The top and beyond: missing energy and little Higgs in ATLAS
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5

Top Quark Pair Selection

At proton collisions of 10 TeV center of mass energy and initial luminosity of $L = 10^{31}$ cm$^{-2}$s$^{-1}$, hundreds of top quark pairs will be created in the ATLAS detector per day. The abundance together with the complexity of the final state make top quark pair events an excellent benchmark on the road to searches for physics beyond the Standard Model. This chapter describes the strategy to select these events. The procedure is illustrated by means of the samples of simulated events as introduced in Section 3.3.1. The characteristics of top quark pair events are discussed in Section 5.1, Section 5.2 describes each step in the selection process, Section 5.3 shows the distributions of the relevant kinematic variables and Section 5.4 contains the resulting selection efficiencies for signal as well as background samples.

5.1 Semileptonic Decays

As described in Section 3.3.1, the branching ratio of semileptonic $t\bar{t}$ decays is 43.8%. Due to the presence of the charged lepton and the neutrino, semileptonic decays render a distinct signature in the ATLAS detector which makes them suitable to fire triggers and to be distinguished from other events by requiring certain properties of the final state. They are favoured over dileptonic decays when studying missing transverse energy (cf. Chapter 6) as the presence of an additional neutrino in the latter type of events prevents the association between the missing transverse energy and the $p_T$ of the neutrino.

Each of the three lepton flavours is equally represented, yet taus are difficult to identify and reconstruct. Moreover, they often render additional neutrinos in the final state, which complicate the kinematics. Therefore only the muon and the electron channel of the $W$ boson decay are pursued here. In order to efficiently select these 29% of all $t\bar{t}$ decays and to reject background events, a set of selection criteria is applied. First, the characteristics of semileptonic $t\bar{t}$ events are outlined.

The final state of semileptonic $t\bar{t}$ decays contain a high multiplicity and variety of reconstructed objects. This specific signature contributes to the possibility to distinguish them from other processes that occur in proton-proton collisions. The main characteristics of semileptonic $t\bar{t}$ events are the presence of a single charged high-$p_T$ isolated lepton, large
$E_T$ due to the corresponding neutrino that escapes detection and at least four jets, two of which originate from $b$ quarks. The kinematic variables on which the event selection criteria are based are shown here for semileptonic $t\bar{t}$ events. The distributions correspond to an integrated luminosity of 200 pb$^{-1}$ and the $W$ boson decays either through the electron or through the muon channel. None of the event selection criteria are applied yet.

Figure 5.1(a) shows the normalized $\eta$ distribution of the electron or muon from the leptonically decaying top quark. The majority of the leptons is produced quite centrally due to the large transverse momentum of the top quark. The $\eta$ distributions of the reconstructed electron and muon are shown here as well and reflect the limited inner detector coverage in the very forward region, the gap in the muon spectrometer at $\eta \approx 0$ and the barrel/endcap transition region in the calorimeters. For the reconstructed electron or muon with the highest $p_T$, the corresponding $p_T$ distribution is displayed in Figure 5.1(b). The normalized distribution for $E_T$ in semileptonic $t\bar{t}$ events is shown here as well.

Figure 5.1(c) displays the number of reconstructed jets satisfying $p_T > 20$ GeV. Figure 5.1(d) shows the $p_T$ distributions of the four highest $p_T$ jets. These characteristics can now be used to select semileptonic $t\bar{t}$ events.

### 5.2 Event Selection

The aim is to obtain a sample of events that is rich in semileptonic $t\bar{t}$ events and simultaneously contains a limited number of background events. As described in Section 3.3, the predominant backgrounds are $W$ production with associated jets, multi-jet events and single top production. The cross sections of the first two are much larger than that of the signal, yet fortunately the experimental signature is only similar in a fraction of the events and the following selection criteria reduce their contribution significantly.

- **The trigger requirement:** The event passed the trigger chain `e20_loose` in case of the electron selection channel and `mu10` in case of the muon selection channel (cf. Section 4.1);

- **The lepton requirement:** The presence of exactly one well reconstructed muon or electron satisfying $p_T > 20$ GeV and $|\eta| < 2.5$ is required. To guarantee the quality of the reconstruction, additional requirements are introduced in Section 5.2.2;

- **The missing transverse energy requirement:** $E_T > 20$ GeV;

- **The jets requirement:** At least four jets are reconstructed with $p_T > 20$ GeV and $|\eta| < 2.5$, three of which satisfy $p_T > 40$ GeV.

Sections 5.2.1 through 5.2.4 describe each of the selection criteria in detail and contain the expected distributions for signal and background events. The event samples and applied filters are described in Section 5.2 and the corresponding cross sections are listed in Table 3.1. The studies performed here are all based on Monte Carlo simulations corresponding to collisions of 10 TeV center of mass energy.
5.2 Event Selection

(a) The normalized $\eta$ distribution of the electron or muon from the leptonically decaying top quark (MC) as well as the normalized $\eta$ distributions of the reconstructed electron and the reconstructed muon that satisfy the requirements of Section 5.2.2.

(b) The normalized distribution of the $p_T$ of the reconstructed electron or muon and the normalized distribution of the missing transverse energy.

(c) The number of jets with $p_T > 20$ GeV (full) and with $p_T > 40$ GeV (dashed) per semileptonic $t\bar{t}$ decay.

(d) The $p_T$ distributions of the leading four jets in semileptonic $t\bar{t}$ events.

Figure 5.1: Characteristics of simulated semileptonic $t\bar{t}$ events. No selection criteria are applied yet.
5.2.1 The Trigger Requirement

The lepton trigger requirement is essential to reject the enormous number of multi-jet events that are produced in collisions and to allow for a pre-selection with high efficiency. The subsequent selection criteria are indispensable for the purity of the sample, yet without a suitable trigger, signal events would be lost either because of the trigger requirement or because of an inevitable prescale. Figure 5.2(a) shows the $p_T$ distribution of the highest-$p_T$ reconstructed electron in each event and illustrates that this provides a strong handle on the rejection of multi-jet events. The impact of the trigger requirement $e_{20\text{loose}}$ on this distribution is shown in Figure 5.2(b). The structure in the distribution at low values of $p_T$ in Figure 5.2(b) is explained as follows: An electron candidate may be accepted by the $e_{20\text{loose}}$ trigger algorithm albeit not reconstructed by the more stringent medium electron algorithm afterwards. The latter algorithm may however find another medium electron at lower $p_T$ in the event.

![Graph](a) The cumulative $p_T$ distributions of the highest-$p_T$ reconstructed electron in each event.

![Graph](b) The cumulative $p_T$ distributions of the highest-$p_T$ reconstructed electron in each event that passes the trigger chain $e_{20\text{loose}}$.

Figure 5.2: The impact of the electron trigger requirement on the number of events in 200 pb$^{-1}$.

5.2.2 The Lepton Requirement

Multi-jet events will generally not contain an isolated charged lepton in their final state and muons from jet fragmentation will usually not reach the muon spectrometer. In multi-jet events that do pass the lepton requirement, a jet is mis-identified as an electron or muon. Often, these mis-identifications are accompanied by hadronic activity, which is quantified by means of the $E_{T\text{cone20}}$ variable, i.e. the $E_T$ in a cone of radius $\Delta R = 0.2$ centered around the lepton, excluding the $E_T$ of the reconstructed lepton itself. Figure 5.3(a) shows the distributions of $E_{T\text{cone20}}$ for the reconstructed medium electrons that satisfy $p_T > 20$ GeV.
and $|\eta| < 2.5$ in multi-jet events compared to those in $t\bar{t}$ events which are matched to the electron from the leptonically decaying top quark with $\Delta R < 0.05$. Figure 5.3(b) shows the distribution of $E_{T}^{\text{cone}20}$ for the reconstructed combined muons that satisfy $p_T > 20$ GeV and $|\eta| < 2.5$ in multi-jet events compared to those in $t\bar{t}$ events, which are matched to the muon from the leptonically decaying top quark with $\Delta R < 0.05$. The falsely identified leptons are generally associated to jets and therefore less isolated.

![Graph](image1.png)

(a) Medium electrons with $p_T > 20$ GeV and $|\eta| < 2.5$.

![Graph](image2.png)

(b) Combined muons with $p_T > 20$ GeV and $|\eta| < 2.5$.

Figure 5.3: The isolation of charged leptons, $E_{T}^{\text{cone}20}$, in multi-jet events (dashed) compared to semileptonic $t\bar{t}$ events (full). The vertical lines indicate the selection requirement $E_{T}^{\text{cone}20} < 6$ GeV and the distributions are normalized to unity.

The number of falsely identified electrons and muons is reduced by demanding the following additional qualities:

**Electrons**

- The electron is classified as medium according to the egamma algorithm (cf. Section 4.4);
- The medium electron satisfies $p_T > 20$ GeV;
- The electron is required to be isolated, i.e. $E_{T}^{\text{cone}20} < 6$ GeV;
- $|\eta| \notin [1.35, 1.57]$ to avoid electrons in the transition regions between the barrel and endcaps of the electromagnetic calorimeter for which the energy measurement is less reliable (cf. Figure 4.7). Simultaneously, the enhanced contribution from fake electrons in this region is eliminated.
Muons

- The muons considered here are combined muons as reconstructed by the Staco algorithm (cf. Section 4.5);
- The combined muon satisfies $p_T > 20$ GeV;
- The muon is required to be isolated, i.e. $E_{\text{cone}20}^\mu < 6$ GeV.

The rate at which these high quality electrons or muons are falsely reconstructed in multi-jet events is expected to be about $5 \cdot 10^{-4}$ per jet [63], yet the large uncertainty on the cross section of multi-jet events complicates the prediction on the number of events that enter the data sample.

The effect of the lepton requirement on the contribution of background events is illustrated by Figure 5.4(a) which shows the transverse momentum of the highest-$p_T$ muon in events that passed the mu10 trigger chain. Recall that the sample of multi-jet events is generated such that they already passed the top mu filter (cf. Section 3.3). Nevertheless, before the lepton requirement is applied, their contribution is enormous and a multiplication by $10^{-3}$ is applied to the multi-jet distribution in Figure 5.4(a) for the other distributions to be visible. The requirement that a muon or electron be reconstructed, which satisfies the restrictions described here as well as $p_T > 20$ GeV, contributes strongly to the reduction of multi-jet events in addition to the impact of the trigger requirement.

![Figure 5.4](image-url)

(a) Distribution of the $p_T$ of the highest-$p_T$ muon. (b) Distribution of $E_T$. 

Figure 5.4: Cumulative distributions of the $p_T$ of the muon and of the $E_T$ for events that pass the trigger chain mu10. The number of events corresponds to 200 pb$^{-1}$, except for the contribution of multi-jet events, which has been multiplied by $10^{-3}$ for cosmetic reasons.
5.3 Kinematic Distributions

5.2.3 The Missing Transverse Energy Requirement

The $E_T$ criterion is applied to the refined missing transverse energy as defined in (4.9). Multi-jet events hardly contain any real missing transverse energy as there are no high-$p_T$ neutrinos present in their decays. Leptonic decays of $B$ hadrons in jets actually are accompanied by neutrinos, yet their momenta are generally low. Unfortunately, the mis-identification of jets as leptons, which allows some events to pass the lepton requirement, often results in a mis-reconstruction of the missing transverse energy. Moreover, detector and reconstruction imperfections generally add to nonzero values of $E_T$, which may exceed the 20 GeV requirement.

The distribution of $E_T$ is shown in Figure 5.4(b). The selection requirement, $E_T > 20$ GeV, mainly impacts the contribution of multi-jet events, which is scaled by $10^{-3}$ in the figure. The $W +$ jets background events do contain actual missing transverse energy when the $W$ boson decays leptonically, as do the leptonic single top events.

5.2.4 The Jets Requirement

Jets are reconstructed using the Cone4H1TopoJets algorithm (cf. Section 4.2), i.e. their constituents are H1 calibrated TopoClusters and their cone size is $R_{cone} = 0.4$. Due to their energy deposit in the calorimeter, electrons generally classify as jet candidates as well. Therefore, jets within $\Delta R < 0.2$ from reconstructed electrons that satisfy the requirements of Section 5.2.2 are not taken into account.

In semileptonic $t\bar{t}$ events, four jets are naively expected to enter the detector, two resulting from the $b$ quarks and another two from the quarks from the hadronically decaying $W$ boson. However, initial state radiation (ISR) and final state radiation (FSR) often result in additional jets. At the same time, not all jets are identified as such and the number of expected reconstructed jets actually varies between zero and ten, as shown in Figure 5.1(c). Nevertheless, in order to reject background events, at least four reconstructed jets with $p_T > 20$ GeV are required in the event selection. The distributions of the number of jets per event are shown in Figure 5.5(a). The requirement that this number exceeds three severely reduces the contribution of multi-jet events and $W +$ jets events. The $p_T$ distribution of the hardest jet is shown in Figure 5.5(b). Again, the multi-jet contribution is scaled by a factor $10^{-3}$ in the figures.

5.3 Kinematic Distributions

In this section, the final impact of each of the event selection criteria on the signal to background ratio is illustrated. The Monte Carlo samples and the corresponding cross sections are listed in Table 3.1. The distributions correspond to 200 pb$^{-1}$ integrated luminosity and contain the events that pass all event selection criteria except for the one of interest. The electron selection channel and muon selection channel selection are treated separately in Figures 5.6 and 5.7 respectively. The selection criterion that is applied to the displayed variable is indicated by a dashed line in each histogram.

Figures 5.6(a) and 5.7(a) show the $p_T$ distributions of the highest-$p_T$ electron and muon in events that pass the trigger, the $E_T$ and the jets requirements. The reconstructed electron
or muon satisfies the criteria of Section 5.2.2. The distributions clearly display the impact of the trigger requirement and in case of the muon channel, the effect of the top\_mu filter on the multi-jet contribution is visible. The $E_T$ distributions for events that pass the trigger, the lepton and the requirements are displayed in Figures 5.6(b) and 5.7(b). The selection of events that satisfy $E_T > 20$ GeV severely reduces the contribution of multi-jet events.

Figures 5.6(c) and 5.7(c) contain the number of reconstructed jets satisfying $p_T > 40$ GeV for events that pass the trigger, the lepton and the $E_T$ criteria and in which at least four jets are reconstructed with $p_T > 20$ GeV. This number is required to be at least three. Finally, Figures 5.6(d) and 5.7(d) show the $p_T$ distribution of the fourth highest-$p_T$ jet in events that pass the trigger, the lepton and the $E_T$ requirement and in which at least three jets satisfy $p_T > 40$ GeV. In case of the electron channel, the multi-jet contribution displays a structure which can be explained by the top\_jet filter. According to the jet selection criterion, the $p_T$ of the fourth jet needs to be larger than 20 GeV for an event to be selected.

As a result, all selected events contain at least four jets, which together with the electron or muon and the missing transverse energy allow for the reconstruction of the top quarks. The combination of all four selection criteria results in a good suppression of background events, which is quantified in the next section.
5.3 Kinematic Distributions

Figure 5.6: Cumulative kinematic distributions for signal and background events that pass all electron channel selection criteria except for the one of interest in 200 pb$^{-1}$. The vertical lines indicate the selection requirement corresponding to each variable.
Top Quark Pair Selection

(a) The $p_T$ distribution of the muon that satisfies the requirements of Section 5.2.2.

(b) The $E_T$ distribution.

(c) The number of reconstructed jets with $p_T > 40$ GeV.

(d) The $p_T$ distribution of the fourth highest-$p_T$ jet.

Figure 5.7: Cumulative kinematic distributions for signal and background events that pass all muon channel selection criteria except for the one of interest in 200 pb$^{-1}$. The vertical lines indicate the selection requirement corresponding to each variable.
5.4 Selection Efficiencies

Table 5.1 shows the fraction of events that pass each of the requirements in Section 5.2 for the samples of \( t\bar{t} \), \( W + \) jets, single top and multi-jet events. The impact of the combination of all four requirements on each sample is shown in the last column and the strategy proves effective in rejecting the background contributions. The large difference in efficiency between the electron and muon channel requirements in the multi-jet samples is not physical and simply due to the filters applied at event generation level (cf. Section 3.3). As a consequence of the top\_mu filter, the trigger and lepton requirement efficiencies are severely biased in case of the muon channel.

The resulting composition of selected events in 200 pb\(^{-1}\) is given in table 5.2 for the electron and muon channel separately. The purity of the sample of selected events is thus expected to be 51 % for the electron channel and 50 % for the muon channel. Chapter 6 will make use of this sample of events to study the performance of the missing transverse energy reconstruction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trigger</th>
<th>Lepton</th>
<th>( E_T )</th>
<th>Jets</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t}(e) )</td>
<td>72 (7.8) %</td>
<td>56 (0.2) %</td>
<td>90 %</td>
<td>52 %</td>
<td>22.0 (0.05) %</td>
</tr>
<tr>
<td>( t\bar{t}(\mu) )</td>
<td>2.3 (74) %</td>
<td>0.2 (71) %</td>
<td>91 %</td>
<td>46 %</td>
<td>0.05 (25.6) %</td>
</tr>
<tr>
<td>( t\bar{t}(\tau) )</td>
<td>8.4 (15) %</td>
<td>4.0 (5.1) %</td>
<td>92 %</td>
<td>55 %</td>
<td>1.67 (1.86) %</td>
</tr>
<tr>
<td>dileptonic ( t\bar{t} )</td>
<td>46 (50) %</td>
<td>22 (27) %</td>
<td>94 %</td>
<td>19 %</td>
<td>3.32 (4.07) %</td>
</tr>
<tr>
<td>( W + ) jets</td>
<td>39 (12) %</td>
<td>28 (10) %</td>
<td>85 %</td>
<td>12 %</td>
<td>1.05 (1.31) %</td>
</tr>
<tr>
<td>single top</td>
<td>33 (36) %</td>
<td>24 (31) %</td>
<td>91 %</td>
<td>10 %</td>
<td>1.23 (1.44) %</td>
</tr>
<tr>
<td>multi-jet</td>
<td>1.4 (49) %</td>
<td>6.7·10(^{-2}) (2.2) %</td>
<td>16 (16) %</td>
<td>17 (8.8) %</td>
<td>5.7 (40) ·10(^{-4}) %</td>
</tr>
</tbody>
</table>

Table 5.2: The expected composition of selected events in 200 pb\(^{-1}\). The statistical uncertainties are determined by the size of the Monte Carlo samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>semileptonic ( t\bar{t}(e) )</td>
<td>2547±23</td>
<td>6±1</td>
</tr>
<tr>
<td>semileptonic ( t\bar{t}(\mu) )</td>
<td>6±1</td>
<td>2977±26</td>
</tr>
<tr>
<td>semileptonic ( t\bar{t}(\tau) )</td>
<td>193±6</td>
<td>214±7</td>
</tr>
<tr>
<td>dileptonic ( t\bar{t} )</td>
<td>288±8</td>
<td>344±9</td>
</tr>
<tr>
<td>( W + ) jets</td>
<td>1509±20</td>
<td>1885±27</td>
</tr>
<tr>
<td>single top</td>
<td>98±10</td>
<td>90±10</td>
</tr>
<tr>
<td>multi-jet</td>
<td>743±133</td>
<td>929±148</td>
</tr>
</tbody>
</table>

Table 5.1: Selection efficiencies of each requirement for the electron (muon) channel.