-train basis. Beam energy and polarization have to be stable and measurable at a level of about 0.1%. The ILC is based on 1.3 GHz nine-cell superconducting radio-frequency accelerating cavities that should operate with a nominal accelerating gradient of 31.5 MV/m, a pulse rate of 5 Hz and a beam length of 1 ms with an average beam current in pulse of about 9.0 mA. For a general layout of the International Linear collider, the related tunnel and hypothetical collider experiment see Fig. 10.a, Fig. 10.b and Fig. 10.c. In ILC, the Main Linacs (ML) accelerate the beam from 15 GeV to a maximum energy of 250 GeV at an average accelerating gradient of 31.5 MV/m. The linacs are composed of RF units, each of which are formed by three contiguous SCRF cryomodules containing 26 nine-cell cavities. A picture of a typical 9-cell SCRF cavity is given in Figure 4.d. The positron linac contains 278 RF units, and the electron linac has 282 RF units. Each RF unit has a stand-alone RF source, which includes a conventional or other type pulse-transformer type high-voltage (120 kV) modulator, a 10 MW multi-beam klystron, and a waveguide system that distributes the RF power to the cavities. It also includes the low-level RF (LLRF) system to regulate the cavity field levels, interlock systems to protect the source components, and the power supplies and support electronics associated with the operation of the source. To operate the cavities at 2 K, they are immersed in a saturated He II bath, and helium gas-cooled shields intercept thermal radiation and thermal conduction at 5-8 K and at 40-80 K. The estimated static and dynamic cryogenic heat loads per RF unit at 2 K are 5.1 W and 29 W, respectively. Liquid helium for the main linacs and the RTML is supplied from 10 large cryogenic plants, each of which has an installed equivalent cooling power of ~20 kW at 4.5 K. The main linacs follow the average Earth's curvature to simplify the liquid helium transport. The cryomodule design is a modification of the Type-3 version (Figure 2.2) developed and used at DESY. The Main Linac components are housed in two tunnels, an accelerator tunnel and a service tunnel, each of which has an interior diameter of 4.5 meters. To facilitate maintenance and limit radiation exposure, the RF source is housed mainly in the service tunnel as illustrated in Figure xx.

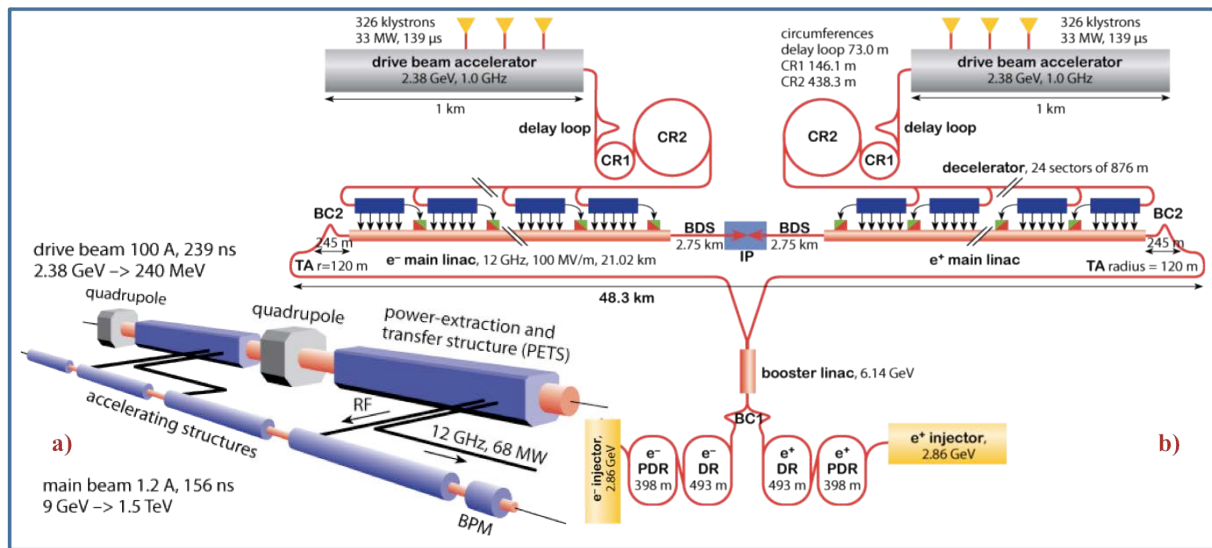


Figure 11: a) Compact Linear Collider (CLIC) module layout; b) the CLIC general layout [26].

The Americas sample site lies in Northern Illinois near Fermilab. The site provides a range of locations to position the ILC in a north-south orientation. The site chosen has approximately one-quarter of the machine on the Fermilab site. The surface is primarily flat. The long tunnels are bored in a contiguous dolomite rock strata (Galena Platteville), at a typical depth of 30-100 m below the surface. The Asian site has been chosen from several possible ILC candidate sites in Japan. The sample site has a uniform terrain located along a mountain range, with a tunnel depth ranging from 40 m to 600 m.

3.6.2. The Compact Linear Collider

The Compact Linear Collider (CLIC) is an under study possible future electron-positron collider that would allow physicists to explore a new energy region beyond the capabilities of today's particle accelerators [27]. It would provide significant fundamental physics information even beyond that available from the LHC and a lower-energy linear e⁺/e⁻ collider, as a result of its unique combination of high energy and experimental precision. Within the framework of a worldwide collaboration on Linear Colliders, the Compact Linear Collider study aims at a center-of-mass energy range for electron-positron collisions of 0.5 to 5 TeV, optimized for a nominal center-of-mass energy of 3 TeV (3 TeV CLIC). In order to reach this energy in a realistic and cost efficient scenario, the accelerating gradient has to be very high - CLIC aims at an acceleration of 100 MV/m. Superconducting technology being fundamentally limited to lower gradients, only room temperature travelling wave structures at high frequency (12 GHz) are likely to achieve this gradient. In order to optimize the production of sufficient RF power for this high gradient, and CLIC relies upon a two-beam-acceleration concept: The 12 GHz RF power is generated by a high current electron beam (drive beam) running parallel to the main beam. This drive beam is decelerated in special power extraction structures (PETS) and the generated RF power is transferred to the main beam. This leads to a very simple tunnel layout without any active RF components (i.e. klystrons). Both beams can be generated in a central injector complex and are transported along the linac. A schematic general layout of the CLIC collider together with the layout of an accelerating module is given in Fig. 11.a and in Fig. 11.b.

3.6.3. The Muon collider

All of the problems with TeV-scale e⁺e⁻ colliders are associated with the relative smallness of the electron mass. The proposed technology of a muon collider aims to solve, or at least greatly reduce, these problems by instead colliding muons, which are leptons that are 207 times heavier than

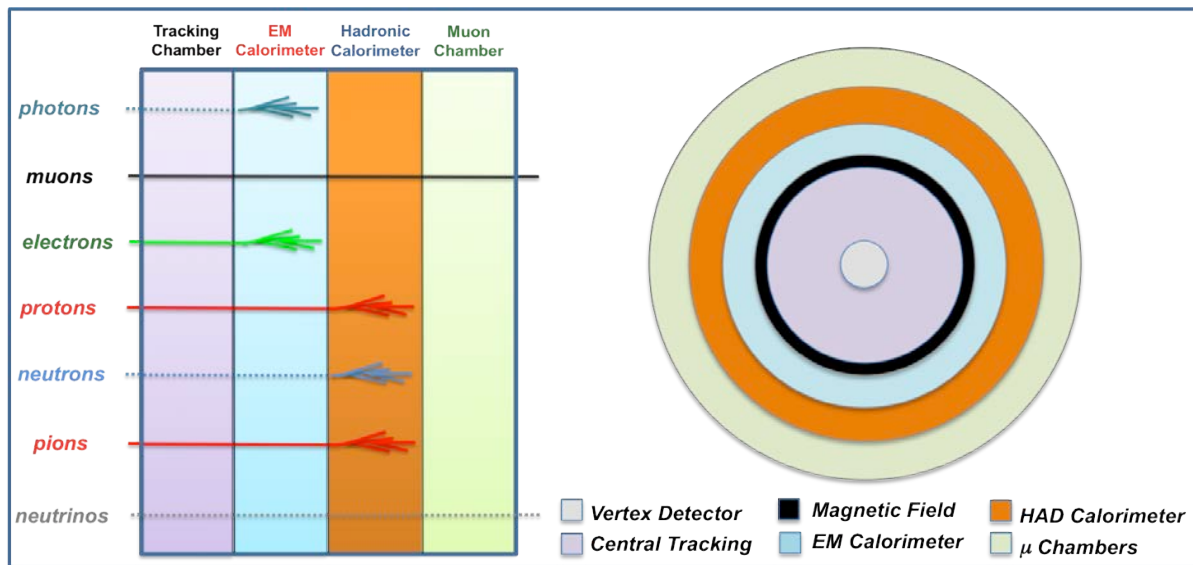


Figure 12: Schematic layout of the central part of a general-purpose collider detector [28].

electrons. Replacing the mass-related problems of e^+e^- colliders, the main problems at muon colliders arise because muons are unstable particles, with an average lifetime of approximately $2.197 \mu\text{s}$ in their rest frame. The preparation, acceleration and collision of the muon beams must all be done quickly and the supply of muons must be replenished often. The products of the muon decays also cause problems: the decay electrons deposit energy all along the path of the muon beams and create backgrounds in the detectors and, more surprisingly, the neutrinos can cause a radiation hazard in the surroundings of the collider ring.

3.6.4. The Very Large Hadron Collider

The Very Large Hadron Collider (VLHC) is a proposed hadron collider with performances significantly beyond the CERN Large Hadron Collider. There is no planned location or time schedule for this machine, as the project has not been approved, so far. In this paragraph we want to discuss, mainly, the technological feasibility of such a collider and the ways that it might be designed. The basic idea of the Design Study [29] consists in constructing a low field (1.9 T) collider (VLHC stage 1) design in a tunnel, which also can be used for a future high field (9.8 T) collider (VLHC stage 2) [30]. While the second collider is seen as far in the future, one needs to anticipate its requirements as best one can before laying out the components of the first machine since they ultimately must reside in same tunnel. This entails anticipating the geometric requirements, beam optics requirements, and physical space requirements for future technical equipment – much of which may not be known yet. The fundamental lattice parameters, common to both low and high field rings are the following. By design, the collider circumference is 233 km with an average arc radius of 35.0 km and two interaction points. The number of buckets should be 41280 and the bunch spacing (53.1 MHz) 5.645 m. In the stage one, the collider is supposed to have 3440 dipoles with a dipole field at collision energy of 1.9 T and delivers proton-proton collision at a center of mass energy of 40 TeV, with a peak luminosity of $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ and a luminosity lifetime or about 24 hours. In this regime the average number of interactions, for beam crossing, is expected to be around 21. In the phase 2 the collider should work at center of mass energy of 175 TeV, with a peak luminosity of $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, and a luminosity lifetime or about 8 hours. In these conditions, an average number of 58 interactions, per beam crossing, is expected. The stage 2 can be reached by using 9728 dipoles with a dipole field, at collision energy, of 9.8 T [31].

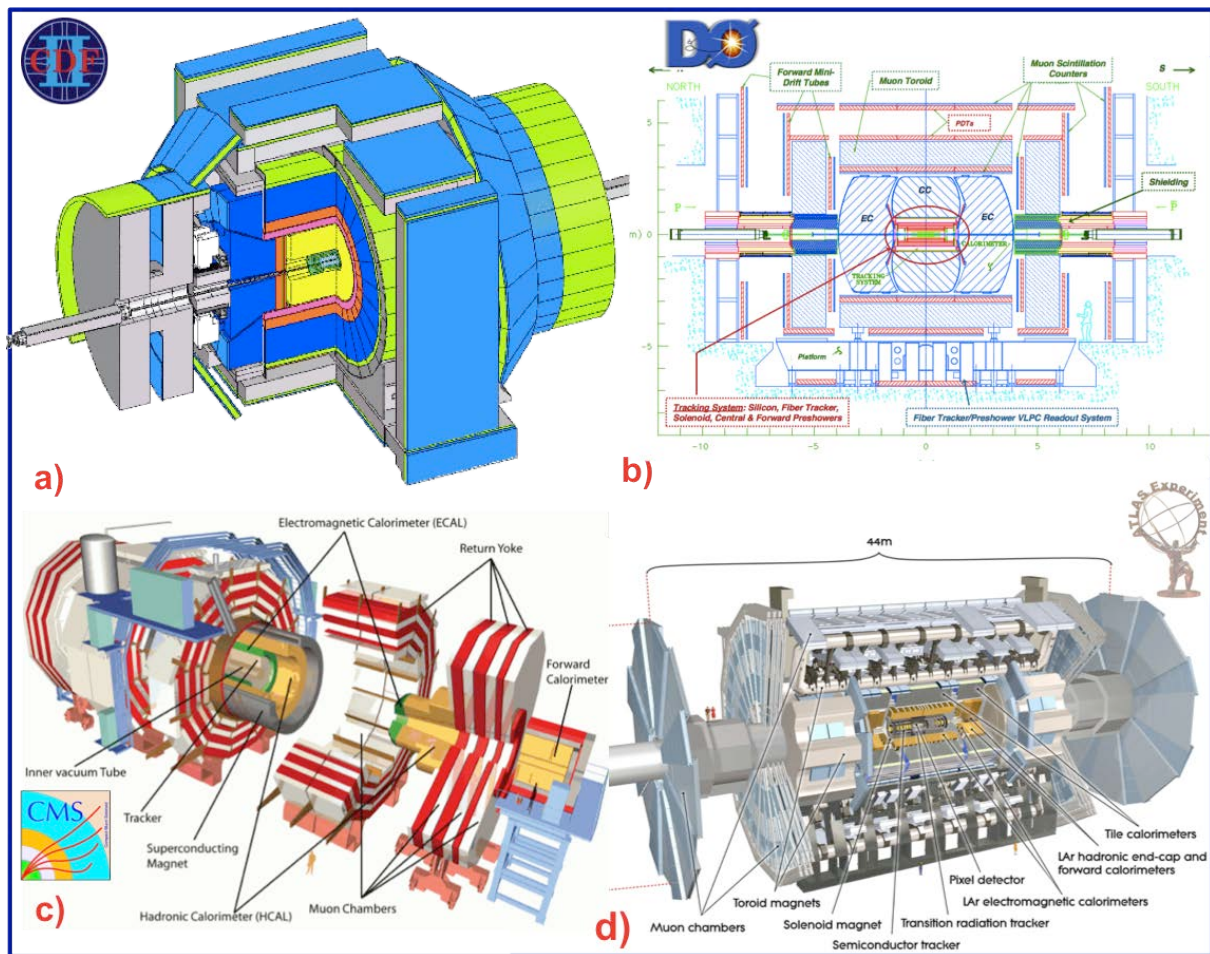


Figure 13: A schematic view of four hadron collider detectors: a) the CDF-II Experiment [32, 23], b) the DØ Experiment at Tevatron Collider [33], c) the Compact Muon Solenoid Experiment (CMS) [34] and d) the ATLAS Detector [35].

4. Collider Particle Detectors

In order to perform physical measurements or particle searches we need to collect a “proper” number of signal events over the possible sources of backgrounds. As we saw, the importance of reaching the energy frontier and to achieve the highest possible beam intensity is needed in order to get a rate, for a given physical process, that is high enough to make possible to perform a measurement or to hunt for new particles, predicted in models beyond the SM. Besides of these aspects, high precision experiments, with the highest possible overall acceptances and efficiencies, are needed. The detection (identification) of the products of each high-energy collision (very often several in the same event) is crucial in order to be able to reconstruct, topologically, the initial states that produced them. In order to perform such a task it is necessary to identify the particles present in the event. This implies the experimental ability to reconstruct the 4-momentum (m and $\vec{p}_{Lab}$), the charge and the spin of the collision products. From a experimental point of view, in most of the case, it’s not possible to fully reconstruct all these information because for example part of the energy is unseen along the longitudinal direction or because our detectors cannot measure directly the spin and so on. In elementary particle physics most particles produced have unit charge. Both the charge sign, of non-neutral particles and their momentum can be measured using a magnetic field. The deflection of a charged particle in a magnetic field determines its momentum p ; the radius of curvature ρ is given by:

$$\rho = \frac{p}{ZeB} \propto \frac{p}{Z} = \frac{\gamma m_0 \beta c}{Z} \quad [18]$$

where m_0 is the particle mass in the rest frame and Z its charge, B the magnetic bending field and as usual $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor. The particle velocity can be determined, e.g., by a time-of-flight method yielding: $\beta = 1/\tau$. A calorimetric measurement provides a determination of the kinetic energy:

$$E^{kin} = (\gamma - 1)m_0 c^2 \quad [19]$$

that is achieved making, the particles entering the calorimetric apparatus, initiating a particle shower that is then deposited in the calorimeter, collected, and measured. Particle detectors at lepton or hadron colliders have, then, evolved to be pretty similar. The technologies used, in each component, differ but they all have the same basic layout as shown in Fig. 12. Starting from the interaction point moving to the outside, there is a tracking volume with almost no material and a high magnetic field. This is used to measure the momentum of charged particles with high precision. It normally has an inner, high resolution section, built of silicon detectors to recognize the decays of short lived particles and an outer tracker made of less expensive materials and optimized for momentum and higher multiplicities measurements. Moving outside of the tracking system, we find the so-called calorimeters that are detectors made of very heavy materials, which absorbs and detects almost all strongly and electromagnetically interacting particles. It is normally divided into a high Z electromagnetic part (EM) and a cheaper outside hadronic part (HAD). A muon detection system, which measures the momentum of any muons, which passed through the calorimeters, follows the outside of those detectors. For massless particles, which is a good approximation for the decay products of almost any particle in a collider, the rapidity function y reduces to a new variable called pseudo-rapidity:

$$\eta = -\ln(\tan(\theta/2)) \quad [20]$$

The pseudorapidity is commonly used as a spatial coordinate describing the angle of a particle relative to the beam axis. Detectors are then segmented in η and designed so that each detector element covers the same area in the $\eta - \phi$ space. In a particle detector is possible to identify photons, neutrons, π , K , protons, muons, b-quarks/c-quarks, light-quarks, neutrinos or any weakly interacting neutral particles like i.e. the Lightest Supersymmetric Particle (LSP). A μ in a collider experiments is a minimum ionizing particle (MIP). It will be characterized by having a charge track originated in the interaction point (IP), matching the “stub” reconstructed in the muon detectors (the multiple coulombian scattering is taken into account) and releasing an amount of energy, in both EM and HAD calorimeters, compatible with a MIP. An electron will be characterized as a charged track, originated in the IP, completely absorbed in the EM calorimeter. A photon will only appear to be as a trackless object releasing all its energy in the EM calorimeter and so on. Fig. 12 summarizes the signatures for the most common collision products. Quarks are identified as a cluster of tracks called jets that are reconstructed by using special clustering algorithms. Between the quarks, in particular, b-quarks are identified by their unique feature of hadronizing in B-hadrons. B-hadrons have sufficient lifetime to travel some distance before decaying. This distance can be measured by using high precision dedicated silicon detectors, then b-jets can be tagged. The detector cannot directly observe neutrinos but its transverse momentum can be inferred by the unbalancing of the event total observed momenta:

$$\vec{p}_T = -\sum \vec{p}_T^{observed} \quad [21]$$

This quantity is called missing transverse momentum and is identified with the neutrino momentum: $p_T = p_T^\nu$. The Missing Transverse Energy (E_T or MET) is similarly defined: $E_T = E_T^\nu$. This variable works only if the $p_\perp$ and direction of all scattered particles, except the missing particle, are detected. This requires a hermetic detector, a detector that covers almost all of 4π solid angle with active components. Such coverage is very difficult to achieve and it is expensive. Detectors such as DØ and

CDF-II, for example, have an active calorimetry down to a pseudorapidity of $|\eta| < 4$ and then are they are able to achieve p_T resolution of the order of 5 GeV/c. However there is a potential for very large E_T fluctuations that have to be taken into account in the data analysis. For this and for other similar reasons any result obtained by a Montecarlo simulation, of the physical process, have to be passed through a detailed Detector simulation before being able to make a comparison between data and models. The detector and trigger efficiencies and acceptances have also to be carefully evaluated. Figures 13 gives some example of collider detectors such as the CDF-II and DØ presently taking data at Tevatron collider and the ATLAS and CMS detectors working on LHC.

5. Conclusions

In the present paper we reviewed some of the contents of a set of lectures, presented at the XIV International School of Particles and Fields in Morelia, Mexico. Those lectures were intended for students and the main goal have been to introduce some basic concept about particle accelerators, energy and luminosity. We described for this reason some of colliders presently running. A small description of the future collider R&Ds was also given together with a description of how common detectors work and are used for data analysis.

6. Acknowledgments

I would like to heartily thank the organizers of the XIV School of Particles and Fields in Morelia, for inviting me to give this set of lectures in such beautiful land. I would like to thank in particular A. Ayala, A. Bashir, G. Contreras, I. León, G. Murguía, A. Raya and M. E. Tejeda for their very kind hospitality and for providing a greatly stimulating and lively environment in which have been possible to wonderfully work, exchange ideas and relax.

7. Bibliography

- [1] CERN Courier, vol. 51, number 1, January/February 2011.
- [2] C. Rubbia, Phys.Rept. 239 (1994) 241-284.
- [3] F. Abe, *et al.* [CDF collaboration] Phys.Rev. **D50** (1994) 2966-3026; Phys.Rev.Lett. **73** (1994) 225-231.
- [4] F. Abe, *et al.* [CDF collaboration], Phys. Rev. Lett. **74**, 2626 (1995).
- [5] S. Abachi, *et al.* [DØ collaboration], Phys. Rev. Lett. **74**, 2632 (1995).
- [6] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD, the LEP EWK Group, the Tevatron EWK Group, and the SLD EWK and heavy flavour groups Collaboration, *Precision electroweak measurements and constraints on the Standard Model*, Fermilab-tm-2480-ppd.
- [7] G. Altarelli, CERN-PH-TH-2010-249. Oct 2010. 17 pp.
- [8] C. Pagliarone, *Searching for Physics beyond the SM with High Energy Colliders*, to appear on the Proceedings of the XIV Mexican School on Particle & Fields, Morelia, Mexico, November 2010.
- [9] G. Flüge, *Future Research in High Energy Physics*. N. Ellis and M. B. Gavela, editors, 1993 *European School of High Energy Physics*, Yellow reports. CERN 94-04, 1994.
- [10] T. K. Gaisser, *The cosmic-ray spectrum: from the knee to the ankle*, J. Phys. Conf. Ser. **47**, 15-20 (2006).
- [11] H. Wiedemann, Particle Accelerator Physics, Springer-Verlag, 2007.
- [12] N. Nakamura *et al.* [Particle Data Group], J. Phys. G **37**, 075021 (2010).
- [13] T. K. Gaisser, J. Phys. Conf. Ser. **47**, 15 (2006).
- [14] V. Tatischeff, arXiv:0804.1004 [astro-ph], E. G. Berezhko, Adv. Space Res. **41**, 429 (2008).
- [15] C. Pagliarone, *From Accelerators to Cosmic Rays Physics*, published on the Conference Proceedings of the XII Mexican Workshop on Particles and Fields, Mazatlan, 2009.
- [16] The Fermilab chain of accelerators can be found here: <http://www-bd.fnal.gov/public/>.
- [17] This picture have been taken close to the CERN cafeteria by the author, see also <http://livefromcern.web.cern.ch/livefromcern/antimatter/factory/AM-factory02.html>.

- [18] L. Evans and P. Bryant, (editors), LHC Machine, JINST **3**, S08001 (2008).
- [19] J. Brau, *et al.* [ILC Collaboration], *ILC Reference Design Report: ILC Global Design Effort and World Wide Study*, [arXiv:0712.1950 [physics.acc-ph]].
- [20] W. K. H. Panofsky, *Evolution of Particle Accelerators & Colliders*, Spring 1997.
- [21] <http://www-bd.fnal.gov/pplot/today/DataSummaryTables.html>.
- [22] See also <http://www-bd.fnal.gov/>.
- [23] C. Pagliarone, *Results on QCD Physics from the CDF-II Experiment*, Published on the Proceedings of New trends in High energy physics, Edited by P.N. Bogolyubov, L. Jankovszky, V.K. Magas, Z.I. Vakhnenko. Kiev, Bogolyubov Inst. Theor. Phys., 2006. 287p.
- [24] K. Jacobs, *Physics at the LHC and sLHC*, to be published on NIM A, ISBN 0168-9002.
- [25] T. Behnke, *et al.* [ILC Collaboration], *ILC Reference Design Report Volume 4 - Detectors*, [arXiv:0712.2356 [physics.ins-det]].
- [26] J. P. Delahaye, *Towards CLIC Feasibility*, IPAC-2010-FRXCMH01. May 2010; see also <http://clic-study.web.cern.ch/CLIC-Study/intro.html>.
- [27] J. P. Delahaye, *Towards CLIC Feasibility*, Proceeding of IPAC'10, Kyoto, 2010.
- [28] C. Grupen, *Physics of Particle Detection*, Proceedings of the ICFA School, 2001.
- [29] P. Limon *et al.*, *Design Study for a Staged VLHC*, Fermilab-TM-2149, May 2001.
- [30] J. Johnstone *et al.*, *Lattice Design of the VLHC Rings*, PAC 01, Chicago, 2001.
- [31] M. Blaskiewicz *et al.*, *VLHC accelerator physics*, Fermilab-TM-2158, November 2001.
- [32] C. Pagliarone, *Recent results from CDF and status of CDF-II*, published on the Proceedings of the XI International School on Particles and Cosmology, Baksan, FERMILAB-CONF-01-363-E.
- [33] V. M. Abazov *et al.* [D0 Collaboration], *The Upgraded D0 Detector*, Fermilab-Pub-05/341-E.
- [34] G. Tonelli [CMS Collaboration], *The CMS experiment: Status and highlights*, PoS **ICHEP2010**, 565 (2010).
- [35] G. Aad *et al.* [ATLAS Collaboration], *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3**, S08003 (2008).