Thesis

Ekaterina Avdeeva

University of Nebraska-Lincoln, USA

September 29, 2016

Abstract

This paper reviews

Contents

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 elecrtrodynamics (QED), quantum chromodynamics (QCD) 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 than those 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 LHC 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 the beyond SM (BSM) physics as well as the precision measurements of the SM parameters themselves.

In this dissertation the analysis of $pp \to W\gamma + X$ 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 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^γ) has been measured. The P_T^γ is sensitive to the potential anomalous TGC (aTGC) in the high P_T^γ region. The disagreement between the measured and theoretically predicted differential cross section at the higher P_T^γ end would be an indication of the possible presence of the aTGC.

The rest of this chapter gives general introductory information about the SM while chapter 2 concentrates on the theory of the SM and BSM $W\gamma$ production and also discusses previous measurements of this process. Chapter 3 describes LHC and CMS in more details. Chapter 4 explaines on specific aspect of the CMS operation which is the tracker alignment. Finally, chapter 5 describes the details of the measurement of this dissertation and reports the results.

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

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 $\mu^- \to e^- + \bar{\nu_e} + \nu_\mu$, 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. 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 a photon and a 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 are protons and antiprotons, electrons and positrons, neutrinos and antineutrinos, photons, and, in some sense, gluons. However, if a particle cannot 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 scatter 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 $W^\pm \to e^\pm \nu_e(\bar{\nu_e})$ 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, 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 various background processes. Subsections 1.2-1.4, chapter 2 and [1] describe particle interactions in more details.

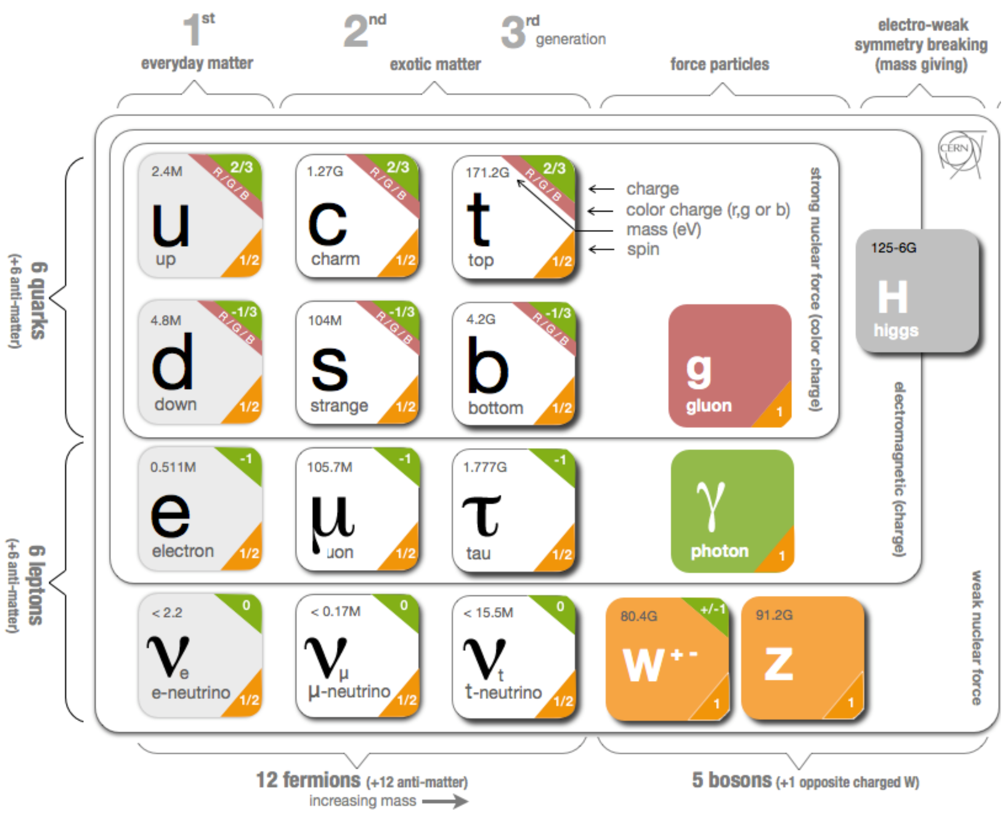

Figure 1: Standard Model Particles and Interations. Source of the figure: [2].

1.2 Electroweak Interactions

All electrically charged particles participate in electromagnetic interactions. All electromagnetic interactions are mediated by a photon, a spin-one electrically neutral massless particle, and 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.

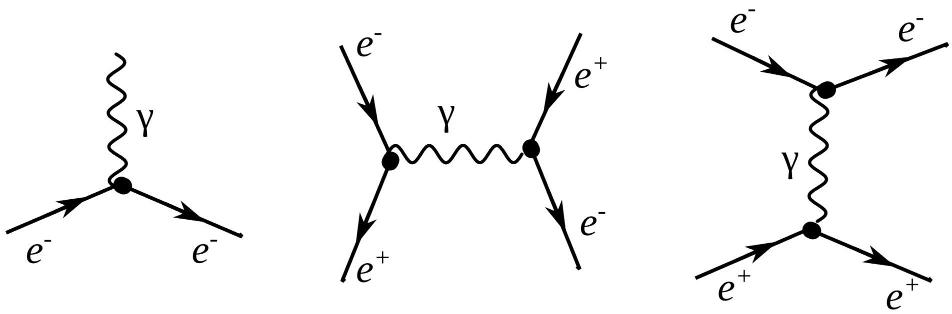

Figure 2: Electromagnetic interations

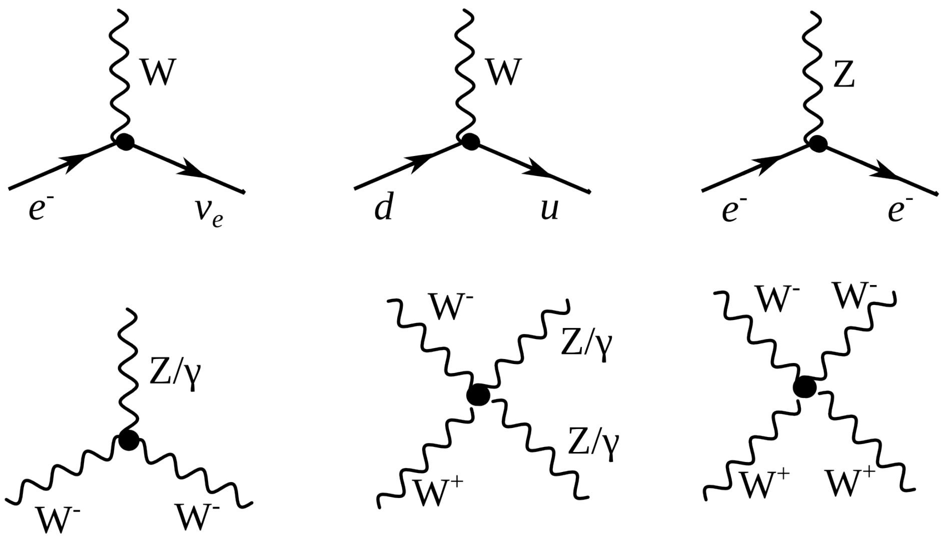

Figure 3: Weak elementary processes and gauge couplings

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_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 quark is 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 Cabibbo Kobayashi Maskawa 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 interaction 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)xU(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 [3], [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 triple gauge coupling $WW\gamma$. Thus, the measurement is a good test of the SM electroweak theory.

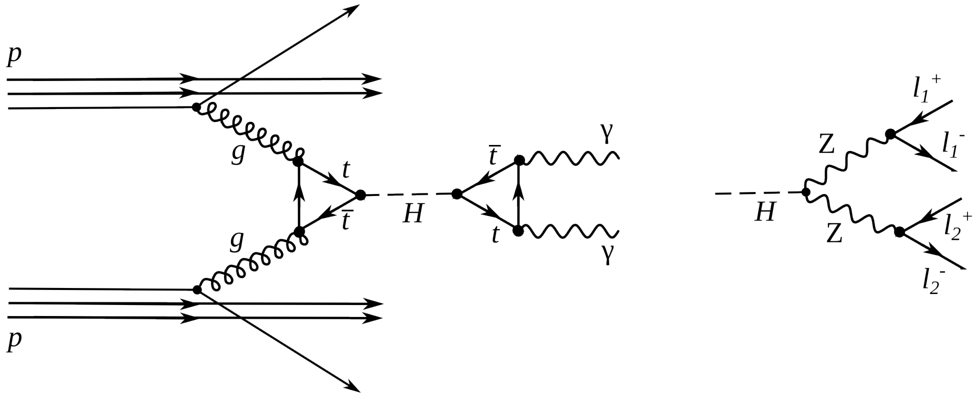

Figure 4: The Higgs boson production and decay

1.3 Strong Interactions

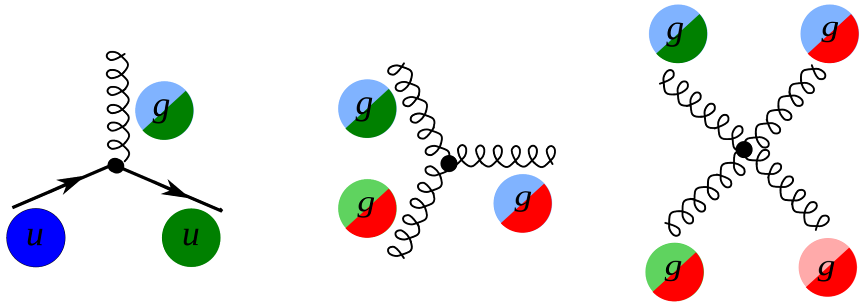

Figure 5: Elementary processes of strong interations

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 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: 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. 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 color 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 an antiquark with the opposite color charges, and baryons are comprised of three quarks: red, green and 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 QCD which 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 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 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 interact. Physics of proton-proton collisions is discussed in the subsection 1.4.

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 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. Probabilities $f_i(x, Q^2)$ of any particular constituent i to interact are described partially by QCD and partially by experimental measurements and depend on the momentum transfer Q and the momentum fraction of a specific parton x. These probabilities are called parton distribution functions (PDFs).

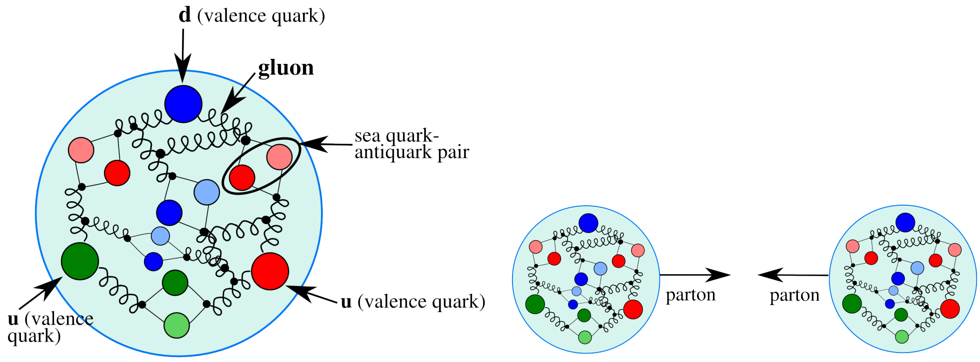

Figure 6: The proton structure (left) and the proton-proton collision (right).

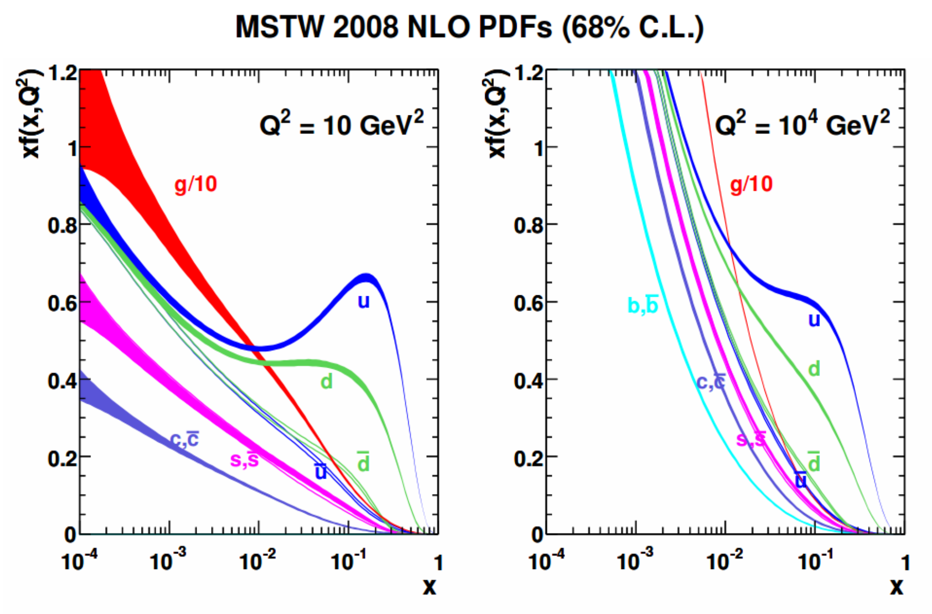

Figure 7: Martin-Stirling-Thorne-Watt parton distribution functions [5].

For large Q^2 and x gluon-gluon interactions have the largest probabilities to occur (Fig. 7).

However, gluons do not couple directly to a W boson, thus, in the $W\gamma$ measurement we are mostly 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. 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 mimicking our process. Such background events can be produced by any pair of partons.

1.5 Open Questions of the Standard Model

While the SM 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 SM. 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 at the moment of the Big Bang. Then most of it has annihilated but because of asymmetry, there was more matter than antimatter which led to the state of the Universe we observe now. 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 large 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^γ) of the $W\gamma$ process has a goal to both test the SM and search for the BSM physics. The low P_T^γ region is not expected to be affected by any new physics 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 enhance over the SM predictions. The enhance would be an indirect evidence of the BSM particles like supersymmetric particles, additional gauge bosons or higher generation fermions. More theoretical details about the SM descriprion of Wγ process as well as the possible BSM physics are given in the chapter 2.

2 The Wγ Process

2.1 Standard Model Wγ Production

A W boson in proton-proton collisions can be produced in the processes $q\bar{q'} \to W$ 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 $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$ 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 $W^\pm \to l^\pm \nu_l(\bar{\nu_l})$ 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 $W \to q\bar{q'}$ decays. In this dissertation we only consider $W^\pm \to \mu^\pm \nu_\mu(\bar{\nu_\mu})$ and $W^\pm \to e^\pm \nu_e(\bar{\nu_e})$ as the cleanest channels.

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

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).

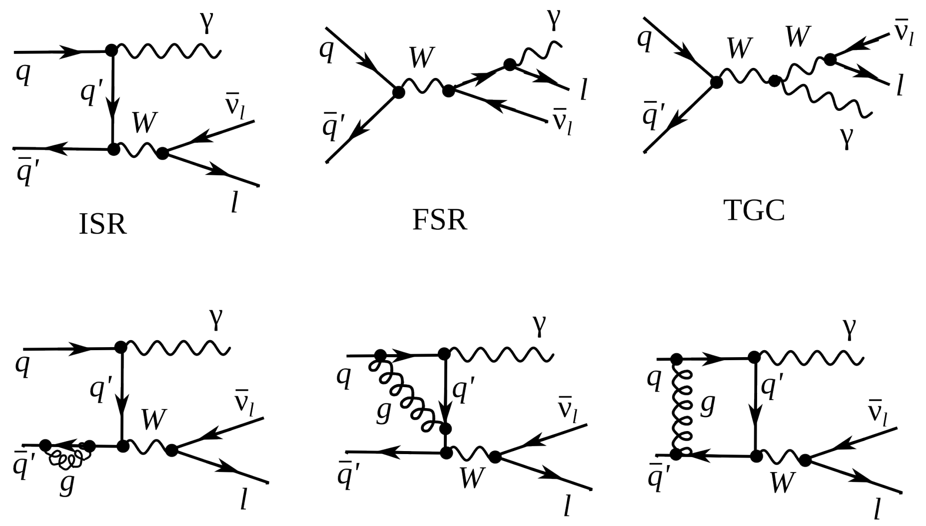

Figure 8: Feynman diagrams of Wγ production

In this dissertation we are measuring the total and the differential cross section. Fig. 9 illustrates the concept of the differential cross section in the classical case. An incident particle must appear within area $d\sigma$ to be scattered off by an angle $d\theta$ by the scattering center. The relashionship between these two quantities would give us the expression for the differential cross section $d\sigma/d\theta$. Integrating over $d\theta$, one would get the total cross section σ. Differentiating σ by any kinematic parameter X of the incident particle would give the expression for the differential cross section $d\sigma/dX$.

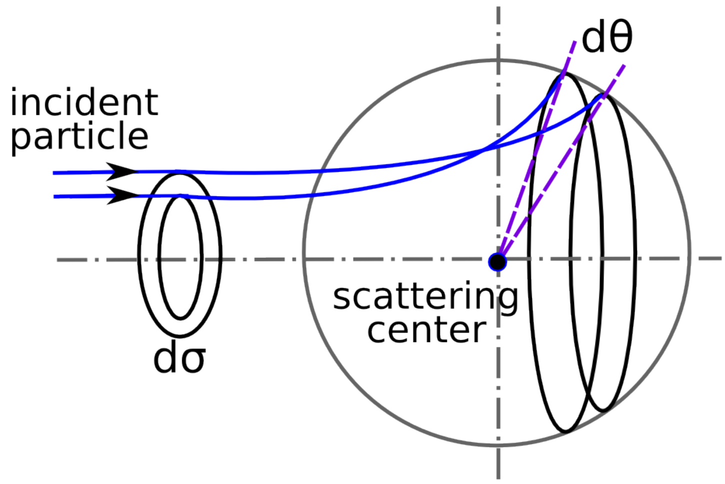

Figure 9: Illustration of the differential cross section concept in the classical case

In particle physics the cross section characterizes the probability of two particles to interact or, more specifically, the probability of two particles to interact to produce the specific final state. For example, the probability of a quark and an antiquark to interact to produce a charged lepton, a neutrino and a photon like in our measurement.

Referring to the Fig. 9, a number of particles passing through the area σ per unit time is $N = L \cdot \sigma$, where L is the number of particles crossing the unit area per unit time. Therefore, the cross section σ of a specific process $\sigma = N/L$ where N is a number of events of the process occurred. L in this expression refers to the number of the initial state particles and is called the luminosity.

Thus, 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 satisfy analysis selection criteria. Therefore, the number of events N has to be corrected in a measurement: $N \rightarrow N/(A \cdot \epsilon)$, where A is a detector acceptance and ϵ is an efficiency of a signal process to pass selection criteria. Other corrections to N may have to be applied depending on the analysis.

The luminosity L is determined based on the 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 rather than the differential cross section as a function of time and therefore integrate the luminosity over the period of time.

To compute a cross section theoretically, one has to use Fermi's Golden rule. In case of the scattering of two particles to three final state particles 1+2 $\rightarrow$ 3+4+5, it takes the following form:

$$\sigma = \frac{\hbar^2}{4\sqrt{(p_1 p_2)^2 - (m_1 m_2 c^2)^2}} \int |M|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4 - p_5) \prod_{j=3}^{5} \frac{1}{2\sqrt{\bar{p}_j^2 + m_j^2 c^2}} \frac{d^3 \bar{p}_j}{(2\pi)^3}$$

where $\hbar$ is the Planck constant, c is the speed of light, p_i are 4-momenta and $\bar{p}_i$ are three momenta of the initial state and the final state particles, m_i are masses of particles, M is the process amplitude.

The calculation of the process amplitude starts with writing the relevant Lagrangian similarly to how it is done in the classical mechanics but in particle physics instead of coordinates we have quantum fields. The Lagrangian allows us to derive the equations of motion however they cannot be solved exactly and, therefore, the perturbative approach is used if coupling constants are $g \ll 1$.

The Lagrangian term responsible for the triple gauge coupling is the following [9]:

$$iL_{eff}^{WW\gamma} = e[A^{\mu}(W_{\mu\nu}^{-}W^{+\nu} - W_{\mu\nu}^{+}W^{-\nu}) + W_{\mu}^{+}W_{\nu}^{-}A^{\mu\nu}]$$

where e is the absolute value of the electron charge, A^{μ} is the photon field, $W^{\pm\mu}$ are fileds of $W^{\pm}$ bosons, $W_{\mu\nu} = \partial_{\mu}W_{\nu} - \partial_{\nu}W_{\mu}$, and $A_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$.

To represent the process graphically Feynman diagrams were invented. Also the diagrams can be used to calculate the process amplitude. There is infinite number of Feynman diagrams corresponding to any specific process and the total amplitude of the process is a sum of individual amplitudes of each diagram and it is not technically possible to take into account all of them. The perturbative approach arranges all the diagrams by orders of contribution because each vertex is assigned a coupling constant and, therefore, the Feynman diagrams with fewer vertices would give a significantly larger contribution to the amplitude. In Fig. 8 we have examples of the Leading Order (LO) and the Next-to-Leading Order (NLO) Feynman diagrams (top and bottom diagrams respectively).

The NLO corrections shown in Fig. 8 are QCD corrections only which include gluon loops at the same quark line and exchange of a gluon between two different quark lines hovewer QED and weak NLO diagrams are also possible. QED corrections mean radiations of extra photons by charged particles, exchange of photons between different charged particles or a photon can be radiated and absorbed by the same charged particle forming a loop. Similarly, weak corrections mean extra virtual W or Z bosons. But the QCD corrections are the largest.

The theoretical cross section in particle physics is important not only for analysing the measurement result but also for producing the simulation which is then actively used while performing the measurement. The simulation consists of two parts: the generation of the process and the simulation of the particles paths through the detector. While the second one depends on the well-known properties of the particles and the detector configurations, the first part relies on the theory.

The most precise theoretical $W\gamma$ cross section available is the NNLO cross section in QCD [7]. The effect of the NNLO correction ranges from 19% to 26% compared to the NLO cross section depending on the selection conditions. The contributions from the higher order corrections is estimated to be $\pm 4\%$. However, the NNLO theoretical result was published in 2015 only and there is still no simulation available based on that result. The simulation used in this analisys is LO + up to two hadronic jets simulation which found to give the same predictions as the NLO result [REFERENCE to APPENDIX?].

In addition to the SM predictions, there are certain BSM theories which predict an enchancement of the contribution from the TGC diagram. The discussion of these BSM effects on the $W\gamma$ process takes place in chapter 2.2.

2.2 Anomalous $W\gamma$ Production

Triple and quartic gauge couplings (QGC) are represented by vertices with three and four bosons (Fig. 10). TGC and QGC can be charged or neutral. There are variety of the SM processes where charged TGC and QGC are possible. Such processes can occur through a Feynman diagram with a vertex involving a W boson and conserving charge. Corresponding vertices are $WW\gamma$, WWZ, $WWWW$, $WW\gamma\gamma$, $WWZ\gamma$, and $WWZZ$ (Fig. 10, 1^st, 3^rd, and 5^th diagrams). To search for the new physics, all these vertices are described by extended Largangian term than the SM description, involving several constants which have known values in the SM. A significant deviation of one of these constants from the known values would be an indication of a new physics.

As for neutral TGC and QGC, they are forbidden in the SM at the tree level but extended Lagrangian contains terms which describes neutral TGC and QGC vertices: $Z\gamma\gamma$, $ZZ\gamma$, ZZZ, $Z\gamma\gamma\gamma$, $ZZ\gamma\gamma$, $ZZZ\gamma$, and $ZZZZ$. Similarly to charge TGC and QGC cases, neutral TGC and QGC Largangian terms involve contants which are zero in the SM.

In $W\gamma$ measurement we can probe $WW\gamma$ vertex only. The most general Lorentz invariant Lagrangian of this vertex takes the following form [9]:

$$iL_{eff}^{WW\gamma} = e[g_1^\gamma A^\mu(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_\gamma W^+_\mu W^-_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} A^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g_5^\gamma \epsilon_{\mu\nu\rho\sigma}((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu}))V^\sigma + i g_4^\gamma W^-_\mu W^+_\nu(\partial^\mu A^\nu + \partial^\nu A^\mu) - \frac{\tilde{\kappa_\gamma}}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} A_{\rho\sigma} - \frac{\tilde{\lambda_\gamma}}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} A_{\alpha\beta}]$$

where e is the absolute value of the electron charge, A^μ is the photon field, $W^{\pm\mu}$ are fileds of $W^\pm$ bosons, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, m_W is the mass of a W boson, g_1^γ, κ_γ, λ_γ, g_5^γ, g_4^γ, $\tilde{\kappa_\gamma}$, and $\tilde{\lambda_\gamma}$ are constants.

Despite there are 7 constants in the extended Lagrangian, only λ_γ and κ_γ are considered in the BSM searches. The rest of the constants are fixed to their SM values based on various considerations. Thus, $g_1^\gamma = 1$ and $g_5^\gamma = 0$ are fixed to obey the electromagnatic gauge invariance for the on-shell photons. The non-zero value of g_5^γ also violates C and P conservations, and non-zero values of g_4^γ, $\tilde{\kappa_\gamma}$, $\tilde{\lambda_\gamma}$ violate the CP conservation law. Such violation parametrizations are not considered in charged TGC measurements now but might get considered in the future.

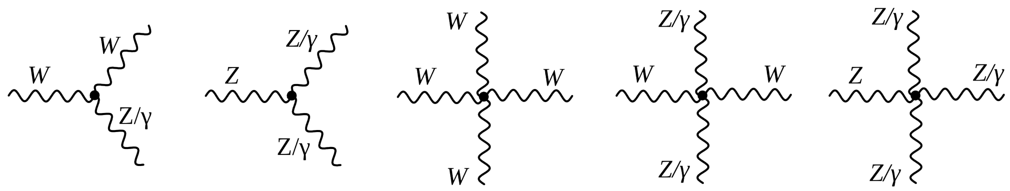

Figure 10: TGC and QGC vertices

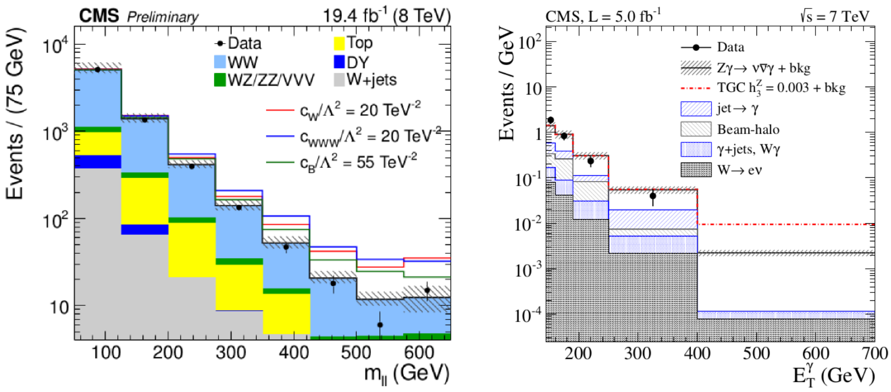

Figure 11: Examples of the possible effects of non-zero TGC constants in m_{ll} spectrum in 8 TeV $WW \to l\nu l\nu$ measurement (left) and P_T^{γ} spectrum in 7 TeV $Z\gamma \to \nu\nu\gamma$ measurement (right).

2.3 Measurements in the Past

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

The most recent measurement of the Wγ cross section by the CMS is performed based on 5 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^{γ} >15 GeV were considered. The same CMS detector was used as for the analysis reported in this disseratation. 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^{μ} >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 Wγ process signature is a prompt,isolated photon, a prompt isolated energetic lepton (μ or e) and a significant missing trensverse 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, η^e <2.5, one well-identified photon with $p_T^{\gamma} > 15$ GeV, $|\eta^{\gamma}|$ <2.5, and M_W^T >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^{μ} >10 GeV, $|\eta^{\mu}|$ <2.4. The second electron veto requirements included p_T^{μ} >20 GeV, $|\eta^{\mu}|$ <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 $p_T^{\gamma} > 15GeV$ 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 supress the contribution from the FSR diagram and, therefore, make the TGC contribution more significant.

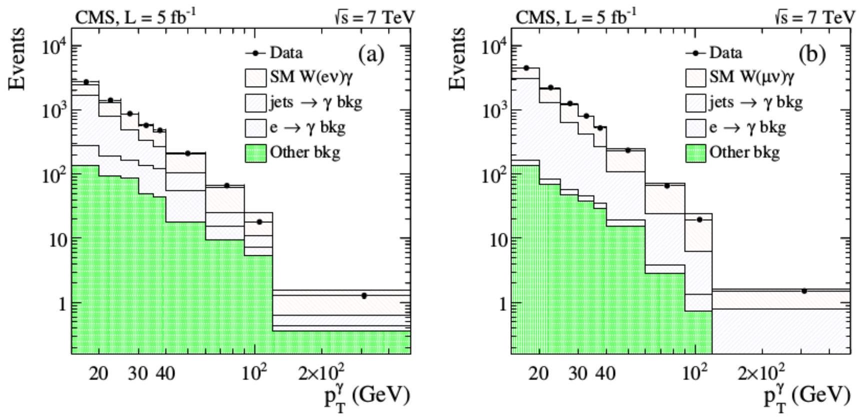

Figure 12: The distribution fo the p_T^{γ} of Wγ candidates in the analysis of 7 TeV CMS data. Data vs signal MC + background estimates. Left: $W\gamma \rightarrow e\nu\gamma$, right: $W\gamma \rightarrow \mu\nu\gamma$. Figure from [REFERENCE]

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 $\bar{t}t$+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

$\sigma^{\gamma}_{i\eta i\eta}$ 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 $Z \to ee$ 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-γ backgrounds, fake lepton + real photon and fake lepton + fake photon sources.

The p_T^{γ} 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. 12. The figure shown a good agreement within the estimated uncertainties.

The estimated cross sections are:
$\sigma(pp \to W\gamma \to e\nu\gamma)$=36.6±1.2(stat.)±4.3(syst.)±0.8(lumi) pb
$\sigma(pp \to W\gamma \to \mu\nu\gamma)$=37.5±0.9(stat.)±4.4(syst.)±0.8(lumi) pb
And the combination result:
$\sigma(pp \to W\gamma \to l\nu\gamma)$=37.0±0.8(stat.)±4.0(syst.)±0.8(lumi) pb

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

2.3.2 Measurement of the Wγ 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 critea are slightly different: $p_T^{l} > 25$ GeV, E_T^{miss} >35 GeV, $M_T^{W} > 40$ GeV. In the electron channel Z mass window cut was applied to reduce the contribution from $Z \to e^+e^-$ events.

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

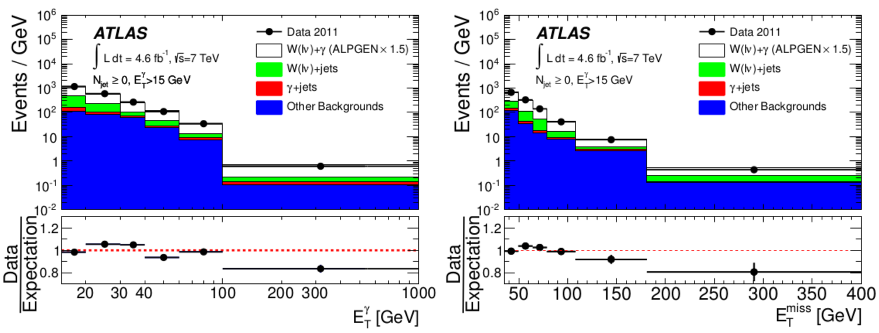

Figure 13: The distribution fo the p_T^{γ} (left) and E_T^{γ} (right) of Wγ candidates in the analysis of 7 TeV ATLAS data. Data vs signal MC + background estimates. Figure from [REFERENCE]

3 Experimental Setup

4 CMS Tracker Alignment

5 Wγ Cross Section Measurement

Place analysis outline here

References

[1] Griffiths textbook

[2] website: http://www.isgtw.org/spotlight/go-particle-quest-first-cern-hackfest

[3] CMS Paper about Higgs boson discovery

[4] ATLAS Paper about Higgs boson discovery

[5] website: https://mstwpdf.hepforge.org/

[6] PDG

[7] NNLO theory paper

[8] NLO theory paper

[9] aTGC paper

[10] 7TeV Wg CMS paper

[11] 7TeV Wg ATLAS paper