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Introduction

Chapter 1

Secrets of the nature

1.1 The Standard Model

1.1.1 Introduction

The Standard Model (SM) is a theory that describes the fundamental 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 explanation of experimental results, but is also able to predict a wide variety of phenomena.

The behavior of the matter in the Universe is lead by only four forces:

- The electromagnetic (EM) interaction: acts on the electric charges
- The weak force: acts on all the fermions and is responsible for the β decay
- The strong force: acts on color-charges particles and is responsible for the confinement of quarks
- The gravitational force: acts on all particles

The three firsts forces are well described by the SM. However, the gravitational force is not included in that theory. 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.

The matter and the interactions are made of fundamental particles. From a quantum point of view, a particle is defined by its intrinsic angular momentum, called spin. That quantum number is a key to distinguish between the particle of 'matter' and the 'carrier force' particle: half integers spin are called fermions and the integer spin are the bosons.

As the two kind of particles has different quantum number, they obey to different principle. The fermions are obeying to the Pauli exclusion principle: two fermions can not occupied the same quantum state at the same time. The bosons are following the Bose-Einstein statistics: they are not limited to single occupancy of the same state.

Fermions

They are to the number of 12. The particles are classified into three categories, called generation. The first generation contains the lightest and more stable particles. They are the particles that form the ordinary matter. The other particles are heavier and tempt to decay to a particle of the first generation. They are divided in two categories: the leptons and the quarks.

The leptons are free particles and are to the number of 6. Three of them are charged particles sensitive to the EM and weak interaction and the three other are neutral particles called neutrinos. They are only sensitive to the weak processes.

The quarks are particular fermions and are to the number of 6. They were never observed alone in the nature. They are always in bounded states, called hadrons. The quarks are carrying quantum color numbers. This quantum color numbers are green, blue, red plus the anti-color associated. Only colorless particle can be observed. They are in double quarks state, called mesons or triple quarks state, called baryons. The hadrons are sensible to the electro-weak interaction but also to the strong interaction.

Type	Family	Particle	L	B	Q_e	Mass
Leptons	1^{st}	e	1	0	-1	511 keV
		ν_e	1	0	0	< 2 ev
	2^{nd}	μ	1	0	-1	105.66 MeV
		ν_μ	1	0	0	< 2 eV
	3^{rd}	τ	1	0	-1	1.78 GeV
		ν_τ	1	0	0	< 2 eV
Quarks	1^{st}	u	0	1	2/3	$2.3^{+0.7}_{-0.5} MeV$
		d	0	1	-1/3	$4.8^{+0.5}_{-0.3} MeV$
	2^{nd}	s	0	1	-1/3	$95 \pm 5 MeV$
		c	0	1	2/3	$1.275 \pm 0.0025 GeV$
	3^{rd}	b	0	1	-1/3	$4.66 \pm 0.03 GeV$
		t	0	1	2/3	$173.21 \pm 0.51 \pm 0.71 GeV$

Table 1.1 – Summary of the 12 fermions.

Bosons

It can be found also some intermediate gauge bosons, that are mediators of interactions and are particles of spin 1.

Higgs boson is a particle predicted particle by the S.M and is the only one to have been found in 2012 at the LHC. It is a product of the Higgs mechanism which is assumed to be responsible for the generation of the masses and can be explained by the electroweak symmetry breaking.

The S.M. tempts to describe also the fundamental interaction of the particles. It has been able to describe only three out of four interaction: the electromagnetic, the weak and the strong interactions. Some theories try to explain the gravity but this theme will not be discussed.

The interaction between fermions is carried by particle of spin 1 called gauge boson. The electromagnetic interaction is mediated by the photon γ, a mass-less boson. The weak interaction is mediated by three massive bosons: an neutral electrical charged boson Z^0, and two electrical charged W^+ and W^-. The strong interaction is mediated by eight gauge bosons, the gluons.

In this theory, the matter is made up of fermions (spin 1/2) which interact via bosons. Bosons are gauge field, they propagate the interaction and generate particles mass. They are two types of fermions: the leptons and the quarks. The leptons are made of six particles plus the six anti-particles associated. Neutrons are associated to the leptons. A quantum number describes those particles: L Leptons interact only via weak interaction.

The quarks are six plus six anti-quark. They are the components of neutron and protons. Lonely quarks were never observed in the nature. The quarks have a charge color : green, red, blue. The quarks are confined into "white color" objects call hadrons. The hadrons are subdivided into three categories: the mesons, the baryons and the anti-baryons. The mesons are made of a quark and a anti-quark are always of integer spin. The baryons (or anti-baryons) are made of three quarks, like the proton or neutron. A quantum number is associated to the quarks: the baryon number B which is conserved for every interaction and has the same properties as the L number.

Force	Gauge bosons	Mass (GeV/c^2)	Electric charge
Electromagnetic	γ	0	0
Weak	Z^0	91.1876 ± 0.0021	0
	$W^{\pm}$	80.3980 ± 0.0250	± 1
Strong	g (8 gluons)	0	0

There are four fundamental interactions in the nature: the gravity, the weak interaction, the electromagnetic interaction and the strong interaction. Those interactions have different characteristics and interact via gauge bosons.

The electromagnetic (E.M.) interaction acts on the electric charges. The range of the interaction is infinite. The mediator for the E.M. interaction is the photon γ. It has a spin-0 and no mass.

The weak interaction acts on all the fermions. The mediators are the Z and $W^{\pm}$ bosons. The range of the interaction is only courte portée.

The weak and E.M. can be combined together: electro-weak interaction.

The strong interaction behaves on color-charges particles (quarks and gluons). They are 8 gauge bosons called gluon. The range is infinite due to the color charged and the confinement inside hadrons.

The last force is the gravitation. It is felt by all particles. The mediator is the graviton but is not yet observed. This interaction is not described by the S.M. and several theories try to explain that interaction.

1.1.2 Quantum Field Theory

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

$$SU_C(3) \otimes SU_L(2) \otimes U_Y(1) \tag{1.1}$$

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 used to described the electromagnetic interactions using a $U(1)$ gauge group.

Lets first consider the Dirac equation for a free fermion:

$$\mathcal{L}_{Dirac} = \overline{\Psi}(x)\left(i\gamma^{\mu}\partial_{\mu} - m\right)\Psi(x) \tag{1.2}$$

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

$$\begin{array}{rcrcl} \Psi(x) & \rightarrow & \Psi'(x) & = & e^{-i\alpha}\Psi(x) \\ \overline{\Psi}(x) & \rightarrow & \overline{\Psi}'(x) & = & e^{i\alpha}\overline{\Psi}(x) \end{array} \tag{1.3}$$

The corresponding local symmetry is:

$$\begin{array}{rcrcl} \Psi(x) & \rightarrow & \Psi'(x) & = & e^{-i\alpha(x)}\Psi(x) \\ \overline{\Psi}(x) & \rightarrow & \overline{\Psi}'(x) & = & e^{i\alpha(x)}\overline{\Psi}(x) \end{array} \tag{1.4}$$

Considering the local symmetry, the mass term of the Lagrangian REF-Dirac-Lagrangian stays invariant but the term which contains the derivative is not anymore: By introducing a material derivative that includes a gauge field A_μ, it is possible to keep the derivative invariant under local gauge transformation:

$$D_\mu\Psi(x) = (\partial_\mu - iQ_eA_\mu)\Psi(x) \tag{1.5}$$

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_μ field is:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{1.6}$$

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

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

A mass term $mA_\mu A^\mu$ for the field A_μ is missing because it is not gauge invariant. It can be explain by the fact that the photon is massless.

Weak interaction

Experimental experiments with β decays lead to the fact that only left-handed fermion chiralities participate in the weak interaction.

The weak interaction is described by a SU(2) symmetry group.

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 spinners 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:

$$T^a = \frac{1}{2}\lambda^a \tag{1.8}$$

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

$$if^{abc} = 2Tr([T^a, T^b]T^c) \tag{1.9}$$

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

$$q_i = \begin{pmatrix} q_i^1 \\ q_i^2 \\ q_i^3 \end{pmatrix} \tag{1.10}$$

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

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

The gauge field A_μ can be introduced in the group:

$$A_\mu = g_S A_\mu^a \frac{\lambda^a}{2} \tag{1.11}$$

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

The material derivative is then:

$$D_\mu = \partial_\mu - iA_\mu = \partial_\mu - ig_S A_\mu^a \frac{\lambda^a}{2} \tag{1.12}$$

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:

$$G_{\mu\nu}^a = \left(\partial_\mu A_\nu^a - \partial_\nu A_\mu^a\right) + g_S f^{abc} A_\mu^b A_\nu^c \tag{1.13}$$

Finally, the QCD Lagrangian is given by:

$$\mathcal{L} = \sum_{i=1}^{6} \bar{q}_i \left(i\gamma^\mu D_\mu - m_i\right) q_i - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \tag{1.14}$$

Glashow-Weinberg-Salam model

Lagrangian EW goes here:

1.2 The Higgs physics

The Standard Model constitutes one of the most successful achievement in modern physics. One of its strength is to provides a 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.

1.2.1 Symmetry Breaking

Here talk about the Goldstone theorem (may be.)

1.2.2 Higgs mechanism

Here talk about the Higgs mechanism but may be added in a Higgs chapter)...

I don't know what to write and say about it. It is just so boring.

Higgs Decays

As explained before, the Higgs boson couples to all particles of the Standard Model. The figure FIGXXX, the branching ratios for different decay modes are shown as a function of the mass of the Higgs boson. For a Higgs mass of 125.5 GeV, a large number of decays are accessible to experiments

Higgs production at the ILC

FIGXXX

1.3 Limitations of the Standard Model

1.3.1 Matter-antimatter asymmetry

As discussed before, the SM defines equal number of particles and anti-particles. However, the entire universe is only made of matter. Why preference to matter and no one to anti-matter?

1.3.2 Dark Matter

Nowadays only twelve particles (plus the anti-particles associated) have been observed. The idea of dark matter comes from the way we estimate the mass of galaxy.

1.3.3 Gravitation

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