Thesis

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Abstract

This paper reviews

Contents

1 Introduction

The elementary particle physics studies our World in terms of its the smallest constituents: the elementary particles. All the matter consists of the molecules and the molecules consist of atoms. In an atom, there is a nucleus made of neutrons and protons and some number of electrons occupying their orbits around the nucleus. Protons and neutrons have a structure while an electron is not known to have any structure: it is a fundamental particle.

The interactions of the elementary particles can not be described by classical mechanics laws. For the objects which have sizes comparable to the Plank length, we have to use the quantum mechanics. For the speeds close to the speed of light, the special relativity is used. In particle physics, the objects are always small and are typically fast and are described by the quantum field theory.

The theory describing the behavior of elementary particles is called the Standard Model (SM). It has been proven to be an accurate description of the production of elementary particles observed so far. However, there are several experimental observations which are not described by the SM (gravity, dark matter, dark energy, matter/antimatter asymmetry). Therefore, the SM is not the complete theory of particle interactions but the one which is working in certain conditions. There are several SM extensions offered by theorists waiting for the experimantal confirmation or disproval.

There are three types of the particle physics experiments: cosmic rays, nuclear reactors and accelerators. Cosmic rays are free (do not require any machinery to be produced) and some of them can be very energetic. However, this source of particles is uncontrollable and the particles with very high energies can be rare. Nuclear reactors are moderately expensive and provide low-energetic particles coming from nuclear decays. Large accelerators are the most expensive way to study particle physics but they are well-controllable and allow to produce as many particles as needed with given energy. An accelerator can produce a beam which would hit a target or an accelerator can be a collider and produce a beam which would hit another beam. In the case of the symmetric meeting beams, the total momentum of two colliding particles is zero and the whole energy can potentially go to production of a new particle. Thus, meeting beams can create the most massive particles and should be used to study particle physics at the highest energy frontier.

Some SM extensions predict the existence of heavy particles beyond the discovered energy threshold. The search of these particles is the way to search for the SM extensions.

The Large Hadron Collider is the collider with the highest energy in the World ever, it can produce the most massive particles to probe physics beyond the SM. It collides two proton beams with the several TeV of energy each. The highest center-of-mass energy LHC will work with is 14 TeV but it also probes several lower energy points.

Compact Muon Solenoid (CMS) is one of two general-purpose detectors at the LHC placed at the collision point. CMS has a wide physics program including searches for different SM extensions as well as the precision measurements of the SM itself.

In this dissertation the analysis of inclusive $W\gamma+X$ processes using leptonic decays of $W \to \ell\nu$ where $\ell = e, \mu$ is reported. The $W\gamma$ productions with leptonic W decays can go through one of the following three processes: initial state radiation (ISR) where a photon is produced from one of the incoming partons, final state radiation (FSR) where a photon is radiated off the charged lepton from the W boson decay, and finally when a photon is produced via the triple gauge coupling (TGC) where a photon is emitted from the W boson. A W boson is a charged particle, therefore, the TGC is possible in the SM. The interaction of W bosons with photons is particularly important as a test of the self-coupling of these bosons as predicted by the electroweak sector. To search for the deviations from the SM, one would try to find an anomalous TGC (aTGC) which would be indicated by the TGC production to have much larger probability than expected from the SM prediction.

The total and the differential cross section with respect to P_T^γ has been measured. The P_T^γ is sensitive to the potential aTGC in the high P_T^γ region. The disagreement between the measured and theoretically predicted $d\sigma/dP_T^\gamma$ differential cross section at the higher P_T^γ end would be an indication of the possible presence of the aTGC.

1.1 Fundamental Particles and Interactions

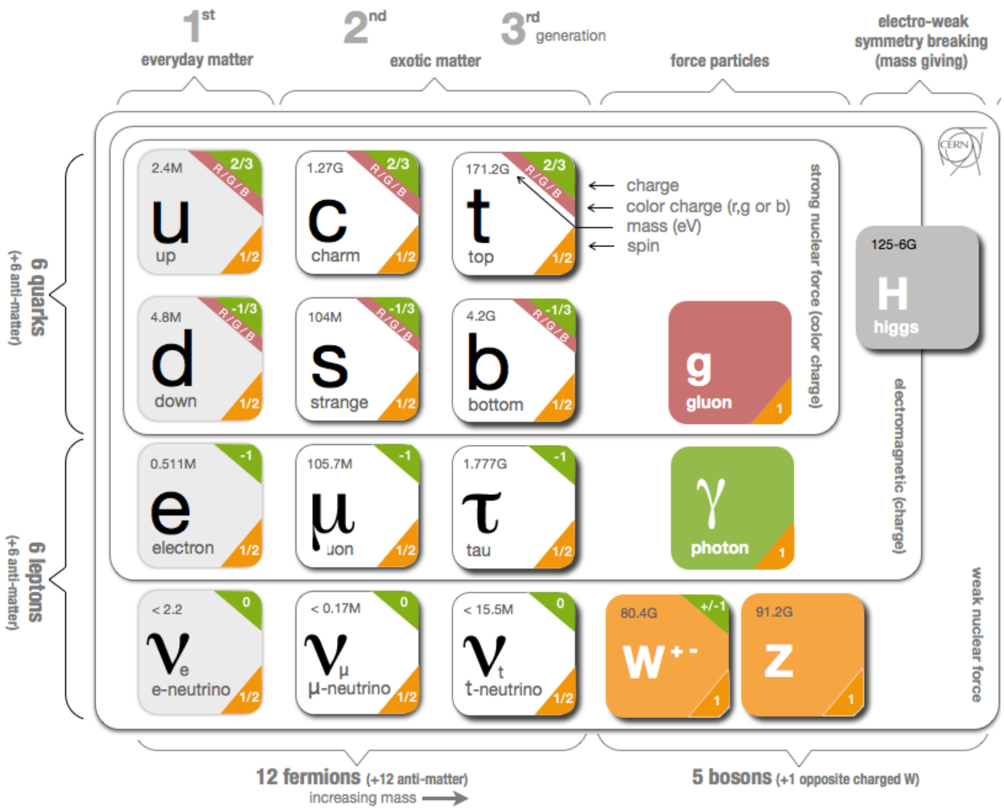

Figure 1: Standard Model Particles and Interations

The SM particles and summarized in Fig. 1.

The fermions are arranged into three generations, each generation consists of a quark with charge Q=+2/3(up, charm and top quarks), a quark with Q=-1/3 (down, strange and bottom quarks), a lepton with Q=-1 (electron, muon, tau-lepton) and a neutrino which is electrically neutral. (The unit of the electric charge used is an absolute value of an electron charge). Higher generation particles have larger masses compared to the corresponding low generation particles.

In addition to fermions, the SM include four bosons which are mediators for the SM interactions. Gluons are mediators of the strong interactions. Only quarks, antiquarks and gluons can participate in the strong interactions. These particles possess a special quantum number - the color charge. Quarks can be red, green or blue (although these are just names of the properties, not actual colors). Antiquarks can be antired, antigreen or antiblue.

Photon is a mediator for the electromagnetic interactions. All electrically charged particles participate in electromagnetic interactions. $W^{\pm}$ and Z^0 bosons are mediators of the weak interactions. All particles participate in weak interactions. $W^{\pm}$ and Z^0 bosons are massive while photon and gluon are massless particles.

The Higgs boson is the boson which is responsible for W and Z bosons to get masses.

All the particles are listed in Fig. 1. These and only these fundamental particles have been discovered by now (and their antiparticles). However, there are many composite particles which are called hadrons. Hadrons can consist of three quarks (baryons), quark and antiquark (meson), or three antiquarks (antibaryons). Hadrons always possess an integer charge and are colorless.

Protons and neutrons are baryons.

Most of the particles are short-lived and decay into lighter particles within microseconds. The only stable particles (in terms that they do not decay) are protons and antiprotons, electrons and positrons, neutrinos and antineutrinos, photons and gluons. However, if a particle can not decay, it does not mean that it would live forever. Antiprotons and positrons would immediately annihilate in the presence of a substance, and color-charged free gluons can not exist.

In addition to the three fundamental forces mentioned above, there is also the fourth one: the gravity. It is not included into the SM but its effect on particles is negligible compared to the other forces which makes it possible to develop theory and conduct experiments of particles physics even without having the gravity included into the model.

1.2 Electroweak Interactions

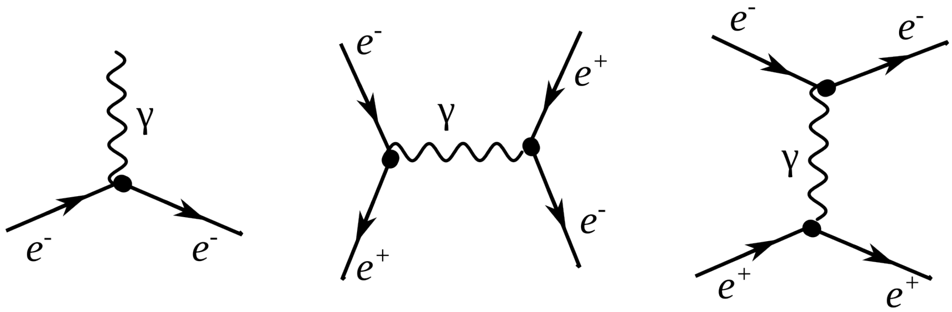

Figure 2: Electromagnetic interations

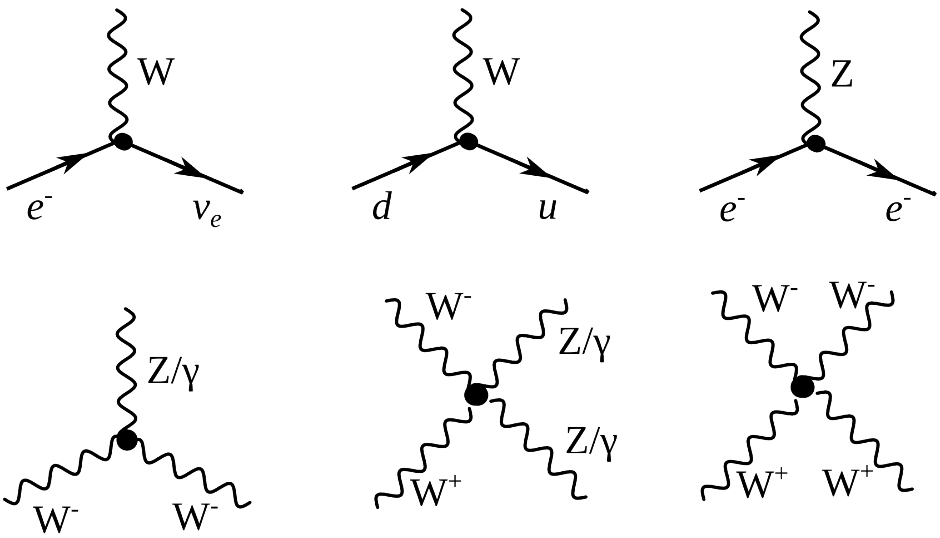

Figure 3: Weak interations

All electrically charged particles participate in electromagnetic interactions. Photon, the mediator of the electromagnetic interactions, is a spin-one electrically neutral massless particle. All electromagnetic interactions can be reduced to one elementary process (Fig. 2, left). This process reads: an electron enters, radiates or absorbs a photon, and escapes. Although there is an electron is drawn in this figure, it can be any other charged fermion as well. Such elementary process itself is forbidden by the energy conservation law but this element is a base of actual process (for example, Fig. 2, middle and right). Such graphical representations of the particle physics processes are called Feynman diagrams.

As for the weak interactions, there are two kinds of them: neutral (mediated by a Z boson) and charged (mediated by a W boson). Elementary processes with W and Z bosons are shown in Fig. 3. An electric charge must be conserved at any vertex. Therefore, if a charged lepton enters and radiates a W boson, a neutrino or antineutrino escapes (top left in Fig. 3). That is how a W boson interacts with a charged lepton and a neutrino. A lepton flavor number is always conserved in this interaction (Tab. 1).

Table 1: Lepton Flavor Number

particles	L_e	L_μ	L_τ
e^-, ν_e	+1	0	0
$e^+, \bar{\nu_e}$	-1	0	0
μ^-, ν_μ	0	+1	0
$\mu^+, \bar{\nu_\mu}$	0	-1	0
τ^-, ν_τ	0	0	+1
$\tau^+, \bar{\nu_\tau}$	0	0	-1

From top middle diagram in Fig. 3 we see that if a quark with Q=-1/3 enters, then a quark with Q=+2/3 escapes and, therefore, the flavor of the quarks has changed. The charged weak interaction is the only interaction which changes a quark flavor. The probability of each of three quarks with Q=+2/3 to be born is determined by the CabibboKobayashiMaskawa matrix and is the highest for the quark of the same generation as an initial state quark (in this particular case, d is the initial state quark and u has the highest probability to be produced after an interaction with a W boson but c and t can also be produced if there is enough energy).

The right top diagram in Fig. 3 is an emission of a Z boson off a fermion line. An electron is shown here as an example however it also could be any lepton, antilepton, quark or antiquark. All the same diagrams are possible with a photon instead of a Z boson except diagrams with neutrinos and antineutrinos.

The bottom diagrams in Fig. 3 show self-coupling of a W boson, its interaction with Z boson and its electromagnetic radiation of a photon. WWZ, WWγ, WWZZ, WWZγ, WW$\gamma\gamma$ and WWWW vertices are all possible in the SM.

Electromagnetic and weak interactions are unified by the electroweak theory. The mathematical formalism describing these two kinds of interactions is very similar. The difference between a photon and a Z boson is that a Z boson is massive and it can produce a neutrino-antineutrino pair or be scattered off a neutrino which a photon can not. The mass of Z boson is 91 GeV and that is why for low energies the probability of an electromagnetic process is much higher that the probability of similar neutral weak process. However, for particles with energies of E$\gg$91 GeV the mass of the Z boson can be neglected and these probabilities become the same.

1.3 The Higgs Boson

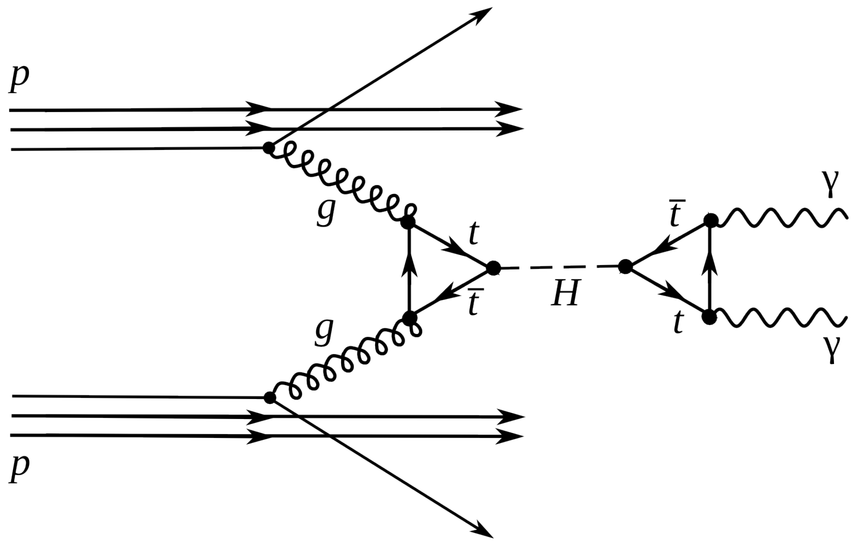

Figure 4: Higgs production and decay

In combining the electromagnetic and the weak interactions there is a question why the photon is massless while W and Z bosons are massive and how to accommodate these masses in the Standard Model. It was proposed independently by three different groups of theorists in 1960s that these bosons are getting mass by interacting with a massive scalar field. The quant of this field is called the Higgs boson (following the name of one of the theorists) and the mechanism of W and Z boson to get mass is called the Higgs mechanism.

At the descriptive level the mechanism can be explained in a way that a particle is born massless but while traveling through the Higgs field it is being slowed down and that is how is gets its inertia. In this understanding, it is intuitive that higher mass of a particle means stronger interaction with the Higgs field.

Although the Higgs mechanism was introduced to accommodate masses of $W^{\pm}$ and Z bosons only, the same approach can be used to introduced masses of all elementary particles.

For many years the Higgs boson was the only missing particle in the Standard Model however in 2012 it was discovered by ATLAS and CMS collaborations in the reaction shown in Fig. 4 in $\gamma\gamma$ and ZZ decay channels.

The Feynman diagram with the dominant process of the Higgs production and its further decay to $\gamma\gamma$ is shown in Fig.4 where the Higgs is produced in the process of the gluon-gluon fusion through the top quark loop. The Higgs boson can be produced through any quark loop however a top quark is much more massive than any other quark and therefore has a much higher probability to produce a Higgs boson.

The discovery of the Higgs boson is one of the most important scientific results in the past few years (alongside with the direct detection of the gravitational waves). Two of the theorists who proposed the Higgs mechanism, Francois Englert and Peter Higgs, were awarded the Nobel Prize in Physics in 2013.

1.4 Strong Interactions

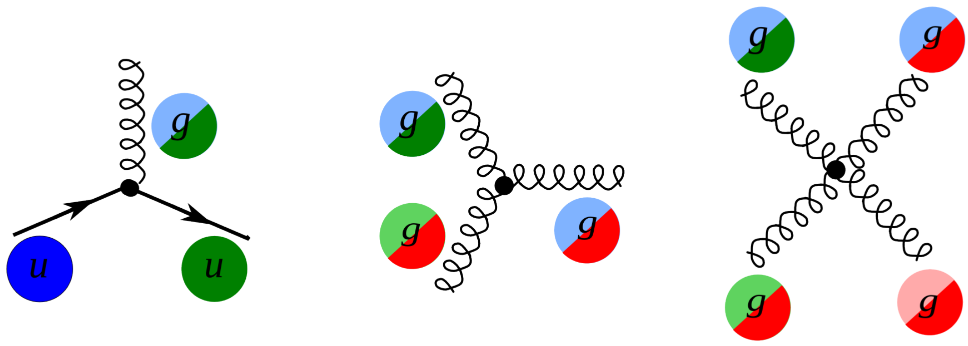

Figure 5: Strong interations

The strong interactions are performed by exchanging a gluon. Only particles which possess a color charge can participate in the strong interactions (quarks, antiquarks, and gluons). There are eight types of gluons corresponding to different color-anticolor combinations. Gluons are spin-one massless electrically neutral particles. Gluons possess color charges, therefore, they can self-interact.

The elementary strong processes are shown in Fig. 5. There are three elementary processes: qqg, ggg and gggg. Both electrical and color charges must be conserved at each vertex.

The coupling constant of the strong interaction depends on a distance between interacting particles: it becomes larger as the distance becomes smaller. This property leads to two consequences: the confinement and the asymptotic freedom.

The confinement comes from the fact that the interaction at large distances becomes stronger. That makes quarks always stay in the colorless combinations (hadrons). A combination becomes colorless when there is the same amount of color and anticolor or if there is the same amount of each of the three colors. Mesons are comprised of a quark and antiquarks with the opposite color charges. The baryons are comprised of three quarks: a red, a green and a blue one.

The asymptotic freedom means that when quarks are very close to each other they almost do not interact with each other and therefore they are free.

When the distance between quarks is low which corresponds to high energy, and thus the coupling constant $1/\alpha_s \ll 1$ is low, the strong interactions can be described by a perturbative theory which is called quantum chromodynamics (QCD). When the coupling constant is large, it is not possible to use a perturbative theory.

1.5 Physcis of Proton-Proton Collisions

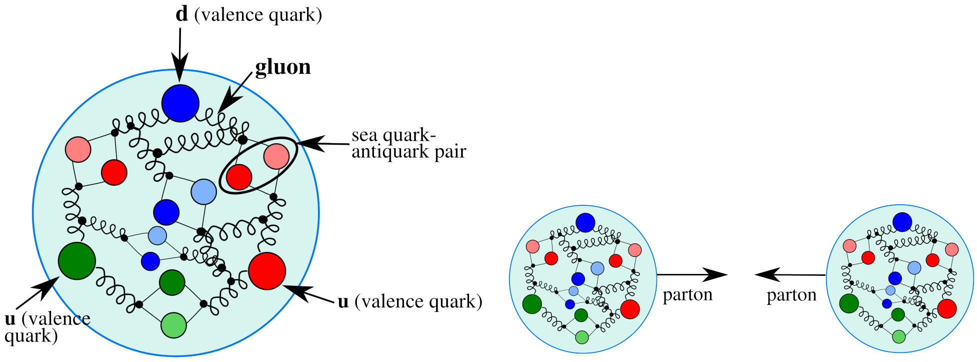

Figure 6: The proton structure (left) and the proton-proton collision (right).

The schemes of the proton structure and a proton-proton collision are shown in Fig. 6. A proton consists of three quarks: uud. An electric charge of a proton is a sum of the quarks charges: Q=+2/3+2/3-1/3=1. The situation with the mass is different: the mass of a u quark is 6 GeV and the mass of a d quark is 3 GeV while the mass of a proton is 940 GeV. The mass of a proton is an invariant mass of a system of the quarks which is mostly comprised of their kinetic energy. These three quarks are called valence quarks. They interact with each other by exchanging gluons. Gluons emit other gluons and produce $q\bar{q}$ pairs. Such virtual quarks are called sea quarks.

If two low energetic protons interact, it corresponds to the large distance between them and such protons do not probe one another's structure. They see each other as colorless electrically charged particles and therefore interact electromagnetically by exchanging a photon. Protons of higher energy see one another's intrinsic structure: its constituents, quarks, antiquarks and gluons, interact strongly with each other. Valence quarks, as well as sea quarks and antiquarks, can participate in the couplings.

In LHC collisions quark-(anti)quark, gluon-(anti)quark, gluon-gluon interactions are all possible however at such high energies, gluon-gluon interactions are prevalent. That is why the LHC sometimes is being called the gluon collider.

One important specific of high energetic proton collisions is the fact that an interacting particle possesses only part of a proton energy and momentum. Therefore, the energies and longitudinal momenta of the initial state particles are unknown. Although, the total transverse momenta is known to be equal to zero.

1.6 Open Questions of the Standard Model

While the Standard Model is an accurate description of all particle physics experimental results, there are certain things which are not included into the SM and it is possible that the SM is working only within certain restrictions and there is a more general extension which would explain everything.

First of all, gravitational interactions do not fit into the Standard Model. It is the open question whether the quantum theory of gravity is possible and whether there is a mediator of the gravitational interactions. Also, it is not known why the gravitational force is so much weaker than any other force. One possible explanation comes from the theory which predicts extra spatial dimensions beyond the three we are dealing with (the string theory). In this case, it is possible that the gravitational force is shared with other dimensions and that is why the fraction available in our regular three dimensions is that small.

Another mystery of the Universe is its composition: it is known from the studies of the gravitational effects that our Universe consists of dark energy by 70%, by dark matter by 26% and by baryon matter only by 4%. Dark matter is a substance interacts with the baryon matter by gravitational effects only however it does not radiate and that is why it can not be detected by telescopes. The nature of the dark matter is not known but it must be something very stable to remain since the Big Bang. The theory of the supersymmetry which is unifying fundamental particles and mediators predicts many of new heavy particles and the lightest supersymmetric particle, the neutralino, is a good candidate for the dark matter.

The dark energy resists the gravitational attraction and accelerates the expansion of the Universe and is also not detectable by any effects except gravitational.

One more open question is the reason for the matter/antimatter asymmetry. The matter and antimatter should have been created in the same amount. Then most of it has annihilated but because of asymmetry, there was more matter than antimatter which leads to the creation of the whole Universe. There is a phenomenon of the CP-violation in weak interactions observed and described, it predicts the asymmetry at a certain level. However, the effect of the CP-violation is not enough to account fot the observed amount of the matter and therefore the total matter/antimatter asymmetry remains unexplained.