The Architecture of the Standard Model

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Abstract

The standard model (SM) of elementary particles represents our present understanding of known fundamental fermions (quarks and leptons) and the forces between them. The electroweak theory and quantum chromodynamics have been unified into the SM, which is represented by the gauge group SU(3) X SU(2) X U(1). In this article, we discuss the architecture of the SM briefly.

1. Introduction

At the end of 20th century, the search for understanding the mysteries of matter and the forces which holds it together has created the theory of fundamental forces based on nonabelian gauge fields, physicists have named it the standard model (SM) of particle physics [1]. This model unifies the three fundamental forces: strong, electromagnetic and weak force. These forces (electromagnetic, weak and strong force) are mediated by the gauge bosons: the photon (γ); the W^+, W^- and Z^0 boson; and the gluons respectively. There are 6 types of quarks and 6 types of leptons in the SM. Quarks are called up (u), down (d), charm (c), strange (s), top (t) and bottom (b). Leptons are called electron (e^-), electron-neutrino (ν_e), muon (μ^-), muon-neutrino(ν_μ), tau (τ^-) and tau-neutrino(ν_τ). Fig.1 shows elementary particles in the SM and their mass, charge and spin. Higgs boson is expected to be the final particle of the SM. Recently, the discovery of this particle is confirmed in the large hadron collider (LHC) experiment at CERN, Geneva but till now it is not confirmed whether it is the SM Higgs boson or beyond the SM particle. This particle is responsible for the Higgs mechanism by which all particles acquire mass.

In the mid 19th century, Maxwell unified three different phenomena, i.e. electricity, magnetism and optics in one theory known as electromagnetic theory and established a set of four equations. These equations are gauge symmetric [2]. The classical form of Maxwell's equations (MEs) describes the EM field with its continuous energy distribution in space-time. But latter this theory was reinterpretended by Feynman, Schwinger and Tomonaga [3]. They replace the continuous energy distribution by discrete field quanta or discrete packets of energy. This is called field quantization and the revised electromagnetic theory was named as quantum electrodynamics (QED) which was the first quantum field theory (QFT) [2]. The relativistic approach of QFT can be the basis to describe all the fundamental interactions (except gravity). The fields involved in QFT are gauge fields. A gauge field is a physical field whose existence is inferred from "a principle of local gauge invariance", this means that the laws of physics are independent of local changes of the phase at all positions and in the universe. This is how the first QFT was coined. The quantum theory of strong force (colour force) is known as quantum chromodynamics (QCD). The two theories, the electroweak theory and the QCD, form the *standard model* (SM) of elementary particles.

Electricity + Magnetism + Optics = Electromagnetism

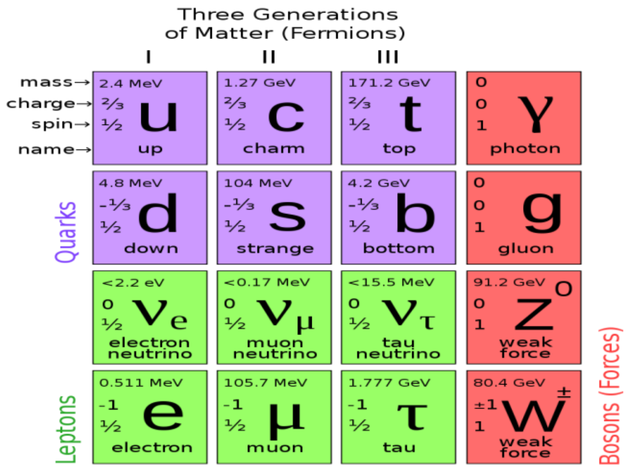
Electromagnetism + Quantum theory = QED

QED + Weak force = Electroweak theory

Strong force + Quantum theory = QCD

QCD + Electroweak theory = SM

In the next sections we explain the different QFTs starting from QED to QCD and the architecture of the SM briefly.



I	II	III	
2.4 MeV 2/3 ½ u up	1.27 GeV 2/3 ½ c charm	171.2 GeV 2/3 ½ t top	0 0 1 γ photon
4.8 MeV -1/3 ½ d down	104 MeV -1/3 ½ s strange	4.2 GeV -1/3 ½ b bottom	0 0 1 g gluon
<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Fig. 1: **Elementary particles in standard model**

2. Quantum Electrodynamics

In particle physics, quantum electrodynamics (QED) is the relativistic quantum field theory of electrodynamics. In QED, each particle is described by a wavefunction which contains the information that can be used to calculate the probability of finding the particle at different locations. In QED, two charged particles interact by the exchange of electromagnetic vector boson of spin 0 known as photon. For example, let us consider the interaction between a proton and an electron. The proton emits a photon and the electron absorbs it. This is represented in the Feynman diagram shown in Fig. 2 [2]. Feynman diagram describes the particle interaction quantitatively and gives a diagrammatic visualization. Each external line represents a real particle and the Feynman rules define propagation of particle mathematically. The internal lines describe the intermediate particle which cannot be observed directly, but can only be observed in indirect decay process. QED is based on the symmetry group U(1) and the generator is electric charge Q. The strength of the interaction is determined by coupling constant. The coupling constant for the emission of an extra photon is 1/137 (known as fine structure constant). The Nobel Laureate Richard Feynman, one of the founding father of QED, has called QED as "*the jewel of physics*".

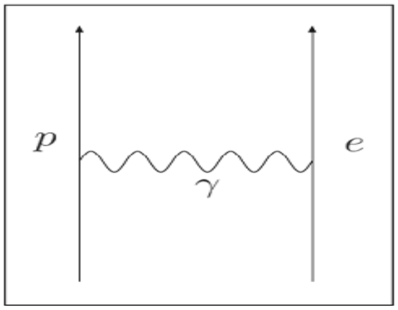


Fig. 2 [2]

3. Electroweak Theory

The weak force is a universal force which affects all particles. The intermediate vector bosons for weak interaction are W^+, W^- and Z^0 boson. Here W^+ and W^- have electric charge which carries out the charged current interactions and Z^0 boson is neutral which carries out the neutral current interactions. The W and Z^0 bosons carry weak isospin (T_3) and weak hypercharge (Y) and so they can interact with each other as well as with other particles. These self interactions are important in the SM. Fig. 3 [2] shows a weak interaction namely the decay of neutron into proton, electron and antineutrino (beta decay). Neutron and proton are the composites of three quarks udd and uud respectively. This figure shows that the d quark turns into a u quark by emitting the weak quantum W^- which turns into a pair of leptons (electron and antineutrino).

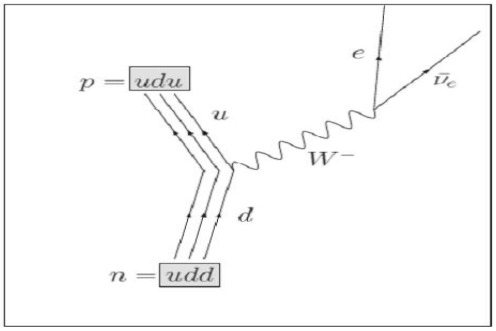


Fig. 3 [2]

The quantum electrodynamics and weak forces have been unified into EW dynamics as they are two facets of one entity called the electroweak (EW) theory. The EW interactions are mediated by four quanta called electroweak gauge boson (W^+, W^-, Z^0 and γ) and these gauge bosons were predicted by the EW theory. Fig. 4 [2] shows the Feynman diagram of the electromagnetic and weak interactions among the quarks and leptons mediate by electroweak quanta. From Fig. 4 we can see the exchange of W can generate a force between particles or can cause decay of a particle. But photon and Z^0 boson can only generate force among particles.

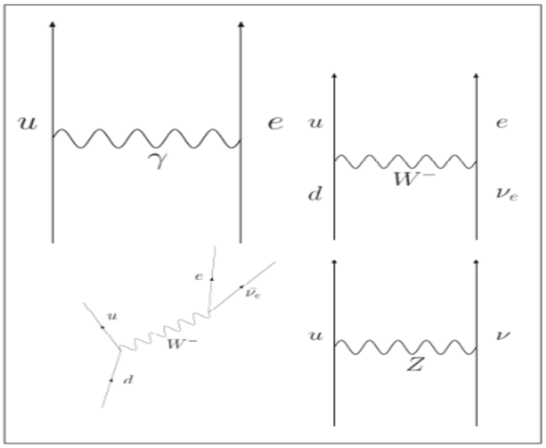


Fig. 4 [2]

4. Quantum Chromodynamics

A theory of quark interactions was constructed by analogy with QED. This theory postulated the existence of massless particles called gluons by which the quarks are held together and describes the strong interaction by using the colour charge of quarks and gluons. This theory is called as quantum chromodynamics (QCD) [4,5]. The theory of strong interaction involves the exchange of meson and between baryons where both mesons and baryons made of quarks [6]. The idea of colour was first put forward by Oscar Greenberg in 1965. Just to distinguish the colours, one normally calls the three colours red (R) , green (G) and blue (B) [5]. Let us consider the interaction between two quarks. In this case, the colour charge on each quark is changed after the interaction, whereas in QED the electric charge on the electron was not changed by the photon. The colour charge must be conserved at each vertex of the strong interaction. Hence this condition implies that each gluon must carry a colour/anticolour combination.

The gluon and the photon are very much different from each other in many ways [3].

Firstly, the photon has no electric charge but the gluons carries colour/anticolour charge. Then another point is that a photon cannot interact directly with another photon by the electromagnetic force because it is neutral. But a gluon-gluon interaction can occur via the strong force. This interaction is very important in LHC because the most interesting proton-proton collisions arise from gluon-gluon interactions. One more difference is that the coupling constant for emission of an extra gluon is much higher for the strong force than for photon emission in QED. For photon emission the coupling constant is 1/137 whereas the value of coupling constant for strong interaction is 1/10. An interesting nature of quarks is that, when they are very close together the force between them is very small and behave as free particles. This is known as *asymptotic freedom* and due to this property the quarks which are close together inside a proton barely interact with each other. But when a quark tries to move away from another quark in a bound system like proton the required energy to do this becomes infinitely large. This is the reason that no single quark has ever been observed. This property is called *quark confinement* [1-3, 5].

5. Architecture of the Standard Model

The standard model of particle physics is now known to be the most successful theory in describing almost all of known physics except gravity [2]. Six types of quarks: up (u), down (d), strong (s), charm (c), bottom (b) and top (t); six number of leptons: electron (e^-), electron-neutrino (ν_e), muon (μ^-), muon-neutrino(ν_μ), tau (τ^-), tau-neutrino(ν_τ); and Higgs boson with their antiparticles are the building blocks of the SM [1,8]. The SM is also known as *quark-lepton model*. In the SM the quarks and leptons are categorized in three generations (Fig. 1). The first generation particles are found in ordinary matters and they are the lightest among three generation particles, whereas the 2nd and 3rd generation particles are found in cosmic rays and can be reproduced in particle colliders [6]. The quarks have fractional charges. Each type of quark is a colour triplet and also carries electroweak charges, in particular electric charges + 2/3 for up-type quarks and -1/3 for down-type quarks. The electroweak theory and QCD are the two pillars of the SM. In the SM the fundamental forces are based on nonabelian gauge fields and the symmetry group SU(3)XSU(2)XU(1). This group has 8+3+1=12 generators with non-trivial commutator algebra. Not all the generators belong to SM commute with each other, so this theory is a nonabelian gauge theory [7]. SU(2)XU(1) symmetry group describes the electroweak interaction. One of the generator of SU(2) group is T_3 (the third component of isospin) and Y (hypercharge) is the generator of U(1). The electric charge Q, the generator of QED gauge group is given as $Q= T_3+ Y/2$. SU(3) is the colour group of the theory of strong interaction. Every symmetry group has one or more number of generators and each generator is associated with a vector boson or simply gauge boson with same quantum number. If the gauge symmetry is unbroken then vector boson will have vanishing mass. The gauge bosons are mediating particles for fundamental interactions. For example, photon is the vector boson which mediated the interaction between two charged particles in QED. Similarly, there are 8 gluons associated to the SU(3) colour generators, while for SU(2)X U(1) there are 4 gauge bosons : W^+, W^-, Z^0 and γ [9]. Hence, the SM contains total 12 mediating particles. Out of these 12 generators only the gluons and the photon are massless because the symmetry induced by the other 3 generators is actually spontaneously broken. The W^+, W^- and Z^0 are quiet heavier particles (M_W ~80.4 GeV, M_Z ~91.2 GeV). The mass problem is therefore primarily concerned with the force carriers of weak force. So, the completion of the SM required a way of including massive force carriers without breaking the symmetries that were crucial to its predictive power. It was found that via spontaneous symmetry breaking (SSB) [2] this could be achieved. There are many different examples of spontaneous symmetry breaking (SSB) in physics and in everyday life. If a pin is held vertically and downward pressure is applied the pin will be bent but the direction of this bend is random and not predictable. Starting from the top of a hill you have an almost infinite number of ways to walk down to ground level, where you have lower potential energy. The situation is symmetrical- we can choose any of the equivalent possible directions. When you choose one way down you have broken the symmetry. The idea of spantaneous breakdown of symmetry (SBS) in particle physics originates from Nambu although he applied it in a different context [3]. In a gauge theory like the SM the SSB is realised by the Higgs mechanism. Higgs mechanism postulates the existence of a universal field called the Higgs field and this field gives masses to W and Z^0 and also gives masses to all the femions. The variation of Higgs field with potential energy is shown in Fig. 5 [3]. The vertical axis is the magnitude of potential energy and the horizontal axes represent the magnitude of the Higgs field. When the Higgs field is zero (point A) the potential energy is maximum. When the spontaneous symmetry breaking occurs, the potential energy is reduced to one of the minimum points around the valley (point B) and the Higgs field becomes nonzero. The radius of the bottom of the valley is related to the magnitude of the Higgs field.

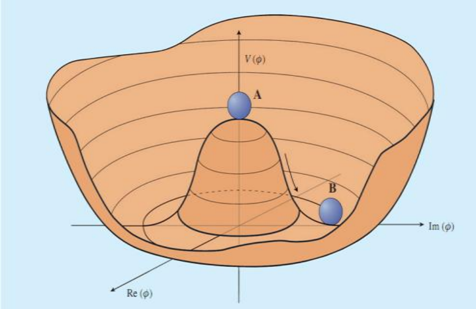


Fig. 5 [3]

According to the scientists, when the universe was created at that moment there was no Higgs field, so all the particles were massless and travelled at the speed of light. Gradually as the universe cooled the potential energy of the universe decreased and the Higgs field became non- zero. In this process the Higgs field breaks the symmetry. Then the particles which couples with the Higgs field acuires mass. But there is an important byproduct of the Higgs mechanism: a massive spin zero boson, called the Higgs boson, must exist as a relic of the original Higgs field. Although it is theoretically predicted almost half a century ago, scientists are still trying to confirm the existence of it and to find its properties. The mass of Higgs boson is not specified in the SM. From the LHC experiment, the mass of this particle is found to be 125.3± 0.4 (stat) ± 0.5 (syst) GeV (CMS) [10] and 125.5 ± 0.2 (stat.)$^{+0.5}_{-0.6}$ (syst.) (ATLAS) [11]. At the Tevatron, the CDF and D0 Collaborations have observed the mass of Higgs boson in the range 115 to 140 GeV [12]. Their observed signals are consistent with a standard model Higgs boson with a mass of 125 GeV. Recently, on 14th March, 2013, the 'Moriond' conference held in Italy, has confirmed the existence of Higgs particle [13]. But till now it is not confirmed whether it is the SM Higgs boson or beyond the SM particle.

6. Further Discussions

The SM is the most successful theory for describing the phenomena of fundamental interactions of elementary particles. In spite of this fact this model has several drawbacks; some of them are discussed below.

Gravity, one of the fundamental forces, is not included in the SM. So, the physicists are not satisfied with the unification at this stage. The ultimate goal of particle physics is to construct a unified theory that would reveal how all observed particles and forces are just different manifestations of a single underlying system, which can be expressed within a common mathematical framework [14]. The gravitational force is based on the Einstein's general theory of relativity. This theory is based on the principles of classical mechanics and not of quantum mechanics. Since other forces in nature obeys the rules of quantum mechanics, any theory that attempts to explain gravity as well as the other forces of nature must satisfy both gravity and quantum mechanics. General theory of relativity describes gravity at large distances whereas quantum mechanics works at very small distances. In quantum theory the range of a force is inversely proportional to the mass of the quantum that is exchanged. Since gravity has infinite range, quantum theory of gravity (if it is constructed) will have its quantum, called graviton, with zero mass and spin-2. But till now Einstein's general relativity has resisted all attempts at being combined with the quantum world as we do not have a quantum theory for spin-2 particle. Hence, quantum gravity had become the most fundamental problem of physics at the end of the twentieth century. This is the reason for the rise of string theory, for it promises to be a theory of quantum gravity. It is seen that string theory [15–18] works very well at large distances where gravity becomes important as well as at small distances where quantum mechanics is important. In the standard model the elementary particles are mathematical points. But in string theory, instead of many types of elementary point-like-particles, we assume that in nature there is a single variety of one-dimensional fundamental objects known as strings [15]. It is not made up of anything but other things are made up of it. Like musical strings, this basic string can vibrate, and each vibrational mode can be viewed as a point-like elementary particle, just as the modes of a musical string are perceived as distinct notes. String theory [19,20] provides a framework to address some fundamental issues in cosmology and elementary particle physics.

The number of parameters in the SM is too large to regard it as a fundamental theory and also there is no such underlying principle to choose the parameters. The Lagrangian of the SM contains many arbitrary parameters such as the three gauge couplings corresponds to three parts of the gauge group, flavour mixing parameters (CKM mixing angles and phases), coupling constants of Higgs self interaction, and Higgs mass parameter. The three gauge groups involved in the SM were seemed to be unrelated, which means that the formal unification of strong and electroweak interaction is also a question.

Neutrinos are massless in the SM, because neutrinos do not couple with Higgs field. But, about 15 years ago, experimenters discovered that neutrinos do have tiny masses and this has been hailed as a great discovery since this may show us how to go beyond the SM. The dominance of baryonic matter over antimatter is not explained in the SM. The problem of CP-violation is not well understood including CP-violation in strong interactions. The SM does not answer why there are only three generations not more than that.

According to the standard model of cosmology, the universe contains 4 % visible, 23 % dark matter and 73 % dark energy. These measurements rely on the validity of the hot big bang model, general relativity and the cosmological principle (that the universe is uniform on the largest scales). But the SM says nothing about where these dark matter and dark energy came from. What is the nature of dark matter and dark energy?

Apart from the above discrepancies of the SM, there are some more problems which have to be taken care. Such as, the SM can't explain the Higgs interaction's of different specific couplings to different particles, it is not valid above Planck Scale ($\sim 10^{19}$ GeV). Both the srting and the extra curled-up dimensions will be revealed only when we can access Planck's length scale ($\sim 10^{-33}$cm). But so far we have reached only 10^{-17}cm. So, we have a long way to go. Quantum gravity is an important part to explain the today's physics. Apart from string theory there are other approaches to quantum gravity. We hope the future discoveries from LHC will show us the right choice of a theory which would be able to explain all the four fundamental forces exist in nature.

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