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# Thesis

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## Abstract

This paper reviews

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# 1 Introduction

Elementary particle physics describes our world in terms of its smallest constituents, fundamental particles, and their interactions. Going from larger to smaller scales, 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 an example of a particle which is considered to be fundamental.

Interactions of elementary particles are described by quantum field theories which incorporate principles of the quantum mechanics and the special theory of relativity. The set of such theories, including quantum electrodynamics, quantum chromodynamics and the theory of weak interactions is called the Standard Model (SM). It has been proven to be an accurate description of interactions of elementary particles observed by now.

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. There are several SM extensions offered by theorists as well as radically new theories waiting for the experimental confirmation or disproof.

Some SM extensions and new theories predict the existence of heavy particles mass of which possibly lies beyond experimentally reachable energies. 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 observed came from this source. However, cosmic rays are totally uncontrollable and such highly energetic particles are rare. If we want to produce a large number of particles at certain energies, we need to use a particle accelerator. A large number of events at certain energy allows experimentalists to perform a statistical analysis and increase the probability of finding a new particle if it exists in the given energy range.

Symmetric colliding beams is the most effective way to produce as heavy particles as possible given the energies of the colliding particles. The Large Hadron Collider (LHC) is such a collider with the highest energy in the world ever built. 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 design center-of-mass energy of is 14 TeV but it also probes several lower energy points and may go higher.

Compact Muon Solenoid (CMS) is one of two general-purpose detectors at the LHC. It is placed at one of six collision points. CMS has a wide physics program including searches for different SM extensions as well as the precision measurements of the SM parameters themselves. The chapter 3 describes LHC and CMS in more details.

In this dissertation the analysis of  $pp \rightarrow W\gamma + X$  processes using leptonic decays of  $W \rightarrow \ell\nu$  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 where a photon is produced from one of the incoming partons, final state radiation 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.

To search for the deviations from the SM, one would search for an anomalous TGC which would be indicated by the enhance of the TGC production over the SM prediction.

The total and the differential cross section with respect to the photon transverse momentum ( $P_T^\gamma$ ) has been measured. The  $P_T^\gamma$  is sensitive to the potential anomalous TGC in the high  $P_T^\gamma$  region. The disagreement between the measured and theoretically predicted differential cross

79 section at the higher  $P_T^\gamma$  end would be an indication of the possible presence of the anomalous  
80 TGC. The theoretical descriptions of the SM and anomalous TGC  $W\gamma$  productions are available  
81 in the chapter 2 of this dissertation. Chapter 5 describes the details of the measurement and  
82 reports the results.

83

## 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 a theory of the particle physics and conduct experiments even without having the gravity included into the model.

All fundamental elementary particles in the SM can be split into three categories by their spins. There are fermions possess spin  $s=1/2$ , there are gauge bosons which are also called force mediators are vector particles ( $s=1$ ) and there is the Higgs boson which is a scalar particle ( $s=0$ ).

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 charged lepton with  $Q=-1$  (electron, muon, tau-lepton) and a neutrino (electron, muon or tau) which is electrically neutral. Each quark can carry any of three colors: red, blue and green. Additionally, each fermion has its antiparticle. Therefore, the total number of fundamental fermions is  $(6(\text{leptons}) + 6(\text{quarks}) \cdot 3(\text{colors})) \cdot 2(\text{to include antiparticles}) = 48$ .

Corresponding particles in different generations have the same charges, spins and interaction properties but masses of particles increase with a generation. 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  $m_A > m_B + m_C$ . Thus, an electron is a stable particle, a muon decays as  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ , a tau-lepton, as the heaviest charged lepton, has the largest number of decay channels:  $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$ ,  $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$ ,  $\tau^- \rightarrow \nu_\tau + \text{quarks}$ .

In addition to fermions, the SM includes gauge bosons which are mediators for the SM interactions. A photon is a mediator for the electromagnetic interactions, a gluon is a mediator for the strong interactions, and  $W^\pm$  and  $Z^0$  bosons are mediators for 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. The Higgs boson is a scalar neutral particle which is playing a critical role in the electroweak symmetry breaking. The Higgs mechanism describes how  $W$  and  $Z$  bosons become massive particles.

All the particles are summarized in Fig. 1. These and only these fundamental particles and their antiparticles have been discovered by now. 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, in some sense, 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 disappear. Antiprotons and positrons would immediately annihilate with protons and electrons, photons can be absorbed by charged particles, electrons and protons can interact and disappear to produce neutrons and neutrinos and many other reactions are possible.

In this dissertation a process is studied where quark and antiquark interact to produce a  $W$  boson which then decay as  $W^\pm \rightarrow e^\pm \nu_e(\bar{\nu}_e)$  or  $W^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$ . 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, the focus of this study is an interaction between a photon and a  $W$  boson however many other SM particles are relevant too. Thus, a charged lepton and a neutrino appear as the final state particles, a quark and an antiquark appear as initial state particles and all fundamental particles except the Higgs boson participate in the various back-

ground processes. Subsections 1.2-?? and chapter 2 describe particle interactions in more details.

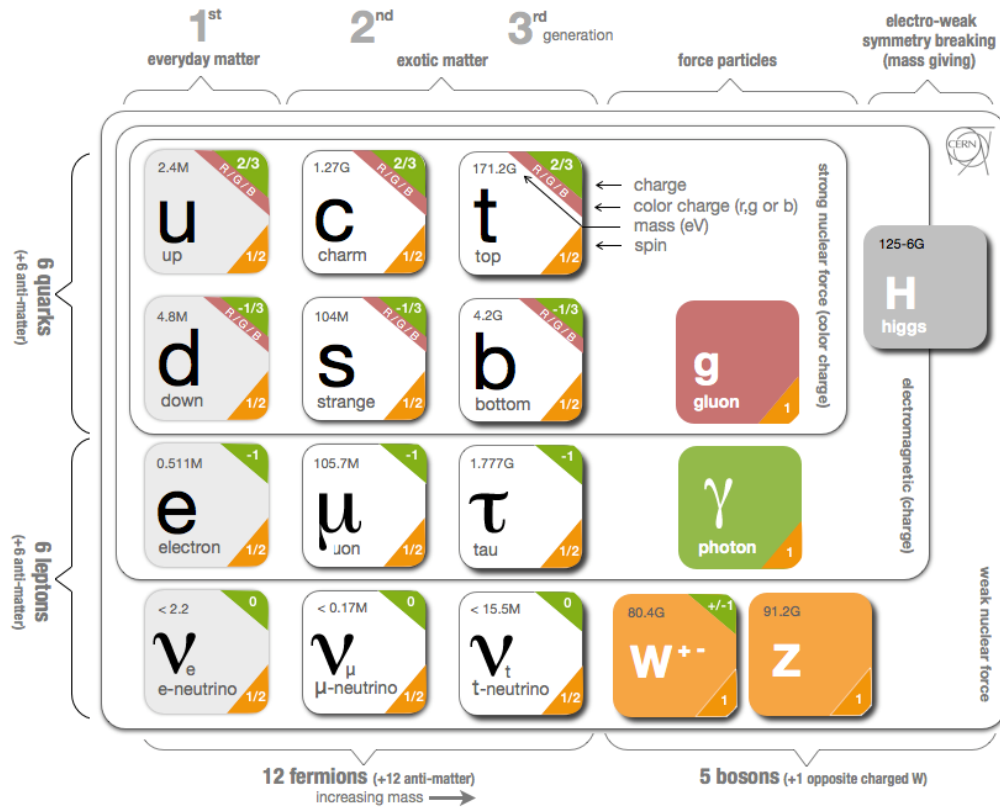


Figure 1: Standard Model Particles and Interactions

## 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. 2, left). This process represents an electron radiating or absorbing a photon. Although 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. 2, middle and right). Such graphical representations of the particle physics processes are called Feynman diagrams.

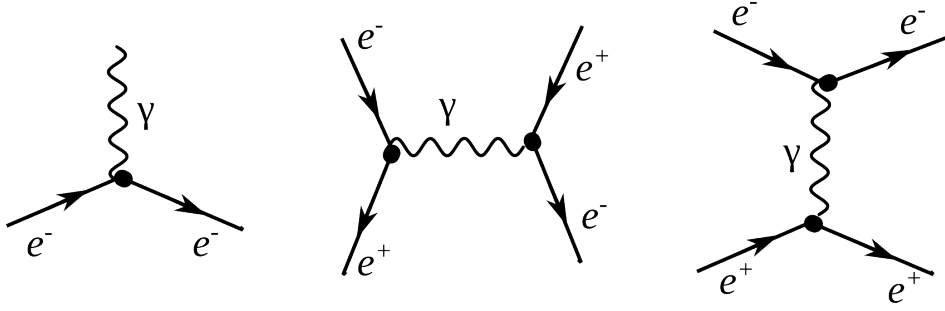


Figure 2: Electromagnetic interactions

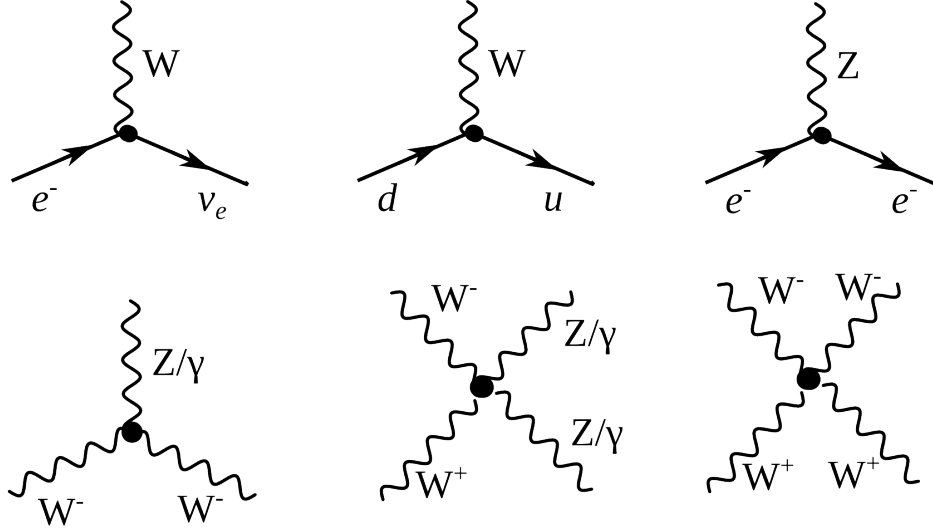


Figure 3: Weak interactions

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. 3. 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. 3, top left. Each lepton carries a lepton flavor number (Tab. 1). A lepton flavor number is conserved in any interaction, thus an electron radiating a  $W$  boson always converts to an electron neutrino, a muon converts to a muon neutrino etc.

Table 1: Lepton Flavor Number

particles	$L_e$	$L_\mu$	$L_\tau$
$e^-, \nu_e$	+1	0	0
$e^+, \bar{\nu}_e$	-1	0	0
$\mu^-, \nu_\mu$	0	+1	0
$\mu^+, \bar{\nu}_\mu$	0	-1	0
$\tau^-, \nu_\tau$	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 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. 3). An electron is shown here as an example however it could also 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. 3 are gauge bosons coupling diagrams including self-coupling of a  $W$  boson, its interaction with a  $Z$  boson and its electromagnetic radiation of a photon.  $WWZ$ ,  $WW\gamma$ ,  $WWZZ$ ,  $WWZ\gamma$ ,  $WW\gamma\gamma$  and  $WWWW$  vertices are all possible in the SM.

Electromagnetic and weak interactions are unified by the electroweak Glashow-Weinberg-Salam (GWS) theory which is based on  $SU(2) \times U(1)$  symmetry.  $SU(2)$  is the symmetry of weak isospin which generates three bosons:  $W^1$ ,  $W^2$  and  $W^3$ .  $U(1)$  is the symmetry of the weak hypercharge and generate one neutral boson  $B$ .  $W^1$  and  $W^2$  are mixed to create  $W^+$  and  $W^-$  mediators while  $W^3$  and  $B$  are mixed to create a  $Z$  boson and a photon. Therefore, the GWS theory considers electromagnetic and weak forces as different manifestations of the electroweak force.

However, weak interactions are mediated by heavy bosons ( $M_W = 80$  GeV,  $M_Z = 91$  GeV) while electromagnetic interactions are mediated by a massless photon, thus, the electroweak symmetry is broken. 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 LHC by ATLAS and CMS collaborations through the processes shown in Fig.4.

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

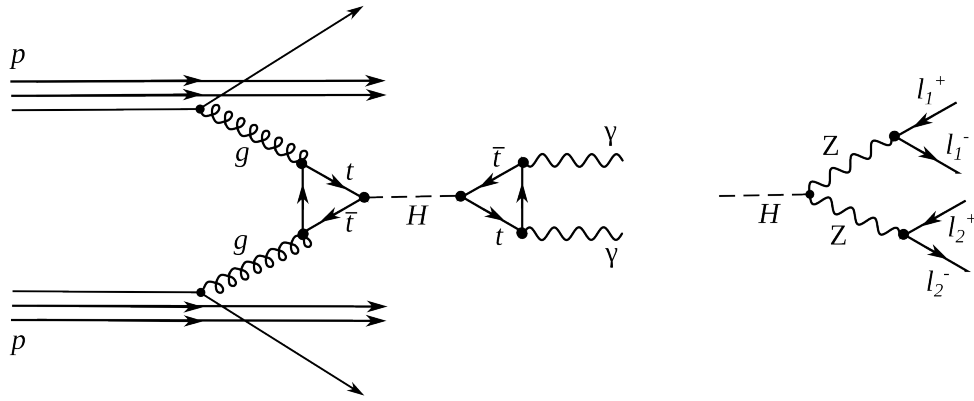


Figure 4: Higgs production and decay

193 triple gauge coupling  $WW\gamma$ . Thus, the measurement is a good test of the SM electroweak theory.  
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### 1.3 Strong Interactions

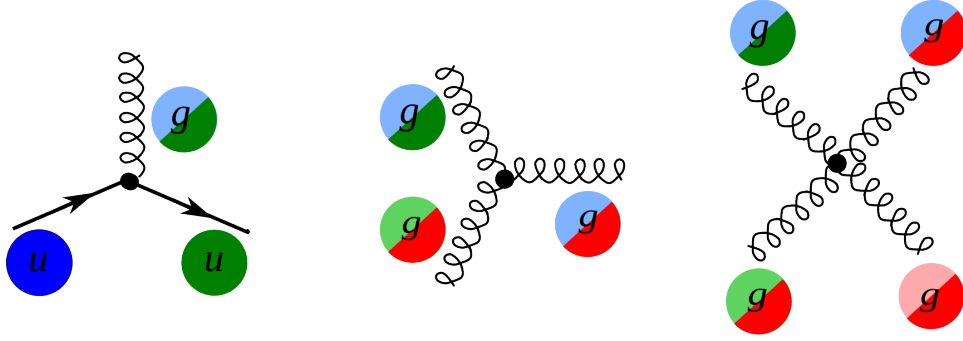


Figure 5: Strong interactions

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 nuclei as well as for forming protons and neutrons themselves. The strong interactions occur by exchanging gluons which are spin-one massless electrically neutral particles.

The elementary strong processes are shown in Fig. 5. There are three elementary processes:  $q\bar{q}g$ ,  $ggg$  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. 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 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. The confinement is the property of quarks to always stay in the color 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. Thus, mesons are comprised of a quark and antiquarks with the opposite color charges, and baryons are comprised of three quarks: a red, a green and a blue one. Examples of baryons include such well-known particles as a proton and a neutron are baryons.

The strong interactions can be described by the quantum chromodynamics (QCD). QCD is a quantum field theory invariant under  $SU(3)$  color transformations. When the distance between quarks is small which corresponds to high energy, and thus the coupling constant  $\alpha_s \ll 1$  is small, the perturbative approach can be used to compute observables.

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

## 1.4 Physcis of Proton-Proton Collisions

At LHC two protons are collided. The LHC energy is so high that a proton behaves as a complex structure. 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. 6). Such quarks are called sea quarks.

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) (Fig. ??). P.D.F. depend on a collider energy and for LHC gluon-gluon interactions have the largest probabilities to occur.

However, gluons do not couple directly to a W boson, thus, in the  $W\gamma$  measurement we are only interested in quark-antiquark pairs which would have a total charge corresponding to the charge of a W boson ( $\pm 1$ ). 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  $\pm 1$  are also possible. The antiquarks come from virtual  $q\bar{q}$  pairs inside of each proton.

As we look for events containing  $W\gamma$  we also have other events mimicing our process. Such background events can be produced by any pair of partons.

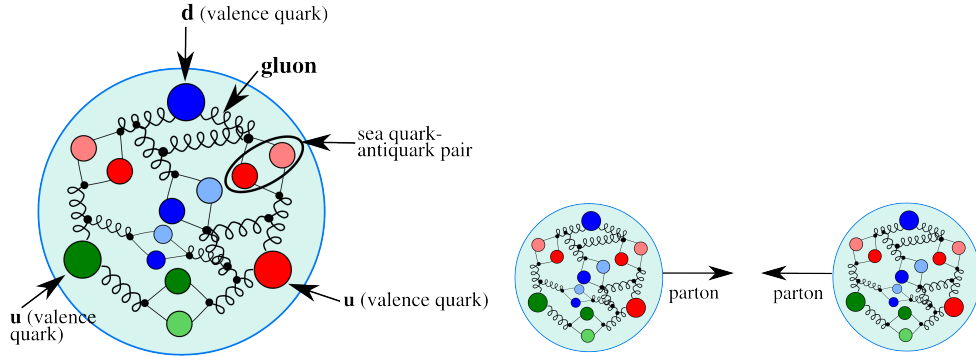


Figure 6: The proton structure (left) and the proton-proton collision (right).

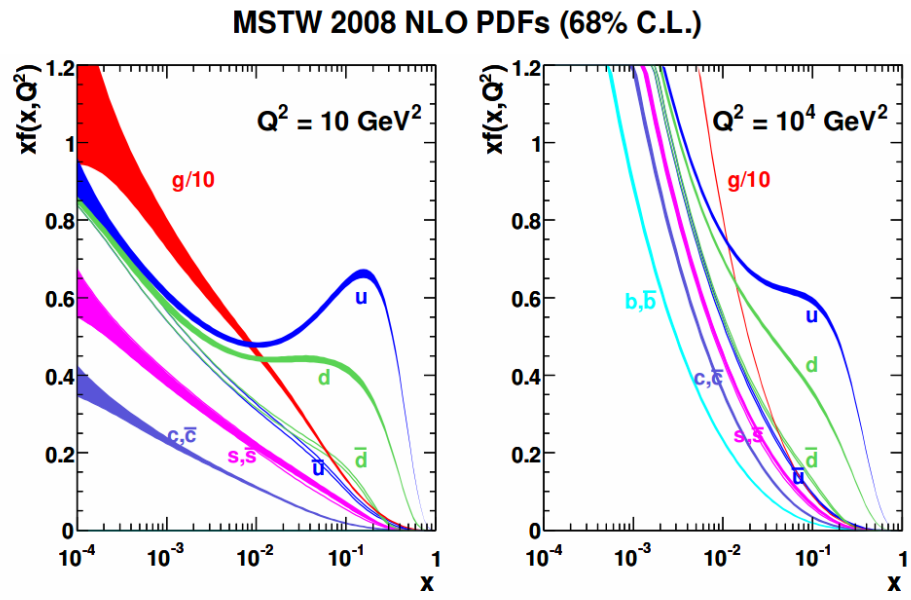


Figure 7: Martin-Stirling-Thorne-Watt Parton Distribution Functions [?]

## 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. In this subsection we discuss some of them.

The 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 a theory which predicts extra spatial dimensions beyond the three we are dealing with (e.g. 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%, of dark matter by 26% and of 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 the general relativity rather than the particle physics. The dark matter however likely consists of particles and therefore is a subject of the particle physics. It does not radiate and that is why it cannot 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 that 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 the photon transverse momentum spectrum ( $P_T^\gamma$ ) of the  $W\gamma$  process has a goal to both test the SM and search for a physics beyond the SM. The low  $P_T^\gamma$  region is not expected to have any new physics and must agree well with the SM predictions while the high  $P_T^\gamma$  region may indicate an existence of a new physics if there is an enhance over the SM predictions. The enhance may come from supersymmetric particles or other theories with additional gauge bosons. More theoretical details about the SM description of  $W\gamma$  process as well as the possible beyond the SM physics are given in the chapter 2.

## 297   **2   The $W\gamma$ Process**

## 2.1 Standard Model $W\gamma$ Production

A  $W$  boson in the proton-proton collisions can be produced in the processes  $q\bar{q}' \rightarrow W$  where  $q$  and  $\bar{q}'$  are a quark and an antiquark which have a total charge of +1 if producing a  $W^+$  boson or of -1 if producing a  $W^-$  boson. The processes  $u\bar{d} \rightarrow W^+$  and  $d\bar{u} \rightarrow W^-$  are the most likely to occur because  $u$  and  $d$  are valence quarks in a proton. Antiquarks  $\bar{d}$  and  $\bar{u}$  come from sea  $q\bar{q}$  pairs of the other proton.

Decay modes of a  $W$  boson include  $W^\pm \rightarrow l^\pm \nu_l(\bar{\nu}_l)$  where  $l^\pm = e^\pm, \mu^\pm$  or  $\tau^\pm$  with branching fractions of 11% per a leptonic channel [6]. The rest 67% stands for various  $W \rightarrow q\bar{q}'$  decays. In this dissertation we only consider  $W^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu)$  and  $W^\pm \rightarrow e^\pm \nu_e(\bar{\nu}_e)$  as the cleanest channels.

Mass of a  $W$  boson  $M_W = 80 \text{ GeV}$  is much larger than masses of its decay products:  $M_\mu = 105 \text{ MeV}$ ,  $M_e = 0.5 \text{ MeV}$ ,  $M_\nu < 2 \text{ eV}$ . Therefore, almost all mass of a  $W$  boson converts to the kinetic energy of a muon(electron) and a neutrino.

A photon can be emitted from any charged particle of the process: a quark, an antiquark, a charged lepton or a  $W$  boson (Fig. 8, top). A quark and an antiquark are initial state particles and, therefore, if one of them radiates a photon, we call such process the Initial State Radiation (ISR). A muon or an electron is a final state particle and if it radiates a photon, we call such process the Final State Radiation (FSR). Finally, a  $W$  boson is a gauge boson and if it radiates a photon, the process has a vertex with three gauge bosons:  $WW\gamma$ , and we call such process the Triple Gauge coupling (TGC).

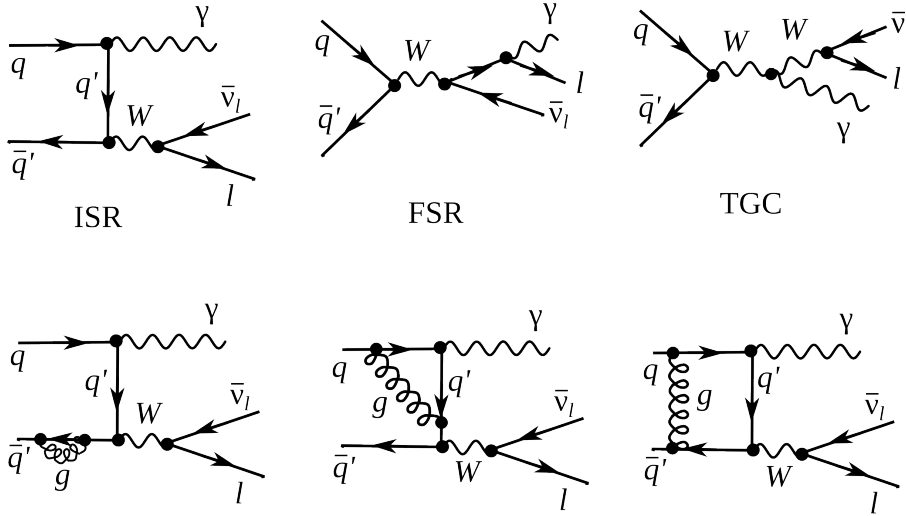


Figure 8: Feynman diagrams of  $W\gamma$  production

In this dissertation we are measuring the total and the differential cross section.

The cross section of an interaction of two particles can be interpreted as an area around one of the particles which has to be crossed by the other particles so that these two particles would interact. The cross section characterizes the probability of two particles to interact. In the narrower case, the probability of two particles to interact in the exactly way to give a given final state.

A number of particles passing through the area  $d\sigma$  per unit time is  $dN = L \cdot d\sigma$ , where  $L$

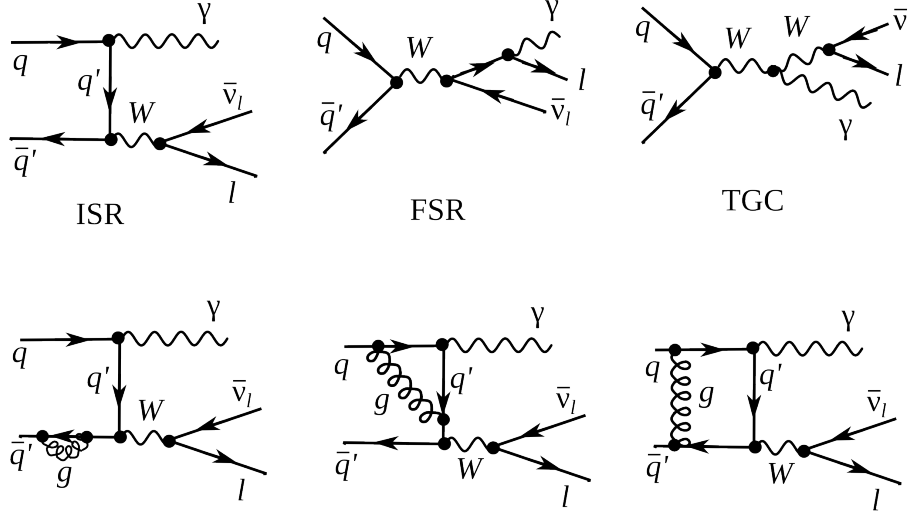


Figure 9: Illustration of the differential cross section concept in the classical case

is the luminosity (the number of particles passing through the unit area per unit time). This expression is used to measure the cross section in collision experiments. The actual quantity which can be measured is a number of events of a given process and the luminosity is determined by collider characteristics.  $L$  may not be uniform in time however we are usually interested in measuring the total or differential cross section as a function of a certain kinematic parameter of a final state particle or of a system of final state particles.

However, to measure the cross section we need to know total number of events of the given process but we cannot detect events which are out of the detector acceptance or which do not fall into the selection criteria we are using in the analysis. Therefore, the number of events  $dN$  has to be corrected in a measurement:  $dN \rightarrow \frac{dN}{A \cdot \epsilon}$ , where  $A$  is a detector acceptance and  $\epsilon$  is an efficiency of a signal process to pass selection conditions. Other corrections to  $dN$  may have to be applied depending on the analysis.

To compute a cross section theoretically, one has to use Fermi's Golden rule which for the scattering of two particles

$$1 + 2 \rightarrow 3 + 4 + \dots + n$$

has the following form:

$$\sigma = \frac{S\hbar^2}{4\sqrt{(p_1 p_2)^2 - (m_1 m_2 c^2)^2}} \int |M|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4 - \dots - p_n) \prod_{j=3}^n \frac{1}{2\sqrt{p_j^2 + m_j^2 c^2}} \frac{d^3 \vec{p}_j}{(2\pi)^3}$$

To estimate the amplitude  $M$ , one has to use the Feynman calculus. In Feynman calculus each vertex is assigned a vertex factor which include a coupling constant. For electromagnetic or weak interactions the coupling constant is always much less than one, for strong interactions the coupling constant depends on energy we are dealing with.

In case of  $W\gamma$ , the cross section is the probability of a quark and an antiquark to annihilate with the production of a lepton ( $\mu^\pm$  or  $e^\pm$ ), a neutrino or antineutrino and a photon. Several of the corresponding Feynman diagrams are shown in Fig. 8.

The energy is high enough for coupling constant of the strong interactions to be less than one and, therefore, the Feynman diagrams with fewer vertices would give a significantly larger contribution to the amplitude. The perturbative theory can be used. The minimal number of

361 vertices for the  $W\gamma$  process is three which correspond to the diagrams in Fig. 8, top. The  
362 amplitudes from these diagrams form the leading order contribution to the cross section (LO).

363

364 There are many NLO corrections are possible to these diagrams. QED corrections would  
365 mean radiations of extra photons by charged particles, exchange of photons between different  
366 charged particles or a photon can be radiated and absorbed by the same charged particle forming  
367 a loop. Similarly, weak corrections are possible however they would be much weaker than the  
368 QED corrections. But even the QED corrections are too weak compared to QCD corrections  
369 which include gluon loops at the same quark line and exchange of a gluon between two different  
370 quark lines (Fig. 8, bottom).

371



## 372 **2.2 Anomalous $W\gamma$ Production**

373 ATGC

374 Maybe, general words about ATGC, where does it come from

375 How it would affect the distributions and cross section

376 Specific for  $Wg$  process,  $WWg$  TGC

377 Retell theory paper: effective Lagrangian in most general form which coefficients are fixed as

378 1 or 0 and why which coefficients are considered

## 2.3 Measurements in the Past

### 2.3.1 Measurement of the $W\gamma$ cross section in pp collisions at $\sqrt{s} = 7$ TeV at CMS

The most recent measurement of the  $W\gamma$  cross section by the CMS is performed based on  $5 \text{ fb}^{-1}$  of data collected in 2011 at  $\sqrt{s} = 7$  TeV of LHC. The measurement was performed in the  $e\nu\gamma$  and  $\mu\nu\gamma$  final states. Only photons with the transverse momenta of  $p_T^\gamma > 15$  GeV were considered. The same CMS detector was used as for the analysis reported in this dissertation. The detector is described in Sec.[REFERENCE].

For the  $W\gamma \rightarrow \mu\nu\gamma$  events the isolated single muon trigger is used, it includes requirements of  $p_T^\mu > 30$  GeV and  $|\eta^\mu| < 2.4$  (2.1) for Run 2011A(2011B). For the electron channel, the isolated single electron trigger was used. The trigger requirements were  $p_T^e > 32$  GeV except a small fraction of data where it was  $p_T^e > 27$  GeV,  $|\eta_3| > 3$ ,  $M_T^W > 50$  GeV, where  $M_T^W = \sqrt{2 \cdot p_T^e \cdot MET \cdot (1 - \cos\Delta\phi(e, MET))}$  is a transverse mass of a W boson.

The  $W\gamma$  process signature is a prompt, isolated photon, a prompt isolated energetic lepton ( $\mu$  or  $e$ ) and a significant missing transverse energy due to the neutrino. Therefore, the event-level selection requirements included one well-identified lepton with kinematic requirements  $p_T^l > 35$  GeV,  $|\eta^\mu| < 2.1$ ,  $\eta^e < 2.5$ , one well-identified photon with  $p_T^\gamma > 15$  GeV,  $|\eta^\gamma| < 2.5$ , and  $M_T^W > 70$  GeV. To reject events from  $Z\gamma \rightarrow ll\gamma$  process, events with the second reconstructed lepton of the same flavor were vetoed. The second muon veto requirements included  $p_T^\mu > 10$  GeV,  $|\eta^\mu| < 2.4$ . The second electron veto requirements included  $p_T^e > 20$  GeV,  $|\eta^e| < 2.5$ , and weak electron identification criteria. The separation between a photon and a lepton were required to be  $\Delta R(l, \gamma) = \sqrt{\Delta\eta(l, \gamma)^2 + \Delta\phi(l, \gamma)^2} > 0.7$ .

The  $p_T^\gamma > 15 \text{ GeV}$  and  $\Delta R(l, \gamma) > 0.7$  are also phase space requirements. They are necessary to avoid divergence of the total cross section and also to suppress the contribution from the FSR diagram and, therefore, make the TGC contribution more significant.

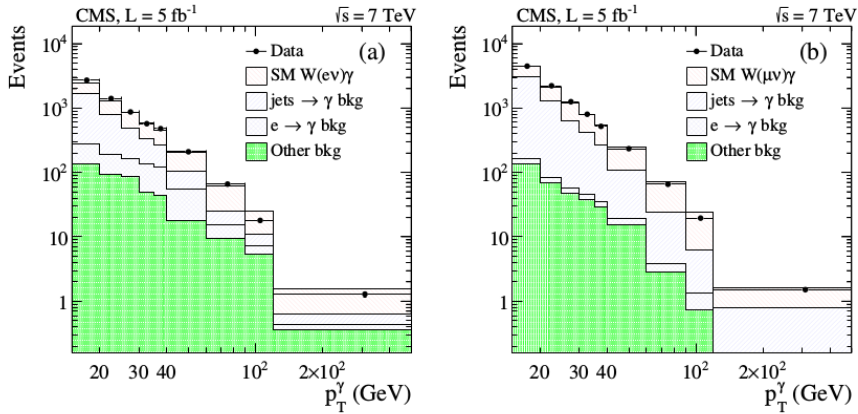


Figure 10: The distribution for the  $p_T^\gamma$  of  $W\gamma$  candidates in the analysis of 7 TeV CMS data. Data vs signal MC + background estimates. Left:  $W\gamma \rightarrow e\nu\gamma$ , right:  $W\gamma \rightarrow \mu\nu\gamma$ . Figure from [REFERENCE]

Events selected according with the criteria described represent a mixture of the signal and background events. The major source of the background is the fake photon background where hadronic jets are misidentified as photons. Such events originate from  $W$ +jets process mostly but  $Z$ +jets and  $t\bar{t}$ +jets events contribute to this source of the background as well. The template method was used as a major method to estimate this background. The shower-shape variable

$\sigma_{i\eta i\eta}^\gamma$  was used as a discrimination variable. The ratio method was used as a cross check by measuring and comparing the probabilities for jets to pass photon or jets selection criteria.

The second major background for the electron channel is the fake photon background where electron can be misidentified as a photon. Such events are coming from  $Z$ +jets events. Diboson processes contribute to this background for both channels. The fake rates are estimated from the  $Z \rightarrow ee$  sample, by checking how often one of the electrons would pass photon selection criteria given the other one passed stringent electron selection criteria.

Other sources of backgrounds include real- $\gamma$  backgrounds, fake lepton + real photon and fake lepton + fake photon sources.

The  $p_T^\gamma$  spectra of the selected events in data superimposed with selected events in the simulation of the signal and estimated background contribution for the muon and electron channels are shown in Fig. 10. The figure shown a good agreement within the estimated uncertainties.

The estimated cross sections are:

$$\sigma(pp \rightarrow W\gamma \rightarrow e\nu\gamma) = 36.6 \pm 1.2(\text{stat.}) \pm 4.3(\text{syst.}) \pm 0.8(\text{lumi}) \text{ pb}$$

$$\sigma(pp \rightarrow W\gamma \rightarrow \mu\nu\gamma) = 37.5 \pm 0.9(\text{stat.}) \pm 4.4(\text{syst.}) \pm 0.8(\text{lumi}) \text{ pb}$$

And the combination result:

$$\sigma(pp \rightarrow W\gamma \rightarrow l\nu\gamma) = 37.0 \pm 0.8(\text{stat.}) \pm 4.0(\text{syst.}) \pm 0.8(\text{lumi}) \text{ pb}$$

The paper also provides the cross section measurements for  $p_T^\gamma > 60$  GeV and for  $p_T^\gamma > 90$  GeV. The combination of two channels for  $p_T^\gamma > 60$  GeV is  $\sigma = 0.76 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.}) \pm 0.02(\text{lumi})$  pb while the theoretical NLO prediction is  $\sigma = 0.58 \pm 0.08$  pb. The result for  $p_T^\gamma > 60$  GeV is  $\sigma = 0.200 \pm 0.025(\text{stat.}) \pm 0.038(\text{syst.}) \pm 0.004(\text{lumi})$  pb while the theoretical NLO prediction is  $\sigma = 0.173 \pm 0.026$  pb.

### 2.3.2 Measurement of the $W\gamma$ cross section in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS

ATLAS collaboration also required each candidate event to have an exactly one lepton, at least one isolated photon and a significant missing transverse energy. The phase space requirements are the same as those for CMS:  $p_T^\gamma > 15$  GeV and  $\Delta R(l, \gamma) > 0.7$  however other selection criteria are slightly different:  $p_T^l > 25$  GeV,  $E_T^{\text{miss}} > 35$  GeV,  $M_T^W > 40$  GeV. In the electron channel  $Z$  mass window cut was applied to reduce the contribution from  $Z \rightarrow e^+e^-$  events.

The sideband method was used to estimate the major background (jets  $\rightarrow \gamma$ ).

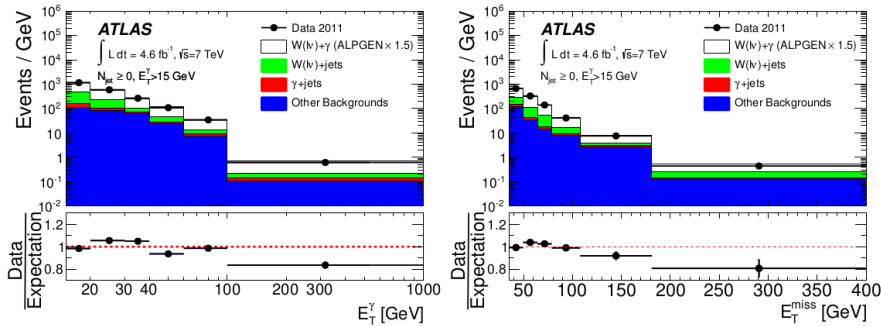


Figure 11: The distribution for the  $p_T^\gamma$  (left) and  $E_T^\gamma$  (right) of  $W\gamma$  candidates in the analysis of 7 TeV ATLAS data. Data vs signal MC + background estimates. Figure from [REFERENCE]

447 **3 Experimental Setup**

448 **4 CMS Tracker Alignment**

## 449 5 $W\gamma$ Cross Section Measurement

450 Place analysis outline here

## References

- 451
- 452 [1] Griffiths textbook
- 453 [2] website: <http://www.isgtw.org/spotlight/go-particle-quest-first-cern-hackfest>
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- 455 [4] ATLAS Paper about Higgs boson discovery
- 456 [5] website: <https://mstwpdf.hepforge.org/>
- 457 [6] PDG