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# Chapter 1

## Secrets of the nature

In this chapter, we will try to understand the world surrounding us thanks to a mathematical framework which describes the matter and its interaction. We will first have a look on the law that lead our Universe. Then, we will focus on the mathematical framework with the description of three interactions: the electromagnetism, the weak and the strong interactions. After that, we will study the electroweak interaction and the spontaneous symmetry breaking. We will finally discuss the limits of the theory and the solutions to avoid the limits.

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## 1.1 The Standard Model

### 1.1.1 Introduction

The Standard Model (SM) is a theory that describes the elementary structure of the matter surrounding us. It is one of the most successful achievement in modern physics. The elegant theoretical framework of the SM is able to provide good explanations of experimental results, but is also able to predict a wide variety of phenomena.

The SM depicts the interactions between the fundamental constituents of matter, called particles. From a quantum point of view, a particle is defined by its intrinsic angular

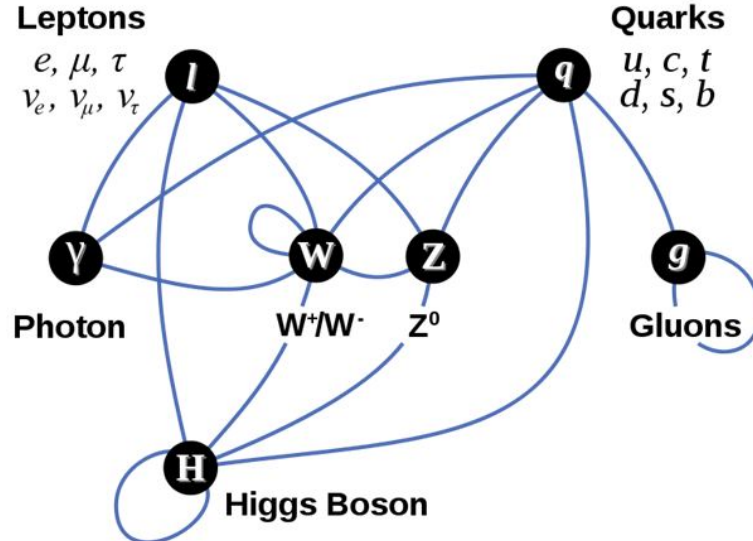


Figure 1.1 – Summary of the Standard Model particles with their interactions.

<http://www.brighthub.com/science/space/articles/84750.aspx>

momentum, called spin. This quantum number is a key to distinguish between the particles of 'matter' and the 'carrier force' particles.

The half integers spin particles are obeying to the Fermi-Dirac statistics and are submitted to the Pauli exclusion principle: they can not occupied the same quantum state at the same time. These particles are called fermions. They are the constituents of the matter and are to the number of twelve.

The fermions are divided into two categories: the leptons and the quarks. The leptons are to the number of six: three charged particles and three neutral particles called neutrino. The first fundamental particle discovered in particle physics was the electron ( $e^-$ ) at the end of the 19<sup>th</sup> century. The two other charged leptons were discovered in 1937 for the muon ( $\mu$ ) and in 1975 for the tau ( $\tau$ ). Three neutrinos are associated to the three flavored leptons: the electron neutrino ( $\nu_e$ ) discovered in 1953, the muon neutrino ( $\nu_\mu$ ) in 1962 and the tau neutrino ( $\nu_\tau$ ) discovered in 2000.

The quarks are to the number of six. They can't be find alone in the nature. They are carrying a quantum number: the color. The color quantum numbers are green, blue and red (and the anti-color associated). They are always in a bounded state to form composite particles that are colorless and are called hadrons. A quark and an anti-quark form an integer spin composite particle, a meson. Three quarks bounded together are called baryons. The most known baryons are the proton and the neutron. They are made of the up quarks (u) and the down quarks (d). The other quarks were discovered in the second half of the 20<sup>th</sup> century. The strange quark (s) was discovered in 1968, followed by

the charm quark (c) in 1974. Then, the bottom quark or beauty quark (b) was discovered in 1977. The last quark discovered was the top quark (t) in 1995.

The fermions are also divided into three categories which depends on the mass of the particle. They are called generations. The first generation of particles is composed of the electron, the electron neutrino, the u and d quarks. They form the ordinary matter. The two other generations are particles found in cosmic rays or in collision with accelerators. All the fermions and their properties are summarised in the table 1.1.

Type	Family	Particle	L	B	$Q_e$	Mass (MeV)
Leptons	$1^{st}$	$e$	1	0	-1	0.511
		$\nu_e$	1	0	0	$< 2 \times 10^{-6}$
	$2^{nd}$	$\mu$	1	0	-1	105.66
		$\nu_\mu$	1	0	0	$< 2 \times 10^{-6}$
	$3^{rd}$	$\tau$	1	0	-1	$1.78 \times 10^3$
		$\nu_\tau$	1	0	0	$< 2 \times 10^{-6}$
Quarks	$1^{st}$	u	0	1	2/3	$2.3^{+0.7}_{-0.5}$
		d	0	1	-1/3	$4.8^{+0.5}_{-0.3}$
	$2^{nd}$	s	0	1	-1/3	$95 \pm 5$
		c	0	1	2/3	$1.275 \times 10^3 \pm 2.5$
	$3^{rd}$	b	0	1	-1/3	$4.66 \times 10^3 \pm 30$
		t	0	1	2/3	$173.21 \times 10^3 \pm 511 \pm 711$

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Table 1.1 – Summary of the 12 fermions. L is a quantum number associated to the leptons. Its value is 1 for leptons and -1 for anti-leptons. B is a quantum number associated to the baryons. It is equal to 1 for a baryon and to -1 for an anti-baryon. [9]

The second kind of particles are integer spins particles and are labelled bosons or gauge bosons. They are following the Bose-Einstein statistics. It means that the bosons are not limited to a single occupancy of the same state as the fermions. The bosons are the mediators of the four fundamental interactions.

The electromagnetic interaction (EM) is mediated by the photon  $\gamma$ , a massless and chargeless particle of spin 1. The EM is responsible for the interaction between two charged particles. The weak interaction which is responsible of the  $\beta$  radioactive decay (a nucleon is able to transform into an other one with the emission of a lepton and a neutrino). The gauge bosons associated to the weak interaction are the neutral electrical charged boson  $Z^0$ , and two electrical charged one  $W^+$  and  $W^-$ . The strong interaction is mediated by eight gauge bosons, the gluons. It is responsible for the nucleus and the hadrons cohesion. The last force is the gravitational interaction but it is not included into the SM. Trying to find a framework where the equation of the general relativity used to describe the macro world and the equation of the quantum mechanics describing the micro world is a difficult challenge. From a quantum theory, the boson associated to the gravitational force might be the graviton, a spin 2 particle.

The Higgs boson (H) is a particle predicted by the S.M and has been discovered in 2012 at the Large Hadron Collider (LHC) It is the gauge boson of the Higgs mechanism. This mechanism is the mass generator of particles and will be presented later in section 1.2.2.

The table 1.2 summarises the different bosons of the SM.

Force	Gauge bosons	Mass (GeV/ $c^2$ )	Electric charge	Range
Electromagnetic	$\gamma$	0	0	$\infty$
Weak	$Z^0$	$91.1876 \pm 0.0021$	0	$10^{-18}$ m
	$W^\pm$	$80.3980 \pm 0.0250$	$\pm 1$	
Strong	g (8 gluons)	0	0	$10^{-15}$ m
	H	125 GeV	0	

Table 1.2 – Summary of the interactions and the boson defined by the Standard Model. [9]

N.B.: the graviton was not included in this table because the gravitational force is not taken into account in the SM.

### 1.1.2 Quantum Field Theory

The mathematical basis of the SM is the Quantum Field Theory (QFT). All the interactions are described by the gauge group:

$$SU_C(3) \otimes SU_L(2) \otimes U_Y(1) \quad (1.1)$$

The gauge theory is invariant under a continuous set of local transformation. Taking the gauge symmetries and the least action into account, physicists were able to set up equations that describe the dynamic of the interactions by Lagrangian. The steps to build Lagrangian for the three forces and the unification of the EM and weak interactions are going to be presented.

#### Quantum Electrodynamic

The Quantum Electrodynamic (QED) is the QFT that combines the electromagnetism formalism and the quantum mechanics formalism to describe the interaction thanks to a relativistic Lagrangian. As the charge  $Q_e$  of the electron is invariant on every part of the Universe, the QED Lagrangian should be invariant under some transformations. The  $U(1)$  gauge group is a unitary group of one dimension which is invariant under space transformations.

Lets first consider the Dirac Lagrangian for a free fermion:

$$\mathcal{L}_{Dirac} = \bar{\Psi}(x) (i\gamma^\mu \partial_\mu - m) \Psi(x) \quad (1.2)$$

The Lagrangian is invariant under global  $U(1)$  transformation:

$$\begin{aligned} \Psi(x) &\rightarrow \Psi'(x) = e^{-i\alpha} \Psi(x) \\ \bar{\Psi}(x) &\rightarrow \bar{\Psi}'(x) = e^{i\alpha} \bar{\Psi}(x) \end{aligned} \quad (1.3)$$

The corresponding local symmetry is:



$$\begin{aligned}\Psi(x) &\rightarrow \Psi'(x) = e^{-i\alpha(x)}\Psi(x) \\ \bar{\Psi}(x) &\rightarrow \bar{\Psi}'(x) = e^{i\alpha(x)}\bar{\Psi}(x)\end{aligned}\quad (1.4)$$

Although the mass term of the Lagrangian in the equation 1.2 stays invariant under the local symmetry, the term containing a partial derivative is not anymore. A gauge field  $A_\mu$  has to be added to the derivative to keep it invariant under local gauge transformation. The covariant derivative will be then:

$$D_\mu \Psi(x) = (\partial_\mu - iQ_e A_\mu) \Psi(x) \quad (1.5)$$

The gauge field is not yet a dynamic field. To get a physical gauge field, a kinetic term should be added to the equation. This gauge invariant term that includes derivative from the  $A_\mu$  field is:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (1.6)$$

The Lagrangian which is local invariant, is the one that describes the QED:

$$\mathcal{L}_{QED} = \bar{\Psi}(x) (i\gamma^\mu D_\mu - m) \Psi(x) - \frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \quad (1.7)$$

A mass term  $m A_\mu A^\mu$  for the field  $A_\mu$  is missing because it is not gauge invariant. That consideration matches to the fact that the photon is a massless boson.

## Weak interaction

In 1930, Pauli assumed that the continuous energy spectrum of the electron in the  $\beta$  decay could be explained by the existence of a new particle to respect the principle of energy conservation. It is a light particle, which does not interact so much with matter.

After the discovery of the neutron by Chadwick in 1932, Fermi wrote a theory on weak interaction to explain the  $\beta$  decay. [5] He postulated that the neutron is decaying into a proton by emitting an electron and a light neutral particle, called neutrino. In analogy to the electromagnetism, he proposed a current-current Lagrangian to describe the  $\beta$  decay.

$$\mathcal{L}_{weak} = \frac{G_F}{\sqrt{2}} (\bar{p}\gamma_\mu n) (\bar{e}\gamma_\mu \nu) \quad (1.8)$$

where the  $G_F$  is the Fermi constant  $G_F = 1.16610^{-5} GeV^{-2}$ .

Nevertheless, the non-relativistic limit leads to an incomplete theory. The interaction considered with a 2-components spinor transforms a proton into a neutron without changing the position, the spin or the parity. However, T.D. Lee and C.N. Yang have postulated in 1956 that the weak interactions violate the parity after analysing the decays of the  $\tau$  and  $\theta$  particles[8]. The Wu experiment [11] confirmed this hypothesis in 1957 by studying the decay of  $^{60}Co$ .

The Fermi interaction was modified by Feynman and Gell-Mann[6] to a  $V - A$  theory<sup>1</sup>. The vector current is now subtracted by a axial vector current. For example, the neutrino current is replaced by:

<sup>1</sup>V stands for vector and A for axial-vector

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$$\begin{aligned}\bar{e}(x)\gamma_\mu\nu &\rightarrow \bar{e}\gamma_\mu(1-\gamma_5)\nu \\ &= \bar{e}\gamma_\mu\nu - \bar{e}\gamma_\mu\gamma_5\nu\end{aligned}\tag{1.9}$$

It was established that the weak current has the form  $V - A$  instead of  $V + A$ . The weak interaction is only coupling left-handed particles and right-handed anti-particles.

The lagrangian describing the weak interactions can be written as a currents interaction:

$$\mathcal{L}_{weak} = -\frac{G_F}{\sqrt{2}} J^\mu J_\mu^\dagger\tag{1.10}$$

and  $J^\mu$  is a combination of leptonic and hadronic currents.

Contrary to the QED, the weak interaction obeys to a non-Abelian symmetry group<sup>2</sup>, the SU(2) symmetry group. The matter field could be represented as a doublet  $\Psi_L$  and a singlet  $\Psi_R$  of this group.

$$\Psi_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \quad \Psi_R = e_R\tag{1.11}$$

The generators of the group are the three Pauli matrices  $\sigma_i$ , associated to a gauge field  $W_\mu^i$ . The bosons of the weak interactions are the  $W^\pm$  and  $Z$ .

As the left-handed leptons are combined into a doublet, a quantum number called weak isospin ( $I_3$ ) is associated to them. The charged leptons have a weak isospin  $I_3 = \frac{-1}{2}$  and for the neutrinos  $I_3 = \frac{1}{2}$ . Concerning the gauge bosons  $W^\pm$  and  $Z$ , the weak isospin is respectively  $I_3 = \pm 1, 0$ .

## Quantum Chromodynamics

The Quantum Chromodynamics (QCD) is the quantum field theory of the strong interaction. In this model, the interaction is due to a SU(3) gauge group. It produces 8 gauge fields called gluons. The spinors of this theory are the six quarks that form a triplet with respect to the gauge symmetry.

The SU(3) gauge group is a group of  $9 - 1 = 8$  real parameters and of 8 generators. Those generators are the Gell-Mann matrices. The normalised generators are defined by:

$$T^a = \frac{1}{2}\lambda^a\tag{1.12}$$

The structure constant  $f^{abc}$  can be expressed as:

$$if^{abc} = 2Tr([T^a, T^b]T^c)\tag{1.13}$$

Some theories arguments and the results of experiments in high energy physics have required to introduce six spinor fields, the quarks. Each of them are considered as a triplet state with respect to the SU(3) group:

$$q_i = \begin{pmatrix} q_i^1 \\ q_i^2 \\ q_i^3 \end{pmatrix}\tag{1.14}$$

---

<sup>2</sup>A group is non-Abelian when the elements of the group are not commuting.

where  $q_i$  are the six quarks. These quarks can appeared in three different states, called color and that are named red, blue and green.

The local gauge symmetry  $U(1)$  should be included into the  $SU(3)$  group.

The gauge field  $A_\mu$  can be introduced in the group:

$$A_\mu = g_S A_\mu^a \frac{\lambda^a}{2} \quad (1.15)$$

with  $a = 1, \dots, 8$  and corresponds to the 8 gluons. A mass term  $m_g A_\mu^a A_\mu^a$  would not be gauge invariant, it implies that the gluons have to be massless.

The covariant derivative is then:

$$\begin{aligned} D_\mu &= \partial_\mu - i A_\mu \\ &= \partial_\mu - i g_S A_\mu^a \frac{\lambda^a}{2} \end{aligned} \quad (1.16)$$

The QED field  $F_{\mu\nu}$  is not gauge invariant in QCD. Nevertheless an additional term to obtain gauge invariant field tensor can be introduced:

$$G_{\mu\nu}^a = (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a) + g_S f^{abc} A_\mu^b A_\nu^c \quad (1.17)$$

Finally, the QCD Lagrangian is given by:

$$\mathcal{L} = \sum_{i=1}^6 \bar{q}_i (i \gamma^\mu D_\mu - m_i) q_i - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.18)$$

## 1.2 The Glashow-Weinberg-Salam model

Late 1960, a model of unification was postulated by Glashow, Weinberg and Salam to describe the electroweak interaction (EW). The theory rests on a  $SU(2)_L \otimes U(1)_Y$  symmetry group. It is the simplest group which conserves the properties of EM charge conservation and parity violation of weak interaction.

For the EW unification, the  $U(1)_{EM}$  symmetry group describing the EM has to be rewritten. As the fermions are considered by left-handed doublets and right-handed singlets, the  $U(1)_{EM}$  will break the gauge invariance. The weak isospin group  $SU(2)_L$  is combined to the EM charge to create the hypercharge give by the Gell-Mann-Nishiima relation:

$$Q = I_3 + \frac{1}{2} Y \quad (1.19)$$

The  $I_3$  term is the third component of the weak isospin. With the introduction of the hypercharge, the EM gauge invariance is conserved.

The EW Lagrangian could be given as:

$$\mathcal{L}_{EW} = \mathcal{L}_{YM} + \mathcal{L}_{fermions} \quad (1.20)$$

The first term  $\mathcal{L}_{YM}$  is the Yang-Mills Lagrangian that describes the bosons gauges interactions (kinetic term + interaction between bosons). It has the form below:

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$$\mathcal{L}_{YM} = -\frac{1}{4}\mathbf{W}_{\mu\nu}^a\mathbf{W}^{a\mu\nu} - \frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} \quad (1.21)$$

With

$$\mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu - ig[\mathbf{W}_\mu, \mathbf{W}_\nu] \quad (1.22)$$

$$\mathbf{B}_{\mu\nu} = \partial_\mu\mathbf{B}_\nu - \partial_\nu\mathbf{B}_\mu \quad (1.23)$$

In the equation 1.22,  $\mathbf{W}_\mu = \sum W_\mu^i \sigma^i / 2$  is a vector of three gauge fields associated to  $SU(2)_L$  and  $\sigma^i$  are the Pauli matrices. The term  $[\mathbf{W}_\mu, \mathbf{W}_\nu]$  is associated to the interactions between the gauge fields. In the equation 1.23,  $\mathbf{B}_\mu$  is the only gauge field associated to the  $U(1)_Y$ .

The Lagrangian describing the fermions field is given by:

$$\mathcal{L}_{fermions} = \bar{\Psi}_L \gamma^\mu D_\mu \Psi_L + \bar{\Psi}_R \gamma^\mu D_\mu \Psi_R \quad (1.24)$$

$$\text{With } D_\mu \Psi_L = \left( \partial_\mu + ig\mathbf{W}_\mu - i\frac{g'}{2}Y\mathbf{B}_\mu \right) \Psi_L \text{ and } D_\mu \Psi_R = \left( \partial_\mu - i\frac{g'}{2}Y\mathbf{B}_\mu \right) \Psi_R \quad (1.25)$$

In the equation 1.25, the covariant derivative has two forms. The weak interaction does not allow coupling of the W bosons to right-handed fermions whereas the  $\gamma$  and Z bosons do.

With the EW Lagrangian described above, the gauge bosons were considered as massless fields. The electroweak interaction does not allow a  $m\bar{\Psi}\Psi$  term because it does not transform as a scalar under  $SU(2)_L \otimes U(1)_Y$ . Moreover, the  $m^2\mathbf{W}_\mu\mathbf{W}^\mu$  violates the  $SU(2)_L$  gauge invariance of the Lagrangian. The mass terms associated to the physical fields of the gauge bosons are given by spontaneous symmetry breaking via the Higgs mechanism.

### 1.2.1 Symmetry Breaking mechanism and Goldston theorem

Before to introduce the Higgs mechanism, we will study the spontaneous symmetry breaking for a global symmetry. This phenomenon is also seen in phase transitions or laser theory.

Lets consider first the Lagrangian density for a complex scalar field  $\phi$ :

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2 \quad (1.26)$$

The first component of the Lagrangian density corresponds to the kinetic term of a complex scalar field, while the second component is related to a scalar potential. The coefficient  $\mu^2$  is a real parameter. Nevertheless, depending on its sign, the potential can take two forms.

If  $\mu^2 > 0$ , the symmetry is unbroken and the potential has a minimum at  $\phi = 0$  which is not degenerated. It describes a particle with a mass  $\mu$  and a quartic self coupling. As the transformation  $\phi \rightarrow -\phi$  is respected, this solution is a symmetric one.

When  $\mu^2 < 0$ , there is not a unique ground state for this system but multiple states with the same vacuum energy. The minima is located on a circle of radius:

$$v = \sqrt{\frac{-\mu^2}{2\lambda}} > 0 \quad (1.27)$$

By choosing a particular solution as the ground state, the symmetry gets spontaneously broken.

A parametrisation of the excitations around the ground state is possible by introducing a new field  $\phi$ :

$$\phi(x) = \frac{1}{\sqrt{2}} (v + \rho(x) + i\Theta(x)) \quad (1.28)$$

The value  $v$  is given by one of the solution from equation 1.32,  $\rho(x)$  and  $\Theta(x)$  are real fields.

By adding the new field in the equation 1.26, the Lagrangian becomes:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \rho)^2 + \frac{1}{2}(\partial_\mu \Theta)^2 - \lambda v^2 \rho^2 - \lambda v(\rho^3 + \rho\Theta^2) - \frac{\lambda}{4}(\rho^2 + \Theta^2)^2 \quad (1.29)$$

The field  $\rho(x)$  describes a state of mass  $m_\rho = 2\mu^2$ , coupled to the massless field  $\Theta(x)$ .

The field  $\Theta(x)$  describes excitations around a direction in the potential. The excitations are not costing any energy, so they correspond to massless bosons called Goldstone bosons.

### 1.2.2 Higgs mechanism

As we have seen with the Lagrangian of the QED and QCD, the bosons generated are massless. Nevertheless, the  $W^\pm$  and the  $Z$  bosons have a mass and the equation ?? of the EW interaction does not include a mass generator. The origin of the fermions masses is solved in the SM thanks to the Higgs-Englert-Brout mechanism [7][4].

Lets consider first a doublet of complex scalar fields  $\Phi$ :

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.30)$$

The invariant Lagrangian density under  $SU(2)_L \otimes U(1)_Y$  gauge transformation is:

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (1.31)$$

The covariant derivative is the one of  $SU(2)_L \otimes U(1)_Y$  given by the equation 1.25 and represents the kinetic term. The Higgs potential is similar to the one considered first and has also two solutions depending on the sign of  $\mu^2$ . Lets focus only on the negative solution. There is an infinite set of degenerated states with minimum energy:

$$\phi_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \text{ with } v = \sqrt{\frac{-\mu^2}{\lambda}} > 0 \quad (1.32)$$

Lets expand the field  $\Phi$  around its minima by including a field  $h(x)$  which describes quantum fluctuations and three massless Goldstone fields, denoted  $\theta^i(x)$ :

$$\Phi(x) = e^{i\frac{\sigma_i}{2}\theta^i(x)} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (1.33)$$

A particularly gauge can be defined in a way that the Goldstone fields are absorbed by the physical field of  $SU(2)_L \otimes U(1)_Y$ . It implies the apparition of mass terms in equation 1.31. First, we are interesting on the mass generation mechanism, we will focus only on the impact of the new field on the derivative covariant, we will omit any h-mixed terms and drop down the partial derivative:

$$\left| \left( i\frac{g}{2}\mathbf{W}_\mu + i\frac{g'}{2}Y\mathbf{B}_\mu \right) \Phi \right|^2 = \frac{1}{8} \left| \begin{pmatrix} gW_\mu^3 + g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g'B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2 \quad (1.34)$$

The charged fields can be expressed as a linear combination of gauge field:

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \quad (1.35)$$

The eigenstates are rewritten as decorrelated terms representing the neutral fields from the EW symmetry group:

$$Z_\mu = \cos \theta_w W_\mu^3 - \sin \theta_w B_\mu \quad (1.36)$$

$$A_\mu = \sin \theta_w W_\mu^3 + \cos \theta_w B_\mu \quad (1.37)$$

$\theta_w$  is the Weinberg angle and represent a bound between the coupling  $g$  and  $g'$ :

$$\sin \theta_w = \frac{g'}{\sqrt{g^2 + g'^2}} \text{ and } \cos \theta_w = \frac{g}{\sqrt{g^2 + g'^2}} \quad (1.38)$$

The equation 1.34 becomes:

$$\begin{aligned} \left| \left( i\frac{g}{2}\mathbf{W}_\mu + i\frac{g'}{2}Y\mathbf{B}_\mu \right) \Phi \right|^2 &= \frac{1}{8} \left| \begin{pmatrix} A_\mu \sqrt{g^2 + g'^2} & gW_\mu^- \\ gW_\mu^+ & -Z_\mu \sqrt{g^2 + g'^2} \end{pmatrix} \right|^2 \\ &= \frac{1}{2} M_Z^2 Z Z^* + \frac{1}{2} M_W^2 W^- W^+ \end{aligned} \quad (1.39)$$

With  $M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}$  and  $M_W = \frac{1}{2}vg$ , the mass of the Z boson and the  $W^\pm$  bosons. The mass of the photon is coherent to the expectation and is null.

The Higgs mechanism implies the existence of a massive gauge field, the Higgs boson. It is coupled to the other bosons and also to itself. This could be shown by extending the Higgs potential with the field defined in equation 1.33:

$$- \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4} \lambda h^4 \quad (1.40)$$

The first term gives the mass of the Higgs boson,  $M_H^2 = 2\lambda v^2$ , while the second and third terms are the higgs self-interactions. The Higgs mass can not be predicted by the theory because it is given by a function of the parameter  $\lambda$ , which is one of the free parameters of the SM.

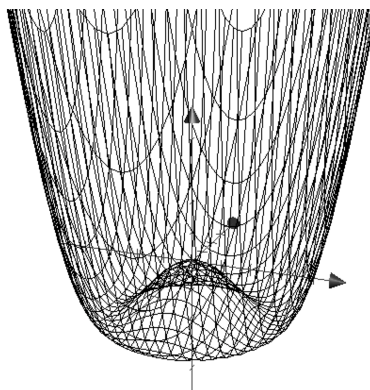


Figure 1.2 – Scalar potential: ADD A GOOD CAPTION.

## 1.3 Beyond the Standard Model

The SM constitutes one of the most successful achievement in modern physics. One of its strength is to provides an elegant theoretical framework to describe the known experimental facts about particles, but also it was able to predict the existence of a mechanism to generate the particle masses via the Higgs mechanism. Nevertheless, a lot of mysteries in the Universe are not explained by this theory.

### 1.3.1 Limitations of the Standard Model

Despite the fact that the experimental results are not contradictory to the SM, the theory is far away to be the answer to all the questions. The particle physics community is facing a challenge to find the ultimate theory of everything. An exhaustive list of some limitations are going to be presented.

#### Free parameters

The SM does not explain the existence of the free parameters, which are to the number of 19. It does not explain also why there are three generations of particles and why the gap between generations is spread over five orders of magnitude.

This is not really a problem for the physics itself, nevertheless the particles physics community has a lack to understand these values.

#### Hierarchy problem

The hierarchy problem refers to two main scales problem about the SM.

First of all, the difference between the energy scale of the SM and the Planck scale is of the seventeen orders of magnitude. No "intermediate" physics have been found between the two scale.

A second problem occurs while considering the Higgs boson mass. The SM does not predict its mass, but it sets some theoretical bounds with respect to  $\Lambda$ , the scale energy at which the SM is not valid anymore. The theoretical Higgs mass is higher than what it should be compared to the EW scale. The Higgs interacts with the particles of the SM (fermions, W and Z boson), but it also interacts with himself. Due to the scalar nature of the boson, they are quartic divergences while calculating the loop corrections. The quantum corrections, which take into account the coupling of the Higgs, are  $\Lambda^2$  divergent and lead to a huge Higgs mass. To avoid that, delicate cancellations should occur between the quantum corrections. These cancellations are known as the fine-tuning problem.

### Gravitation

Although particle physicists are dreaming of a "theory of everything" that will unify the electroweak, strong and gravitational interactions, there is no viable theory to describe gravity in a quantum point of view to include it in the SM and which would be still valid at a macro-scale.

### Neutrino mass

The neutrinos defined by the SM are assumed to be exactly massless. Nevertheless at the end of the 90's, the Super Kamiokande experiment had surprising results. There was a lack on the expected solar and atmosphere neutrinos flux. The result was interpreted by an oscillation of neutrinos between the three leptonic flavors. However, the oscillation is possible only if the neutrino has a mass. That phenomenon could be considered as a proof of physics beyond the SM.

### Matter-antimatter asymmetry

As discussed at the beginning of this chapter, the SM defines equal number of particles and anti-particles. Although everyone assumes that the matter and antimatter were created in exactly equal amount by the Big Bang, a mechanism has favoured electrons, protons and neutrons to positrons, antiprotons and antineutrons. If the amount of matter and antimatter was equal, our Universe would have been completely annihilated. The matter domination could be a local phenomenon with an antimatter surrounding region. However, the region of contact between matter and antimatter would be a violent place of interaction, which would disturb the cosmic microwave background.

An assumption to explain the asymmetry is that the antimatter was produced in an infinity proportion compared to the matter. Hence, the annihilation would lead to create a Universe only made of matter. A mechanism which tends to prefer the matter has been observed in the study of the kaon oscillation. This particle is able to transform spontaneously to its own anti-particle and vice-versa. Nevertheless, this transformation is not symmetric: the kaon is slower to turn into an antikaon than the inverse transformation. Unfortunately, the SM provides no explanation about that mechanism.

### Dark Matter

Several astrophysical observations are indicating that the Universe is made not only of visible matter but also of matter that seems to be invisible to the electromagnetic interaction,



the dark matter. In 1933, a measurement of the galaxies velocities in the Coma cluster to determine the cluster mass gives a surprising result. The mass was more than two orders of magnitude bigger than the mass of a visible stars in the cluster. It was found that the matter of the SM describes only 5% of the Universe content. The rest of the Universe is made of 22% of dark matter and around 73% of dark energy. The neutrinos are possible candidates to dark matter, as it couples to SM matter via only weak interaction, but they cannot account for the entire density of the universe. Nowadays only twelve particles (plus the anti-particles associated) have been observed. The idea of dark matter comes from the way we the mass of a galaxy is estimated.

### 1.3.2 Theories beyond the Standard Model

#### Supersymmetry

The Supersymmetry (SUSY) is a QFT, that relates the elementary fermions known to corresponding bosons, called sfermions and the bosons to corresponding fermions, sbosons [10]. The related particles are called super-partners. They have the same mass, the same quantum numbers but the spin is differing by a half factor. SUSY might be a broken symmetry. This will allow the super-particles to acquire very high masses.

SUSY is a good candidate for physics beyond the SM. It will solves the hierarchy problem without any fine tuning. For example, the loop contributions of one particle to the Higgs are cancelled by the loop contributions of its super-partner. It will be able to provide a framework for the unification of the three gauge interactions at a GUT scale. The lightest super-particle is a good candidate for the Dark Matter.

Despites it will answered many questions from the SM, there is a lack to understand why SUSY is a broken symmetry.

#### Grand unification theory

After the success of the electroweak unification, the next step is to include the strong interaction to build the Grand Unification Theory (GUT), an extension of the SM. In this framework, the three forces are different manifestations of a single interaction. It includes the  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$  symmetry group into a larger  $SU(5)$  group. The quarks and leptons are ordered in left decuplets and right quintets. The coupling constants are described by only one parameter. There are 24 mediators, the 12 mediators of the SM plus 6 X mediators (charge  $\pm 4/3$  and 3 colors) and 6 Y mediators (charge  $\pm 1/3$  and 3 colors). It predicts the existence of new particles as leptoquarks<sup>3</sup>, multiple Higgs bosons and new currents.

Unfortunately, the theory is not validated because of its prediction of the proton life time. The first GUT was introduced by Georgi and Glashow in 1974 and was predicting a decay of the proton. The actual experimental limit of the proton life-time is set to  $5 \times 10^{32}$  years, whereas the predicted life-time defined by the  $SU(5)$  group is one order of magnitude lower. [9]

---

<sup>3</sup>Coupling between a lepton and a quark

### Technicolor

The technicolor is a theory that explains the mass generation. Contrary to the EW symmetry, the masses of particles are not generated by the spontaneous symmetry breaking but they are generated by a strong gauge interaction. This interaction is strong and confined at the energy that have been experimentally probed. The approach of the theory avoids the hierarchy problem induced by the SM.

### String theory

The particle physicists have the dream of unifying the forces of the nature to have only one single interaction with four different manifestations. The string theory proposes a framework for the "theory of everything". The basic unit of matter is no more considered as particles but one-dimensional string of which particles are various vibrational modes.

The string theory is a theory of quantum gravity. It tries to unify the gravitation to the quantum Extra dimensions of 10 -11 space time dimensions. Possible explanation for the hierarchy problem.

## 1.4 Conclusions

We have seen the beauty and the limits of the SM. The high energy physics community is trying to study as far as possible the limit of the SM and is also trying to find some proof of new physics beyond the SM. The (LHC) at CERN has permitted in 2012 to point out the existence of a Higgs boson. Nevertheless, the beam structure of the LHC is not efficient enough to perform very precise measurements. Because of the collision between protons, the energy of the collision can't be exactly known. The next chapter deals with a future experiment in high energy physics, where electrons and positrons are used to probe the matter instead of protons and antiprotons.

# Chapter 2

## The future of high-energy physics: the International Linear Collider

Since 2008, the Large Hadron Collider (LHC) is actually the most powerful tool in high energy physics to have a better understanding of the universe, particularly with the discovery in 2012 of a new particle compatible to the boson predicted by the spontaneous symmetry breaking of the SM [1, 3]. Although the LHC is an impressive machine able to reach the highest energy scales of collisions available on Earth with a centre-of-mass energy of 14 TeV, the complex environment of the events generated hides the access to some fundamental parameters. To achieve more precise measurements of the Higgs boson, but also to test the validity of the SM and other physics theories introduce in the chapter 1, the high energy physics community has merged on the necessity to build a linear electron-positron collider, that will work as a complementary accelerator to the LHC.

This chapter will explain the motivations to invest a huge amount of money in a new great world project. It will present the complementary nature of the lepton and hadron colliders and the main advantages of the lepton collisions will be discussed. After giving an overview of the ILC with its basic design and the experiment models, we will focus on the design of one of the experiments: the International Large Detector (ILD).

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## 2.1 To a linear lepton collider

The most impressive accelerator ever built is located at CERN in Geneva, Switzerland. It is the world largest particle accelerator, with a circumference ring of nearly 27 kilometers, straddling the Swiss and French borders. It is designed to collide two counter rotating beams of protons or heavy ions, with a possibility to reach centre-of-mass energies of 14 TeV with a high peak luminosity of  $10^{34} \text{ cm}^2\text{s}^{-1}$ . The goals of the LHC are to perform further tests on the SM, search for new forces or produce dark matter candidates. Indeed, the collider covers a wide energy range at the constituent level while running at a fixed beam energy. Unfortunately, the measurements can not reach the highest precision.

Complementary to a discovery machine such as the LHC, a machine to perform precise measurement should be built: the lepton collider.

### 2.1.1 Advantages of a linear lepton collider

First of all, during each collision at an hadron collider, only a part of the total centre-of-mass energy is available for the process evolved, so the initial four-vector momentum is not known. By colliding leptons, which are structureless objects, the full centre-of-mass energy is available for the elementary process. The initial four-vector momentum of an interaction is exactly known, hence the event can be fully reconstructed.

Secondly, with a lepton collider, the beam energy is tunable and both electron and positron beams can be polarised. The selection of an appropriate polarisation can boost the signal and suppress the background cross-section.

Thirdly, as seen on the first point, at the LHC, only a fraction of the partons are contributing to the interesting process. The proton-proton interaction cross section is dominated by inelastic background QCD processes. The signal event is then accompanied by large backgrounds produced by the interaction of other partons collisions. This background has an impact on the detector design (high radiation tolerance and selective trigger implementation) and masks the elementary process of interests. The lepton colliders do not suffer from this kind of background and at similar energies, the event rate is lower as those of hadron colliders. Moreover, the interaction of electrons and positrons is purely electroweak. So, the detectors do not have to handle extreme data rates and they can be use without any trigger. This will allow to get a better sensitivity to any possible signature of new physics.

This main advantages of the lepton colliders do not explain the choice of a linear collider to perform fine and precise measurements, as it is planed for the ILC or CLIC. The reason of that choice is provided by the equation 2.1 describing the synchrotron radiation emitted by a particle moving a circular accelerator.

$$E = \dots \quad (2.1)$$

The radiative energy loss is proportional to the radius, the energy of the particle and its mass. To compensate that loss, a circular electron-positron accelerator should have an extremely big radius.

To reach the same energy scale at a linear collider, it requires a bigger number of accelerating cavities and would be bigger than a circular collider. Indeed, in a circular collider, the particle bunches are being accelerated many time in the ring up to reach the

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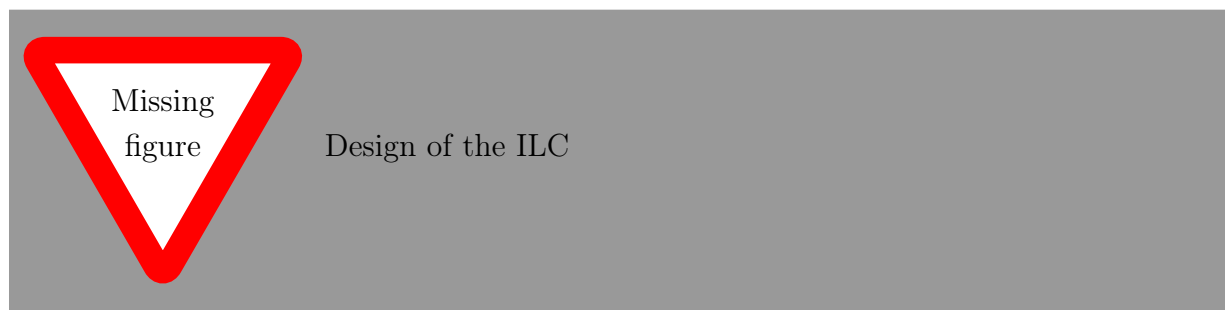


Figure 2.1 – Basic design of the International Linear Collider

energy of collision. Unfortunately, the track of particles are bended, leading to an energy lose through synchrotron radiation. The energy loss is proportional to the particle's energy

### 2.1.2

blablabla

## 2.2 The ILC machine

The ILC should be the next lepton collider experiment and will be situated in Japan. During 2016, the final site where the experiment will be hold is going to be decided. The more likely site candidate will be in the north of Japan, in the region of Kitakami.

### 2.2.1 Baseline design

The ILC is plane to collide electrons an positrons at a center-of-mass energy up to 500 GeV, with energy variability down to 200 GeV for 31 kilometers long accelerator. An upgrade to reach the centre-of-mass energy of 1 TeV is also possible, but the accelerator should be extended to achieve a length of 50 kilometers in total. It is designed to generate a total of  $500\text{fb}^{-1}$  of data during the first four years of operation.

The luminosity will reach a peak of  $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$  at  $\sqrt{s} = 500\text{GeV}$ .

The main components of the ILC are the electrons and positrons sources, the damping ring, the main LINAC, the beam delivery system and the interaction region. Two experi-ment will participate and will share the same interaction region. Via a push-pull system, the detector will be alternatively positioned and running, while the other one would be maintain.

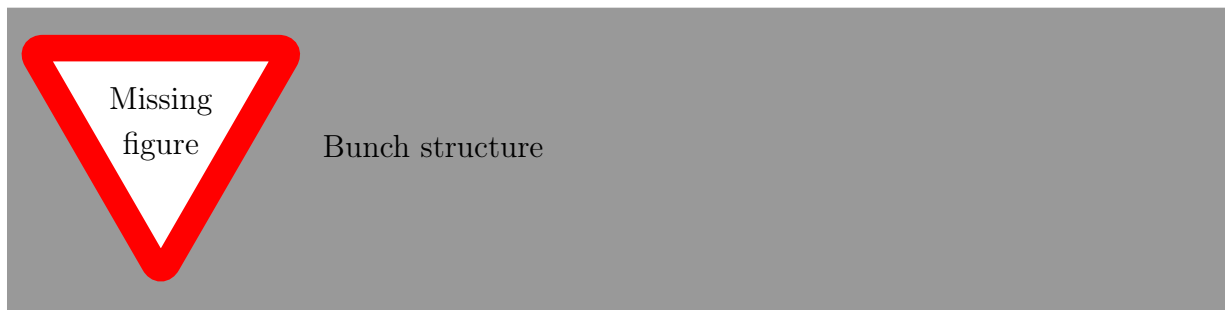


Figure 2.2 – Bunch structure of the ILC: ...

### 2.2.2 Beam parameters

### 2.2.3 Background

## 2.3 The ILC detectors concept

### 2.3.1 Overview of the two experiments

Although the ILC is a linear collider with only one beam line, two experiments will participate. The duplication of the beam to get two permanent fixed detectors is too expensive and difficult to build. Instead, the collaboration has the idea to have only one interaction point. A push/pull system will allow to change the detector

Two detector designed with complementary features have been developed. Their designs will reach the ILC precision measurements and search for new physics. They are optimised for the particle flow algorithm (PFA) to measure the final states with high accuracy. This leads to a high hermeticity, high granular calorimeters and excellent tracking and vertexing. The two experiments are the Silicon Detector (SiD) and the International Large Detector (ILD) and a global comparison of the two detectors is going to be presented on the next subsection.

### 2.3.2 SiD VS ILD

### 2.3.3 The ILD detector

The ILD is a detector designed to follow the requirements given before.

#### Vertex detector

The chapter 4 will introduce more in details the vertex detector requirements for the ILD and the different design proposals. For the moment, two designs are under study for the vertex detector. The first one is made of five single sided layers and the other one three double sided detection layers. The design of a vertex detector is driven by the material budget and the precision of the measurements.

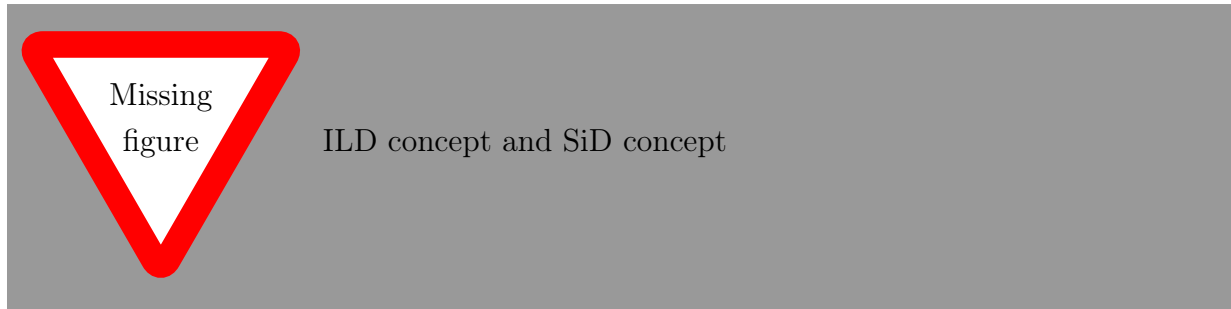


Figure 2.3 – The ILC detectors concept: on the left, a design of the SiD, on right a design of the ILD

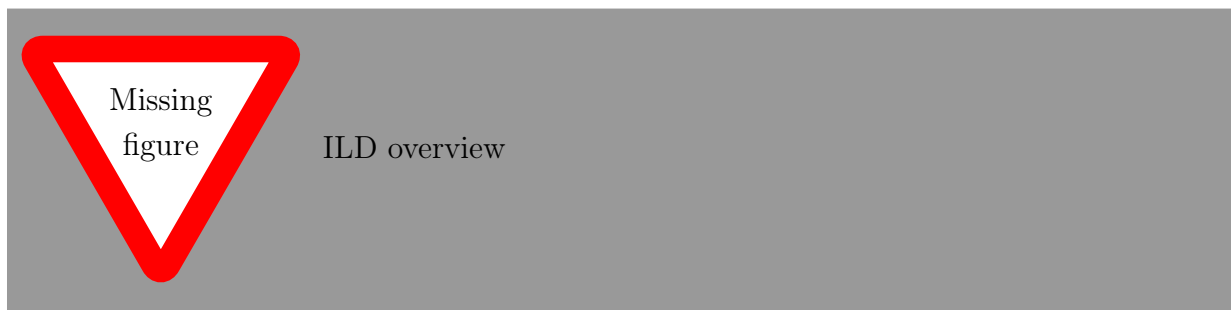


Figure 2.4 – The ILD detector concept with its subdetector system

## Tracking

The main tracking system for the ILD is done by the Time-Projection-Chamber (TPC). It is a gaseous detector with a low material budget designed to measure the particles' trajectory. When a particle goes through the TPC, it ionises the gas, creating electrons that are drifting to the anode thanks to a high voltage. The anode is the part where the readout plates are installed. It provides 3D position of the particles tracks thanks to the wires and the anode (give x-y) and the z coordinate is given by the drifting time. In addition to the exact position measurement, this detector is also able to measure the energy  $\frac{dE}{dx}$  deposited by the particle and would be a first step for a particle identification.

The requirements to design a TPC at the ILC are given by two main values:

- Single point resolution  $\sigma_{s.p.}$  which should be lower than  $100\mu\text{m}$  in the  $r\phi$  direction and less than  $500\mu\text{m}$  in the z direction
- The minimum distance to separate two hits which should be lower than 2 mm.

The TPC thought for the ILD is constituted of a central barrel part, with an inner radius of  $\simeq 33\text{cm}$  and a outer radius of  $\simeq 180\text{cm}$  and two endcaps with a detection area of  $10\text{m}^2$ . The solid angle coverage is up to  $|\cos\theta| \simeq 0.98$ . The barrel will be filled with a gas mixture called T2K (3 % of Ar-CF<sub>4</sub> and 2 % of isobutane). Due to the low material budget and the ability to cope with a high magnetic field, the TPC is compliant with a Particle Flow Algorithm ??.

To improve the track reconstruction, the TPC is surrounded by high silicon detectors: two barrel components, the Silicon Internal Tracker (SIT) and the Silicon External Tracking (SET); an end-cap component, the End-cap Tracking Detector and the Forward Tracking Detector (FTD). The SIT is linking the tracking between the VXD and the TPC, whereas the SET is giving an entry point to the ECAL after the TPC. Both system provide precise space points and improve the overall momentum resolution. The goal of the SIT is to improve the momentum resolution, the reconstruction of low  $p_T$  charged particles and the reconstruction of long lived particles. The coupling of the SIT and SET provide also a time stamping information.

The ETD is located within the gap separating the TPC and the end-cap calorimeter. It improves the momentum resolution for charged tracks with a reduce path in the TPC. It also reduces the effect of the material of the TPC end-plate. The material budget of this end-plate is estimated to 15 % of  $X_0$ .

As the TPC does not provide any coverage in the forward region, seven silicon disks ensure efficient and precise tracking down to very small angles. The ETD and FTD make sure to get a full tracking hermeticity.

To simplify the system layout and the maintenance, the SIT, SET and ETD are made of single sided strip layers tilted by a small angle with respect to each other. They are placed in a so called false double-sided layers. The SIT has two layers of micro-strip, instead of one layer for the SET. The technology studied are micro-strip sensors with an area of  $10 \times 10 \text{cm}^2$ , with a pitch of  $50 \mu\text{m}$ , a thickness of  $200 \mu\text{m}$  and a edgeless. The dead area of the sensors will be reduced down to few microns instead of  $100 \mu\text{m}$ . The table 2.1 gives the single point resolution aimed, as well as the angular coverage and the material budget.

Rewrite description of the TPC, it is such shitty right now...

Add PFA citation



Detector	Single point resolution ( $\mu\text{m}$ )	coverage	material budget $X_0$ (%)
SIT	$\sigma_{R-\phi} = 7.0$ $\sigma_Z = 50.0$	$\cos \theta \simeq 0.91$	0.65
SET	$\sigma_R = 7.0$	$\cos \theta \simeq 0.79$	0.65
ETD	$\sigma_X = 7.0$	$\cos \theta \simeq 0.799 - 0.985$	0.65

Table 2.1 – Parameters aimed for the silicon tracker using microstrips sensors.

**Calorimeters****Magnetic Field and yoke**



# Chapter 3

## Physics at the ILC

In the chapter 1, the framework of particles physics was described. Since the beginning of High Energy Physics, different experiments have been done to confirm the exactness of the SM but also to find new physics beyond the SM. The beam structure allow different kind of measurements. For example, the LHC has a high luminosity and high energy beam, able to reach new energy scale on earth, whereas the ILC is trying to reach more precise results, with less energy. This chapter will discuss the physics that will be studied at the ILC. It will focus particularly on the Higgs physics. An introduction to a physic analysis will be given.

### Contents

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### 3.1 Potential studies

As seen in chapter 2, the ILC will have a vast and variable tunable centre-of-mass energy. Due to the features of an  $e^+e^-$  collider, the initial state of collision is well defined. Contrary to the LHC, there are no strong interaction backgrounds and the electroweak background is controlled and calculable. This conditions will help to perform precise measurements and looking for new physics.

For example, the ILC will be able to collect more Z boson events than the LEP did at the centre-of-mass energy  $\sqrt{s} = 91$  GeV. It will allow to perform ultra precise measurements of the Z boson and the electroweak sector to study the Z asymmetries and couplings, but also to measure rare processes that where limited by statistics at LEP.

By increasing the centre-of-mass energy to  $\sqrt{s} = 160$  GeV, ultra precise measurements of the W mass could be performed (MeV precision) and with higher energy, it is also

possible to measure precisely the W boson couplings. Also, at higher energy, there is a new perspective to measure precisely the nature of the Higgs boson and its coupling. The large statistics given by the ILC will permit to study rare Higgs decay.

Top physics

New physics

Energy (GeV)	Reaction	Physics Goal
91	$e^+e^- \rightarrow Z$	ultra-precision electroweak
160	$e^+e^- \rightarrow WW$	ultra-precision W mass
250	$e^+e^- \rightarrow Zh$	precision Higgs coupling
350 - 400	$e^+e^- \rightarrow t\bar{t}$	top quark mass and couplings
	$e^+e^- \rightarrow WW$	precision W couplings
	$e^+e^- \rightarrow \nu\bar{\nu}h$	precision Higgs couplings
500	$e^+e^- \rightarrow f\bar{f}$	precision search for $Z'$
	$e^+e^- \rightarrow t\bar{t}h$	Higgs coupling to top
	$e^+e^- \rightarrow Zh\bar{h}$	Higgs self-coupling
	$e^+e^- \rightarrow \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \rightarrow AH, H^+H^-$	search for extended Higgs states
700-1000	$e^+e^- \rightarrow \nu\bar{\nu}h\bar{h}$	Higgs self-coupling
	$e^+e^- \rightarrow \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \rightarrow \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \rightarrow t\bar{t}^*$	search for supersymmetry

Table 3.1 – Summary of the major processes that will be studied at the ILC for different energies[2].

## 3.2 Higgs physics

### 3.2.1 Production of the Higgs at the ILC

Contrary to the LHC, the Higgs will be accessible by direct measurement. They are three major processes Higgs boson production at the ILC, the Higgs-strahlung, the WW-fusion and the ZZ-fusion:

$$\textbf{Higgs-strahlung: } e^+e^- \rightarrow ZH \rightarrow f\bar{f}X$$

$$\textbf{WW-fusion: } e^+e^- \rightarrow \nu\bar{\nu}W^+W^- \rightarrow \nu\bar{\nu}H$$

$$\textbf{ZZ-fusion: } e^+e^- \rightarrow e^+e^-ZZ \rightarrow e^+e^-H$$

The Higgs-strahlung is a s-channel process that is dominant at 250 GeV and its cross-section falls off as  $1/s$  as the centre-of-mass energy  $\sqrt{s}$  increases. The WW-fusion and ZZ-fusion are t-channel processes. The cross-section grows logarithmically with the center-of-mass energy and the contribution of the fusion processes is small at 250 GeV.

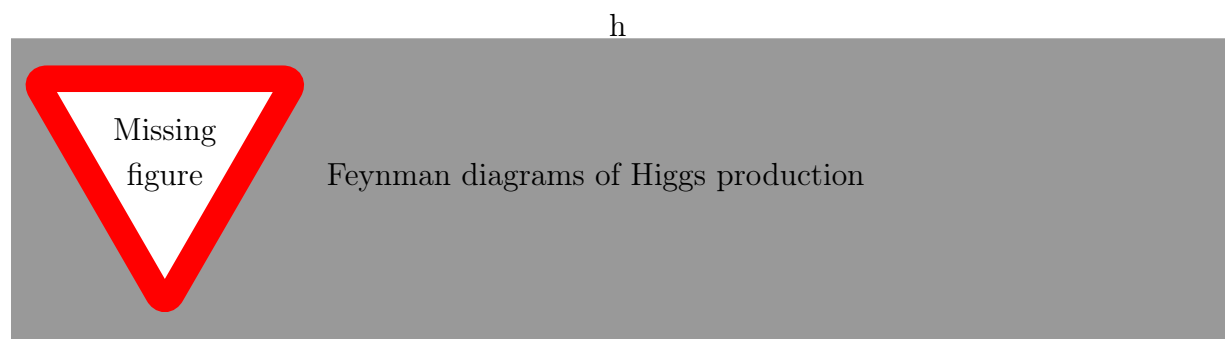


Figure 3.1 – The higgs production processes at the ILC.

The polarisation of the beam will help the experimenters to select Higgs reactions or to change the mixture of signal and background. For example, the WW-fusion occurs only with left-handed electrons associated to right-handed positrons.

The figure shows the cross-section production of the Higgs at the ILC regard to the energy of the collision.

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### 3.2.2 Decays of the Higgs

The Higgs boson couples to all the particles of the SM. There are many decay modes:  $b\bar{b}$ ,  $WW$ ,  $ZZ$ ,  $gg$ ,  $c\bar{c}$ ,  $\tau\tau$ ,  $\gamma\gamma$ ,  $\gamma Z$ . At the LHC, the decay  $h \rightarrow b\bar{b}$  can be observed with special kinematics but the  $h \rightarrow c\bar{c}$  and  $h \rightarrow gg$  decays are extremely challenging to observe.

## 3.3 Analysis of simulated data

The goal of this section is to present how to perform an analysis from simulated data. Measuring the Higgs coupling to  $c\bar{c}$  is important to have a reference value to understand any deviations from the SM predictions in the Higgs coupling to  $t\bar{t}$  and  $gg$ . To study this coupling, the analysis will focus on the final state that gives two neutrinos and two jets coming from the Higgs.

### 3.3.1 Background processes

There are many background processes to take into account

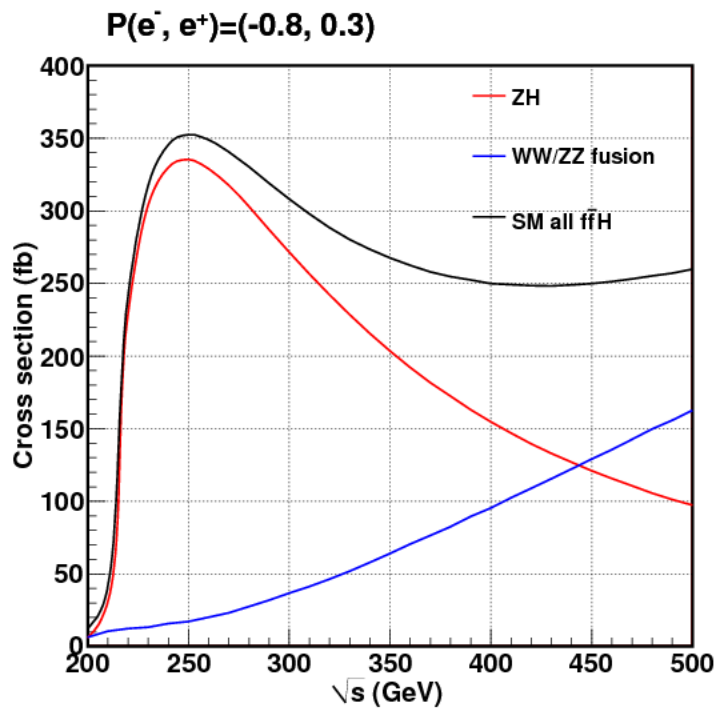


Figure 3.2 – The cross section production of the Higgs boson with a mass of 125 GeV. REF HIGGS WHITE PAPER

# Chapter 4

## Double-sided VXD: PLUME

### 4.1 The ILD vertex detector specifications

For the ILD, the resolution at the interaction point should be given by the equation [4.1](#)

$$\sigma_{IP} = 5\mu\text{m} \oplus \frac{10 - 15\mu\text{m}}{p \sin \theta^{3/2}} \quad (4.1)$$

Where the first term is the impact parameter resolution which depends on the radii of the inner and outer layers and the single point resolution. In the case of the ILD, the single point resolution should not be higher than  $\sigma_{sp} \simeq 3\mu\text{m}$ . The second term is related to the multiple scattering.

### 4.2 Integration of CMOS sensors

### 4.3 A versatile mechanical structure

Reference  
: Marco  
Battaglia  
- Vertex  
Tracking  
at a  
Future  
Linear  
Collider





## Chapter 5

# Electrical Validation and laboratory testing



# Chapter 6

## Test beam analysis

6.1 Experimental set-up

6.2 Deformation studies

6.3 Benefits of double-point measurements



# Bibliography

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