Chapter 1

Introduction

1.1 The Standard Model

A physics model is a description of a system using physics and mathematical concepts and language. Standard Model (SM) is a physics model that summarizes what is currently known about the subatomic world. The SM is composed of two gauge symmetry theories: the Glashow-Salam-Weinberg Model (GSW) [1–3] describing electroweak interactions; the Quantum Chromodynamics (QCD) [4] describing the strong interactions. In SM, there are two types of fundamental particles, fermions and bosons. Fermions are the building block of matter, and bosons are the intermediate particles of the four fundamental interactions of SM, i.e., strong, weak, electromagnetic, and gravitational force. In this chapter, we briefly introduce the components of the SM and the related theories to this thesis.

1.1.1 Fundamental particles

Fermions are defined as particles with half integer spin (intrinsic angular momentum), like leptons, quarks, proton, etc, while bosons are particles with integer spin, like the photon and the Higgs boson. The fundamental particles of SM are shown in Figure 1.1.

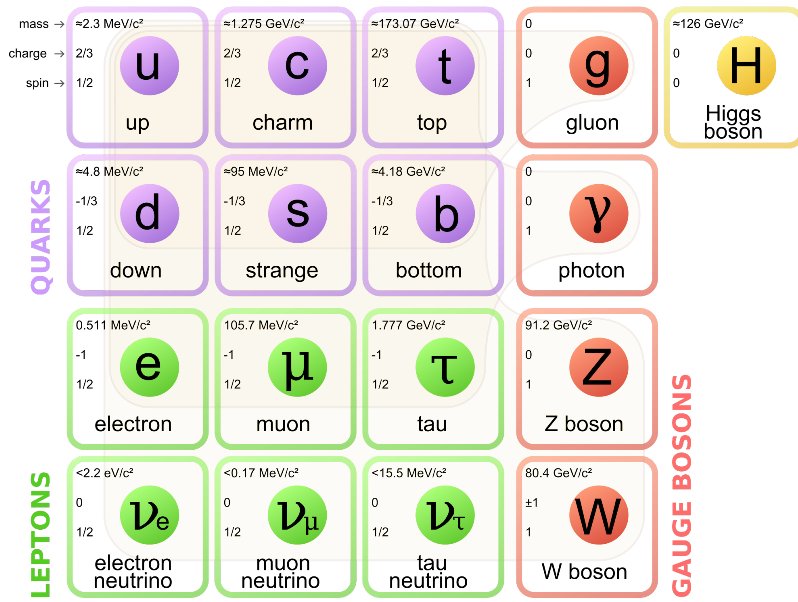

Figure 1.1: Standard model of elementary particles: the 12 fundamental fermions and 5 fundamental bosons. [5]

Quarks

In SM, there are six flavors of quarks: up (u), down (d), strange (s), charm (c), top (t), and bottom (b). Quarks carry properties like flavor, color, spin, charge, mass, etc. All quarks have spin $\frac{1}{2}$ in SM and they belong to one of the three generations: u and d quarks belong to the first generation; s and c quarks are the second generation quarks; t and b quarks make up the third generation. The color is a property of particle. In Quantum Chromodynamics, color is conserved in strong interactions. There are normally 3 types of color: red, blue, green. A particle is colorless if it carries a net color charge of zero.

Leptons

Leptons are fundamental particles, which are also fermions. As shown in Figure 1.1, there are three generation of leptons: electron (e) and electron neutrino (ν_e) are the first generation; muon (μ) and muon neutrino (ν_μ) are the second generation; tau (τ) and tau neutrino (ν_τ) are the third generation. Leptons have electronic charge, but do not carry color charges. Thus they are involved in the electroweak interactions, but not the strong interactions.

Bosons

Every interaction has its mediator: the photon (γ) for electromagnetic force, W and Z boson for weak force, gluon (g) for strong force and graviton (not found yet) for gravity. Higgs boson (H), although not a mediator, accounts for the mass of other fundamental particles, which will be elaborated in the following section. The W, Z, γ and g bosons having spin 1, are called vector boson. H boson has spin 0, which is called a scaler boson. There are two W bosons, distinguished by their electron charges, W^+ and W^-.

1.2 Fundamental interactions

In SM, there are four fundamental forces : strong, electromagnetic, weak and gravitational force, as shown in Table 1.1. The "Strength" column in Table 1.1 is not the real strength of the force, but a value to show the relative strength of these forces.

Since gravity is so small compared to other three forces, it is mostly not considered in the process of particle physics. The strong force is described by the Quantum Chromodynamics. And the electromagnetic force and weak force are unified into electroweak interaction, described by the Glashow-Weinberg-Salam (GSW) model. The theory of particular interest to this thesis is the Quantum Chromodynamics (QCD), which will be introduced in the following section.

Force	Strength	Mediator
Strong	10	Gluon
Electromagnetic	10^{-2}	Photon
Weak	10^{-13}	W and Z
Gravitational	10^{-42}	Graviton

Table 1.1: Summary of the four fundamental forces in Standard Model [6].

1.2.1 Quantum Electrodynamics (QED)

QED is the theory describing the electromagnetic interaction: the interaction between electric charged particles via the exchange of photons. The primitive process in QED, in the form of Feynman diagram, is shown in Figure 1.2. An electron comes in, and radiates a photon, then goes out. By connecting couple of these primitive processes together, we can get complex process like the one in Figure 1.3. In Figure 1.3, the electron and positron annihilate into a photon, which further decays to a pair of quarks, and then one of the two quarks radiates a gluon. The photon in Figure 1.3 is a virtual particle. Virtual particles are not observable, which are called "off-shell" particles. While real particles, in Figure 1.3, are the incoming electron and positron, and outgoing quarks and gluons, which can be observed and are "on-shell".

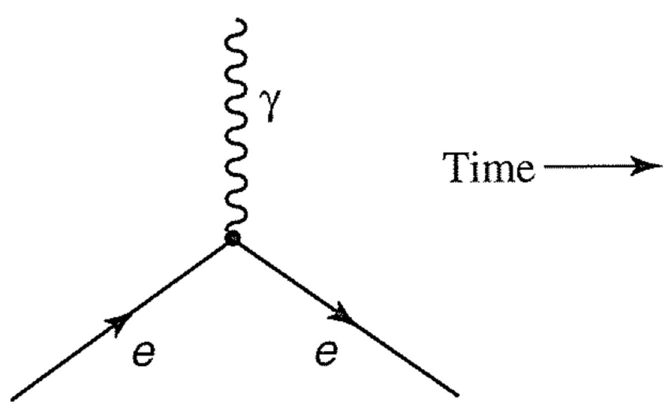

Figure 1.2: The primitive QED process in SM.

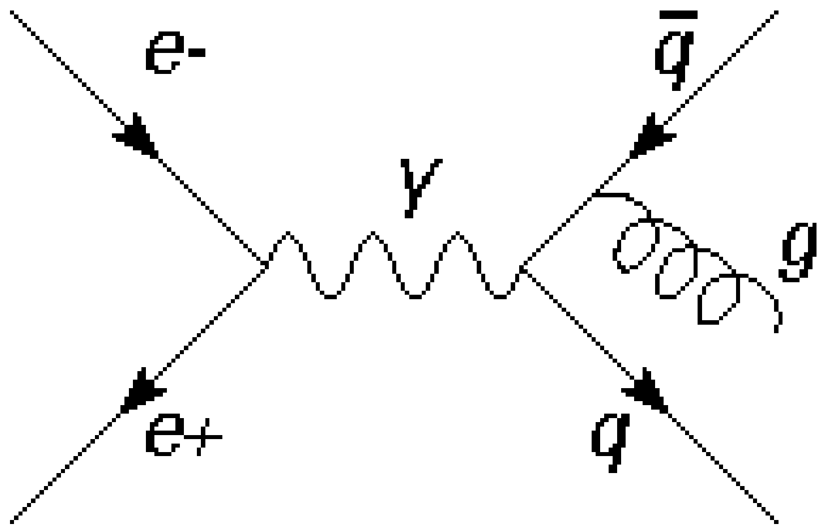

Figure 1.3: Feynman diagram for electron annihilation.

1.2.2 Quantum Chromodynamics (QCD) and jets

QCD is a theory describing the strong force and the involved fundamental particles. As we see from Table 1.1, strong force is the strongest force of the four. However, unlike the long range electromagnetic force, the strong force could only affect $\approx 10^{-15}$ m (1 fm), which is about the radius of a nucleus.

Color is one of the unique properties of QCD. The color of QCD is an analogy to the charge of QED. There are three types of colors charges: red, blue, green. Each quark carry one kind of color. So, for example, there are three types of top quarks in QCD: the blue top quark, the green top quark, and the red top quark. This is the same for all the other five flavors of quarks. Anti-quark carries one kind of anti-color. Gluons is the boson intermediating the strong force, just like the photon is the mediator of the electromagnetic force. Gluons has a color and an anti-color. When two quarks interact with each other, they interact through a gluon by exchanging colors. For example, as shown in Figure 1.4, one red quark comes in, radiates a gluon with color red and anti-blue, and a blue quark goes out. In terms of the color SU(3) symmetry, there are 8 gluons in QCD, as shown in Equation 1.1.

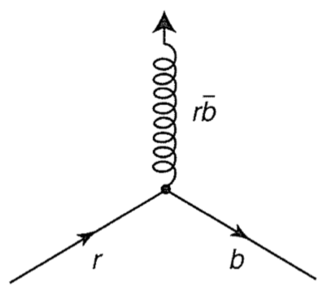

Figure 1.4: The illustration of quark-gluon interaction [6].

$$
\begin{array}{cc}
(r\bar{b}+b\bar{r})/\sqrt{2} & -i(r\bar{g}-g\bar{r})/\sqrt{2} \\
-i(r\bar{b}-b\bar{r})/\sqrt{2} & (b\bar{g}+g\bar{b})/\sqrt{2} \\
(r\bar{r}-b\bar{b})/\sqrt{2} & -i(b\bar{g}-g\bar{b})/\sqrt{2} \\
(r\bar{g}+g\bar{r})/\sqrt{2} & (r\bar{r}+b\bar{b}-2g\bar{g})/\sqrt{6}
\end{array}
\tag{1.1}
$$

Unlike charged particles, colored particle could not be free. What we see in experiments and daily life is color-singlet. So we can never observe a single quark or a single gluon in an experiment. What we observe is the "hadronization" products of quarks and gluons, which are called "jets" and introduced in the following text. The existence of quarks and gluons is proved by indirect experiments via jets. Here we introduce the essential components of QCD.

The coupling constant

The coupling constant is a scaler quantity describing the strength of an interaction. Here in QCD, the coupling constant α_s is :

$$\alpha_s(|q^2|) = \frac{2\pi}{(11n - 2f)ln(|q^2|/\Lambda^2)} \quad (|q^2| \gg \Lambda^2) \tag{1.2}$$

where $|q|^2$ is the squared energy-momentum 4-vector of the mediator gluon, n is the number of colors (3, in SM), f is the number of flavors (3, in SM), and Λ is a parameter determined from experimental data, which is in the range of 100$\sim$500 MeV.

Notice that α_s is not a constant. It is a function of $|q|^2$. Because of this, it is also named the "running coupling constant". The experimental measurements are shown in Figure 1.5.

Asymptotic freedom

As we see from Equation 1.2, when $|q|^2$ increases, α_s decreases. At large $|q|^2$, corresponding to short distances ($\leq$1 fm), the strong force is so weak that quarks

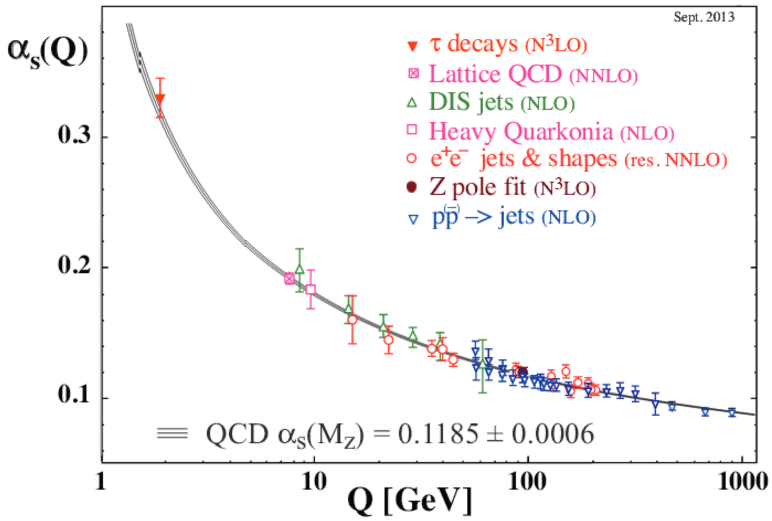

Figure 1.5: The running coupling constant of QCD. NLO is short for the next leading order. NNLO is short for next-next-leading order.

inside of proton travel freely. At very high energies, it is also possible to form quark-gluon plasma, since their interactions are so weak. This is called the asymptotic freedom.

QCD confinement

QCD confinement means that the force between quarks will hugely increase when they are separated. So one has to exert a lot energy to try to separate a quark from other quarks. And this energy will become large enough for the mediator gluon to decay into a new quark pair. As illustrated in Figure 1.6, when the two charm quarks are pulled apart, the strong force between them increases, and the mediating gluon will have a large amount of energy. Before the $c\bar{c}$ quarks are further separated, the gluon creates a pair of $d\bar{d}$ quarks. This process continues, and eventually the particle formed by $c\bar{c}$ quarks will become two particles formed by $c\bar{d}$ and $\bar{c}d$ quarks. The gluon could create any pair of quarks, as long as its energy is large enough. Here we use $d\bar{d}$ quark pair as an illustration. Also $d\bar{d}$ quark pair requires relatively low energy to create, compared to other quark anti-quark pairs.

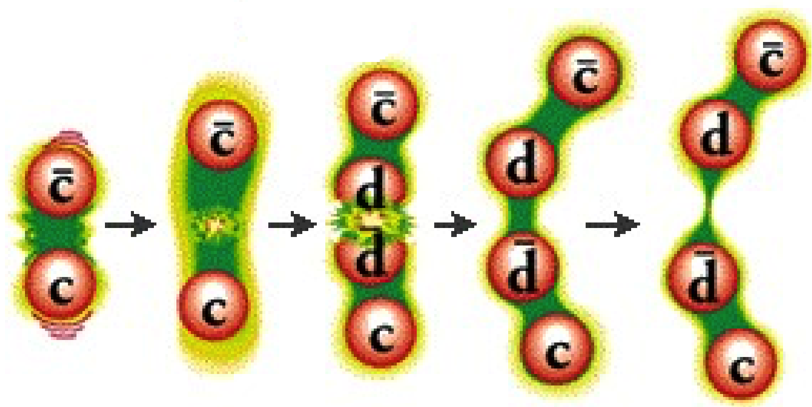

Figure 1.6: The illustration of QCD confinement [7].

Jet formation

When quarks and gluons are created in a high energy collision, they will move away from the collision position freely for a brief moment. And then, because of QCD confinement, when the quarks are separated by a distance $\geq 1\ fm$, new quark pairs are created from the virtual gluons exchanged by the interaction between the initial quarks, as shown in Figure 1.7. This process stops when the gluons or quarks don't have enough kinetic energy to create new quark-aniquark pairs. The quarks or gluons initially created by the the energetic collision, enentually become hadrons; this process is called hadronization. The stream of particles created by the hadronization of a single quark or gluon is called a jet, as shown in Figure 1.7 and 1.8.

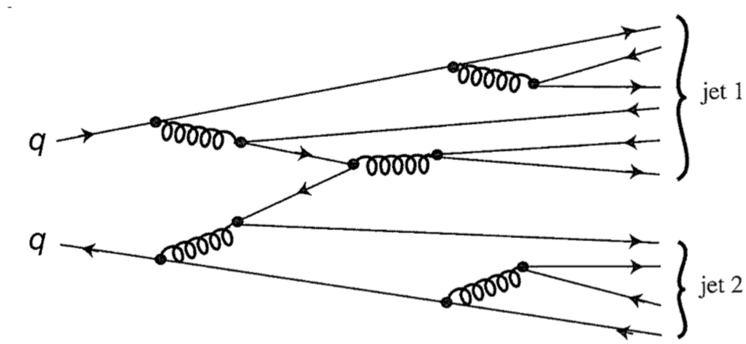

Figure 1.7: The hadronization process [6].

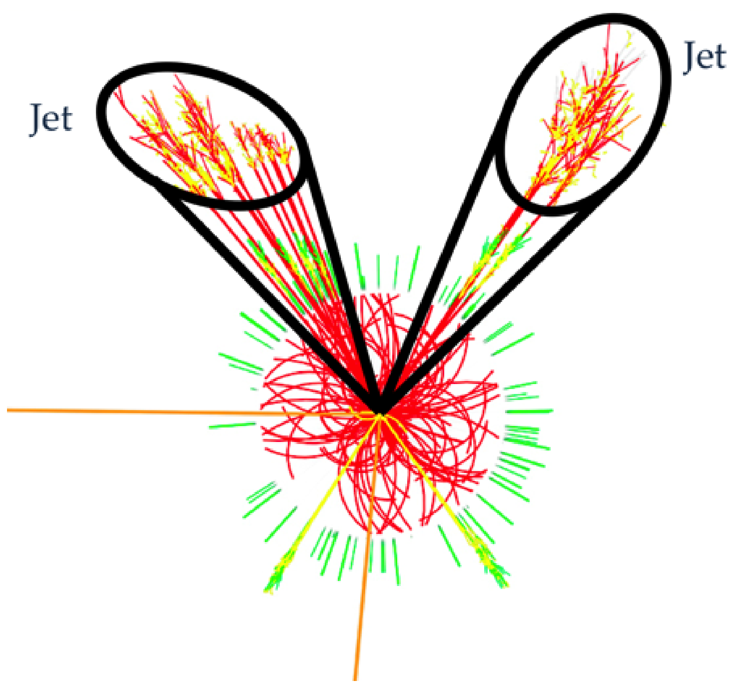

Figure 1.8: A sketch of jets formation in a high energy collision. Hadrons are clustered together to make jets.

1.2.3 The SM Higgs mechanism

The SM Higgs boson is a scaler boson, with spin 0. In SM, Higgs has a non-zero vacuum expectation value (VEV), as shown in Figure 1.9, while all other particles have zero VEVs. As shown in Figure 1.9, the Higgs particle with the non-zero VEV is tending to slide down to the bottom of the potential. While the Higgs particle is on top of the potential, a rotation of the whole system in space-time dimensions, does not change its symmetry. However, when the Higgs particle is sliding off the potential to the bottom, as shown in Figure 1.9, the rotation symmetry is broken. This is called the spontaneous symmetry breaking. The Higgs field with non-zero VEV is permeating all the space. And fermions, by their interactions with the Higgs particle, gain their masses. The magnitude of a fermion's mass is proportional to the its coupling strength with the Higgs field.

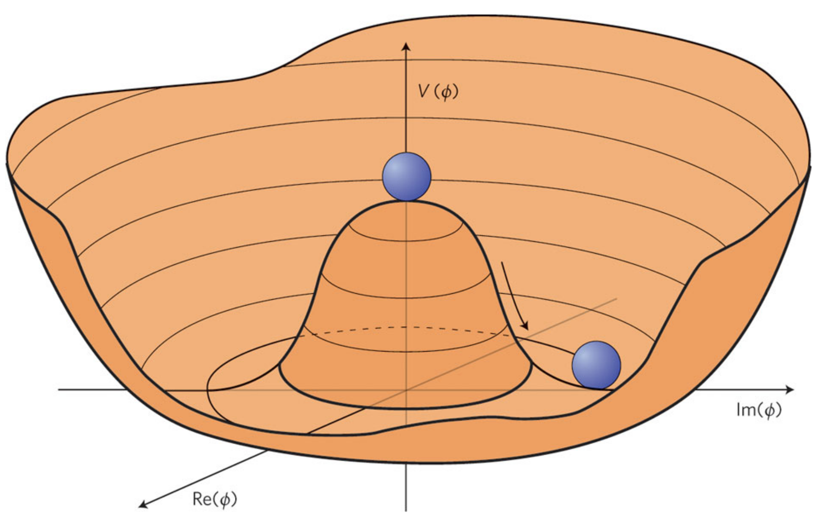

Figure 1.9: The non-zero vacuum potential of Higgs field. The $Im(\phi)$ and $Re(\phi)$ axes represent the plane of space and time. The $V(\phi)$ axis represents the potential energy. And the circle on top of the concave potential is the Higgs particle.

The W^+, W^- and Z bosons gain their masses through the spontaneous electroweak symmetry breaking mechanism. In an unbroken unified electroweak theory, there are four types of massless bosons: W1, W2, W3, and X. And there are also four types of Higgs particles, which can not be distinguished from each other. After spontaneous symmetry breaking, these four Higgs particles become distinguishable: charged H^+, H^-, and neutral H_0 and h. The W1 boson coupling with the H^+ becomes the massive W^+ boson. The W2 coupling with the H^- becomes the W^- boson. The W3 boson combined with the X boson together coupling with the H_0 becomes the Z boson. And the residual component of W3 and X combination becomes the massless photon.

The h, as one of the four Higgs bosons, is not absorbed by other particles, which is called the Higgs particle in SM. However, there is no constraint on the mass of this Higgs particle in SM.

1.3 The physics beyond the SM

Although the SM explains a lot of facts of current experiments and also achieves another tremendous success on the discovery of the SM-like Higgs boson in 2012. However, the SM cannot explain several important phenomena, and thus it is believed to be an effective theory of a more fundamental theory.

Dark matter and dark energy

As shown in Figure 1.10, the universe is expanding. However, the expansion is accelerating, instead of slowing down. Thus there must be some mysterious force overcomes the attractive force of gravity ad causes the accelerated expansion with time. This unknown force, is usually referred to as "dark energy". Dark here is the thing invisible to us.

The need for dark matter arises from the astronomy observations that the rotational motion of the stars or galaxies suggests a 5$\sim$10 times larger gravitational force than the one could be provided by the matter of the clusters. The lack of matter in this kind of case indicates the existence of matter that couldn't be observed by us, which is called "dark matter".

The current compositions of matter and energy of our universe, from studies, are about 4.9% normal matter (like stars, planets, etc.), 26.8% dark matter, and 68.3% dark energy. The neutrinos of the SM, are stable and have tiny masses, and also interact weakly with other particles. So on a cosmic scale, they behave like the dark matter. However, the redundancy of dark matter (26.8%) over normal matter (4.9%) suggests that neutrinos are insufficient to explain the observed amount of dark matter.

The hierarchy problem

As shown in Table 1.1, the gravitational force is quite small compared to other three forces. It is about 10^{-30} smaller than the weak force. This large discrepancy of scale is called the hierarchy problem of the SM.

The more formal way to state the hierarchy problem is why the Higgs mass in SM is in the scale of $\approx$125 GeV, rather not 10^{18} GeV, while the latter is more natural [9].

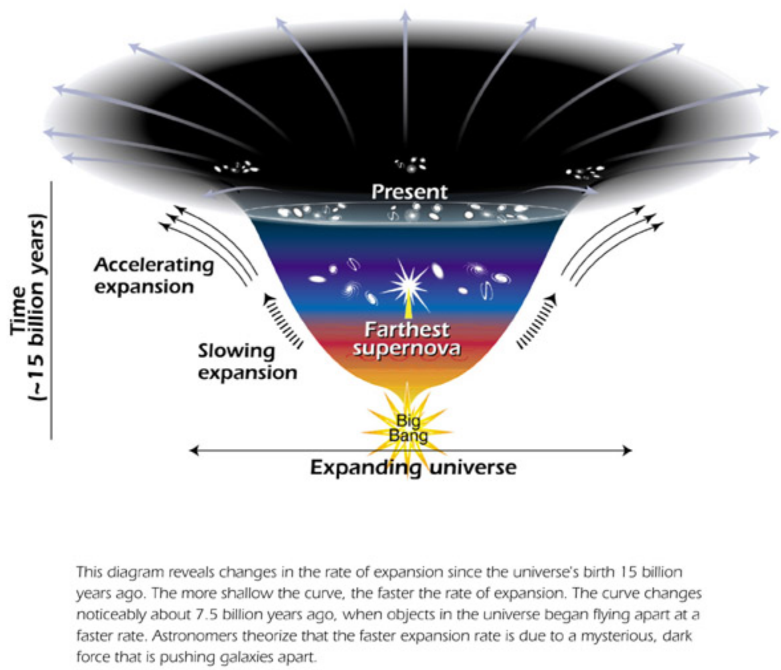

Figure 1.10: Accelerating expansion of the universe [8].

Baryon-anitbaryon asymmetry

The imbalance in baryonic matter and anti-baryonic matter in our observed universe can not be explained by the SM, while the Big Bang should produce equal amount of matter and antimatter.

Gravitation

The graviton is the mediator for gravitational force in SM. However, it has not been found yet. Unlike the QED and QCD, there is no known way to explain relativity in SM.

Since SM leaves us a lot of mysteries, the scientific research towards a better understanding of our universe has never been stopped. Several theories beyond the SM are raised. Composite models of quarks (q*) [20, 21] with their potential to explain the generation structure of quarks have been quite popular. The Randall-Sundrum model with its potential to solve the hierarchy problem in SM predicts the existence of Randall-Sundrum Graviton (G_{RS}) [22, 23]. There are also extensions of Randall-Sundrum models predicting the existence of bulk Graviton (G_{Bulk}) [24–26]. Many theories beyond the SM also predict the existence of W′and Z′ [27], the heavy partners of the SM W and Z bosons.

According to experimental measurements, these predicted resonances are expected to have resonance masses at least a few hundred GeV. The Large Hadron Collider (LHC), with its high collision energy, is a great farm to possibly produce these massive resonances. The predicted massive resonances decaying into a quark and a W or Z vector boson, or into two bosons (WW, ZZ, WZ, WH, or ZH) are searched in this thesis.

In proton-proton (pp) collisions at the energies reached at the LHC, bosons emerging from such decays usually would have sufficiently large momenta so that the hadronization products of their $q\bar{q}'$ decays would merge into a single massive jet [15]. So the event has a dijet topology. In this thesis, two dijet searches for physics beyond the SM are conducted with the CMS detector at LHC.

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