Cross-Section Measurement and New Physics Search with $W^\pm Z$ Production in purely leptonic decay channels with ATLAS experiment

by

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Abstract

This dissertation presents my research work with the ATLAS experiment at the Large Hadron Collider (LHC). The LHC is built in a circular tunnel 27 km in circumference that buried around 50 to 175 m underground and straddles the Swiss and French borders on the outskirts of Geneva. It designed to produces proton-proton collisions at center-of-mass energy (CME) of 14 TeV with peak luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. ATLAS is a particle physics experiment at the LHC. The ATLAS detector is a state of art general purpose detector with almost $4\pi$ coverage to detect particles created in the proton-proton collisions from the LHC. The LHC is a dream machine for particle physicists to create particles that existed about 0.001 ns after Big Band, the start of the universe. Research conducted in experiments at the LHC will significantly advance our understanding how our universe works at its most fundamental level. My thesis work has focused on studies of the vector boson pair, $W^\pm Z$, productions at the LHC to search for new physics through the measurements of the $W^\pm Z$ production cross-section and the triple-gauge couplings.

The LHC and the ATLAS detector have been operated remarkably since fall of 2009. The peak luminosity of the LHC increased from $2 \times 10^{29}\text{cm}^{-2}\text{s}^{-1}$ to $7.7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, more than 4 orders of magnitude in increase over past three years. With over 93% data taking efficiency, ATLAS has collected data with an integrated luminosity of 5 fb$^{-1}$ at 7 TeV in 2011, and 15 fb$^{-1}$ at 8 TeV up to Sept. 2012. Using data collected in 2011 this thesis work has made the first measurement at the LHC on $W^\pm Z$ production cross-section, which is one of the major milestones of the LHC physics programs as the steppingstone for discovery of new physics at TeV energy scale. Using this data-set, the most stringent limits on the anomalous triple gauge boson couplings (TGCs) of the WWZ vertex are set. The massive new resonance productions are searched in the $WZ$ production mass spectrum. No evidence of new physics beyond the standard model (SM) is observed.

The measurements of the $WZ$ production cross-section provide test of the non-Abelian $SU(2) \times U(1)$ gauge structure of the SM electroweak theory, and the understanding of the background for the Higgs searches. The $WZ$ production cross section is measured from leptonic decay channels, namely the combination of $Z \rightarrow ee (\mu\mu)$ and $W \rightarrow e\nu_e (\mu\nu_\mu)$: $ee\nu\nu$, $e\mu\nu$, $e\nu\mu\mu$ and $\mu\mu\nu\nu$ final states. Major background of this measurement comes from other physics processes, such as $ZZ$, $Z+\text{jets}$ and $\text{Top}$. Data-Driven method is developed to estimate the background contributions from $Z+\text{jets}$ and $\text{Top}$, while The background from $ZZ$ is estimated from MC simulation. The total $WZ$ production cross-section is measured to
be $19.0^{+1.4}_{-1.3}(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.4(\text{lumi.})$ pb, based on total 317 events selected from data and 68 $\pm$ 10 estimated background. The uncertainty of the measurement is much smaller in compared to previous measurements from Tevatron at $\sqrt{s} = 1.96$ TeV.

The measurements of TGCs provide a sensitive prober for new physics at high energy scale beyond the SM. The anomalous triple gauge boson couplings (aTGC) are probed from the $WZ$ events by comparing the observed transverse momentum spectrum of the $Z$ boson with that of the theoretical predictions with aTGC. Data agree with the SM prediction from the likelihood fit, which results in 95% C.L. limits on aTGC as $\Delta g_1^Z \in [-0.057, 0.093]$, $\Delta \kappa^Z \in [-0.37, 0.57]$ and $\lambda^Z \in [-0.046, 0.047]$. These limits are much more stringent compared to the previous measurement at Tevatron.

Many physics models predict new particles decaying to $WZ$ final state. A search for high mass $WZ$ resonance is carried out using the same data-set. The invariant mass of the $WZ$ system is reconstructed using measured energies and momenta of leptons and missing energy constrained to the $W$ mass. To avoid event selection bias, a blinded analysis approach is used. In this analysis a control region is defined, where underlying new physics signal is minimal. Only when the principal background from the known physics process is understood in the control region we unblind the analysis in the signal region to search for new resonance. No new physics is observed in the signal region. The result is interpreted by setting cross-section limits on new gauge boson $W'$ from Extend Gauge Models (EGM) and $\rho_T$ from Low Scale Technicolor model (LSTC). The exclusion limit on $W'$ mass is 1.1 TeV, and 580 GeV for $\rho_T$ at 95% C.L.

Searching for new physics at the LHC is still at its early stage in terms of luminosity and energy of the LHC. The methods and techniques developed in this thesis work have paved the way for the continued searches with ATLAS experiment at the LHC.
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Chapter 1

Introduction

The object of particle physics is to understand how our universe works at its most fundamental level. Researches in this field is to discover the most elementary constituents of matter and energy, to probe the interactions between elementary particles and to explore the basic nature of space and time itself. Understanding of the laws of nature by human beings is an evolution of our civilization. This process has last over a few thousand years long and achieved a very elegant and successful theory of particle physics, called standard model (SM).

Physics originates from Philosophy, particularly when people started to seek for answers for many questions related to the world they lived in. Ancient Chinese, Greek and Indian have independently developed their own worldview; but, coincidentally, they all came up with theories suggesting some essential “elements” which act as the fundamental building bricks of the living world. For instance, the Chinese developed an understanding of the five elements, earth, metal, wood, water and fire, even prior to the creation of Chinese characters; and they generally believed different combinations of them form everything in the world. Furthermore, in 5-6th centuries BCE, the theory of “atomism” emerged in a philosophical way stating that everything is composed entirely of various imperishable, indivisible elements called “atoms”. In western world, this idea was first developed in Greece by two philosophers, Leucippus and Democritus; and coincidentally again, similar theory was brought up by Indians from the East. The idea of “atomism” symbolically started the era of particle physics. In the consecutive centuries, the knowledge of this field grew rather slowly, whilst the West underwent wars and plagues during dark Middle Ages, and the Indian science was challenged by invaders and religions, and the Chinese concentrated on either pure philosophy or pragmatic technologies.

Then came the Renaissance, the era of changes in Europe. There were many great advances in humanism, arts and science. Science took a big step forward, as significant changes were made in the way how the universe was viewed and the methods to study natural phenomena. The very famous “Earth moved around the Sun” from Nicolaus Copernicus is one of this kind. A new scientific method was proposed and consolidated, which focused on empirical evidence, the importance of mathematics, and discarded Aristotelian science. The new scientific method would led to great progress in science, and it motivated the discoveries of “real” things in our physical world (in contrast to only philosophical deduction), which is of vital importance to nowadays physics.

Economic prosperity advances science, and in the meantime, science stimulates prosperity. Ever since the Industrial Revolution, this phenomenon has become a lasting scenario on the
stage of history. At that time, classical physics had already been well developed in the fields of Mechanics and Thermodynamics by continuous work from many geniuses, such as Isaac Newton, in the preceding centuries. Physicists started to study electricity, magnetism and light and made enormous discoveries and inventions, which brought profound revolutions in the way we live. At the end of the 19th century, classical physics had evolved to be rather competent; classical mechanics, thermodynamics, optics had been well developed and applied in many aspects of the world. Therefore, by that time, many people believed scientific research would focus more on clearing up minor problems to improve the method and measurement but instead of discovering new things. However, this was just the start.

In 1896, Henri Becquerel, a French physicist, accidentally discovered radioactivity while studying the uranium ores. And in the next year, J.J. Thomson discovered electrons from a study of cathode rays, which is often said to mark the start of particle physics. With the hints from Rutherford’s scattering experiment, Niels Bohr constructed a “planetary” model of the atom, in which electrons orbit around the nucleus (proton). Apart from proton, in 1932, James Chadwick discovered another neutral charge constituent of nucleus, neutron. The existence of the neutrino was postulated in 1930 by the Austrian theorist Wolfgang Pauli who was looking for an explanation for the fact that energy did not appear to be conserved in beta decays; and it was confirmed in experiment later in 1956. Muons were discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936. Experiments verified that there are two distinct types of neutrinos (electron and muon neutrinos) in 1962. Around the year of 1976, The tau lepton and neutrino were discovered at SLAC. Quarks were mostly validated in the form of mesons or baryons (except top quark). The $J/\Psi$ particle, a charm-anticharm meson, was discovered in 1974 by two independent groups at BNL and SLAC. In 1977, the bottom quark was observed by a team at Fermilab, when collisions produced bottomonium. And the last and heaviest one, top quark, was discovered later in 1995 by the CDF and D0 experiments at Tevatron of Fermilab. The $W^\pm$ and $Z^0$ intermediate bosons demanded by the electroweak theory were observed by two experiments at CERN in 1984. A brief timeline of particle discoveries can be found in Figure 1.1 (not complete list).

![Figure 1.1: A brief timeline of particle discoveries in 20th century](image)

The theory is developed along with observations. In 1900, Max Planck suggested that radiation is quantized. It could be considered as the starting point for modern particle physics theory. However, unfortunately at that time, most people couldn’t accept this edgy idea except a few. Among them, one took Planck’s idea seriously and later on proposed a quantum of light (the photon) which behaves like a particle. The name is Albert Einstein, whose other theories include equivalence of mass and energy, the particle-wave duality of photons, the
equivalence principle, special relativity and general relativity, which all became the fundamental framework for either particle physics or cosmology. One step further, Louis de Broglie proposed that matter has wave properties in 1924. Then came the intensive work of the construction of quantum theories. There were exclusion principle from Wolfgang Pauli in 1925, wave mechanics equation from Erwin Schroedinger in 1926, and the uncertainty principle from Werner Heisenberg in 1927. Then, Paul Dirac combined quantum mechanics and special relativity in his theory. In the year of 1954, C.N. Yang and Robert Mills developed a new class of theories called “gauge theories”, which now forms basis of the “standard model”. Weak interaction was included into the gauge theory by Julian Schwinger, Sidney Bludman, and Sheldon Glashow; and the massive W bosons were considered to mediate the weak interaction, which must break the gauge symmetry in the theory. During 1964 to 1968, theorists (Higgs, Kibble, Guralnik, Hegen, Brout and Englert) from three independent groups developed a mechanism to break the symmetry in vacuum to describe the massive weak bosons in the gauge theory. This mechanism predicts a new elementary scalar particle, called Higgs boson, which becomes a cornerstone of the standard model. With the Higgs idea Steven Weinberg and Abdus Salam separately proposed a theory that unifies electromagnetic and weak interactions into the electroweak interaction. In 1964, the “quark” model was brought into birth by Murray Gell-Mann and George Zweig, and it was further developed into gauge theory for strong interactions later on in 1970s. The “Standard Model” of particle physics was then formed.

The elementary particles predicted by the SM have all been confirmed in experiments except the Higgs boson before July 4th, 2012. Huge experimental efforts have been made more than two decades to test of the SM and search for new phenomena beyond the SM. No deviations were observed from data compared to the SM predictions. The last mysterious particle, the Higgs Boson, is discovered at the LHC this year. The announcement was made on July 4th 2012 at CERN by ATLAS and CMS experiments that a new boson has been found in proton-proton collision data at the large hadron collider (LHC) in searches of the SM Higgs programs. The new particle has a mass around 126 GeV and its decays are consistent with the SM Higgs properties. Is it really the SM Higgs boson? More test must be done to pin-down the nature of the new particle in the next few years.

The SM has been enormous success during last few decades, but it is certainly not the end of the story. It leaves out gravitation in its framework, and does not explain the particular values of the masses of quarks and electrons and other elementary particles. Furthermore, none of its particles can account for the dark matter that astrophysics experiments tell us makes more than 80% of the mass of the universe. We need to continue seeking the answers to these most profound questions regarding mass and energy at the energy frontier. The experiments at the LHC have provided physicists the unique opportunity to test the new ideas and search for new phenomena beyond the SM.

Many theoretical models for new physics involve di-boson (W+W−, W±Z, ZZ, W±γ and Zγ) productions at the LHC. The tree-level diboson production at the LHC can be illustrated as $q\bar{q} \rightarrow V_1 V_2$ (where $V_1$, $V_2$ represent the vector boson), in which triple gauge couplings (TGCs) are included in the s-channel diagram. In the SM electroweak theory, gauge boson couplings are precisely predicted by the non-Abelian $SU(2) \times U(1)$ gauge symmetry. Any deviation from the SM predictions on these couplings will indicate new physics. Many models beyond SM provide consistent SM behavior at low energy, but deviate from the SM at certain high energy scale. Therefore, the diboson physic at the highest energy frontier can provide
not only the most stringent test of the SM electroweak theory, but also the key to probe new physics. The studies of TGCs have been an interesting and hot topic in colliding beam experiments. The signature for anomalous TGCs (aTGCs) is the enhancement of diboson production cross-sections, especially at high mass or high transverse momentum regions. The sensitivity of aTGCs strongly depend on the four-momentum of the diboson. The high energy and luminosity make the diboson physics at the LHC the world leading program compared to other contemporary experiments.

The $W^\pm Z$ production is the least studied in diboson physics, given its small cross-section and the fact that it can only be produced in hadron colliders. QCD jet background often have enormous contribution in the final state events given its large production cross-section at hadron collider. In order to have a clean signature and better control of background, only the purely leptonic decay final states are studied in this dissertation. The physics results in this dissertation are based on the 4.7 fb$^{-1}$ collision data collected with the ATLAS detector during the year of 2011. The major contents include the $W^\pm Z$ production cross-section measurement, TGCs study in the case of $WWZ$ vertex and resonance search by using EGM $W'$ and technicolor $\rho_T$ as theoretical reference.

The dissertation is organized as following. Chapter 2 briefly describes the related theory, including the SM, the hadron collider physics and the $WZ$ physics. The LHC and ATLAS detector are introduced in Chapter 3. Chapter 4 lists the physics objects used in the analysis. Chapter 5 presents the SM $W^\pm Z$ cross-section measurement and TGCs study in details, and the resonance search are presented in Chapter 6. The conclusion and future prospect are given in the Chapter 7.
Chapter 2

Theory

2.1 The Standard Model

The Standard Model (SM) reflects the current knowledge of elementary particles and several basic interactions (electromagnetic, weak and strong), which has been developed continuously during last century and considered as the most prominent and successful theory ever built. It is a non-Abelian Lorentz invariant and gauge invariant quantum field theory based on the symmetry group $SU(3) \times SU(2) \times U(1)$, with the color group $SU(3)$ representing the strong interaction and with $SU(2) \times U(1)$ for the electroweak interaction spontaneously broken by the Higgs mechanism.

There are a set of so-called elementary particles in the SM, from which the matter are constructed and with which the forces are mediated. The particles are generally divided into fermions and bosons. Fermions have half spin and obey Pauli’s exclusion principle; bosons have integer spin and follow the Bose-Einstein statistics. Furthermore, the force carriers mediating the interactions are called gauge bosons (spin-1); the massive Higgs boson (spin-0) helps generate mass in the theory. The family of fermions can be further classified into leptons and quarks, based on the fact that leptons only participate in electromagnetic and weak interactions while quarks can take all three interactions. As you can see in Figure 2.1, there are three generations of leptons and quarks, five gauge bosons and a Higgs boson; the lines conjugating particles represent the interactions. The SM describes three fundamental interactions in the nature: electromagnetic interaction, weak interaction and strong interaction. The force strength and ranges are summarized in Table 2.1: the gravity is listed for comparison, which is not included in the SM.

<table>
<thead>
<tr>
<th>Forces</th>
<th>Strength</th>
<th>Range(m)</th>
<th>Mediating Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong</td>
<td>$1$</td>
<td>$10^{-15}$</td>
<td>gluons</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>$\frac{1}{137}$</td>
<td>Infinite</td>
<td>photon</td>
</tr>
<tr>
<td>weak</td>
<td>$10^{-6}$</td>
<td>$10^{-18}$</td>
<td>$W^\pm, Z$</td>
</tr>
<tr>
<td>gravity (not in the SM)</td>
<td>$10^{-38}$</td>
<td>Infinite</td>
<td>graviton?</td>
</tr>
</tbody>
</table>

Table 2.1: The interactions and their strength

The SM is formulated in a complicate, yet simple way. Very sophisticated mathematical tools and knowledge are needed to cover the deductions and calculations, and in the mean-
while, very much classical physics knowledge is required to make a good base. Then, this language of modern physics is brought into birth by melting the classics and mathematics together. The simplicity is represented by its origin. The origin is believed to be the symmetries. The special relativity brings us the framework with Lorentz symmetry, and the internal symmetry, also called gauge symmetry, essentially builds the theory. I will briefly go through the theory in the following texts and try to reveal the overall picture of the SM.

The Lagrangian formalism of quantum field theory is the most common representation. Based on the knowledge of special relativity and symmetries, Lagrangian is required to have: space-time symmetry in terms of Lorentz invariance, internal symmetries like gauge symmetries, causality and local interactions. Particles are described by fields that are operators on the quantum mechanical Hilbert space of the particle states, acting as creation and annihilation operators for particles and antiparticles. The elementary particles in the SM are described by these fields:

- spin-0 bosons, described by scalar field $\phi(x)$, e.g. Higgs boson
- spin-1 gauge bosons, described by vector fields $A_\mu(x)$, e.g. $\gamma, W^\pm, Z$
- spin-1/2 fermions, described by Dirac spinor fields $\psi(x)$, e.g. leptons and quarks

The Lagrangian $\mathcal{L}$ yields the action of the physical system, which in principle determines the complete state of the system.

$$ S = \int d^4x \mathcal{L}(\phi(x), \partial_\mu \phi(x)) $$

The equation of motion follows as Euler-Lagrange equations from Hamilton’s principle,

$$ \delta S = 0 \Rightarrow \partial_\mu \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} - \frac{\partial \mathcal{L}}{\partial \phi} = 0 $$

Here, $\phi$ represents a generic field. Then, the major job becomes the construction of $\mathcal{L}$ and the interpretation of experimental results with the theory.
In the SM, the Lagrangian contains the free particle part and the interaction part.

\[ \mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}} \]  \hspace{1cm} (2.3)

The \( \mathcal{L}_{\text{free}} \) can be classified into scalar field, vector fields and Dirac fields, with the forms evolving closely from the knowledge of classical physics, especially electrodynamics and special relativity. However, the \( \mathcal{L}_{\text{int}} \) is completely constructed from the gauge theory; in other words, the SM tends to tell us that the three fundamental forces come from some internal symmetries in the world. In a more convenient and detailed way, Eq 2.3 can be reorganized as

\[ \mathcal{L} = \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{QCD}} = \mathcal{L}_{G} + \mathcal{L}_{F} + \mathcal{L}_{H} + \mathcal{L}_{Y} + \mathcal{L}_{\text{QCD}} \]  \hspace{1cm} (2.4)

Since electromagnetic interaction and weak interaction are unified in the electroweak theory, they are combined in the term of \( \mathcal{L}_{\text{EW}} \), which can be further divided into the gauge boson self interaction term \( (\mathcal{L}_{G}) \), the free fermion term and fermion interaction term \( (\mathcal{L}_{F}) \), the Higgs field term \( (\mathcal{L}_{H}) \) and the Yukawa term \( (\mathcal{L}_{Y}) \), in which fermions or bosons coupling with Higgs field to generate mass. The \( \mathcal{L}_{\text{QCD}} \) is the term from Quantum chromodynamics representing the strong interaction in the nature; and it is separated because currently the electroweak and strong interactions haven’t yet been unified in one framework.

Gauge symmetry plays the key role in the construction of the Lagranges. It dictates the structure of the interactions between fermions and vector bosons as well as vector boson self-interactions. For example, Quantum Electrodynamics (QED) can be derived by the requirement of local \( U(1) \) symmetry; the Electroweak theory is formed by extending it to the non-Abelian case of \( SU(2) \times U(1) \) symmetry, and the Quantum Chromodynamics (QCD) comes with the extension to \( SU(3) \) group.

In QED, the Lagrangian for free charged fermion field \( \psi \) can be denoted as

\[ \mathcal{L}_0 = \bar{\psi} (\gamma^\mu \partial_\mu - m) \psi \]  \hspace{1cm} (2.5)

Where \( \gamma^\mu \) is the covariant Dirac matrices, and \( \bar{\psi} = \psi^+ \gamma^0 \). It takes the form of Dirac equation, which was originally postulated to describe the free relativistic electrons. If consider the invariance under the local phase transformation

\[ \psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)} \psi(x) \]  \hspace{1cm} (2.6)

It is necessary to introduce a vector field \( A_\mu \) and minimal substitution of the derivative in \( \mathcal{L}_0 \) by the covariant derivative

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu - ie A_\mu, \ A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) + \frac{1}{e} \partial_\mu \alpha(x) \]  \hspace{1cm} (2.7)

Which form the electromagnetic gauge group \( U(1) \), and consequently, modify the Lagrangian to be

\[ \mathcal{L} = \bar{\psi} (\gamma^\mu D_\mu - m) \psi = \mathcal{L}_0 + e \bar{\psi} \gamma^\mu \psi A_\mu = \mathcal{L}_0 + \mathcal{L}_{\text{int}} \]  \hspace{1cm} (2.8)

In order to make the gauge field \( A_\mu \) a dynamical field, a kinetic term \( (\mathcal{L}_A) \) should be introduced. The expression is well defined in classical electrodynamics, especially in the formalism
of Maxwell’s equation, which can be denoted as

\[ \mathcal{L}_A = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu}, \]  

with the field strength \( F_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \) (2.9)

\( A_\mu \) becomes the photon field obeying Maxwell’s equations and mediating the electromagnetic force via the interacting term in the Lagrangian. QED gained remarkable success in predicting and interpreting experimental measurements, e.g. the precise agreement between prediction and experimental results for electron’s fine structure constant \([1]\). This success motivated people to seek for similar application of the gauge symmetry on other fundamental phenomenon (e.g. weak and strong interactions). Based on the experience of QED theory, the basic steps of constructing gauge theory can be concluded as three steps: identifying the global symmetry of the free Lagrangian, replacing original derivative \( \partial_\mu \) by the covariant derivative \( D_\mu \) with the introduction of a vector field and adding in kinetic term for the vector field.

To be more generic, let’s consider the extension to \( N \)-dimensional non-Abelian cases. The free Lagrangian for a \( N \)-dimensional multiplet of fermion fields with mass \( m \) can be denoted as

\[ \mathcal{L}_0 = \bar{\Psi} (\gamma^\mu \partial_\mu - m) \Psi, \quad \Psi = (\psi_1, \psi_2, \ldots, \psi_N)^T \]  

(2.10)

Then, the covariant derivative can be simultaneously introduced as

\[ \partial_\mu \rightarrow D_\mu = \partial_\mu - ig W_\mu, \quad W_\mu(x) = T_a W^a_\mu(x) \]  

(summation over \( a = 1, \ldots, N \)) (2.11)

Where \( T_a \) \((a = 1, \ldots, N)\) represents the generators of the Lie group and \( g \) is the introduced coupling constant. The local gauge transformation is then the unitary matrices \( U = U(x) \), which can be written as follows,

\[ U(\alpha^1, \ldots, \alpha^N) = e^{i(\alpha^1 T_1 + \ldots + \alpha^N T_N)} \]  

(2.12)

Similarly, to make sure the Lagrange invariant under this gauge transformation, the vector fields must satisfy

\[ \Psi \rightarrow \Psi' = U \Psi, \quad W_\mu \rightarrow W'_\mu = U W_\mu U^{-1} - \frac{i}{g} (\partial_\mu U) U^{-1} \]  

(2.13)

The last step is to add in the kinetic part. Because of the non-Abelian nature of Lie group with \( N > 1 \), one can find the term a bit different from Eq 2.9

\[ \mathcal{L}_W = -\frac{1}{4} F_{a \mu \nu} F^{a \mu \nu}, \quad F^{a \mu \nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + gf_{abc} W^b_\mu W^c_\nu, \quad a = 1, \ldots, N \]  

(2.14)

Here, \( f_{abc} \) denotes the structure constants for the group. Therefore, the generic Lagrangian can be noted as

\[ \mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{int} + \mathcal{L}_W = \bar{\Psi} (\gamma^\mu \partial_\mu - m) \Psi + g \bar{\Psi} \gamma^\mu W_\mu \Psi + (\partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f_{abc} W^b_\mu W^c_\nu) \times (\partial_\mu W^{a, \nu} - \partial_\nu W^{a, \mu} + g f_{ade} W^{d, \mu} W^{e, \nu}) \]  

(2.15)

There is no mass term for the vector fields, and one can verify that any terms like \( \frac{m^2}{2} W^a_\mu W^a_\nu \) will violate the local gauge symmetry. This infers that the force-mediating bosons in gauge
theory have zero mass, which is in contrary to experimental observations; later we will see how gauge bosons get mass through Higgs mechanism. Another important feature is that $L_W$ contains the vector boson self-coupling terms, which provide many important physics topics, such as the triple-gauge-boson-couplings in this dissertation.

QCD is the gauge theory of strong interaction. Quarks are considered to have three different color states (RGB), i.e. they take “color charge”. The hadrons are constructed by two (mesons) or three quarks (baryons), but they are color neutral. QCD models the strong interaction via interactions between quarks (or gluons) by exchanging gluons. The colors of quarks form the fundamental representation of $SU(3)$ group, and we denote the fermion fields in QCD as $\Psi = (q_1, q_2, q_3)^T$ for each quark flavor (u,d,...) By introducing the additional gluon filed, the covariant derivative and the field strength turn out to be

$$D_\mu = \partial_\mu - ig_s \frac{\lambda^a}{2} G^a_\mu$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f_{abc} G^b_\mu G^c_\nu$$ (2.16)

Where $\lambda^a$ is the Gell-Mann matrices having $\lambda^a = 2T^a$ (SU(3) generators), and the dimensionless parameter $g_s$ is the coupling constant of QCD, which is often expressed in terms of fine structure constant of the strong interaction $\alpha_s = \frac{4\pi}{g^2}$. The QCD Lagrangian can be easily written down as

$$L_{QCD} = \bar{\Psi} \left( i \gamma_\mu \partial_\mu - m \right) \Psi + g_s \bar{\Psi} \gamma^\mu \frac{\lambda^a}{2} \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$ (2.17)

It contains the quark-gluon interaction terms as well as the gluon self-coupling terms, which therefore defines the strong interaction. Since there are six flavors of quarks and each of them is associated with one mass $m_q$, there are totally seven free parameters in the Lagrange (together with the coupling constant).

The remaining parts of the SM are the unification of electromagnetic and weak interactions (electroweak theory) and the generation of mass through Higgs mechanism. Only the left-handed fermions participate in weak interactions, and fermions can be divided into left-handed doublet and right-handed singlet, which represents the group $SU(2) \times U(1)$. In terms of electroweak theory, there are two important historical quantum numbers: the weak isospin $(I, I_3)$ and the weak hypercharge $Y$. The isospin separates the left-handed fermions ($I = \frac{1}{2}$) and right-handed fermions ($I = 0$), and the hypercharge is related to electric charge via Gell-Mann-Nishijima relation [2],

$$Q = I_3 + \frac{Y}{2}$$ (2.18)

The group of $SU(2) \times U(1)$ is 4-dimensional, and it could be generated by $I_1, I_2, I_3$ and $Y$. According to the generic rules of constructing local gauge invariant theory and the fact that right-handed and left-handed fermions follow different gauge groups, we need to introduce two sets of vector fields, with one istriplet and one isosinglet as

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon_{abc} W^b_\mu W^c_\nu, \ a = 1, 2, 3$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$ (2.19)
The group have the Abelian $U(1)$ part and the non-Abelian $SU(2)$ part, so there are two independent coupling constants, denoted by $g_2$ for $SU(2)$ and $g_1$ for $U(1)$. Similar to Eq 2.9 and Eq 2.14, the kinetic terms of the vector fields can be written as

$$L_V = -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \ a = 1, 2, 3$$

(2.20)

Given that left-handed and right-handed fields are represented by different gauge groups, it is convenient to define

$$\psi_L = \frac{1 - \gamma^5}{2} \psi, \ \psi_R = \frac{1 + \gamma^5}{2} \psi, \ \psi_L^j = \begin{pmatrix} \psi^j_L^+ \\ \psi^j_L^- \end{pmatrix}, \ \psi_R^j$$

(2.21)

with $\sigma = \pm$ to denote the up and down types of fermions. The covariant derivative and the modified Lagrangian can be written as

$$D_{\mu}^{L,R} = \partial_{\mu} - ig_2 I^{L,R}_a W^a_{\mu} + ig_1 \frac{Y}{2} B_{\mu}, \ I^L_a = \frac{1}{2} \sigma_a, \ I^R_a = 0, \ a = 1, 2, 3$$

$$L_F = \sum_j \overline{\psi}_L^j i \gamma^\mu D^L_{\mu} \psi_L^j + \sum_{j, \sigma} \overline{\psi}_R^j i \gamma^\mu D^L_{\mu} \psi_R^j$$

(2.22)

The question of the origin of mass is solved by the spontaneous breaking of $SU(2) \times U(1)$ symmetry with the introduction of Higgs field and Yukawa interactions. Consider the Higgs field as a doublet of complex scalar fields with $Y = 1$,

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$$

(2.23)

which satisfies the Klein-Gorden equation and therefore has the Lagrangian as

$$L_H = (D_{\mu} \Phi)^+(D^\mu \Phi) - V(\Phi)$$

(2.24)

with the covariant derivative ($I = \frac{1}{2}, \ Y = 1$) following Eq 2.22

$$D_{\mu} = \partial_{\mu} - ig_2 I_a W^a_{\mu} + ig_1 \frac{Y}{2} B_{\mu}$$

(2.25)

The Lagrange is easy to note down, but you can find the potential (self interaction term) is left undefined. For free massive scalar particles, there is $V(\Phi) = \mu^2 \Phi^+ \Phi$ with $\mu$ denoting the mass; however, in order to make this term renormalizable, we will have

$$V(\Phi) = \mu^2 \Phi^+ \Phi - \frac{\lambda}{4} (\Phi^+ \Phi)^2, \ \mu^2, \lambda > 0$$

(2.26)

It is natural that the potential become minimum in the ground state, so one can get $\Phi^+ \Phi = 2\mu^2 / \lambda$, which proposes the vacuum expectation value as

$$< \Phi_{vacuum} >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \ v = \frac{\mu}{\sqrt{\lambda}}$$

(2.27)

The Lagrangian itself is symmetric under local gauge transformation of $SU(2) \times U(1)$, but
the vacuum expectation value is certainty not invariant under SU(2) transformation, which corresponds to the famous “spontaneous symmetry breaking”. The field in Eq 2.23 can be expressed as

\[ \Phi(x) = \left( \frac{\phi^+(x)}{(v + H(x) + iK(x))/\sqrt{2}} \right) \quad (2.28) \]

By certain gauge transformation, one can eliminate the \( \phi^+ \) and \( K(x) \). This particular gauge is called unitary gauge, and it yields the Higgs field with form

\[ \Phi(x) = \left( 0 \right) \quad (v + H(x))/\sqrt{2} \quad (2.29) \]

Then, one can easily verify that \( V = V(M_H, H^2) \); The real scalar field \( H(x) \) (Higgs boson) is thus introduced, which has mass \( M_H = \mu \sqrt{2} \). The Lagrangian in Eq 2.24 yields the couplings between Higgs fields and gauge boson fields, which generate mass for bosons and introduce the triple or quadratic vertices between them. Similarly, in order to generate mass for fermions, the Yukawa interactions between Higgs field and fermion fields are introduced. And in the unitary gauge, the Yukawa Lagrangian is rather simple as

\[ L_Y = -\sum_f m_f \bar{\psi}_f \psi_f - \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f H \quad (2.30) \]

Where \( m_f \) represents the mass of fermion, and relates to Yukawa coupling constants \( G_f \) via

\[ m_f = G_f \frac{v}{\sqrt{2}}. \]

By applying Eq 2.27 to the Lagrangian in Eq 2.24, we can evaluate the mass terms of vector gauge fields. In order to make the term diagonal, we can introduce

\[ W^\pm_{\mu} = \frac{1}{\sqrt{2}} (W^1_{\mu} \mp iW^2_{\mu}) \]

\[ \begin{pmatrix} Z_{\mu} \\ A_{\mu} \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W^3_{\mu} \\ B_{\mu} \end{pmatrix} \quad (2.31) \]

This transformation makes the mass term like

\[ M_W^2 W^+_{\mu} W^-_{\mu} + \frac{1}{2} (A_{\mu}, Z_{\mu}) \begin{pmatrix} 0 & 0 \\ 0 & M_Z^2 \end{pmatrix} \begin{pmatrix} A_{\mu} \\ Z_{\mu} \end{pmatrix} \quad (2.32) \]

with some relations in the following

\[ M_W = \frac{1}{2} g_2 v, \ M_Z = \frac{1}{2} \sqrt{g_1^2 + g_2^2} v, \ \cos \theta_W = \frac{M_W}{M_Z} \quad (2.33) \]

One can also relate the electric charge \( e \) as

\[ g_2 = \frac{e}{\sin \theta_W}, \ g_1 = \frac{e}{\cos \theta_W} \quad (2.34) \]

These expressions reveal that there are two massive vector bosons and one massless vector
boson in the electroweak theory, which are the mass eigenstates of original interaction term between vector fields and Higgs fields. The $\theta_W$ is the Weinberg angle, also referred to as weak mixing angle; and experimentally the massive bosons are $W^\pm$ and $Z$, massless one is the photon.

In reality, one needs to take the flavor mixing into account in the quark sector; it makes the Yukawa interaction not diagonal. To diagonalize the mass term, we need the help of the mixing matrices

$$\tilde{u}_{iL,R} = (V^u_{L,R})_{ik} u^k_{L,R}, \quad \tilde{d}_{iL,R} = (V^d_{L,R})_{ik} d^k_{L,R} \quad (2.35)$$

Where $u$ and $d$ denote the index of up and down type quarks. The mass term can be diagonalized as

$$\text{diag}(m_q) = \frac{v}{\sqrt{2}} V^q_L G_q V^q_R, \quad q = u, d \quad (2.36)$$

This expression illustrates the quark masses and the mass eigenstates; and the Yukawa interaction between quarks and Higgs in Eq 2.30 remains the same under this transformation. An important feature on the quark mixing occurs in the flavor changing case via interacting with the vector bosons (Eq 2.22), where applying the mass eigenstates yields the unitary CKM matrix,

$$V^u_L V^d_L \equiv V_{CKM} \quad (2.37)$$

The CKM matrix is a fundamental content in the SM, which demonstrates the mixing behavior of quarks, and it has four independent physical parameters including three real angles and one complex phase.

The fermion-gauge interactions are part of the fermion Lagrangian in Eq 2.22. These terms can be expressed and classified into the interactions between the electromagnetic current $J^\mu_{em}$, the weak neutral current $J^\mu_{NC}$ and the weak charged current $J^\mu_{CC}$ with corresponding vector bosons fields.

$$\mathcal{L}_{FG} = J^\mu_{em} A_\mu + J^\mu_{NC} Z_\mu + J^\mu_{CC} W^-_\mu + J^\mu_{CC} W^+_\mu \quad (2.38)$$

To get a clear view, the mathematical expressions are listed below (obtained from the Lagrangian)

$$J^\mu_{em} = -e \sum_{l,q} Q_f \bar{\psi}_f \gamma^\mu \psi_f$$

$$J^\mu_{NC} = \frac{g_2}{2 \cos \theta_W} \sum_{l,q} \bar{\psi}_f (\gamma^\mu - a_f \gamma^\mu \gamma^5) \psi_f$$

$$J^\mu_{CC} = \frac{g_2}{\sqrt{2}} \left( \sum_{i=1,2,3} \bar{\tilde{d}}_i \gamma^\mu \frac{1 - \gamma^5}{2} e^i + \sum_{i=1,2,3} \bar{\tilde{u}}_i \gamma^\mu \frac{1 - \gamma^5}{2} V_{ij} d^j \right)$$

The $e$ and $\nu$ denote the three generation of leptons, and the neutral current coupling constants
are defined as

\[ v_f = I_3^f - 2Q_f \sin^2 \theta_W, \quad a_f = I_3^f \]

By writing down these expressions in detail, one can easily see that the neutral current flavor changing process is suppressed (may only occur at high order). It is because of the flavor-diagonal feature of the CKM matrices.

The gauge field self interaction term is essentially the kinetic term of the vector gauge fields as described in Eq 2.20 for electroweak theory and partially in Eq 2.17 for QCD. And it is induced from the non-Abelian feature of SU(2) or SU(3), as you can check in Eq 2.14. Expanding the full expression of \( \mathcal{L}_{G,\text{self}} \) could be very complicate, but you can refer to Eq 2.15 for a generic analogy. The actual expression will be formed by substituting the \( W_\mu^a \) fields with the physical \( W^\pm, Z \) and photon fields. The key point here is that the self-interaction (including triple, quadratic vertices) is completely determined by gauge theory; i.e. the SM predict it precisely, and any deviation from the SM predicts new physics.

We’ve briefly reviewed the SM via gauge theory and Lagrangian formalism. Now, the total Lagrangian in Eq 2.4 can be completed by adding the QCD term in Eq 2.17, the fermions term in Eq 2.22, the Higgs term in Eq 2.24, the gauge field self interaction term in Eq 2.20 and the Yukawa interaction term in Eq 2.30. The combined Lagrangian is

\[
\mathcal{L} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} \\
= \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_H + \mathcal{L}_Y + \mathcal{L}_{QCD} \\
= -\frac{1}{4} W_\mu^a W^{a,\mu\nu} - \frac{1}{4} B_\mu B^{\mu\nu} \\
+ \sum_j \bar{\psi}_L^j i \gamma^\mu D^L_\mu \psi_L^j + \sum_{j,\sigma} \bar{\psi}_{R,\sigma}^j i \gamma^\mu D^L_\mu \psi_{R,\sigma}^j + \\
(D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) + \\
- \sum_f m_f \bar{\psi}_f \psi_f - \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f H + \\
\bar{\psi} (i \gamma^\mu \partial_\mu - m) \psi + g_s \bar{\psi} \gamma^\mu \frac{\lambda_a}{2} \Psi G_\mu^a - \frac{1}{4} G_{\mu\nu}^a G^{a,\mu\nu} 
\]

The covariant derivative in QCD and electroweak Lagrangian are different. The purpose of Eq 2.41 is just to provide one single place to demonstrate all the components in the SM. The SM is determined by a set of free parameters (19 in total), which are mostly measured empirically through experiments. The parameters are three lepton masses, and six quark masses, the \( U(1) \) coupling constant \( g_1 \), the \( SU(2) \) coupling constant \( g_2 \), the \( SU(3) \) coupling constant \( g_3 \) (or strong interaction constant \( \alpha_s \)), Higgs mass \( M_H \) and its vacuum expectation value \( v \), QCD vacuum angle (\( \theta_{QCD} \)), and four parameters from CKM matrix including three angles and one phase. At present, all parameters have been measured except the Higgs mass (tends to be around 125 GeV from hints in recent LHC results).

Experimentally, we measure the cross-section for given process and compare with the SM prediction. The theoretical calculation could be very lengthy and sophisticated and not intuitive. Feynman diagram is widely adopted by physicists as the very tool, which enables us to visualize the process in terms of lines presenting particle flows and vertices representing interactions and form the integral from those lines (field propagators) and vertices (couplings).
to determine the interaction amplitude. An example of Feynman diagram can be found in Figure 2.2, which demonstrates the process of $e^+e^- \rightarrow q\bar{q}$. For a given physical process, the cross-section is calculated as combination of the amplitudes from all possible diagrams. The propagator comes from the Lagrangian, which gives the amplitude of field (particle) transition from one space-time point to another, and it often takes the form like

\begin{align}
\text{Fermions:} & \quad i(\gamma^\mu k_\mu - m) \frac{1}{k^2 - m^2 + i\epsilon}, \\
\text{Bosons:} & \quad ig_\nu \rho \frac{1}{k^2 - m^2 + i\epsilon},
\end{align}

(2.42)

Where $k$ is the momentum transfer and $\epsilon$ is the casual boundary condition for integral. One can demonstrate the “weakness” of weak interaction via its small cross-section at low energy since the mediating particles have heavy mass ($W^\pm, Z$).

In reality, the high order diagrams must be included in order to compare with experiment results. Renormalization is introduced to cope with the ultraviolet divergence of high order diagrams. In physical point of view, the divergence mainly come from the high energy limits of the momentum integration, and from this perspective, renormalization is a procedure which allows us to sensibly calculate the effects of the low-energy physics, independent of how it is corrected at high energies. The mathematics can go very complicate, but for a general description, I will say the procedure is about defining a cutoff scale ($\Lambda$) according to the experimental limit, separating the high order term into finite and divergent terms ($\Lambda \rightarrow \infty$), and then absorbing the divergent term into tree-level propagator by modifying the parameters (e.g. the mass and couplings) and fields. The finite term then becomes measurable. By renormalizing the parameters and fields, the Lagrangian remains at same format, which is essential to satisfy the gauge symmetry in the model; in the meantime, the prediction of tree level plus high order terms become finite under certain cutoff scale, which is directly comparable to experiment.

The SM has done perfectly well so far. The electroweak theory is verified in many manners: the discovery of $W^\pm$ and $Z$ in LEP, the precise agreement of theoretical cross-sections and experimental measurements and etc. With the approximations to place space-time on a four dimensional lattice, QCD (lattice QCD [3]) can be simulated on a computer, which yields some important understanding, such as the "running coupling constants" saying the nature of confinement of quarks in hadrons. Although a beautiful and powerful theory, the SM still has some uncertainties and shortage,
- Higgs boson has not been verified
- Neutrino mass from neutrino oscillation experiments
- The hierarchy problem and the question that is the fine-tuning natural?
- Gravitation is not described in the theory, and the Grand unification of electroweak and QCD has not been formed
- As a fundamental theory for physical world, should be able to describe dark energy and dark matter

which will be answered in the future particle physics researches.

2.2 Hadron Collider Physics

Our knowledge of physics in the sub-nuclear domain ($10^{-13}$ cm and smaller) is largely derived from the outcomes of high-energy collisions of elementary particles produced in colliders. While the size and sophistication of colliders have steadily grown, the basic experimental setup has remained unchanged since late 1960s. First, a particle accelerator uses a carefully designed combination of electric and magnetic fields to produce narrowly focused beams of energetic particles (typically electrons, protons, and their antiparticles). Then, two beams collide head-on, usually with equal and opposite momenta so that the center-of-mass frame of the colliding system coincides with the laboratory frame. The region where collisions occur is surrounded by a set of particle detectors, which attempt to identify the particles coming out of the collision, and measure their energies and momenta. The typical modern detector consists of an inner detector measuring the momenta of outcoming particle trajectories, an calorimeter system monitoring the energy deposit through electromagnetic or hadronic cascades, a muon system detecting the long living muons and magnets providing bending power for momentum measurements. According to the uncertainty principle $\Delta x \Delta p \geq \frac{\hbar}{2}$, the higher energy we collide, the smaller scale we can probe. The Tevatron and the LHC have been operated in CME of TeV scale, providing amazing discovery potentials which had never been reached before. Collider experiments collect and analyze outcomes of huge number of collisions, and the rate of interested events can be compared to the cross-section predicted by theory. Therefore, the agreement or disagreement between theory and data correspond to the validation of the tested theory or discovery of new physics, which are the main physics activity in collider experiments.

Consider the head-on collision of two elementary particles, the four momenta of colliding particles in the center-of-mass frame are

$$p_A = (E, 0, 0, +E), p_B = (E, 0, 0, -E) \quad (2.43)$$

with choosing z axis along the direction of the A momentum. The total energy of the colliding system, the center-of-mass energy (CME), is then $E_{CM} = 2E$. We will also frequently use the Mandelstam variable $s = (p_A + p_B)^2 = E_{CM}^2$. The scattering cross section for particular final state can be expressed below

$$\sigma = \frac{(Number\ of\ events) \cdot A}{N_A N_B} \quad (2.44)$$

Where A denotes the beams’ cross-sectional area and $N_A$ and $N_B$ denote the number of particles in each beam. If beam collide with frequency $f$, then the rate of the interested
events can be written as

\[ R = L \cdot \sigma, \quad L = \frac{N_A N_B f}{A} \]  \hspace{1cm} (2.45)

Here, \( L \) is the instantaneous luminosity. The rate \( R \) is measured directly by experimentalists, and carefully compared to theoretical predictions. The \( L \) (together with \( E_{CM} \)) contains all the information about the accelerator needed to analyze the experiment. For hadron colliders, high-energy processes are initiated by partons, which only carry a fraction of the hadron’s momentum, the energy scales that can be probed at a hadron collider are substantially lower than this energy, typically by factors of \( 3 - 10 \) depending on the process. Electron-positron colliders, on the other hand, are able to explore many reactions at energy scales extending all the way to their nominal \( \sqrt{s} \). The luminosity values are often shown as the integrated luminosities, \( L_{int} = \int L dt \). Table 2.2 shows the basic parameters of recent colliders.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( L_{int} ) (pb(^{-1}))</th>
<th>Years of operation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>( e^+e^- )</td>
<td>91.2 (LEP-1)</td>
<td>( \approx 200 ) (LEP-1)</td>
<td>1989-95 (LEP-1)</td>
<td>CERN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>130-209 (LEP-2)</td>
<td>( \approx 600 ) (LEP-2)</td>
<td>1996-2000 (LEP-2)</td>
<td></td>
</tr>
<tr>
<td>SLC</td>
<td>( e^+e^- )</td>
<td>91.2</td>
<td>20</td>
<td>1992-98</td>
<td>SLAC</td>
</tr>
<tr>
<td>HERA</td>
<td>( e^\pm p )</td>
<td>320</td>
<td>500</td>
<td>1992-2007</td>
<td>DESY</td>
</tr>
<tr>
<td>Tevatron</td>
<td>( pp )</td>
<td>1800 (Run-I)</td>
<td>160 (Run-I)</td>
<td>1987-96 (Run-I)</td>
<td>FNAL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1960 (Run-II)</td>
<td>12K</td>
<td>2000-2011 (Run-II)</td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td>( pp )</td>
<td>7000</td>
<td>5000</td>
<td>2010-2011</td>
<td>CERN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8000</td>
<td>( \approx 13K )</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>14000</td>
<td></td>
<td>2014-</td>
<td></td>
</tr>
<tr>
<td>ILC</td>
<td>( e^+e^- )</td>
<td>500-1000</td>
<td>?</td>
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</table>

Table 2.2: Recent and future particle colliders

The important feature of hadron collisions is that the initial state consists of composite particles. According to the parton model, production of final states with total invariant mass large compared to \( \Lambda_{QCD} \) is initiated by a pair of partons, with the rest of colliding hadrons serving as spectators, which can be written as \[ 4 \]

\[ d\sigma(p(P_1) + p(P_2) \rightarrow Y + X) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i_1,i_2} f_{i_1}(x_1) f_{i_2}(x_2) d\sigma(i_1(x_1)P_1 + i_2(x_2)P_2 \rightarrow Y) \]  \hspace{1cm} (2.46)

Here, \( Y \) denotes the high-invariant-mass final state of interest; \( X \) denotes anything else (including the remnants of the colliding protons); \( P_1 \) and \( P_2 \) are the momenta of incoming protons, and \( x_1 \) and \( x_2 \) are the fractions of those momenta carried by the partons that participate in the reaction; the index \( i_1 \) and \( i_2 \) represent the types of partons, which need to be summed over while calculating the cross-section. The \( f(x) \) is the parton distribution function (PDF), and the parton-level cross-section is express as \( \sigma(i_1(x_1)P_1 + i_2(x_2)P_2 \rightarrow Y) \). The frame in which the center of mass of the colliding partons is at rest (parton frame), is moving with
respect to the lab frame in the case of equally head-on collision with velocity

\[ \beta = \frac{x_1 - x_2}{x_1 + x_2} \]  

(2.47)

along the beam axis. The invariant mass of the state Y has to be equal to the parton center-of-mass energy \( \sqrt{s} \),

\[ \hat{s} = x_1 x_2 s \]  

(2.48)

The \( \beta \) and \( \hat{s} \) can be determined event by event if the state of \( Y \) can be fully reconstructed, but not if there is invisible particles (e.g. neutrinos) in the final states.

The PDFs in Eq 2.46 represent the probability densities to find a parton carrying a momentum fraction \( x \) at certain energy scale. It accounts for emission of collinear initial state radiation (ISR) gluons, whose transverse momentum is too small for them to be detected individually and for further splitting of these gluons into collinear \( q\bar{q} \) and \( gg \) pairs. The PDFs depend on the minimal transverse momentum \( Q \) (related to the energy scale of the hard interaction) for which a gluon (or a quark from gluon splitting), and thus they are real functions of two arguments, \( x \) and \( Q \), which could be expressed as

\[ \frac{\partial f_g(x, Q)}{\partial \log Q} = \frac{\alpha_s}{\pi} \int_x^1 \frac{dz}{z} \left[ P_{q\to g}(z)(f_q(xz, Q) + f_{\bar{q}}(xz, Q)) + P_{g\to g}(z)f_g(xz, Q) \right] \]  

(2.49)

with the splitting function given by [4]

\[ P_{q\to g} = \frac{4}{\pi} \left( \frac{1 + (1 - z)^2}{z} \right) \]  

\[ P_{g\to g} = 6 \left[ \frac{z}{(1 - z)} + \frac{1 - z}{z} + z(1 - z) + \left( \frac{11}{12} - \frac{n_f}{18} \delta(1 - z) \right) \right] \]  

(2.50)

Where \( f_q \), \( f_{\bar{q}} \) and \( f_g \) denote the quark, antiquark and gluon distribution function; \( z \) is the proportion of energy taken from the initial parton by emitted gluon (thus \( z = 1 - x \)), and \( n_f \) is the number of quark types with \( m < Q \). The physical meaning of Eq 2.50 is as follows: if we shift the \( Q \to Q + dQ \), the previous detected gluons with transverse momentum \( \in [Q, Q + dQ] \) become undetectable and part of the beam, which is then included in \( f_g \). And this process is reflected in the right as the probabilities of emitting gluons at \( z \cdot E \) from initial partons.

Cross sections are calculated by convoluting the parton level cross section with the PDFs. Since QCD does not predict the parton content of the proton, the shapes of the PDFs are determined by a fit to data from experimental observables in various processes, using the DGLAP evolution equation (Eq 2.50). The knowledge of proton PDFs mainly comes from the Deep Inelastic Scattering (DIS) HERA [5], fixed target and Tevatron data. The recent precise Tevatron and LHC data has a potential to improve constraints of the PDFs further. For example, through the W lepton asymmetry the different quark contributions can be accessed and with inclusive jet productions it is possible to constrain the gluon PDF.

As for the modern hadron colliders like Tevatron and LHC, the total scattering cross-section \( \sigma_{\text{tot}} \sim 0.1 \) barn is completely dominated by low \( p_T \) QCD scatterings. The inclusive cross section for \( b \) quark production is about 2 – 3 orders of magnitude lower. However, the strongest electroweak productions of single W and Z are at the level of \( 10 \sim 100 \) nb. Therefore,
conducting precise SM measurements and searching for new physics require particularly careful handle of the QCD background.

2.3 WZ Physics

2.3.1 WZ Production

The underlying structure of the electroweak theory in the SM is the non-Abelian \(SU(2) \times U(1)\) gauge group, as you can see in Section 2.1. This model has been very successful in describing currently available experimental data. Features like vector boson masses and their coupling to fermions have been precisely tested at LEP and Tevatron. However triple gauge boson couplings (TGC) predicted by this theory have not yet been determined with the same precision. In the SM the TGC vertex is completely fixed by the electroweak gauge structure and so a precise measurement of this vertex, through the analysis of diboson production at the LHC, is essential to test the high energy behavior of electroweak interactions and to probe for possible new physics in the bosonic sector. Any deviation from gauge constraints can cause a significant enhancement of the production cross-section at high diboson mass region due to anomalous gauge boson couplings.

At the LHC, the dominant diboson production mechanism is from quark-antiquark initial states; the gluon-gluon fusion normally contributes much less, and it is precluded in the case of \(W^±Z\) because of the requirement of charge conservation. Figure 2.3 shows the leading-order Feynman diagrams for \(W^±Z\) production with \(q\bar{q}'\) initial states. The SM total cross-section at 7TeV in the LHC is calculated to be 17.6\(^{+1.1}_{-1.0}\) pb using MCFM with parton density function set CT10 and an \(66 < M_{\ell\ell} < 116\) GeV mass cut. Since the LHC is a proton-proton collision machine, there is a larger \(W^+Z\) production cross-section than \(W^-Z\) (around 50%).

Figure 2.3: \(W^±Z\) production with \(q\bar{q}'\) initial states, in s-channel (left), t-channel (middle) and u-channel (right)

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The first major goal of studying the \(W^±Z\) production is to further test the SM electroweak theory at new high energy frontier. And the opportunity is unique since it is one of the least tested processes because of its small cross-section and high energy requirement and the fact that it can only be created in hadron collider. Then follows the interesting topic of TGC measurement, which can act as either precise test of the SM or the door to new physics. \(W^±Z\) production would also give hints to some extended models, such as supersymmetric models with an extended Higgs sector (charged Higgs), models with extra vector bosons (e.g. \(W^0\)) and technicolor.
2.3.2 Search for new physics

The theoretical approach to new physics in the SM falls broadly into two areas: model dependent and model independent. The model dependent approach has supersymmetric minimal standard model as the leading candidate. There are also the dynamical symmetry breaking technicolor model, left-right model, top color model, top color assisted technicolor model, and various other models. The model independent approach is mainly the effective Lagrangian approach.

The search for anomalous triple gauge boson couplings (aTGC) belongs to the model independent approach. In Eq 2.15, we already see what the universal format of gauge field self interaction terms look like. In order to formulate the test of the self couplings of the gauge bosons as effective Lagrangian, we usually introduce a Lagrangian containing non-standard-model interactions, assuming some symmetry for them. The most general Lagrangian assuming the electromagnetic gauge invariance, the Lorentz symmetry, and C and P conservation is given by \[ \mathcal{L}_{WWV}^{g_{WWV}} = ig_1 V \left( W_{\mu}^{+} W_{\mu}^{\mu} V^{\nu} - W_{\mu}^{+} V_{\nu} W^{\mu \nu} \right) + i \kappa_{V} W_{\mu}^{+} W_{\nu} V^{\mu \nu} + i \frac{\lambda_{V}}{m_{W}} W_{\mu}^{+} W_{\mu}^{\nu} V^{\nu \lambda} \] (2.51)

Where \( V \) can be \( Z \) or \( \gamma \), \( W_{\mu}^{\nu} \) and \( V_{\mu}^{\nu} \) are the corresponding field strength and \( g_{WWZ} = -e \) and \( g_{WWZ} = e \cot \theta_{W} \). In the SM, we have \( g_1 Z = \kappa_{V} = 1 \) and \( \lambda_{V} = 0 \). Since the electromagnetic \( U(1) \) gauge symmetry requires \( g_1 \gamma \) to be 1, there are five parameters in the Lagrangian. And in the case of WZ production shown in Figure 2.3, only the WWZ vertex contributes, which contains three parameters as

\[ \Delta g_1 Z = g_1 Z - 1, \ \Delta \kappa_{Z} - 1, \ \lambda_{Z} \] (2.52)

And in the SM, they are exactly zero. Furthermore, to avoid tree-level unitarity violation, the anomalous couplings must vanish as \( \hat{s} \), which is the four-momentum squared of the \( W^{\pm} Z \) system, approaches infinity. To achieve this, a form factor is introduced as

\[ \alpha_{S} = \frac{\alpha_{0}}{\left(1 + \hat{s}/\Lambda^{2}\right)^{2}} \] (2.53)

Where \( \alpha_{S} \) stands for the three aTGC parameters and \( \alpha_{0} \) is their value in low energy limit and \( \Lambda \) is the cutoff scale defined as the threshold above which new physics may occur. The enhancement of aTGC on the \( W^{\pm} Z \) production grows with the \( \hat{s} \), which is analogous to the case in renormalization of the SM that divergent terms grow bigger and bigger with \( \Lambda \) arising. This understanding predicts that the aTGC is most sensitive to the tail of kinematics distribution, which enables us to further improve the limit with proper binning the distributions.

As for the model dependent approach, the extended gauge models (EGMs [8]) and the technicolor model will be compared to data in this dissertation; therefore, I will briefly describe them below.

The EGMs are the nature extensions of the SM. Current experimental measurements at the “electroweak” scale (100GeV) greatly support the hypothesis of the SM as \( SU(3) \times SU(2) \times U(1) \) group. And many scenarios infer that the SM is just an effective low energy version of the more conclusive and complex gauge structure which might occur at higher energy regime. With gauge theory extended to high energy (e.g. in TeV scale), new heavy gauge boson must
be proposed; and searching for those heavy gauge bosons (e.g. $W'$, $Z'$) would be the clean signature for new physics beyond the SM. There are enormous models within the EGMs, and the EGMs can be divided into two very general classes depending upon whether or not they originate from a GUT (Grand Unification Theory) group. The unifiable EGMs normally predict new gauge bosons similar to the SM with generation-independent couplings (similar to $W$, $Z$); however, it is not certain in non-unifiable EGMs. The Sequential Standard Model (SSM), one of the unifiable kinds, is often used as the reference in experiments. The new gauge boson $W'$ and $Z'$ are just heavy versions of the SM gauge bosons, which couples to fermions in similar manner but the couplings to the SM gauge bosons are suppressed by the factor of $M_{W'}/M_{W_0}$. The strong mass limit certainly comes from leptonic decay channels, but the diboson decay of $W'$ is still an independent clean channel which could contribute and even contribute mostly in the case that the new gauge boson is leptophobic (coupling to fermions suppressed). The typical cross-section for $p\bar{p} \rightarrow W' \rightarrow W + Z$ with 500GeV mass at 7TeV in the LHC is about 100 fb. It doesn’t exactly differ from the previous SM cross-section by a factor of $M_{W'}/M_{W_0}$, because of the fact that the $WWZ$ vertex is one of the three production modes in the SM. Although having smaller cross-section and the final yields of possible $W'$ signal are expected to be negligible compared to the SM $W^\pm Z$ production, we can still have good sensitivity by looking at the mass or transverse mass distributions of the $W^\pm Z$ system given the resonant nature of $W'$ signal. The typical Feynman diagram can be seen on the left in Figure 2.4.

The technicolor model (TC) emerged when people started to consider the unnaturalness of Higgs mechanism in the SM and its related hierarchy and fine-tuning problems. The first question is how gauge bosons get mass without introducing Higgs field. While studying the SM Lagrangian without scalar Higgs fields, people found that the vacuum polarization inside a gauge boson propagator gives it a mass-like term [9]. As you can see in Figure 2.5, a quark-antiquark loop is induced in the propagator of a SM $W$ boson. Technically, the vacuum

Figure 2.4: The Feynman diagrams for $p\bar{p} \rightarrow W' \rightarrow W + Z$ (left) and $p\bar{p} \rightarrow \rho_T \rightarrow W + Z$ (right)

Figure 2.5: The illustrative diagram for virtual $q\bar{q}$ pair loop in $W$ boson propagator
polarization $\pi(k^2)$ appears in the propagator of W boson

$$\frac{g_{\mu\nu} - k_{\mu}k_{\nu}/k^2}{k^2(1 + g^2\pi(k^2))} \tag{2.54}$$

Where $\pi(k^2)$ is the polarization function and it develops a pole at $k^2 = 0$ with residue $F^2$ (the square of the Goldstone boson $\pi$’s decay constant). Consequently, the W boson acquires mass as $M \approx gF$, which is at the level of 100 MeV$^2$. Although the mass is several order of magnitudes lower than the electroweak scale, this finding illustrates the fact that the composite Goldstone boson like $\pi$ can act similarly as Higgs to generate boson mass.

Based on this knowledge, the TC [10] is proposed as a new strong gauge interaction at the electroweak scale $\Lambda_{TC} \sim F_{EW} \sim 100$ GeV (to be compared with the $\Lambda_{QCD}$ round 200 MeV), which forms $SU(N_{TC})$ group. The coupling $\alpha_{TC}$ becomes strong at electroweak scale, and spontaneously breaks the technifermion’s chiral symmetry and introduces Goldstone bosons, three of which become the longitudinal components of $W^{\pm}$ and $Z$ bosons, with $M_W = M_Z \cos \theta_W = \frac{1}{2}gF_{\pi}$. Here $F_{\pi}$ is the decay constant of the “technipions” ($\pi_{TC}$). Analogous to the previous example, the mass of SM bosons can be considered as the results of their mixture with $\pi_{TC}$. The TC, like QCD, is asymptotically free, which could be a cure to the naturalness problem. However, there is no way to give mass to fermions in the original TC model, therefore the extended technicolor (ETC) is introduced. In the ETC, ordinary $SU(3)$, $SU(N_{TC})$ and flavor symmetries are unified into the ETC gauge group, $G_{ETC}$. The energy scale of ETC gauge symmetry breaking into $SU(3) \otimes SU(N_{TC})$ is high, well above the TC scale of 0.1 – 1.0 TeV. The broken gauge interactions, mediated by massive ETC boson exchange, give mass to quarks and leptons by connecting them to technifermions. Producing realistic values of fermion masses from the ETC interactions without simultaneously generating large flavor-changing neutral currents (FCNC) is difficult; the best prospects are “walking” technicolor models where the presence of many technifermions flavors causes the technicolor gauge coupling to vary only slowly with energy scale. Even in those models, it is difficult to generate the observed mass of the top quark from ETC interactions without producing unacceptably large weak isospin violation. The best known solution is to generate most of the top quark’s mass via new strong “topcolor” dynamics, without a large contribution from ETC.

The Low scale technicolor model (LSTC) (see reference [11]) predicts presence of an isospin-1, vector technirho $\rho_T$, decaying to vector boson pairs, which could share similar final states in the $W^{\pm}Z$ production, as in the right of Figure 2.5. In this dissertation, limits on $\rho_T$ is set, based on the principal LSTC parameters: number of technicolors $N_{TC} = 4$, charges of up-type and down-type technifermions $Q_U = Q_D + 1 = 1$, the mixing angle between technipions and electroweak gauge bosons $\sin \frac{\delta}{2} = \frac{1}{3}$, and the axial and vector mass parameters affecting the couplings of the vector and axial-vector mesons to transversely polarized gauge bosons and technipions $M_{V_{1,2}} = M_{A_{1,2}} = M_{\rho_T}$. The axial-vector mass $M_{\omega_T}$ will be studied in two cases: $M_{\omega_T} = 1.1M_{\rho_T}$ and $M_{\omega_T} \rightarrow \infty$. Besides, the isor triplet $\rho_T$ and the isosinglet $\omega_T$ are pretty much degenerated in mass due to the techni-isospin asymmetry assumed in LSTC, so the signal is generally the mixing of the two, but will be referred to $\rho_T$ for simplicity. The typical production cross-section for $\rho_T$ at 7 TeV at the LHC is around 100 fb. Again, this tiny signature could be manifested at the tail region of $W^{\pm}Z$ system mass spectrum since the SM
contribution drops exponentially as the mass goes high.
Chapter 3

LHC and ATLAS detector

3.1 LHC

The large hadron collider (LHC), world’s largest and highest-energy particle accelerator, lies between 45 m and 170 m beneath French-Swiss border near Geneva, Switzerland. It is a two-ring-superconducting-hadron accelerator and collider installed in the existing 26.7 km tunnel that was constructed between 1984 and 1989 for the CERN LEP machine. The underground geometry circumstance is excellent, with 90% in molasse rock and only 10% in limestone under the Jura mountain. The LHC design depends on some basic principles linked with the latest technology, such as the superconducting technology used in magnets. Unlike particle-antiparticle colliders (e.g. Tevatron) that can have both beams sharing the same phase space in a single ring, the LHC, a particle-particle collider, consists two rings with counter-rotating beams. It can serve as proton-proton collider or ion-ion collider at the designed highest luminosity of \(10^{34}\) cm\(^{-2}\)s\(^{-1}\) for proton-proton collisions and \(10^{27}\) cm\(^{-2}\)s\(^{-1}\) for ion-ion collisions. The proton beams can be bunched with a bunch-to-bunch distance of 25 ns (or a multiple of 25 ns), which corresponds to a maximum bunch crossing frequency of 40 MHz. The aim of the LHC is to reveal the physics beyond the Standard Model with center-of-mass collision energies of up to 14 TeV, and this goal will probably be achieved in next two years after three years’ smooth running at 7 TeV (8 TeV).

The basic layout of the LHC can be seen in Figure 3.1. There are eight arcs and eight straight sections in the LHC. Each straight section is approximately 528 m long and can serve as an experimental or utility insertion. The two high luminosity insertions include he ATLAS experiment located at Point 1 and the CMS experiment at Point 5, aiming at peak luminosity of \(10^{34}\) cm\(^{-2}\)s\(^{-1}\) for proton beams. There are also two low luminosity experiments: LHCb at point 8 for B-physics, aiming at peak luminosity of \(10^{32}\) cm\(^{-2}\)s\(^{-1}\), and TOTEM (near CMS) for the detection of protons from elastic scattering at small angles, aiming at a peak luminosity of \(2 \times 10^{29}\) cm\(^{-2}\)s\(^{-1}\). Besides, there is a dedicated ion experiment at point 2, ALICE, aiming at peak luminosity of \(10^{27}\) cm\(^{-2}\)s\(^{-1}\) for lead-lead ion collision.

The injection of protons are conducted through Linac2, Proton Synchrotron Booster (PSB), Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), as shown in Figure 3.2. Protons are produced with 50 MeV kinematics energy and accelerated step by step to be around 450 GeV after SPS, before injected into the main ring.

On 10 September 2008, the proton beams were successfully circulated in the main ring
Figure 3.1: Overview schematic shows the four main experiments and the two ring structure of the LHC

Figure 3.2: Overview of the LHC layout
of the LHC for the first time, but 9 days later operations were halted due to a magnet quench incident resulting from an electrical fault. On 20 November 2009 proton beams were successfully circulated again, with the first recorded proton-proton collisions occurring 3 days later at the injection energy of 450 GeV per beam. On 30 March 2010, the first collisions took place between two 3.5 TeV beams, setting the current world record for the highest-energy man-made particle collisions, and the LHC began its planned research program. The LHC has been operated under CME of 7 TeV in the year of 2010 and 2011, and increased to 8 TeV in 2012. After the end of 2012, it will then go into shutdown for about 20 months for upgrades to allow full energy operation (CME of 14 TeV), with reopening planned for late 2014.

3.2 ATLAS

3.2.1 Detector Overview

ATLAS (A Toroidal LHC ApparatuS) is one of two general-purpose detectors at the LHC. It will investigate a wide range of physics, including the search for the Higgs boson, extra dimensions, and particles that could make up dark matter. It is 45 meters long, 25 meters in diameter, and weighs about 7000 tons. The experiment is a worldwide collaboration involving roughly 3,000 physicists at 175 institutions in 38 countries.

The coordinate system and nomenclature are defined as following: The nominal interaction point is defined as the origin of the coordinate system, while the beam direction defines the z-axis and the x–y plane is transverse to the beam direction. The positive x-axis is defined as pointing from the interaction point to the center of the LHC ring and the positive y-axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z. The azimuthal angle $\phi$ is measured as usual around the beam axis, and the polar angle $\theta$ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$ (if the object is massive, the rapidity $y = \frac{1}{2} \ln [E + p_z / E - p_z]$ is used). The transverse momentum $p_T$, the transverse energy $E_T$ and the missing transverse energy $E_T^{\text{miss}}$ are defined in the $x–y$ plane. The distance $\Delta R$ in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

The overall ATLAS detector layout is shown in Figure 3.3. The ATLAS detector is nominally forward-backward symmetric with respect to the interaction point. The magnet system consists of a thin superconducting solenoid surrounding the inner-detector, and three large superconducting toroids (one barrel and two end-caps) around the calorimeters. This fundamental choice has driven the design of the rest of the detector. The inner detector is immersed in a 2 T solenoidal field. Pattern recognition, momentum and vertex measurements, and electron identification are achieved with a combination of discrete, high-resolution semiconductor pixel and strip detectors in the inner part of the tracking volume, and straw-tube tracking detectors with the capability to generate and detect transition radiation in its outer part. High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, cover the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is a scintillator-tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. The LAr technology is used for hadronic calorimeters in end-caps ($|\eta| > 1.5$) region. The LAr forward calorimeters provide both electromagnetic and hadronic
energy measurements, which extend the coverage to $|\eta| = 4.9$. The outermost subsystem the muon spectrometer. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. Multiple-scattering effects are thereby minimised, and excellent muon momentum resolution is achieved with three layers of high precision tracking chambers. The muon instrumentation includes, as a key component, trigger chambers with timing resolution of the order of $1.5 - 4$ ns. The muon spectrometer defines the overall dimensions of the ATLAS detector.

Figure 3.3: the ATLAS detector and its sub-systems

The event rate at designed luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ is about 1 GHz, which largely exceeds the technology and resource limitation of 200 Hz. The trigger system is built to suppress minimum-bias processes while maintaining efficiency for interested physics processes. The Level-1 (L1) trigger, based on detector information, can reduce the rate to 75 kHz; the subsequent Level-2 (L2) and Event Filter (EF) trigger make the rate down to realistic value [12].

The general performance goal for the ATLAS detector can be found in Table 3.1.

<table>
<thead>
<tr>
<th>subsystem</th>
<th>designed resolution</th>
<th>$\eta$ coverage</th>
<th>trigger coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>$\sigma_{p_T}/p_T = 0.05% \oplus 1%$</td>
<td>$\pm 2.5$</td>
<td></td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 10%/\sqrt{E} \oplus 0.7%$</td>
<td>$\pm 3.2$</td>
<td>$\pm 2.5$</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td>$\sigma_E/E = 50%/\sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>barrel and endcap</td>
<td>$\sigma_E/E = 100%/\sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>forward</td>
<td>$\sigma_{p_T}/p_T = 10%. p_T = 1$ TeV</td>
<td>$\pm 2.7$</td>
<td>$\pm 2.4$</td>
</tr>
</tbody>
</table>

Table 3.1: The interactions and their strength
3.2.2 Inner Detector

The layout of the Inner Detector (ID) is illustrated in Figure 3.4.

Figure 3.4: Overview of the ATLAS Inner Detector, with labels and dimensions

The ID is immersed in a 2 T magnetic field generated by the central solenoid. The precision tracking detectors (pixels and SCT) cover $|\eta| < 2.5$. In the barrel region, they are arranged on concentric cylinders around the beam axis while in the end-cap regions they are located on disks perpendicular to the beam axis. The silicon pixel detector, the innermost one, has finest granularity yielding very good intrinsic accuracy of about $10 \mu m$ ($R - \phi$) and $100 \mu m$ in $z$ or $R$ direction only; besides, typically each track can cross three pixel layers. For the SCT, eight strip layers (four space points) are crossed by each track; and its resolution is about $17 \mu m$ ($R - \phi$) and $580 \mu m$ in $z$ or $R$. The transition radiation detector (TRT) lies as the outlier of ID, and it consists of 4 mm diameter straw tubes, which could produce typically 36 hits per track. The TRT only provide $R - \phi$ measurement with an accuracy of 130 $\mu m$ per tube.

The combination of precision trackers at small radii with the TRT at a larger radius gives very robust pattern recognition and high precision in both $R - \phi$ and $z$ coordinates. The ID measurements can be combined with the energy measurements from calorimetry to further improve the precision. Beside, the TRT gives an enhancement of detecting transition ration photons, and SCT together with pixel detector can allow the impact parameter measurements which are essential to flavor physics with second vertices.

3.2.3 Calorimetry

Experimentally, calorimeters must provide good containment for electromagnetic and hadronic showers, and must also limit punch-through into the muon system. Therefore, the depth of calorimeter should be carefully considered. The EM calorimeter has a thickness of $> 22$ radiation length ($X_0$) in the barrel and $> 24X_0$ in the endcap. The approximate 9.7 interaction lengths ($\lambda$) in active calorimeter yields a very good resolution for jets (in Table 3.1).

The EM calorimeter contains a barrel part ($|\eta| < 1.475$) and two endcap parts ($1.375 < |\eta| < 3.2$). The barrel calorimeter consists of two identical half-barrels, separated by a small gap (4 mm) at $z = 0$. And the endcap part can be divided into two wheels at $|\eta| = 2.5$. The EM calorimeter is a lead-LAr sampling detector with accordion-shaped kapton electrodes and
lead absorber plates over its full coverage, which yields a complete $\phi$ symmetry. Beyond the precision measurement region ($|\eta| > 2.5$), EM calorimeter is segmented in three sections in depth. For the end-cap inner wheel, the calorimeter is segmented in two sections in depth and has a coarser lateral granularity than for the rest of the acceptance.

The hadronic calorimeters include the tile calorimeter, the LAr hadronic end-cap calorimeter and the LAr forward calorimeter. The tile calorimeter is placed directly outside the EM calorimeter envelope, with its barrel covering $|\eta| < 1.0$ and two extended barrels covering $0.8 < |\eta| < 1.7$. It is a sampling calorimeter using steel as the absorber and scintillating tiles as the active material. It is segmented in depth in three layers, approximately 1.5, 4.1 and 1.8 $\lambda$ thick for the barrel and 1.5, 2.6, and 3.3 $\lambda$ for the extended barrel.

The Hadronic End-cap Calorimeter (HEC) contains two independent wheels, located directly behind the end-cap electromagnetic calorimeter. To reduce the loss at transition region of HEC and forward calorimeter, the HEC is extend to $|\eta| = 3.2$; and due to the similar reason, it overlap with tile calorimeter by extending to $|\eta| < 1.7$.

The forward calorimeter (FCal) extends to $|\eta| = 4.9$ and help to reduce the radiation background in the muon spectrometer. Besides, in order to suppress neutron albedo in the inner detector cavity, the front face of the FCal is recessed by about 1.2 m with respect to the EM calorimeter front face. Because of this reason, the length is limited and therefore the FCal is designed to have larger density in order to provide similar interaction length. The length is roughly 10, and the FCal consists of three modules: copper, optimized for electromagnetic measurements; the other two, tungsten, for hadronic measurements.

### 3.2.4 Muon Spectrometer

The layout of muon spectrometer is illustrated in Figure 3.5.

![Figure 3.5: Overview of the ATLAS muon spectrometer](image_url)

The muon momentum measurement is based on the bending power of the large superconducting air-core toroid magnets and the separate trigger and high-precision tracking chambers. The barrel magnets $(1 - 5.5T)$ cover $|\eta| < 1.4$, while the endcap magnets $(1 - 7.5T)$ cover $1.6 < |\eta| < 2.7$. And the region between is called transition region, where the magnetic
deflection is provided by both barrel and endcap, resulting in worse momentum resolution.

As you can see in Figure 3.6, in the barrel region, tracks are measured in chambers arranged in three cylindrical layers around the beam axis; in the transition and end-cap regions, the chambers are installed in planes perpendicular to the beam, also in three layers (EI, EM, EO).

![Figure 3.6: The components of ATLAS muon spectrometer in R – z plane](image)

The majority of the muon spectrometer are the Monitored Drift Tubes (MDT), which provide precision measurement of the track coordinates in η. At large pseudorapidities, Cathode Strip Chambers (CSC), which are multiwire proportional chambers with cathodes segmented into strips) with higher granularity are used in the innermost plane over $2 < |\eta| < 2.7$, to fulfill the demanding rate and background conditions.

The trigger system covers the pseudorapidity range $|\eta| < 2.4$, which provide the measurement of the second coordinate (φ) as well. Resistive Plate Chambers (RPC) are used in the barrel and Thin Gap Chambers (TGC) in the end-cap regions.

The overall muon momentum resolution at the highest momenta, depends on the alignment of the muon chambers with respect to each other and with respect to the overall detector.

### 3.2.5 Triggers

The ATLAS trigger system is designed to record events at approximately 200 Hz from the LHC’s 40 MHz bunch crossing rate. The system has three levels; the first level (L1) is a hardware-based system using information from the calorimeter and muon sub-detectors, the second (L2) and third (Event Filter, EF) levels are software-based systems using information from all sub-detectors. Together, L2 and EF are called the High Level Trigger (HLT). A schematic diagram for the ATLAS trigger system is shown in Figure 3.7.

The L1 trigger searches for high transverse-momentum muons, electrons, photons, jets, and τ-leptons decaying into hadrons, as well as large missing and total transverse energy. Its selection is based on information from a subset of detectors. High transverse-momentum muons are identified using trigger chambers in the barrel and end-cap regions of the spectrometer. Calorimeter selections are based on reduced-granularity information from all the calorimeters. Results from the L1 muon and calorimeter triggers are processed by the central trigger processor, which implements a trigger ‘menu’ made up of combinations of trigger
selections. Pre-scaling of trigger menu items is also available, allowing optimal use of the bandwidth as luminosity and background conditions change. Events passing the L1 trigger selection are transferred to the next stages of the detector-specific electronics and subsequently to the data acquisition via point-to-point links. In each event, the L1 trigger also defines one or more Regions-of-Interest (RoI), i.e. the geographical coordinates in h and f, of those regions within the detector where its selection process has identified interesting features. The RoI data include information on the type of feature identified and the criteria passed, e.g. a threshold. This information is subsequently used by the high-level trigger.

The L2 selection is seeded by the RoI information provided by the L1 trigger over a dedicated data path. L2 selections use, at full granularity and precision, all the available detector data within the RoI (approximately 2% of the total event data). The L2 menus are designed to reduce the trigger rate to approximately 3.5 kHz, with an event processing time of about 40 ms, averaged over all events. The final stage of the event selection is carried out by the event filter, which reduces the event rate to roughly 200 Hz. Its selections are implemented using offline analysis procedures within an average event processing time of the order of four seconds.
Chapter 4

Analysis Objects

As discussed in Section 2.2, the basic approach for studying interested physics at colliders is to measure the cross-section of corresponding processes using the information recorded in the particle detector and compare the measured value with theoretical predictions. The collision data (referred to as “data” in latter context) consist of the recorded momenta and position information of final state particles. Those information comes from the measurements in sub-detectors, including the vertices and tracking momentum measurement from inner detector, the energy deposition and shower shape measured in calorimetry, the muon momentum information derived from muon spectrometer and the trigger objects provided by various trigger setup throughout the detector. The direct measurements from detectors are finally formed to, via very complicate reconstruction software, the final analyzable physics objects, such as collision vertices, leptons, photons, jets and missing transverse momentum ($E_T^{\text{miss}}$, the $p_T$ unbalance yielded by neutrino escape in the detector). We notice that in hadron collider experiments, QCD events are produced enormously; therefore, necessary selection criteria should be applied on those physics objects to filter the set of recorded events into a small sample, in which our interested physics signature dominates or at least visible. The interested physics process is treated as “signal”, and the remaining contributions are referred to as “background”. In order to determine the number of signal events, background must be carefully studied; and to calculate the cross-section, one needs to extract the selection efficiency of signal events to get hold of their states before making the selection. Furthermore, to maximize the analysis sensitivities, event selection should be optimized in a way that the signature is more cleaner and the related uncertainties of the estimations are smaller. To achieve those analysis goals, Monte-Carlo (MC) simulation is needed. MC simulation usually consists of two steps: the event generation and the detector simulation. The Event Generator randomly generates events of a specific process according to the preferred theory model keeping the four-momenta of initial and final state particles. Then, those generated events go through detector simulation, in which they interact with materials and produce detector signals. The final MC events are alike the real collision events; however, they could be produced specifically in certain physics process, which make it vital important. The sections in this chapter is organized as following: section 4.1 and section 4.2 will briefly introduce the data and MC samples used in the analysis; The reconstruction of physics objects are discussed in details in section 4.3, including trigger, electron, muon, $E_T^{\text{miss}}$, jets, vertices and $W$, $Z$ bosons.
4.1 Data

The analysis in this dissertation use data collected during the 2011 LHC $p-p$ run at CME of 7 TeV, corresponding to typically 4.7 fb$^{-1}$. The delivered and recorded integrated luminosities in the ATLAS detector can be found in the left of Figure 4.1, whilst the right plot shows the peak luminosity per day. The peak luminosity has reached to $3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, and in the meanwhile, all the subsystem of the ATLAS detector has performed remarkable well during the data taking periods, as you can see in Figure 4.2.

![Figure 4.1: The integrated luminosity of pp collision (left) and the peak luminosity per day at the ATLAS detector in 2011](image)

The collected data corresponds to the runs between data taking period D and M when the bunches are collided at 50 ns interval. The tiny contributions from period A and B are discarded, since the bunch spacing was 75 ns then, which introduces extra complication for analysis. In case of detector performance issue, the recorded data must be filtered to prevent bad reconstructed events. The Good Run List (GRL) is used as the data quality check, which flags each event as good or bad according to the detector status during the data taking luminosity block. The actual integrated luminosity calculated with the GRL is therefore smaller than the recorded number; besides, slightly different GRLs can yield slightly different
integrated luminosities. This is the case when the two analysis in the dissertation were taken, so quoted luminosity can be either $4.7 \, \text{fb}^{-1}$ or $4.64 \, \text{fb}^{-1}$.

An important feature in the LHC collision data is the multiple interaction per bunch, which is shown in Figure 4.3. This is the consequence of decreasing bunch spacing and increasing luminosity, and it may result in multiple events recorded in one (pileup). The pileup affects mostly the soft terms in the $E_{\text{T}}^{\text{miss}}$ calculation and enlarge the uncertainties in many physics analysis. To compensate for this, a pileup reweighting procedure is often introduced at MC events to make the average number of interactions per bunch crossing $<\mu>$ distributions consistent between data and MC, for which more details can be found at section 4.3.6.

![Figure 4.3: The average number of interactions per bunch crossing in the ATLAS during 2011 data taking period](image)

The data collected in the ATLAS detector are processed and distributed within a worldwide grid computing system (Grid). As we discussed in section 3.2, we have no way to store the data except slimming them via triggers. Trigger objects will be revealed in more detailed manner in section 4.3.1. As a general description, the collision data are organized in different streams, where triggers are applied before writing out the events. For the studies we perform on leptonic decay final states, usually “Muons” and “Egamma” streams are used, which, by their name, indicate the application of muon and electron(photon) triggers.

### 4.2 MC Simulation

MC simulation is essential for particle physics experiment, and it can be used in many ways, such as estimating the background, studying the signal efficiency, deriving systematic uncertainties, conduct detector performance studies and etc.

In hadron collider (more info referred to section 2.2), a typical event structure of a hadron-hadron collision involves a primary hard subprocess, parton showers associated with the incoming and outgoing colored participants in the subprocess, non-perturbative interactions that convert the showers into outgoing hadrons and connect them to the incoming beam hadrons, secondary interactions that give rise to the underlying event, and the decays of unstable particles that do not escape from the detector. And these steps are normally implemented by
the models in the Event Generators.

The user selects hard subprocesses of given types, and then partonic events are generated according to their matrix elements and phase space (the PDF needed here). The outgoing partons from hard subprocesses can radiate gluons, and these gluons can radiate others, or produce quark-antiquark pairs, generating showers of outgoing partons. This process can be simulated with a step-wise Markov chain by choosing probabilistically to add one more parton to the final state at a time, called a parton shower algorithm. The incoming hadrons are complex bound states of strongly-interacting partons and it is possible that, in a given hadron-hadron collision, more than one pair of partons may interact with each other. These multiple interactions go on to produce additional partons throughout the event, which may contribute to any observable, in addition to those from the hard process and associated parton showers that we are primarily interested in. We therefore describe this part of the event structure as the underlying event. When the event is evolved downwards in momentum scales it will reaches the scales of order 1 GeV, in which QCD becomes strongly interacting and perturbation theory breaks down. Therefore, at this level, we must substitute the perturbative evolution with a non-perturbative hadronization model that describes the confinement of the system of colored partons into colorless hadrons. These models are not derived directly from QCD and thus often have more free parameters. And an important fact is that they are approximately universal, which means once tuned on one data set, they are applicable on other new collision types or energies. Since most hadrons are unstable, for the last step, we need many models to simulate their decays to the lighter hadrons that are long-lived enough to be considered stable on the time-scales of particle physics detectors. Please note that it is not always necessary to incorporate so many steps while generating the events, e.g. the electroweak production of the $W^\pm Z$.

Measurements of SM processes in data can provide important input to MC simulations. They provide validation of theoretical predictions and tuning of the free parameters. Generally speaking, the validation and tuning should be performed by comparing unbiased observables from unbiased processes between data and models. The unbiased process means the event selection should be inside detector fiducial region and contain no model dependent cuts. The unbiased observables normally mean the combinations of initial and final states particle kinematics information. If any intermediate particle information is concerned, model dependent corrections must be includes, which make the tuning not natural.

The generator level events can then be input to GEANT4 [13] simulating their interactions with the ATLAS detector, yielding the final MC events. The full ATLAS GEANT4 simulation is very time consuming, given the complicated detector geometry and detailed physics description. The fast simulation [14] is often used to cope with the requirement of large statistics. There are two types of fast simulation, ATLFAST-I and ATLFAST-II. ATLFAST-I just smears the truth objects by detector resolution to mimic reconstructed objects, which is not accurate but get 1000 times reduction of processing time; while ATLFAST-II is similar to full simulation, but with sacrificing the accuracy to a less extent, e.g. simplifying the particle interactions in calorimetry which is most CPU consumed.

The event generators inside the ATLAS software framework are listed below. Large-scale production has been run with PYTHIA [15] (including an ATLAS variant, PythiaB used for production of events with B-hadrons), HERWIG [16], Sherpa [17], Hijing [18], Alpgen [19], MC@NLO [20], POWHEG [21] and AcerMC [22]. Tauola [23] and Photos [24] are routinely
used to handle tau decays and photon emission. EvtGen [25] is used for B-decays in cases where the physics is sensitive to details of the B hadron decays. ISAJET [26] is used for generating supersymmetric particles in conjunction with HERWIG. The newer C++ generators PYTHIA8 and HERWIG++ are being tested.

Brief descriptions of a few related generators are given below. PYTHIA and HERWIG have been tested and validated over many year in $e^+e^-$ and hadron colliders, and they are the benchmark generators in ATLAS. They both start with a hard scattering process calculated to lowest order in QCD, and add additional QED and QCD radiation in a shower approximation which is most accurate when the radiation is emitted at small angle. In the showering model, the multiple scatterings which make up the underlying event are interleaved with the parton shower according to the hard scale of the scatter or the emission. At the end of the shower, a phenomenological model is used to combine the quarks and gluons into hadrons. The hadronization model is tuned with $e^+e^-$, ep and hadron collider data; The underlying event model is tuned within ATLAS to get an acceptable description of Tevatron data. HERWIG a flexible generator with a large number of built in processes and has been tuned to agree with the Tevatron data. Sherpa is a generator written in C++, which implements the CKKW duplicate removal prescription to match fixed-order QCD matrix elements to QCD showers; it interface to PYTHIA to make the hadronization. And Sherpa is expected to give better approximations for final states with large numbers of isolated jets. Alpgen and MC@NLO (next-to-leading order generator) can only produce hard processes, so they must be interfaced with PYTHIA or HERWIG in order to produce full MC events.

The SM $W^\pm Z$ production and its purely leptonic decays are modeled by MC@NLO with interfacing to HERWIG/JIMMY. Hard gluon emission is treated with a NLO computation and soft/collinear emission is treated with a regular parton shower MC. There is no double-counting between these two regions. V+jets backgrounds are modeled with Alpgen for both high mass ($m_{ll} > 40$ GeV) and low mass ($10 < m_{ll} < 40$ GeV) regions. Among the other diboson backgrounds, $WW$ is modeled with HERWIG, $ZZ$ is modeled with PYTHIA, $Z+\gamma$ is modeled with Sherpa, and $t\bar{t}$ and single top events are modeled with MC@NLO and AcerMC. The cross-sections, filter efficiencies and k-factors for SM $W^\pm Z$ MC samples are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Events</th>
<th>k-factor</th>
<th>$\epsilon_{\text{filter}}$</th>
<th>$\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ Z \rightarrow \ell_1 \nu \ell_2^+ \ell_2^-$</td>
<td>MC@NLO</td>
<td>50000</td>
<td>1.0</td>
<td>1.0</td>
<td>0.04114</td>
</tr>
<tr>
<td>$W^- Z \rightarrow \ell_1 \nu \ell_2^- \ell_2^- (aTGC)$</td>
<td>MC@NLO</td>
<td>50000</td>
<td>1.0</td>
<td>1.0</td>
<td>0.02243</td>
</tr>
<tr>
<td>$W^- Z \rightarrow \ell_1 \nu \ell_2^- \ell_2^- (aTGC)$</td>
<td>MC@NLO</td>
<td>50000</td>
<td>1.0</td>
<td>1.0</td>
<td>0.05516</td>
</tr>
<tr>
<td>$W^- Z \rightarrow \ell_1 \nu \ell_2^- \ell_2^- (aTGC)$</td>
<td>MC@NLO</td>
<td>50000</td>
<td>1.0</td>
<td>1.0</td>
<td>0.02849</td>
</tr>
</tbody>
</table>

Table 4.1: The SM $W^\pm Z$ production processes, cross-sections, k-factors and filter efficiencies. The $\ell_1$ and $\ell_2$ denote $e$, $\mu$ or $\tau$. The aTGC samples shown here are produced with $\Delta g = 0$, $\Delta \kappa = 0$ and $\lambda = 0.13$.

The V+jets background MC samples are listed in Table 4.2 with their corresponding cross-section information. The other SM background samples are provided in Table 4.3.

The above MC samples generally correspond to 5-1000 fb$^{-1}$ of integrated luminosity, and the statistics are sufficient for electroweak processes, but not for QCD backgrounds, which will be normally evaluated using Data-Driven methods.
<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Events</th>
<th>k-factor</th>
<th>$\epsilon_{\text{filter}}$</th>
<th>$\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZeeNp0</td>
<td>Alpgen</td>
<td>6615230</td>
<td>1.25</td>
<td>1.0</td>
<td>668.34</td>
</tr>
<tr>
<td>ZeeNp1</td>
<td>Alpgen</td>
<td>6615230</td>
<td>1.25</td>
<td>1.0</td>
<td>668.68</td>
</tr>
<tr>
<td>ZeeNp2</td>
<td>Alpgen</td>
<td>50000</td>
<td>1.25</td>
<td>1.0</td>
<td>0.83</td>
</tr>
<tr>
<td>ZeeNp3</td>
<td>Alpgen</td>
<td>50000</td>
<td>1.25</td>
<td>1.0</td>
<td>0.77</td>
</tr>
<tr>
<td>ZeeNp4</td>
<td>Alpgen</td>
<td>50000</td>
<td>1.25</td>
<td>1.0</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 4.2: MC samples/processes used to model Z+X, including Z+jets, Zbb+jets and Drell-Yan samples. The corresponding cross-sections, generator names, generator level filter efficiencies and total numbers of events are shown. The listed cross sections do not include k-factors or filter efficiencies. NpX ($X = 0,...5$) in the process name refers to the number of additional partons in the final state.
Table 4.3: MC samples/processes used to model other diboson backgrounds (WW, ZZ, Z + γ) and Top background (t ¯t, single top).

As for the two reference models used in W±Z resonance search, EGM W’ signal is generated via PYTHIA with the PDF set MRST2007 LO* [27]. For all signal mass points, the k-factors are calculated with regarding to NNLO with PDF set MSWT2008 using ZW-PROD [28] with zero-width approximation. These k-factors were applied to both the EGM W’ and technicolor signals as a function of the pole mass of the resonance. This procedure had negligible on the acceptance. The W’ MC samples are listed in Table 4.4 with their cross-sections, k-factors and etc.

Table 4.4: EGM W’ MC samples with the generator used, the number of simulated events, k-factor, generator level filter efficiencies and the corresponding cross-sections times branching ratios

Concerning the TC model, samples used in this analysis with the respective cross-sections times branching ratios are summarized in Table 4.5.

Please note that the PYTHIA implementation of ρT does not account for the polarizations of vector bosons in the decay. Besides, the W’ and ρT samples behave quite similarly in terms of final states kinematics distributions, it would be reasonable to use the W’ process as template for an interpretation in terms of ρT.

In order to compare with data, all the MC expectations are normalized with corresponding
<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Events</th>
<th>$\epsilon_{\text{filter}}$</th>
<th>k-factor</th>
<th>$\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 200\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.16795</td>
<td>0.48</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 300\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.16492</td>
<td>0.16</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 400\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.16025</td>
<td>0.059</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 500\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.15394</td>
<td>0.025</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 600\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.14598</td>
<td>0.012</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 700\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.13639</td>
<td>0.006</td>
</tr>
<tr>
<td>$p_T \rightarrow WZ \rightarrow \ell \nu \ell \ell (M = 800\text{GeV})$</td>
<td>PYTHIA</td>
<td>20000</td>
<td>-</td>
<td>1.12515</td>
<td>0.0033</td>
</tr>
</tbody>
</table>

Table 4.5: Technicolor $p_T$ MC samples the generator used, the number of simulated events, k-factor, generator level filter efficiencies and the corresponding cross-sections times branching ratios.

\[ f = \frac{L \times \sigma \times B \times \epsilon_{\text{filter}}}{N_{\text{gen}}} \]  

(4.1)

Where $\sigma$ denotes the total cross-section, $B$ denotes the branching ratio, $L$ is the integrated luminosity, $\epsilon_{\text{filter}}$ represents the filter efficiency at generator level and finally the $N_{\text{gen}}$ is the total number of generated events with weights applied if any.

### 4.3 Physics Objects

#### 4.3.1 Trigger

The ATLAS trigger system is briefly described in Section 3.2.5. Data for events selected by the trigger system are written to inclusive data streams based on the trigger type. For examples, currently there are four primary physics streams, $Egamma$, $Muons$, $JetTauEtmiss$ and $MinBias$, and several other calibration streams. The overlap between $Egamma$ and $JetTauEtmiss$ is roughly at the level of 10%; while the overlap between $Muons$ and other streams is typically between 2-4%.

The trigger system is configured via trigger menu. It defines trigger chains, each of which start from L1 trigger and specify a sequence of reconstruction and selection steps in the HLT for that trigger chain. The trigger chain is often referred to simply as trigger, which is what we choose to apply in the physics analysis. Each chain is composed of Feature Extraction algorithms which create the trigger objects (like calorimeter clusters) and hypothesis algorithms that apply selection criteria to the trigger objects (e.g. transverse momentum greater than 20 GeV).

There are approximately 500 triggers defined in ATLAS trigger menu. The trigger names are usually formed as

\[ \text{trigger level} + \_ + \text{trigger object} + L1 \text{ threshold(GeV)} + \_ + \text{Specific HLT algorithm} \]  

(4.2)

where trigger level takes either ”L1”, ”L2” or ”EF”; trigger objects include ”e”, ”mu”, ”tau” and etc.; the L1 threshold is rather important, which should be chosen carefully in the analysis.
according the offline selection criteria.

The ATLAS trigger performance is very promising, e.g. the HLT trigger reconstruction efficiency matches the offline objects quite well, as shown in Figure 4.4. The trigger efficiencies often go to plateau region after \( p_{T} \) of the objects exceed the corresponding threshold, as you can see in Figure 4.5. The muon trigger efficiency is normally lower in the barrel and higher in the endcap, which is resulted from detector design.

![Figure 4.4: The HLT trigger tracking reconstruction efficiency w.r.t. to the offline objects; muon in the left and electron in the right](image)

![Figure 4.5: The muon trigger efficiency vs muon \( p_{T} \); the barrel region in the left and the endcap region in the right](image)

If the rate of a trigger is too high due to the increasing luminosity and relatively low L1 threshold, it will be pre-scaled. Therefore, in the analysis, one usually need to choose proper triggers which are not pre-scaled and satisfying the lepton momentum requirements to makesure the trigger efficiency is in the plateau region.

\( W^{\pm}Z \) candidate events with multi-lepton final states are recorded with single muon (electron) triggers. For single muons the trigger chains used during different periods are EF\_mu18\_MG (periods D-I), EF\_mu18\_MG\_medium (periods J-M). For single electrons they are EF\_e20\_medium (periods D-J), EF\_e22\_medium (period K), (EF\_e22\_vh\_medium1 || EF\_45\_medium1, where the vh means that hadronic leakage and dead material corrections were applied at L1) (periods L-M). For the event to pass the final trigger matching requirement at least one of the three final state muons (electrons) must be matched to the trigger object within \( \Delta R < 0.1 \) (0.15). The lepton matched to the trigger must have \( p_{T} \) above the corresponding thresholds. Due to the presence of three leptons with large \( p_{T} \) the trigger efficiencies for \( W^{\pm}Z \) events is higher.
than the single lepton trigger efficiency.

Scale factors to account for mis-modelling of the single-lepton trigger efficiency in the MC have been derived using the tag-and-probe method (T&P) on Z events. The scale factors are applied to leptons forming the W and Z and satisfying the leading lepton $p_T$ cut. The per event scale factor depends on the lepton flavor and $p_T$ of the individual leptons,

$$SF_{trig} = \frac{1 - \prod_{n=1}^{N_{\ell}} (1 - \epsilon_{Data,\ell_n})}{1 - \prod_{n=1}^{N_{\ell}} (1 - \epsilon_{MC,\ell_n})}$$ (4.3)

Where $N_{\ell}$ is the number of leptons identified as coming from W or Z and passing out selection cuts; $\epsilon_{Data,\ell_n}$ ($\epsilon_{MC,\ell_n}$) is the trigger efficiency determined with T&P from data (MC) for the lepton $\ell_n$. The trigger efficiencies are found to be close to, or above 99% in all channels. Systematic uncertainties due to the application of scale factors are studied independently for electron and muon triggers, which is typically < 0.3%.

4.3.2 Electron

In general, electrons are reconstructed from information provided by inner tracking system and calorimetry, and then identified by applying certain criteria on the calorimeter and inner track information.

Electron reconstruction in the central region ($|\eta| < 2.47$) starts from the energy deposits in the EM calorimeter. First, a sliding-windows algorithm searches for seed clusters of longitudinal towers with total transverse energy larger than 5 GeV. In MC simulation, the efficiency is nearly 100% for electrons with $E_T > 15$ GeV from W and Z decays. With the acceptance volume of tracking system, reconstructed tracks extrapolated from their last measurement point to the middle layer of the calorimeter are very loosely matched to the seed clusters, with requiring the distance between the track impact point and cluster position satisfy $\Delta \eta < 0.05$. To account for bremsstrahlung losses, the size of $\Delta \phi$ windows is 0.1 (or 0.05 depending whether or not extrapolation of electron track into calorimeters will be affected by magnets). If at least one track is matched to seed cluster, an electron is reconstructed. And the one with smallest $\Delta R$ distance to the seed cluster is picked if there are multiple matched tracks. Then, electron cluster is rebuilt with optimized lateral cluster sizes in order to take into account the different overall energy distributions in the barrel and endcap calorimeters. The cluster energy is then determined by summing 1) the estimated energy lose in the materials in front of calorimeter, 2) the cluster energy, 3) the estimated energy leakage outside the cluster (lateral leakage) and 4) the estimated leakage beyond calorimeter (longitudinal leakage). The four terms are parametrized as function of measured cluster energies in presampling detector and the three EM calorimeter longitudinal layer. MC simulations are of vital importance here to study and provide calibration of energy measurements. The four-momentum of central electrons are taken from the cluster and the matched track. The electron energy is given by cluster, and the $\phi$ and $\eta$ are derived from track. In the forward region ($2.5 < |\eta| < 4.9$) where no tracking system is present, electrons are constructed only from calorimeter information. Usually, the algorithm groups neighboring cells in three dimensions, based on the significance of their energy content with respect to the expected noise; and the electron direction is then determined by the barycenter of the cluster. An electron candidate in the forward region is reconstructed only if it has a small hadronic energy component and a transverse energy of 5
The electron identification in the central region relies on a cut-based selection using calorimeter, tracking and combined variables that provide good separation between isolated or non-isolated signal electrons, background electrons and jets faking electrons. There are three reference sets of cuts: loose, medium and tight, which are defined with increasing background rejecting power: 500, 5000, 50000, respectively (from MC simulation). The loose criterion depends on shower shape variables of the EM calorimeter middle layer and hadronic leakage variables. It is tightened to be medium by adding requirements on variables from EM calorimeter strip layer, track quality requirements and track-cluster matching quality. The tight electrons are further cleaned with cuts on $E/p$, particle identification using the TRT, and discrimination against photon conversions via a b-layer hit requirement and information about reconstructed conversion vertices. Electron identification in the forward region only bases on the cluster moments and shower shapes.

It might need to mention that the EM calorimeter conditions affect the electron reconstruction. Therefore, a quality cut is usually applied to prevent construction of bad measured electron when failures of electronic front-end boards, high voltage problems, or isolated cells producing a high noise signal or no signal at all, are presented.

The performance of electron reconstruction and identification are illustrated as the amazing resonance spectrum shown in Figure 4.6, where dielectron events are selected requiring tight and central (except transition region, $1.37 < |\eta| < 1.52$) electrons using the 2010 collision data at CMS of 7TeV.

![Figure 4.6: Reconstructed dielectron mass distribution of electron candidate pairs passing the tight identification cuts for events selected by low ET threshold dielectron triggers, using 2010 collision data.]

The initial electromagnetic calorimeter energy scale was derived from test-beam measurements, which gives very large uncertainties, such as 3% in central region and 5% in forward region. Please note that the large uncertainty comes from the extrapolation from test-beam results to real ATLAS collision circumstance. Therefore, with real collision data, energy scale
is considerably improved via studying the collision events. One approach is to study the
well-known masses of $J/\psi$ or $Z$ via dielectron events. It can provide much precise electron
energy scale information and establish the response of the EM calorimeter. An alternative
approach is studying the ratio $(E/p)$ of the energy measured in calorimeter and the momen-
tum measured in inner detector. The statistics in use can be much larger ($W \rightarrow e\nu$), but
there is dependence on the momentum which relates to the alignment of inner detector. The
energy scale correction $\alpha$ can be denoted as

$$E_{\text{measured}} = E_{\text{true}}(1 + \alpha)$$  (4.4)

$\alpha$ is normally measured in electron $p_T$ or $\eta$ bins, and it should be applied for both data
and MC per electron. The energy scale correction $\alpha$ determined from 2011 data is shown in
Figure 4.7. The energy scale uncertainty is estimated by checking the additional materials,
electronics, method dependence, pileup and etc., and it is typically around 1% for central
electrons and between 2% and 3% for forward electrons; for central electrons, high-$p_T$ ones
have smaller uncertainty ($\sim 0.4\%$ at 40 GeV), while low-$p_T$ region has uncertainty exceeding
1%.

Figure 4.7: The energy scale correction determined from 2011 data

The fractional energy resolution in the calorimeter is parametrized as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$  (4.5)

Here $a$, $b$ and $c$ are $\eta$ dependent parameters: $a$ is the sampling term, $b$ is the noise term, and
c is the constant term. The resolution study also uses $J/\psi$ or $Z$ events, and resolution can
be derived by fitting the invariant mass distributions using a Breit-Wigner convolved with a
Crystal Ball function, where Breit-Wigner width is fixed with measured $Z$ width and Crystal
Ball function describe the resolution. The uncertainties on electron resolution is also small
and typically at 1% level.

Beside the energy scale and resolution, the detection efficiency difference between data
and MC should be considered as well. Usually, the electron selection efficiency can be written
\[ \epsilon_e = \epsilon_{\text{reco}} \cdot \epsilon_{\text{ID}} \cdot \epsilon_{\text{trig}} \cdot \epsilon_{\text{iso}} \ldots \] (4.6)

Where \( \epsilon_{\text{reco}} \) and \( \epsilon_{\text{ID}} \) denote the electron reconstruction and identification efficiency; \( \epsilon_{\text{trig}} \) is the trig selection efficiency for electron; \( \epsilon_{\text{iso}} \) represents the electron isolation cut efficiency; and there could be more other terms depending on the cuts. The MC efficiencies can be easily derived. To derive the efficiency from data, it is necessary to select a sample with clearly defined electrons. The Tag-and-Probe (T&P) method is often the favorite choice, in which \( Z \rightarrow ee \) or \( J/\psi \rightarrow ee \) events are selected and we derive the efficiencies from the probe electron while the other one is tagged. The efficiency differences between data and MC will be applied to MC as scale factors per event. The uncertainties mostly come from the background determination and selection bias, and the values are again typically around 1% per electron, but can go high in the low energy region.

The overall performance of the electron reconstruction and identification can be reflected in Figure 4.8, where the energy scale corrections and resolution smearing and efficiency scale factors are applied. The electron detection is amazingly performed in the ATLAS detector.

![Figure 4.8: The Z mass reconstructed from dielectron events using 2011 data at CME of 7TeV. Corrections and scale factors are applied in the plots.](image)

Concerning the electron selection in analysis, usually we need to place cut on the electron author (reconstructed from which algorithm, normally be 1 or 3 for real electrons), the calorimeter quality, the electron identification (in 2011, plus-plus menu is used as the improved version of old menu), the \( p_T \) threshold, the \( \eta \) range (within ID coverage but excluding the transition region), the isolation and probably the impact parameters. Most cuts are straight-forward, but there are a few that need careful treatment. \( p_T \) threshold should be chosen with balancing the signal strength and background reduction. The isolation variables have two types: calorimeter-based and track-based. They are calculated essentially as the sum of nearby deposited \( E_T \) or track’s \( p_T \) depending on the distance \( \Delta R \), and sometimes they are expressed as the ratio of the sum over the transverse energy or momentum, namely relative isolation. The fake backgrounds usually contain leptons inside a jet, which usually have large energy deposited in nearby \( \Delta \eta \times \Delta R \) region. Therefore, choosing a good isolation variable and cut value is essential to suppress these fake background.
4.3.3 Muon

The ATLAS detector is optimized for muon identification, with an efficiency greater than 95% and a fractional momentum resolution better than 3% over a wide $p_T$ range and 10% at 1 TeV. Muon momenta are independently measured in the inner detector and the muon spectrometer. The deflection of muons by the magnetic field generated by a system of air core toroid coils in the muon spectrometer is measured by three layers of precision drift tube (MDT) chambers in $|\eta| < 2$ and by two layers of MDT chambers in combination with one layer of cathode strip chambers (CSC) at the entrance of the muon spectrometer for $2 < |\eta| < 2.7$. Three layers of resistive plate chambers (RPC) in the barrel region ($|\eta| < 1$) and three layers of thin gap chambers (TGC) in the endcap region ($1 < |\eta| < 2.4$) provide the muon trigger.

In ATLAS four kinds of muon candidates are distinguished depending on the way they are reconstructed: stand-alone muons, combined muons, segment tagged muons, and calorimeter tagged muons.

- **Stand-alone muon**: The muon trajectory is only reconstructed in the muon spectrometer. The muon momentum measured in muon spectrometer is corrected for the parametrized energy loss of the muon in the calorimeter, to obtain the muon momentum at the interaction point. The direction of flight and the impact parameter of the muon at the interaction point are determined by extrapolating the spectrometer track back to the beam line.

- **Combined muon**: The momentum of the stand-alone muon is combined with the momentum measured in the inner detector. The muon trajectory in the inner detector also provides information about the impact parameter of the muon trajectory with respect to the primary vertex.

- **Segment tagged muon**: A trajectory in the inner detector is identified as a muon if the trajectory extrapolated to the muon spectrometer can be associated with straight track segments in the precision muon chambers.

- **Calorimeter tagged muon**: A trajectory in the inner detector is identified as a muon if the associated energy depositions in the calorimeters is compatible with the hypothesis of a minimum ionizing particle.

Stand-alone muons can be reconstructed in the whole acceptance range of the muon spectrometer of $|\eta| < 2.7$ while combined and segment tagged muons are restricted to the acceptance of the inner detector of $|\eta| < 2.5$. Segment tagged muons are mainly needed to identify muons with low transverse momenta, $p_T < 5$ GeV, because the deflection of these low energy muons in the muon spectrometer is so large that they do not cross two layers of muon chambers, which is the minimum for a stand-alone track. The calorimeter tagged muons are important to cover the acceptance gap of the muon spectrometer at $|\eta| \sim 0$.

The identification of combined and tagged muons uses the fitted tracks from the set of reconstructed inner detector charged particles. Due to the high granularity of the pixel and SCT detectors incorrect associations of hit clusters to track are minimized and fake tracks can be rejected before a track is considered as a muon candidate. The matching between inner detector tracks, calorimeter deposits and muon spectrometer tracks or track segments uses a precise propagation of the track parameters and errors through the inhomogeneous magnetic field.
field and takes into account an accurate and optimized description of the active and passive material of the full detector.

In the early phase of the LHC operation, ATLAS uses more than one reconstruction algorithm for each muon category following different pattern recognition strategies. The two track-based algorithm families are STACO and Muid.

In STACO, the muon stand-alone reconstruction is initiated in a muon chamber by the search for straight line track segments in the bending plane of the toroidal field. Hits in the precision chambers confirmed by trigger chambers hits wherever possible are used and the segment candidates are required to point loosely to the center of ATLAS. The hit coordinate $x$ in the non-bending plane measured by the trigger chambers is associated with the segment when available. Otherwise $x$ is determined by the chamber position. As the drift tubes of the precision chambers are almost 100% efficient in their active volume, segments crossing the active areas of tubes which give no hit are disfavored. If more than at least two track segments in different muon chambers are found in a constrained $\eta - \phi$ region of interest, these are combined to form a muon track candidate using three-dimensional tracking in the magnetic field. The resulting stand-alone track extrapolated to the interaction point is statistically combined with the matching inner detector track.

In MUID, the global pattern recognition in the muon spectrometer is based on two independent Hough transforms in the bending and non-bending plane while search roads are used during the pattern recognition in chain 1. The hit patterns obtained in the two projections are then combined in the segment finding. Straight line segments are reconstructed in each chamber and hits from trigger detectors from the same pattern are associated with them. Track candidates are built from the segments associated to the same hit pattern found by the Hough transforms. Segments in the outermost chambers are used to seed the track fit with all the segments in the next chamber closer to the interaction point. All the successful combinations are considered in extending the track fit to the segments in the innermost chamber layer. If more than one track is found, the track with the highest number of hits is selected, but, unlike the procedure in chain 1, tracks crossing many unhit tubes are not rejected. If two tracks have the same number of hits, the track with the smaller $\chi^2$ value is selected. The final track candidates are refitted with the full treatment of material effects.

Combined muons are identified by a common track fit to the hits in the inner detector and the muon spectrometer. This fit has high rejection power against mismatches between inner detector and stand-alone muon tracks. MUID offers an alternative approach to the combined muon reconstruction: here the pattern recognition in the muon spectrometer is seeded by the extrapolation of an inner detector track.

The muon measurement is mostly depending on the track momentum, therefore its energy scale correction is very small compared to electron. Since combined muon measurement come from both inner detector and muon spectrometer, the muon resolutions ($\eta$ dependent) are
parametrized approximately as

\[ \text{MS: } \frac{\sigma_p}{p} = \frac{p_0^{MS}}{p_T} \oplus p_1^{MS} \oplus p_2^{MS} \cdot p_T \]

\[ \text{ID: } \frac{\sigma_p}{p} = p_1^{ID} \oplus p_2^{ID} \cdot p_T, \quad |\eta| < 1.9 \]

\[ \text{ID: } \frac{\sigma_p}{p} = p_1^{ID} \oplus p_2^{ID} \cdot p_T \frac{1}{\tan^2 \theta}, \quad |\eta| > 1.9 \]

Where \( p_0, p_1 \) and \( p_2 \) denotes the energy loss in the calorimeters material, multiple scattering and intrinsic resolution terms, respectively. Usually, \( Z \rightarrow \mu\mu \) and \( W \rightarrow \mu\nu \) events are used to derive muon resolution. In the \( Z \) events, \( Z \) mass can be fitted by adding an additional Gaussian term with \( \sigma_M \) denoting the detector resolution to the \( Z \) lineshape; while in the \( W \) events, the ID-MS difference \( \rho = \frac{p_{ID} - p_{MS}}{p_{ID}} \) can be fitted with a normal distribution. Then, the resolution measurements are performed by creating a series of \( \sigma_M \) and \( \rho \) via changing the resolution parameters and then comparing with data. The determined resolutions are then compared with original MC value, and the residual should be applied to MC muons as additional Gaussian smearing. The corrected \( p_T \) for combined muon is then determined assuming the independence of ID and MS resolutions as

\[ p_T'(CB) = p_T(CB)[1 + \frac{\Delta(MS)}{\sigma^2(MS)} + \frac{\Delta(ID)}{\sigma^2(ID)} + \frac{1}{\sigma^2(ID)}] \]

Figure 4.9 shows the agreement of \( Z \) mass resolution between data and smeared MC events, where two STACO combined muons are selected with \( p_T > 20 \text{ GeV} \), calorimeter isolation within \( \Delta R = 0.3 \) less than 2 GeV and \( |\eta| < 2.5 \). Besides, the resolution smearing uncertainty is considered mostly from ID multiple scattering and misalignment in MS, which turns out to be typically less than 1%. Since, the 1% is applied on muon resolution, its impact on real analysis is often much smaller.

![Figure 4.9: Dimuon invariant mass resolution for both data (2011, 7TeV) and MC Z events (PYTHIA)](image)

Muon efficiencies are determined in similar ways as electrons. In the tag-and-probe
method, $Z \rightarrow \mu\mu$ events are selected by requiring two oppositely charged isolated tracks with a dimuon invariant mass near the mass of the $Z$ boson. One of the tracks must be a CB muon. This track is called the “tag muon”. The other track, the so-called “probe”, must be a standalone muon if the ID efficiency is to be measured. If the MS and matching efficiency is to be measured the other track must be an inner detector track. The ID reconstruction efficiency is the fraction of stand-alone muon probes which can be associated to an inner detector track. The MS and matching efficiency is the fraction of ID probes which can be associated to a CB or ST muon. For other cut efficiency, combined muons can be used as tag and probe. The STACO combined muon reconstruction efficiency with respect to the inner tracking efficiency as a function of the pseudorapidity of the muon for muons with $p_T > 20$ GeV in 2011 data is shown in Figure 4.10. The uncertainty can be reflected by the disagreement between data and MC, which is less than 1%.

Figure 4.10: The STACO combined muon efficiency w.r.t. inner tracking efficiency for muons with $p_T > 20$ GeV

The typical cut variables for muon are the type (STACO combined ...), $p_T$, $\eta$, hits requirement, impact parameter and isolation. And in the case of studying high $p_T$ muons, often a ID-MS significance cut is applied to make sure the ID measurement and MS measurement are consistent to avoid bad measurement.

### 4.3.4 Jet

The ATLAS calorimeters have very high lateral granularity and several samplings in depth over $|\eta| < 3.2$. The forward calorimeters also provide adequate granularity to reconstruct forward jets with reasonable accuracy and efficiency. Jets are reconstructed using the anti-$k_t$ algorithm with distance parameter $\Delta R = 0.4$ or $\Delta R = 0.6$ using the FASTJET [29] software. The jet finding is done in the $y - \phi$ plane, while often the correction and performance study are conducted in $\eta - \phi$ plane. The reconstructed jets have $p_T$ threshold at 7 GeV. The jet reconstruction starts with building the basic objects, such as topological calorimeter clusters (topo – clusters), calorimeter towers or track jets. And later on the objects, also called constituents, are formed into a full jet via jet finding algorithm.

Topological clusters are groups of calorimeter cells that are designed to follow the shower
development taking advantage of the fine segmentation of the ATLAS calorimeters. The clusters are formed as the following:

- Pick up a seed cell with signal-to-noise ratio \((S/N)\) above a threshold of four, where the noise is measured as the absolute value of the energy deposited in the calorimeter cell divided by the RMS of the energy distribution measured in events triggered at random bunch crossings.
- Add neighboring cells to the seed cell, and neighbors must have \(S/N\) larger than two.
- Search for cells with local maximum energy with a threshold of 500 MeV within the formed topo-cluster; the selected cells are then used as seed for new iterations, while split the original cluster into more topo-cluster.

A topo-cluster is then defined to have an energy equal to the energy sum of all the included calorimeter cells, zero mass and a reconstructed direction calculated from the weighted averages of the pseudorapidities and azimuthal angles of the constituent cells. Calorimeter towers are static grid elements built directly from calorimeter cells within \(\Delta \eta \times \Delta \phi = 0.1 \times 0.1\). There are two types of calorimeter towers, with or without noise suppression; and the one with noise suppression is built from the cells that already validated in a topo-cluster. Both types of calorimeter towers have an energy equal to the energy sum of all included calorimeter cells. The formed Lorentz four-momentum has zero mass. The track jets built from charged particle tracks originating from the primary hard scattering vertex (track jets) are used to define jets that are insensitive to the effects of pile-up and provide a stable reference to study close-by jet effects. and normally tracks with \(p_T > 0.5\) GeV and \(|\eta| < 2.5\) are considered.

The reconstruction of jets from basics objects are done by \(anti-k_t\) algorithm \([30]\). For each object, a list of variables are built as

\[
d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta^2 R_{ij}}{R^2}; \quad d_B = k_{ti}^{2p}
\]

Where \(k_{ti}\) is the transverse momentum, \(p = -1\) for \(anti-k_T\) is a parameter added to govern the relative power of the energy versus geometrical scales and \(i\) represents the considered object and \(j\) denotes the adjacent object. If the smallest entry is a \(d_{ij}\), the two objects are combined and the list of variables will be remade; if the smallest one is \(d_B\), the object is considered as a complete jet and removed from the list. The algorithm normally merges close-by soft objects to the hard objects and sometimes merge two hard objects together depending on the \(k_T\) and \(\Delta R\). The jets built from calorimeter towers are often call “Tower” jets, and the jets from topo-clusters are often referred to as “EM” jets.

Since our main interest is in the hard scattering events, the jets induced from other backgrounds or noises (beam-gas, beam-halo, cosmic ray muons, large calorimeter noise, etc.) should be suppressed. Therefore, as analogy to electron identification, jet quality cut is often applied in physics analysis. For example, the noises in the calorimeter often result in a large energy fraction in the HEC (EM) as well as a large fraction of energy with poor signal quality and sometime negative energy calculated in neighboring cells; the non-collision backgrounds not usually in-time with the beam collision. Adopting these variables, we can make a combined cut to tighten jet quality. In ATLAS, two quality selections are provided: a loose selection is designed with an efficiency above 99% which can be used in most physic analysis and a medium selection designed for selecting jets at high \(p_T\).

The simplest jet energy calibration is the \(EM + JES\) scheme, in which the JES correc-
tion factor is directly applied to calorimeter measurement at the electromagnetic scale. The correction, often derived as a function of jet energy and pseudorapidity, contains contribution from pileup correction, vertex correction and jet energy and direction correction (mostly derived by comparing jet response with MC truth information). The JES uncertainties are estimated using single hadron response measured in situ and in test beams and by studying MC simulations. In the central region $|\eta| < 0.8$, the $EM + JES$ uncertainty is typically lower than 4.5% for jets with $p_T > 20$ GeV and less than 2.5% for jets with $p_T > 60$ GeV. Towards the forward region, the uncertainty increases mainly because the difference between PYTHIA and HERWIG simulations. The uncertainty induced by pileup effects are additionally estimated, which is around 1% for low energy and intermediate energy jets, and negligible for high energy jets. Besides, the uncertainties are found to be similar for both cone40 ($R = 0.4$) and cone60 ($R = 0.6$) jets.

More sophisticated jet energy calibration schemes based on cell energy density weighting or jet properties are also studied. The global sequential jet calibration (GS) based on global properties of the internal jet structure improves the energy resolution and reduces flavor dependence of the $EM + JES$ calibration scheme. The JES uncertainty for the GS jet is the sum in quadrature of $EM + JES$ uncertainties and additional GS correction uncertainties (0.5%-1%). The global cell weighting scheme (GCW) derives cell weights by optimizing the resolution of reconstructed jets relative to their respective truth jets. The local cluster calibration (LCW) derives energy corrections for calorimeter clusters using single hadron Monte Carlo simulations. The JES uncertainty is obtained from in situ techniques. Over a wide kinematic range the JES uncertainties for the various schemes are similar, except that at low $p_T$ and high $p_T$ regions, uncertainties from in-situ methods are often worse. Besides, for all jet calibration methods, additional uncertainties are derived for close-by jet topologies and for response differences for jets induced by quarks, gluons or heavy flavor quarks. It is expected that the close-by jet uncertainty mainly affects low energy jets, which is estimated below 2-3% in ATLAS. For the flavor uncertainty, The JES uncertainty of jets containing B-hadrons is typically 2% for low-$p_T$ jets and around 1% for high-$p_T$ jets.

The jet reconstruction efficiency is derived using the MC simulation and the systematic uncertainty evaluated with a T&P technique using track jets. The efficiency is found to be well described by the MC simulation, and the associated systematic uncertainty is below 2% for low-$p_T$ jets and negligible for high-$p_T$ jets.

The jet energy resolution is measured in data, from Dijet in-situ techniques, for all calibration schemes. The parametrization can be written as

$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} + \frac{S}{\sqrt{p_T}} + C$$

(4.10)

where $N$, $S$ and $C$ are the noise, stochastic and constant terms, respectively. Currently, there are two methods to derive the jet energy resolution, and they are based on the understanding that the $p_T$ imbalance of dijet events is mostly contributed from jet energy resolution.

- The Dijet balance method. The asymmetry between the transverse momenta of two leading jets $A$ is defined as

$$A(p_{T1}, p_{T2}) = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

(4.11)
Then the jet resolution is approximately derived as

\[
\sigma_A = \frac{\sqrt{\sigma_{pT1}^2 + \sigma_{pT2}^2}}{pT_{1,2}} \approx \frac{\sigma_{pT}}{\sqrt{2}pT} \Rightarrow \frac{\sigma_{pT}}{pT} = \sqrt{2}\sigma_A \tag{4.12}
\]

- The Bi-sector method. First, define an imbalance vector \( \vec{p}_T \) as the vector sum of two leading jets in the dijet events. This vector is projected along an orthogonal coordinate system in the transverse plane \((\Psi, \eta)\), where \( \eta \) is chosen in the direction that bisects the angle formed by two jet momenta. At particle level, the jet momentum fluctuation is thought to mostly come from initial state radiation, and this effect is assumed to be isotropic in the \((\Psi, \eta)\) plan (validated in MC). Then, the fluctuation of momentum has \( \sigma_{\Psi}^{\text{part}} = \sigma_{\eta}^{\text{part}} \). In reality, the particle level momentum is replaced by calorimeter measurements, and form a function to calculate the jet energy resolution:

\[
\frac{\sigma_{pT}}{pT} = \frac{\sqrt{\sigma_{\Psi}^2 - \sigma_{\eta}^2}}{\sqrt{2}pT |\cos \Delta \phi_{12}|} \tag{4.13}
\]

The systematic uncertainties on the jet energy resolution have been determined from the simulation, which turns out to around 10% for both methods. Figure 4.11 shows the measured jet energy resolution in 2011 data.

![Figure 4.11: The energy resolution for central jets measure in two methods using 2011 data at CME of 7TeV](image)

In principle, MC jets should be smeared to the data in terms of resolution in physics analysis, and the energy scale correction uncertainty and the resolution uncertainty should be taken into account. In the case of \( W^\pm Z \) purely leptonic decay, jet uncertainty is very small, which mostly comes from the usage of jets in MET reconstruction; however, in other cases when jet is directly used, the jet uncertainty can be the dominate systematic sources in the analysis.

### 4.3.5 Missing Transverse Energy

In a hadron collider event the missing transverse momentum is defined as the event momentum imbalance in the plane transverse to the beam axis, where momentum conservation is expected. Such an imbalance may signal the presence of undetectable particles, such as neutrinos or new
stable, weakly-interacting particles. The vector momentum imbalance in the transverse plane is obtained from the negative vector sum of the momenta of all particles detected in a proton-proton (pp) collision and is denoted as missing transverse momentum $E_T^{miss}$. And $E_T^{miss}$, its magnitude, is called missing transverse energy. A good measurement of $E_T^{miss}$ is critical for the study of many physics channels in ATLAS, in particular in the new physics search involving undetected particles such as supersymmetry and in the SM precision measurements involving neutrinos. Even with the requirement of $E_T^{miss}$, its measurement uncertainties could largely enhance the background from QCD multi-jets events due to jet mis-measurement and the $Z$ events due to bad measurement of high-$p_T$ leptons or jets.

The $E_T^{miss}$ reconstruction includes contributions from energy deposits in the calorimeters and muons reconstructed in the muon spectrometer. For low-$p_T$ particles, which are missing in calorimeter, their corresponding tracks are added to recover the contribution; for the regions not covered by muon spectrometer, muons reconstructed from inner tracks are used. The $E_T^{miss}$ reconstruction uses calorimeter cells calibrated to their associated physics objects in a specific order: electrons, photons, hadronically decaying $\nu$, jets and muons. Cells which are not associated to any objects are also taken in to account, which are often referred to as "CellOut" term. The calculation can be written as

$$E_T^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets}$$

$$+ E_{x(y)}^{miss,softjets} + (E_{x(y)}^{miss,calo \mu} + E_{x(y)}^{miss,CellOut} + E_{x(y)}^{miss,\mu})$$

(4.14)

where each term is calculated from the negative sum of calibrated cell energies projected to $x$ or $y$ plane, inside the corresponding objects $|\eta| < 4.9$ and the $E_{x(y)}^{miss,\mu}$ is calculated from the negative sum of the momenta of muon tracks within $|\eta| < 2.7$. Please note that the $E_{x(y)}^{miss,calo \mu}$ term accounts for the double counting of muon energy deposited in calorimeters.

The cells used in $E_T^{miss}$ calculation mostly belong to topo-clusters (described in Section 4.3.4), expect electrons and photons for which a different algorithm is used (see Section 4.3.2). And the energy calibration is done in a object-based way, and the calibration scheme for 2011 is chosen as the one yielding best performance in 2010 analysis. For example, the electrons are calibrated with the default electron calibration, photons are used at electromagnetic scale, $\tau$ jets are calibrated using LCW scheme, and the jets are reconstructed with LCW scheme if soft jets ($p_T < 20$ GeV) and with LCW+JES scheme if hard jets. The value and the azimuthal angle of $E_T^{miss}$ can be denoted as

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

$$\phi^{miss} = \arctan(E_x^{miss} / E_y^{miss})$$

(4.15)

The $Z \rightarrow \ell\ell$ events are often used to study $E_T^{miss}$ performance because of its clean signature and relatively large cross-sections. Besides, apart from a small contribution from semi-leptonic decays and heavy-flavor hadrons in jets, there should be no real $E_T^{miss}$ in the events. Therefore, any imperfection of reconstructions can be directly spotted. As you can see in Figure 4.12, the data and MC agrees perfectly on muon terms and hard jets term, but there are discrepancies in softjets term and cellout term, which is mostly affect by pileup effects.

The $E_T^{miss}$ resolution measurement is usually conducted in $Z \rightarrow \ell\ell$ events as well. The
Figure 4.12: Distribution of $E_T^{\text{miss}}$ computed from reconstructed muons (top-left), jets with $p_T > 20$ GeV (top-right), soft jets with $p_T < 20$ GeV (bottom-left) and cellout term (bottom-right) for $Z \rightarrow \mu\mu$ data using 2011 data. The expectation from Monte Carlo simulation (PYTHIA 6) is superimposed and normalized to data, after each MC sample is weighted with its corresponding cross-section. The lower parts of the figures show the ratio of data over MC.
resolution is estimated from the width of the combined distribution of $E_T^{\text{miss}}$ and $E_Z^{\text{miss}}$ in bins of $\sum E_T$. It is found that $E_T^{\text{miss}}$ resolution follows an approximately stochastic behavior as a function of the total transverse energy, which can be described with the function

$$\sigma = k \cdot \sqrt{\sum E_T} \quad (4.16)$$

Figure 4.13 shows the measured $E_T^{\text{miss}}$ resolution in 2011 data and the fitted value $k$ of Eq 4.16 in the left and the corresponding MC resolution in the right. As you can see, the data matches simulation quite well. In 2011 data, the fitted $k$ is around $0.7 \text{ GeV}^{1/2}$, which is larger than the value in 2010 $\sim 0.5 \text{ GeV}^{1/2}$, mainly because of the increasing pileup condition. There are a few methods studied to help suppress pileup effect, which you can find in reference.

Figure 4.13: $E_T^{\text{miss}}$ and $E_Z^{\text{miss}}$ resolution as a function of the total transverse energy in the event calculated by summing the $p_T$ of muons and the total transverse energy in the calorimeter in 2011 data at CME of 7 TeV (left) and in MC events (right); the according fitting parameter $k$ in Eq 4.16 is provided on the plots.

The $E_T^{\text{miss}}$ systematic uncertainties can be evaluated by combining the uncertainties on each individual term corresponding to the uncertainties on the related objects. Besides the well reconstructed objects, there are significant contributions from soft terms ($E_T^{\text{miss,soft jets}}$ and $E_T^{\text{miss,cellout}}$) to the final $E_T^{\text{miss}}$ uncertainties in $W$ and $Z$ boson final states. To estimate the uncertainties on soft terms, we can either pick up $Z$ events with $E_T^{\text{miss}}$ less than 20 GeV (soft term dominates) and consider $E_T^{\text{miss}} \approx E_T^{\text{miss,soft term}}$, or use the inclusive $Z$ events and consider the soft term as balanced by sum of momenta of hard objects

$$p_T^{\text{hard}}(x) = \sum_{\mu} p_T^{\mu}(x) + \sum_{e} p_T^{e}(x) + \sum_{jets} p_T^{jets}(x) + ...$$

$$E_T^{\text{miss,soft}} = p_T^{\text{hard}} = \sqrt{(p_T^{\text{hard}})^2 + (p_T^{\text{hard}})^2} \quad (4.17)$$

Then, the systematic uncertainties can be evaluate by comparing the data and MC agreement or pileup dependence in both $E_T^{\text{miss,soft term}}$ scale and resolution. Figure 4.14 shows the overall and individual $E_T^{\text{miss}}$ uncertainties for $W \rightarrow e\nu$ MC events, and the soft term uncertainty is evaluated using low $E_T^{\text{miss}}$ events in the left plot and $p_T^{\text{hard}}$ method in the right.

As for the $W^+Z$ final states, there exits real $E_T^{\text{miss}}$ from escaping neutrinos in $W$ decays. Therefore, the pileup dependence is smaller; in the analysis, we vary the $E_T^{\text{miss}}$ terms individually according to their uncertainties, reconstruct the full $E_T^{\text{miss}}$ int each case and count...
Figure 4.14: The overall and individual $E_T^{\text{miss}}$ systematic uncertainties for $W \to e\nu$ MC events

the difference in selection. By this mean, we propagate $E_T^{\text{miss}}$ into analysis and get hold of its influence on final observables.

4.3.6 Others

Besides the major physics objects described in above sections, other important facts, such as the vertex reconstruction and the reconstruction of W and Z bosons, are summarized here.

The interaction region in ATLAS is described by a Gaussian with the standard deviation of 5.6 cm in the direction of the beam and 15 $\mu$m in the perpendicular plane. This is adequate for some analysis, but not for many others. The precise reconstruction of physics processes such as $H \to \gamma\gamma$, identification of $b-$ and $\tau-$ jets and electroweak measurement require a precise knowledge of the primary vertex. In 2011, the number of proton-proton interactions per bunch crossing is distributed according to the Poisson distribution with average of approximate 10. Therefore, in a real event, the physical primary vertex (physical events) is present together with other vertices (minibias events), as you can see in Figure 4.15 for a typical event recorded with 20 vertices in 2011 data.

Figure 4.15: An event with total 20 vertices

The vertex reconstruction in ATLAS is generally as following. First, the tracks with $p_T > 100$ MeV are pre-selected; then exactly one vertex is fitted from all pre-selected tracks. After that, tracks which are incompatible with the vertex (by $7\sigma$) are used to seed and reconstruct new vertex candidate. This process will continue until all available tracks are associated. The beam-spot information was used to constrain the vertex fit. The pile-up events are identified as triggerd bunch-crossings where at least one additional primary vertex with at least 4 fitted tracks is reconstructed. The final vertices list is often ordered by $\sum p_T^2/N_{\text{trk}}$, so the first one is usually the true primary vertex. The vertex reconstruction efficiency is close
to 100%, and the resolution can reach 30µm and 50µm in transverse and longitudinal planes, respectively.

The vertex reconstruction is promising, but the real “annoying” thing is the pile up vertices in the events. Although they are mostly soft events, some important physics objects are largely affected, e.g. the soft terms in \(E_T^{miss}\). MC simulation is often done prior to the change of collision condition, which makes MC and data differ in terms of number of vertices. In this circumstance, usually a pileup reweighting technique is introduced. The distribution of a more essential variable, average number of interaction per bunch crossing \(<\mu>\), is compared between data and MC; the comparison yields a scale factor to match MC to data based on each \(<\mu>\) bin. Then this scale factor is applied to MC events, which is referred to as “pileup reweighting”. The reweighting can’t eliminate the problem induced by pileup, but the agreement of data and MC is largely improved, as you can see the good \(E_T^{miss}\) agreement in Figure 4.16.

Figure 4.16: Distribution of missing ET as measured in a data sample of \(Z \rightarrow \mu\mu\) events. The expectation from Monte Carlo simulation is superimposed and normalized to data, after each MC sample is weighted with its corresponding cross-section.

The W boson and Z boson in \(W^{\pm}Z\) final states are reconstructed from leptons and \(E_T^{miss}\). Some of the kinematics calculations might be ambiguous, e.g. the calculation of W transverse mass and invariant mass of \(WZ\) system. The W transverse mass is calculated as

\[
M_W^T = \sqrt{(E_T^\ell + E_T^{miss})^2 - (p_\ell^x + p_{\mu}^{miss})^2 - (p_\ell^y + p_{\mu}^{miss})^2}
\]

The neutrino four-momentum is needed to reconstruct W four-momentum; therefore we solve the equation of

\[
(E^W)^2 = (p_W)^2 + (M_W^T)^2
\]

\[
(E^\ell + \sqrt{(p_T^\nu)^2 + (p_{\mu}^\nu)^2})^2 = (p_\ell^x + p_{\mu}^{\nu})^2 + (p_\ell^y + p_{\mu}^{\nu})^2 + (p_z + p_{\mu}^{\nu})^2 + (M_W^T)^2
\]

Where only \(p_z^{\nu}\) is the variable to be solved. If there are two real solutions, the one with smaller absolute magnitude is picked; If there is no real solution, the real part is chosen. This choice has been valid with MC simulation, and thought to be slighted better than other. This procedure can be interpreted as deriving W four-momentum via W mass constraint. Once W
is fully reconstructed, the invariant mass of WZ system is then straightforward.
Chapter 5

The SM WZ Cross-Section Measurement and aTGC Limits

5.1 Analysis Overview

This section briefly introduces the important points of the SM $W^\pm Z$ analysis. The signal selection consists of three high $p_T$, isolated leptons plus significant $E_T^{\text{miss}}$. With this selection the signal has relatively little background from SM processes. For this analysis of $W^\pm Z$ production a cut-based analysis approach is chosen with a simple set of cuts.

In order to measure the cross section, we need the number of observed events, an estimate of the number of background events, the detector acceptance, trigger and reconstruction efficiencies and the integrated luminosity of our data sample. The acceptance is calculated using the MC simulation so it is important to know the level of agreement between the MC simulation and data. We rely on measurements done by the trigger and combined performance groups for calculating the correction factors.

The muon and electron trigger efficiencies each have scale factors to account for discrepancies between data and MC samples. The electron and muon reconstructed objects are corrected for the mismatch between data and MC in the identification efficiencies and also the energy (electron) and momentum (muon) resolution. In addition, there is a small correction needed to account for detector problems that affect electron reconstruction that are not in the MC simulation. Finally, we must apply a re-weighting to account for the difference in the amount of pileup in the data and MC samples.

The background is estimated using both data driven methods and MC samples. For backgrounds which include at least one fake lepton (fake leptons include pion, kaon, and heavy quark decays to real leptons in addition to jets pass the lepton identification), the contributions are estimated from data (“Fake Factor Method”) for $Z$+jets and MC rescaling for $t\bar{t}$. The estimates are cross-checked with MC methods. Electroweak backgrounds including contributions from top quarks are estimated from data driven methods and MC simulation.

For electroweak backgrounds, the systematic uncertainties are assumed to be the same as for the signal which is reasonable since they also consist of high $p_T$ isolated leptons. For the backgrounds with at least one fake lepton, systematic uncertainties are evaluated separately.

The cross section is calculated using a maximum likelihood technique to combine different decay channels. Limits on the presence of anomalous Triple Gauge Couplings (aTGCs) are
given in the form of 95% confidence intervals (C.I.) for the different coupling parameters from one and two dimensional fits. These C.I. are extracted from a kinematic distribution sensitive to the change both in cross section and in $W^\pm Z$ event kinematic properties due to the presence of aTGCs: the transverse momentum of the Z boson, $p_T^Z$, has been selected.

5.2 Event Selection

The analysis are based on all the $W^\pm Z$ final states with electrons and muons, including $\mu\mu\mu$, $\mu\mu e$, $\mu ee$ and $eee$ channels. The $W^\pm Z$ candidate events are selected by finding good leptons in the events, applying event level pre-selection and conducting specific $W^\pm Z$ selection in the end.

The criteria for good leptons are described below:

- **Electrons** are selected with standard author requirement (1 or 3), and required to pass "loose++" identification criterion. To avoid problems with the front-end boards of the liquid argon calorimeter or other data quality issues, the electron candidates are required to pass the object quality cut, in which all of the following shouldn’t occur: the presence of a dead front-end board in the first or second sampling layer, a dead region affecting the three samplings or a masked cell in the core. To ensure that the candidates come from the primary vertex, the impact parameters are constrained as $|z_0| < 1$ mm and $d_0$ significance less than $10\sigma$. Electron energy is taken from calorimeter measurement and the directions are derived from inner tracks. With four-momentum built in this way, electrons are required to have $p_T > 15$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ (avoid transition region). The final electron requirement applied is a relative isolation condition. The sum of the calorimeter transverse energies of other EM clusters in a cone of $\Delta R = 0.3$ around the electron candidate ($etcone_{30}$) must be less than 14% of the $E_T$. The sum of the transverse momentum of all other tracks with $p_T > 1$ GeV a cone of $\Delta R = 0.3$ around the electron candidate ($ptcone_{30}$) must be less than 13% of the $p_T$. Besides, the energy scale correction is applied for electrons in data events, the energy resolution smearing is applied for electrons in MC events, and pileup correction on $etcone_{30}$ is made in MC events as well. In order to compensate the efficiency difference in data and MC, electron efficiency scale factors are applied to MC events on per electron base.

- **Muons** in this analysis are required to be STACO combined (CB) or segment-tagged (ST). ST muons help improve the selection efficiency, while additionally induced backgrounds are minor due to the Z mass constraint. Muons must have $p_T > 15$ GeV and $|\eta| < 2.5$. The isolation cut can be describe as the inner detector track of the muon must be isolated from other tracks to reject secondary muons from hadronic jets, which can be denoted as $ptcone_{30}/p_T < 0.15$. Additionally, inner detector tracks must have a minimum number of hits in each silicon sub-detector: at least one hit in the B-layer, two in all Pixel layers, six in the SCT, and less than three holes in all silicon layers. For all those hit conditions, dead sensors count as hits observed, not as holes. An $|\eta|$ dependent condition on TRT hits and outliers is also applied: for $|\eta| < 1.9$, require $hits + outliers \geq 6$ and $outliers/(outliers + hits) < 0.9$; for $|\eta| > 1.9$, if $hits + outliers > 6$, require $outliers/(outliers + hits) < 0.9$. To ensure that the candidates come from the primary vertex, impact parameter cuts are also applied, in which $|z_0| < 1$ mm and $|d_0|$
significance less than 3σ.

- **Overlap removal** is applied by removing the lower-$p_T$ electron if two overlap within $\Delta R = 0.1$ and removing jets within $\Delta R < 0.3$ of any selected electrons or muons. The purpose is to reject muon radiated electrons and jets which built from electron clusters.

The pre-selections are mainly event level quality cuts, including:

- **Good Run List**
- **Trigger requirement** (described in Section 4.3.1)
- **Primary vertex cut** The primary vertex is required to be associated with at least three tracks.
- **$E_T^{\text{miss}}$ cleaning cut** Jets with $p_T > 20$ GeV which don’t overlap with selected electrons are require to pass the ”looser” quality. The ”looser” quality is similar to the ”loose” quality describe in Section 4.3.4. If any jets fail the quality requirement, the event is rejected.
- **LAr noise** Events taken when a Liquid Argon Calorimeter noise is presented (lar-Error==2) is removed.

The $W\pm Z$ selection are

- **$Z$ candidate** The event must have two leptons of the same flavor and opposite charge, with an invariant mass that is consistent with the $Z$ mass: $|M_{\ell\ell} - 91.1876| < 10$ GeV. If more than one pair of leptons form a $Z$ candidate, the pair with mass best matching PDG mass is chosen.
- **three leptons** The event must have at least 3 selected leptons. The lepton that is not associated to the $Z$ boson candidate must be the combined muon or tight++ electron. Besides, the third lepton must have $p_T > 20$ GeV.
- **$E_T^{\text{miss}}$ cut** The missing transverse energy in the event must be larger than 25 GeV.
- **$W$ transverse mass** The transverse mass, as defined in Section 4.3.6 must be greater than 20 GeV.
- **Trigger matching** One of the offline leptons from $W$ or $Z$ decays must match the trigger object which firing the single lepton trigger. According to the trigger threshold, the matched lepton $p_T$ is required to larger than 20(25) GeV for muons(electrons).

Please note that the GRL cut and “LAr noise” cut are applied only for data. Based on the fact that there are very little faking backgrounds under $Z$ mass peak, we apply looser criteria to leptons from $Z$ decays in order to enlarge selection efficiency; and in contrast, the $W$ lepton requirement is tightened to suppress faking backgrounds. The $E_T^{\text{miss}}$ cut is essential for rejecting backgrounds from process without neutrino in final states, such as $ZZ$ and $Z + jets$ backgrounds, and the cut value is optimized based on the signal-over-background ratio ($S/B$) and signal efficiency. The $W$ transverse mass cut is correlated with $E_T^{\text{miss}}$, but can provide additional suppression on backgrounds.

### 5.3 Signal and Background

Signal expectation comes from MC samples, as shown in Table 4.1; while background predictions depend on both MC and Data-Driven methods. For backgrounds with three real leptons, $ZZ$ is the largest contribution, which is estimated with MC given the MC statistics is large and the process is well understood. Other events can have two real leptons and a third lepton coming from jet faking, from a heavy quark decay, or from an in-flight pion or
kaon decay. $Z + jets$ and $Top (t\bar{t}$ and single top) fall into this category. Finally, there could be backgrounds in which the event has one hard lepton and two leptons from jet faking or heavy-flavor decay. $W + jets$ events, single top and $t\bar{t}$ may contribute; but they are normally very small, or even negligible. For backgrounds which include at least one “fake” lepton (where fake lepton includes pion, kaon, and heavy quark decays to real leptons in addition to jets which fake lepton identification), the background estimation is performed with data-driven methods whenever possible. The background from $Z + \gamma$ events, where the photon produces an electron via conversion, is calculated using MC simulation.

5.3.1 Signal Acceptance

The signal acceptance is extracted from $W^{\pm}Z$ MC samples, by applying all the lepton corrections and event selections. The expected number of signal events in $\mathcal{L} = 4.64 \text{ fb}^{-1}$ after each selection cut are shown in Table 5.1. In the table, in addition to the absolute yields, the relative efficiency is also provided step by step. The absolute acceptance increases with the number of muons in the final state as expected because the reconstruction efficiency for muons is higher than for electrons. Please note that signal events here don’t include the contribution from $W^{\pm}Z \rightarrow \tau + X$. At the final selection step, the $\tau$ contribution is smaller than 5%; the overall acceptance is around 20% and 8% for the cases with and without $\tau$, respectively.

<table>
<thead>
<tr>
<th>cutflow</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$eee$</td>
</tr>
<tr>
<td>All</td>
<td>1202.26</td>
</tr>
<tr>
<td>Trigger</td>
<td>1116.16</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>51.22 (23.40%)</td>
</tr>
<tr>
<td>$E_{T}^{miss}cleaning$</td>
<td>40.50 (79.07%)</td>
</tr>
<tr>
<td>$Z$ cut</td>
<td>38.07 (93.99%)</td>
</tr>
<tr>
<td>Three leptons</td>
<td>38.04 (99.93%)</td>
</tr>
<tr>
<td>$E_{T}^{miss}$ cut</td>
<td>37.24 (97.89%)</td>
</tr>
</tbody>
</table>

Table 5.1: Expected number of MC events after each cut for $W^{\pm}Z \rightarrow \ell\nu\ell'$ for $\mathcal{L} = 4.64 \text{ fb}^{-1}$. The efficiency relative to previous cut step is shown in parenthesis.

5.3.2 MC background

In all four channels, ZZ events in which both Z bosons decay leptonically are a major background to the $W^{\pm}Z$ signal. For a ZZ event to pass the $W^{\pm}Z$ event selection, it must have $E_{T}^{miss}$ greater than 25 GeV. The source of this $E_{T}^{miss}$ could be mis-measured jets, tail of the $E_{T}^{miss}$ distribution, or from missing a lepton from Z decay outside the detector fiducial acceptance. Leptonic decays of Z bosons produced in association with photons can also mimic the trilepton signature when a photon is converted into electron-positron pair upon interaction with detector material. Requiring three isolated leptons is widely responsible for exclusion of several backgrounds, in particular heavy flavor quarks from QCD. For the processes like $WW$,
QCD dijet and single top, MC samples yield no events, which in our expectation. Therefore, they are neglected in this analysis. The final yields for MC based backgrounds are shown in Table 5.2, compared with signal yields.

<table>
<thead>
<tr>
<th>Process</th>
<th>$e e e$</th>
<th>$e e \mu$</th>
<th>$\mu \mu e$</th>
<th>$\mu \mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{\pm} Z$</td>
<td>38.9±0.5</td>
<td>54.0±0.5</td>
<td>56.6±0.6</td>
<td>81.7±0.7</td>
</tr>
<tr>
<td>$Z + \gamma$</td>
<td>1.4±0.7</td>
<td>-</td>
<td>2.3±0.9</td>
<td>-</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>3.2±0.1</td>
<td>4.9±0.1</td>
<td>5.0±0.1</td>
<td>7.9±0.1</td>
</tr>
</tbody>
</table>

Table 5.2: The MC based background estimation, including $ZZ$ and $Z + \gamma$. The yields are normalized to 4.64fb$^{-1}$.

5.3.3 Data-Driven Background Estimation

For those backgrounds characterized with two real leptons and one additional lepton either induced by or faked by jets, the third lepton are spatially correlated with jets, and therefore the isolation requirement removed majority of them. However, due to the large QCD jet cross-section, the residual background can still be significant. In this analysis, Data-Driven methods are conducted to estimate $t \bar{t}$ and $Z + jets$ backgrounds.

$t \bar{t}$

The typical LO $t \bar{t}$ production and leptonic decay diagram is show in Figure 5.1. For $t \bar{t}$ events, the additional lepton comes from $b$ semi-leptonic decay; and therefore, a large part of this background can be eliminated by rejecting reconstructed leptons from $b$ quark or light quark jets via lepton isolation requirement. From MC simulation, when normalized to 4.6 fb$^{-1}$, approximately only three events remain at final cut step with a very large statistical uncertainty. A $t \bar{t}$ dominated control region is defined as data events passing all the event selection cuts expect the $Z$ mass windows is not applied and $Z$ is formed with two same-sign leptons. As shown in Figure 5.2, the same-sign control region can well represent the nominal region (opposite-sign).
Figure 5.2: The invariant mass (left) and the $E_T^{miss}$ (right) distributions for same flavor lepton pair closest to PDG Z mass in MC $t\bar{t}$ events, with all analysis cut applied except Z mass requirement. The black dots denote the opposite-sign pair, and the red dots denote the same sign pair.

Within this control region, the data events are considered to mostly come from $t\bar{t}$; therefore one can derive a scale factor according to the discrepancies between data (subtracted with non $t\bar{t}$ contribution) and $t\bar{t}$ MC, and apply it to MC in order to compensate the mis-modelling effect. According to Figure 5.3, the scale factor is calculated to be $2.2 \pm 1.0$; here, 1.0 is purely statistical uncertainties.

Figure 5.3: The data and MC comparison in $t\bar{t}$ control region in $ee\mu$ channel (left) and $e\mu\mu$ channel (right).

Besides, The MC@NLO generator, which produces $t\bar{t}$ MC events, doesn’t include weak boson radiation from initial state quarks. Therefore, additional $t\bar{t} + W$ and $t\bar{t} + Z$ samples are taken into account; and in principle, these should be added in together with the Data-Driven yields. The final $t\bar{t}$ background estimation is listed in Table 5.3.

**Z + jets**

Events with fake leptons are major background to the $W^\pm Z$ signal. Because lepton fake rates are expected to depend strongly on event kinematics, we measure the fake rate in a sample (control sample) with event kinematics as similar as possible to our signal region (select Z plus one additional lepton). And, to be orthogonal to the signal region and in the meantime make the $Z + jets$ dominate in the control sample, the sample is selected by reversing the
Table 5.3: The estimation of $t\bar{t}$, $t\bar{t} + W$ and $t\bar{t} + Z$ backgrounds. The $t\bar{t}$ background is scaled by a factor of 2.2 determined in data-driven methods, and its systematic uncertainties is scale up at same amount from MC uncertainties (described in next section).

<table>
<thead>
<tr>
<th>channel</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t\bar{t}$</td>
</tr>
<tr>
<td>$eee$</td>
<td>$0.4 \pm 0.3 \pm 0.2$</td>
</tr>
<tr>
<td>$ee\mu$</td>
<td>$1.7 \pm 0.5 \pm 0.8$</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>$2.3 \pm 0.5 \pm 1.0$</td>
</tr>
<tr>
<td>$\mu\mu\mu$</td>
<td>$2.4 \pm 0.5 \pm 1.1$</td>
</tr>
</tbody>
</table>

$E_T^{miss}$ cut ($E_T^{miss} < 25$ GeV). The extra muons or electrons in the control sample are then classified as to be jet-like or signal-like depending on several criteria, and then the fake rate, so called “fake factor” in this case, is calculated as

$$f_{\text{lepton}} = \frac{N_{\text{tight lepton}}}{N_{\text{loose lepton}}} \quad (5.1)$$

Where $N_{\text{tight lepton}}$ and $N_{\text{loose lepton}}$ correspond to the number of signal-like and jet-like leptons, respectively. For muons, the loose leptons are indeed real leptons but induced inside heavy flavor jets; for electrons, the loose leptons mostly come from jet faking, i.e. charged particles in a hadronic jet interact in the electromagnetic calorimeter and deposit significant amount of energy. The selection criteria should have significant discriminant power so that the selected loose leptons contain mostly the jet-like leptons and the tight leptons are mostly the signal-like leptons. In our case, the selection is quite straightforward: muons passing all cuts are considered to be tight, and be loose if failing the isolation cut; electrons passing all cuts are considered to be tight, and be loose if failing either the isolation cut or electron loose $++$ identification requirements.

Processes which produce three real leptons contribute to both the numerator and denominator of the fake factor calculation. Since we measure the fake factor for $Z + jets$ background, the contributions from other processes (SM Electroweak processes) should be removed; This corresponds to a less than 1% correction to the loose lepton counts and a sizable correction to the tight lepton counts given that $WZ$ have big contribution in three lepton final states even already suppressed by reversing $E_T^{miss}$ cut. The $p_T$ distributions for loose and tight electrons are shown in Figure 5.4, and Figure 5.5 presents the $p_T$ distribution for loose and tight muons in the control samples. And the derived fake factors are shown in Figure 5.6 for electrons in the left and muons in the right.

To get final Data-Driven yields, a loose region must be defined corresponding to the signal region; and the fake factors are applied on the events in the loose region to estimate $Z + jets$ contribution in signal region. The loose region is defined as events passing all event selection cuts but having a loose lepton reconstructed as from $W$ decay, where the loose lepton definition is the same as used in fake factor derivation. In $eee$ and $\mu\mu\mu$ channels, it is possible that the loose lepton is reconstructed as from $Z$ decays. The possibility is rather low given the $Z$ mass constraint, and we find that in $eee$ channel, 10% of $Z + jets$ background comes from events with a loose $Z$ lepton, while MC predicts 8%. For $\mu\mu\mu$ case, we can’t directly measure this percentage from data since $t\bar{t}$ dominates in the loose region, therefore a correction estimated
Figure 5.4: The $p_T$ distribution for loose (left) and tight (right) electrons in the control sample. Error bands show the statistical uncertainty.

Figure 5.5: The $p_T$ distribution for loose (left) and tight (right) muons in the control sample. Error bands show the statistical uncertainty.

Figure 5.6: The electron and muon fake factor measured in $p_T$ bins. The error bars are for statistics only.
from MC is applied. For the $ee\mu$ and $e\mu\mu$ channels, no correction is needed because the $Z$ lepton assignment is unambiguous.

There are a few sources of systematic uncertainties. 1) The fake factor is derived in low $E_T^{miss}$ region, but applied in the loose region defined with high $E_T^{miss}$ requirement. This difference is treated as an systematic uncertainty on the measurement of fake factor, which is derived as the fractional difference between fake factors in the high $E_T^{miss}$ region and the low $E_T^{miss}$ region in $Z + jets$ MC events, or the statistical uncertainty of their ratio, whichever is larger. For the inclusive muon fake factor, this uncertainty is about 35%; for the electron fake factor, it is 20%. 2) An additional systematic uncertainty on the fake factor comes from the subtraction of non $Z + jets$ background to the control region used to determine fake factor. The $WZ$ and $ZZ$ contributions are varied very conservatively $\pm 15\%$, and the $t\bar{t}$ contribution is varied by 100% given the large uncertainty observed at three lepton stage. With the variations, fake factors are re-calculated and then compared to nominal value in order to set the fractional difference as systematic uncertainty.

The final estimates after applying the fake factors to loose region and propagating the systematic uncertainties are listed in Table 5.4.

<table>
<thead>
<tr>
<th>prediction</th>
<th>$eee$</th>
<th>$ee\mu$</th>
<th>$e\mu\mu$</th>
<th>$\mu\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.8 ± 2.1 ± 1.9</td>
<td>3.7 ± 1.7 ± 1.6</td>
<td>10.2 ± 2.4 ± 2.2</td>
<td>9.1 ± 3.9 ± 3.9</td>
</tr>
</tbody>
</table>

Table 5.4: The prediction of $Z + jets$ background from Data-Driven methods together with the statistical and systematic uncertainties.

5.4 Systematic Uncertainties

The systematic uncertainty for $Z + jets$ background is estimated with Data-Driven method. For signal and other background processes, the uncertainties are evaluated from MC study. As mentioned, the event topology for MC based processes are all similarly three leptons plus $E_T^{miss}$, therefore the uncertainty derived from signal MC samples is used for all MC processes. Please note that for $t\bar{t}$ background, the final systematic uncertainty is scaled up from MC uncertainty (Section 5.3.3). The final systematic uncertainty usually consists of uncertainties of corresponding physics objects and some event level uncertainties.

5.4.1 Event level systematic uncertainties

The event level uncertainties generally include the uncertainty on theoretical cross-section and luminosity uncertainties. In 2011, the luminosity uncertainties is determined to be 1.8%. And the theoretical uncertainties on MC processes are shown in Table 5.5. Besides, for signal MC, theoretical uncertainties are evaluated for fiducial acceptance.

PDF and scale uncertainty on fiducial acceptance

The calculation of the total cross section takes into account the fiducial acceptance due to phase-space requirement on the MC simulations. The central value of the acceptance, $A_{WZ}$, is calculated based on events generated with MC@NLO using CT10 PDF and the corresponding ATLAS MC11 tuning. The calculation of the acceptance uncertainties is itemized below:
<table>
<thead>
<tr>
<th>Process</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>+7.5 - 4.6</td>
</tr>
<tr>
<td>WW</td>
<td>+5.5 - 4.5</td>
</tr>
<tr>
<td>ZZ</td>
<td>+5.0 - 4.1</td>
</tr>
<tr>
<td>Z + γ</td>
<td>±5.0</td>
</tr>
<tr>
<td>t ¯ t</td>
<td>+7.0 - 9.6</td>
</tr>
</tbody>
</table>

Table 5.5: The theoretical cross-section uncertainties for MC processes.

- The uncertainty within CT10 PDF set is obtained by following a standard procedure described in the CTEQ manual. The symmetric uncertainty is evaluated by averaging positive and negative 653 uncertainties.

$$\sigma^+ = \sigma^- = \sqrt{\sum_{i=1}^{n} [\max(A_i - A_{WZ}, 0)]^2 + \sqrt{\sum_{i=1}^{n} [\max(A_{WZ} - A_i, 0)]^2}}$$  

Where $A_{WZ}$ is the WZ acceptance evaluated at the central value of CT10. The acceptance of the other PDF set is evaluated by applying event-by-event PDF re-weighting technique to the WZ signal samples.

- The uncertainty between different PDF sets. It is estimated by comparing CT10 to the central 658 MSTW2008 NLO 68% CL PDF set. The uncertainty calculated from 52 CT10 error eigenvectors is about 0.8%, and the central value deviation from MSTW2008 NLO is around 0.8%. The uncertainty due to the statistic of the sample is about 0.3%. The combined systematic uncertainty with quadratic sum is 1.2%, which is the PDF uncertainty for $A_{WZ}$.

The uncertainty due to renormalization scale $\mu_r$ and factorization scale $\mu_f$ are estimated by varying the scales by a factor of 2 or 0.5 and calculating the fractional percentage difference of fiducial acceptances in different cases. It is found to be approximately 0.4%. The $A_{WZ}$ generator dependence is cross-checked with POWHEG MC sample, and the difference is about 0.4%.

5.4.2 Object level systematic uncertainties

The object uncertainty can be generally derived from MC events in several steps: 1) obtain the systematic uncertainties corresponding to a physics quantity of the object from either performance group or via specific studies. 2) vary the physics quantity up or down by 1σ according to the uncertainty, and count how many events are selected after applying all selection cuts. The counting should be done in bins if studying certain kinematic distribution. 3) Compare the number of events selected in nominal analysis and in different analysis conditions with variations of that physics quantity. The fractional percentage difference is quoted as the systematic uncertainty contributed from the physics quantity of that object.

In $W^\pm Z$ analysis, major physics objects are trigger, electron, muon and $E_T^{miss}$. For trigger, the systematic uncertainty comes from the difference between trigger efficiencies in data and in MC. For electron and muon, major sources are energy (momentum) scale correction and resolution re-smearing, identification or reconstruction efficiency scale factor, other cut related efficiency scale factors. For $E_T^{miss}$, the uncertainty are contributed from the uncertainties of
its components. Table 5.6 summarizes the uncertainties from various sources in this analysis.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mu\mu\mu$</th>
<th>$e\mu\mu$</th>
<th>$e\epsilon\mu$</th>
<th>$e\epsilon\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ reconstruction efficiency</td>
<td>0.8</td>
<td>0.53</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$ $p_T$ scale and resolution</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$ isolation and impact parameter efficiency</td>
<td>0.62</td>
<td>0.43</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>$e$ reconstruction efficiency</td>
<td>-</td>
<td>0.8</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>$e$ identification efficiency</td>
<td>-</td>
<td>1.2</td>
<td>2.3</td>
<td>3.5</td>
</tr>
<tr>
<td>$e$ isolation, impact parameter efficiency</td>
<td>-</td>
<td>0.4</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>$e$ energy scale</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$e$ energy resolution</td>
<td>-</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$E_T^{miss}$ cluster energy scale</td>
<td>0.18</td>
<td>0.57</td>
<td>0.17</td>
<td>0.40</td>
</tr>
<tr>
<td>$E_T^{miss}$ jet energy scale</td>
<td>0.08</td>
<td>0.10</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>$E_T^{miss}$ jet energy resolution</td>
<td>0.25</td>
<td>0.39</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>$E_T^{miss}$ pileup</td>
<td>0.13</td>
<td>0.32</td>
<td>0.11</td>
<td>0.32</td>
</tr>
<tr>
<td>Trigger-$\mu$</td>
<td>0.29</td>
<td>0.15</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>Trigger-$e$</td>
<td>-</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
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<tr>
<td>Generator</td>
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<td>0.4</td>
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<td>0.4</td>
</tr>
<tr>
<td>PDF</td>
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<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Scale</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 5.6: Summary of all relative acceptance uncertainties (%) in the cross-section calculation.

### 5.5 Data and Prediction

#### 5.5.1 Comparison in Numbers

The number of expected and observed events after applying all selection cuts are shown in Table 5.7, with both statistical and systematic uncertainties. The $Z + jets$ background is estimated using data-driven methods; $t\bar{t}$ contribution is estimated with MC and rescaled to data, and all other predictions come from MC simulation. All numbers are calculated with 3 but rounded up to 2 decimal places.

For each channel and each process, the fractional systematic uncertainties are calculated by combining different sources (Table 5.6) in quadrature and then applying to the central value of MC-based estimates. The uncertainty on the rescaling method used for top background estimate is added in quadrature to that systematic uncertainty. For $Z + jets$ background, the systematic uncertainties are the ones from the data-driven estimate method.

In total, 317 $W^{\pm}Z$ candidates are observed in data with 231.2 signal and 68.1 background events expected. The data agree with the prediction quit decently. Please note the systematic uncertainties quoted in the Table 5.7 are not used in cross-section fitting.

#### 5.5.2 Comparison in Distributions

The understanding of studied SM process is often referred to the agreement between data and predictions. The comparison of various kinematic kinematics distributions are of vital
that bin and find the excess is largely reduced by re-binning. 

is confirmed to be just statistical fluctuation after we validate the good quality of events in

of W, the transverse mass of

closer look, you can reveal many characterization of W±Z events, e.g. the charge asymmetry

W, the transverse mass of W±Z system peaking at around 150 GeV and the invariant mass of system peaking at around 250 GeV, etc. The central bin in $M_T^{W}$ looks a bit excess, and it is confirmed to be just statistical fluctuation after we validate the good quality of events in that bin and find the excess is largely reduced by re-binning.

<table>
<thead>
<tr>
<th>Final state</th>
<th>eee</th>
<th>eµ</th>
<th>eτµ</th>
<th>µµµ</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>56</td>
<td>75</td>
<td>78</td>
<td>108</td>
<td>317</td>
</tr>
<tr>
<td>ZZ</td>
<td>3.2 ± 0.1 ± 0.2</td>
<td>4.9 ± 0.1 ± 0.2</td>
<td>5.0 ± 0.1 ± 0.1</td>
<td>7.9 ± 0.1 ± 0.2</td>
<td>21.0 ± 0.2 ± 0.7</td>
</tr>
<tr>
<td>Z + jets</td>
<td>8.8 ± 2.1 ± 1.9</td>
<td>3.7 ± 1.7 ± 1.6</td>
<td>10.2 ± 2.4 ± 2.2</td>
<td>9.1 ± 3.9 ± 3.9</td>
<td>31.9 ± 5.3 ± 7.5</td>
</tr>
<tr>
<td>Top</td>
<td>1.1 ± 0.3 ± 0.2</td>
<td>2.9 ± 0.5 ± 0.8</td>
<td>3.5 ± 0.5 ± 1.0</td>
<td>4.0 ± 0.5 ± 1.1</td>
<td>11.5 ± 0.9 ± 3.4</td>
</tr>
<tr>
<td>Z + γ</td>
<td>1.4 ± 0.7 ± 0.1</td>
<td>-</td>
<td>2.3 ± 0.9 ± 0.1</td>
<td>-</td>
<td>3.7 ± 1.1 ± 0.1</td>
</tr>
<tr>
<td>Bkg(total)</td>
<td>14.5 ± 2.2 ± 1.9</td>
<td>11.5 ± 1.8 ± 1.8</td>
<td>21.0 ± 2.6 ± 2.4</td>
<td>21.0 ± 3.9 ± 4.0</td>
<td>68.1 ± 5.5 ± 8.2</td>
</tr>
<tr>
<td>Expected Signal</td>
<td>38.9 ± 0.5 ± 2.0</td>
<td>54.0 ± 0.5 ± 2.1</td>
<td>56.6 ± 0.6 ± 1.6</td>
<td>81.7 ± 0.7 ± 2.0</td>
<td>231.2 ± 1.1 ± 7.8</td>
</tr>
<tr>
<td>Expected $S/B$</td>
<td>2.7</td>
<td>4.7</td>
<td>2.7</td>
<td>3.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 5.7: Summary of observed events and expected signal and background contributions in the four trilepton channels and combined. The first error is statistical while the second is systematic. The Z + jets contribution and uncertainty are taken from Data-Driven method. The systematics for the MC estimates are added linearly since they are correlated across channels. These are summed in quadrature with the systematics from the Z+jets background.

In SM W±Z analysis, the Z selection cut yields a Z control sample which provides a good calibration of object reconstructions and efficiency scale factors and so on. Figure 5.7 shows the invariant mass of the dilepton events before Z mass requirement. There is a few percent of difference (< 5%) between data and MC, which could reflect detection uncertainty on the Z events; other than that, MC predicts data perfectly well. Besides, the cleanness of Z peak validates our original strategy that loosen the lepton criteria from Z decay could gain efficiency but not introduce much background. Other kinematic distributions are also compared. The leading lepton $p_T$, $E_T^{miss}$ and number of leptons in the event are shown in Figure 5.8; the number of primary vertices and Z rapidity are shown in Figure 5.9; the leading lepton $\eta$ and $\phi$ are presented in Figure 5.10. Please note that, for plots at Z selection level, data is compared directly with MC.

After three lepton selection, events enter the W±Z signal region. Before cutting on $E_T^{miss}$, the distribution is investigated in Figure 5.11. You can see, by eye, the best cut value will be around 25 GeV or 30 GeV. Cutting at 25 GeV or 30 GeV actually have very similar $s/\sqrt{s + b}$, and the 25 GeV cut value is chosen to keep more statistics. After applying the $E_T^{miss}$ cut, the $M_T^{W}$ distribution is shown in Figure 5.12. By cutting $M_T^{W}$ at around 20 GeV, Z + jets background can be further reduced, especially in eee channel.

Finally, the data candidates are selected and compared to prediction (MC plus Data-Driven). The plots are shown in Figure 5.13 for various important kinematics variables. The overall picture is that the agreement between data and prediction is quite decent. With a closer look, you can reveal many characterization of W±Z events, e.g. the charge asymmetry of W, the transverse mass of W±Z system peaking at around 150 GeV and the invariant mass of system peaking at around 250 GeV, etc. The central bin in $M_T^{W}$ looks a bit excess, and it is confirmed to be just statistical fluctuation after we validate the good quality of events in that bin and find the excess is largely reduced by re-binning.
Figure 5.7: Invariant mass of dilepton pairs before Z mass cut in the $ee$ (top) and $\mu\mu$ (bottom) channels.

Figure 5.8: Leading lepton $p_T$ (left), $E_T^{miss}$ (middle) and number of leptons for $Zee$ (top) and $Z\mu\mu$ (bottom) events.
Figure 5.9: The number of vertices (left) and \(Z\) rapidity distribution (right) for \(Zee\) (top) and \(Z\mu\mu\) (bottom) events.

Figure 5.10: The leading lepton \(\eta\) (left) and \(\phi\) (right) distributions for \(Zee\) (top) and \(Z\mu\mu\) (bottom) events.
Figure 5.11: The $E_{T}^{miss}$ distribution after three lepton requirement in $eee$ (top left), $ee\mu$ (top right), $e\mu\mu$ (bottom left) and $\mu\mu\mu$ (bottom right) channels.

Figure 5.12: The $M_{T}^{W}$ distribution after $E_{T}^{miss}$ requirement in $eee$ (top left), $ee\mu$ (top right), $e\mu\mu$ (bottom left) and $\mu\mu\mu$ (bottom right) channels.
Finally, the invariant mass of the WZ system. The error band includes both statistical and systematic uncertainties. The invariant mass of three leptons, W charge, and number of jets, number of leptons and finally invariant mass of the WZ system. The error band includes both statistical and systematic uncertainties. And background are modeled with MC, except Z + jets from Data-Driven methods. The last bin is overflow bin.

Figure 5.13: The kinematics distributions for selected W±Z events: from left to right and from top to bottom, leading lepton p_T, E_T^{miss}, p_T^W, p_T^Z, Z mass, p_T of WZ system, M_T of WZ system, invariant mass of three leptons, W charge, M_T^W, number of jets, number of leptons and finally invariant mass of WZ system. The error band includes both statistical and systematic uncertainties. And background are modeled with MC, except Z + jets from Data-Driven methods. The last bin is overflow bin.
5.6 Cross-Section Measurement

Generally, cross-section could be extracted as

\[ \sigma = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \cdot \epsilon \cdot \mathcal{A}} \]  

(5.3)

Where \( N_{\text{obs}} \) is the number of observed data events, \( N_{\text{bkg}} \) is the number of expected background events, \( \epsilon \) is the reconstruction efficiency and \( \mathcal{A} \) is the detector acceptance. The \( \mathcal{A} \) and \( \epsilon \) come directly from signal MC, and the number of events are fixed after event selection and background estimation. The cross-section can be simply extracted from this equation; however, the correlation of systematics is difficult to handle in this simple form, and therefore, a log-likelihood fitting method is adopted in this analysis.

Detector acceptance limits the cross-section measurement in a specific phase space, which is even more reduced when we apply our selection cuts. In order to calculate a total cross-section, an extrapolation must be done from the measurement within the detector acceptance to the total volume. The extrapolation is simultaneously done in Eq 5.3, since the \( \mathcal{A} \) term presents. In cross-section measurement, we often measure both a fiducial cross-section without the extrapolation and the total cross-section. In principle, the calculation of a fiducial cross-section only contains the reconstruction level corrections or efficiencies without much need to know how the fiducial volume is formed. Therefore, the fiducial cross-section is considered to have much less theoretical uncertainties; it could be extrapolated to total phase space with other MC models or generators, which provide a convenient way for theoretical study.

5.6.1 Fiducial acceptance

In order to calculate fiducial acceptance, a fiducial volume must be defined. The volume should be selected with generator level cut, be as general as possible and be similar to our event selection. Consider these factors, we define the fiducial volume as:

- \( p_T > 15 \text{ GeV} \) for the two charged leptons from \( Z \) decay
- \( p_T > 20 \text{ GeV} \) for the charged lepton from \( W \) decay
- \( |\eta| < 2.5 \) for leptons
- \( p_T^{\nu} > 25 \text{ GeV} \) for the neutrino
- \( |M_{\ell\ell} - M_Z| < 10 \text{ GeV} \) for the \( Z \) candidate
- \( M_W^T > 20 \text{ GeV} \) for the \( W \) candidate
- \( \Delta R > 0.3 \) for all the leptons

For those truth object selection, we use “dressed” final states leptons, which means all photons within \( \Delta R < 0.1 \) are added to the four-momentum of the lepton.

The cross-section measured in fiducial region will depends on the efficiency of building the reconstruction level objects out of the truth fiducial region. This efficiency, or sometimes referred by others as a correction, concerns mostly about reconstruction and therefore, is theoretically insensitive. In practice, it can be calculated as

\[ C_{WZ\rightarrow\ell\nu\ell\nu} = \frac{N_{\text{MC Pass All Cuts}}^{\text{Reco}} \times SF}{N_{\text{Generator}}^{\text{FiducialVolume}}} \]  

(5.4)

79
Where $SF$ means the event scale factor including lepton efficiency scale factors, trigger efficiency scale factors and so on; $N_{MC\, Pass\, All\, Cuts}^{Reco}$ means the number of MC events after applying all event selection at reconstruction level; $N_{Fiducial\, Volume}^{Generator}$ denotes the number of generated events in fiducial region. And then the fiducial acceptance can be denoted as

$$A_{WZ \rightarrow \ell \ell' \ell'} = \frac{N_{Fiducial\, Volume}^{Generator}}{N_{ALL}^{Generator}}$$

Where $N_{ALL}^{Generator}$ means the total number of generated MC events. Therefore, the total acceptance is written as $A \times C$.

In this analysis, the $A_{WZ \rightarrow \ell \ell' \ell'}$ is calculated, relative to the theoretical total cross section predicted by MCFM, using the MC@NLO with HERWIG showering. We apply a correction factor (1.018) taken from a comparison of the fiducial cross sections calculated by MC@NLO before showering and MCFM to account for the missing $Z/\gamma^*$ term in the MC@NLO samples. The $C_{WZ \rightarrow \ell \ell' \ell'}$ is calculated using single MC samples. The acceptance numbers are summarized in Table 5.8.

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu\mu$</th>
<th>$e\mu\mu$</th>
<th>$ee\mu$</th>
<th>$eee$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{WZ}$ (pre-showering)</td>
<td>0.352</td>
<td>0.352</td>
<td>0.352</td>
<td>0.352</td>
</tr>
<tr>
<td>$A_{WZ}$ (post-showering)</td>
<td>0.338</td>
<td>0.333</td>
<td>0.332</td>
<td>0.330</td>
</tr>
<tr>
<td>$C_{WZ}$</td>
<td>0.780</td>
<td>0.548</td>
<td>0.525</td>
<td>0.380</td>
</tr>
<tr>
<td>$A_{WZ} \times C_{WZ}$</td>
<td>0.263</td>
<td>0.182</td>
<td>0.174</td>
<td>0.125</td>
</tr>
</tbody>
</table>

Table 5.8: Fiducial and total acceptance corrections per channel

### 5.6.2 Likelihood Fit

In order to calculate cross-section, the number of signal and background events must be known. The expect total number of events can be expressed as

$$N_{exp}^i = N_s^i + N_b^i$$

Where $N_{exp}^i$ is the number of expected events after full selection, $N_b^i$ is the number of background events predicted from either MC or Data-Driven methods and $i$ denote the channel. To account for the systematics errors, we can have

$$N_s^i(x_k) = N_s^i(1 + \sum_{k=1}^{n} x_k S_k^i) \quad and \quad N_b^i(x_k) = N_b^i(1 + \sum_{k=1}^{n} x_k B_k^i)$$

Where $x_k \sim N(0,1)$, $S_k^i$ and $B_k^i$ are the corresponding systematic uncertainty in channel $i$ for signal and background events, respectively. This equation reflects the fact that uncertainties make the observables uncertain.

Therefore, the number of signal events can be expressed with either a function of fiducial
cross-section or total cross-section as

\[ N_i^s(\sigma_{WZ \rightarrow t\bar{t}e^+e^-}, x_k) = \frac{\sigma_{WZ \rightarrow t\bar{t}e^+e^-}^{fid}}{\sigma_{MC,WZ \rightarrow t\bar{t}e^+e^-}} \times (N_{WZ \rightarrow t\bar{t}e^+e^-}^{MC} + N_{WZ \rightarrow \tau+X}^{MC}) \times (1 + \sum_{k=1}^{n} x_k S_k^i) \]

\[ N_i^s(\sigma^{tot}, x_k) = \frac{\sigma_{MC}^{tot}}{\sigma_{MC}^{tot}} \times (N_{WZ \rightarrow t\bar{t}e^+e^-}^{MC} + N_{WZ \rightarrow \tau+X}^{MC}) \times (1 + \sum_{k=1}^{n} x_k S_k^i) \] (5.8)

We can then define the negative log-likelihood function as

\[-\ln L(\sigma, x_k) = \sum_{i=1}^{4} - \ln \left( \frac{e^{-(N_i^s(\sigma, x_k) + N_i^b(\sigma, x_k))} \times (N_i^s(\sigma, x_k) + N_i^b(\sigma, x_k))^{N_i^{obs}}}{(N_i^{obs})!} \right) + \sum_{k=1}^{n} \frac{x_k^2}{2} \] (5.9)

In this function, the key part is essentially a Poisson probability that our expected number of signal and background events produce our observed number of events. The final term in the likelihood equation is the product of the Gaussian constraints on the nuisance parameters \(x_k\). These nuisance parameters account for systematic errors and their effect on the number of expected signal and background events in each channel. The index \(k\) denotes each independent source of systematics. A single random variable \(x_k\) is used over all channels in both signal and background given the fact that each systematic is 100% correlated.

We use the MC to determine the total number of events expected in a given channel. We then scale this number by the ratio of the measured cross-section to the MC generator cross-section used to produce the MC expectations. In this way, we are using the data to drive our measurement to find the best rescaling of our expected signal contributions, and thus allows us to extract a cross-section.

To find the most probable value of \(\sigma\), the log-likelihood function is minimized over \(\sigma\) and all the nuisance parameter \(x_k\). The errors are estimated by taking the difference of the cross-section at the minimum to the cross-section where the log-likelihood is 0.5 units above the minimum along the direction of the parameter \(\sigma\). This calculation is performed both in the positive and negative directions separately, and thus may yield different positive and negative errors. As the nuisance parameters account for the systematic errors on our measurement, this error is the combined statistical and systematic uncertainty on our measurement.

The full likelihood function with nuisance parameters will automatically take into account all the systematic errors, and propagate them to the final uncertainty. To understand the contribution from each systematic error separately, we can propagate by hand each systematic uncertainties on our acceptance to the final cross-section. We do this by adjusting the acceptance of our signal and background in the likelihood function up and down by one sigma, and re-minimizing the likelihood function. The difference in central cross-section value, and the cross-section obtained after adjusting the acceptance in the likelihood function is taken as the estimate of systematic uncertainty on the cross-section.

The final fitted fiducial cross-section and uncertainties are listed in Table 5.9, and the total cross-section and uncertainties are determined as in Table 5.10. The fitted total cross-section is consistent with the SM prediction of 17.6^{+1.1}_{-1.0} within the uncertainties. And the fractional uncertainties are 7% from statistics, 5% from systematics, and \(\sim 2\%\) from luminosity uncertainties. The total fractional uncertainty is about 8.6%, which is still statistical dominated; more precise cross-section measurement will be expected with more data. For instance, with

\[ \text{81} \]
total amount of data collected in 2011 and 2012, approximately the statistical uncertainty will 
be reduced by one half, which will make most precise $W^\pm Z$ production measurement to date.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross-section [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu\mu$</td>
<td>$23.03^{+2.84}<em>{-2.66}(\text{stat})^{+1.53}</em>{-1.53}(\text{syst})^{+0.46}_{-0.45}(\text{lumi})$</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>$21.46^{+3.46}<em>{-3.37}(\text{stat})^{+1.43}</em>{-1.33}(\text{syst})^{+0.43}_{-0.43}(\text{lumi})$</td>
</tr>
<tr>
<td>$ee\mu$</td>
<td>$24.98^{+3.29}<em>{-3.25}(\text{stat})^{+1.31}</em>{-1.30}(\text{syst})^{+0.48}_{-0.48}(\text{lumi})$</td>
</tr>
<tr>
<td>$eee$</td>
<td>$22.53^{+3.85}<em>{-3.85}(\text{stat})^{+1.95}</em>{-1.95}(\text{syst})^{+0.44}_{-0.44}(\text{lumi})$</td>
</tr>
<tr>
<td>Combined</td>
<td>$93.31^{+6.66}<em>{-6.33}(\text{stat})^{+4.31}</em>{-4.26}(\text{syst})^{+1.85}_{-1.79}(\text{lumi})$</td>
</tr>
</tbody>
</table>

Table 5.9: Measured fiducial cross-sections and uncertainties

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross-section [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu\mu$</td>
<td>$18.74^{+2.31}<em>{-2.17}(\text{stat})^{+1.27}</em>{-1.27}(\text{syst})^{+0.38}_{-0.36}(\text{lumi})$</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>$17.72^{+2.86}<em>{-2.64}(\text{stat})^{+1.21}</em>{-1.20}(\text{syst})^{+0.35}_{-0.35}(\text{lumi})$</td>
</tr>
<tr>
<td>$ee\mu$</td>
<td>$20.69^{+2.97}<em>{-2.89}(\text{stat})^{+1.13}</em>{-1.12}(\text{syst})^{+0.41}_{-0.40}(\text{lumi})$</td>
</tr>
<tr>
<td>$eee$</td>
<td>$18.78^{+3.58}<em>{-3.20}(\text{stat})^{+1.69}</em>{-1.66}(\text{syst})^{+0.38}_{-0.37}(\text{lumi})$</td>
</tr>
<tr>
<td>Combined</td>
<td>$19.00^{+1.38}<em>{-1.30}(\text{stat})^{+0.92}</em>{-0.90}(\text{syst})^{+0.38}_{-0.37}(\text{lumi})$</td>
</tr>
</tbody>
</table>

Table 5.10: Measured total cross-sections and uncertainties

5.7 aTGC limit

5.7.1 Sensitivity and Optimization

The basic TGC physics is described in Section 2.3.1. The present of aTGCs not only increases 
the $W^\pm Z$ production cross-section, but also has important impact on some observables. Due 
to the $\sqrt{s}$ dependence of the aTGCs, observables that are related to $\sqrt{s}$, will be sensitive to 
the presence of aTGCs. Figure 5.14 shows the $W^\pm Z$ production cross-section, leading lepton $p_T$, $M_{WZ}$ and $p_T^Z$ dependence on aTGCs. In the plots, the difference between SM and aTGC 
predictions can be considered to represent the sensitivity, and it is easy to validate that the tail 
region of kinematic distributions has much better sensitivity than cross-section. Therefore, 
a kinematic variable should be picked in order to probe aTGCs. Among all the studied 
variables, $p_T^Z$ looks best in terms of sensitivity. Besides, the $Z$ reconstruction is usually not 
affected by bad measured jets or $E_T^{\text{miss}}$ (in contrast to $M_{WZ}$), which further makes it superb 
for searching new physics via aTGCs.

Since high $p_T^Z$ events are more sensitive to aTGCs, the $p_T^Z$ must be properly binned 
to make most advantage of this fact. To study the binning effects on sensitivity, it is better to 
extRACT the limits with different binning conditions and then perform optimization. The actual 
limit setting is done via a frequentist approach, in which the 95% confidence interval is based 
on a likelihood function describing how likely the data is given a particular value of aTGCs 
(details in Section 5.7.2). However, the complete procedure is computationally slow, therefore 
a simplified version is used to enable fast turn-round in optimization study. The simpler 
method is as following: 1) construct the log-likelihood function $L(\alpha, \beta)$ with the similar form
in Eq 5.9 with aTGC parameters $\alpha$ replacing $\sigma$; here, $\beta$ denotes the nuisance parameter representing the systematic uncertainties. 2) maximize the log-likelihood function, and get the best fitted $\alpha$. 3) Find the best fit value $\pm$ the errors by setting the delta log-likelihood to 1.92; then the limits, as 95% confidence interval, is represented by the errors.

The initial $p_\perp^Z$ binning is (0, 30, 60, 120, 500) GeV, which is found to provide best limits after performing a bunch of tests. The upper boundary is chosen to cover the usual kinematic region we are studying. However, considering the sensitivity to $\sqrt{s}$, one would expect better limits if increase the upper boundary. As you can see in Figure 5.15, significant improvements are found by increasing the upper boundary to 2 TeV. The $\kappa^Z$ is less affected, because it is sensitive to $\sqrt{s}$, while other two are sensitive to $\hat{s}$. Finally, a binning of (0, 30, 60, 90, 120, 150, 180, 2000) GeV is chosen. Dividing more bins make slightly better limits, while the most improvement is still from increased upper boundary. The choice of 2 TeV is reasonable for current $pp$ collision at CME of 7 TeV, and further increasing the boundary might introduce unphysical effects.

### 5.7.2 Extraction

Before performing statistical calculation to extract limits, one must construct the log-likelihood function as shown in Eq 5.9. The first question is how number of signal events be related with aTGCs. In MC@NLO version 4.0 it is possible to generate $W^\pm Z$ events with any aTGC value. Each event has a vector of 10 weights ($w_0...w_9$) which can be reweighed to another
Figure 5.15: The expected aTGC limits (95% confidence interval widths determined in the log-likelihood method) for each aTGC parameter, including $\Delta g_{Z}^{T}$ (top left), $\Delta \kappa_{Z}$ (top right) and $\lambda_{Z}$ (bottom) The distribution of widths extracted from original binning (in black) and optimized binning (by increasing upper boundary) (in red) are compared. The cutoff scale is 100 TeV in this comparison.
aTGC phase space point. The weight of a new point is given by

\[ w(\Delta g_1^Z, \Delta \kappa^Z, \lambda^Z) = w_0 + (\Delta g_1^Z)^2 w_1 + (\Delta \kappa^Z)^2 w_2 + (\lambda^Z)^2 w_3 + 2\Delta g_1^Z \Delta \kappa^Z w_4 + 2\Delta \kappa^Z \lambda^Z w_5 + 2\lambda^Z w_6 + 2\Delta g_1^Z \Delta \kappa^Z w_7 + 2\Delta g_1^Z \lambda^Z w_8 + 2\Delta \kappa^Z \lambda^Z w_9 \]  

(5.10)

It is often suggested to check the aTGC limits with cutoff scale $\Lambda$, defined in Eq. 2.53, set to be infinity. Since the default MC@NLO MC has $\Lambda = 100$ TeV, to remove it, we could multiply the aTGC parameter by $(1 + s/\Lambda^2)^2$. And this corresponds to make corrections on the weights accordingly. Please note that one can use this procedure to study limits under other cutoff scales as well. The event weight $w$ should be corrected with generator weights, pileup weights, trigger scale factor and reconstruction scale factors. And after applying these additional weights, we accumulate the event weights for the MC signal events that passing our selection. In the end, the number of expected signal events can be expressed as

\[ N_s^i(\Delta g_1^Z, \Delta \kappa^Z, \lambda^Z) = W_0^i + (\Delta g_1^Z)^2 W_1^i + (\Delta \kappa^Z)^2 W_2^i + (\lambda^Z)^2 W_3^i + 2\Delta g_1^Z \Delta \kappa^Z W_4^i + 2\Delta \kappa^Z \lambda^Z W_5^i + 2\lambda^Z W_6^i + 2\Delta g_1^Z \Delta \kappa^Z W_7^i + 2\Delta g_1^Z \lambda^Z W_8^i + 2\Delta \kappa^Z \lambda^Z W_9^i \]  

(5.11)

Where $i$ denotes the index of $p_T^Z$ bin.

A frequentist approach is used to set limits on aTGC parameters. The 95% C.I. for each anomalous coupling was determined separately with the other couplings set to their SM values. The reweighting procedure described above allows us to express expected number of signal in $p_T^Z$ bins as a function of aTGC parameters. The procedure for determining the 95% C.I. is as following:

- Construct the log-likelihood function $L(n|\alpha, \beta)$, in which $\alpha = \Delta g_1^Z, \Delta \kappa^Z,$ or $\lambda^Z$; $\beta$ is the nuisance parameter. The systematic uncertainty here is derived in $p_T^Z$ bins.

- Form a test statistic $q(\alpha)$ as the ratio of the profile maximum likelihood at a test aTGC parameter value $\alpha$ to the full maximum likelihood. It can be written as

\[ q(\sigma) = \frac{L(n|\alpha, \hat{\beta})}{L(n|\hat{\alpha}, \hat{\beta})} \]  

(5.12)

Where $\hat{\beta}$ maximizes the numerator with test value of $\alpha$, and $\hat{\alpha}$ and $\hat{\beta}$ maximize the denominator.

- Calculate the observed value of test statistic $q_{\text{obs}}(\alpha)$. For each $\alpha$, there is a corresponding $q_{\text{obs}}(\alpha)$.

- Then for each $\alpha$, generate the expected number of events $N_{pe}$ randomly from a Poisson distribution whose mean was computed from the value of $\alpha$ and $\beta$. Here $\beta$ is Gaussian fluctuated around the $\hat{\beta}$. After that, the test statistic $q_{pe}(\alpha)$ can be formed. And for each $\alpha$, a large number of pseudo experiments (10000) are done in order to generate a sample of $q_{pe}(\alpha)$.

- The $p$-value at each value of $\alpha$ is calculated as the fraction of pseudo experiments whose test statistic $q_{pe}(\alpha)$ smaller than $q_{\text{obs}}(\alpha)$.

- By scanning $\alpha$, all values of the aTGC parameter with $p(\alpha) > 5\%$ can be determined and they define the 95% C.I. of $\alpha$ for observed data.
The observed and expected limits are summarized in Table 5.11 at two different cutoff scale: $\Lambda \sim \infty$ and $\Lambda = 2$ TeV.

<table>
<thead>
<tr>
<th></th>
<th>Observed 95% C.I.</th>
<th>Expected 95% C.I.</th>
<th>Observed 95% C.I.</th>
<th>Expected 95% C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda = 2$ TeV</td>
<td>$[-0.074, 0.133]$</td>
<td>$[-0.059, 0.110]$</td>
<td>$[-0.057, 0.093]$</td>
<td>$[-0.046, 0.080]$</td>
</tr>
<tr>
<td>$\Lambda = 2$ TeV</td>
<td>$[-0.42, 0.69]$</td>
<td>$[-0.37, 0.57]$</td>
<td>$[-0.37, 0.57]$</td>
<td>$[-0.33, 0.47]$</td>
</tr>
<tr>
<td>no cut-off</td>
<td>$[-0.064, 0.066]$</td>
<td>$[-0.056, 0.055]$</td>
<td>$[-0.046, 0.047]$</td>
<td>$[-0.041, 0.040]$</td>
</tr>
</tbody>
</table>

Table 5.11: Observed and expected limits as 95% C.I. on the aTGCs $\Delta g_1^Z$, $\Delta \kappa^Z$ and $\lambda^Z$.

The 95% C.I. for 2D fitting are shown in Figure 5.16. The limits extracted with a 2 TeV cutoff scale and with no form factor are both presented.

![Figure 5.16: Observed 2D 95% Confidence Contours. The cut-off scale is 2 TeV for the limits shown with a fine line and no cut-off for the limits shown with a thick line. The horizontal and vertical lines inside each contour correspond to the limits found in the 1D fit procedure.](image)

The comparison between ATLAS and Tevatron results are shown in Figure 5.17. The limits on $\Delta g_1^Z$ and $\Delta \lambda^Z$ are already very stringent, which provide the important information that the anomaly of TGCs is not observed. Compared with results from Tevatron experiments, we already extracted the best limits in $W^\pm Z$ production channels. Further optimization of the analysis and more statistics will be expected to help improve the limits.
Figure 5.17: aTGC limits from ATLAS and Tevatron experiments. Luminosities, center of mass energy and cut-off for each experiment are shown and the limits are for 95% C.I.
Chapter 6

The WZ Resonance Search

6.1 Analysis Overview

The $W^\pm Z$ resonance search is conducted by exploring the $W^\pm Z$ diboson system for resonant structure using events with $W/Z$ bosons in fully leptonic decay channels. Similar to the SM $W^\pm Z$ analysis, there are four channels considered: $eee$, $ee\mu$, $e\mu\mu$ and $\mu\mu\mu$. The exploring region, i.e. resonance at high mass, is often characterized by three high $p_T$ isolated leptons plus large $E_T^{miss}$. Although quite similar to the phase space in SM $W^\pm Z$ production, resonance $W^\pm Z$ final states often contain much harder leptons and larger $E_T^{miss}$. And besides, resonance decaying yields the $W$ and $Z$ bosons most likely to be back to back. Those kinematics features are used in this analysis to control the background contributions, especially the irreducible SM $W^\pm Z$ background, and define control region and signal region in order to conduct so called “blinded” analysis.

The “blinded” analysis is based on the philosophy that “validate what are known before explore what are unknown”. It starts with defining a control region and a signal region. The goal is to have most signal events preserved in the signal region, and least signal contained in the control region. Some discriminating kinematic variables are developed to satisfy this requirement; in this search, the angular variables of $W$ and $Z$ bosons are used to separate the resonance events and non-resonance events. The analysis is initialized with looking at control region to studying the agreement between data and prediction from well known SM processes. Once the control region is validated with careful check, the analysis is then extended to the signal region in order to search for new physics.

The even selection is similar to SM $W^\pm Z$ analysis. According to the event characteristics, there are a few adjustments to further suppress background, including tightening the lepton $P_T$ cut and the identification requirement, requiring exactly three leptons, and etc. Events passing all the basic selection cuts are further classified into signal and control region based on whether the angular variables are more signal-like or background-like.

Most SM electroweak backgrounds are estimated with MC, and Data-Driven methods are developed to evaluate the jet-faking ($Z+jets$) or jet-inducing ($Top$) background contributions. The energy and momentum scale corrections and resolution re-smearing and the efficiency scale factors are applied to MC estimates to get hold of the best reconstruction extracted from data events. Two fake factor methods are used. One is based on the fake factors derived from dijet events; the fake factors in the other methods come from $Z$ events, which is similar
to what are done in SM $W^\pm Z$ analysis. Data-Driven estimates from the two methods are then cross-checked in order to obtain a good understanding of background.

Tail region of the invariant mass of $W^\pm Z$ system ($M_{WZ}$) is most sensitive to the resonance search; however, SM backgrounds fall exponentially as $M_{WZ}$ grows, therefore neither MC estimation nor Data-Driven estimation could provide sufficient information for understanding backgrounds in tail events. The MC samples for irreducible SM $W^\pm Z$ background turns to have adequate statistics in our interested region, and therefore, we use MC to estimate SM $W^\pm Z$ contribution in full mass range. For other backgrounds with little statistics in the tails, an extrapolation is performed to derive the approximate estimation for high mass region based on the background shape in low mass region.

In the case that no excess is observed in the data, we set upper limits on the possible new phenomena cross-section multiplied by the combined diboson branching ratios. To set these limits we use a modified frequentist method based on $M_{WZ}$. While this search is mostly model-independent, we convert the cross-section limit into a lower limit on the mass of the hypothetical EGM $W'$ and LSTC $\rho_T$.

### 6.2 Event Selection

The $W^\pm Z$ resonance search is based on the three lepton plus $E_T^{miss}$ final states. The object selection and the specific $W^\pm Z$ selection are described below.

**Electrons** are selected with similar criteria as described in Section 5.2, expect a few modifications: 1) electron $p_T$ is tightened and required to be larger than 25 GeV; 2) the electron identification requirement is “medium ++”, compared to “loose ++” in SM $W^\pm Z$ analysis; 3) The isolation cut is optimized as requiring the sum of transverse energy surrounding the electron cluster measured in the calorimeter within $\Delta R = 0.2$ ($etcone_{20}$) divided by the electron $p_T$ be less than 0.1. Besides, $etcone_{20}$ is corrected for energy leakage and pileup effect. Instead of using $etcone_{30}$ (in SM $W^\pm Z$ analysis), the cone size 0.2 is chosen given the fact that resonance signal events often decay into boosted $Z$ which make the subsequently decaying leptons close to each other. There, a smaller cone size preserve high signal efficiency.

**Muons** are also selected similarly as in SM $W^\pm Z$ analysis. The modifications are 1) Only STACO combined muons are chosen; 2) muon $p_T$ cut is tightened to be 25 GeV; 3) A tighter $\eta$ cut is applied ($|\eta| < 2.4$) in order to make sure the quality of high $p_T$ muons inside MS coverage (trigger cover up to $|\eta| = 2.4$); 4) The charge over momentum difference between the inner detector and the muon spectrometer divided by the the total significance must be smaller than 5. This ensure the consistency between ID and MS measurement, in order to avoid bad measured muons; 5) The sum of track transverse momenta surrounding the muon track within $\Delta R = 0.2$ ($ptcone_{20}$) divided by muon $p_T$ must be less than 0.1. The migration from cone size 0.3 to cone size 0.2 is due to the same reason as in electron case.

The energy scale correction and the energy resolution re-smearing are applied for each lepton; and the lepton detection efficiency scale factors are applied at per lepton base. Besides, the overlapping between $e$ and $\mu$ within $\Delta R = 0.1$ and the overlapping between $e$ and jet within $\Delta R = 0.3$ are handled by removing the electron is the first case and removing the jet in the second case.
$W^\pm Z$ selection

The event level pre-selection cuts are the same as in SM $W^\pm Z$ analysis (Section 5.2). The specific resonance $W^\pm Z$ selection cuts are:

- **Z candidate** Require at least one same flavor and opposite charge lepton pairs satisfying: $|M_\ell\ell - 91.1876| < 20$ GeV. If more than one pair found, the pair with mass best matching PDG Z mass is chosen.
- **three leptons** Require exactly three lepton in event and reject the event if have additional lepton with $20 < p_T < 25$ GeV.
- **Trigger matching** One of the offline leptons from $W$ or $Z$ decays must match the trigger object which firing the single lepton trigger. According to the trigger threshold, the matched lepton $p_T$ is required to larger than 20(25) GeV for muons(electrons).
- **$E_T^{miss}$ cut** The missing transverse energy in the event must be larger than 25 GeV.
- **$\Delta y$ cut** The $\Delta y$ between $W$ and $Z$ should be smaller than 1.8.
- **$\Delta \phi$ cut** The $\Delta \phi$ between $W$ and $Z$ should be larger than 2.6.

The Z mass window is loosen to increase signal acceptance; and the exact three leptons requirement is meant to further suppress $ZZ$ background, although it turns out to have little effect. The $\Delta y$ and $\Delta \phi$ cuts are used to separate control region and signal region. As you can see in Figure 6.1, signal events are mostly concentrated in high $\Delta \phi(WZ)$ and low $\Delta y(WZ)$ region. The signal region is defined with $\Delta \phi(WZ) > 2.6$ and $\Delta y(WZ) < 1.8$, which preserve majority of $W'$ signal; the control region is then defined with the reserved angular cut ($\Delta \phi(WZ) < 2.6$ or $\Delta y(WZ) > 1.8$), which contains little signal.

![Figure 6.1: The $\Delta y$ (left) and $\Delta \phi$ (right) of $W$ and $Z$ for MC events passing the $E_T^{miss}$ requirement. The SM $W^\pm Z$, $Z + jets$, $ZZ$ and $Z\gamma$ MC events are shown in green, yellow, purple and red, respectively. Three $W'$ signal MC are shown in blue and gray histograms.](image)

### 6.3 Signal and Background

The acceptance and kinematics shape for signal events are derived from PYTHIA sample. The largest background in $W^\pm Z$ resonance search is naturally the SM $W^\pm Z$, whose contribution can be simply estimated using MC. Other diboson backgrounds including $ZZ$ and
$Z + \gamma$ are also estimated with MC. For backgrounds which have at least one jet-faking or jet-induced lepton such as $Z + \text{jets}$ and $t\bar{t}$, Data-Driven methods are introduced to evaluate their contamination. There are two data-driven methods used in this search; one is based on fake factors derived from dijet events, and the other one is based on fake factors derived from $Z$ events. Their consistency indicates a good understanding of background. Finally, all the backgrounds except SM $W^\pm Z$ are combined and extrapolated into high $M_{T}^{W}$ region.

### 6.3.1 MC Estimation

The signal acceptance for typical $W'$ sample ($m = 750$ GeV) is shown in Table 6.1. Please note the $\tau$ contribution is included in the inclusive PYTHIA MC sample. The total acceptance is around 5%-6% depending on the channel.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$\text{ee}$</th>
<th>$\text{e}\mu$</th>
<th>$\mu\mu$</th>
<th>$\mu\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three leptons</td>
<td>0.063</td>
<td>0.068</td>
<td>0.073</td>
<td>0.074</td>
</tr>
<tr>
<td>$Z$ mass cut</td>
<td>0.940</td>
<td>0.912</td>
<td>0.925</td>
<td>0.937</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}} &gt; 25$ GeV</td>
<td>0.971</td>
<td>0.971</td>
<td>0.990</td>
<td>0.974</td>
</tr>
<tr>
<td>$\Delta y(WZ)$</td>
<td>0.951</td>
<td>0.942</td>
<td>0.940</td>
<td>0.933</td>
</tr>
<tr>
<td>$\Delta \phi(WZ)$</td>
<td>0.971</td>
<td>0.964</td>
<td>0.978</td>
<td>0.979</td>
</tr>
<tr>
<td>Total acceptance</td>
<td>0.053</td>
<td>0.054</td>
<td>0.062</td>
<td>0.062</td>
</tr>
</tbody>
</table>

Table 6.1: Relative efficiency for each selection cut and the total efficiency for $W'$ events with $M = 750$ GeV.

Table 6.2 presents the number of expected signal events and estimated background events from MC. Among the MC backgrounds, SM $W^\pm Z$ takes $\sim 90\%$ contribution, which is expected. By comparing the number of expected signal events at different masses with the MC backgrounds, it is expected that the presence of any low mass $W'(m \sim 500$ GeV) would cause significant excess in data. Currently, the good agreement between data and MC simultaneously excludes those low mass resonance signal. For high mass signal, the $M_{T}^{WZ}$ distribution is needed. Qualitatively, any excess in high mass bin would possibly signal new physics; however, this statement is true only if statistics are sufficient.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\text{ee}$</th>
<th>$\text{e}\mu$</th>
<th>$\mu\mu$</th>
<th>$\mu\mu\mu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounds:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WZ$</td>
<td>17.73 ± 0.28</td>
<td>19.99 ± 0.29</td>
<td>22.80 ± 0.31</td>
<td>26.47 ± 0.34</td>
<td>86.99 ± 0.61</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.33 ± 0.05</td>
<td>1.73 ± 0.06</td>
<td>1.93 ± 0.06</td>
<td>2.46 ± 0.07</td>
<td>7.45 ± 0.12</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>2.82 ± 0.95</td>
<td>-</td>
<td>2.05 ± 0.61</td>
<td>-</td>
<td>4.88 ± 1.13</td>
</tr>
<tr>
<td>Signals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W'(m = 350$ GeV$)$</td>
<td>60.53 ± 2.14</td>
<td>55.99 ± 2.06</td>
<td>68.89 ± 2.28</td>
<td>77.92 ± 2.43</td>
<td>263.33 ± 4.47</td>
</tr>
<tr>
<td>$W'(m = 500$ GeV$)$</td>
<td>22.32 ± 0.62</td>
<td>20.77 ± 0.60</td>
<td>25.52 ± 0.66</td>
<td>25.81 ± 0.66</td>
<td>94.42 ± 1.27</td>
</tr>
<tr>
<td>$W'(m = 750$ GeV$)$</td>
<td>4.84 ± 0.12</td>
<td>4.74 ± 0.12</td>
<td>5.13 ± 0.12</td>
<td>4.82 ± 0.12</td>
<td>19.55 ± 0.23</td>
</tr>
<tr>
<td>$W'(m = 1000$ GeV$)$</td>
<td>1.36 ± 0.03</td>
<td>1.33 ± 0.03</td>
<td>1.42 ± 0.03</td>
<td>1.29 ± 0.03</td>
<td>5.40 ± 0.06</td>
</tr>
</tbody>
</table>

Table 6.2: The estimated background yields with MC and expected signal yields. Errors are statistical only. MC numbers are normalized to integrated luminosity.
6.3.2 Data-Driven methods

The two Data-Driven methods used in this search are all based on “fake factor”. The fake factor represents the probability of a jet or non-prompt lepton inside a jet to mimic the prompt lepton. In the electron case, an inner track mismatched with EM clusters inside a jet can trigger reconstruction of an electron; in the muon case, muon from heavy flavor quark decays can be prompt-like muon if its impact parameter and isolation variable pass the selection criteria. The fake factor is often measured in a jet enriched sample, and calculated as

\[
 f \equiv \text{fake factor} = \frac{N_{\text{good lepton}}}{N_{\text{bad lepton}}}
\]  
(6.1)

Where \(N_{\text{good lepton}}\) denotes the number of jets mimicking real leptons by satisfying all lepton requirements, and \(N_{\text{bad lepton}}\) represents the number of jets failing certain lepton selection criteria and therefore being counted as bad leptons.

Please note that our measurement can only be done on the leptons which we think could represent target jets. Therefore, the sample (control sample) where we derive fake factor should be jet-enriched in the first place.

In order to apply fake factor to extract the background yields, a loose sample should be defined. The loose sample can be straightforwardly defined as data events passing all the event selection cuts but having at least one “bad lepton”. The number of events in the loose sample can be written as

\[
 N_{LS} = N_{LS}^{1bad} + N_{LS}^{2bad} + ...
\]  
(6.2)

Where \(N_{LS}^{1bad}\) and \(N_{LS}^{2bad}\) denotes number of events in loose sample containing only one bad lepton and two bad leptons, respectively. Assuming the fake factor independent of lepton \(p_T\), the background yields for one lepton faking and two lepton faking are

\[
 N_{bkg}^{1fake} = N_{LS}^{1bad} \times f - 2N_{LS}^{2bad} \times f^2
\]

\[
 N_{bkg}^{2fake} = N_{LS}^{2bad} \times f^2
\]  
(6.3)

In the case of \(W^\pm Z\) search, because of \(Z\) mass constraint, the \(N_{LS}^{2bad}\) is one order of magnitude lower than \(N_{LS}^{1bad}\); and the \(N_{bkg}^{2fake}\) term take additional \(f\) which is normally \(\sim 0.1\). The \(N_{bkg}^{1fake}\) is often two orders of magnitude lower than \(N_{bkg}^{1fake}\). So we often use this calculation

\[
 N_{bkg}^{1fake} = N_{LS}^{1bad} \times f
\]  
(6.4)

And in the case \(f\) is derived with \(p_T\) or \(\eta\) dependence, the final estimation will be the sum of fake factors times related event weight for all the events in loose sample.

In a specific analysis, the good lepton definition is fixed. Once the control sample is defined, the remaining ambiguity is how to define the bad lepton. Usually, you can veto or loosen identification criteria or isolation requirements to choose bad electrons, and veto or loosen impact parameter cut or isolation requirements to choose bad muons. The actual choice will depends on the statistics of the loose sample, the consistency of bad lepton definition in control sample and loose sample, and non-faking background contamination in the loose sample.
dijet fake factor method

muon fake factor determination

The control sample is consist of dijet events, which are selected by the following criteria:

- require a good jet ($p_T > 25$ GeV, passing quality cut) to be present in the event
- have $E_T^{miss} > 25$ GeV
- pass single muon trigger
- have a muon back-to-back with the jet ($\Delta \phi > 2$)
- veto events with invariant mass of muon and a good quality inner track fall into $\pm 20$ GeV $Z$ mass windows

The bad muon definition is passing all other muon selection criteria but failing isolation.

The $p_T$ distribution of good and bad muons and the derived fake factors as a function of muon $p_T$ or $\eta$ are show in Figure 6.2. When deriving the fake factor, electroweak contributions are subtracted from both bad and good leptons.

Figure 6.2: The bad (top left) and good lepton (top right) $p_T$ in the dijet control sample where fake factor is derived. The muon fake factor as a function of $p_T$ (bottom left) and $\eta$ (bottom right). The fake factor from data in black and from dijet MC in green.

To evaluate the fake factor systematic uncertainties. The following are considered:

- The bias due to muon trigger is evaluated by comparing the fake factors derived in $b\bar{b}$ MC samples with and without trigger requirements. It turns out to be negligible.
- The bias due to the back-to-back jet requirement is evaluated conservatively by comparing the fake factors derived in MC sample with and without this requirement. The uncertainties is provide bin by bin.
- The bias caused by $E_T^{miss}$ requirement in the control sample is estimated by comparing the differences of scale factors with different $E_T^{miss}$ cuts. The uncertainty is found to be around 10%.
- The sample difference is evaluated by comparing MC scale factor in $b\bar{b}$ dijet MC and $Z+jets$ MC (where we want to apply the factor factor on), which turns to be very big. A +0% and -50% systematic uncertainty is assigned.
- The uncertainty due to SM electroweak subtraction is evaluated by varying the electroweak contribution in good and bad lepton up/down 15% and comparing the scale factors.

The final fake factor is shown on the right in Figure 6.3, where the error bar includes both statistical and systematic uncertainties. The plot on the left shows the sample dependence which contributes most to the systematics.

![Figure 6.3](image)

Figure 6.3: The sample dependence of muon fake factor on the left, and the final muon fake factor with full uncertainty on the right

**electron fake factor determination**

The control sample also consists of dijet events, which are selected by the following criteria:
- have two electrons with same charge and back-to-back ($\Delta\phi > 0.5\pi$)
- have invariant mass of two electrons outside $\pm 20$ GeV $Z$ mass windows
- pass a di-photon trigger $EF_{g20\text{loose}}$
- have one electron to be bad electron

The bad electron definition is passing all other electron selection criteria but failing isolation or failing medium $++$ but passing loose $++$ identification requirement. The $p_T$ distribution of good and bad electrons and the derived fake factors as a function of electron $p_T$ or $\eta$ are show in Figure 6.4. When deriving the fake factor, electroweak contributions are subtracted from both bad and good leptons.

To evaluate the fake factor systematic uncertainties. The following are considered:
- The bias due to photon trigger is evaluated by comparing the fake factors derived in $b\bar{b}$ MC samples with and without trigger requirements. It turns out to be negligible.
- The bias due to the back-to-back electron requirement is evaluated conservatively by comparing the fake factors derived in MC sample with and without this requirement. The uncertainties is provide bin by bin.
- The potential bias caused by $E_T^{\text{miss}}$ requirement in the control sample is estimated by comparing the differences of scale factors with (nominal case) and without $E_T^{\text{miss}} > 25$ GeV cuts. The uncertainty is found to be around 15%.
- The sample difference is evaluated by comparing MC scale factor in dijet MC and $Z+jets$ MC (where we want to apply the factor factor on), which turns to be very big. A +0%
Figure 6.4: The bad (top left) and good lepton (top right) $p_T$ in the dijet control sample where fake factor is derived. The electron fake factor as a function of $p_T$ (bottom left) and $\eta$ (bottom right). The fake factor from data in black and from dijet MC in green.

- and -50% systematic uncertainty is assigned.
- The uncertainty due to SM electroweak subtraction is evaluated by varying the electroweak contribution in good and bad lepton up/down 15% and comparing the scale factors.

The final fake factor is shown on the right in Figure 6.5, where the error bar includes both statistical and systematic uncertainties. The plot on the left shows the sample dependence which contributes most to the systematics.

Figure 6.5: The sample dependence of electron fake factor on the left, and the final electron fake factor with full uncertainty on the right

**apply fake factor to loose sample**

The fake factors are derived and used mainly in bins of lepton $p_T$; we also check the $\eta$
distributions for leptons in the control sample from which the fake factors are derived and in the loose sample on which it is applied, and we find the two agree within the statistical uncertainties. i.e. the $\eta$ dependence could be neglected.

The loose sample is selected requiring all event selection cuts but having one and only one bad lepton. The non-fake contamination $WZ$, $ZZ$ and $Z + \gamma$ ($\sim 5\%$) in loose sample is estimated and subtracted using MC simulation. Then apply the fake-factor to remaining events in the loose sample and yield the final estimation. The estimated background contain both $Z + \text{jets}$ and $t\bar{t}$, while $Z + \text{jets}$ takes the majority. The systematics come from fake factor uncertainty and electroweak subtraction in loose sample. Table 6.3 summarize the final estimation and uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>$\text{eee}$</th>
<th>$\text{e}\mu\mu$</th>
<th>$\text{e}\mu\mu$</th>
<th>$\mu\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final estimation</td>
<td>$3.06 \pm 0.5^{+1.31}_{-2.02}$</td>
<td>$2.49 \pm 0.54^{+0.65}_{-1.36}$</td>
<td>$5.10 \pm 0.68^{+2.14}_{-3.19}$</td>
<td>$1.69 \pm 0.45^{+0.36}_{-0.89}$</td>
</tr>
</tbody>
</table>

Table 6.3: The data-driven estimation of fake background ($Z + \text{jets}$, $t\bar{t}$). The first error is statistical uncertainty, the second is systematic uncertainty.

**Z fake factor method**

In this method, the control sample is defined as events with a $Z$ plus an additional lepton. The $Z$ selection criteria are the same as in nominal analysis. This control sample is dominated by $Z + \text{jets}$ events, therefore the fake factor measured here will have little sample dependence. In order to be orthogonal to single region, the control sample is further required to have $E_T^{\text{miss}} < 25$ GeV.

The additional lepton is checked to be good or bad to determine fake factor. The bad electron is defined as failing medium $+$ + electron ID but passing all other cuts; while the bad muon is defined as failing isolation or transverse impact parameter significance cut but passing other cuts. The looser “bad” definition with respect to dijet method is used to improve statistics of the bad leptons. Figure 6.6 shows the distributions of good and bad electrons (muons). As you can see in the plots, this method is limited by poor statistics and the fact that electroweak process contribute significantly in good lepton region. Therefore, the measured fake factor will tend to have large statistic uncertainty and MC subtraction dependence.

Given the poor statistics, the fake factor is derived to be a single number, as the ratio of good leptons to bad leptons after subtracting corresponding electroweak contribution estimated from MC. The fake factor is measured in low $E_T^{\text{miss}}$ region and will be applied to high $E_T^{\text{miss}}$ region. This effect is evaluated by comparing the fake factors in MC $Z$ events with $E_T^{\text{miss}} < 25$ GeV and with $E_T^{\text{miss}} > 25$ GeV. The results suggest a correction of 25% for muons and 15% for electrons with an uncertainty of 15%. The uncertainty from MC subtraction is evaluated by varying the electroweak contribution by ±15%, and it turns out to be 10% for electron and 60% for muon. The final fake factor is determined to be $0.093 \pm 0.014(\text{stat}) \pm 0.017(\text{syst})$ for electrons and $0.066 \pm 0.033(\text{stat}) \pm 0.04(\text{syst})$ for muons.

The loose sample is defined as events with a real $Z$ and a bad lepton with $E_T^{\text{miss}} > 25$ GeV. After subtracting the other backgrounds from loose sample, the estimated $Z + \text{jets}$ background is listed in Table 6.4.

The Data-Driven estimations from dijet fake factor method (Table 6.3) and Z fake factor
Figure 6.6: The $p_T$ distributions of bad electron (top left), good electron (top right), bad muon (bottom left) and good muon (bottom right).

Table 6.4: The data-driven estimation of $Z + jets$ background with $Z$ fake factor method. The first error is statistical uncertainty, the second is systematic uncertainty.

<table>
<thead>
<tr>
<th></th>
<th>$e!e!e$</th>
<th>$e!e!\mu$</th>
<th>$e!\mu!\mu$</th>
<th>$\mu!\mu!\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final estimation</td>
<td>$0.55 \pm 0.12 \pm 0.12$</td>
<td>$1.18 \pm 0.24 \pm 0.61$</td>
<td>$5.82 \pm 0.64 \pm 1.28$</td>
<td>$2.32 \pm 0.36 \pm 1.21$</td>
</tr>
</tbody>
</table>
method (Table 6.4) are consistent with each other within uncertainties. Compared to the $Z$ method, the dijet method provides fake factor with much smaller statistical uncertainty, but defines a loose sample with smaller statistics due to the tighter “bad” definition. Therefore, dijet method yield larger statistical uncertainties for the estimation. Besides, dijet method give larger systematic uncertainty due to the sample dependence systematics. Two methods are comparable and cross-checked, and in nominal analysis, the results from dijet method are used.

6.3.3 Extrapolation

SM backgrounds, estimated from either MC or Data-Driven methods, yield zero at high mass region due to the lack of statistics. In reality, their contribution should be indeed very small, dropping approximately exponentially as $M_{WZ}$ goes up. To properly estimate the backgrounds in the region with $M_{WZ} > 300$ GeV, the estimated backgrounds are fitted to the sum of two weighted exponential functions as

$$N(x) = c_1 e^{k_1 x} + c_2 e^{k_2 x}$$  \hspace{1cm} (6.5)

The normalization of this function is fixed to number of expected background events in the fit region; besides, backgrounds are summed across all analysis channels to maximize the statistics. The used $M_{WZ}$ distribution and resulting fit are shown in Figure 6.7. This functional form can also describe the background for each channel individually, as shown in Figure 6.8. Please note that the fitted backgrounds include $ZZ, Z+\gamma$ and Data-Driven estimated $Z+jets$. The SM $W^\pm Z$ background is not extrapolated since it has sufficient statistics in our interested region. The fitting errors are used as the background uncertainty in the fitted area, given their wide coverage.

![Double exponential fit and its error for $M_{WZ}$ distribution at high mass region ($M_{WZ} > 300$ GeV) of combined backgrounds from all four channel](image)

Figure 6.7: Double exponential fit and its error for $M_{WZ}$ distribution at high mass region ($M_{WZ} > 300$ GeV) of combined backgrounds from all four channel.

6.3.4 Interpolation

The simulated resonance signal samples often have a spacing larger than their resolution, which is not sufficient for limit settings. A set of signal templates with masses in between the existing ones are then created with 50 GeV spacing to cope with this issue.
Figure 6.8: Double exponential fit and its error for $M^{WZ}$ distribution at high mass region ($M^{WZ} > 300$ GeV) of backgrounds in eee (top left), ee$\mu$ (top right) e$\mu$e (bottom left) and $\mu$$\mu$e (bottom right) channels, respectively.

To obtain the mass template, the $M^{WZ}$ distribution of each simulated signal sample is fitted to Voigtian function, which is a Breit-Wigner function analytically convoluted with a Gaussian. The function can be written as

$$V(x; m, g, \sigma) = N \cdot \frac{1}{(x - m)^2 + g^2} \otimes e^{-\frac{1}{2}(\frac{r}{\sigma})^2}$$  \hspace{1cm} (6.6)

The parameters $m$, $\sigma$ and $g$ are derived as a function of $M^{W^0}$ (as for the case of $W^0$ signal); the trends can be fitted with simple linear functions $f(M) = p_0 + p_1 M$. Using these parameter fits, one can easily find the parameters at given mass point and obtain the $M^{WZ}$ distribution using corresponding Voigtian function.

Figure 6.9 shows the parameter fit and obtained $W'$ signal templates in $e\mu\mu$ channel. Validation of the interpolation via comparing the fitted $M^{WZ}$ distribution and simulated $M^{WZ}$ distribution at mass points where simulated samples are available are shown in Figure 6.10. The overall performance is decent. The distribution with $M^{WZ} = 200$ GeV is skewed because it is close to the production threshold, therefore that point is not used in the interpolation.

After the mass templates been obtained, other important quantities, such as uncertainties and acceptances, should also be properly assigned to each template. The statistical uncertainty is set to be the same as simulated sample ($\sim 30000$ events). The above procedure is repeated for each systematic uncertainty separately, therefore producing all the shape uncertainties across all mass points. Furthermore, the acceptance is fitted via a polynomial function of degree three based on the values from simulated samples, as shown in Figure 6.3.4.
Figure 6.9: The parameter fit of Voigtian function (left) and templates of $W'$ signal samples with $M_{WZ}$ between 200 GeV and 1200 GeV at a spacing of 50 GeV. Both plots are in $e\mu\mu$ channel, which is chosen arbitrarily for demonstration.

Figure 6.10: The comparison between fitted $M_{WZ}$ distribution and simulated $M_{WZ}$ distributions

Figure 6.11: The acceptance fitting for $eee$ (left) and $\mu\mu\mu$ (right) channels.
6.4 Systematics

Similar to the SM $W^{\pm}Z$ analysis, systematics here are evaluated on both event base and object base.

The object uncertainties:

- electron: energy scale, energy resolution, identification and reconstruction eff. scale factor, isolation eff. scale factor
- muons: ID, MS resolution, energy scale, reconstruction eff. scale factor, isolation eff. scale factor
- trigger: trigger efficiency scale factor (4.3.1)
- $E_T^{\text{miss}}$: the electron and muon term, soft term

To propagate the corresponding object uncertainties to event selection level, vary the physics quantity up or down according to its uncertainty, perform the event selection and quota the fractional percentage difference between the new results and nominal results as systematics. Please note that when evaluating electron(muon) energy(momentum) scale/resolution uncertainties, the modification of energy(momentum) also goes into $E_T^{\text{miss}}$ calculation, which yields a corresponding change in its lepton term. The $E_T^{\text{miss}}$ lepton term uncertainties are therefore absorbed by lepton systematics.

The event level uncertainties:

- luminosity uncertainty $\sim 1.8\%$
- Theoretical cross section uncertainty: 8% for $Z\gamma$, 7% for $WZ$ and 5% for $ZZ$
- PDF uncertainty on acceptance: $\sim 1\%$, by comparing different PDFs and eigenvectors within each PDF

Shape uncertainty on $M^{WZ}$ The shape uncertainty is quoted as difference between $M^{WZ}$ distribution in two NLO generators: $\text{MC@NLO}$ and $\text{POWHEG}$. The generator level events are studied, and distributions from two generators are normalized to same area in order to compare the shape. As you can see in Figure 6.12, typically there is negligible uncertainty with $M^{WZ} < 400$ GeV, 10% uncertainty with $400 < M^{WZ} < 800$ GeV and 20% uncertainty with $M^{WZ} > 800$ GeV.

![Figure 6.12: The $M^{WZ}$ shape difference between MC@NLO and POWHEG generated events. No cuts is applied in the left plot, while full fiducial cuts are applied in the right plot. Two distributions are normalized to same area.](image-url)
Table 6.5 summarizes the systematics for typical $W'$ signal with $M(W') = 750$ GeV. The systematics for MC estimated SM backgrounds are similar to in the table, given the same three lepton final states.

<table>
<thead>
<tr>
<th>Source</th>
<th>eee</th>
<th>eeeμ</th>
<th>eem</th>
<th>μμμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>2.41%</td>
<td>2.43%</td>
<td>2.33%</td>
<td>2.41%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.001%</td>
<td>0.02%</td>
<td>0.13%</td>
<td>0.28%</td>
</tr>
<tr>
<td>Electron ID</td>
<td>2.93%</td>
<td>1.94%</td>
<td>0.97%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Electron resolution</td>
<td>0.06%</td>
<td>0.13%</td>
<td>0.01%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Electron scale</td>
<td>0.05%</td>
<td>0.46%</td>
<td>0.11%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>3.02%</td>
<td>2.01%</td>
<td>1.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.015%</td>
<td>0.05%</td>
<td>0.01%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.00%</td>
<td>0.07%</td>
<td>0.06%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Muon ID</td>
<td>0.00%</td>
<td>0.33%</td>
<td>0.67%</td>
<td>1.02%</td>
</tr>
<tr>
<td>Muon resolution MS</td>
<td>0.00%</td>
<td>0.06%</td>
<td>0.00%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Muon resolution ID</td>
<td>0.00%</td>
<td>0.06%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Muon scale</td>
<td>0.00%</td>
<td>0.06%</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>MET pileup</td>
<td>5.50%</td>
<td>3.58%</td>
<td>1.84%</td>
<td>0.05%</td>
</tr>
<tr>
<td>MET Clusters</td>
<td>0.13%</td>
<td>0.44%</td>
<td>0.37%</td>
<td>0.11%</td>
</tr>
<tr>
<td>PDF</td>
<td>1.36%</td>
<td>0.17%</td>
<td>0.32%</td>
<td>0.19%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Total (with statistical uncertainty)</th>
<th>Total (without statistical uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.67% 5.93% 3.82% 3.20%</td>
<td>7.28% 5.41% 3.03% 2.11%</td>
</tr>
</tbody>
</table>

Table 6.5: Systematic uncertainties for $W'$ with $M(W') = 750$ GeV

### 6.5 Data and Prediction

Table 6.6 gives the observed number of data events, the estimated background yields as well as the predicted $W'$ signal strength with $M(W') = 1000$ GeV. In 2011 data with integrated luminosity of 4.7 fb$^{-1}$, totally 120 data events are observed in signal region. This is in consistence with predicted SM background of 111.7 and roughly 7% total uncertainty. No excess is observed with respect to the total production cross-section.

<table>
<thead>
<tr>
<th>Process</th>
<th>eee</th>
<th>eeeμ</th>
<th>eem</th>
<th>μμμ</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>26</td>
<td>35</td>
<td>35</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Backgrounds:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td>17.73 ± 0.28 ± 1.29</td>
<td>19.99 ± 0.29 ± 1.08</td>
<td>22.80 ± 0.31 ± 0.68</td>
<td>26.47 ± 0.34 ± 0.53</td>
<td>86.99 ± 0.64 ± 3.59</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.33 ± 0.05 ± 0.10</td>
<td>1.73 ± 0.06 ± 0.09</td>
<td>1.93 ± 0.06 ± 0.06</td>
<td>2.46 ± 0.07 ± 0.05</td>
<td>7.45 ± 0.12 ± 0.30</td>
</tr>
<tr>
<td>Zγ</td>
<td>2.82 ± 0.95 ± 0.21</td>
<td>2.05 ± 0.61 ± 0.06</td>
<td>-</td>
<td>-</td>
<td>4.88 ± 1.13 ± 0.27</td>
</tr>
<tr>
<td>Fake Background</td>
<td>3.06 ± 0.5 ± 0.1</td>
<td>2.49 ± 0.34 ± 0.65</td>
<td>5.10 ± 0.68 ± 1.14</td>
<td>1.69 ± 0.45 ± 0.94</td>
<td>12.34 ± 1.09 ± 7.46</td>
</tr>
<tr>
<td>Total Background</td>
<td>24.94 ± 1.1 ± 1.86</td>
<td>24.21 ± 0.62 ± 1.26</td>
<td>31.88 ± 0.75 ± 2.25</td>
<td>30.62 ± 0.57 ± 1.64</td>
<td>111.66 ± 1.65 ± 8.91</td>
</tr>
<tr>
<td>Signals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W'(m = 1000 GeV)$</td>
<td>1.36 ± 0.03 ± 0.10</td>
<td>1.33 ± 0.03 ± 0.07</td>
<td>1.42 ± 0.03 ± 0.04</td>
<td>1.29 ± 0.04 ± 0.03</td>
<td>5.40 ± 0.06 ± 0.24</td>
</tr>
</tbody>
</table>

Table 6.6: The number of observed data events, the expected background yields and predicted $W'$ signal yields with $M(W') = 1000$ GeV. The statistical (first) and the systematic (second) uncertainties are both presented. Systematic uncertainties from different channels are treated as 100% correlated and added linearly in combined channel; systematics from different processes are added in quadrature to get total systematic uncertainty.
Figure 6.13 shows the comparison of various kinematic distributions between data and prediction in the control region. The good agreement in control region validate the understanding of reconstructions and SM background estimations, which is important in this “blinded” analysis.

Figure 6.14 shows the kinematic distributions in signal region after final selection, and the \( M_{WZ} \) distribution with high mass region extrapolated from fitting is presented in both linear and logarithmic scale in Figure 6.15.

There is a small excess around \( M_{WZ} = 450 \text{ GeV} \); further investigation shows that the four events in that excess bin all come from one channel (\( e\mu\mu \)) and the event qualities including separation between \( E_T^{miss} \) and lepton or jets are checked and found to be reasonably good. Therefore, it is considered to be just a statistical fluctuation.

### 6.6 Limit for \( \rho_T \) and \( W' \)

In this search the likelihood ratio method is used to observe the exclusion limits on two resonance signal \( W' \) and \( \rho_T \). The method and the results are described in details below.

#### 6.6.1 Likelihood Ratio Method

**The likelihood ratio**

The method used to distinguish a new physics signal above the SM background is based on the likelihood ratio test statistic as shown in Eq 6.7.

\[
\Lambda(x) = \frac{L(s+b|x)}{L(b|x)} = \frac{(s+b)^x e^{-(s+b)}}{x!} / \frac{(b)^x e^{-b}}{x!}
\]  

Where \( s \) and \( b \) represent the signal prediction and background estimations, respectively. The likelihood function is based on Poisson statistics, representing how likely the observed data can be described with signal plus background (signal and background hypothesis) or only background (background-only hypothesis). When multiple analysis channels and kinematics binning are concerned, the Eq 6.7 can be written as

\[
\Lambda(x) = \prod_i \prod_j \frac{(s_{ij} + b_{ij})^{x_{ij}} e^{-(s_{ij}+b_{ij})}}{x_{ij}!} / \frac{(b_{ij})^{x_{ij}} e^{-b_{ij}}}{x_{ij}!}
\]  

And normally we use the log-likelihood ratio (LLR), which is formed as negative two multiplied by the natural logarithm of \( \Lambda \), as

\[
LLR(x) = -2 \ln(\Lambda(x)) = -2 \sum_i \sum_j [s_{ij} - x_{ij} \ln(1 + \frac{s_{ij}}{b_{ij}})]
\]

**Confidence level determination**

The LLR is easily obtained in data, which can be denoted as \( LLR(x = D) \). The LLR for background only hypothesis and signal and background hypothesis can also be determined as \( LLR(x = B) \) and \( LLR(x = S+B) \), respectively. In real analysis, both \( S \) and \( b \) are determined
Figure 6.13: The kinematics distribution in SM control region (selected with applying all signal selection cuts but reversing $\Delta y$ or $\Delta \phi$ cut): leading lepton $p_T$ (top left) and $\eta$ (top right), $E_T^{miss}$ (middle left), $W$ transverse mass (middle right), $Z$ mass (bottom left) and $WZ$ transverse mass (bottom right). The $W'$ signal with $M(W') = 500, 750, 1000\text{ GeV}$ are shown in green, blue and gray histograms, respectively.
Figure 6.14: The kinematics distribution in final selected signal region: leading lepton $p_T$ (top left) and $\eta$ (top right), $W$ transverse mass (middle left), $Z$ mass (middle right), $p_T^{W}$ (bottom left) and $p_T^{Z}$ (bottom right). The $W'$ signal with $M(W') = 500, 750, 1000$ GeV are shown in green, blue and gray histograms, respectively.
Figure 6.15: The $m_{WZ}^{}$ distribution in final selected signal region in linear scale (top left) and logarithmic scale (top right). The corresponding plots with the region $m_{WZ}^{} > 300$ GeV extrapolated from fitting are shown on the bottom.
with uncertainties; therefore they can be considered as
\[
S_{ij} = S_{ij}^0 (1 + \sum_k g_k), \quad B_{ij} = B_{ij}^0 (1 + \sum_k g_k)
\]  
(6.10)

Where \(S_{ij}^0\) and \(B_{ij}^0\) are the number of signal and background events estimated in the analysis; index \(i\) and \(j\) represent the analysis channel and the kinematics binning; \(g_k\) generally represents the systematic uncertainty from \(k\)-th source (where \(N\) is the number of total sources). The systematic uncertainty \(g_k\) could be different over channels, kinematics bins and background processes, and it follows a Normal distribution with width equal to the magnitude of the systematics or a bifurcated Gaussian in the case that corresponding systematics is asymmetric.

Let’s denote \(D_b \equiv S_{ij}\) and \(D_{s+b} = S_{ij} + B_{ij}\). We can then perform pseudo-experiments on the systematics, and generate a smooth distribution of \(LLR(x = D_b)\) and \(LLR(x = D_{s+b})\). These two distributions actually describe the possibility of \(LLR\) when the hypothesis is true by taking into account the uncertainties from various sources. The PDFs (probability density function), \(f(y = LLR(D_s))\) and \(f(y = LLR(D_{s+b}))\) can be obtained by normalizing the corresponding distribution to unity. The interpretation of how data agree with the hypothesis can be done by simply checking the confidence level of \(y = LLR(D)\) with corresponding PDF.

The two confidence levels are defined as shown in Eq 6.11.

\[
CL_{s+b} = \int_{LLR(x = D_{s+b})}^{\infty} f(y = LLR(D)) \, dy
\]
\[
CL_b = \int_{LLR(x = D_b)}^{\infty} f(y = LLR(D)) \, dy
\]

(6.11)

Usually the \(CL_{s+b}\) is used when searching for specific new physics signal. However, it is known to be unstable if the background model dramatically disagrees with the data. Therefore, commonly used confidence level \(CL_s\) is defined as

\[
CL_s = \frac{CL_{s+b}}{CL_b}
\]

(6.12)

The \(CL_s\) will be close to one if data agrees with signal hypothesis, and be near zero if no signal is present in data.

Normally, a new physics signal model is excluded at 95% C.I. if \(CL_s < 0.05\); and an evidence of new physics is observed at 3\(\sigma\) if \(1 - CL_b = 1 - 2.7 \times 10^{-3}\) and discovered at 5\(\sigma\) if \(1 - CL_b = 1 - 4.3 \times 10^{-7}\).

### 6.6.2 Observed Limits

#### \(W'\) limit

In this search a multi-bin log-likelihood ratio is used based on the distribution of \(M_{WZ}\) (0-2000 GeV with 20 GeV bin size). The number of data, signal and background events are taken from this distribution, as shown in Figure 6.15. Please note that for \(M_{WZ} > 300\) GeV, the extrapolation distributions are used for backgrounds (except SM \(W^\pm Z\)). And when setting limits for signal at mass pointed where no simulated samples is present, the interpolated \(M_{WZ}\) distribution and interpolated signal acceptance are used. In the determination of \(CL_s\),
the common systematics (shown in Tab 6.5) are sampled coherently for MC based signal or backgrounds. Systematics that only affect one process are sampled independently for that process (e.g. the Data-Driven systematics and PDF uncertainty for signal).

The CLs value is calculated for each new physics signal sample. And if CLs < 0.05, the signal sample is excluded at 95% C.L. In the case that the signal is excluded, the excluded cross-section is determined by adjusting the signal lower until CLs = 0.05. The corresponding scaled signal cross-section is denoted as $\sigma^{95\% CL}$.

Take $W'$ as example, the actual limits are set on the cross-section ($\sigma$) times branching ration ($B$). For each mass point, the limit is divided by the cross section multiplied by the branching fraction for the theoretical predictions as shown in Eq 6.13.

$$R_{W'\rightarrow WZ} = \frac{[\sigma \times B]^{\text{excluded at 95\% CL}}}{\sigma(pp \rightarrow W') \times B(W' \rightarrow WZ)}$$

Therefore, if $R < 1$, the signal hypothesis at that mass point is excluded at 95% C.L.

The $\sigma \times B$ limits for $W'$ are set in each individual channel, as you can see in Figure 6.6.2. The limit for combined channel is shown in Figure 6.17. And the expected and observed mass limits for $W'$ are summarized in Table 6.7. As you can see, with four channels combined, the $W'$ is excluded up to $M(W') = 1156$ GeV.

Figure 6.16: The $\sigma \times B$ limits for $W'$ in $eee$ (top left), $ee\mu$ (top right), $e\mu\mu$ (bottom left) and $\mu\mu\mu$ (bottom right) channels. The observed limits are shown as red line, and the expected limits are shown as black line with 2$\sigma$ uncertainty bands.
$$ \sigma \times B \left( \frac{W^Z}{W^0} \right) $$

<table>
<thead>
<tr>
<th>$e + e^-$</th>
<th>$e + \mu^-$</th>
<th>$\mu + \mu^-$</th>
<th>$\mu + \mu^-$</th>
<th>combined (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected limit</td>
<td>845 853 842 850 1157</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>observed limit</td>
<td>842 853 649 848 1156</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7: The expected and observed lower mass limits for $W'$ in individual channels and combined channel

**$\rho_T$ limit**

The limit setting for $\rho_T$ follows the same procedure as in the $W'$ case. However, the obtained $\rho_T$ signal acceptances are not accurate, because the $W$ and $Z$ polarization is not properly simulated in PYTHIA $\rho_T$ samples. Consider the similarity between $W'$ and $\rho_T$, we use the $W'$ signal acceptance to set limits on $\rho_T$. In this case, the $R$, described in Eq 6.13 can be simply calculated by substituting the $\sigma(pp \rightarrow W') \times B(W' \rightarrow WZ)$ with $\sigma(pp \rightarrow \rho_T) \times B(\rho_T \rightarrow WZ)$. Furthermore, two cases for the mass of the axial-vector $a_T$ are studied: $M(a_T) \rightarrow \infty$ and $M(a_T) = 1.1 M(\rho_T)$. The two different assumptions gives different cross-sections for $\rho_T$. The $\sigma \times B$ limits for the two cases in combined channel are shown in Figure 6.18.

Figure 6.18: The $\sigma \times B$ limits for $\rho_T$ in combined channel with assuming $M(a_T) \rightarrow \infty$ in the left and $M(a_T) = 1.1 M(\rho_T)$ in the right.
The lower mass limits are summarized in Table 6.8. The observed mass limits are slightly worse than the expected limits because of the statistical fluctuations in the high $M^{WZ}$ region. In this search, $\rho_T$ is excluded up to $M(\rho_T) = 449$ GeV.

<table>
<thead>
<tr>
<th>lower mass limits (GeV)</th>
<th>$M(a_T) = 1.1 M(\rho_T)$</th>
<th>$M(a_T) \to \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected limit</td>
<td>749</td>
<td>680</td>
</tr>
<tr>
<td>observed limit</td>
<td>534</td>
<td>449</td>
</tr>
</tbody>
</table>

Table 6.8: The expected and observed lower mass limits for $\rho_T$ in combined channel with assumptions of $M(a_T) = 1.1 M(\rho_T)$ and $M(a_T) \to \infty$
Chapter 7

Conclusion and Prospect

The LHC and ATLAS has been performing remarkably well during 2011, and thanks to the high data taking efficiencies and stable run conditions, very rich physics programs are uniquely offered even at this early stage. In this dissertation, the $W^\pm Z$ production is studied in $W^\pm Z \rightarrow \ell\nu\ell\ell$ final states, based on 4.7 fb$^{-1}$ $pp$ collision data at CME of 7 TeV collected in the ATLAS detector at the LHC in the year of 2011. Several physics analysis are presented, including the SM $W^\pm Z$ production cross-section measurement, the indirect new physics search via probing anomalous triple gauge couplings with $WWZ$ vertex and directly searching for new physics resonance decaying to $WZ$ pairs.

In the SM $W^\pm Z$ production cross-section measurement, the $W^\pm Z$ candidates are selected from events with three high $p_T$ and isolated leptons by requiring the presence of a on-shell $Z$ reconstructed by two leptons and a large $E_T^{miss}$. The major backgrounds include $ZZ$, $Z+jets$, $t\bar{t}$ and $Z+\gamma$; the jet-related backgrounds including $Z+jets$ and $t\bar{t}$ are estimated using Data-Driven methods, while the remaining electroweak backgrounds are estimated with MC samples. In total, 317 $W^\pm Z$ data candidates are observed with $68\pm10$ estimated background events. Systematic uncertainties are evaluated in various sources, including the uncertainty of luminosity, theoretical prediction, lepton reconstruction and trigger determination. The cross-section is extracted through a log-likelihood fit in both total phase space and fiducial volume. The measured total cross-section is $19.00^{+1.38}_{-1.50}^{stat}(stat)+^{0.92}_{-0.90}(syst)+^{0.38}_{-0.37}(lumi)$, which is in good agreement with the SM NLO prediction of $17.6^{+1.1}_{-1.0}$.

The aTGC study is based on the events selected in cross-section measurement. Due to the dependence of aTGC parameters on $\sqrt{s}$, the $p_T^Z$ distribution is used and optimized to improve the sensitivity. A frequentist approach based on log-likelihood function is adopted and the resulting 95% C.I. define the aTGC limits. The limits with a reasonable cut-off scale of 2 TeV are given as $\Delta q_1^Z \in [-0.057, 0.093]$, $\Delta \kappa^Z \in [-0.37, 0.57]$ and $\lambda^Z \in [-0.046, 0.047]$, which are
more stringent than Tevatron results.

Given new physics signals tend to produce harder leptons, the resonance search are conducted in a harder but similar phase space to the SM cross-section measurement. Based on the event characterization of resonance signal, a control region is defined with minimal signal contamination and carefully check before analyzing events in the signal region (orthogonal to control region). The background estimation are very similar as in the cross-section measurement, except a few detailed treatment and the extrapolation done to evaluate background contribution is high mass region. Data agree with MC in the signal region, which means there is no new physics found in this search. A log-likelihood ratio method is used to extract the cross-section times branching fraction limits on the two reference new physics signal: $W'$ and $\rho_T$. The lower mass limit for $W'$ and $\rho_T$ are found to be 1156 GeV and 449 GeV, respectively. The limits are largely improved with respect to previous Tevatron measurement.

The cross-section measurement has a large statistical uncertainty and a small systematic uncertainty. Its precision will be improved with larger data samples coming. This is the same case for aTGC; besides, aTGC limits will be largely improved with higher CME in the future, e.g. 14 TeV LHC run in next few years. As for the new physics search, the opportunity provided at the LHC is rather unique. With more data and higher CME, we are looking closer and closer into the tail region of kinematics distribution. More and more interesting results are on their ways.
Bibliography


