Vector Boson Scattering at the LHC

Aaron Webb
Duke University
Advisers: Al Goshaw, Andrea Bocci, Shu Li

April 14, 2015
Abstract

This study used ATLAS data and Monte Carlo simulations to investigate diboson production and vector boson scattering (VBS). Vector boson scattering is essential for understanding the electroweak sector of the standard model and a good candidate for detecting anomalous gauge couplings and physics beyond the Standard Model. Monte Carlo simulations, data driven methods, and multi-variant analysis techniques are used to estimate the backgrounds associated with this channel and distinguish signal events from strong force production of the same final state. Additionally, Monte Carlo simulations produced in MadGraph are used to place estimates on interference effects between background and signal processes, which are found to decrease as a function of both dijet mass and jet separation.
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Acknowledgments

I would like to thank my advisor, Professor Al Goshaw, for all he has done for me these past few years; for sharing with me his knowledge, experience, and enthusiasm for physics. Despite his busy schedule, he was always willing to take time to help answer questions and give advice. He has taught me so much in my time at Duke, and his patience and support has been invaluable. I would also like to thank the other members of my thesis committee, Mark Kruse and Hubert Bray, for the time they have volunteered to help me with this project.

Finally, I would like to thank Andrea Bocci and Shu Li, who have been immensely helpful in every step of this project. They have assisted me with everything from solving any number of technical problems, to generating all the Monte Carlo samples I needed, to explaining anything I didn’t understand. I could always go to them with any questions or problems I had, and I could not have completed this project without their patience and expertise, and all the time and energy they invested to help me.
1 Introduction

The Standard Model (SM) of particle physics has predicted the results of particle physics experiments with remarkable accuracy. It describes all known fundamental particles, as well as the electromagnetic, weak, and strong interactions. However, the SM does not account for gravitational interactions or experimental observations of dark matter, and some aspects of the SM remain untested.

The SM includes a unified description of the electromagnetic and weak interactions, referred to as the electroweak (EWK) interaction. The EWK interaction is mediated by the $W^\pm$ and $Z$ bosons, and the photon. The EWK sector of the SM is described by an underlying SU(2)$\times$U(1) gauge symmetry, which predicts self-couplings between these gauge bosons. Vector boson scattering is one of the processes that include these self-couplings. Precise SM predictions for these processes can be calculated for comparison with experiment. Measuring signatures of diboson production would give evidence of these interactions, providing a valuable test of a previously unexplored aspect of the SM. Furthermore, as physics beyond the SM can change the multi-boson production rate, vector boson scattering is a good candidate for searches for physics beyond the standard model (BSM).

Recent data collected by the ATLAS detector provides a unique opportunity to study vector boson scattering through signatures of diboson production, and search for new physics. This thesis reports on current measurements of $Z$ boson production with an associated high energy photon based on data collected by the
The content of this thesis will be presented as follows: The theoretical framework and physical motivations for studying diboson production and vector boson scattering are described. This is followed by a brief description of the LHC and the ATLAS detector. The major backgrounds associated with this analysis are discussed, along with the techniques that are being applied to account for them, followed by an analysis of signal and background interference. The thesis concludes with a summary of ongoing work, and the future goals of these studies.

2 Theory and Motivation

2.1 The Standard Model and the Electroweak Interaction

The Standard Model of particle physics, developed in the latter half of the twentieth century, has become the prevailing theory for describing the interactions of the known fundamental particles. Shown in figure 1, it includes three generations of quarks, three generations of leptons, four gauge bosons, and the recently discovered Higgs boson.

The SM describes three kinds of interactions: electromagnetic, weak, and strong. Each of these interactions is mediated by the bosons shown in red. These are vector gauge bosons, meaning they are spin-1 particles that are invariant under local gauge transformations. Electromagnetism is mediated by the photon (often notated as $\gamma$ for convenience), the weak interaction through the $W^\pm$ and $Z$ bosons, and the strong
interaction through gluons.

The SM is described by an overall $SU(3)\times SU(2)\times U(1)$ gauge structure [6]. Gauge bosons are quanta of the gauge fields, which means there are as many gauge bosons as there are generators in the gauge field. Electromagnetism is described by the gauge group U(1), for which there is a single generator. This leads to a single gauge boson, the photon. The gauge theory of the weak interaction is based on the $SU(2)$ symmetry, which has three generators. These (roughly) correspond to the $W^\pm$ and $Z$ bosons which mediate this interaction. The more complicated $SU(3)$ symmetry which describes QCD interactions has eight generators, corresponding to eight gluons.

Though they appear distinct from one another at low energies, the electromagnetic and weak forces can be unified into a single interaction described by an overall $SU(2)\times U(1)$ symmetry. Above a certain energy, on the order of 100 GeV, these two
forces merge into a single electroweak (EWK) interaction. This symmetry is broken at low energy through a process known as electroweak symmetry breaking (EWSB). EWSB is the process by which the $W^+$, $W^-$, and $Z$ acquire their mass, and explains our observations of the electromagnetic and weak interactions as distinct forces.

With the discovery of the Higgs boson in 2012, the Higgs Mechanism has become the leading explanation for EWSB \[5\]. The non-zero vacuum expectation value (VEV) of the Higgs field produces a ground state that is not invariant under gauge transformations, providing an explanation for spontaneous EWSB and the masses of the $W^\pm$ and $Z$ bosons \[8\].

### 2.2 Vector Boson Scattering

The SU(2)$\times$U(1) structure of the electroweak sector of the Standard Model predicts self-interactions between the electroweak gauge bosons \[3\]. These self-couplings can involve either three or four gauge bosons at a single vertex, known as triple and quartic gauge couplings, respectively. While the triple gauge couplings (TGCs) have been studied extensively, and found to be in agreement with the SM, the much more rare quartic (QGCs) have not been studied in depth. Vector boson scattering processes involve four electroweak vector bosons, namely $Z$, $W^+$, $W^-$, and photons coupling at this single vertex. The Feynman diagrams for the possible VBS interactions are shown in figure 2.

The QGC involved in VBS is a large part of what makes it a good candidate for study. It is possible that the quartic gauge couplings deviate from the SM even
though the triple gauge couplings do not [11]. In fact, some models of supersymmetry involve deviations from the SM for these quartic couplings. As such, the measurement of the production of multiple electroweak gauge bosons represents an important test of the SM, and a good candidate to search for physics beyond the SM.

The energy scales reached by the LHC allow us to probe these new sectors of the Standard Model and study these processes for the first time. For this analysis, the data collected by the ATLAS detector in 2012 at an energy of $\sqrt{s} = 8$ TeV and an integrated luminosity of 20.3 $fb^{-1}$ is used, and the techniques developed will later be applied to the full $\sqrt{s} = 13$ TeV data, which is expected to reach an integrated luminosity greater than 100 $fb^{-1}$.

The goals of the analysis include using ATLAS data to measure the cross-section of electroweak production of this final state, place limits on anomalous gauge couplings, and search for physics beyond the Standard Model.
2.3 $Z\gamma$ Production

This analysis focused on production of both $Z\gamma$ and opposite sign $W$ final states. $W$ and $Z$ bosons are short lived massive particles, decaying with a lifetime on the order of $10^{-25}\text{s}$ to either leptons or quarks. Although the branching ratios for the hadronic decay channels are higher, there are fewer backgrounds associated with lepton decays. As such, the fully leptonic decay channels are chosen for study. Five channels in total are being included as part of the analysis: a $Z$ boson decaying to oppositely charged electrons, oppositely charged muons, and neutrinos, and a $W$ boson decaying to an electron and a neutrino, and a muon and a neutrino.

This project focused on the $Z\gamma$ channel with the $Z$ decaying to two oppositely charged muons. The Feynman diagram for this process is shown in figure 3.

![Figure 3: Diagram of Vector Boson Scattering with a $Z\gamma$ final state](image)

The initial state quarks from the proton collision emit two oppositely charged $W$ bosons. The two quarks hadronize and enter the detector as high energy forward jets. The two $W$ bosons scatter, emitting a $Z$ and a photon. The $Z$ then decays
almost instantaneously, leaving a final state of two oppositely charged muons, a high energy photon, and two high energy jets. Events with this final state are selected and used in the analysis.

However, diboson production can occur through several other processes, including both QCD and EWK interactions. Several possible methods of $Z\gamma$ production are shown in figure 4:

![Figure 4: Three methods of Z\gamma production. Top left: QCD production. Top right: EWK production. Bottom: VBS EWK production.](image)

The presence of a QCD vertex causes the top left diagram to be classified as QCD production, while the process in the top right includes only EWK vertices and is therefore classified as EWK production. The bottom diagram includes only EWK vertices as well as a quartic gauge couplings between EWK vector bosons, making
it VBS production of the $Z\gamma$ final state. VBS therefore represents a subset of EWK production of dibosons. QCD interactions are by far the predominant method of $Z\gamma$ production - with a cross-section on the order of 1000 times EWK production - and they represent the largest background for this channel. Both of these production methods must be well understood in order for sensitivity to VBS $Z\gamma$ production to be achieved.

2.4 Monte Carlo Event Generation

In order to compare our experimental observations with theoretical predictions, the physics processes of interest and the action of the detector must be accurately simulated. To this end, Monte Carlo (MC) event generators are used to model the collisions that occur within the LHC, the physics processes that result, and the response of the detector.

There are three variable "levels" generated using MC simulations: parton level variables, particle level variables, and reconstructed level variables. Parton level variables - often called "truth level" variables - are the most simple, including only the identity and kinematics of the partons involved in the interaction. Particle level variables include other secondary effects, such as particle showering, the hadronization of quark and gluons, and possible non-zero transverse momentum of the incoming quarks. The reconstructed level variables are meant to simulate the action of the detector, accounting for complications of the hardware such as the resolution of the detector and mis-identification of particles. These simulations are used to
understand details of the relevant interactions, and compare the data collected by ATLAS to theoretical predictions.

The matrix-element based event generator MadGraph was used to generate parton level $pp \rightarrow Z(\mu^+, \mu^-)\gamma$ events [9]. Samples of QCD $Z\gamma$ production and EWK $Z\gamma$ production are generated separately in order to better understand and compare background and signal events.

3 The LHC and the ATLAS Detector

3.1 The LHC

Located near the French-Swiss border at the European Center for Nuclear Research (CERN), the Large Hadron Collider (LHC) is the highest energy particle accelerator in the world, and the largest single machine ever constructed. The purpose of the LHC is to investigate some of the most fundamental questions in particle physics. The data collected at the LHC will be used to test the predictions of the Standard Model and search for new physics, such as dark matter, evidence of extra dimensions, and new particles predicted by Supersymmetry.

The LHC is a circular hadronic collider, designed to collide protons and lead ions at high energies. Constructed from 1998 to 2008, it consists of a 27 kilometer ring along which four major detector experiments - ATLAS, CMS, ALICE, and LHCb - are located [7]. CMS and ATLAS are general purpose detectors designed to record the results of proton-proton collisions with maximum efficiency. ALICE
and LHCb are more specialized. ALICE is optimized to detect the results of heavy-ion collisions in order to study strong force interactions and quark-gluon plasma. LHCb specializes in detecting b-hadrons with the goal of investigating the matter-antimatter asymmetry we see in our universe.

The LHC first ran proton-proton collisions in 2010 at a center of mass energy of $\sqrt{s} = 7\text{ TeV}$. This energy was increased in 2012 to $\sqrt{s} = 8\text{ TeV}$, with an integrated luminosity of $20.3\ fb^{-1}$. Luminosity (L) is the ratio between the number of events detected per unit time (t) and the interaction cross-section ($\sigma$). This integrated over time is referred to as the integrated luminosity ($\mathcal{L}$).
\[ L = \frac{1}{\sigma} \frac{dN}{dt} \quad \mathcal{L} = \int L dt \quad (1) \]

The LHC is expected to run again this year at an energy of \( \sqrt{s} = 13 \) TeV, and achieve an integrated luminosity greater than \( 100 \, fb^{-1} \).

### 3.2 The ATLAS Detector

The ATLAS detector, represented in figure 6, is one of two general purpose detectors located at the LHC. Weighing over 7,000 tons, the ATLAS detector is 44 meters long, and 22 meters in diameter. Within ATLAS are several layers of detectors, designed to record the results of collisions with maximum accuracy and efficiency [4].

The detector consists of three main layers: the inner tracking detector, the hadronic and electromagnetic calorimeters, and the Muon Spectrometer. It also consists of two magnet systems designed to bend charged particles through the inner detector and the muon spectrometer, allowing the momentum of charged particles to be measured.

The basic function of the inner tracking detector, located at the center of ATLAS, is to measure charged particles. By tracking a particle’s path based on its interaction with the material in the tracking detector, its momentum and charge can be determined. Surrounding the inner detector are the calorimeters, designed to measure the energy of particles. First, the electromagnetic calorimeter absorbs
energy from charged particles and photons, making a precise measurement of the amount and location of the energy deposited. Outside this first calorimeter is the hadronic calorimeter, designed to measure the energy of particles that pass through the electromagnetic calorimeter and interact via the strong force, primarily hadrons.

Located at the outside of the detector is the muon spectrometer system. It consists of an extremely large tracking system, which includes 1200 chambers measuring the tracks of outgoing muons with high spatial accuracy. It extends from just outside the calorimeters to near the edge of the detector. This size is required to accurately measure the energy and momentum of muons, which are able to pass...
through both the electromagnetic calorimeter (because of their large mass) and the hadronic calorimeter (because they do not strongly interact).

There is a separate set of calorimeters in the forward region, designed to detect particles that enter at small angles relative to the beam. This allows the detector to make an accurate calculation of missing transverse energy and detect particles that travel just along the beam line. The forward calorimeter plays an important role in this analysis, as VBS involves two forward jets that are not always detected by the central calorimeters.

These many layers of detectors ensure that as many particles can be detected as possible. The only known particles the detector is incapable of detecting are neutrinos. However, their presence can be inferred from missing transverse energy when the energy of all particles in each collision are summed. Also included in the detector is a complex trigger system, designed to record only the most interesting events. Three levels of triggers are used to select a few hundred events per second out of nearly 40 million collisions per second, all in real time.

4 Background Estimation

4.1 Introduction

There are two major backgrounds associated with electroweak $Z\gamma$ production. The first comes from jets being misidentified by the detector as photons. Because this process is distinct from our signal, this background can be reduced using data-
driven techniques. The other background is strong force (QCD) production of the $Z\gamma$ final state. This QCD background is irreducible, as it is identical to our signal. However, it is well understood, and can therefore be estimated with Monte Carlo simulations. Further, kinematic differences between these two production processes can be exploited to suppress these background events. Because this background is large compared to expected signal events, sophisticated multivariate analysis techniques are investigated as a way to reduce this background.

### 4.2 Jets Faking Photons

QCD objects known as "jets", such as gluons and hadrons, will sometimes leave a signature in the detector similar to that of a photon, causing them to be misidentified by the detector. Because they are point particles with no internal structure, photons tend to be "tight" - meaning their energy is deposited in a small, concentrated area of the detector - and "isolated" - separated from other particle - compared to jets. Photons are therefore selected based on how tight and isolated they are within the detector.

There are still some jets that meet this additional selection criteria. The rate of this misidentification depends on detailed properties of the detector that cannot be modeled accurately with simulations. Instead, a data driven technique, known as the ABCD method, is used to estimate this background. The general idea behind this method is as follows: Three background or control regions (B, C, D) and one signal region (A) are defined as shown in figure 7.
Based on the assumption that the two variables are uncorrelated, and that the control regions are exclusively background, the number of background events in the signal region can be calculated from the simple relation:

\[ N_A = N_C \frac{N_B}{N_D} \]  

(2)

Both of these assumptions are only approximately true, and the application of this method must account for potential correlation between these two variables and signal events in the background regions.

### 4.3 QCD Z\(\gamma\) Production

VBS processes are incredibly rare compared to strong force (QCD) production of the same final state; QCD production of \(Z\gamma\) has a cross-section of order \(10^3\) higher than VBS production. Figure 8 shows one of these QCD processes.

This large QCD background presents one of the major challenges of this analysis,
as effectively differentiating between signal events and this background is crucial to making a significant measurement of vector boson scattering. Because QCD and VBS production of $Z\gamma$ have an identical final state, this background is irreducible, and methods like those used to suppress the background of jets faking photons are ineffective. This is further complicated by the fact that, because they are identical, these two processes can interfere at the matrix level. This interference will be discussed in more depth in a later section.

However, because QCD production is well understood, it can be modeled using Monte Carlo simulations. These simulations can then be used to accurately account for this background. Further, while they are identical at the tree-level, there are several distinguishing kinematic features between the two processes, such as the energy and angular separation of the two jets, that are used to suppress these background events.
4.4 Event Selection

Candidates VBS events are selected according to the following criteria:

- Two muons with opposite charge, each with $p_T > 25$ GeV and $|\eta| > 2.5$. The separation between the two muons is required to be $\Delta R_{\mu\mu} > 0.3$, and the invariant mass of the muon pair, $M(\mu^+\mu^-)$, must be greater than 40 GeV.

- At least one photon with $p_T > 15$ GeV, within the range $|\eta| > 2.37$ and separated from the muons, $\Delta R_{\mu\gamma} > 0.7$.

- Two jets with $p_T > 30$ GeV within the range $|\eta| > 4.5$. For VBS/QCD differentiation, the invariant mass of the two jets, $M_{jj}$, is required to be greater than 500 GeV, and the jets separated such that $\Delta Y_{jj} > 2.4$.

Here $p_T$ refers to the transverse momentum of the particle, i.e. the momentum in the direction perpendicular to the beam line. $\eta$ is the psuedorapidity, a lorentz invariant measure of the angle between the object and the beam line. It is defined as $-\ln[\tan(\theta/2)]$, where $\theta$ is measured from the beam line.

![Figure 9: Pseudorapidity (\(\eta\)) as a function of \(\theta\)](image-url)
\[ \Delta R \] is a measure of the angular distance between two particles, defined as 
\[ \sqrt{\eta^2 + \phi^2} \], where \( \phi \) is the azimuthal angle. \( Y \) is a modified version of rapidity as used in relativity, but defined relative to the beam axis. It is given as

\[
Y = \frac{1}{2} \ln \frac{E + p_zc}{E - p_zc}
\]  

(3)

where \( p_z \) is the momentum along the beam axis [2]. \( \Delta Y \) is the difference in rapidity of two particles, and it is also a measure of angular distance.

4.5 Multivariate Analysis

4.5.1 Introduction

Multivariate analyses are a set of techniques designed to analyze complex sets of data using the inter-relatedness of several variables. Many of these techniques have been developed recently, due in part to the fact many of the calculations involved are sufficiently complex to require modern computational technology. The small signal to background ratio and the complexity of the data involved in this analysis make it a good candidate for these methods.

TMVA is a multivariate analysis framework designed to process and evaluate multivariate classification within the ROOT environment [1]. It uses a training sample, where the desired output is known, to determine a mapping function that can be used to classify future inputs.

The MVA requires two data samples to separate, such as a signal file and a back-
ground file, to perform this training. These include several physics variables that are
given as inputs for the MVA. Based on the variables provided, the MVA develops a
mapping function to maximally differentiate between the two. This training is used
to characterize events within a data sample, assigning them a probability of being
either signal or background. The many dimensional input is converted into a single
dimensional output. TMVA provides an optimal cut on this variable based on the
training, as well as an estimate of the signal and background efficiency that can be
expected.

4.5.2 Preliminary Results

Signal and background samples containing VBS and QCD parton level variables
generated using MadGraph are used to test the effectiveness of these multivariate
techniques. The kinematic variables used are shown in table 1. Several methods
are tested within the framework of TMVA: Boosted decision tree (BDT), Fischer
Discriminant (FD), a neural network (MLP), and H-Matrix discriminant (HMatrix).
Training is performed for each of these methods using these signal and background
samples.
In each case, the MVA converts the multi-dimensional input provided into a one-dimensional output. Each event is assigned a value in this 1-D space corresponding to its predicted probability of being either signal or background based on the kinematics of the event. The signal and background samples plotted to this 1-D output for each method are shown in figure 10.

Based on this separation, the rate of background rejection as a function of signal efficiency, shown in figure 11, can be calculated. A cut on this distribution is applied which will maximize the signal significance, which is calculated as $S/\sqrt{S+B}$.

Of those tested, the BDT method is found to provide the best signal/background discrimination based on this criteria. The boosted decision tree (BDT) method uses a binary tree structure to classify an event as either signal or background. Repeated yes/no decisions are taken on different variables until a stopping criteria is reached, and this processes is repeated for a large number of decision trees. The event is

<table>
<thead>
<tr>
<th>Input Variables</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{jj}$</td>
<td>$\eta_{\gamma}$</td>
</tr>
<tr>
<td>$\Delta Y_{jj}$</td>
<td>$\Delta R_{\mu\gamma}$</td>
</tr>
<tr>
<td>$\Delta R_{j\gamma}$</td>
<td>$\Delta R_{\mu\mu}$</td>
</tr>
<tr>
<td>$\eta_{\mu}$</td>
<td>$pT_{\gamma}$</td>
</tr>
<tr>
<td>$pT_{jet}$</td>
<td>$pT_{\mu}$</td>
</tr>
</tbody>
</table>

Table 1: Kinematic variables used as input for the MVA training
assigned a probability of being either signal or background based on its place at the end of each tree.

Based on the training samples used, the BDT MVA method achieves a maximum signal significance, $S/\sqrt{S+B}$, that is 81% higher than the event selection described in section 4.4.

Work is still ongoing. Future studies will further investigate which kinematic variables provide the best discrimination. The MVA will be trained using reconstructed level variables, which take into account the functioning of the detector, and better resemble data. This trained MVA will then applied to the data to maximize background suppression.
5 QCD/EWK Interference

5.1 Introduction

The cross-section for a given process is calculated as the square of the sum of all diagrams that contribute to that process. Therefore, processes that are identical at the tree-level - i.e. processes with an identical initial and final states - can interfere with one another, giving a cross-section that differs from what would be calculated by taking each process individually. This interference can be either constructive or destructive, increasing or decreasing the overall cross-section of a particular region of phase space. For example, the probability of $WW$ scattering at high energies is calculated to be greater than one when the exchange of a Higgs boson between
two pairs of W bosons is not included in the calculation. This Higgs exchange
destructively interferes with the other diagrams, solving the problem of non-unitarity
[10].

![Figure 12](image)

Figure 12: The exchange of a Higgs boson interferes with other $WW \rightarrow WW$ processes

Similar interference effects are potentially present for EWK and QCD production
of $Z\gamma$. Because they must be identical at the tree-level, interference will only occur
when the flavors of the initial and final state quarks are the same. As such, most
QCD and VBS processes, such as those shown in figure 13 will not interfere.

![Figure 13](image)

Figure 13: Example of two non-interfering VBS (left) and QCD (right) processes
Within the QCD sample, 75.5% of events are found to include a gluon as at least one of the initial or final state partons. No events in the VBS sample include gluons, and therefore the majority of events within the QCD sample do not contribute to the interference. Only events such as those shown in figure 14, where both diagrams represent processes where $ud \rightarrow ud + Z\gamma$, will contribute to the interference.

![Figure 14: An example of interfering VBS (left) and QCD (right) processes](image)

In our simulations, samples of QCD and EWK production are generated independently. This allows us to quantify what portion of our data can be considered signal, and how much is accounted for by the QCD background. This means, however, that our simulations will not include any potential interference between QCD and EWK production of $Z\gamma$. If this interference is significant, it must be accounted for as an additional systematic error.

### 5.2 Results

Three samples are generated using MadGraph 5 to investigate this interference:

1. Only the EWK component
2. Only the QCD component

3. The combination of QCD and EWK

The first two, where no interference is present, are compared to the third to estimate interference effects. Because we are interested in estimating the matrix-level interference, the parton level variables are chosen to provide the clearest estimate of the effect. These variables are used to calculate interference as a function of the dijet mass, $(M_{jj})$ and jet separation, $\Delta Y_{jj}$. Because we are attempting to understand interference as a function of these variables, the selection criteria requiring $M_{jj} > 500$ GeV and $\Delta Y_{jj} > 2.4$ are not included in this part of the analysis.

A comparison of the $M(jj)$ distributions of the mixed sample and the separately generated QCD/EWK samples are shown in figure 15. The same is shown for the $\Delta Y_{jj}$ in figure 16.

![Figure 15: M(jj) distribution of interfering sample compared to QCD+EWK samples](image)

Figure 15: M(jj) distribution of interfering sample compared to QCD+EWK samples
Figure 16: dYjj distribution of interfering sample compared to QCD+EWK samples

These plots suggest general agreement between the QCD and EWK samples produced separately and the mixed sample. However, this comparison is insufficient to make any quantitative estimates of the interference effect.

Because the goal is to estimate a systematic error on our signal that results from interference effects, we quantify the interference relative to signal. This is calculated as the difference between the mixed sample and the QCD and EWK samples together, divided by the EWK component, (Interfering - (QCD + EWK))/EWK. This quantity as a function of dijet mass is shown in figure 17:
Figure 17: Interference as a fraction of EWK

This shows significant interference in the low mass region, as much as 65% of signal. While the interference appears to decrease in the high mass region, near 1 TeV, the statistics of the sample are insufficient to draw any quantitative conclusions.

Studying particular initial and final states, those where interference is expected, provides a clearer demonstration of the interference effect. The parton level variables in Madgraph can be used to identify the flavor of the quarks involved in each event. This is used to determine which processes are most common in each sample.
Table 2: Most common processes within the VBS sample

<table>
<thead>
<tr>
<th>Initial</th>
<th>Final</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$du$</td>
<td>$du$</td>
<td>56.87%</td>
</tr>
<tr>
<td>$u\bar{u}$</td>
<td>$d\bar{d}$</td>
<td>8.91%</td>
</tr>
<tr>
<td>$us$</td>
<td>$dc$</td>
<td>7.10%</td>
</tr>
<tr>
<td>$d\bar{d}$</td>
<td>$u\bar{u}$</td>
<td>6.09%</td>
</tr>
<tr>
<td>$u\bar{c}$</td>
<td>$d\bar{s}$</td>
<td>3.26%</td>
</tr>
<tr>
<td>$du$</td>
<td>$dc$</td>
<td>3.11%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>85.34%</strong></td>
</tr>
</tbody>
</table>

Within the VBS sample, the processes $ud \rightarrow ud$ is found to be the most common, representing over half of the total number total events. Because this process is relatively common within the QCD sample as well, $ud \rightarrow ud$ events are expected to provide a major contribution to interference effects. A Monte Carlo sample is generated containing only these events.

Plotting interference as a fraction of the VBS component for just $ud\rightarrow ud$ events, figure 18 shows a clearer distribution of the interference as a function of $M(jj)$. 

31
This is fit to a second order exponential in the region from 150 GeV to 3 TeV.

Similarly, the interference as a function of $dY_{jj}$ is shown in figure 19:

There are also processes for which no interference is expected. Shown in figure 32.
20 is the interference as a fraction of the QCD component (as the VBS component is zero) for events with an initial and final state of a u quark and a gluon. The interference effect for these events is consistent with zero, as expected.

Figure 20: Interference as a fraction of the QCD component for \( ug \rightarrow ug \) events

In the future, these studies will work to place a quantitative value on the uncertainty of EWK production of \( Z\gamma \) based on interference with QCD background. Samples will be generated with several processes other than \( ud \rightarrow ud \), to test if this trend of interference decaying exponentially hold true for all processes. From there, the interference effect for EWK production as a whole will be extrapolated.

6 Conclusions and Ongoing Work

The SU(2)×U(1) structure of the electroweak sector of the Standard Model predicts self-interactions between the electroweak gauge bosons, the \( W^\pm, Z, \) and \( \gamma \).
These processes can be measured with data collected by the ATLAS detector by searching for signatures of diboson production. These measurements directly probe important aspects of the electroweak sector of the SM, and provide an opportunity to search for new physics.

The theory and motivation behind this measurement have been presented, and the major challenges associated with this analysis have been discussed. A preliminary study of multivariate analysis techniques has been presented, and these techniques have been found to significantly improve signal/background differentiation compared to selection based on individual variables. The interference between QCD and VBS $Z\gamma$ production is studied, and found to be decrease with dijet mass and jet separation.

Future work will suppress the backgrounds associated with this channel using data driven methods and multivariate analysis techniques. Numerical estimates of interference will be made, which will accounted for as an additional systematic error. These techniques will be applied to the full 2012 ATLAS dataset, which will be compared to theoretical predictions for each of the five analysis channels being studied. This comparison will be used to test SM predictions and place limits on anomalous gauge couplings. The LHC is scheduled to begin collecting data again in June of 2015 at an increased energy and luminosity. Applying the methods developed in this analysis to this data set will provide new opportunities to study vector boson scattering more precisely at a new energy scale.
References


