Thesis

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Abstract

This paper reviews

Contents

1 Introduction

Elementary particle physics describes our world in terms of its smallest constituents, elementary particles, and their interactions.

Surrounding matter consists of chunks and as we go to smaller and smaller scale, it consists of fundamental particles which cannot be split any further. Substances around us consist of molecules, 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, therefore, an electron is a fundamental particle.

Interactions of elementary particles are described by quantum field theories which incorporate principles of the quantum mechanics and the special theory of relativity. The collection of such theories which describe the behavior of elementary particles, including quantum elecrtrodynamics, quantum chromodynamics and the theory of weak interactions is called the Standard Model. It has been proven to be an appropriate description of interactions of elementary particles observed by now. The accuracy of the SM is as good as or better than experimental results.

However, there are several experimental observations which are not described by the SM such as gravity, dark matter, dark energy, matter/antimatter asymmetry and others. Therefore, the SM is not the complete theory of particle interactions but one which is working in the experimental conditions available. There are several SM extensions offered by theorists as well as radically new theories waiting for the experimental confirmation or disproval.

Some SM extensions and new theories predict the existence of heavy particles mass of which possibly lays beyond the discovered energy threshold. The search of these particles is one of the prioritized directions in particle physics. For such searches we need to reach higher energies which were probed before. One source of highly energetic elementary particles is cosmic rays. The most energetic particles ever came from this source. However, cosmic rays are totally uncontrollable and such highly energetic particles are rare. If we want to produce a large amount of particles at certain energies, we need to use a particle accelerator. A large amount of events at certain energy allows to perform a statistical analysis and increase the probability to find a new particle if it exists in the given energy range.

To produce as heavy particles as possible, symmetric colliding beams work the best because the total momentum of two symmetrically colliding particles is zero and the whole energy can potentially go to the production of new particles. 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 a collision point. CMS has a wide physics program including searches for different SM extensions as well as the precision measurements of the SM parameters themselves.

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 (Fig. 1).

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. The presence of the aTGC would be an indirect indication of new particles.

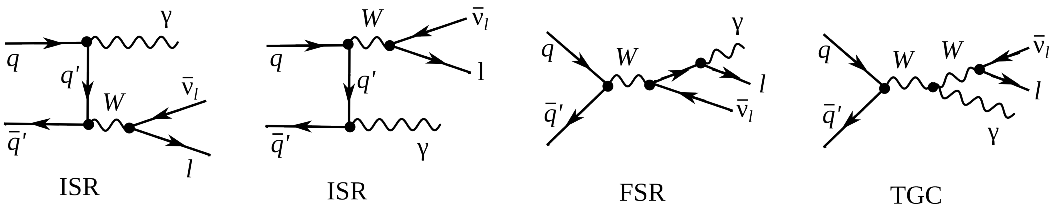

Figure 1: Feynman diagrams of Wγ production

1.1 Fundamental Particles and Interactions

The SM describes interactions of elementary particles. There are four fundamental interactions: electromagnetic, strong, weak and gravitational. The gravity 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 the particle physics even without having the gravity included into the model.

All fundamental elementary particles in the SM can be split into two cathegories: fermions and bosons.

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). Each quark is present in three colors: red, blue and green. And each fermion has its antiparticle. Therefore, the total number of fundamental fermions if $(6(leptons) + 6(quarks) \cdot 3(colors)) \cdot 2(toincludeantiparticles) = 48$.

Corresponding particles in different generations have the same charges, spins and interaction properties but higher generation particles have larger masses compared to the corresponding lower generation particles. These mass differences lead to different decay properties because a particle A can decay to particles B and C only if the mass of A m_A
$llm_B + m_C$. Thus, an electron is a stable particle, a muon decays as $\mu^- \to e^- + \bar{\nu_e} + \nu_\mu$, a tau-lepton, as the heaviest charged lepton, has the largest number of decay channels: $\tau^- \to \mu^- + \bar{\nu_\mu} + \nu_\tau$, $\tau^- \to e^- + \bar{\nu_e} + \nu_\tau$, $\tau^- \to \nu_\tau +$ quarks.

In addition to fermions, the SM includes gauge bosons which are mediators for the SM interactions. Gluons are mediators of the strong interactions, there are eight of them. 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.

Bosons included into the SM are mediators of different interactions. A photon is a mediator for the electromagnetic interactions, a gluon is a mediator of strong interactions, and $W^\pm$ and Z^0 bosons are mediators of the weak interactions. $W^\pm$ and Z^0 bosons are massive while photon and gluon are massless particles.

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

All the particles are summarized in Fig. 2. 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.

Most of the particles are short-lived and decay 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. There are many different kinds of reactions in which particles can dissapear. Antiprotons and positrons would immediately annihilate with protons and electrons in the presence of a substance, photons can be absorbed by charged particles, electrons and protons can annihilate to produce neutrons and neutrinos and many other reactions are possible.

The measurement in this dissertation studies a process where quark and antiquark annihilate to produce a W boson which then decay as $W^\pm \to e \pm \nu_e(\bar{\nu_e})$ or $W^\pm \to \mu \pm \nu_\mu(\bar{\nu_\mu})$. A photon is radiated off a quark or antiquark, a charged lepton or a W boson. The most interesting mechanism out of three is a radiation from a W boson because this is the triple gauge coupling where we potentially can have a new physics. Therefore, out of all SM fundamental particles, in this measurement we mostly study a photon and a W boson, also we have lepton and quarks in our process and it is important for us to know basic properties of many other fundamental particles too.

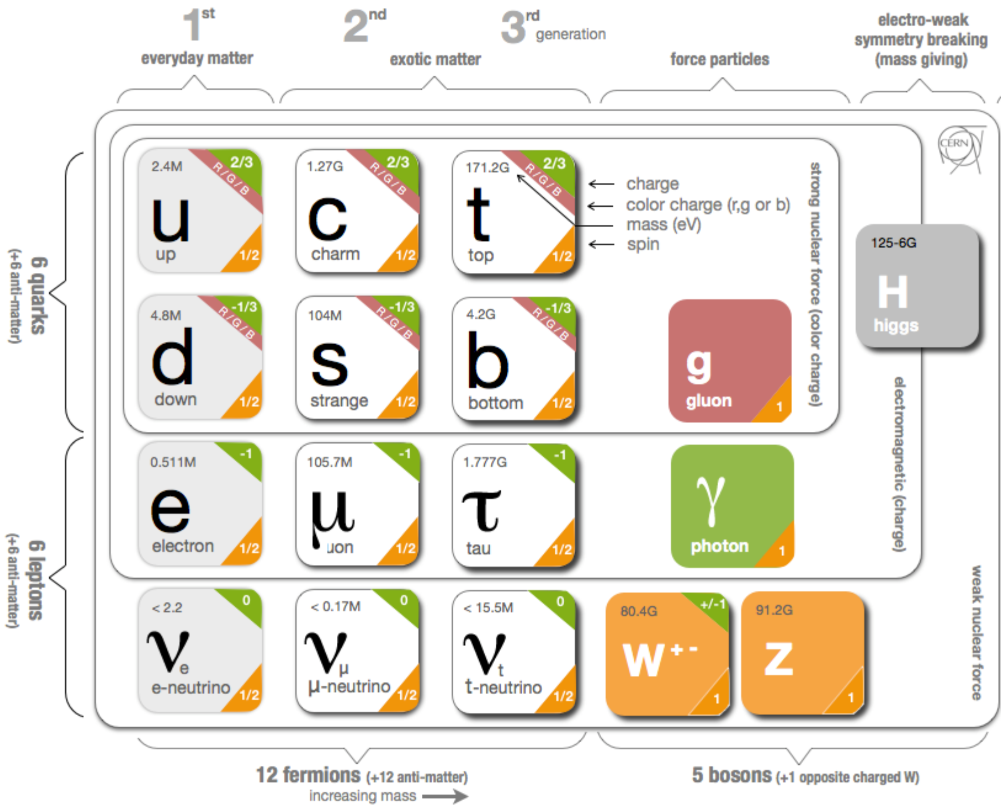

Figure 2: Standard Model Particles and Interations

1.2 Electroweak Interactions

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. 3, 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 particle 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. 3, middle and right). Such graphical representations of the particle physics processes are called Feynman diagrams.

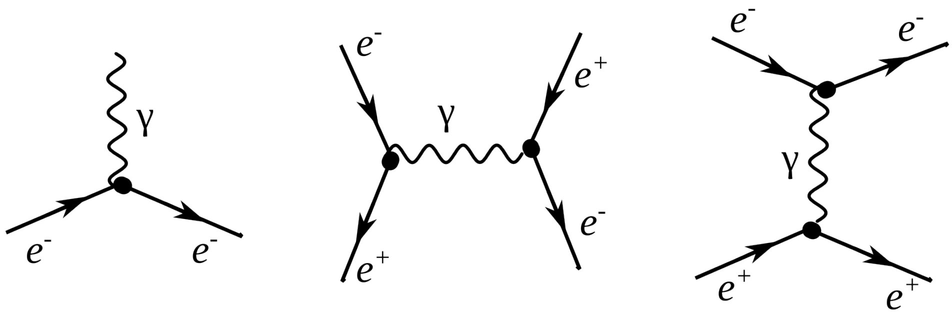

Figure 3: Electromagnetic interations

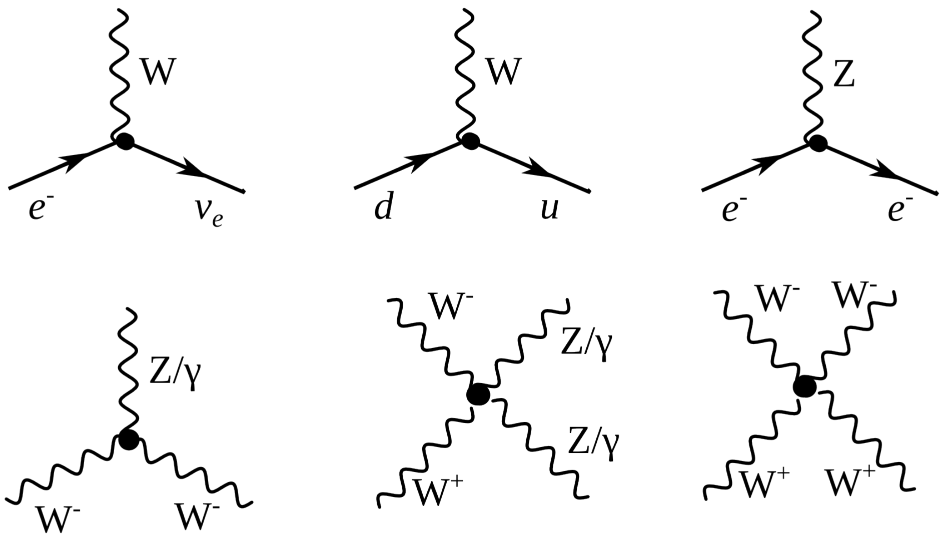

Figure 4: Weak interations

As for the weak interactions, there are two kinds of them: neutral (mediated by a Z boson) and charged (mediated by a W$\pm$ boson). Elementary processes with W and Z bosons are shown in Fig. 4. Because the electric charge must be conserved at any vertex, a particle radiating or absorbing a W boson converts to a different particle. Thus, a charged lepton converts to a neutrino (or vice versa) as shown in Fig. 4, top left. A lepton flavor number is always conserved in such interactions (lepton flavor numbers assigned to different lepton are summarized in Tab. 1), thus an electron always converts to an electron neutrino, a muon always converts to a muon neutrino etc.

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. 4 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 quark 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).

An elementary process of a neutral weak interactions is an emission of a Z boson off a fermion line (right top diagram in Fig. 4). An electron is shown here as an example however it also could be any lepton, antilepton, quark or antiquark. Diagrams with a Z boson are very similar to ones with a photon except a photon can only be radiated off a charged particle but a Z boson can also be radiated off a neutrino or antineutrino.

The bottom diagrams in Fig. 4 are gauge coupling diagrams. Gauge couplings include 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. This theory considers these two forces as different manifestations of the electroweak force. While both forces can be described by very similar formalism, there is also a big difference between them: weak interactions are mediated by heavy bosons (M_W = 80 GeV, M_Z = 91 GeV) while electromagnetic interactions are described by a massless photon.

To explain this phenomenon, the Higgs mechanism was introduced. The mechanism predicted an existence of an additional boson - the Higgs boson. The Higgs boson was a missing piece of the SM for many years and was finally discovered in 2012 at the LHC by ATLAS and CMS collaborations through the processes shown in Fig.5.

The measurement in this dissertation is an electroweak measurement because the process involves a W boson. It includes an interaction of a W boson with leptons and quarks as well as the gauge coupling WWγ. Thus, the measurement is a good test of the SM electroweak theory.

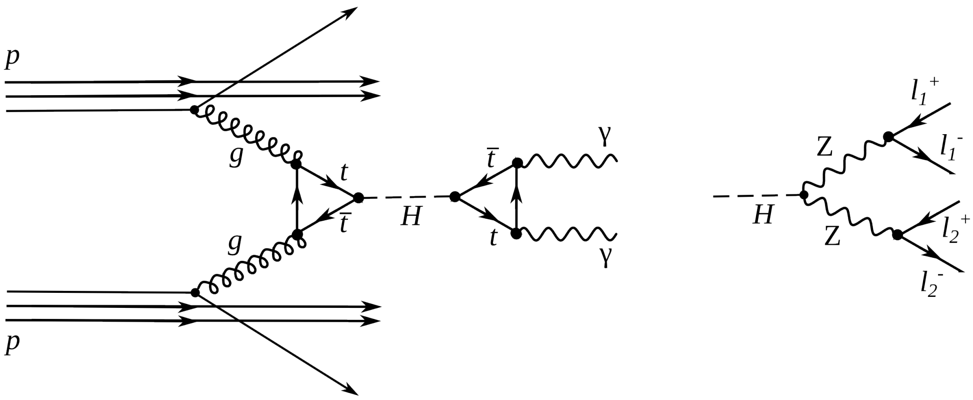

Figure 5: Higgs production and decay

1.3 Strong Interactions

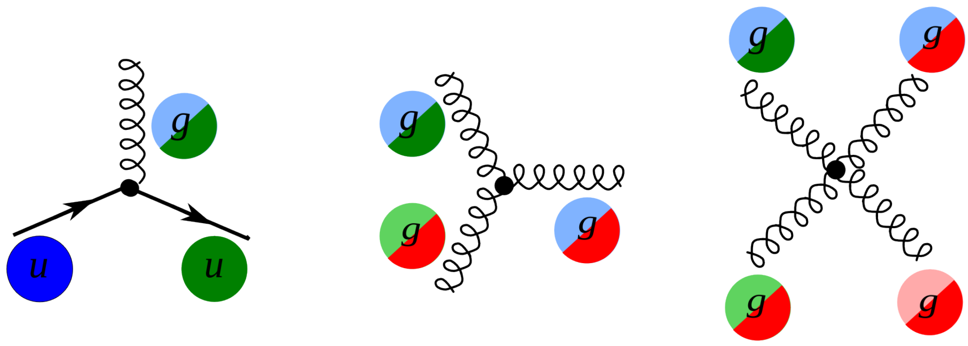

Figure 6: Strong interations

The third fundamental force after the electromagnetic and weak ones is the strong force. The strong force is responsible for glueing protons and neutrons together in the nuclea as well as for forming protons and neutrons themselves. The strong interactions are performed by exchanging gluons which are spin-one massless electrically neutral particles.

The elementary strong processes are shown in Fig. 6. There are three elementary processes: qqg, ggg and gggg, all are involving particles with color charges. Thus, gluons couple to quarks and self-couple. Color charges must be conserved at each elementary process of the strong interaction. And because quarks can possess three colors, there are eight types of gluons to cover all possible color exchanges.

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

The confinement is the property of quarks to always stay in the colorly neutral combinations (hadrons), it forbids the existence of free quarks. A combination becomes colorly neutral when there is the same amount of color and anticolor or if there is the same amount of each of the three colors. There are two types of hadros: mesons (comprised of a quark and antiquarks with the opposite color charges) and baryons (comprised of three quarks: a red, a green and a blue one). The widely known particles a proton and a neutron are baryons.

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 quantum field theory which is called quantum chromodynamics (QCD).

The Wγ process being measured in this dissertation is not intended to test QCD, but a good understanding of QCD is essential for performing this measurement. First of all, QCD describes the dynamics of quarks and gluons within colliding protons and predicts probabilities of one or another quark-antiquark pair to annihilate. Secondly, the QCD corrections to the Feynman diagrams of the process are large and has to be taken into account in producing simulation. Possible QCD correction include quark-gluon loops at any of three quark lines as well as exchanges of gluons between different quark lines.

1.4 Physcis of Proton-Proton Collisions

A proton is a baryon, it consists of three quarks: uud. These three quarks are called valence quarks. They interact with each other by exchanging gluons which can produce virtual $q\bar{q}$ pairs (Fig. 7). Such quarks are called sea quarks.

The dymanics of proton interactions depend on the protons energies. 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 partons (quarks, antiquarks and gluons) interact strongly with each other.

Any parton from one proton can interact with any parton from another proton. QCD describes probabilities of any particular constituent to interact depending on the total momentum transfer and a momentum fraction of a specific parton. These probabilities are called P.D.F. (parton distribution functions). P.D.F. depend on a collider energy and for LHC gluon-gluon interactions have the largest probabilities to occur.

However, in Wγ measurement we are only selecting events with original partons which can produce a W boson. Gluons do not couple directly to a W boson, thus, we are only interested in quark-antiquark pairs which would have a total charge corresponding to the charge of a W boson (± 1). Since we have u and d as valence quarks and we know that the probability to couple to the same generation quark in charged weak interactions is the highest, most of the W bosons are created by $u\bar{d}$ and $d\bar{u}$ pairs however other $q\bar{q}'$ combinations with the total charges of ± 1 are also possible.

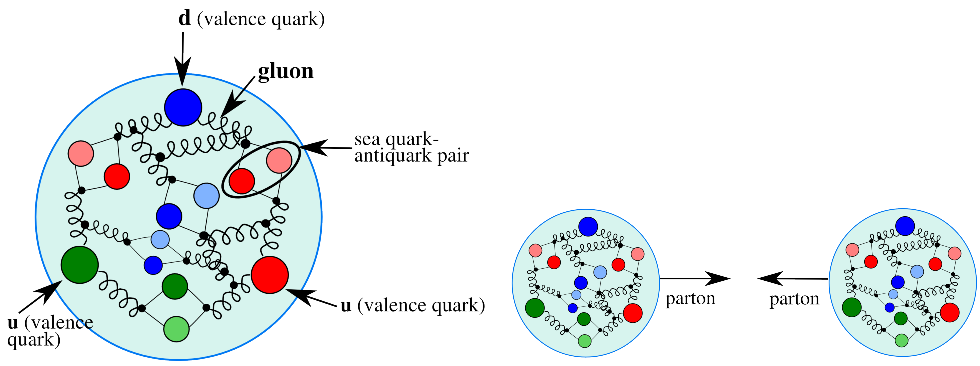

Figure 7: The proton structure (left) and the proton-proton collision (right).

1.5 Open Questions of the Standard Model

While the Standard Model is an accurate description of all particle physics experimental results, there are certain phenomena which are not included into the SM.

Thus, 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 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%. The dark energy resists the gravitational attraction and accelerates the expansion of the Universe and is not detectable by any effects except gravitational. The understanding of the dark energy is a question of a general relativity rather than a particle physics. The dark matter however likely consists of particles and therefore is a subject of a particle physics. The dark matter is a substance which interacts with the baryon matter by gravitational effects only. 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 its constituents must be 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.

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 led 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 for the observed amount of the matter and therefore the total matter/antimatter asymmetry remains unexplained.

The measurement of this dissertation has a goal to both test the SM and search for a physics beyond the SM. Since it is the measurement of the photon transverse momentum spectrum (P_T^γ), the low P_T^γ region is well-described and must agree well with the SM predictions while the high P_T^γ region may indicate an existence of a new physics if there is an anchance over the SM predictions. More theoretical details about the SM descriprion of Wγ process as well as the possible beyond the SM physics are given in the next chapter.