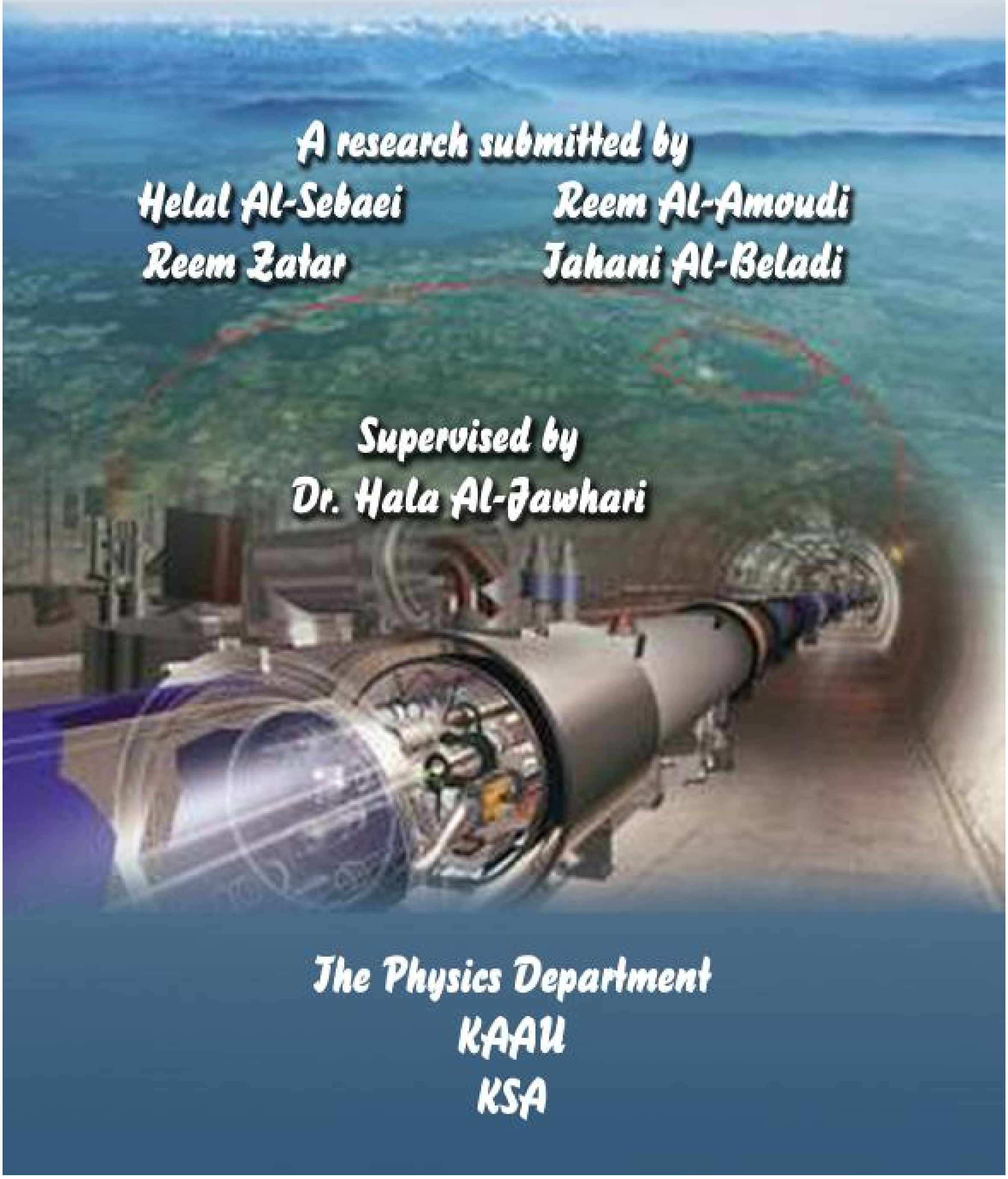
The Large Hadron Collider



A research submitted by
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The Large Hadron Collider
(LHC)

A research submitted
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As a request of phys 491
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بسم الله الرحمن الرحيم

الحمد لله الذي بنعمته تتم الصالحات ، وبفضله تفتح للإنسان أبواب الخيرات ، وبلطائفه تنكشف المعارف بعد كمون ، و تنار العقول بعد خمول ...
والصلاة والسلام على سيدنا محمد، معلم البشرية.. وقائد البرية إلى الهداية والرشاد .. ورحيق الحكمة ومعدن العلم.. وعلى آله وصحبه وسلم...

إهداء و شكر

إلى الذين فتحوا لنا عقولهم وقلوبهم لننهل من بحور علمهم وفيوض عطائهم ..

إلى أنفاس الحياة فينا ... إلى من أشفقوا علينا من الجهل فحمَلونا برداء العلم ... إلى أول من علَّمونا حرفا ننطلق به في الحياة ... إلى أمي وأبي ..

إلى الأستاذة القديرة الدكتورة : هالة الجوهري سلمها الله ورعاها . روح هذا البحث.. المحلقة في آفاق العلم .. من غمرتنا بكريم أخلاقها وعميق معرفتها و لم تأل جهداً في نصحنا وتوجيهنا.. فكانت أمامنا مثالا للعلم حين يشرف به صاحبه..

إلى جامعتنا الحبيبة.. جامعة العلم التي نقف اليوم على أبواب الحياة انطلاقاً من مقاعدها.. ونجني حصاد البحث العلمي إهتداءً بمنارتها..

إلى كل هؤلاء نهدي هذا البحث، سائلين الكريم المنان أن يعظم لهم الأجر والمثوبة على ما بذلوه لطلاب العلم والمعرفة، وأن يجعل ما قدموه نورا لهم في معارج الخيرات وموازين الأعمال .

وختاما نسال الله أن يجزي الجميع خير المثوبة والجزاء، وأن يلهمنا وإياهم الإخلاص في القصد والعمل.

Contents

CHAPTER 1

INTRODUCTION

Introduction:

During the last few decades there has been enormous progress in our understanding of the basic composition of matter. The theory of fundamental particles and their interactions, the ***S**tandard **M**odel* (**SM**), answers many of the questions of the structure and stability of matter with its six types of quarks, six leptons, and three of the nature four forces. Yet, the Higgs boson, needed to introduce particle masses in the Standard Model has not been observed.

The search for Higgs boson had been the goal for many colliders such as **LEP**, ***E**lectron*-***P**ositron* collider, at CERN and Tevatron at Fermilab. However, no experiment has directly detected the existence of the Higgs boson. The appropriate collider to do so should be capable not only to produce particles at energies of (TeV) range, but its *luminosity*, the probability of collision between particles, must be high as well.

Achieving this goal was probably the main motivation for the construction of the ***L**arge **H**adron **C**ollider* (**LHC**) at **CERN**, Switzerland. The **LHC** project was approved by **CERN** Council in December 1994. But to keep the budget of the project as low as possible, they decided to host the **LHC** machine in the 27 km circumference tunnel was using by the **LEP** that time. Therefore, the assembly of the **LHC** actually begun in 2000 , after the whole machine of the **LEP** was dismantled. The **LHC** project is currently under construction, and it been scheduled to start-up in 2007.

In addition to the detection of Higgs bosons, the **LHC** will also investigate other aspects such as the search for heavy W- and Z-like objects, supersymmetric particles, CP violation in *B-mesons* decays and it also intends to have ion-ion collisions.

The **LHC** is designed to bring protons into head-on collision at energy of 14 TeV and luminosity of 10^{34} cm^{-2} s^{-1}, which is highest among all present colliders. It also will provide heavy (Pb) ion collisions with energies more than 10^{3} TeV and luminosity in a range of 10^{27} cm^{-2} s^{-1}. This will allow scientists to penetrate further into the structure of matter and recreate the conditions prevailed in the Universe just 10^{-12} seconds after the "Big Bang" when the temperature was 10^{16} Kelvin.

In order to deliver the maximum energy within the confined 27 km circumference tunnel, the machine employs a two-in-one supermagnets structure operating in superfluid helium.

Six experiments had already built to utilize the **LHC** machine**.** Two general-purpose experiments, **ATLAS** and **CMS**, will search for the Higgs bosons, and study other unsolved aspects of the Standard Model. For the purpose of the heavy ion collisions, a dedicated experiment, **ALICE**, is being built. **LHCb** is a forward detector made to study **CP** violation and other phenomena in ***Beauty*** particle decays. **TOTEM**, partially housed inside **CMS**, will study physics in the very forward direction. While, **MOEDAL**, in the **LHCb** pit, is proposed to search for monopoles and other highly ionizing exotic particles. At a later stage, proton beams from **LHC** can also be made to collide with electron beams, opening up another field of research. This wide range of physics possibilities will enable **LHC** to hold a unique position on the frontiers of physics research into the next century.

The building of the **LHC** and its detectors is a challenge for both European scientists and European industry in many fields, for example, superconductivity, ultra high vacuum, ultra low temperatures and unprecedented data rates. The **LHC** is funded and being built in collaboration with over two thousand physicists from 34 countries, universities and laboratories. The overall budget for the **LHC** machine is of the order of 2 billion Swiss Francs[1].

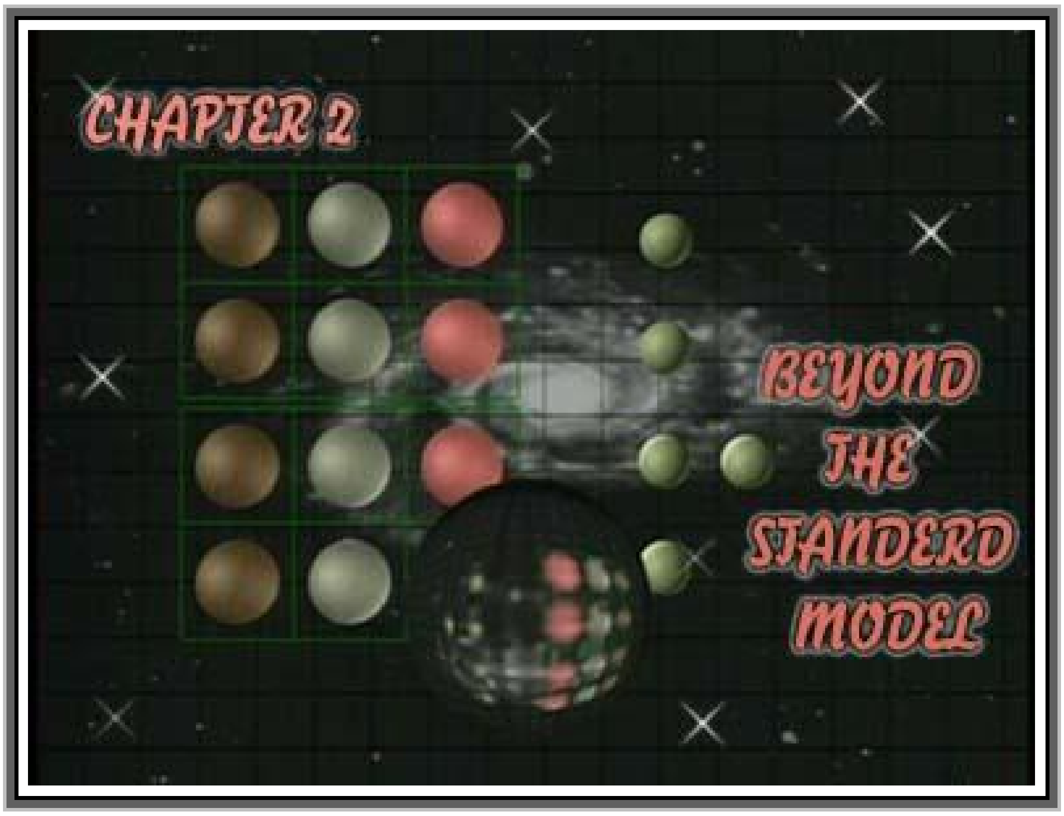
In this study the objective and the structure of the **LHC** along with its six experiments are considered. First, we will introduce the issues that still unconfirmed in physics such as Higgs bosons, Supersymmetry, and the CP violation. Those topics, sometimes known as *physics beyond The Standard Model*, will be the subject of the second chapter.

Chapter three will concentrate on **LHC** machine, including its unique pipe that has a two-in-one superconducting magnets to control the protons beams, and the challenges that the collider has to face to get the required high luminosity.

The main six detectors located around the **LHC** ring, which will carry out the scientific experiments at **LHC**, are discussed in chapter four.

The **LHC**, with its high-energy collisions of protons and of lead ions, will be a unique instrument for studying the main problems of particle physics of today. From the basic structure of the Standard Model to the exploration of what is beyond it, from the violation of the symmetry between matter and antimatter to the unlimited state of matter at the beginning of the universe.

The **LHC** is surely the biggest project ever made by mankind that gathers all its intelligence and resources into a coherent task. The difficulties will be severe and the path will be long, but hopefully, the obtained results will justify such an effort.


CHAPTER 2
BEYOND
THE
STANDERD
MODEL

2.1 The Standard Model:

The Standard Model (**SM**) is the name given to the current theory that explains what fundamental particles are and how they do interact. The (**SM**) is a quantum field theory, and it consistent with both quantum mechanics and special relativity [2]. It gathers the hundreds of particles and their complex interactions with two general categories: *Fermions* and *Boson* as shown in Fig. (2.1). Fermions are the matter constituents, in contrast, bosons are the force carrier particles.

The Standard Model also includes the so called Higgs particle, which is thought to be responsible of the different masses of the particles [3].

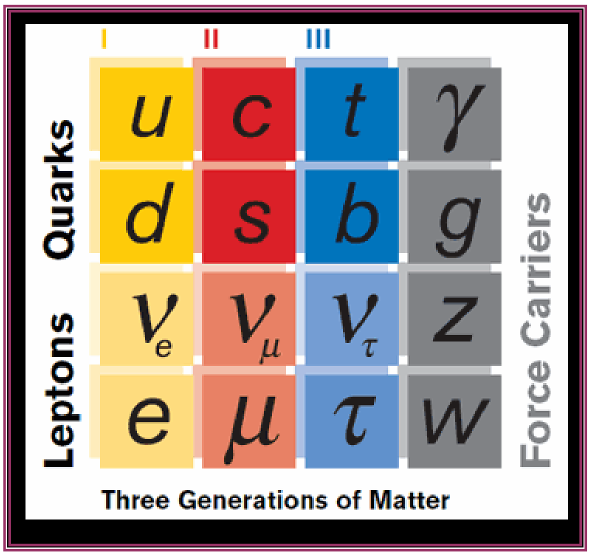


Fig. (2.1) The three generations of fundamental particles.

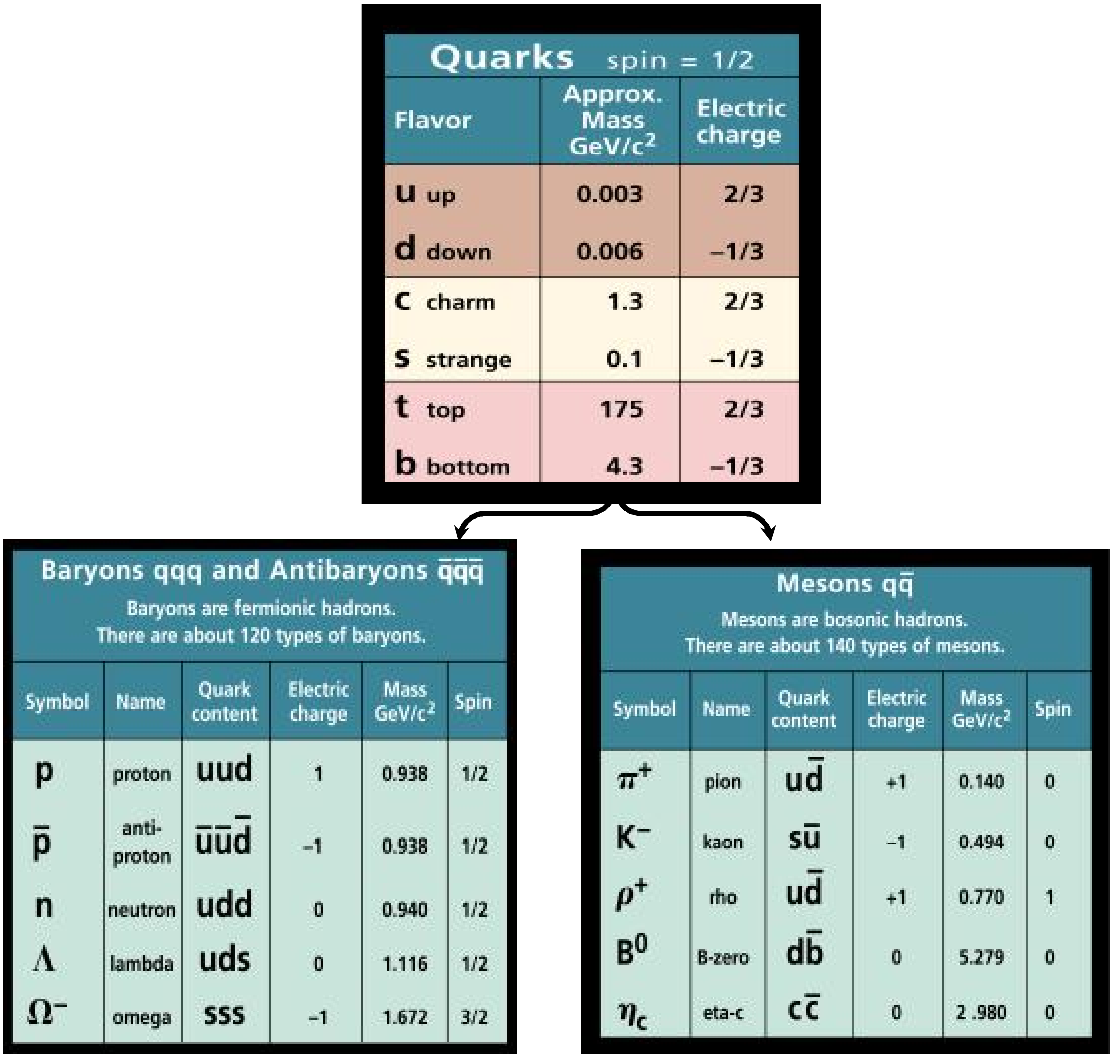
2.1.1 Fermions:

Fermions are particles which possess half-integer spin and obey the *Pauli Exclusion Principle*. Fermions are the building blocks of the entire world and they are divided into two main groups: *quarks* and *leptons*;

i) Quarks:

There are six different quarks which are usually grouped, as in Table (2.1), into three pairs because of their mass and charge proprieties: **u**p / **d**own, **c**harm / **s**trange and **t**op

/ **b**ottom[1] [4]. Quarks are observed to exist only in combinations known as *Hadrons*. Hadrons that consist of combination of three quarks called *Baryons*, while hadrons consist of combination of 1 quark and 1 antiquark [2] known as *Mesons*. There are as well antibaryons that consist of three antiquarks, and the recently discovered particle with five quarks (pentaquarks) [6].



Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Table (2.1). The main two types of hadrons; Baryons and Mesons [7].

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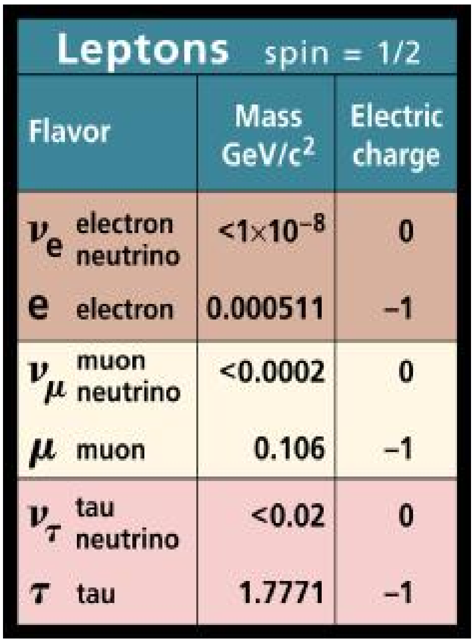
[1] When the *bottom* quark was discovered in 1977, it was named as the "*Beauty*" quark. Nowadays, it is more commonly referred to as the "*bottom quark*", nevertheless, some physicists are still use its old name [5].

[2] Any particle have a corresponding antiparticle, that has some properties but with an opposite electrical charge[4]

ii) Leptons:

On the other hand, there are six leptons, three with a charge and mass: electron (e^-), muon (m), and tau (t), and their associated neutrinos which are neutral and have very little mass (table 2.2) [4,6].



Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Table (2.2). The six types of leptons [7].

The four particles (electron, electron neutrino, up quark, and dawn quark) constitute the matter of the whole universe and they form what is known as *the first generation* [8]. The second generation contains the muon (m), its neutrino, the charm and the strange quarks see Fig. (2.2). The masses of the second generation particles are larger than the corresponding masses of the first generation particles. The third generation contains the tau particles, its neutrino, the top and the bottom quarks. Third generation particles have even larger masses [8]. All three generations were important in the very early universe but since the particles in the second and third generations are not stable, they have decayed into particles of the first generation. That is why the first generation particles are the only ones we observe in our every day world.

2.1.2 Bosons:

Bosons possess integer spin and do not obey the *Pauli Exclusion Principle* [2]. The standard model classifies the forces between fermions by coupling them to bosons which mediate (or "carry") the forces. SM includes three types of forces [3]. **electromagnetic, strong** and **weak.** The electromagnetic is the force that binds negative electrons to the positive nuclei in atoms, and underlies the interactions between atoms themselves. Looking deeper inside the nuclei, even inside nucleons, the weak force and strong force become more important. The weak force leads to the decay of neutrons (which underlies many natural occurrences of radioactivity) and allows the conversion of a proton into a neutron. On the other side, the strong force holds quarks together to form protons, neutrons and other hadrons. It also prevents the protons in the nucleus from flying apart under the influence of the repulsive electrical force between them. Because of this, the strong force within the nucleus is about 100 times stronger than the electromagnetic .

Forces are transformed between particles by bosons, which carry discrete amounts of energy from one particle to another. Each force has its own characteristic bosons: the gluon is the carrier of the strong force, while the photon is the electromagnetic force carrier. The carriers of the weak interaction are W^+, W^- (the antiparticle of W^+), and Z^0 particles (see table 2.3).

The standard model does not include the effects of the fourth force of the nature, *gravity*. Since these effects are tiny under high-energy physics situations, and can be neglected in describing the experiments.

Forces	**Relative strength**	**Carrier particle**	**Mass GeV/c^2**	**Electric Charge**	**Presence**
Strong nuclear interaction	$\simeq 1$	Gluon	0	0	Atomic nuclei
Electromagnetic interaction	$\sim 10^{-3}$	Photon	0	0	Atomic layers electrical devices
Weak nuclear interaction	$\simeq 10^{-5}$	W- W+ Z	80.4 80.4 91.187	-1 +1 0	Radioactive decay

Table (2.3). Properties of the three fundamental forces [7].

2.1.3 Interactions in Nature:

Feynman diagrams (Fig. (2.2)) devised by physicist Richard P. Feynman, serve as useful shorthand to describe interactions in quantum field theory [9].

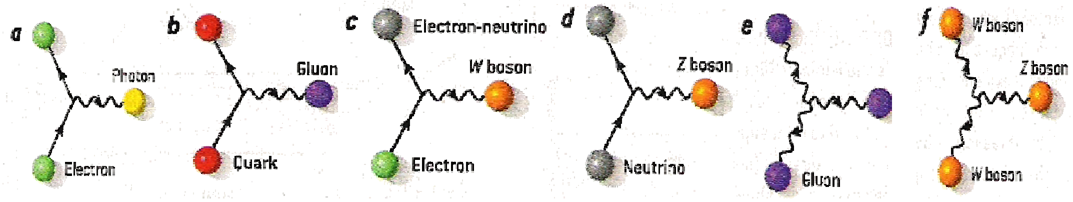


Fig. (2.2). The main interactions in nature [9].

The straight lines represent the trajectories of matter particles; the wavy lines represent those of force particles. Electromagnetism is produced by the emission or absorption of photons by any charged particles, such as an electron or quark. In (**a**), the incoming electron emits a photon and travels off in a new direction. The strong force involves gluons emitted (**b**) or absorbed by quarks. The weak force involves W & Z particles (**c**,**d**) which are emitted or absorbed by both quarks and leptons according to the methods shown in Fig. (2.3) [9].

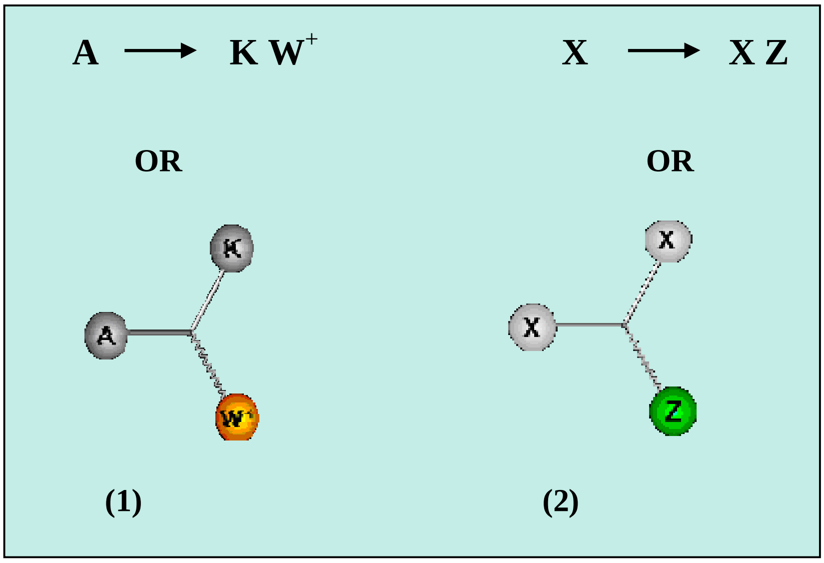


Fig. (2.3). The main two methods involved W & Z particles [8].

In Fig. (2.3), **A** stands for any particle of the first row in Fig. (2.4), **K** is any particle in the second row and **X** is any particle.

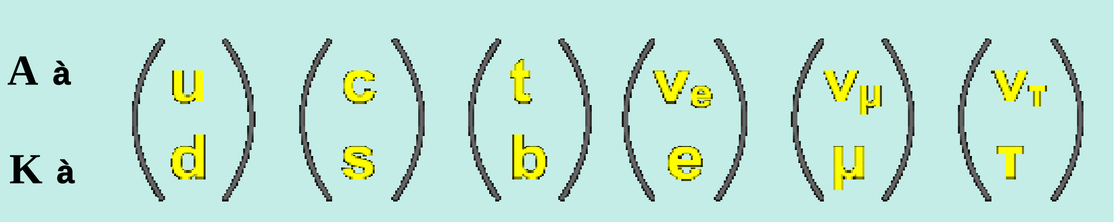


Fig. (2.4) Another arrangement for the elementary particles [8].

Gluons (**e**) , W and Z (**f**) (in Fig. 2. 2) have self-interact, but photons do not.

2.1.4 Beyond the Standard Model:

The Standard Model, at this time, is the best description we have of the world of quarks and other particles. However, its current form cannot explain the whole story since there are important questions that the standard model cannot answer, such as:

- ý Can the electroweak and the strong forces be unified? And where dose gravity fit in?
- ý What is the origin of the mass of particles?
- ý Why are there three generations of matter and where did the antimatter go?

These questions and other more lead us to look for physics *beyond the standard model*.

2.2 Supersymmetry and Superpartners:

2.2.1 Introduction:

The standard model performed one of the major asymmetry in the world of practical physics. This was the distinction between 'particles' (fermions) and 'forces' (boson), which is more than cosmetic difference. In geometric term, a key difference between these two kinds of entities is that a fermion has to rotate twice (through 720 degrees) to get back to where it started, while a boson has to rotate only once (through 360 degrees) to get back to its original state.

This encouraged theoretical physicsts to search for a geometrical description that can unify these two different patterns of behavior in one great geometrical symmetry. In the 1970s the breakthrough came with the discovery of a kind of symmetry known as ***Supersymmetry*** **(SUSY)**. The supersymmetric theory postulates that every particle we observe has a massive "shadow" particle partner called s***uperpartner*** with spin 1/2 difference between them (see Fig.2.2) [10].

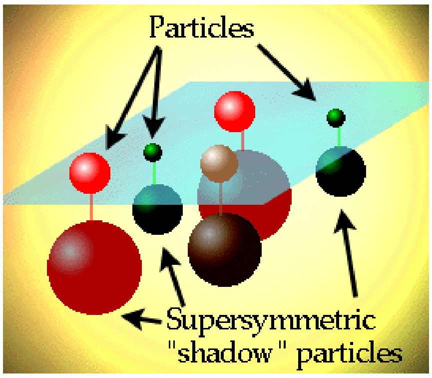


Fig.(2.5) Particles and their *superpartners* [11]

2.2.2 How Does SUSY Work?

Supersymmetry works by attaching anther four dimensions to the four dimensions of our ordinary spacetime. By this it provides room for the extra rotation that a fermion has to make to get back it its starting configuration. But these extra dimensions are not space or time dimensions. In the mathematics of supersymmetry, there is an operation which is equivalent to rotation in the everyday world. But instead of rotating an object in three-dimensional space, this operation rotates an object from the usual four-dimensional spacetime into the eight-dimensional geometry inhabited by fermion. And, of course, there is an equivalent operation which rotates an object out of the eight-dimensional geometry inhabited by fermions into the everyday geometry of four-dimensional spacetime. This means that it is possible to transform bosons into fermions, and vice verse. In other words, there is no longer any distinction between bosons and fermions, and what we see as tow different kinds of particle in an illusion caused by geometry [10].

2.2.3 SUSY Particles (or Superpartners):

It is clear that rotating an electron in the way described above would not produce any of the known bosons. Indeed none of the known bosons corresponds to the rotated versions of known fermions, and none of the known fermions corresponds to rotated versions of the known bosons. Supersymmetry requires that for every known fermion, there is a "New" boson and for every known boson, there is a "New" fermionic partner. The new bosons are named by modifying the name of the equivalent fermion, adding an "s" at the front- thus; the counterpart to the *electron* is the *selectron*. While the new fermions are named by modifying the name of the equivalent boson to make it end in "ino", thus, the counterpart to the *photon* is the *photino*. The main differences between any particle and its superpartner are spin and mass. Spin 1/2 fermions, (like leptons and quark) have spin 0 superpartners, while spin 1 bosons, like photons, have spin 1/2 superpartners.

This is illustrated in Table (2.2), where the various particle are listed, together with their superpartners and the corresponding spin.[10,12]

Particle	Symbol	Spin	Superpartner	Symbol	Spin
quark	Q	1/2	Squark	$\tilde{q}$	0
Electron	e	1/2	Selectron	$\tilde{e}$	0
Muon	μ	1/2	Smuon	$\tilde{\mu}$	0
Tauon	τ	1/2	Stauon	$\tilde{\tau}$	0
W	W	1	Wino	$\tilde{W}$	1/2
Z	Z	1	Zino	$\tilde{Z}$	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Gluon	g	1	Gluino	$\tilde{g}$	1/2
Higgs	H	0	Higgesino	$\tilde{H}$	1/2

Table (2.4) The particles of standard model and their superpartners [12]

To incorporate Supersymmetry into particle physics, the Standard Model must be extended to include at least twice as many particles. With the addition of the new particles, there are many possible new interactions. The simplest possible supersymmetric model that consists with the Standard Model with the minimum number of new particles is known as the ***Minimal Supersymmetric Standard Model* (MSSM)** [13].

2.2.4 Broken Symmetry:

If supersymmetry applies in the real world, there must be a superpartner for every type of known boson and one for every type of known fermion, doubling the number of varieties of particle in the world**.** But since no superpartner had been observed yet, it seems that we are dealing with a **broken symmetry**. When a symmetric system, at high energies, falls into its ground state the symmetry will break spontaneously. Similarly, it is thought that, under the extreme condition that existed at the birth of the universe, there was a complete symmetry and each type of boson was accompanied by a fermions superpartner but as the universes cooled down, this symmetry spontaneously broken. This is assumed to be because the superpartners are much more massive than the counterparts we know today, and they could only be produced at very high energies. But there would have to be a stable **lightest supersymmetric partner**, or **(LSP),** into which the other superpartner would decay and this particle could be detectable. Searches for such particles (**LSPs**) are under way. However, until they are found, supersymmetry will still an unproven description of the world we live in [10].

2.2.5 CP Violation:

Another example of the broken symmetry is what so called **CP violation**. Where **C** refers to *Charge Conjugation* ,the operation of reversing the *Charges* of particles in a physical system. And **P**, or *Parity,* is the operation of space inversion, or reflecting a coordinate system in a mirror[14].

Although neither the *charge conjugation* nor the *parity* is precisely conserved in all particles interactions. Physicists hoped that the way in which C and P are violated would always precisely cancel each other out, so that combination of the two, CP, would always be conserved in particles interactions. Thus, **CP** (Charge-parity) was supposed as the symmetry relating matter to antimatter. But in 1964 it was discovered that the decay of the neutral **kaons** (short for **K-mesons**), to produce **pions** (short for p**-mesons**), dose not conserved **CP** symmetry. **CP violation** means that *antimatter does not act exactly as a mirror matter in its behavior* [10] **.**

The big bang should have created equal amounts of matter and antimatter, with subsequent annihilation leaving neither behind. And yet, the observable universe has about ten billion galaxies that consist entirely of matter (protons, neutrons, and electrons) with no antimatter (antiprotons, antineutrons, and positrons). Very soon after the big bang, some forces must have caused the **CP violation** that skewed the equality in the number of matter and antimatter particles and left behind excess matter.

The weak force by itself can only explain a small amount of **CP violation**, not enough to leave matter for even a single galaxy. Some other hidden force—not accounted for in our Standard Model of particles and forces—must have been responsible for the extra **CP violation** that led to the universe we observe. Current and future particle accelerator experiments are designed to search for sources of **CP violation** large enough to account for the all-matter universe around us [15].

2.3 The Mystery of Mass:

2.3.1 What Is Mass?

This question does not have a clear answer in physics!

Newton in his 1st law defined mass as *Inertia* which is kind of body resistance. He then gave it a mathematical formula with his 2nd law

$$a = \frac{F}{m} \qquad (2.1)$$

Which states that: *the mass of a body is the characteristic that relates the acting force on the body to the resulting acceleration* [16].

On other hand, Newton's gravitation law defines mass totally different. In this law Newton treated mass as a measure of the *gravitational* force.

$$F = G\frac{m_1 m_2}{r^2} \qquad (2.2)$$

Tow centuries later, Einstein's emphasized that the mass is not a constant value for the body but rather it changes with the body's velocity. Einstein, also predicted that the mass is equivalent to the *energy*, through the famous relation:

$$E = mc^2 \qquad (2.3)$$

So, up to now we do not have a clear definition for the *mass*. As a sequence, there are many questions still unanswered!

- How does the mass arise?
- Why different species of elementary particles, shown in Fig. (2.6), have their *specific quantities* of mass that extend over range of about 11 order of magnitude?
- Why the sum of masses of three quarks is much smaller than the mass of hadron they make?

Understanding the meaning and origins of mass will complete and extend the Standard Model of particle physics. Also it will resolve some other mysteries in physics such as dark matter and neutrinos.

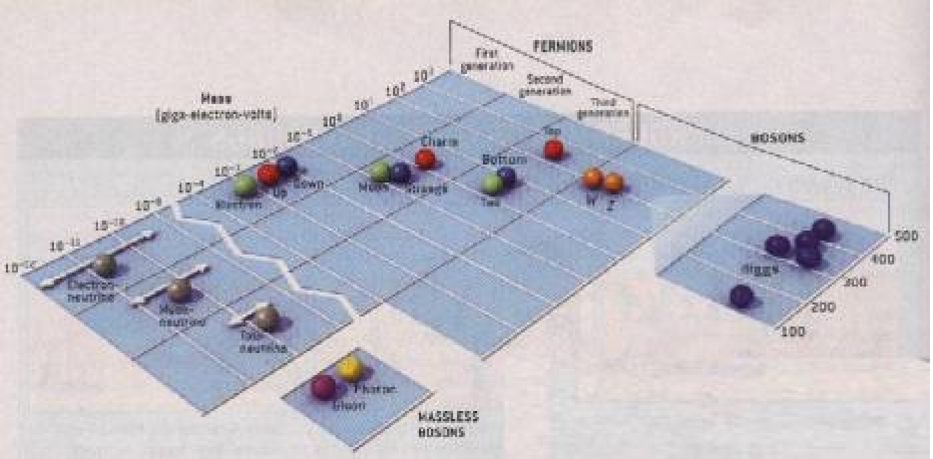


Fig. (2.6) Masses of the SM particle differ at least 11 or orders of magnitude [17].

2.3.2 The Higgs Field:

To come over the mystery of mass, contemporary theoretical physicists proposed that fundamental particles masses arise from interactions with a new field called ***Higgs field.*** The Higgs field is a quantum field that existing throughout the universe with nonzero strength on cosmic scales unlike the electromagnetic field. The corresponding quantum particle of the Higgs field is the ***Higgs boson.*** According to this proposal, elementary particles such as quarks and electrons are not made up of smaller pieces. Instead, they acquire their rest masses from interacting with the Higgs field. To visualize the picture, let us consider the empty space filled with the Higgs bosons is like a beach full of children, and the elementary particle crossing that region of space is like an ice-cream vender arriving and attracting the kids. His interaction with kids (Higgs particles) will slow him down as if he acquires mass.

The Higgs field, however, differs from all other quantum fields in three crucial ways [17]:

1- All fields have a property called spin which is an intrinsic quantity of angular momentum that is carried by each of their particles. Particles such as electrons have spin 1/2 and particles such as the photon have spin 1. The Higgs boson in contrast has spin 0. Having 0 spin enables the Higgs field to appear in the Lagrangian in different ways than the other particles do, which in turn allows and leads to its other two distinguishing features.

2- The second unique property of the Higgs field explains how and why it has nonzero strength throughout the universe. Any system, including a universe, will tumble into its lowest energy state, like a ball bouncing down to the bottom of a valley. For the familiar fields, such as the electromagnetic fields the lowest energy state is the one in which the fields have zero value (that is, the fields vanish). But for the Higgs field, the energy is lower if the field has a constant nonzero value. In terms of the valley image, for ordinary fields the valley floor is at the location of zero field; for the Higgs, the valley has a hillock at its center and the lowest point of the valley forms a circle around the hillock as it shown in Fig. (2.8). The universe, like a ball, comes to rest somewhere on this circular trench, which corresponds to a nonzero value of the field. That is, in its natural, lowest energy state, the universe is permeated throughout by a nonzero Higgs field.

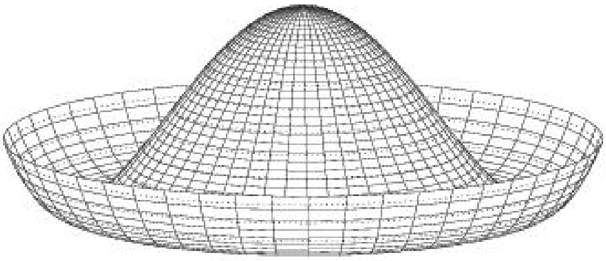


Fig. (2.8). The shape of the Higgs potential explains why other particles in the Standard Model are massive [3].

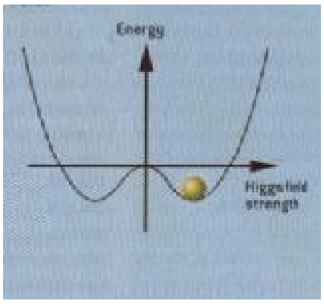


Fig. (2.9) The Higgs field function [17].

3- The final distinguishing characteristic of the Higgs field is the form of its interactions with the other particles. Particles that interact with the Higgs field behave as if they have mass, proportional to the strength of the field times the strength of the interaction. The masses arise from the terms in the Lagrangian[3] that the particles interacting with the Higgs field have.

The understanding of the whole picture is not yet complete and scientists are not sure how many kinds of Higgs fields there are. The Standard Model requires only one Higgs field to generate all the elementary particle masses. However, the *Minimal Supersymmetric Standard Model* (**MSSM**) requires at least two different kinds of Higgs fields to produce masses of superpartners. The masses of particles called **neutrinos**, which are tiny compared with other particle masses, could arise rather indirectly from interactions with these two fields or yet from a third kind of Higgs field.

So, in summary there are three ways in which mass can arise [17]:

1- The main form of mass that we are familiar with, the mass of protons and neutrons and therefore of atoms. Each proton or neutron is composed of elementary particles, quarks, that are bound together by massless particles, gluons. Although these constituents are whirling around inside each proton, from outside we see a proton as a coherent object. Nearly all the mass of (the proton) (and the neutron) is from the kinetic energy of the quarks and gluons (the remainder is from the quarks' rest mass). And this is the reason of difference between the total mass of constituents and actual proton mass.

2- The mass of quarks themselves and the mass of electrons are entirely caused by interactions with the Higgs field. Those masses would vanish without the existence of such field.

3- Dark matter particles which will be discussed later.

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[3] The **Lagrangian** of a system is defined as $L = T - V$, where T is the total kinetic energy and V is the total potential energy. A physical system changing as time goes on from one state to another along a particular evolutionary path. The system selects that particular path out of all the imaginable paths because the physical system sums the values of its Lagrangian function for all the points along each imaginable path and then selects that path with the smallest result [18].

2.3.3 Testing the Theory:

In order to prove the idea that mass arises from the interactions with different Higgs fields, there are three features can be tested.

First, the Higgs bosons must exist, or else the explanation is not right. Thus, physicists are currently looking for Higgs bosons at the Tevatron collider in Fermi Lab.

Second, once Higgs bosons are detected physicists can observe how they will interact with other particles.

Third, different sets of Higgs fields imply different sets of Higgs bosons with various properties, so tests can distinguish these alternatives, too.

All what we need to carry out such tests is an appropriate particle collider with sufficient energy to produce different Higgs bosons, sufficient intensity to make enough of them and very good detectors to analyze what is produced. And this is what the *Large Hadron Collider* (**LHC**) is mainly made for.

2.4 Dark Matter and Neutrinos:

2.4.1 Introduction:

The theory of Higgs field proposed to explain how the elementary particles, the smallest building block of the universe, acquire their masses. But this is not the only source of mass in the universe.

The relative amounts of the different substances comprising our universe are distributed as shown in Fig.(2.10) [17].

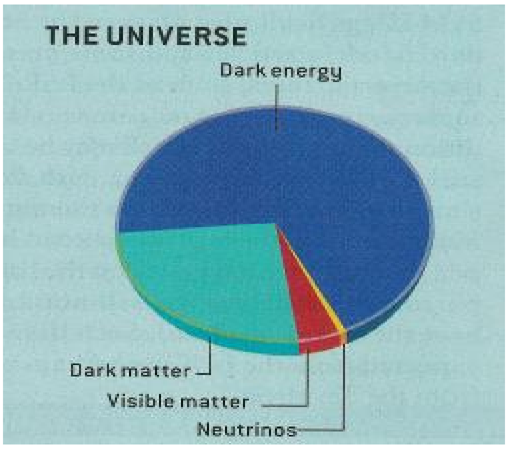


Fig.(2.10) The universe's matter

- About 4%- 5% is provided by **ordinary matter**, particles with mass, such as protons, neutrons and electrons which are called “Baryons”. Those particles make up atoms, molecules, dust, stars, planets and all what we see.
- 95% of the universe is completely invisible and it comes in two components; dark matter and dark energy.

Dark matter that acts some how like ordinary particles forms around 25% of the universe . While 70% of the universe substance is **dark energy** which is not directly associated with particles. The dark energy spreads uniformly throughout space as a kind of anti-gravity, or a repulsive force that is pushing the universe apart [19].

- A smaller contribution to the universe’s matter (less than 0.5%) comes from particles called **neutrinos,** which come in three varieties (electron neutrino, tau neutrino, and muon neutrino). Neutrinos have a very little mass which are not measured yet.

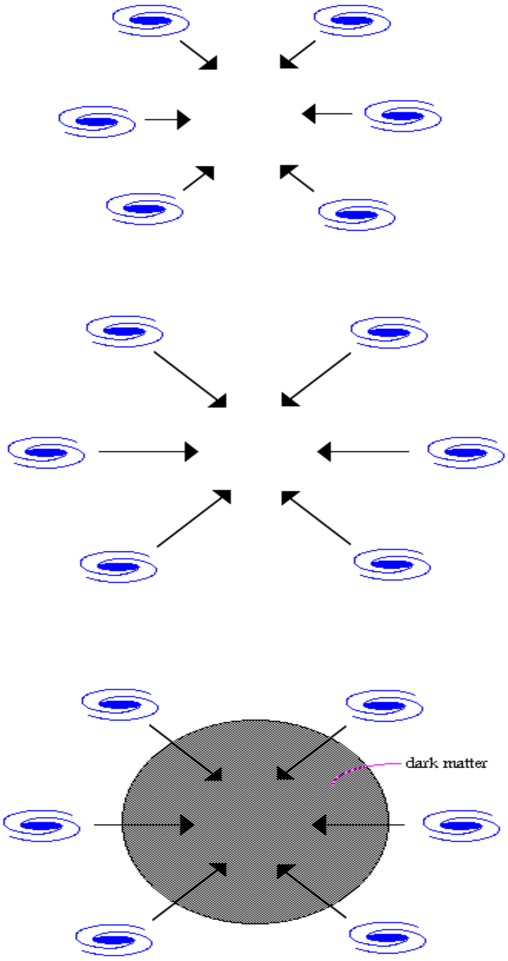
2.4.2 Dark Matter:

i) Evidence of Existence:

Dark matter is a matter that can not be seen or detected directly with any type of telescope, because they do not emit or reflect enough electromagnetic radiation, but its presence can be inferred from their gravitational effects on visible matter such as stars and galaxies [20].

The dark matter hypothesis suggests that every observable galaxy in the universe is embedded in a massive “halo “of dark matter, whose diameter is about 30 times the diameter of the visible galaxies. According to this hypothesis several astronomical mysteries can be explained [17].

One of these mysteries is the rotation of spiral galaxies like the Milky Way which is described in Fig. (2.11). By measuring Doppler Shifts it is possible to determine the rotation speeds of stars and gas at various distances from the center of the galaxy, which in turn allows us to calculate the mass of the galaxy. As not expected the orbital speed of stars at the outer visible edge of the galaxy is about the same as that of stars close to the galactic center. This is not what would be expected if all the mass of the galaxy were represented by visible matter [21].



The members of a cluster of galaxies move because of their mutual gravitational attraction.

In most clusters, the velocity of the cluster galaxies is much higher than can be accounted for from the individual galaxy masses.

The result is there must be an unseen core of dark matter attracting the galaxies with more gravity and, therefore, more velocity.

Fig.(2.11) The rotational mystery of the spiral galaxies [22].

ii) What the Dark Matter is?

This is an open question. There are many possibilities, nobody really knows much about this yet.

Nevertheless, the dark matter has shaped the universe as we know it, and without its gravitational pull the universe would be probably too smooth to form galaxies, stars, and planets. So, the dark matter must be composed of massive particles that may not be found within normal standard model particles.

Several categories of dark matter have been postulated but the most common one is that which defines dark matter as: **Baryonic** and **Non- baryonic** [23].

1- Baryonic Dark matter:

It is composed of the ordinary baryonic particles included in the standard model, but with large masses condensed in a small area which make them appear as dark matter.

The common objects represent it are the black holes, brown dwarf stars and white dwarf stars; the latter are not massive enough to become actual stars, but they shine as a result of fusion. This type of dark matter is known as ***M**assive **C**ompact **H**alo **O**bjects*, or "**MACHO**s" [24].

MACHOs can be detected through phenomenon known as gravitational lens, which produced when a massive object such as a **MACHO** passes between the earth and a distant star, its gravitational field cause the light from the star to bend leading to a characteristic change in the brightness of the star . But the chances of this happening are very small, so it is necessary to observe millions of stars to record just a few lensing events [25].

2- Non-Baryonic (Cold) Dark matter:

The name came from the assumption that these dark matter particles were moving slowly when galaxies and galaxy clusters began to form after the Big Bang .It is known as **WIMP**s (***W**eakly **I**nteracting **M**assive **P**articles*). If **WIMP**s were indeed created in the Big Bang, we will be surrounded by them because of their gravitational interaction with the visible matter in the universe. Indeed, as you read this article there could be billions **WIMP**s streaming through your body every second, traveling at a million kilometer per hour. But **WIMP**s only interact weakly with matter; most of them will pass straight through you without hindrance. This what makes them so difficult to detect [16].

One of the candidate particles for this matter is ***neutralino*** which supposed to have a mass about 100 times that of the proton. It is predicted by the supersymmetric theory as a quantum superpartner of the tow neutral Higgs bosons, the Z boson and the B boson. Moreover the neutralino is stable, which means that the density neutralinos left over from the big bang will still be cosmologically significant [20].

The neutralino has its own anti-particle, and can self – annihilate, creating a shower of new particles including gamma – rays [26].

Another candidate is ***axion*** which lies at the end of the mass spectrum. It has a mass smaller than a proton or even an electron [20].

Another candidate is so-called sterile neutrinos. Sterile neutrinos can be added to the standard model to explain the small neutrino mass. These sterile neutrinos are expected to be heavier than the ordinary neutrinos, and are a candidate for dark matter [24].

Neither of neutralinos nor any of the many dark matter candidate particles has ever been observed experimentally. They had been predicted by the **M**inimal **S**upersymmetric **S**tandard **M**odel **(SSM)** to be the ***L**ightest **S**uper**P**artners* (**LSP**).
The LSP is the one with the lowest mass came from a chain of decays of the superpartners that created early in the big bang. So LSP will be stable because it has no lighter particle into which it can decay.

As mentioned earlier, the two basic SSM Higgs fields gives mass to the Standard Model particles and some mass to superpartners, such as LSP. The other superpartners acquire more mass via additional interactions, with a further Higgs field.
Scientists had theoretical models of how these processes can happen, but they will not know how they work in detail until they have data on superpartners themselves that expected to be discovered at the **LHC** [17].

1.4.3 Neutrinos:

The name neutrino means “little neutral one “. Neutrinos have very small mass, and they are not partake within two of the four fundamental forces, the electromagnetic force and the strong force. They do interact with the weak nuclear force and gravity .They are extremely difficult to be detected, and that what make them sometimes classified as a kind of the dark matter [27].

The need for the existence of neutrinos arises during the study of Beta decay, to verify the energy and momentum conservation laws as it shown in Fig. (2.12).

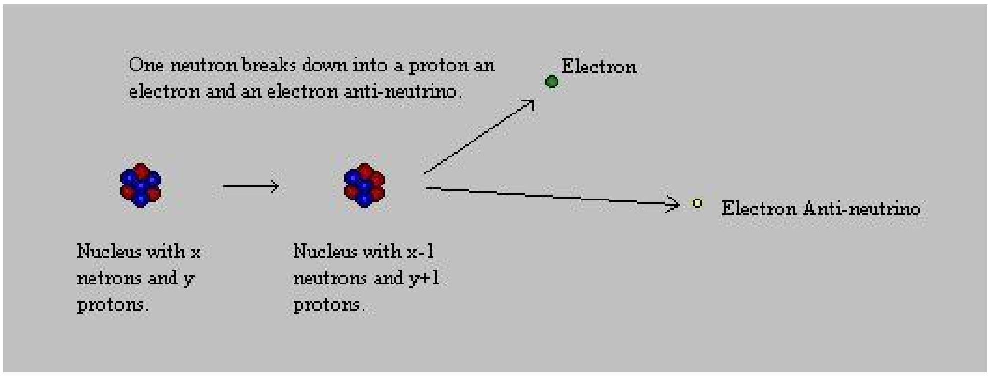


Fig. (2.12) Beta decay is a process whereby a free neutron decays into an electron, proton and an electron anti-neutrino [27].

Scientists suggested that neutrinos formed in the early universe were formed from interactions with an additional Higgs or Higgs –like field.

2.5 Tying All Together:

As we have seen, **S**tandard **M**odel (**SM**) provides a very good description of phenomena observed by experiment, but it is still an incomplete theory.

So we need to extend it with something totally new. We need to look beyond the Standard Model to explain mass, gravity and other phenomena.

The only way to achieve this is through high energy experiments, which managed to collide particles together at the range of TeV.

*The **L**arge **H**adron **C**ollider* (**LHC**) built at **CERN** will provide such collisions at the highest energies obtained in laboratory condition. In addition to the high energy, the **LHC** also will have the most intense beams (i.e. the highest luminosity).

Thus, the **LHC** with its associated experiments **(ATLAS, CMS**, **ALICE**, **LHCb**, **TOTEM** and **MOEDAL)** is expected to pave the way for exploring the unknown world of new particles and forces**.**

ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**) and **CMS** (**C**ompact **M**uon **S**olenoid) are general – purpose experiments that will search for the Higgs particles, which has not yet been convincingly observed, and study other unsolved aspects of the Standard Model.

ATLAS is designed to make a precise measurement during both high and low luminosity. This detector has been optimised to be especially precise for measurements of leptons and photons transverse energy.

Similarly to **ATLAS**, **CMS** will be able to identify and measure muons, photons and electrons through its high performance muon system, high quality central tracking and best possible calorimeters.

LHC will also be able to produce ion-ion collisions, for which a dedicated experiment ,**ALICE** (**A L**arge **I**on **C**ollider **E**xperiment),is being built .One of the key physics aims of **ALICE** is to study the physics of strongly interacting matter at extreme energy densities , where the formation of a new phase of matter , the quark-gluon plasma, is expected.

LHCb (**L**arge **H**adron **C**ollider **b**eauty) is a forward collider detector to study (**CP)** violation and other phenomena in Beauty particle decays.

TOTEM, is partially embedded inside **CMS** , will concentrate on measuring the total cross-section , elastic scattering and diffractive processes. An important goal of this experiment is providing a very precise measurement of the luminosity especially for its experiment.

MOEDAL is a further experiment has been proposed to operate in conjunction with **LHCb** . It is designed to search for magnetic monopoles and other highly ionising exotic particles through the use of passive track-etch detectors [17].


CHAPTER 3
WHAT IS THE LHC?

3.1 Basic Information:

3.1.1 Objective of the LHC:

The Large Hadron Collider **(LHC)** is a particle accelerator which will ultimately bring protons and ions into head-on collisions at energies higher than ever achieved before. In fact, it is designed to reach 14 TeV in order to recreate the conditions prevailed in the early moments of the universe, just after the **"Big Bang".** This will allow scientists to penetrate further into the structure of matter and find the answers of some questions which are needed to complete our current understanding of the universe.

As we mentioned in the previous chapter, the **Standard Model** is the best description we have for the world of quarks and other particles. However, it is unable to solve the mystery of mass. And the question why elementary particles have mass and why their masses are different is yet unanswered.

The answer may lie within an idea called the Higgs mechanism. According to this idea, the whole space is filled with a filed called **'Higgs field'**, and particles acquire their masses by interacting with this field. Particles which interact strongly with the Higgs field are heavy, whilst those which interact weakly are light. The Higgs field has at least one new particle associated with it, known as the *Higgs boson*. If such particle really exists, the **LHC** will be able to detect it.

More importantly the **SM** managed to describe the 5% of the universe (the fraction made up of quarks and leptons), but it failed to describe the rest 95% of the unknown universe represented by neutrinos, dark matter and energy.

In addition to that, the four fundamental forces in our universe are yet (not unified). When the Universe was young and much hotter than today, perhaps these forces all behaved as one. Particle physicists hope to find a single theoretical framework to prove this .One of the suggested framework is the concept of supersymmetry or **SUSY** for short. **SUSY** predicts that for each known particle there is a 'supersymmetric' partner. If **SUSY** is right, then supersymmetric particles should be found at the **LHC.**

The **LHC** will also help us solve the riddle of antimatter. It was once thought that antimatter was a perfect 'reflection' of matter - that if you replaced matter with antimatter and looked at the result in a mirror, you would not be able to tell the difference. We now know that the reflection is imperfect because of the **CP** violation. This has led to the matter-antimatter imbalance. The **LHC** will be a very good 'antimatter-mirror', allowing us to put the Standard Model through one of its most grueling tests yet.

These are just a few of the questions the **LHC** should answer, but history has shown that the greatest advances in science are often unexpected. Although we have a good idea of what we hope to find at the **LHC**, future may have well surprises for us. The most certain thing is that the **LHC** will change our view of the Universe [28].

3.1.2 Situation of the LHC:

The best place for such project was **CERN** (The European Organization of Nuclear Research), the world's largest particle physics laboratory which is half a century old this year.

Therefore, the **LHC** is being built across the Franco-Swiss border west of Geneva, at the foot of the Jura Mountain, as shown in Fig. (3.1).

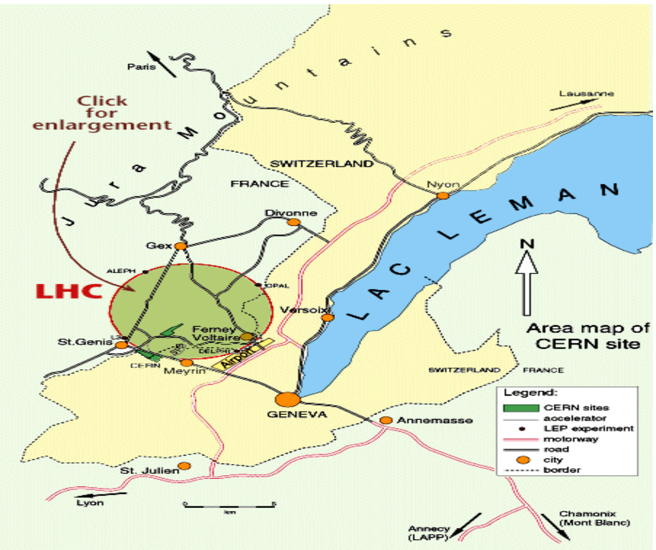


Fig. (3.1). LHC Geographical Situation

i) Brief History of CERN:

During the first half of this century, progress in physics from the discovery of the atom to the discovery of nuclei and its constituents, including the tow main revolutions as relativity and quantum mechanics was Europe dominated. By the early 50s, the Americans had understood that further progress needed more sophisticated instruments, and that investment in basic science could drive economic and technological developments. While scientists in Europe still relied on simple equipments based on radioactivity and cosmic rays, powerful accelerators were being built in the US.

The creation of a European Laboratory was recommended at a **UNESCO** meeting in Florence in 1950. Less than three years later a Convention was signed by 12 countries of the **C**onseil **E**uropéen pour la **R**echerche **N**ucléaire, and **CERN** was born. **CERN** was the prototype of a chain of European institutions in space, astronomy and molecular biology, and Europe was poised to regain its illustrious place on the scientific map.

CERN currently employs 3000 people full-time, 6500 scientists and engineers (representing 500 universities and 80 nationalities), about half of the world's particle physics community, work on experiments conducted at **CERN** [29].

ii) CERN as Accelerators Complex:

The main goal of **CERN** is to provide the particle accelerators needed for high energy physics researches**.** Because studying particle collisions is like "looking back in time" by recreating the environment present at the origin of our Universe. So **CERN** has built a large system of accelerators since the 1950s. The biggest one among those accelerators was the **LEP** (***l**arge **E**lectron **P**ositron*) accelerator which was in operation between 1989 and 2000.

When the **LHC** project was proposed, scientists decided to use the same tunnel of **LEP** instead of building a new one to save cost and efforts. So the whole **LEP** machine was dismantled to make room for the new accelerator (**LHC**) in the same tunnel.

In contrast to **LEP**, **LHC** will collide beams consisting of protons or lead ions . Collisions with much higher energy, 14 TeV, will be possible by replacing the electrons and positrons from LEP with protons [30].

3.2 Layout of the LHC Machine:

The **LHC** machine is installed in the same tunnel of the **LEP** machine which is 27 km in circumference, 3.8 m in diameter, buried 50 to 175, below ground. As in Fig. (3.2), the layout of the **LHC** ring is divided into octants. At the octant center the beams can intersect, but only four of the eight possible crossing regions are used for physics. **ATLAS** and **CMS** are situated at points 1 and 5, respectively. Point 2 and 8, respectively, house **ALICE** and **LHCb**. These four points are equipped with so-called high luminosity insertions that focus the beams down to very small dimensions. At points 2 and 8 the beams are injected into the machine. The points that are unused for experiments contain essential elements for the operation of the machine; **RF**, beam cleaning and beam dump. The eighth of the machine between the intersection points are called a *sector*. The central region of each sector equipped with the bending magnets. These magnets form the backbone of the **LHC** project and are the most costly element in the whole project [1].

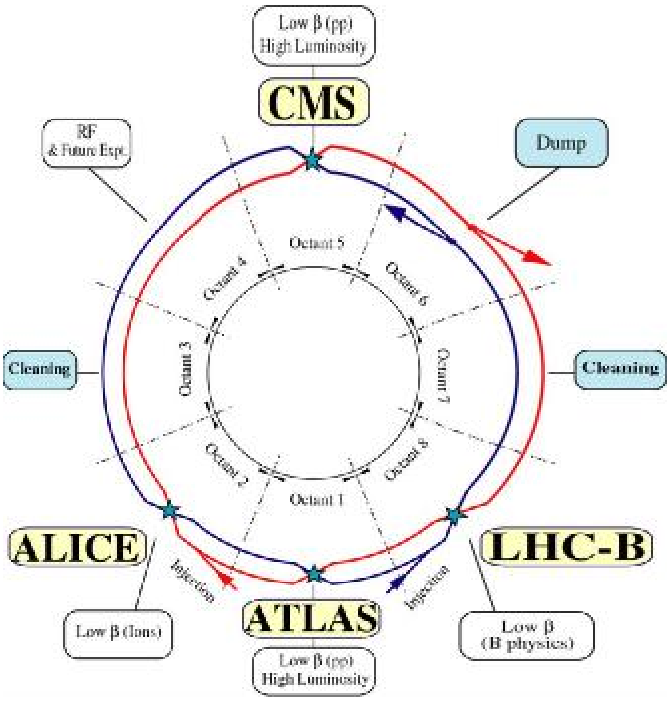


Fig. (3.2) Layout of the LHC machine

To bend the path of accelerating particle beams and to keep them on course superconducting magnets are used. These magnets are designed to produce magnetic fields stronger than what ever been used before in any accelerator. The **LHC** will operate at about 300 degrees below room temperature so a huge cryogenic system is needed.

Thus, the main parts of the **LHC** machine are accelerators, supermagnets, bunches and detectors. Accelerators, supermagnets, and bunches will be the subject of the three following sections, while detectors will be described next chapter in details.

3.2.1 Accelerators:

i) What are Accelerators?

Accelerators work with charged particles that are accelerated to speeds close to the speed of light. By letting very fast and energetic particles collide in the accelerators, new particles will be created for a fraction of a second, before they decay into more ordinary ones. By a process of computational detective work, they can then deduce the proprieties on the new particles they created.

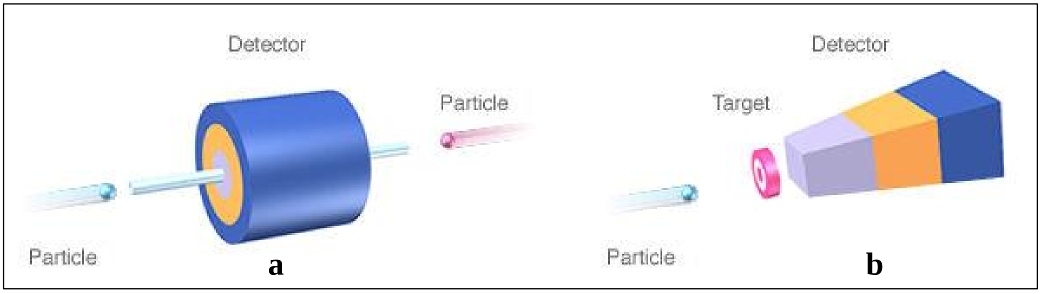


Fig. (3.2). Difference between the collider (a) and fixed target (b) experiments.

Particles can be collided by two methods [31]:

1- Fixed Target Experiments: which study what happens when a beam of particles smashes into the atoms of a target. In this configuration, most of the beam energy is used in the recoil of the target and only a small fraction is left to create new particles. In a fixed-target configuration, the particles produced generally fly forwards, so experiments usually have cone shaped detectors, placed downstream of the beam line.

2- Collider Experiments: which study the head-on collisions of two beams of particles traveling in opposite directions. In this way, no recoil energy is wasted, and all the energy is available for the production of new particles.
In such events, the newly created particles radiate in all directions from the collision point, so the detectors are spherical or, more commonly, cylindrical
In all accelerators the particle beams are kept in a vacuum tube so that the particles will not collide with air molecules.
A particle is accelerated by letting it pass through electrical fields that have a potential of several billions Volt, at these high energies the particles in the accelerator will have

speeds very close to the speed of light. A circular accelerator uses electromagnets to force the charged particles to go in curved trajectories.

Different kinds of particles can be accelerated, e.g. electrons, positrons, protons and different kinds of ions. The only requirement is that they must be **stable** and **charged** [32].

ii) LEP (Large Electron Positron Accelerator):

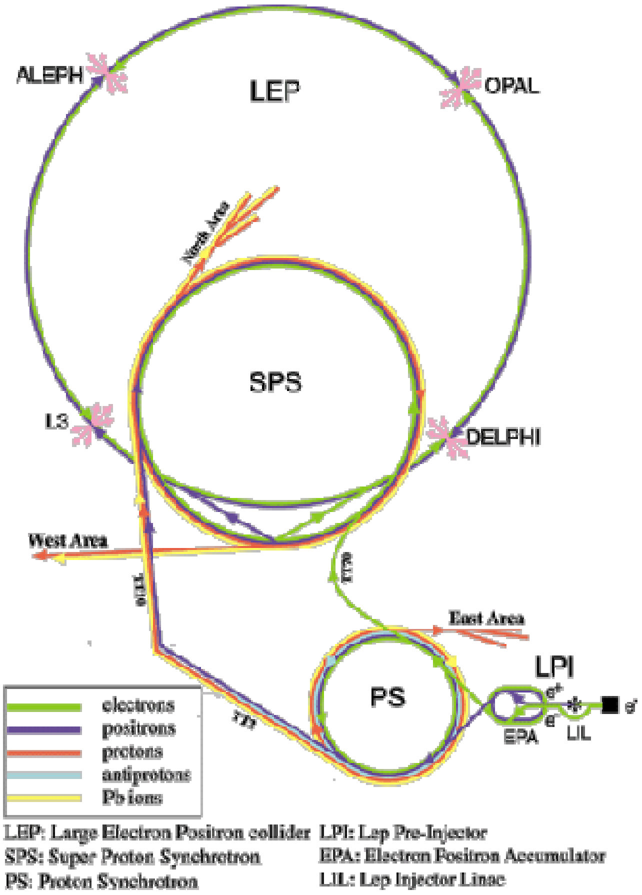


Fig. (3.3) Schematic diagram of the LEP accelerator [3].

As it was mentioned before, the **LE**P was in operation between 1989 and 2000 with maximum energy of 104 GeV. It is very important to understand the working mechanism of the **LEP**, since it will be same for **LHC** but with higher energy and different particles. When **LEP** was in used, electrons and positrons were accelerated through the following process [3] :

1. Heat is used to transfer energy to a metal wire in existence of an electrical field. The electrons in the wire then get enough energy to liberate themselves from the atoms in the wire. A **LIN**ear **AC**celerator (**LINAC**) is then used to accelerate those liberated electrons to energy of 200 MeV. Some of the

electrons are deflected and let to collide with a heavy metal target. These collisions create the **positrons** used in the accelerator system.

2. The linear accelerator then accelerates the electrons and the newly created positrons further to energy of 600 MeV. After that particles are led into a storage ring called where they are kept while accumulating more particles.
3. When a suitable amount of electrons and positrons have been gathered in the storage ring, they are steered into a circular accelerator called the *Proton Synchrotron* (**PS).** Where they are accelerated further to energy of 3.5 GeV.
4. After the PS the particles are led into a bigger circular accelerator, the *Super Proton Synchrotron* (**SPS)**, where they are accelerated to 22 GeV.
5. Finally they are moved to the main circular accelerator (**LEP** previously). Inside **LEP** electrons and positrons can be accelerated in opposite directions to energy of 104 GeV.

In the **LHC** the same steps will be followed and particles will be accelerated till they acquire energy of 14 TeV.

iii) Accelerator Constituents:

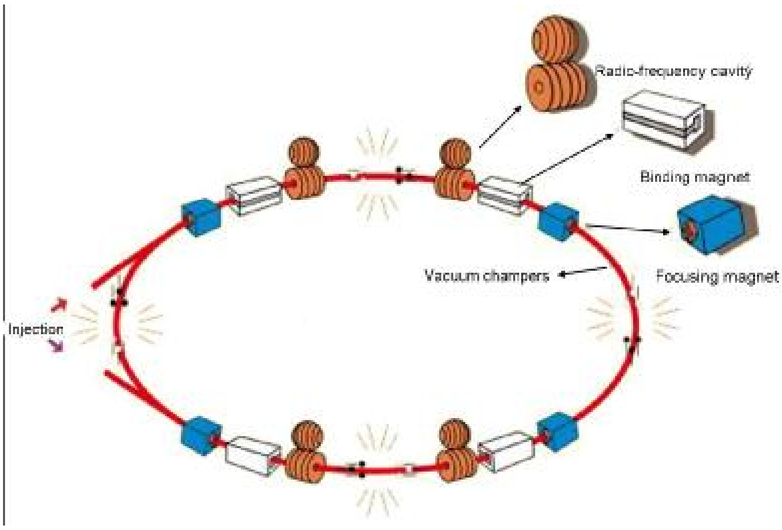
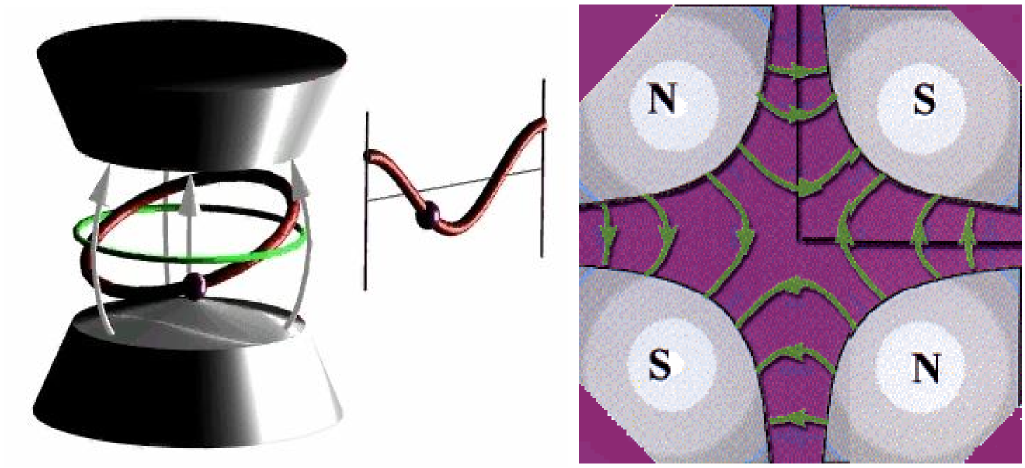


Fig. (3.4) The main component of accelerator [32].

The accelerator consists of [32]:

1. **The Vacuum Tube**: which is a metal pipe where air is permanently pumped out by the vacuum pumps to avoid collisions between the accelerated particles and air molecules.

2. **Radio-Frequency (RF) Cavities**: which produce high electric fields that accelerate the particles inside the pipe .In other words, the electric field inside the **RF** cavity gives the charged particle a "kick" when they cross through the cavity. They are accelerated because some of the radio wave energy is transferred to them. To make the limited number of RF cavities more benefit, the particle beam is forced to go through them many times and this is achieved by curving the beam trajectory into a closed loop. That is why most accelerators are roughly circular.
3. **Magnets**: The main two types of magnets placed around the accelerator ring are; the *dipoles* and the *quadrupoles*. Dipoles, shown in Fig. (3.5) (a), serve to change the direction of movement and make sure that particles stay within their circular track. They are also called "*bending magnets*". On the other hand, quadrupoles, shown in Fig. (3.5) (b), are used as "*lenses*" or "*focusing magnets*" that keep the size of the beam is smaller than the size of the vacuum pipe [33]. In the case of the **LHC**, *supermagnets* are used as it will be explained in following paragraph.



(a) **(b)**

Fig. (3.5). Magnetic flux lines in (a) dipole magnet and (b) quadrupole magnets

These are the basic components needed to make an accelerator, but there are some other components such as:

ý High voltage instruments.

ý Electronic circuits

- Injection/ejection elements to put the beam into the accelerator or to take it out.
- Measurement devices to give the operators information on the behavior of the beam.
- Safety elements to ensure smooth operation of the accelerator.

All of these elements are controlled from **CERN** control centre **CCC**, which is very much like the control centers used for space missions.

3.2.2 The LHC Supermagnets and Cryogenic System:

Superconductivity is the ability of certain materials, usually at very low temperatures, to conduct electric current without resistance or power loss. Such materials can produce high magnetic fields, hence they called ***supermagnets*** [34]. There are around 30 different types of magnets in the **LHC** ring, the majority of them are supermagnets.

i) Supermagnets:

The **LHC** requires a huge dipole magnet that can accelerate the protons to 7-on-7 TeV. After that the beams will counter-rotate for several hours before collide at the experimental points on the ring. It is well known that the stronger the magnetic field the tighter the arc of the beam. And as the beam's energy gets higher, it will need a stronger magnetic field to bend it.

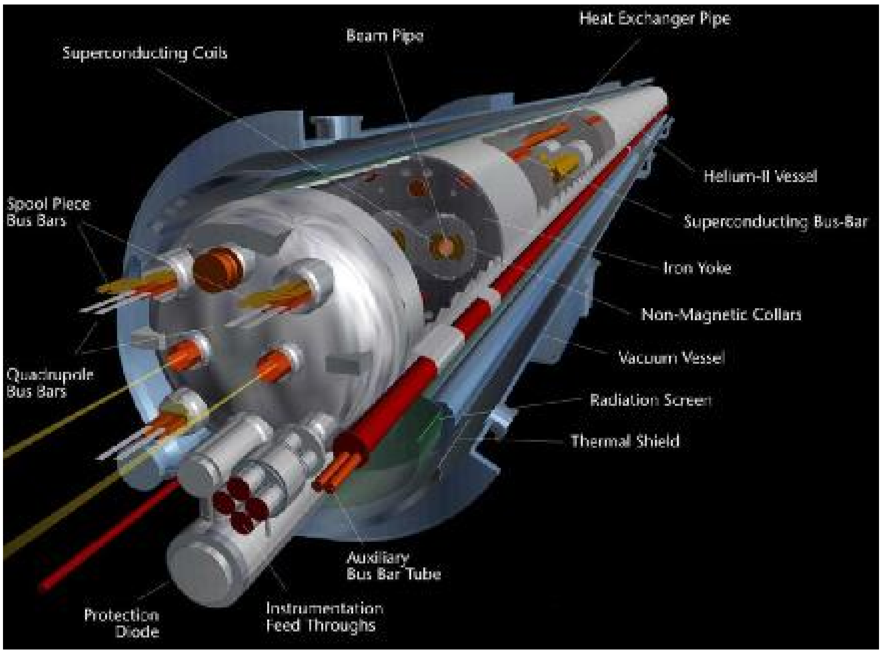
Therefore, to bend 7 TeV protons around the 27 km ring, the **LHC** dipoles must be able to produce fields of 8.36 Tesla, which is five times of those used at LEP a few years ago and almost 100,000 times the earth's magnetic field. The only solution then should be the use of the *supermagnets***.**

The use of strong field superconducting magnets has always posed technical challenge because superconductivity weakens or vanishes in the presence of a strong magnetic field. Most of superconducting magnets cannot achieve a dipole field stronger than 2 Tesla. But since the **LHC** magnets are expected to operate at field strength of 8.36 Tesla. The search for new and better superconducting alloys has continued, and Niobium-titanium which can approach 10 Tesla has been chosen for the **LHC** superconducting magnets [34].

ii) The LHC Cryodipole:

The **LHC** needs two beams that can follow the same horizontal circular path but in opposite direction. This can be preformed if the two proton beams are in separate beam pipes going through oppositely directed magnetic fields, or more cheaply, by using "tow-in-one" dipole magnet. In this technique a twin aperture device, known as *the dipole cold mass*, is housed inside a cryostat as in Fig (3.6) to form what so- called *the **LHC** Cryodipole* [35]. Conductors running along the sides of the beam pipes produce magnetic field in these apertures. A current of 11.5 kA is needed to produce the design field of 8.4 T. The polarity of the current is such that the magnetic fields in the apertures point in opposite directions [1].

Each *cryodipole* is a cylinder of 15 m long and 0.57 m diameter. It is composed of superconducting coils, which produce the magnetic field, surrounded by non-magnetic collars and an iron yoke which ensures the mechanical stability. All enclosed in a shrinking cylinder, which in turn situated inside a special cryostat [35].



Fig(3.6) The Cryodipole or "tow-in-one" dipole magnet of the LHC [36].

The whole of the cold mass is bathed in superfluid helium at 1.9 K. To keep the cold mass at low temperature, it is contained from outside in a vacuum. To further reduce radiation losses, a shield at 4.2 K is placed between the cold mass and the vacuum vessel [36].

The construction of the **LHC** ring requires 1232 of those cryodiploes and about 600 main quadrupole magnets. Each sector the **LHC** ring has an '**arc**' of bending magnets, which made up of 23 cells. In turn, each of these cells contains six cryodiploes with a pair of oppositely polarized quadrupoles as it is illustrated in Fig. (3.7). These quadrupoles provide the necessary function in maintaining the particles in orbit by sequentially focusing and defocusing the protons. In addition, each cell contains a number of sextupole, octupole and decapole correctors to offset unavoidable inaccuracies in the main dipoles [1,37].

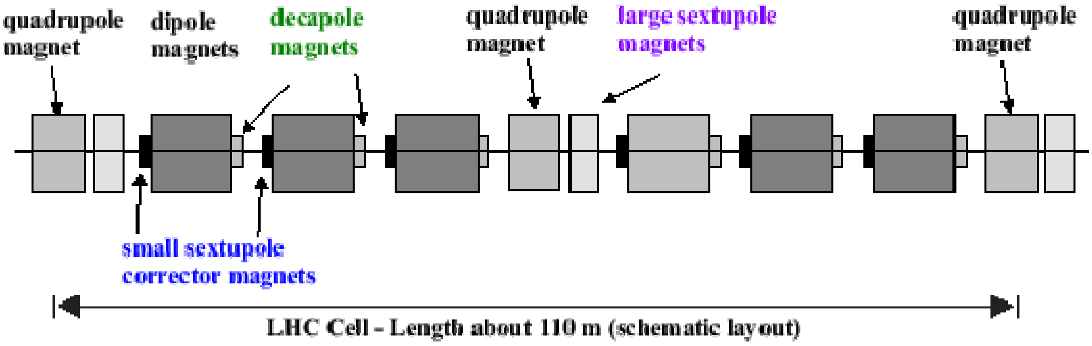


Fig. (3.7). Schematic layout of one LHC cell with dipole, quadrupole and corrector magnets [38].

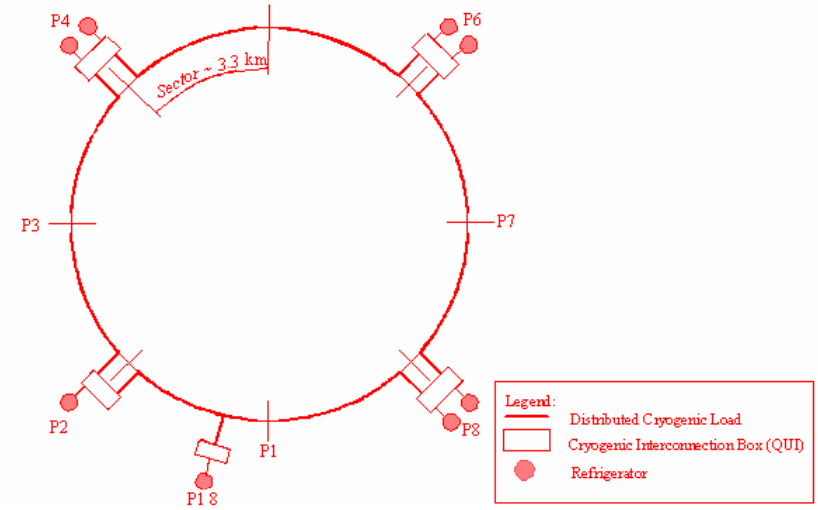
iii) Cryogenic System:

Since the **LHC** will use the strongest superconducting magnets operating at superfluid helium temperatures, it will need the largest cryogenic system.

Although normal liquid helium at 4.5 K would be able to cool the magnets so that they became superconducting, the **LHC** will use superfluid helium at the lower temperature of 1.8 K. Superfluid helium has unusually efficient heat-transfer properties, allowing kilowatts of refrigeration to be transported over more than 1 km with a temperature drop of less than 0.1 K.

Cryogenic refrigerator distributed around the **LHC** ring, with a total power exceeding 140 kW, will cool the helium in two stages, first to 4.5 K and then to the final 1.8 K. In all, **LHC** cryogenics will need 40,000 leak-tight pipe junctions, 12 million litres of liquid nitrogen and 700,000 litres of liquid helium. Supplying all of this liquid helium is a major cryoengineering challenge. To come over such challenge **(*Cryogenic Ring Line*) QRL** was introduced. [34,39].

The term **QRL** refers to all the equipments necessary to transfer liquid and gaseous helium at various temperatures and pressures between the refrigerators and the superconducting **LHC** machine cryostats. The present system, consists of eight cryogenic plants distributed over five points around the **LHC** ring to feed the superconducting magnets via eight approximately 3.2 km long QRL sectors. Each of those sectors, shown in Fig. (3.8), will operate independently. [39,40]



Fig(3.8) The present system of QRL [41]

3.2.3 Bunches:

i) What are Bunches?

In the **LHC** protons are chosen because they are heavy and charged and hence very high energy can be reached. A "proton beam" is in fact a chain of squeezed groups of protons called "*bunches*". Each bunch is roughly cylindrical in shape with a few centimeters long and a few µm in radius. The distance from one bunch to the next is 7.5 m, which is equivalent to 25 ns since protons are practically moving at the speed of light. Therefore, head-on meetings between bunches at every collision point occur every 25 ns, or 40 million times per second. In other words, the collisions rate is 40 MHz. Each beam of the two **LHC** beams will consist of 2835 bunches with 10^{11} particles in each. The particles are so tiny that the chance of any two to be collided is very small [42].

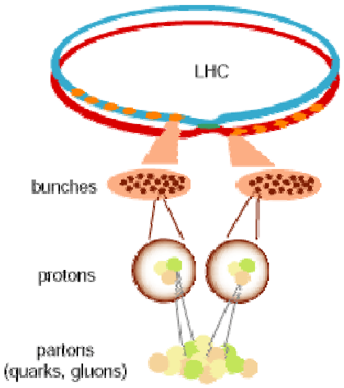


Fig. (3.9). Each proton beam is a chain of squeezed groups called "*bunches*".

ii) How Many Collisions?

If two bunches of protons meet head on, there might be no proton-proton collisions between protons from one bunch and protons from the other, or one collision, or ten collisions. For a fixed bunch size, collisions depend on how many protons there are in each bunch, and how large each proton is. In the case of **LHC** there will be only about **20 collisions** among the 2x10^{14} particles. However, the particle beams will cross about 40x10^{6} times per second, so the **LHC** will generate about **800x10^{6} collisions** per second [43].

iii) Luminosity:

In fact the number of **collisions** per second, n_x, is proportional to the *p-p* cross section s_x, through a proportionality constant, *L*, known as the "*luminosity*".

$$n_x = L s_x \qquad (3)$$

In order to increase the number of collisions n_x, which is a vital need of the collider, s_x and/or *L* must be increased.

The cross section, at a given energy, is fixed for each expected process in *p-p* interactions as it is shown in Fig.(3.10). In addition, the cross section for heavy particle varies as $1/E^2$ (*E* is the mass of the particle), i.e, the massive the particles, the smaller cross section they have. Therefore, obtaining an acceptable rate for the massive Higgs particles, the LHC made for, requires a very high luminosity. Indeed, in LHC, achieving high luminosity is as important as achieving high energy.

The luminosity itself depends on some parameters of the collider such as the number of bunches per beam, the number of protons per bunch and the distance between two following bunches. According to the properties of the LHC proton beams, keeping the bunch spacing fixed at 25 ns, leads to a corresponding luminosity of 10^{34} cm^{-2} s^{-1}. With this high luminosity the production of the 500 GeV Higgs bosons at the LHC will be around 4-5 x10^{-3} per second [1,44,45].

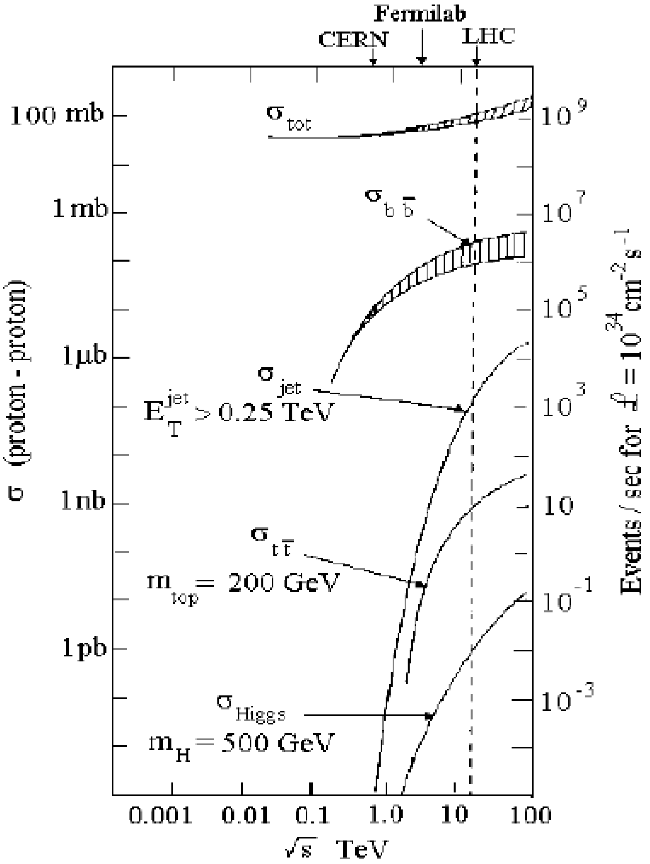


Fig (3.10). Cross section for various processes expected in p-p interactions as a function of the center- of -mass energy [44].

iv) Challenges Facing Luminosity:

While the bunches touring their four hundred million revolutions around the machine, they could be effected by some factors that dilute beams and degrade the luminosity. Those factors are[46]:

1- Beam-Beam Effect:

When two bunches cross in the center of the detector a strong electromagnetic field will be produced. this, in turn, causes deflections for large fraction of the particles. The deflections strength proportional to the bunches density (stronger for denser bunches). As a sequence of the beam-beam effect only a tiny fraction of the particles will collide head-on, and the luminosity will be reduced . This beam-beam effect was studied in previous colliders (**LEP**) , where experience showed that one cannot increase the bunch density further than a certain beam-beam limit to preserve a sufficiently long beam lifetime. The **LHC** has to operate as close as possible to this limit to reach the most wanted luminosity. The **LHC** injectors, the old **PS** and **SPS**, are being refurbishing to provide exactly the required beam density.

2- Collective Instabilities:

While the 2835 proton bunches traveling down the 27 km long **LHC** beam pipe at a speed close to the speed of light, each of them (the 2835 proton bunches) leaves behind an electromagnetic wake-field which disturbs the succeeding bunches and can lead to beam loss. These collective instabilities can be severe in the **LHC** because of the large beam current needed to provide high luminosity. Their effect is minimized by a careful control of the electromagnetic properties of the elements surrounding the beam. For instance the convolutions of the thousands of bellows which are used to allow the machine to contract during cooldown are shielded from the beam by thin fingers equipped with sliding contacts; the inner side of the stainless steel beam pipe is coated with pure cooper to reduce its resistance to beam induced wall currents. However these precautions cannot suppress all instabilities, and sophisticated feedback systems as well as non linear lenses are being designed to damp the remaining ones.

3- Chaotic Motion:

Tiny spurious (imitation) non linear components of the guiding (binding) and focusing magnetic-fields of the machine can make the motion slightly chaotic, so that after a large number of turns the particles may be lost.

In the **LHC** the destabilizing effects of magnetic imperfections is more pronounced at injection energy, because the imperfections are larger and because the beams occupy a larger fraction of the ring cross section.

There are two ways to cure this:

- The Dynamic Aperture, the fraction of the coil cross section within which particles remain stable for the required time, must be evaluated and make sure that it exceeds the dimension of the injected beam with a sufficient safety edge.
- For the time being, no theory can predict with sufficient accuracy the long term behavior of particles in non linear fields. Instead we use fast computers to follow hundreds of particles step by step through the thousands **LHC** magnets for up to a million turns. Results are used to define tolerances for the quality of the magnets at the design stage and during production.

4- Quenches:

In spite of all precaution the beam lifetime will not be infinite. A fraction of the particles will diffuse towards the beam pipe wall and be lost. Then, their energy is converted into heat in the surrounding material and this can "quench" the magnet out of its cold, superconducting state. A quench in any of the 5,000 **LHC** superconducting magnets will disrupt machine operation for several hours! To avoid this a collimation system will catch the unstable particles before they reach the beam pipe wall, so losses are confined in well shielded regions far from any superconducting element. To design effective controls systems, safety engineers are using extremely advanced computer programs to perform coupled mechanical-magnetic-thermal analyses of stresses induced by a quench.

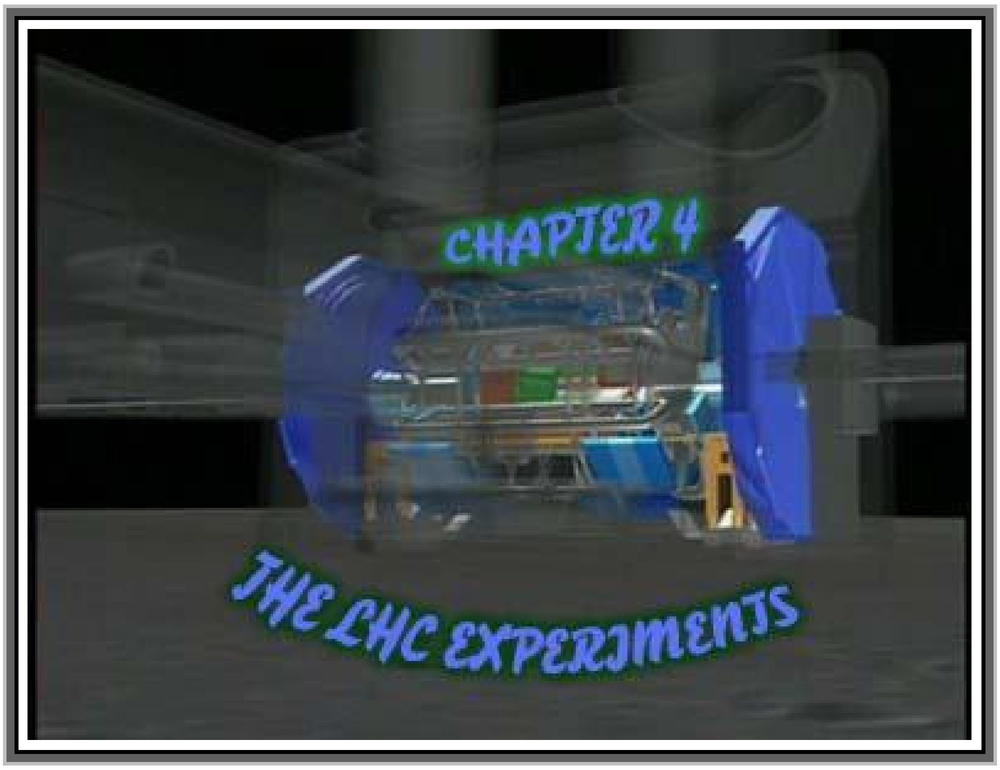
3.2.4 Some Important Parameters:

The main features of the **LHC** machine can be summarized in some important parameters. These parameters are shown in table (3.1).

Beam energy (TeV)	7.0
Number of particles per bunch	1.15 x10^{11}
Number of bunches per beam	2808
Time between crossing (ns)	25
Crossing angle (μrad)	285
Normalized transverse emittance (μm rad)	3.75
Collisions rate (MHz)	40
Beta function (β) at P: 1, 2, 5& 8 (m)*	0.55, 10, 0.55 &10
Luminosity in P: 1 & 5 ($cm^{-2}s^{-1}$)*	10^{34}
Luminosity in P: 2 & 8 ($cm^{-2}s^{-1}$)*	~5 x 10^{32}
Transverse beam size at P: 1 & 5 (μm)*	16.7
Transverse beam size at P: 2 & 8 (μm)*	70.9
Stored energy per beam (MJ)	362

Table (3.1) Some main features of the LHC machine [47].

*** The points (1, 2, 5 & 8) refer to the corresponding octants.**


CHAPTER 4
THE LHC EXPERIMENTS

4.1 The LHC Detectors:

The **LHC** consists of six experiments (or detectors) located at four points as it was shown previously in Fig. (3.2). **ATLAS** and **CMS** are general-purpose experiments, although they will search particularly for the Higgs particles. Other experiments are **ALICE** experiment which is built to produce ion–ion collisions, the **LHCb** experiment which is a forward collider detector studying **CP** violation and other phenomena in Beauty particle decays, **TOTEM** experiment which is partially housed inside **CMS** to study physics in the very forward direction and **MOEDAL** experiment in the **LHCb** pit to search for monopoles and other highly ionizing exotic particles. In this chapter a general idea about the particle detector will be given. For more clarification we will explain one of the **LHC** experiments, **ATLAS**, in details. The other experiments will be then described briefly.

4.1.1 What is a Detector?

Modern particle detectors consist of a large number of different subdetectors of different types, each type has a well-defined task in the detection procedure. A detector must be capable of doing:

1. Measure the directions, momentum, and signs of charged particles.
2. Measure the energy carried by electrons, photons and hadrons in each direction from the collision.
3. Identify which charged particles from the collision, if any, are electrons and which are muons.
4. Identify whether some of the charged particles originate at points a few millimeters from the collision point rather than at the collision point itself (signaling a particle's decay a few millimeters from the collision point).
5. Deduce, through momentum conservation, the presence of undetectable neutral particles such as neutrinos.
6. Have the capability of processing the above information fast enough to permit flagging. About 10-100 interesting events per second out of the billion collisions per second that occur, must be recorded and measured.
7. The detector must also be capable of long and reliable operation in a very hostile radiation environment [48].

4.1.2 Some Important Parameters:

i) The Transverse Momentum p_T:

Energy conservation cannot be used in a hadronic collider, because so much energy is taken away in unmeasurable particles inside or very near the beampipe. For the same reason, momentum conservation along the beampipe cannot be used. However, conservation of momentum transverse to the beampipe (p_T) should work. The ***transverse momentum***, p_T, is the particle mass times its velocity that goes sideways to the direction that the two ions were traveling before they collided. Some particles that are neutral and do no interact in our detector will show up by carrying off large p_T which is not balanced by the other particles in the event. For example, if we have a 40 GeV transverse momentum particle that goes to the left at 90 degrees, there must be a total of 40 GeV transverse momentum particle(s) going off to the right. If we do not see any energetic particles to the right, then there must be one or more particles that we can not detect. These non-interacting neutral particles include neutrinos, as well as possibly some new particles of similar persuasion. Particles with a high transverse momentum are generally traveling faster and are more energetic, but they are seen rarely [49,50,51].

ii) Pseudorapidity <η>

η is convenient measure of angle for many physics particle production modes and defined by

$$h = \ln(\tan(\frac{q}{2})) \qquad (4.1)$$

where θ is angle between the outgoing particle and the undeflected beam. Three terms '***barrel***', '***end-cap***' and '***forward***' are used to describe angular ranges and parts of detectors. A barrel detector sits in the centre of the experiment and typically covers an angular range of $-45^o < \boldsymbol{\theta} < 45^o$. An 'end-cap' detector covers the approximate angular range of $15^o < \boldsymbol{\theta} < 45^o$ (if it were located on the positive side). 'Forward' is used to describe detectors for particles within 15^o of the beam axis. It should be emphasized, that there is by no means any consistency in these definitions [1].

Table (4.1) represents some typical values of q and the corresponded h.

θ	η
0	∞
5	3.13
10	2.44
20	1.74
30	1.31
45	0.88
60	0.55
80	0.175
90	0

Table (4.1) some representative values of h [52]

4.1.3 How Do Particles Interact Inside the Detector?

Particle detectors, in general, consist of three main parts; *tracker*, *Calorimeter*, and *muon chamber*. Each of these parts has a specific function according to its interaction with incident particles, See Fig. (4.1);

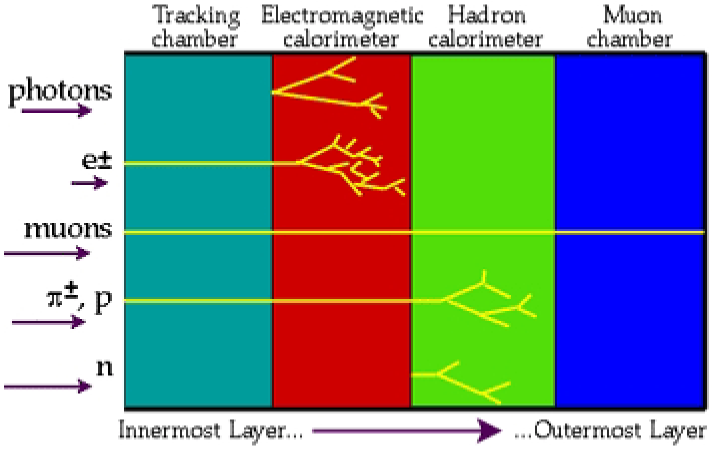


Fig. (4.1) The particles interactions inside the detector.

1. *Track detectors* are closest to the collision point. They show the trajectories and scattering angles of charged particles.
2. *Calorimeters* are outside the track detectors. They measure the energy of both charged and neutral particles. The calorimeters are further divided into electromagnetic and hadronic calorimeters, with the electromagnetic ones closest to the collision point.
3. *Muon detectors* are furthest from the collision point. They identify muons, which are charged massive particles [53].

On the base of this, Charged particles, like electrons and protons, are detected both in the tracking chamber and the electromagnetic calorimeter. While neutral particles, like neutrons and photons, are not detectable in the tracking chamber; they are only evident by measuring the transverse momentum in the calorimeters . Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter. Each particle type has its own "signature" in the detector. For example, if a physicist detects a particle only in the electromagnetic calorimeter, then he is fairly certain that he observed a photon. Some particles such as neutrinos rarely interact with matter; hence they can only be detected by missing matter and energy [54].

4.2 The ATLAS Experiment:

ATLAS detector is one of the largest and most complicated particle physics experiments ever constructed. It is designed as a multi-purpose experiment to investigate many different processes at **LHC**. **ATLAS** detector is designed similarly to the onion structure. The beam pipe, where collision will take place, is completely surrounded by layers of different type of detectors.

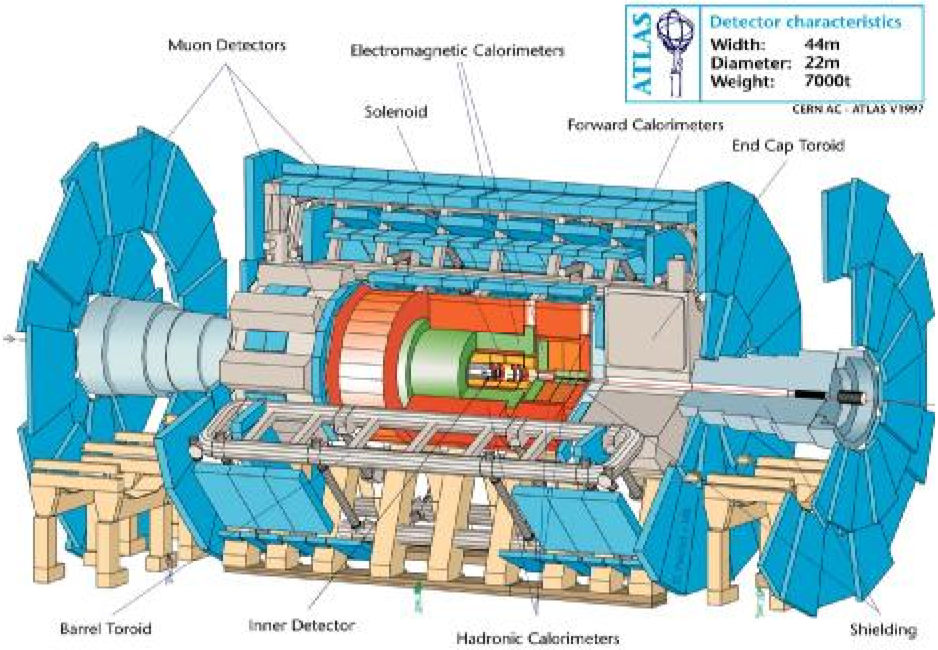


Fig. (4.2) Schematic diagram of ATLAS Detector.

A schematic diagram of **ATLAS** detector is illustrated in Fig.(4.2). It consists of three main effective components that will be able to identify particles and make accurate measurements of energy and momentum. These components are [55,56]:

- The Inner Detector, located inside the solenoid that provides 2 T axial field.
- The Calorimeter, located outside the solenoid, with a precision measurements for photons, electrons, muons, τ-leptons and b-quark jets over $|\eta| < 2.5$. The complete hadronic energy measurements extend over $|\eta| < 4$ [57].
- The Muon Spectrometer, located inside a huge Toroidal field, which covers the range $|\eta| < 2.7$.

The interactions in the **ATLAS** detectors will create an enormous dataflow. To process this data the detector needs [58]:

- The Trigger System which, through its three levels, selects 100 events with promising characteristics per second.
- ***Data Acquisition System*** (**DAQ**), which directs the data from the detectors to the storage.
- Computing System that manages data storage and analysis.

In the following sections, each of **ATLAS** Measurement and Computing components will be discussed in detail.

4.2.1 The Inner Detector:

The Inner Detector measures the directions, momentum, and charge of electrically-charged particles produced in each p-p collision. It consists of three different systems all immersed in a 2 T magnetic field parallel to the beam axis.

This magnetic field is produced by a central superconducting solenoid located outside the Inner Detector. This field deflects each charged particle coming from the collision point. If a particle emerges perpendicular to the beam, it continues perpendicular and travels in a circle whose radius is proportional to its momentum. The paths of very slow particles can "curl up" within the detector, whereas those of very fast particles have very large radii and can leave the detector (unless absorbed or deflected).

The direction of rotation around the magnetic field (clockwise or counter-clockwise) indicates the sign of charge of the particle. If the particle is not perpendicular to the beam, the field changes the trajectory to a circular loop with axis parallel to the beam line. The radius of the loop is proportional to the momentum of the particle.

The main components of the Inner Detector are: Pixel Detector, Strip Detector, and Transition Radiation Tracker shown in Fig. (4.3)

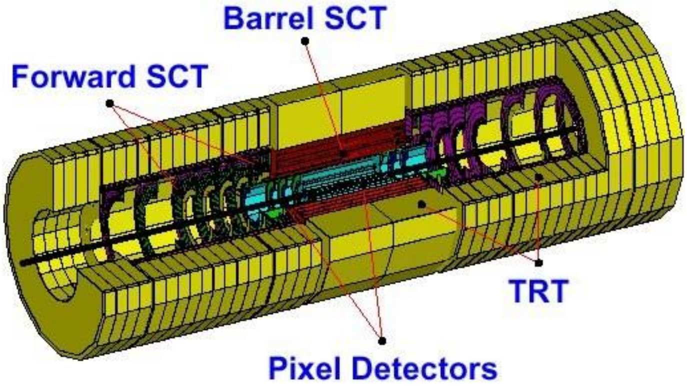


Fig. (4.3) Components of ATLAS Inner Detector.

i) Pixel Detector:

High-precision and high-efficiency semiconductor elements are needed near the collision point in order to distinguish individual tracks from hundreds produced in each collision. For this purpose pixel detectors are used and located closer to the collision point. They consist of thin layers of silicon subdivided into rectangular regions of dimensions 50 by 300 μm. The **ATLAS** will have approximately 140 million of these tiny pixel sensors. Closer to the collision, pixel are placed cylindrically, whereas they are located on disks further away (see Fig. (4.4)).

Each time a charged particle passes through such a layer an electron-hole pair is created in the semiconductor. By applying an electric field the electrons and holes are separated and collected at the electrodes. The measured signal identifies which pixel has been struck, and thereby gives a precise measurement of the particle position. Because of their high precision, pixel sensors are mainly used to study short-lived particles.

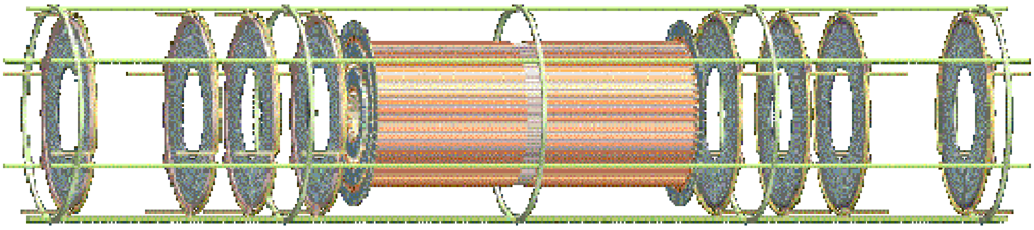


Fig. (4.4) ATLAS Pixel Detectors.

ii) Strip Detectors:

To provide additional position measurements a little further from the collision point, additional layers of silicon subdivided into narrow strips with 80 μm wide and few centimeters long .Each layer actually has two sets of strips, running at an angle of 2.3 degrees relative to each other. On the cylinders, the strips run parallel to the beam axis, while on the disks, the sets run radially. When a charged particle goes through the strip detector, signals identify which strip in each set has been crossed.

iii) Transition Radiation Tracker (TRT):

At larger radii, it becomes too expensive to cover the required areas with silicon strip detectors. The alternative cheaper solution is the Transition Radiation Tracker.

Each tracker contains around 10^5 of narrow, like straw, gas-filled tubes. A high-voltage wire runs along the axis of each tube to maintain a high voltage between the wire and the metallized tube wall. When a charged particle passing through any tube it will collide with the gas atoms and ionize them. The high applied voltage makes the electrons move to the anode and the ions to the cathode. The electrons will then be recorded as an electrical current. The librated electrons take some time to travel to the anode. By measuring this time, the position of the original particle can be determined accurately.

Gaps between tubes are filled with some special materials which cause electrons to produce X-rays when they pass through them. This will help **ATLAS** to distinguish between electrons produced in collisions and other heavier particles such as *pions*.

4.2.2 The Calorimeter:

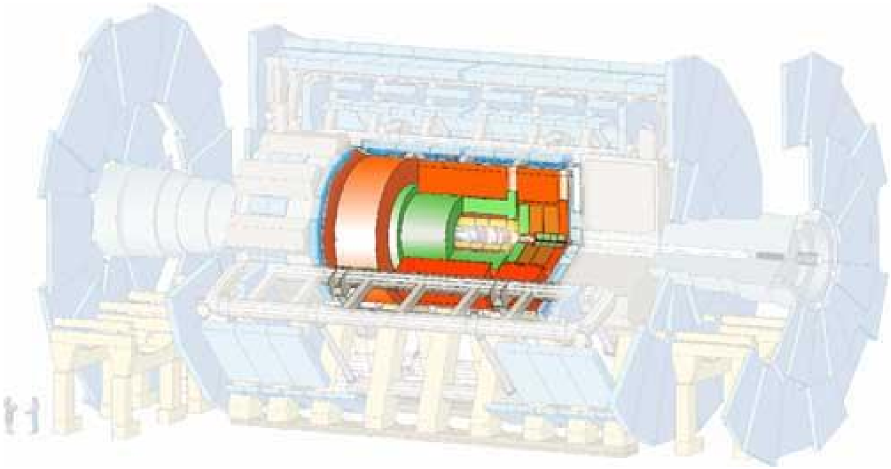


Fig. (4.5) ATLAS Calorimeters.

Surrounding the Inner Detector are calorimeters (shown in Fig. (4.5)), which measure the energies of charged and neutral particles coming from the collision point. They are consisting of many layers of dense plates which absorb incident particles and transform their energies into large 'showers' of lower energy particles. For this reason the calorimeter is usually located outside the track detectors, so the trajectory of the particle can be registered before it is absorbed in the calorimeter. The only particles that could pass through the calorimeters, with no absorption, are muons and neutrinos. Such particles will be caught by the muon detectors.

There are two kinds of calorimeters; electromagnetic and hadronic.

i) Electromagnetic Calorimeter:

The Electromagnetic Calorimeter absorbs and measures the energies of electrons and photons produced in collisions. It consists of closely-spaced absorber layers of stainless steel lead plates immersed in a bath of liquid argon. When the particle showers interact with the liquid argon they will produce ions that can be recorded as electric pulses by segmented electrodes.

ii) Hadronic Calorimeter:

The hadronic calorimeter surrounds the electromagnetic calorimeter to absorb and measure the energies of those particles that are not stopped by the electromagnetic calorimeter. Such particles are mainly hadrons, like protons, neutrons, *pions* and *kaons* .

The hadronic calorimeter consists of steel absorbers separated by tiles of scintillating plastic which emit light when charged particles pass through them. The light pulse are carried by optical fibers to photomultiplier tubes behind the calorimeter and then converted into electronic signals.

In the *end-cap* and *forward* regions close to the proton beams, the radiation levels are so high that they would cause damage to scintillating tile detectors. In these regions liquid argon calorimeters with copper and tungsten absorbers are used to provide the full coverage for detecting jets at angles as small as 1 degree relative to the beam.

4.2.3 The Muon Detector:

Different particles have different capabilities to penetrate through matter, and muons have a very high penetration capability. Because of this, only muons (and neutrinos[4]) have the ability to go through the tracker then the calorimeters until they reach the muon champers. The muon detectors are therefore located furthest out in the layer of detectors as shown in Fig. (4.6).

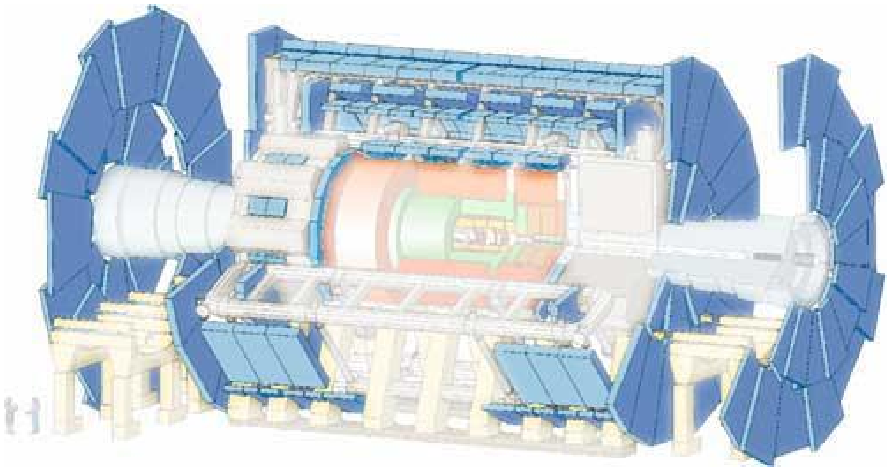


Fig. (4.6) ATLAS Muon Detector.

The muon, compared to the electron, is a heavy (106 MeV) unstable negatively charged lepton. So they are much less affected by the electric forces of the atomic nuclei they come across. Therefore, they do not produce the same kind of electromagnetic shower. Instead, they lose energy by the formation of electron-ion pairs along their path. For a substance like steel or copper, this amount of energy loss is about 1 MeV per millimeter of path. Thus, muons with energy above, say, 5 GeV will penetrate 5 meters of steel, whereas hadrons of almost any energy are completely absorbed in about 1.5 meters of steel. Thus, energetic particles seen outside the hadronic calorimeter are guaranteed to be muons.

The muon system consists of layers of iron interleaved with track chambers to determine the signs and momentum of muons with better precision than the inner tracking system does. It is able to measure momentum even at the highest luminosities.

The muon system components are; Toroid magnets, Monitored Drift Tubes, Cathode Strip Chambers and Trigger Chambers.

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[4] The ability of neutrinos to penetrate through matter is referred to their small mass that makes their interactions with the surroundings very rare.

i) Toroid Magnets:

Although muons momentum is measured in the Inner Detector, more precise measurements are desired. To achieve this, an additional set of magnets is located in the downstream regions (outside) of the calorimeters. Those magnets will produce a magnetic field whose flux lines are circles centered on, and perpendicular to the beam line. Such Magnets are known as *toroid* magnets and their field, encircling the beam line, is a *toroidal* field. The toroidal field deflects the muons in the plane defined by the beam axis and the muon position (very different from the deflection in the Inner Detector).

The **ATLAS** detector uses an unusually large system of air-core toroids arranged outside the calorimeter to provide a large-volume magnetic field with a large bending power of 3-8 tesla meters. The toroid system (shown in Fig. (4.7)) consists of :

- *Barrel Toroid* : this has 8 flat superconducting race-track coils, each 25 meters long and 5 meters wide, grouped in a torus shape. The 8 coils are kept in position by 16 support rings.
- *End-Cap Toroid*: two End-Cap Toroid positioned inside the Barrel Toroid at both ends of the Central Solenoid to provide the high magnetic field across a radial span of 1.5 to 5 meters [59].

This system contains over 70 Km of superconducting cable, and has a design current of 20,000 Amperes with a stored energy of more than one Gigajoule.

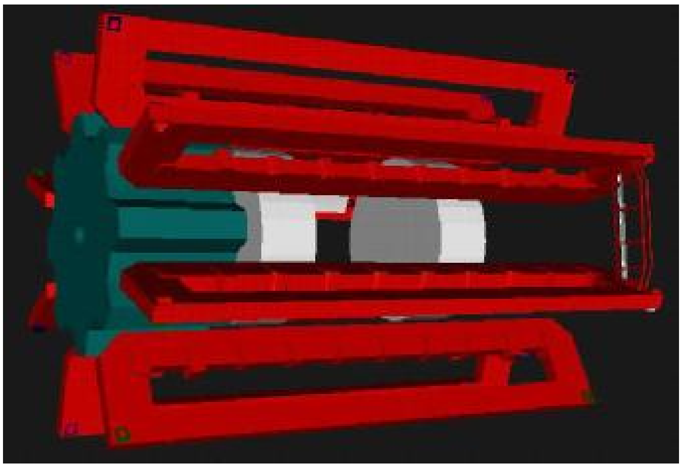

Fig. (4.7) ATLAS Toroid Magnets.

ii) Monitored Drift Tubes:

The muon sensors consist principally of gas-filled metal tubes, 3 cm in diameter, with wires running down their axes. With high voltage between the wire and the tube wall, traversing muons can be detected by the electrical pulses they produce. With careful timing of the pulses, muon positions can be measured to an accuracy of 0.1 mm. The reconstructed muon path determines its momentum and the sign of its charge.

iii) Cathode Strip Chambers:

Drift tubes are unsuitable to do precise measurements of muons moving at small angles to the beam pipe. For such particles it is better to use Cathode strip chambers, which are arrays of closely spaced parallel wires in a narrow gas enclosure with metal walls arranged in the form of strips. With high voltage between wires and wall strips, traversing muons produce signals on the strips that allow position measurement precision at the level of 0.1 mm.

vi) Trigger Chambers:

In addition to the high-precision chambers, the Muon Spectrometer also contains several layers of resistive plate Chambers and Thin Gap Chambers. These detectors provide fast information on muon tracks to enable online selection of events containing muons.

4.2.4 ATLAS Trigger System:

The ATLAS trigger system, shown in Fig. (4.8), is organized into three levels (**LVL1**, **LVL2** and the ***Event Filter***, **EF**). Level-1 is implemented in hardware, whilst the higher level triggers (level-2 and the Event Filter) are based on general-purpose processors [60].

i) LVL1 Trigger:

The level-1 triggers are based on information from the calorimeter and muon trigger chambers. Inner-tracking information is not used at **LVL1** because of the complexity of the events at high luminosity and because the rates can be reduced to acceptable levels without it. The **LVL1** trigger accepts data at the full **LHC** bunch-crossing rate of 40 MHz. The **LVL1** *latency* (time taken to form and distribute the trigger decision) is 2 μs, and the maximum output rate is limited to 100 kHz. During the **LVL1** trigger processing, the data from all parts of the detector are held in pipeline memories until the **LVL1** decision is available [61].

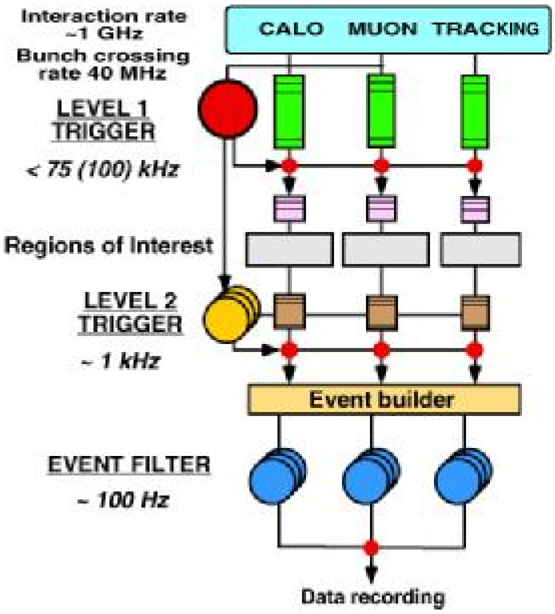

Fig. (4.8) The three levels of ATLAS trigger system.

ii) LVL2 Trigger:

The information of those events selected by the **LVL1** trigger, must be retained for further analysis. The data for such events are transferred to readout buffers where they remain until the **LVL2** decision is available. The **LVL2** trigger refines the selection of candidate objects compared to **LVL1**, using full-granularity information from all detectors, including the inner tracker which is not used at **LVL1**. In this way, the rate can be reduced to 1 kHz. Many events are analyzed concurrently by the **LVL2** trigger system using processor farms, with an average *latency* of 10 ms [61].

iii) Event Filter (EF):

After an event is accepted by the **LVL2** trigger, the event fragments are collected and sent to one of *the* ***E****vent-****F****ilter* (**EF**) farms via *the event-builder* unit. On the event-filter farm the full event will be processed in an offline-like manner. Complete event reconstruction is possible at **EF**, with decision times up to 1s. The target rate for the (**EF**) output is 100Hz [62].

The trigger processors at all three levels will be programmable, so that the trigger criteria can be adapted according to the experience from the initial running, and to the luminosity of **LHC**.

4.2.5 Data Acquisition System (DAQ):

The data-merging stage will be based on a high-speed switching network, interconnecting ***Data Acquisition*** (**DAQ**) memories and **EF** processing units.

Event filter processing is performed to use farms of processors acting on the full-event data. The complicated selection criteria of the full- line analysis will be used in a real- time environment. The processing time per event could be about one second on a 1000 **MIPS** (**M**illion **I**nstructions **P**er **S**econd) processor (today's processors are typically 100-200 **MIPS**) [63].

4.2.6 ATLAS Computing System:

The ATLAS computing system is designed to analyze the data produced by the **ATLAS** detectors. The amount of data will be huge, for example, the annual **ATLAS** data volume will need around 700 million disks. To analyze such vast data, a compute power equivalent to 50,000 of today's PCs will be needed.

The software to obtain the physics results will be produced as a common effort from many people in the **ATLAS** institutes. In order to ensure the required software quality, new methods for software engineering and project management are applied [64].

4.3 Other LHC Experiments:

In last section we explained the largest **LHC** experiment, **ATLAS**, in detail to provide a particular example of the detector components along with their detection mechanism.

In this section the objective and technical design of the other five **LHC** experiments will be discussed briefly. For the sake of comparison, **ATLAS** experiment will be discussed as well in brief.

4.3.1 A Toroidal LHC ApparatuS (ATLAS):

i) Objective:

ATLAS is a multi-purpose detector built, in particular, for detection and study of muons with minimum limit of $p_T \sim 6$GeV. The detector capable of making precise measurements during a wide range of luminosities up to 10^{34} $cm^{-2}s^{-1}$ runs with a broad η coverage for muons and hadrons, $|\eta| \leq 2.7$ [60] . The **ATLAS** experiment is substantially bigger and essentially relies upon an air cored toroidal magnet system for the measurement of the muons.

ii) Main Components:

The layout of the experiment is shown in Fig. (4.2). **ATLAS** magnet system (with a peak field of 2T) consist of Solenoid magnets and Toroidal magnets. As it is discussed before, the main components of **ATLAS** are:

- Inner Detector (including Pixel detector, Semiconductor Tracker and Transition Radiation Tracker).
- Calorimeters (including both Electromagnetic and Hadronic calorimeters)
- Muon chambers
- Trigger consists of three levels.

4.3.2 Compact Muon Solenoid (CMS):

i) Objective:

CMS is another general purpose detector. It is designed to get high performance muon system with a high p_T cutoff ~ 4GeV. The detector capable of making precise measurements during a wide range of luminosities up to nominal $10^{34}cm^{-2}s^{-1}$ runs with a η coverage of $|\eta| \leq 2.4$ [60].

ii) Main Components:

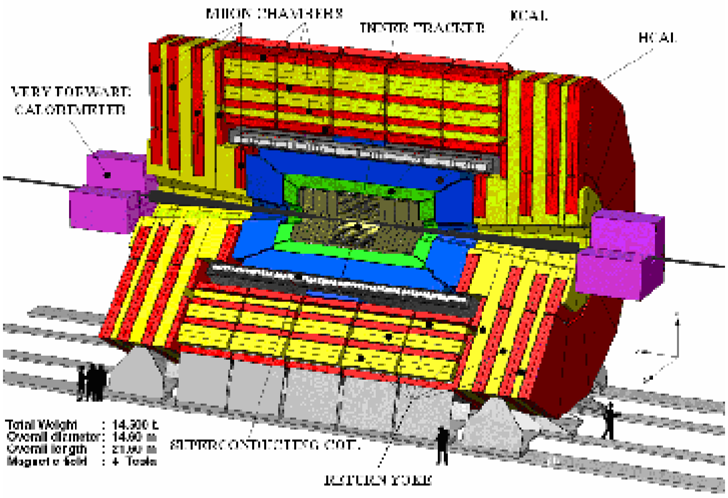

Fig. (4.9) Schematic diagram of CMS Detector

The layout of the **CMS** experiment is shown in Fig. (4.8). It is 22 m long with a diameter of 15 m and a mass of 14,000 tonnes. **CMS** and **ATLAS** differ in terms of the magnet system, **CMS** uses a single large solenoid (with a peak field of 4 T) situated inside an iron yoke. The calorimeters are located inside the coil of the solenoid and the muon chambers outside it but within the iron yoke. The **CMS** component divided to [1]:

- Inner Tracker consisted of an inner Silicon part surrounded by Microstrip Gas Chambers. As in **ATLAS** the innermost detector is a removable Pixel device. The outer silicon detector has strips with a pitch of between 60 and 180 µm. The **CMS** Inner Tracker will also suffer from the effects of prolonged exposure to high radiation levels and it is also foreseen to operate at low temperatures. The Tracker will be cooled to around -15ºC .
- The **CMS** electromagnetic calorimeter is divided into barrel and end-cap detectors. The barrel and end-caps of the Hadron Calorimeter cover the same pseudo rapidity range as the electromagnetic.
- The muon detector is interleaved in the iron plates of the magnetic flux return yoke. In both the barrel and end-cap, there are four layers of tracking chambers. The barrel is instrumented with drift chambers. In the end-caps, on account of the high particle flux, Cathode Strip Chambers are used.
- The **CMS** trigger consists of tow levels the lowest trigger level (Level-1) and High-Level trigger (HLT).

4.3.3 A Large Ion Collider Experiment (ALICE):

i) Objective:

ALICE detector (shown in Fig. (4.9)) is being built as a dedicated heavy-ion detector that will utilize the unique physics of nucleus–nucleus interactions at **LHC** energies. At these extreme energies a new phase of matter, the quark-gluon plasma, will be produced. **ALICE** is designed to work in a luminosity of (~ 3 $x10^{30}$ $cm^{-2}s^{-1}$) during the proton-proton collisions[60].

ii) Main Components:

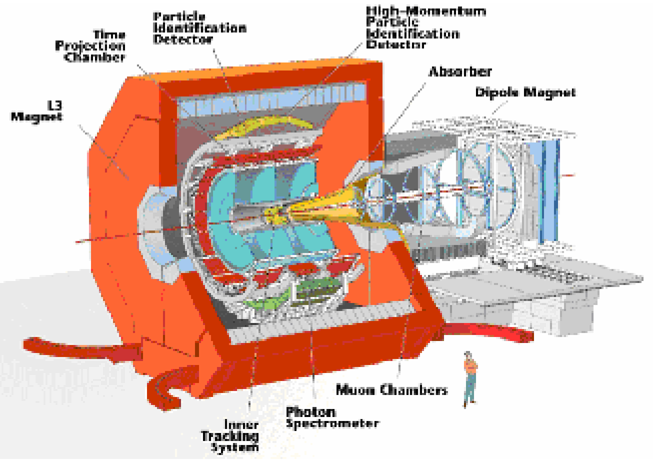

Fig. (4.10) Schematic diagram of ALICE Detector

The produced events will have very high multiplicities (in the order of 50 000 particles per interaction). The tracking and identification of these particles presents a real challenge to the detector builder. **ALICE** re-uses the existing solenoid magnet of the LEP experiment, L3 with an additional dipole magnet.

ALICE components can be divided into [1]:

- ***I****nner* ***T****racking* ***S****ystem* (**ITS**) that uses Pixel and Silicon Drift Chambers for vertex reconstruction. ITS will look for particles containing strange and charm quarks by identifying their decay points. This will cover the pseudorapidity range of, $|\eta| \leq 0.9$ [60].
- Calorimeters (including The ***T****ime* ***P****rojection* ***C****hamber* (**TPC**) , Particle identification detectors, Cherenkov detectors (with CsI photocathodes) and $PbWO_4$ crystals (profiting from **CMS**'s experience) for photon energy measurement.
- Muon chambers ; Tracking and trigger chambers, are located on either side of the dipole magnet in the muon arm to cover the range of $2.5 < \eta < 4$ [60].

4.3.4 The **LHC B**eauty Experiment (**LHCb):**

i) Objective:

The **LHCb** is a detector designed to study the decays of Beauty particles such as B-mesons[5]. The study of ***Charge-Parity*** (**CP**) violation which results in a difference in the decay rate of particles and anti-particles, is one of the main goals of the **LHCb** experiment. The **LHCb** optimal luminosity will vary in the range (2-5) x10^{32} cm^{-2}s^{-1} [60].

ii) Main Components:

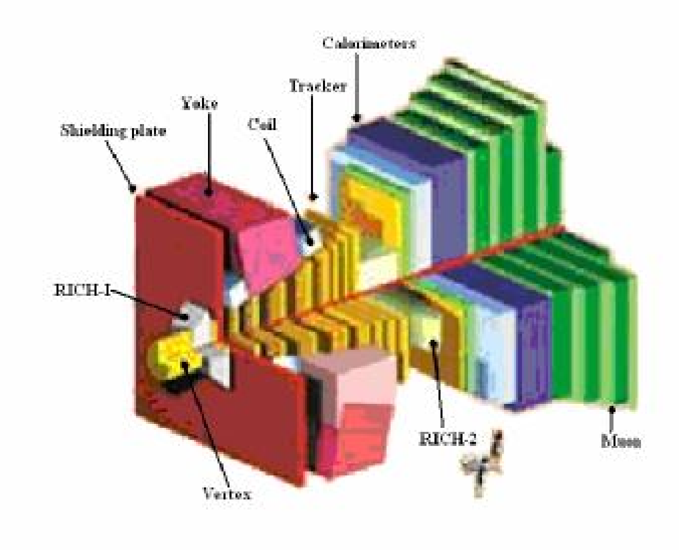

Fig. (4.11) Schematic diagram of LHCb Detector

LHCb , shown in Fig. (4.11), contains a variety of detectors, most of which are used in the production of the high performance trigger system. This is of fundamental importance since only a small fraction of proton–proton collisions will produce B-mesons. The **LHCb** components are divided into [1]:

- ý Vertex detector positioned as close as possible to the collision point. It is typically made of cylindrical layers from semiconductor detectors. The goal of a vertex detector is to measure particle tracks very close to the interaction point, thus allowing one to identify those short-lived decaying particles [65].

---

[5]- A B- meson consists of a b-antiquark and either a u- or d-quark. Its antiparticle, called the is made up of a b-quark and a u- or d- antiquark. The B meson and the B antimeson are known together as "**B mesons**".
The B meson is a relatively heavy particle, having a mass of 5.28 GeV/c^2, which is more than five times the mass of the proton. This is because the b-quark it contains is almost that massive[17].

- The tracking system is partially situated in the magnet. The system must be capable of coping with high particle fluxes at high pseudorapidity range, $2< \eta <5$ [60]. The tracker consists of; Outer Tracker using straw tubes operating in CF_4 and Inner Tracker based on a Triple GEM and Silicon Micro-strip devices.
- The **LHCb** detector includes two ***R**ing **I**maging **Ch**erenkov* (**RICH**) counters which provide charged particle identification over the momentum range from 1 - 150 GeV/c. The first detector (**RICH I**) uses aerogel and C_4F_{10} gas as radiators. The second detector (**RICH II**), used for high momentum particles, is placed after the magnet and has CF_4 gas as radiators [66].
- The calorimeter in the experiment consists of a pre-shower detector consisting of two radiation lengths of lead sandwiched between scintillator planes. This is followed by the electromagnetic calorimeter and the hadronic calorimeter.
- The technology for the moun stations is a combination of ***R**esistive **P**late **C**hambers* (**RPC**'s) for regions with low rate, and ***M**ulti **W**ire **P**roportional **C**hambers* (**MWPC**'s) for regions where the expected rate exceed 5 kHz/cm^2 [66].

The **LHCb** trigger system is organized in three levels **L0**, **L1** and **HLT**.

4.3.5 **T**otal Cross Section and **E**lastic Scattering **M**easurements (TOTEM):

i) Objective:

TOTEM detector, which is partially embedded inside **CMS**, will concentrate on the very forward direction measurements ($3< \eta <7$) of total cross-section, elastic scattering and diffractive processes at the **LHC**. An important consequence of this experiment is that it will provide a very precise measurement of the luminosity especially for its host experiment [1].

ii) Main Components:

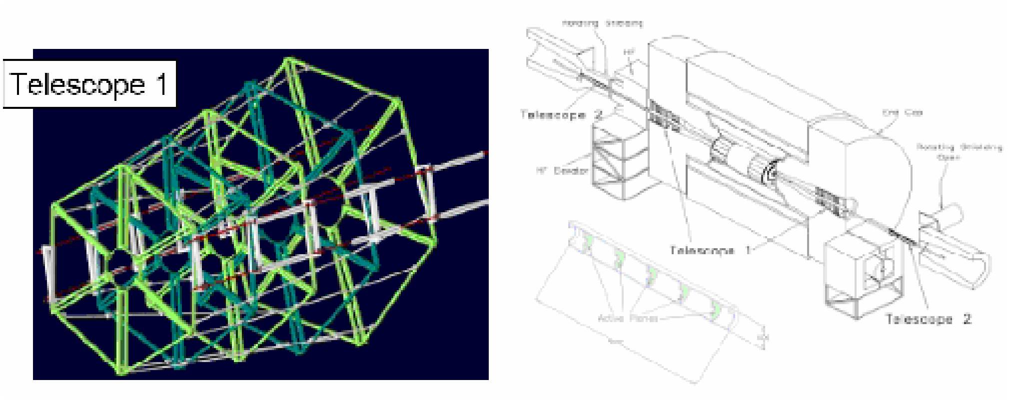

Fig. (4.12) Schematic diagram of TOTEM Detector

The experimental apparatus shown in Fig. (4.11) consists of elastic scattering detectors based on a system of Roman pots, and a forward inelastic detector which will be integrated into **CMS** detector .**TOTEM** is actually 2 simultaneous experiments and is made up of 3 parts [67]:

- Telescope 1, placed inside the end-cap region of **CMS** at a distance between 7.5 and 10.5 m from the interaction point ($\mathbf{3} < |\eta| < \mathbf{4.9}$).
- Telescope 2, placed at a distance between 15 and 18 m from the interaction point ($\mathbf{5} <| \eta| < \mathbf{7}$).
- Silicon detectors in Roman pots along the beam pipe (~150 m away from the interaction point).

4.3.6 Monopole and Exotic Particles Detector At LHC (MOEDAL):

i) Objective:

MOEDAL detector has been proposed to operate in conjunction with **LHCb**. This experiment is designed to search for magnetic monopoles and other highly ionizing exotic particles through the use of passive track-etch detectors[1].

ii) Main Components:

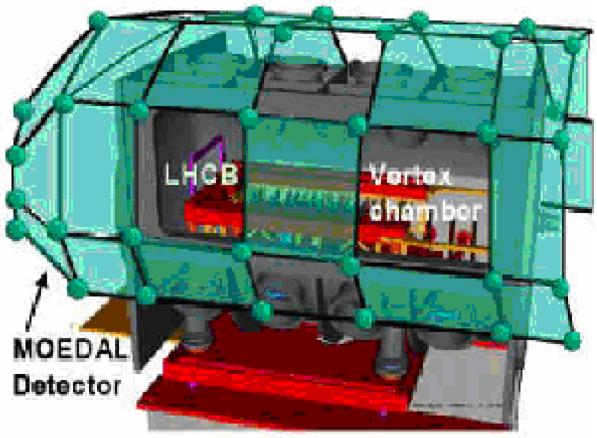

Fig. (4.13) Schematic diagram of MOEDAL Detector

The sensitive elements of the **MOEDAL** detector, are the polymer Lexan/CR-39 track-etch sheets. The detector itself will comprise of a fast assembly/disassembly frame whose facets will hold 3-5 layers of track-etch detector polymer. This frame is designed to surround the **LHCb** vertex region as illustrated in the Fig. (4.12). The frame covers 50% to 70 % of the solid angle. the final design of the MOEDAL detector depends on the final design of the **LHCb** vertex region.

The signal for a monopole in the **MOEDAL** detector would be a set of collinear etch-pits traversing the 3 to 5 layers of track-etch polymer. There are no conventional backgrounds for this type of event. The main backgrounds to the search for highly ionizing particles using the **MOEDAL** detector are primarily due to the radiation environment at the **LHCb** intersection region[68].

4.3.7 Brief Comparison:

One can summarize the main characteristics of the **LHC** experiments through Fig. (4.13), which shows schematically the *transverse momentum* (p_T) against the pseudorapidity (η), for ***charm*** (c) and ***beauty*** (or ***bottom***) (b) hadrons in the four main experiments. Those values are as expected for one year of running at supposed luminosity (note that the value of the luminosity is different for each experiment).

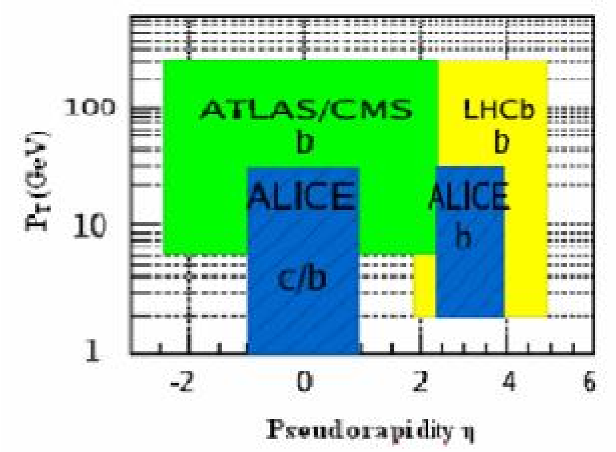

Fig. (4.14). Schematic diagram of range of the *transverse momentum* (P_T) and pseudorapidity (η) for *charm* (c) and *beauty* (b) hadrons in the four main experiments [60]**.**

ATLAS and **CMS** have almost a similar range of η. The minimum reachable p_T is relatively large (4-6 CeV) because of their strong magnetic fields, which in turn, together with the high luminosity, allow to cover p_T up to 200-300 GeV.

The range of η of **LHCb** calorimeter, although centered at *forward* rapidity, has a significant overlap, with those of **ATLAS** and **CMS**.

ALICE range of η for beauty particles overlaps with **ATLAS** and **CMS** at *central* rapidity and with **LHCb** at *forward* rapidity. Since **ALICE** magnetic field will vary within low values (0.2-0.5) T , this will lead to a very low p_T cutoff of 0.1-0.2 CeV [60].

For particles with high pseudorapidity (very small θ), **TOTEM** was embedded into **CMS** to cover the range ($3 <|\eta|< 7$) [67].

4.4 Computing Challenge at the LHC Experiments:

When the **LHC** starts running in 2007, CERN will face a huge data storage and analysis challenge. The **LHC** will produce roughly 40 million collisions per second. After filtering only 100 events of interest per second will be recorded. Each event represents a few Megabytes of data, so the total data from the experiment approaches 1 Gigabyte per second. Each year the **LHC** will produce 15 Petabytes (15 million Gigabytes) of data which is equivalent to 20 million CD's [69].

4.4.1. **LHC C**omputing **G**rid project (LCG):

The only reasonable way to access this amount of information seems to be the **Grid technology** [70]. Grid technology is a service for sharing computer power and data storage capacity over the internet. As it can be seen from Fig. (4.15), Grid technology is a simple communication between computers and aims ultimately to turn the global network of computers into one vast computational resource [71]. CERN has taken a big gamble on Grid technology by building anew project known as the ***LHC*** *Computing* ***G****rid project (****LCG****)* [72].

Fig. (4.15) The Grid Technology.

LCG was launched in 2002, with goal to integrate thousands of computers worldwide into a global computing resource. This will be used to store and analyze the huge amounts of data that will soon be produced at **CERN**. It permitted to thousands of scientist's independent on their location to access and analyzes the **LHC** data. The **LCG** involves more than 200 sites in over 30 countries [72].

The data from the **LHC** experiments will be distributed around the globe, according to a ***four-tiered*** model [73]. The centre of **LCG** is **CERN**, the "**Tier-0**", where a primary backup of the data will be recorded. After initial processing, this data will be distributed to a series of **Tier-1** centers, which are large computer centers with sufficient storage capacity for a large fraction of the data.

The **Tier-1** centers will make data available to **Tier-2** centers, which can store sufficient data and provide sufficient computing power for specific analysis tasks. Individual scientists will access these facilities through **Tier-3** computing resources, which can consist of local clusters in a University Department or even individual PCs, and which may be due to **LCG** on a regular basis [73].


IN SUMMARY

In Summary:

As we have seen, *the **S**tander **M**odel* has left many unsolved questions. This led scientists worldwide to extend that model by looking for physics beyond it. So they have assembled the huge and expensive **LHC** machine with an aim to solve questions like: where does mass come from? what is the dark matter that fills most of the universe? how many dimensions do we need to describe our physical world? and why is there more matter than antimatter?

The **LHC**, with its six experiments, will bring experimental physics into a new territory. It could reveal new processes and particles that would change our understanding of energy and forces that have shaped our universe.

Although the **LHC** has a lot of benefits, it is not completely safe. This is because there is a high probability that ***M**icro **B**lack **H**oles* (**MBH**s) will be produced in the **LHC**. In fact, one **MBH** could be produced every second. According to CERN studies, **MBH**s present no danger because they will evaporate with *Hawking Evaporation*. But since that factor has never been tested, there is still a risk of the existence of **MBH**s. Once a **MBH** is created, the speed of it will decrease as it interacts with matter. Then, all slow **MBH**s will go toward the gravitational center of the earth where they will join together to form a single **MBH**. The center of the earth, with its high pressure and temperature, forms a suitable environment for catching the MBHs. This may lead to a beginning of a dangerous exponential growth process, which makes the risk of the **LHC** forming **MBH**s, around 7- 10% [74]. Even though this ratio is small, it should be taken into account.

We all know that knowledge is important, but we have to remember that knowledge without wisdom means nothing. So the **LHC** staff has to consider this risk and take all the necessary safety procedures to avoid it.

Abbreviations:

ATLAS: A Toroidal **L**HC **A**pparatu**S.**
CERN: The European Organization of Nuclear Research (**C**onseil **E**uropéen pour la **R**echerche **N**ucléaire).
CMS: **C**ompact **M**uon **S**olenoid.
CP: Charge**-P**arity.
DAQData **A**cquisition **S**ystem.
EF: Event **F**ilter.
HLT: **H**igh-**L**evel **T**rigger.
ITS: **I**nner **T**racking **S**ystem.
LCG: LHC Computing **G**rid project.
LEP: **l**arge **E**lectron **P**ositron.
LHC: Large **H**adron **C**ollider.
LHCb: **L**arge **H**adron **C**ollider **b**eauty.
LINAC: LINear **AC**celerator
LSP: Lightest **S**uper**P**artners.
LVL: **L** : **L**evel.
MACHO: **M**assive **C**ompact **H**alo **O**bjects.
MBH: **M**icro **B**lack **H**oles.
MIPS: **M**illion **I**nstructions **P**er **S**econd.
MOEDAL: Monopole and **E**xotic Particles **D**etector **A**t **L**HC.
MSSM: Minimal **S**upersymmetric **S**tandard **M**odel.
MWPC: Multi **W**ire **P**roportional **C**hambers.
PS: Proton **S**ynchrotron
P_T :. Transverse momentum.
QRL: Cryogenic **R**ing **L**ine**.**
RPC: Resistive **P**late **C**hambers.
RF: Radio**-F**requency**.**
RICH: Ring **I**maging **Ch**erenkov.
SM: Standard **M**odel.
SPS: Super **P**roton **S**ynchrotron.
SUSY: SUper**sy**mmetry.
TPC: **T**ime **P**rojection **C**hamber.
TOTEM: Total Cross Section and **E**lastic Scattering **M**easurements**.**
TRT: Transition **R**adiation **T**racker**.**
WIMP: **W**eakly **I**nteracting **M**assive **P**articles.

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