A Search For Z Pair in a Three Lepton Channel

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Abstract

We present a search for Z-boson pair production in a three lepton channel using the ATLAS detector at $\sqrt{s} = 14$ TeV. The search was motivated by the inefficiencies in electron reconstruction in the four lepton channel. In ATLAS, the sliding window algorithm which covers the range $|\eta| < 2.5$ is designed for electron identification. We used different clustering algorithms with a higher $\eta$ coverage to identify the missing electron. We used a likelihood method for partially identify electrons and established kinematic selection for events. Although the three lepton channel has a higher acceptance, it suffers from a higher background relative to the four lepton channel which consists mainly of $Zb\bar{b}$, $Zb$, $WZ$, and $t\bar{t}$. The analysis was performed using Monte Carlo samples generated by different event generators, and the ATLAS detector was simulated by the GEANT4 software. We estimate a gain of 36% of the acceptance of ZZ for 1 fb$^{-1}$ with respect to the explicitly fully reconstructed four lepton final state ZZ $\rightarrow 4l$. In terms of the significance, which is defined as $S/\sqrt{S+B}$, we find an increase from 3.6 to 4.09±0.04.


1 Introduction

The Standard Model (SM) of electroweak interactions predicts very precisely the couplings between gauge bosons due to the non-Abelian gauge symmetry $SU(2)_L \times U(1)_Y$. The self-interactions are described by the Triple Gauge Couplings (TGC) $WWV$, $Z\gamma V$, and $ZZ (V = \gamma, Z)$ [1]. Vector boson pair production provides a sensitive ground for direct tests of the TGC. The TGC ($ZZZ$ and $ZZ\gamma$) are strongly suppressed and are of order $O(10^{-4})$ [2]. Any deviations of the couplings from the expected values would be a sign of new physics. Thus, $ZZ$ searches provide a test for any gauge-coupling anomalies. The on-shell $Z$ pairs are also a main physics background for the Higgs in its four-lepton decay mode, particularly at high mass. The existence of the Higgs boson will manifest itself by a peak in the invariant mass distribution of the $Z$-boson pair. Therefore, it is important to evaluate precisely the production rate of the $ZZ$ continuum in order to get a realistic estimate of the signal-to-background ratio.

![Feynman diagrams](image.png)

Figure 1: The Feynman diagram for the tree level process contributing to $ZZ$ production in the SM (left). The forbidden contributions of $ZZZ$ and $ZZ\gamma$ diagrams to $ZZ$ production (right).

In the SM, the main process for continuum $Z$ pair production is $q\bar{q}$ annihilation [3] as shown in Figure 1. The next-to-leading order (NLO) contributions are due to virtual processes where the gluon is emitted and absorbed by the interacting quark or anti-quark. The other process is the soft-gluon emission where a gluon gets emitted with the $Z$ pair. The next-to-next-to-leading order (NNLO) contributions are due to gluon-gluon fusion.

2 Motivation for the three lepton channel

In ATLAS, electron identification is based on a sliding window algorithm. It covers only the region $|\eta| < 2.5$ which leaves the forward region out of reach. Moreover, the inefficiencies in track, cluster reconstruction, and crack regions have reduced electron reconstruction efficiency in the central region. Figure 2 shows the number of reconstructed electrons in a $ZZ \rightarrow 4e$ event. One can see that the number of events with three reconstructed electrons is twice the number of events with four reconstructed electrons. This observation was first made in the similar $H \rightarrow ZZ^*$ case [6, 7], and this led to a strategy of a three-lepton analysis in that search. Based on that observation, we pursued a complementary analysis to search for on-shell $ZZ$ in the three-lepton channel. There are two sets of decay channels in our study which can give rise to an unidentified electron. The first one is based on events with three reconstructed electrons and the second one is based on two reconstructed muons and one electron. The background is high.
Figure 2: Number of electrons reconstructed in an event of $ZZ \rightarrow 4e$. 

in those channels; it consists of $Zb\bar{b}, Zb, t\bar{t}$, and $WZ$ in their decay to three leptons. The $Z^+(\text{light})\text{jets}$ background is very important as a jet can fake an electron. The search conducted in this analysis was exclusive to the three-lepton channel which is complementary to the four-lepton channel analysis.

3 Event Samples

3.1 Monte Carlo Samples

The Monte Carlo samples in this analysis used a variety of different generators for a center of mass collision of 14 TeV with ATHENA release 13.0.30. The ATLAS detector was simulated by the GEANT4 software [8]. The signal Monte Carlo sample of on-shell $ZZ$ decay to four leptons was modeled using the MC@NLO [9] generator. The leptons in the $ZZ \rightarrow 4\ell$ sample are electrons or muons [12]. The $Zb$ and $Zb\bar{b}$ background Monte Carlo samples were both generated with AcerMC [10]. The $t\bar{t}$ was modeled using the MC@NLO generator while $WZ$ was modeled using the generator JIMMY [11]. The background data sets and their cross-section calculations used in this analysis are based on Ref. [13].

The background $Z^+\text{jets}$ was not produced in the release in which this analysis was conducted. We believe that the impact of $Z^+$ jets background would be less significant than the $Z^+b$ jets considered in this analysis. This background is the main background for Higgs searches mainly at low mass and it has been found that no event (out of 500k events) had passed the basic lepton identification [13]. Our requirements on the three leptons are very stringent; all three leptons are required to be high in $p_T$ and well isolated, while the electrons from soft jets are relatively low $p_T$ in $Z^+\bar{b}$jets. Moreover, the rate by which a soft jet can fake an electron is very low $10^{-4}$ [4]. Since the background kinematics are similar to $Zb\bar{b}$, the same background rejection will be achieved in backgrounds with heavy flavor. It is unlikely that the jets that will fake the electron and the partially reconstructed electron will form a $Z$ resonance.

3.2 Trigger Analysis

It is very important to know if the signal can pass the triggers, and evaluate the trigger efficiencies. In the presented analysis, we considered the lepton triggers available in the trigger menu of release 13.0.30 [14].
Table 1: Monte Carlo signal and background samples, number of events generated, and the cross sections with branching ratios and filter acceptance of each process evaluated to the next leading order.

<table>
<thead>
<tr>
<th>Signature</th>
<th>ID sample</th>
<th>Number of events</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>5931</td>
<td>20000</td>
<td>66.8</td>
</tr>
<tr>
<td>Zbb</td>
<td>5176</td>
<td>26500</td>
<td>12663</td>
</tr>
<tr>
<td>Zb</td>
<td>6540</td>
<td>20000</td>
<td>14000</td>
</tr>
<tr>
<td>tt</td>
<td>5211</td>
<td>400000</td>
<td>6064</td>
</tr>
<tr>
<td>WZ</td>
<td>6359</td>
<td>15000</td>
<td>807</td>
</tr>
</tbody>
</table>

1. **EF.e20**: Requires an electromagnetic cluster with $p_T > 20$ GeV at L1, and requires an electron with $p_T > 20$ GeV at L2, and EF. No isolation is required.

2. **EF.mu20**: Requires a single muon with $p_T > 20$ GeV at L1, L2, and EF. No isolation is required.

The instantaneous luminosity assumed for 1 fb$^{-1}$ is $10^{-32}$ cm$^{-2}$ s$^{-1}$. The trigger items described above are not prescaled for this instantaneous luminosity.

The relative trigger efficiencies were evaluated as the ratio of the number of times a given trigger is fired $N_{\text{trigger}}$ to the number of events with three reconstructed leptons $N_{3\text{leptons}}$ with $p_T > 10$ GeV as shown in equation 1.

$$\epsilon_{\text{trigger}} = \frac{N_{\text{trigger}}}{N_{3\text{leptons}}}$$  \hspace{1cm} (1)

The final trigger efficiencies are summarized in Table 2. In the case of an efficiency from a single trigger being less than 100%, we can combine the two triggers in such a way that either one of them should be triggered.

Table 2: Trigger efficiencies. Errors are binomial.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>eee channel</th>
<th>$\mu\mu e$ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EF.e20</strong></td>
<td>0.996 ± 0.001</td>
<td>0.851 ± 0.005</td>
</tr>
<tr>
<td><strong>EF.mu20</strong></td>
<td>-</td>
<td>0.902 ± 0.004</td>
</tr>
<tr>
<td><strong>EF.mu20 OR EF.e20</strong></td>
<td>-</td>
<td>0.985 ± 0.006</td>
</tr>
</tbody>
</table>

4 **Event Selection for the Three Lepton Channel.**

There are two sets of decay channels in this study which can give rise to an unidentified electron. The first one is based on events with three reconstructed electrons and the second one is based on two muons and one electron which are reconstructed in the pseudorapidity range of $|\eta| < 2.5$.

4.1 **Lepton Identification**

Electrons were required to pass the ATLAS “Medium” electron criteria which is based on calorimeter and tracking information [4]. Muons were identified using the STACO algorithm [15], which is based on the statistical combination of two independent measurements; the track in the inner tracker and the track
from the muon system. The pair of tracks corresponding to the full muon path is retained for the best combined $\chi^2$.

4.2 Impact Parameter

Leptons from $t\bar{t}$, $Zb\bar{b}$, and $Zb$ are most likely to originate from displaced vertices. This is due to the relatively long lifetime of the $b$ quark. In order to select only prompt electrons originating from the $Z$ bosons and to get more background rejection, we used the transverse-impact parameter significance. It is defined as the ratio of the distance of closest approach to its measured error; we refer to this ratio as DCA. Bremsstrahlung, in case of electrons, smears the impact parameter distribution for electrons which reduces the discriminating power of this cut with respect to muons, as shown in Figure 3. The impact parameter is evaluated with respect to the event primary vertex fitted using a set of tracks reconstructed in the inner detector. Therefore, one can remove the effect of the spread of the vertex position, which is $\sigma_{xy} = 15 \mu m$ in the transverse axes $x$ and $y$, and $\sigma_z = 5.6 \text{ cm}$ along the beam axis.

4.3 Lepton Isolation

A distinctive feature of the signal event is lepton isolation; all the leptons in a signal event are isolated while in the background events at least one lepton is non-isolated. In the $t\bar{t}$, $Zb\bar{b}$, and $Zb$ backgrounds, one lepton originates from a jet; this lepton is generally from a semi-leptonic $b$ decay. In that case, the lepton is produced moderately far from a jet axis. The environment of a lepton originating from a jet should contain some hadronic signature, unlike a lepton from a signal event which is isolated. The transverse energy in a cone of a certain size around the direction of a given particle with the subtraction of the transverse energy of the particle itself can be used to impose isolation on leptons. For this analysis we used a cone size of $\Delta R = 0.2$; this is known as the $E_T$ in the cone (“etcone”). The ratio of transverse energy in a cone of $\Delta R = 0.2$ to the transverse energy of the particle gives the isolation information $\frac{E_{\text{etcone}}(\Delta R=0.2)}{E_T^{\text{lepton}}}$; in this analysis we require this ratio to be less than 0.14 for both electrons and muons. In Figure 4, we show the isolation information for signal and background for electrons (left) and muons (right).

![Figure 3: Transverse-impact parameter significance for electrons (left) and muons (right) in signal and background events.](image)

![Figure 4: Isolation information for signal and background for electrons (left) and muons (right).](image)
Figure 4: Isolation information for electrons (left) and for muons (right) where isolation is defined as $\frac{\Delta R}{E_\text{lepton}} = 0.2$.

5 Kinematic Selection

5.1 Transverse Missing Energy

The $WZ$ and $t\bar{t}$ background events are characterized by large missing transverse energy ($E_T$) as shown in Figure 5, unlike the signal events which have very little $E_T$.

Figure 5: Transverse missing energy in signal and background in reconstructed 3 medium electrons events normalized for luminosity of 1 fb$^{-1}$. The ZZ signal is scaled by a factor of 10, $t\bar{t}$ by a factor of 2, and WZ by a factor of 3.

We considered two channels in the ZZ selection. The first one is based on events with 3 reconstructed medium electrons while the fourth electron is not reconstructed. The second one is based on two STACO muons and one medium electron where the second electron was not reconstructed. We did not consider the 3 muon channel where one muon does not get reconstructed. Moreover, we consider only events with on-shell Z bosons. The pre-selection cuts were chosen by inspection of the distributions of each variable. The $p_T$ cut on all three leptons was chosen to be higher than 10 GeV as the third leading lepton on the
main background event has a low \( p_T \) as shown in Figure 6. The impact-parameter significance cuts are chosen in such a way that the loss in signal efficiency is tolerable (-3\%) while the background rejection improves, and similarly with the isolation cuts and the transverse missing energy. We summarize the pre-selection cuts of the three lepton events in Table 3. The efficiency of these cuts are shown in Table 4. The efficiency is calculated for the 3\( e \) channel and the cuts shown in Table 4 are applied on all three electrons.

![Figure 6](image)

**Figure 6:** The \( p_T \) spectra of the three reconstructed electrons: ZZ signal (left) and Zb\( b \) background (right).

<table>
<thead>
<tr>
<th>( p_T ) of the lepton</th>
<th>( p_T^{3e} &gt; 10 \text{ GeV and } p_T^\mu &gt; 10 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCA/( \sigma_{\text{DCA}} ) significance</td>
<td>DCA/( \sigma_{\text{DCA}} ) &lt; 5 for electrons, DCA/( \sigma_{\text{DCA}} ) &lt; 3 for muons</td>
</tr>
<tr>
<td>Isolation</td>
<td>etcone20/et &lt; 0.14 for all the three selected leptons</td>
</tr>
<tr>
<td>Missing Energy</td>
<td>( E_T &lt; 24 \text{ GeV} )</td>
</tr>
</tbody>
</table>

Table 3: Initial selection of the 3 leptons.

<table>
<thead>
<tr>
<th>Process</th>
<th>( \varepsilon(p_T^{3e} &gt; 10 \text{ GeV})(%) )</th>
<th>+ ( \varepsilon(\text{DCA})(%) )</th>
<th>+ ( \varepsilon(\text{Isolation})(%) )</th>
<th>+ ( \varepsilon(E_T)(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>36( \pm )0.3</td>
<td>33.2( \pm )0.31</td>
<td>32.4( \pm )0.34</td>
<td>28.2( \pm )0.31</td>
</tr>
<tr>
<td>Zb( b )</td>
<td>16( \pm )0.2</td>
<td>9.1( \pm )0.1</td>
<td>3.1( \pm )0.1</td>
<td>2.5( \pm )0.1</td>
</tr>
<tr>
<td>Zb</td>
<td>16( \pm )0.3</td>
<td>8.4( \pm )0.2</td>
<td>4.2( \pm )0.1</td>
<td>3.23( \pm )0.12</td>
</tr>
<tr>
<td>WZ</td>
<td>39( \pm )0.4</td>
<td>28.3( \pm )0.36</td>
<td>24.6( \pm )0.35</td>
<td>4.2( \pm )0.1</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>8( \pm )0.1</td>
<td>2.86( \pm )0.08</td>
<td>0.54( \pm )0.01</td>
<td>0.05( \pm )0.01</td>
</tr>
</tbody>
</table>

Table 4: Efficiency of signal and background selection with different cuts applied in the 3\( e \) channel. The uncertainties are statistical.

5.2 The Z peak in the three lepton event

In a background event such as Zb\( b \) or Zb, the first leading electron and the second leading electron come from the Z decay. Thus a combination of the first leading electron and the second leading electron will give an invariant mass near the Z mass as shown in Figure 7. The third leading electron comes from the \( b \) quark. If we consider a configuration of first-leading and third-leading electron, a mainly flat distribution
will be seen. However, in the case of the ZZ events the electron in the direction of the Z will get a boost and hence a higher $p_T$. As shown in Figure 7, the first leading electron in that case will be from one Z while the second leading electron will be from the other Z. This is true only in the case of the 3e channel. This combinatorics issue does not appear in the $2\mu 1e$ channel as the two reconstructed muons should originate from the same Z boson. As a consequence, the $2\mu 1e$ channel has a built in suppression of $Z \rightarrow e^+ e^-$ and $b\bar{b} \rightarrow \mu \mu$.

We defined a new variable $M_{Zbest}$ by using the invariant mass of two combinations with verified opposite electric charges. We evaluate the invariant mass of the first-leading electron and third-leading electron or second-leading electron and third-leading electron. The variable $M_{Zbest}$ is chosen as the combination that gives the closest invariant mass to the nominal Z mass as shown in Figure 8. In the case of the signal, one can see a peak within a certain window around the nominal Z mass. However, a flat distribution can be seen in the case of the main background. In the case of the $2\mu 1e$ channel, the Z peak originates from the two muons reconstructed in the event. $M_{Zbest}$ is shown in Figure 8 in the 3e channel for signal and main backgrounds normalized to 1 fb$^{-1}$. To reject a higher amount of background, we will require $M_{Zbest}$ to be within a certain window of the Z mass.

![Figure 7: The expected $p_T$ of electron in ZZ signal events (left) and $Zb\bar{b}$ background events (right). $e_1$ is for the first-leading electron, $e_2$ is for the second-leading electron and so on.](image)

![Figure 8: The $M_{Zbest}$ variable in the ZZ, Zb$\bar{b}$, and Zb samples.](image)
6 Partially Reconstructed Electron

Further background rejection requires that we identify the missing electron. Based on observed inefficiencies in electron reconstruction, we sought an algorithm which does not assume or require a track and does not have a restriction in $|\eta|$. Moreover, it should not have shower-shape requirements and can retain a whole cluster across the detector cracks. We define the efficiency of the algorithm in finding the unidentified electron as follows:

$$\varepsilon = \frac{N_{\text{cluster}}(\Delta R < 0.2)}{N_{\text{ue}}}$$  \hspace{1cm} (2)

where $N_{\text{cluster}}(\Delta R)$ is the number of reconstructed clusters matching a number of unidentified truth electrons $N_{\text{ue}}$ within $\Delta R < 0.2$. Truth information from the Monte Carlo signal was used to check the efficiency of the jet and topological cluster algorithms in finding the unidentified electron. The $p_T$ resolution is defined as follows:

$$p_T^{\text{resolution}} = \frac{p_T^{\text{reconstructed}} - p_T^{\text{truth}}}{p_T^{\text{truth}}}$$  \hspace{1cm} (3)

The summary of different algorithm performances for the ZZ signal is shown in Table 5. The jet and topological cluster algorithms [16] are the most efficient as the $|\eta|$ coverage is high, $|\eta| < 4.9$. The EM topological cluster has an $|\eta|$ coverage of $|\eta| < 3.2$ which explains the relatively higher efficiency compared to the sliding window algorithm $|\eta| < 2.5$. Given that the jet cone of $\Delta R = 0.4$ and the topological cluster algorithms are the most efficient, we will consider only these two algorithms for this analysis.

Table 5: Summary table of different algorithm performances for the ZZ signal in overall $\eta$.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Efficiency %</th>
<th>$p_T$ resolution</th>
<th>$\Delta \phi$ resolution</th>
<th>$\Delta \eta$ resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>sliding window</td>
<td>60 ± 1.1</td>
<td>0.19</td>
<td>0.009</td>
<td>0.018</td>
</tr>
<tr>
<td>Jet ($\Delta R = 0.4$)</td>
<td>92 ± 0.4</td>
<td>0.25</td>
<td>0.02</td>
<td>0.028</td>
</tr>
<tr>
<td>Topological Cluster</td>
<td>96 ± 0.3</td>
<td>0.22</td>
<td>0.02</td>
<td>0.023</td>
</tr>
<tr>
<td>Tau</td>
<td>54 ± 1.1</td>
<td>0.29</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>EM Topological Cluster</td>
<td>75 ± 0.6</td>
<td>0.33</td>
<td>0.03</td>
<td>0.030</td>
</tr>
</tbody>
</table>

6.1 The Jet Cone Algorithm

The jet algorithm, which has the advantages of good behavior near cracks and in the forward region, was used to find the unidentified electron. The reconstructed electrons were also seen in the jet algorithm. Electron-jet overlap removal was performed before searching for the unidentified electron by requiring $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 0.2$ between the reconstructed electrons and the jets. A collection of “jet candidates” was created in which potential electrons were reconstructed.

The efficiency of the jet algorithm in finding the unidentified electron is $(92 ± 0.4)\%$ calculated by Equation 2. The $p_T$ spectra are shown in Figure 9 (left), where the $p_T$ of the truth electron (red) and the $p_T$ of the jet matched to truth (blue) are similar. The $p_T$ of the jet candidate is slightly higher than the $p_T$ of the matching truth electron. This is due to the fact that a cone of $\Delta R = 0.4$ is quite large for an electron, which results in larger $p_T$. The jet algorithm covers the forward region as shown in Figure 9 (right) which shows the $\eta$ distribution of partially reconstructed electrons which extends beyond $|\eta| > 2.5$. Moreover,
many electrons that were not reconstructed by the sliding window in the central region are recovered by the jet algorithm.

![Figure 9: $p_T$ distributions of truth electron and the jet matching the truth (left). The $\eta$ distribution of the jet candidate (right).](image)

The $p_T$ resolution is comparable to the sliding window (Table 5) if the transverse momentum of the partially-reconstructed electron is higher than 20 GeV, as shown in Figure 10 (right). However, the $p_T$ resolution worsens in the case of low $p_T$ for the unidentified electron.

![Figure 10: Reconstructed $p_T$ resolution in bins of truth $p_T$. Lower than 20 GeV (left) and higher than 20 GeV (right) in the case of the jet algorithm.](image)

### 6.2 The Topological Cluster

In the same fashion, we used the topological cluster algorithm to find the unidentified electron. Its efficiency in finding topological cluster within a cone of $\Delta R \leq 0.2$ is $96 \pm 0.2\%$. The $p_T$ distributions of the topological cluster (blue) with a truth match $\Delta R < 0.2$ and the truth electron (red) seem to be in good agreement as shown in Figure 11 (left). However, a small disagreement can be seen at lower $p_T$ which is due to the cluster-splitting in the crack region. The $\eta$ coverage beyond the $|\eta| > 2.5$ is seen in the $\eta$ distribution shown in Figure 11 (right). Similarly, the $p_T$ resolution is comparable to the sliding window algorithm (Table 5), especially at high $p_T$. Unfortunately, the $p_T$ resolution at lower transverse momentum tends to be worse although significantly better than for the jet algorithm. The $p_T$ resolution is shown in Figure 12 for $p_T < 20$ GeV (left) and $p_T > 20$ GeV (right).
Figure 11: $p_T$ distributions of truth electron and the cluster matching the truth (left). The $\eta$ distribution of the cluster candidate (right).

Figure 12: Reconstructed $p_T$ resolution in bins of truth $p_T$. Lower than 20 GeV (left) and higher than 20 GeV (right) in the case of the cluster algorithm.
7 Particle Identification

The object that was identified as the partially reconstructed electron by either the jet algorithm or the topological cluster is required to pass further particle identification. We used a set of variables that were available in the reconstruction software release used for the analysis (release 13) in each algorithm to discriminate real electrons from fake ones. In the case of the jets, we used a cut-based approach, while a likelihood method was used in the case of the topological cluster.

7.1 The Jet Cone Algorithm

In order to reject the background from $b$ jets in $Zb\bar{b}$ and $Zb$ events, the jet candidate was chosen in order to exclude those jets which originated from the $b$ quarks. This was done by using the secondary-vertex finding in the ATLAS $b$-tagging algorithm [16]. The $b$-tagging algorithm is based on variables which show significant differences in behavior between a $b$ jet and a light-quark jet. Three properties of the vertex are used: the invariant mass of all tracks associated with the vertex, the ratio of the sum of the energies of the tracks of the vertex to the sum of all energies of all tracks in the jet, and the number of two-track vertices. SV2 uses a 3D-histogram of the three properties. Moreover, a likelihood ratio method is used in the secondary-vertex tagging. The measured values ($S_i$) of a discriminating variable are compared to pre-defined smoothed and normalized distributions for both the $b$- and light-quark jet hypotheses, $b(S_i)$ and $u(S_i)$. The ratio of the probabilities $b(S_i)/u(S_i)$ defines the track or vertex weight which can be combined into a jet weight $W_{Jet}$ as the sum of the logarithms of the $N_T$ individual track weight $W_i$ as shown in Equation 4:

$$W_{Jet} = \sum_{i=1}^{N_T} \ln W_i = \sum_{i=1}^{N_T} \ln \frac{b(S_i)}{u(S_i)}$$

Equation 4

The SV2 variable for both signal and background is shown in Figure 13. The jet is tagged as a $b$-jet if $SV2 > 0$. A summary of $b$-tagging veto efficiencies is shown in Table 6. There is a 5% chance of jet candidates in $ZZ$ events being tagged as $b$-jets, but it is a tolerable loss in the signal. We will use anti-$b$-tagging by selecting events with $SV2$ less than 0 which provides a background rejection by a factor of 2 in $Zb\bar{b}$ and $Zb$.

![Figure 13: The weight of the jet ($W_{Jet}$) used for secondary vertex finding.](image-url)
Table 6: $b$ veto efficiencies for signal and background.

<table>
<thead>
<tr>
<th>Process</th>
<th>$b$ veto efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>95±0.1</td>
</tr>
<tr>
<td>Zbb</td>
<td>49±0.3</td>
</tr>
<tr>
<td>Zb</td>
<td>56±0.4</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>20±0.1</td>
</tr>
<tr>
<td>WZ</td>
<td>92±0.2</td>
</tr>
</tbody>
</table>

Unlike an electron which will deposit all its energy in the EM calorimeter, a jet will leave most of its energy in the hadronic calorimeter during showering. However, a fraction of that energy will be deposited in the EM calorimeter, mainly due to the existence of neutral pions ($\pi^0 \rightarrow 2\gamma$) in the jet. Therefore, knowing the fraction of energy deposited in the EM calorimeter can be useful to distinguish between a real electron and a fake one.

The EM fraction (EMF) is defined as the ratio of the sum of energies of the jet deposited in each layer of the EM calorimeter to the total energy of the jet as shown in the following equation.

$$EMF = \frac{\sum_i E_i^{EM-layers}}{\sum_i E_i^{All-layers}} \quad (5)$$

where $\sum_i E_i^{EM-layers}$ are the energies of all constituent cells in the EM layers of the calorimeter and $\sum_i E_i^{All-layers}$ are the energies of all constituents cell in all layers of the calorimeters.

The EMF is shown in Figure 14 for different samples, signal and background in barrel (left) and end cap (right). In the ZZ sample, the partially reconstructed electron (in red) is matched to the truth electron. It is evident that most of these partially reconstructed electrons have deposited more than 80% of their energy in the EM calorimeter. In the case of the background, the bulk of EMF ranges from 20% to 80% with some events with higher EMF. We get a sufficient background rejection and signal efficiency by selecting the partially-reconstructed electrons with an EMF higher than 80% in the Barrel (85% in End-Cap). After the partially-reconstructed electrons have passed the EMF cut, the first-leading jet in the event was taken to be the potential unidentified electron for the ZZ analysis. The EM fraction applied on the jet candidate provided a background rejection factor of 4.

![Figure 14: The EM fraction for signal and background in Barrel (left) and End-Cap (right).](image-url)
7.2 The Topological Cluster

Some of the properties of the shower shape, called moments, may be calculated to classify clusters and to help in particle identification and calorimeter calibration. The cluster moment of degree \( n \) for variable \( x \) is defined as:

\[
< x^n > = \frac{1}{E_{\text{norm}}} \times \sum_i E_i x_i^n, \tag{6}
\]

where \( E_{\text{norm}} = \sum_i E_i \) is the cell energy and \( i \) is the index of the cell in the cluster. The shower axis is needed as a reference for many of these moments. Once the shower axis \( \vec{s} \) and the shower center \( \vec{c} \) are defined, one can calculate two useful quantities. The first one is the distance of the cell \( i \) from the shower axis which can be defined as:

\[
r_i = |(\vec{x}_i - \vec{c}) \times \vec{s}| \tag{7}
\]

The second quantity, \( \lambda_i \), is the distance of the cell \( i \) from the shower center along the shower axis. It is defined as:

\[
\lambda_i = (\vec{x}_i - \vec{c}) \cdot \vec{s} \tag{8}
\]

Two moments and two variables are calculated for each cluster and used them to build the likelihood method.

- **The normalized second longitudinal moment**

  The longitudinal moment is defined as:

  \[
  \text{Longitudinal moment} = \frac{\text{long}_2}{(\text{long}_2 + \text{long}_{\text{max}})} \tag{9}
  \]

  where \( \text{long}_2 \) is the second moment in \( \lambda_i \), i.e. \( \text{long}_2 = < \lambda_i^2 > \), where the two most energetic cells have their \( \lambda_i \) set to 0. Also, another second moment in \( \lambda_i \) was defined, \( \text{long}_{\text{max}} = < \lambda_i^2 > \), with \( \lambda_i = 10 \) cm for the two most energetic cells and \( \lambda_i = 0 \) for all other cells. This moment gives normalized distributions between 0 and 1; 0 means that the shower is shorter, while 1 means the shower is longer. For example, the \( \pi^\pm \) depositions are known to be deep, while the \( \pi^0 \to 2\gamma \) depositions are not. Figure 15 (left) shows the normalized second longitudinal moment in the cases of signal and background.

- **The normalized second lateral moment**

  The lateral moment is defined as:

  \[
  \text{Lateral moment} = \frac{\text{lat}_2}{(\text{lat}_2 + \text{lat}_{\text{max}})} \tag{10}
  \]

  where \( \text{lat}_2 \) is the second moment in \( \lambda_i \), i.e. \( \text{lat}_2 = < \lambda_i^2 > \), where the two most energetic cells have their \( \lambda_i \) set to 0. Also, another second moment in \( \lambda_i \) was defined, where \( \text{lat}_2 \) is the second moment in \( r_i \) for the two most energetic cells at \( r_i = 0 \). This can be expressed as \( \text{lat}_2 = < r_i^2 > \), with \( r_i = 0 \). Similarly, \( \text{lat}_{\text{max}} = < r_i^2 > \), with \( r_i = 4 \) cm for the two most energetic cells and \( r_i = 0 \) for all other cells. Again, this gives normalized distributions between 0 and 1. Thus, the value 1 means wide showers, and 0 means narrow showers. For example, the \( \pi^\pm \) gives broad showers, while \( \pi^0 \to 2\gamma \) results in small concentrated ones. Figure 15 (right) shows the normalized second lateral moment in the cases of signal and background.
• Isolation

The isolation of each cluster is evaluated by the fraction of cells on its outer perimeter that are not included in other clusters. The isolation is calculated for each layer separately due to the variety of granularities. The overall isolation of a cluster is the layer-energy weighted average of the individual isolation ratios. An isolation of 0 means that all cells on its outer perimeter are included in neighboring clusters. A value of 1 means that the cluster is totally isolated. Figure 16 shows the isolation variable for both signal and background.

• Maximum energy fraction

The measurement of the energy fractions deposited in the cells of a segmented calorimeter helps in distinguishing between hadrons and electrons. Figure 16 shows the Maximum energy fraction variable for both signal and background.

Because of the overlap between the signal and background distributions, the use of these variables as a rectilinear cut will not provide optimal signal efficiency and background rejection, see Figure 17. In order to combine information from various variables into a single quantity that provides an optimal discrimination power, we rely on a multivariate technique, the likelihood method. This requires probability distributions for signal and background. The method uses knowledge of the probability of signal and
background to have a parameter \( x \) with specific values and calculates an overall likelihood to the signal. To differentiate between signal-like and fake-like electron candidates, we defined a likelihood discriminant as following:

\[
L(x) = \frac{P_s(x)}{P_s(x) + P_b(x)}
\]  

The multiplication of these variables gives the overall probability for each cluster to be a real electron \( P_s(x) \) or a fake electron \( P_b(x) \).

\[
P_s(x) = \prod_i P_{s,i}(x) = P_{s,\text{Longitudinal}} \times P_{s,\text{Lateral}} \times P_{s,\text{Isolation}} \times P_{s,\text{E_{max}}}
\]

\[
P_b(x) = \prod_i P_{b,i}(x) = P_{b,\text{Longitudinal}} \times P_{b,\text{Lateral}} \times P_{b,\text{Isolation}} \times P_{b,\text{E_{max}}}
\]

The closer \( L(x) \) tends toward 1, the more signal-like the candidate is, the closer \( L(x) \) tends toward 0, the more background-like the candidate is. We used four variables with good discriminating power between real (signal) and fake (background) electrons to build the likelihood. Figure 17 shows the longitudinal moment versus the isolation variable for signal and background. The real electrons populate different areas than the fake ones.

Figure 17: Longitudinal moment versus Isolation in signal events (left). Longitudinal moment versus Isolation in background events (right). The signal and background populate in different areas.

7.2.1 Formulation of Likelihood

There are various steps involved in the formulation of the likelihood function. First, the distributions in Figures 15 and 16 are normalized to a unit area to produce probability distributions for each variable as shown in Figures 18 and 19. These distributions can be used to determine a probability for a given topological cluster to be signal, \( P_s(x) \), or background, \( P_b(x) \), where \( x \) is a vector of the likelihood variable. We used \( Z \rightarrow e^+ e^- \) for the signal probabilities and \( t \bar{t} \rightarrow 4l \) to get the background probabilities as these two processes should be straightforward to isolate in early LHC data. All backgrounds give similar likelihood distribution as shown in in Figure 21. We expect to isolate a high statistics clean \( t \bar{t} \) sample by requiring two leptons in the event, \( E_T \), and tagging a \( b \) jet. In general, one can rely on a system of linear equations obtained by changing a combination of cuts that will result in a clean sample of the desired signature. For example, the requirement of a high DCA and high \( E_T \) on a sample will result in a clean \( t \bar{t} \) sample.

Figure 20 (left) illustrates the likelihood for the partially reconstructed (matched to truth) electrons in \( ZZ \) events and fake electrons from \( Zb\bar{b} \) events with a good separation between them. For a likelihood
Figure 18: The normalized pdf of the second-longitudinal moment in signal and background (left). The normalized pdf of the second-lateral moment in signal and background (right).

Figure 19: The normalized pdf of the isolation variable in signal and background (left). The normalized pdf of the maximum-energy fraction in signal and background (right).
cut of 0.3, we obtain 82% signal efficiency versus 20% background efficiency as a fake rate for each background sample as shown in Figure 20 (right).

![Figure 20: The distributions of likelihood for signal and background (left) and efficiency versus fake rate (right).](image)

The choice of the MC Background sample from which one can get the probability functions for the likelihood is crucial. To avoid any bias, we compared the background shapes and we found that they are similar as shown in Figure 21.

![Figure 21: Background likelihood shapes: they look similar.](image)

The likelihood can be improved by taking into account the fact that the cell sizes in the calorimeters are not uniform. Therefore, the likelihood is strongly $\eta$ dependent. We divided the detector into seven regions in which the size of the cell is similar. In order to optimize the likelihood, we used different probabilities in different $|\eta|$ regions. These results show an increase in the signal efficiency accompanied by a decrease in the fake rate (Table 7). The low fake rate in the background is due to the $|\eta|$ cut at generator level, we estimate the fake rate average to be around 15%.

The topological cluster has somewhat better efficiency, fake rate, and resolution. Using the jet algorithm to partially reconstruct the unidentified electron will result in a higher background as the anti-$b$-tagging will cease to be useful at $|\eta| > 2.5$. Given that the background shapes are similar in the likelihood and
no tracking requirements, we believe that the topological cluster is the most suitable algorithm for our analysis.

Table 7: Signal selection efficiency of the unidentified electron in the ZZ sample and fake rate for two backgrounds ($Zb\bar{b}$ and $WZ$) in different regions of the detector at $L > 0.5$.

<table>
<thead>
<tr>
<th>$\eta$ regions</th>
<th>Signal efficiency (%)</th>
<th>$f_{Zb\bar{b}}$ (%)</th>
<th>$f_{WZ}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 0.7$</td>
<td>85±2.1</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 0.7$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 1$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 1.375$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 1.9$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 2.5$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&gt; 3.2$</td>
<td>89±1.6</td>
</tr>
</tbody>
</table>

8 Final Selection Cuts

We have investigated the possibility of the three lepton analysis, in which we came to the conclusion that finding the unidentified electron is crucial to lower the background. Furthermore, we developed a set of techniques to partially reconstruct the unidentified electron. In this section, we apply these methods for the ZZ searches. In the case of the jet algorithm, we take the first leading jet to be the partially reconstructed electron after passing the $EM$ fraction. In the case of topological cluster, a likelihood method was used for particle identification with four variables. We take the first leading topological cluster to be the partially reconstructed electron after passing the likelihood cut. In this analysis, the reconstructed electron which was not found to form a $Z$ peak with another reconstructed electron is used to form a second $Z$ peak with the unidentified electron that passed the particle identification, with the mass $M_{Z\text{second}}$, as shown in Figure 22 in case of the jet algorithm (left) and topological cluster (right). In the case of the jet algorithm, the $M_{Z\text{second}}$ seems to be higher (mean = 98 GeV) than the nominal mass of the $Z$ boson which is 91.2 GeV. This is due to the size of cone ($\Delta R = 0.4$) of the jet algorithm which is bigger than the size of the shower of an electron. As result, there is a possibility that underlying events can be in that cone.

In addition to the pre-selection cuts described above, we finally use a 2D cut which requires the two $Z$'s in the ZZ decay to be on-shell in the event. This was done by requiring that $M_{Z\text{best}}$ to be between 75 GeV and 100 GeV and $M_{Z\text{second}}$ to be between 85 GeV and 110 GeV simultaneously for the jet algorithm. Figure 23 shows a plot of $M_{Z\text{best}}$ versus $M_{Z\text{second}}$ in the case of the jet algorithm. In the case of the topological cluster, we required that $M_{Z\text{best}}$ and $M_{Z\text{second}}$ should be between 80 GeV to 100 GeV simultaneously. A summary of the final selection cuts is provided in Table 8.
Figure 22: $M_{Z_{\text{second}}}$ found via the jet algorithm (left) and via the topological cluster (right) for signal and main background.

Figure 23: $M_{Z_{\text{best}}}$ versus $M_{Z_{\text{second}}}$ for signal and main background in case of the jet algorithm (left). In case of the topological clusters if likelihood is higher than 0.3 (right).

Table 8: Final selection cuts

<table>
<thead>
<tr>
<th>Cut</th>
<th>Jet Algorithm</th>
<th>Topological cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti b-tagging</td>
<td>$&lt; 0$</td>
<td>N/A</td>
</tr>
<tr>
<td>EMF (barrel,end-cap)</td>
<td>$&gt; 0.8$, $&gt; 0.85$</td>
<td>N/A</td>
</tr>
<tr>
<td>first leading jet candidate</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Likelihood</td>
<td>N/A</td>
<td>$&gt; 0.5$</td>
</tr>
<tr>
<td>$M_{Z_{\text{best}}}$</td>
<td>75 – 100 GeV</td>
<td>80 – 100 GeV</td>
</tr>
<tr>
<td>$M_{Z_{\text{second}}}$</td>
<td>85 – 110 GeV</td>
<td>80 – 100 GeV</td>
</tr>
</tbody>
</table>
9 Results

After the selection criteria described above, the background was reduced significantly in both channels, (3$\mu$ + cluster and 2$\mu$1$e$ + cluster), that we considered. We summarize the event selection efficiency as well as the expected number of events for 1 fb$^{-1}$ for both signal and background in Tables 9-12. All the errors are statistical. The two algorithms used in finding the unidentified electron showed fairly similar performances. The $t\bar{t}$ background becomes very negligible after cuts because of the $E_T$. The WZ becomes very low despite its similarity with the signal signature, but the transverse missing energy cut as well the requirement of having two $Z$ peaks in the event are very efficient in reducing its effect. The $Zb\bar{b}$ and $Zb$ channels are the main backgrounds in this analysis and their cross sections are quite large compared to the signal cross section. Thus, despite the good rejection power of our cuts we still see major contributions to the final background from these two samples due to their high cross section.

The topological cluster has somewhat better efficiency, fake rate, and resolution. Using the jet algorithm to partially reconstruct the unidentified electron will result in a higher background as the anti-$b$-tagging will cease to be useful at $|\eta| > 2.5$ and large systematic uncertainties associated with it. Given that the background shapes are similar in the likelihood and there are no tracking requirements, We believe that the topological cluster is the most general and stable algorithm for our analysis.

Table 9: Results for the 2$\mu$1$e$ + partially reconstructed electron channel using the jet algorithm.

<table>
<thead>
<tr>
<th>Channel 2$\mu$1$e$ + X</th>
<th>ZZ</th>
<th>Zb$\bar{b}$</th>
<th>Zb</th>
<th>WZ</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection efficiency %</td>
<td>4±0.13</td>
<td>(1±1)×10$^{-3}$</td>
<td>(2.5±2.5)×10$^{-3}$</td>
<td>(6±6)×10$^{-3}$</td>
<td>(2.5±2.5)×10$^{-4}$</td>
</tr>
<tr>
<td>Number of events</td>
<td>2.67±0.1</td>
<td>0.1±0.1</td>
<td>0.3±0.3</td>
<td>0.04±0.04</td>
<td>(1.5±1.5)×10$^{-3}$</td>
</tr>
</tbody>
</table>

Table 10: Results for the 3$e$ + partially reconstructed electron channel using the jet algorithm.

<table>
<thead>
<tr>
<th>Channel 3$e$+X</th>
<th>ZZ</th>
<th>Zb$\bar{b}$</th>
<th>Zb</th>
<th>WZ</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection efficiency %</td>
<td>2.5±0.11</td>
<td>(3±3)×10$^{-3}$</td>
<td>(2.5±2.5)×10$^{-3}$</td>
<td>(2±1)×10$^{-2}$</td>
<td>(2.5±2.5)×10$^{-4}$</td>
</tr>
<tr>
<td>Number of events</td>
<td>1.67±0.07</td>
<td>0.3±0.3</td>
<td>0.3±0.3</td>
<td>0.1±0.08</td>
<td>(1.5±1.5)×10$^{-3}$</td>
</tr>
</tbody>
</table>

10 Systematics

The quantities associated with the signal efficiencies and background estimation are sensitive to systematic mis-estimation for different reasons. The uncertainties that can affect the number of observed events can be grouped into two categories, theoretical and experimental.

We do not estimate the systematical uncertainties on the secondary vertex variable SV2 as well as on the EM fraction used with the jet algorithm. This is due to the fact that we used the jet algorithm as a test of an algorithm with higher $\eta$ coverage. Thus, we do not use the jet algorithm in ultimately evaluating the significance in the section to follow.
Table 11: Results for the $2\mu 1e+$ partially reconstructed electron channel using the topological cluster.

<table>
<thead>
<tr>
<th>Channel $2\mu 1e+X$</th>
<th>ZZ</th>
<th>Zbb</th>
<th>Zb</th>
<th>WZ</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection efficiency %</td>
<td>4.3±0.13</td>
<td>(1±1)×10^{-3}</td>
<td>(2±2)×10^{-3}</td>
<td>(6±6)×10^{-3}</td>
<td>(2.5±2.5)×10^{-4}</td>
</tr>
<tr>
<td>Number of events</td>
<td>2.87±0.1</td>
<td>0.1±0.1</td>
<td>0.3±0.3</td>
<td>0.04±0.04</td>
<td>(1.5±1.5)×10^{-3}</td>
</tr>
</tbody>
</table>

Table 12: Results for the $3e+$ partially reconstructed electron channel using the topological cluster.

<table>
<thead>
<tr>
<th>Channel $3e+X$</th>
<th>ZZ</th>
<th>Zbb</th>
<th>Zb</th>
<th>WZ</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection efficiency %</td>
<td>2.7±0.11</td>
<td>(3±3)×10^{-3}</td>
<td>(2.5±2.5)×10^{-3}</td>
<td>(2±1)×10^{-2}</td>
<td>(2.5±2.5)×10^{-4}</td>
</tr>
<tr>
<td>Number of events</td>
<td>1.81±0.07</td>
<td>0.3±0.3</td>
<td>0.3±0.3</td>
<td>0.1±0.08</td>
<td>(1.5±1.5)×10^{-3}</td>
</tr>
</tbody>
</table>

10.1 Theoretical Uncertainties

The main theoretical uncertainties on the production cross sections arise from the PDF uncertainties and the QCD factorization scale uncertainties for NLO calculations. The variation of the PDF's in calculating the cross section of $Z$ pair production is of the order of 4% [12]; the cross section varies from 14.74 pb in CTEQ6M to 15.32 pb in MRST03.

10.2 Experimental Uncertainties

The experimental systematic effects on the $ZZ \rightarrow 4l$ analysis arise from the uncertainties of the luminosity determination, lepton energy scale, and lepton energy resolution. The material distributions in ATLAS affect the lepton energy reconstruction.

1. Luminosity
   Precise determination of the luminosity can be achieved by using the W and Z production in their leptonic decays. Thus, the luminosity uncertainties may be controlled to 5% [17].

2. Lepton Energy Scale
   Uncertainties of the energy scale of electrons arise from the EM calibration. In order to estimate the impact of this contribution on our analysis, we varied $E_T$ of the reconstructed electrons by ±1%. The impact of the energy scale on our analysis is shown for signal and the main backgrounds in Table 13. Our cuts are sensitive to the energy scale by ±2.9% for the signal and ±4.7% for the background.

3. Lepton Energy Resolution
   To account for the electron energy resolution, I smeared the reconstructed electron energies using a Gaussian distribution. I used the smearing function defined as:
   \[ \Delta E_T = 0.1 \times E_T \]  \hspace{1cm} (14)
   From the performance studies [4], I choose the smearing to be around 10% of the lepton $E_T$ with a Gaussian distribution. Thus the new $E_T$ of the variable will read:
   \[ E_T^{\text{new}} = E_T \left( 1 + \Delta E_T \right) \]  \hspace{1cm} (15)
The effect of the smearing of the electron energies on our cuts is shown in Table 8.6. As a conclusion, our cuts are not sensitive to the energy resolution of the electrons. They cause a 2% downward shift on our cuts.

4. **Material Effects in Electron Efficiency**
The uncertainties in the knowledge of material in the LAr results in uncertainties in electron efficiency. These systematic effects have a direct effect on the shower-shape discriminants [4] which are part of the electron identification criteria. The mean energy fraction in a core of $3 \times 7$ sampling cells normalized to a window of $7 \times 7$ cells is an example of these discriminants. As a result the discriminant power of these cuts is reduced. These effects are found to be rather small, on the order of 2% [4].

5. **Lepton Acceptance**
The lepton acceptance uncertainty is estimated to be about 2-3%. This is due to the isolation requirement which involves the hadronic jet energy uncertainties as well as the lepton trigger efficiency uncertainties [12].

6. **Pileup Effects**
The pileup reduces the trigger efficiency, the calorimeter and the tracker isolation cut efficiencies. The effect of pileup on our cuts is estimated to be a 10% decrease in signal selection efficiency [13].

7. **Transverse Missing Energy**
The uncertainty on the $E_T$ was estimated to be 8% [16]. The $E_T$ in signal events is instrumental with a distribution that mainly peaks at 10 GeV. Thus, any fluctuation in $E_T$ measurement is not expected to dramatically affect our cut on $E_T$.

8. **Impact parameter significance**
At the instantaneous luminosity assumed for this analysis, the uncertainty on the impact parameter is estimated to be 10% [16].

9. **Likelihood Method**
In the central region, the rate by which a jet fakes an electron is around 20% per background. We evaluate the RMS of the fake rate of all backgrounds and it is found to be 19%. We estimate the uncertainty on the likelihood method to be 7%.

Table 13: Impact, in %, of the systematic uncertainties on the overall selection efficiencies as obtained for $ZZ \rightarrow 3e + \text{“e”}$ and $Zb\bar{b} \rightarrow 3e + \text{“e”}$ in the case of topological cluster.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\epsilon_{ZZ} %$</th>
<th>$\epsilon_{Zb\bar{b}} %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale (1%)</td>
<td>$\pm 2.9%$</td>
<td>$\pm 4.7%$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$-2.2%$</td>
<td>$-2.1%$</td>
</tr>
</tbody>
</table>
11 Sensitivity

Although the significance $\frac{S}{\sqrt{S+B}}$, where $S$ and $B$ are the expected yields of signal and background events respectively, is correlated to the number of observed events in a real experiment, it does not completely represent the true sensitivity of a real experiment. This is because some systematics effects can not be modeled and statistics for signal and backgrounds are quite low and they are Poisson distributed rather than Gaussian distributed. This is done for the topological selection.

11.1 Statistical Sensitivity

In order to account for the statistical fluctuation, we ran many pseudo-experiments known as ensembles. The estimates of the number of events for the signal and background ensembles were calculated based on random numbers with a Poisson distribution. The mean of the Poisson distribution should be equal to the number of expected events after selection cuts as shown in Tables 11 and 12. We defined the significance $\rho$ as following:

$$\rho = \frac{N_{ZZ} + N_{Zb} + N_{WZ} + N_{Zh} - \langle N_{BG} \rangle}{\sqrt{N_{ZZ} + N_{Zb} + N_{WZ} + N_{Zh}}}. \quad (16)$$

The term $\langle N_{BG} \rangle$ is the average number of events for all background channels for each ensemble. The significance $\rho$ was calculated for many luminosity points ranging from $50 \text{ pb}^{-1}$ to $2 \text{ fb}^{-1}$ after testing 1000 ensembles for each point.

It is important to get an estimate of the statistical sensitivity over a range of integrated luminosities. For that purpose, we ran a statistical analysis for 40 different integrated luminosity points with 1000 ensembles at each point. The integrated luminosity ranges from 0 to 7 $\text{ fb}^{-1}$ with increments of 50 $\text{ pb}^{-1}$. At each integrated luminosity point, the significance is evaluated over 1000 ensembles and it takes the value of the mean. The expected number of events is scaled from 1 $\text{ fb}^{-1}$. Figure 24 shows the significance versus integrated luminosity where the curve is fitted. Based on the parameters of the fit, the significance dependence on the integrated luminosity ($L$) can be expressed by Eq. 17. The discovery of $ZZ$ in an exclusive three lepton channel +“e” reaches the discovery limit of $\rho = 5$ at an integrated luminosity of 6.1 $\text{ fb}^{-1}$.

$$\rho = (2.08 \pm 0.08) \sqrt{L} - (0.18 \pm 0.15) \quad (17)$$

11.2 Impact of Systematic Uncertainties

The uncertainties in the energy scale of the electrons have an impact on the significance as described in the previous section. The number of signal and backgrounds events after cuts with statistical and systematic errors are shown in Table 14.

Taking into consideration the systematics and statistical uncertainties in the three lepton +“e” channel and the fully reconstructed four lepton channel, the significance is:

$$\sigma = \frac{S}{\sqrt{S+B}} = 4.09 \pm 0.04 \quad (18)$$
Figure 24: Significance, $\rho$, versus luminosity varying from 0 to 7 fb$^{-1}$. The data are fitted by the function $p_1 \sqrt{L} + p_0$. The data points are shown with error bars.

Table 14: Number of signal and backgrounds events from $3e +$ cluster and $2\mu 1e +$ cluster channels after all cuts, with statistical and systematic errors.

<table>
<thead>
<tr>
<th>process</th>
<th>$N_{events}$</th>
<th>$\sigma_{statistical}$</th>
<th>$\sigma_{systematics}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>4.87</td>
<td>0.12</td>
<td>+0.07/-0.3</td>
</tr>
<tr>
<td>Zbb</td>
<td>0.4</td>
<td>0.3</td>
<td>+0/-0.02</td>
</tr>
<tr>
<td>Zb</td>
<td>0.6</td>
<td>0.4</td>
<td>+0/-0.03</td>
</tr>
<tr>
<td>WZ</td>
<td>0.14</td>
<td>0.09</td>
<td>+0.002/-0.008</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.0015</td>
<td>0.002</td>
<td>+0/-0</td>
</tr>
<tr>
<td>Total BG</td>
<td>1.1</td>
<td>0.5</td>
<td>+0.002/-0.03</td>
</tr>
</tbody>
</table>
12 The Impact of the Center of Mass Energy on the Analysis

Given the fact that the LHC will not run at its designed center of mass energy (CME) in early runs, we give an estimate of the impact of the CME on this analysis. We ran on samples produced at a CME of 10 TeV and found that the efficiencies are similar to those at 14 TeV. Thus, we expect that the efficiencies will remain the same for the 7 TeV run. However, the cross sections change with a given CME; for 10 TeV, the reduction on the backgrounds cross sections are expected to be around 50% while the signal cross section drops by only 40% (66.8 fb to 40.61 fb). At low CME, the backgrounds cross section become relatively smaller and that benefits the significance for a given signal yield with CME at a given luminosity. Moreover, the need for the 3 lepton analysis +“e” to improve the significance when combined with the 4 fully reconstructed lepton becomes crucial to reach the 5 $\sigma$.

13 Summary and Conclusion

An exclusive $ZZ \rightarrow 3l$ analysis has been conducted using a Monte Carlo data sample for a $pp$ collision at a center of mass energy of 14 TeV. An overall estimated signal-over-background of 5 was reached for an integrated luminosity of 1 fb$^{-1}$ for both algorithms. A search in the four-lepton channel resulted in 13 signal events and 0.2 background events [12] for an integrated luminosity of 1 fb$^{-1}$ as compared to 5 signal events and 1 background events in the three-lepton channel search we conducted. Therefore, a 36% gain in acceptance can be achieved by considering the three-lepton channel. In terms of significance $\frac{S}{\sqrt{S+B}}$, the three-lepton channel when combined with the four-lepton channel increases from 3.6 to 4.09±0.04. The search was done by considering ZZ events where only three leptons were fully reconstructed, 3$e$ or 2$\mu$1$e$, and one electron does not get reconstructed. We used the topological cluster algorithm to recover the missing electron either in the forward region ($|\eta| > 2.5$) which was not covered in the standard electron identification algorithm used in ATLAS or in the central region where the electron has failed one of the criteria required by the standard electron algorithm. Recovering the missing electron was necessary to suppress the overwhelming background in the three lepton-channel. The possible backgrounds in the three-lepton channel are due to $Zb\bar{b}$, $Zb\bar{t}$, $tt$, and $WZ$ processes.

14 Acknowledgements

We would like to thank Ryszard Strynowski for his original idea for a three lepton analysis in Higgs search. We would like also to thank P. Renkel, H. Hadavand, D. Joffe, J. Hoffman, M. Aharrouche, and H. Ma for many fruitful discussions.

References


