Radiating top quarks

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In hadronic collisions, the production of a $W^\pm$ boson in conjunction with jets, $W + \text{jets}$, is very similar to the production of a $Z$ boson with additional jets, $Z + \text{jets}$. The amount of $W + \text{jets}$ events can therefore be predicted from collision data by counting the number of $Z + \text{jets}$ events, and using the ratio of the $W^\pm$ and $Z$ boson production cross sections determined from Monte Carlo simulation. These cross sections and their ratio are subject to uncertainties due to the modelling of the $W + \text{jets}$ and $Z + \text{jets}$ processes in the event generator. In this chapter a comparison is made of the predictions for $W + \text{jets}$ and $Z + \text{jets}$ production in $pp$ collisions at a centre-of-mass energy $\sqrt{s}$ of 10 TeV in ATLAS between Alpgen, Ariadne, and Pythia. The comparison is eventually used to evaluate the systematic uncertainty on the $W + \text{jets}$ background estimate for a $t\bar{t}$ cross section measurement. Since this study is done for a centre-of-mass energy of 10 TeV (the energy expected at the time of this study), the results in this chapter can not be compared with the results from previous chapters.

### 7.1 Comparison

Alpgen [96] is the default generator in ATLAS used for $W + \text{jets}$ and $Z + \text{jets}$ studies. Alpgen combines matrix element predictions for the hard scattering with the parton showering of Herwig [95] for additional radiation via MLM matching [130], and relies on Jimmy [115] for underlying event simulation. Ariadne [111] is an implementation of the colour dipole model describing radiation from pairs of colour connected partons involved in the hard scattering process. Specifically for the $W + \text{jets}$ and $Z + \text{jets}$ processes it has the option to apply the CKKW-L method [128] to merge predictions from matrix element calculations with the dipole cascade. Parton level configurations are provided to this end by an external matrix element generator (MadGraph [101] in this case). The subsequent dipole cascade is performed by Ariadne, and further hadronisation and decay are handled by Pythia [94]. On its own, Pythia only incorporates a matrix element correction for the first (hardest) emission of the $p_T$-ordered parton showering in $W + \text{jets}$ and $Z + \text{jets}$ production. It is used in the following comparisons to study differences in parton showering and underlying event modelling. In all three cases, the generators are used in combination with the CTEQ6L1 [165] parton distribution functions.
Merging scales

Event generation is carried out in Alpgen with the tree level matrix elements for $W^\pm$ and $Z$ boson production with zero up to five additional partons in the final state. The so-called merging scales, the boundaries of the phase space described by these matrix elements for parton emissions, are defined as follows:\(^1\):

- $E_{T,\text{clus}} > 20\text{ GeV}$, the minimum transverse energy of an emitted parton;
- $\Delta R_{jj,\text{clus}} > 0.7$, the minimum distance between two emitted partons;
- $\eta_{\text{clus}} < 6.0$, the maximum pseudo-rapidity of an emitted parton.

Emissions outside this region are covered by the parton shower.

For the CKKW-L procedure in Ariadne the same merging scales are used as for MLM matching with Alpgen. Because generation of the $W + 5$ jets and $Z + 5$ jets processes with MadGraph/MadEvent are computationally too intensive for the purpose of this study, merging is achieved using tree-level matrix elements with up to four final state partons. To assess the impact of the higher parton multiplicities on the predictions, the maximum number of final state partons used in the matrix elements are varied in both Alpgen and Ariadne. In addition, merging with Ariadne is also performed with an alternative set of merging scales ($E_{T,\text{clus}} > 30\text{ GeV}$, $\Delta R_{jj,\text{clus}} > 0.4$, and $\eta_{\text{clus}} < 2.5$).

Multiple interactions

In Section 7.6 and onwards, the contribution from the underlying event to the jet spectra, as predicted by Jimmy (in combination with Alpgen) and Pythia (stand-alone and in combination with Ariadne), are also taken into account. For Alpgen, Pythia, and Jimmy the default ATLAS parameter settings (MC08) are used. For Ariadne no such ATLAS tunings exist yet. Furthermore, Ariadne only functions with the ‘old’ multiple interactions model of Pythia. Pythia stand-alone uses the ‘new’ multiple interactions model which is interleaved with the $p_T$-ordered parton shower (Section 2.1.4).

7.2 Cross sections

$W +$ jets

The predicted cross section for $W +$ jets in $pp$ collisions at a centre-of-mass energy $\sqrt{s}$ of 10 TeV, obtained with the three generators, are given in Table 7.1. The $W^+$ (and $W^-$) bosons are forced to decay to a $\mu^+$ ($\mu^-$) and a $\nu_{\mu}$ ($\bar{\nu}_{\mu}$). No jet algorithm was applied, hence the cross section on each row corresponds to a partonic cross section and the total cross section in the bottom row corresponds to the inclusive cross section. The subscript of each cross section label denotes the maximum number of final state partons that are

\(^1\)For a more detailed description of the MLM and CKKW-L procedures see Section 2.2.3 in Chapter 2.
7.2. Cross sections

included in the matrix element calculation. The cross section $\sigma_0$ is thus derived from the leading order matrix element only. The cross sections $\sigma_1$, $\sigma_3$, $\sigma_4$, and $\sigma_5$ include the real contributions from higher order diagrams with up to one, three, four, and five additional partons in the final state respectively\(^2\). These contributions are reweighted according to the MLM (ALPGEN) and CKKW-L prescription (ARIADNE) using the merging scales: $p_T = 20$ GeV, $\Delta R_{jj} = 0.7$, and $\eta = 6.0$. For the cross section prediction $\sigma_3^\dagger$ from ARIADNE, matrix elements with a maximum of three final state partons were used with merging scales $p_T = 30$ GeV, $\Delta R_{jj} = 0.4$, and $\eta = 2.5$.

<table>
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<th>ALPGEN $\sigma_0$</th>
<th>ALPGEN $\sigma_1$</th>
<th>ALPGEN $\sigma_3$</th>
<th>ALPGEN $\sigma_4$</th>
<th>ARIADNE $\sigma_0$</th>
<th>ARIADNE $\sigma_3^\dagger$</th>
<th>ARIADNE $\sigma_4$</th>
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</thead>
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<td>12,475</td>
<td>10,142</td>
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<td>10,126</td>
<td>12,478</td>
<td>10,487</td>
<td>8,189</td>
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<td>W + 1p</td>
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<td>2,109</td>
<td>2,156</td>
<td>2,165</td>
<td>1,659</td>
<td>3,037</td>
<td>1,208</td>
</tr>
<tr>
<td>W + 2p</td>
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<td>259</td>
<td>202</td>
<td>37</td>
<td>82</td>
<td>12,478</td>
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<td>56</td>
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<td></td>
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<tr>
<td>W + 5p</td>
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<tr>
<td>Total</td>
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<td>12,475</td>
<td>12,879</td>
<td>13,181</td>
<td>13,237</td>
<td>12,478</td>
<td>12,448</td>
<td>12,962</td>
</tr>
</tbody>
</table>

Table 7.1: Cross sections (in pb) for $W^\pm \rightarrow \mu^\pm \nu_\mu + \text{jets}$ in $pp$ collisions at $\sqrt{s} = 10$ TeV.

The total cross section calculated by Pythia is smaller than those calculated by ALPGEN and ARIADNE. This is mainly caused by the difference of 10.8% versus 11.1% (1/9\(^{th}\)) in branching ratio $\text{Br}(W \rightarrow \mu \nu_\mu)$. Note that comparison of the individual partonic cross sections is only fair if the same matching cuts are used. For example, the differences in the cross sections of the various subprocesses in ARIADNE’s $\sigma_3^\dagger$ and $\sigma_4$ are due to the fact that different merging scales were used. It is remarkable though that, when comparing $\sigma_4$ with $\sigma_3$ and $\sigma_5$, ARIADNE predicts a relatively larger contribution to the total cross section from the higher parton multiplicities than ALPGEN does with similar matching cuts. This corresponds to what was already observed in Figure 2.10 of Chapter 2 for $pp$ collisions at a centre-of-mass energy $\sqrt{s}$ of 14 TeV. Finally, the sum of all cross sections are all within 6% of each other and the predictions are thus consistent with each other.

Z + jets

The predicted cross sections for $Z + \text{jets}$ in $pp$ collisions at a centre-of-mass energy $\sqrt{s}$ of 10 TeV, with $Z \rightarrow \mu^+ \mu^-$ and $60 < M_{\mu^+ \mu^-} < 200$ GeV, are given in Table 7.2. As for the

\(^2\)Although the cross section $\sigma_2$ has not been calculated explicitly, contributions from the tree-level matrix elements with two final state partons are included in cross section calculation of $\sigma_3$, $\sigma_4$, and $\sigma_5$. 

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\( W + \) jets case, the cross section \( \sigma_0 \) is obtained from just the leading order matrix element, while the \( \sigma_3, \sigma_4, \) and \( \sigma_5 \) cross sections include contributions from matrix elements with up to 3, 4, and 5 additional final state partons, respectively, using either MLM or CKKW-L merging. The \( \sigma_3^\dagger \) prediction is made with ARIADNE using the alternative set of matching cuts. Again, all cross sections are within 6\% of each other and ARIADNE predicts on average a higher parton multiplicity than ALPGEN.

<table>
<thead>
<tr>
<th>Process</th>
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<th>ALPGEN</th>
<th>ARIADNE</th>
</tr>
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<td>( \sigma_0 )</td>
<td>( \sigma_0 )</td>
</tr>
<tr>
<td>( Z + 0p )</td>
<td>1,138</td>
<td>1,143</td>
<td>902</td>
</tr>
<tr>
<td>( Z + 1p )</td>
<td>208</td>
<td>205</td>
<td>162</td>
</tr>
<tr>
<td>( Z + 2p )</td>
<td>69</td>
<td>69</td>
<td>26</td>
</tr>
<tr>
<td>( Z + 3p )</td>
<td>27</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>( Z + 4p )</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>( Z + 5p )</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,138</td>
<td>1,143</td>
<td>1,206</td>
</tr>
</tbody>
</table>

Table 7.2: Cross sections (in pb) for \( Z \to \mu^+ \mu^- + \) jets in \( pp \) collisions at \( \sqrt{s} = 10 \) TeV.

7.3 \( W^\pm \) and \( Z \) boson spectra

The predicted transverse momentum distributions for the \( W^\pm \) and \( Z \) boson are shown in Figure 7.1 and Figure 7.2 respectively. The transverse momenta of the simulated \( W^\pm \) and \( Z \) bosons are taken directly from the Monte Carlo truth information. The histograms are normalised to unity and, for clarity, smooth curves interpolating between histogram bins are used. The wiggles in the curves at large transverse momentum are caused by fluctuations in the number of events between neighbouring bins and indicate statistical uncertainties. The smaller inset in each histogram shows the low transverse momentum region of the \( W^\pm \) and \( Z \) boson in more detail.

First of all, the leading order prediction for the \( W^\pm \) boson from ALPGEN (‘Alpgen LO’) clearly shows that, without any matrix element correction or MLM matching applied, HERWIG’s parton shower does not describe the tail of the transverse momentum distribution well. In Figure 2.5 the same phenomenon was already demonstrated for PYTHIA’s parton shower without correction.

Secondly, for both the \( W^\pm \) and \( Z \) boson, the three ARIADNE distributions predict harder spectra than the other generator configurations. The fact that the two predictions in which CKKW-L is applied (‘Ariadne 0123p’ and ‘01234p’) are slightly lower than the ‘default’ prediction (which only includes a matrix element correction for the first emission), is an indication that the uncorrected dipole cascade overestimates the amount of radiation at large transverse momenta.
Subtle differences are also discernible between the ALPGEN distributions for the $W^\pm$ boson, ‘Alpgen 01p’ and ‘Alpgen 0123p’. As opposed to the ARIADNE distributions,
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Here the inclusion of matrix elements with more final state partons leads to a slightly harder spectrum. This implies an underestimation of the $W^\pm$ boson spectrum at large transverse momentum by the parton shower. Comparison between ‘Alpgen 0123p’ and ‘Alpgen 012345p’ distributions for the $Z$ boson shows no further improvement.

It is also remarkable that the ‘Pythia’ and ‘Alpgen 01p’ predictions are in almost complete agreement with each other, because they are obtained via different techniques. Finally, although the inclusion of matrix elements with higher parton multiplicities leads to more similar distributions at large transverse momenta, distinct features remain visible between the distributions.

The predicted rapidity distributions for the $W^\pm$ and $Z$ boson are shown in Figure 7.3. The histograms are normalised to unity. All generators prediction are in good agreement and show that the $Z$ boson is produced more centrally than the $W^\pm$.

![Figure 7.3: Predicted rapidity distributions of (a) $W^\pm$ bosons and (b) $Z$ bosons.](image)

7.4 Jet spectra

To study jet spectra in $W +$ jets and $Z +$ jets events, jets are reconstructed from Monte Carlo truth particles, after hadronisation, with the ATLAS cone algorithm as described in Section 3.2 of Chapter 3 using a cone size $R_{\text{cone}}$ of 0.4, a minimum seed $p_T$ of 2 GeV, and $|\eta| < 5$. The transverse momentum distributions of the leading and subleading jets in $W +$ jets production are shown in Figure 7.4. The distributions are normalised corresponding to the cross sections in Table 7.1. Results for $Z +$ jets are very similar and have therefore been omitted.

All predictions by ARIADNE for the leading jet result in a harder transverse momentum distribution and a larger overall number of leading jets than predictions by ALPGEN and PYTHIA. In the tail at large transverse momentum, the differences between ARIADNE and ALPGEN become smaller again, like in the $W^\pm$ boson transverse momentum distribution in Figure 7.1. Differences between the ‘Alpgen 01p’ and ‘Alpgen 0123p’ distributions on the other hand are more pronounced in this region.
7.4. Jet spectra

![Graphs showing jet spectra](image)

**Figure 7.4:** Comparison between event generators of the predictions for the transverse momentum distributions of (a) the leading jet and (b) the subleading jet in $W + \text{jets}$ events.

The subleading jet distributions display more discrepancies. Below approximately 70 GeV, the ‘Ariadne 01234p’ predicts considerably more jets than the rest, including ‘Ariadne default’ and ‘Ariadne 0123p’, while above this ~70 GeV the ‘Ariadne 01234p’ and ‘Alpgen 0123p’ are in agreement with each other. It is important to note that only ‘Ariadne 0123p’ was generated with the merging scale $\eta$ set to 2.5. For ‘Ariadne 01234p’ and the other ALPGEN predictions 5.0 was used. This indicates that a large fraction of the subleading jets are emitted in the region $|\eta| > 2.5$ according to the ‘Ariadne 01234p’ distribution.

In Figure 7.5 the pseudo-rapidity distributions for the leading and the subleading jet are shown. The jets are required to have a minimum transverse momentum of 20 GeV. The results from the event generator for the leading jet are consistent with each other. ARIADNE predicts an overall larger amount of jets. Differences between the ‘Alpgen LO’ and ‘Alpgen 01p’ distribution demonstrates that without matrix element correction, the parton shower underestimates the jet production rate in the central rapidity region.

Between the predicted distributions for the subleading jet, important differences are again visible. Although the ‘Ariadne 01234p’ prediction suffers a bit from statistical fluctuations, it clearly gives a broader pseudo-rapidity spectrum than the rest. This characteristic feature is attributed to the inclusion of small-$x$ effects$^3$ in the dipole cascade, as explained earlier in Section 2.1.2 of Chapter 2. The ‘Ariadne default’ and ‘0123p’ distributions are also broad but not as flat, since they do not include the matrix element predictions for radiation of multiple partons in the region $|\eta| > 2.5$. A significant difference is also visible between the ‘Alpgen 01p’ and ‘Alpgen 0123p’ distributions in the central pseudo-rapidity region.

In Figure 7.6 the expected jet multiplicity in $W + \text{jets}$ events is shown. Jets are required to have a minimum transverse momentum of 20 GeV and an absolute pseudo-

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$^3$Referring to small momentum fractions, with $x \propto M/\sqrt{s}$. 

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Figure 7.5: Comparison between event generators of the predictions for the pseudo-rapidity distributions of (a) the leading jet and (b) the subleading jet in $W + \text{jets}$ events. The minimum transverse momentum of the jets is 20 GeV.

rapidity within either 5.0 or 2.5. The former corresponds to the maximum acceptance in pseudo-rapidity of the ATLAS detector for jets, and the latter corresponds to the maximum pseudo-rapidity cut used for jets in the $tt$ cross section measurement of Chapter 5. Only predictions including matrix elements for the highest available parton multiplicity are shown.

Figure 7.6: Comparison between the event generators of the jet multiplicity in $W + \text{jets}$ events for jets with a transverse momentum of at least 20 GeV and an absolute pseudo-rapidity within (a) 5.0 and (b) 2.5.

Overall, ARIADNE predicts the largest jet production rate in $W + \text{jets}$ events. This is due to the relative large contributions expected from 1-jet and 2-jet events with a $W^\pm$ boson. The same was observed before in Table 7.1 for the cross sections at parton
7.5. Ratio of \(W + \text{jets}\) and \(Z + \text{jets}\) events

A prediction for the amount of \(W^\pm(\rightarrow \mu^\pm \nu_\mu)\) boson events in a sample of collision data can be attained by counting the number of \(Z(\rightarrow \mu^+ \mu^-)\) boson events in that sample and using the ratio of expected \(W^\pm(\rightarrow \mu^\pm \nu_\mu)\) and \(Z(\rightarrow \mu^+ \mu^-)\) boson events determined from Monte Carlo simulation. When taking into account the jet multiplicity \(i\) of the event:

\[
\left[ \frac{N_{i}^{W}}{N_{i}^{Z}} \right]_{\text{Exp.}} = \left[ \frac{N_{i}^{W}}{N_{i}^{Z}} \right]_{\text{MC}} \times \left[ \frac{N_{i}^{Z}}{N_{i}^{\text{Data}}} \right]
\]

The advantage of this method is that detection of \(Z(\rightarrow \mu^+ \mu^-)\) events is relatively straightforward compared to \(W^\pm(\rightarrow \mu^\pm \nu_\mu)\) events, because \(Z\) bosons do not suffer from large transverse missing energy. In addition, uncertainties due to the luminosity determination and parton distribution functions cancel when taking the \(W^\pm\) and \(Z\) boson event ratio.

In Figure 7.7 the ratio of \(W^\pm(\rightarrow \mu^\pm \nu_\mu)\) and \(Z(\rightarrow \mu^+ \mu^-)\) boson events is given as function of the jet multiplicity. The first plot shows the predictions for the ratio when considering all reconstructed jets, and the second plot shows the predictions for the ratio when considering jets with a minimum transverse momentum of 20 GeV and a maximum pseudo-rapidity of 2.5. In all events the \(W^\pm\) and \(Z\) bosons decay into muons, with an additional requirement for the \(Z\) boson events of \(60 < M_{\mu^+ \mu^-} < 200\) GeV. Only predictions including matrix elements for the highest available parton multiplicity are shown for ALPGEN, while for ARIADNE also predictions are shown without using CKKW-L.

All four predictions indicate that the production of \(W^\pm(\rightarrow \mu^\pm \nu_\mu)\) boson events is an order of magnitude larger than the production of \(Z(\rightarrow \mu^+ \mu^-)\) boson events. However, there is a difference of order \(O(\sim 10\%)\) between the two predicted ratios by PYTHIA and ALPGEN on one side, and the two predicted ratios by ARIADNE on the other side. Without additional requirements on the reconstructed jets, both ARIADNE predictions are in good agreement with each other, like the ALPGEN and PYTHIA predictions. This suggests that the differences between the expected ratios are mainly due to differences in the parton showers. When requiring more central, harder jets, differences between ALPGEN and ARIADNE become smaller, while differences between PYTHIA and ALPGEN become
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Figure 7.7: Ratio of $W^\pm(\rightarrow \mu^\pm \nu_\mu)$ and $Z(\rightarrow \mu^+\mu^-)$ boson events per jet multiplicity for (a) all reconstructed jets and (b) jets with $p_T > 20$ GeV and $|\eta| < 2.5$.

larger. This is expected since PYTHIA only incorporates a matrix element correction for the first emission, while the other generators include contributions from higher order corrections. The same holds for the ARIADNE predictions. Without CKKW-L applied, larger ratios are expected.

In Table 7.1 and 7.2 the partonic cross sections were calculated for $W^\pm(\rightarrow \mu^\pm \nu_\mu)$ and $Z(\rightarrow \mu^+\mu^-)$ boson production with ALPGEN and ARIADNE. In Table 7.3 the ratios of these cross sections are given as function of the number of final state partons together with the total inclusive ratios. It is not fair to directly compare these numbers with those presented in Figure 7.7, because the kinematical cuts on the partons in the cross section calculations differ from the jet level cuts. However, the values show a similar trend at parton level: ARIADNE predicts larger cross section ratios for higher parton multiplicities than ALPGEN. Irrespective of the parton multiplicity, both generators expect in total a factor $\sim 11$ more $W$ + jets events than $Z$ + jets events.

<table>
<thead>
<tr>
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<th>$\sigma^W_{4}/\sigma^Z_3$</th>
<th>$\sigma^W_{3}/\sigma^Z_{1}$</th>
<th>$\sigma^W_{4}/\sigma^Z_{1}$</th>
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<td>11.0</td>
<td>10.9</td>
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<td>10.9</td>
</tr>
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</table>

Table 7.3: Ratio of the partonic cross sections for $W^\pm(\rightarrow \mu^\pm \nu_\mu)$ and $Z(\rightarrow \mu^+\mu^-)$ boson production as predicted by Alpgen and Ariadne. Values are given as function of the number of final state partons $N_p$. On the last row follows the ratio of the inclusive cross sections.
7.6 Underlying event

The jet multiplicity of an event will be dominated by the hard scattering in a \( pp \) collision when one requires fairly hard, central jets such as for the \( t\bar{t} \) cross section measurement. However, the underlying event also contributes to the jet multiplicity. To study the underlying event, \( W^\pm \rightarrow \mu^\pm \nu_\mu \) and \( Z^\pm \rightarrow \mu^\pm \mu^- \) events have been simulated with and without multiple interactions according to JIMMY (for ALPGEN) and PYTHIA (for ARIDNE and stand-alone).

In Figure 7.8, 7.9, and 7.10, the transverse momentum and pseudo-rapidity distributions for jets in \( W^\pm \rightarrow \mu^\pm \nu_\mu \) events are shown as predicted by ALPGEN/JIMMY, ARIDNE/PYTHIA, and stand-alone PYTHIA respectively. For ALPGEN, MLM matching is used to include matrix elements with up to three additional partons. For ARIDNE the CKKW-L method is applied to include matrix elements with up to four additional partons. Below the distributions the relative difference between the prediction with and without multiple interactions taken into account is indicated.

All three multiple interactions models predict a significant amount of additional jet activity due to multiple interactions. The largest impact is expected by JIMMY. As can be seen from Figure 7.8, jets from the underlying event contribute mainly at low transverse momentum, but they reach up to transverse momenta as high as 40 GeV. The pseudo-rapidity distributions show an increase of factor three to four in the amount of jets over the full range. In the very forward direction, for jet pseudo-rapidities above 2.5, the increase is highest.

The transverse momentum distributions in Figure 7.9 show that the ‘old’ multiple interactions model of PYTHIA only contributes considerably for jets below \( \sim 20 \) GeV. The amount of jets almost doubles, but as opposed to JIMMY, this increase is fairly uniform in pseudo-rapidity. Since a tuned set of parameters for the multiple interactions model of PYTHIA does not exist for usage with ARIDNE, the results should only be taken as a rough estimate. For more accurate predictions, further investigations are required. This is however outside the scope of this study.

The ‘new’ multiple interactions model in stand-alone PYTHIA gives transverse momentum and pseudo-rapidity distributions for jets (Figure 7.10) which are similar to that of JIMMY. Comparing the relative difference between the distributions with and without multiple interactions shows that the overall increase in jet activity due to the underlying event is not as large as for JIMMY though. Especially the enhancement in the forward pseudo-rapidity region is less pronounced.

In Figure 7.11 the expected fraction of \( W^\pm \rightarrow \mu^\pm \nu_\mu \) events is shown per jet multiplicity of the event. Unlike Figure 7.6, effects from multiple interactions are included. Jets are again required to have a minimum transverse momentum of 20 GeV and an absolute pseudo-rapidity within either 5.0 or 2.5. This time also predictions from ALPGEN with matrix elements for up to five final state partons (‘Alpgen 012345p’) are shown\(^4\).

Comparing Figure 7.11 with Figure 7.6 points out that the predictions most sensitive to multiple interactions are those for events with high jet multiplicity. ARIDNE still predicts the largest fraction of 1-jet events, but ALPGEN now expects a considerably

\(^4\)This sample is used by convention for analyses at \( \sqrt{s} = 10 \) TeV within the ATLAS collaboration.
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Figure 7.8: Predicted (a) $p_T$ and (b) $\eta$ distributions for jets in $W^\pm \rightarrow \mu^\pm \nu_\mu$ events by Alpgen with and without Jimmy’s multiple interaction model.

Figure 7.9: Predicted (a) $p_T$ and (b) $\eta$ distributions for jets in $W^\pm \rightarrow \mu^\pm \nu_\mu$ events by Ariadne with and without Pythia’s old multiple interactions model.

Figure 7.10: Predicted (a) $p_T$ and (b) $\eta$ distributions for jets in $W^\pm \rightarrow \mu^\pm \nu_\mu$ events by Pythia with and without Pythia’s new multiple interactions model.
larger amount of high jet multiplicity events than ARIADNE. Also for PYTHIA a similar change in jet multiplicity spectrum is observable due to multiple interactions. In particular for jets with a maximum pseudo-rapidity of 2.5, the fraction of high multiplicity events increases such that it is comparable in size to that of ARIADNE. Finally, differences between the two predictions with ALPGEN are subtle. They illustrate once more that the inclusion of matrix elements with higher final state parton multiplicities leads to harder jet spectra. But for jets with a minimum transverse momentum of 20 GeV, this effect is less prominent than the extra jet activity due to the underlying event.

Figure 7.11: Predicted fraction of $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ events per jet multiplicity in the event for jets with a minimum transverse momentum of 20 GeV and (a) $|\eta| < 5.0$ and (b) $|\eta| < 2.5$. The predictions include effects from multiple interactions.

Figure 7.12: Ratio of $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ and $Z^{\pm} \rightarrow \mu^{+}\mu^{-}$ events per jet multiplicity for (a) all reconstructed jets and (b) for jets with $p_{T} > 20$ GeV and $|\eta| < 2.5$. The predictions include simulation of multiple interactions.
Chapter 7. \(W^\pm\) and \(Z\) boson production

Figure 7.12 shows the ratio of \(W^\pm\) and \(Z\) boson events as function of the jet multiplicity, like in Figure 7.7. In this case, effects from multiple interactions also taken into account via the different models. Without any jet cuts applied, differences among the predicted ratios are strongly reduced with respect to what was observed in Figure 7.7. When requiring more central, harder jets, the impact of the multiple interactions diminishes again.

7.7 Background from \(W + \text{jets}\) in \(t\bar{t}\) event selection

Differences in the predicted jet spectra for \(W + \text{jets}\) events will result in varying predictions for the amount of \(W + \text{jets}\) background for a \(t\bar{t}\) analysis. To investigate the magnitude of these variations for the top cross section measurement of Chapter 5, a comparison is made between the predictions of the three event generators PYTHIA, ALPGEN, and ARIADNE. Since the focus of this study in on jet multiplicity, only the two distinct jet requirements of the \(t\bar{t}\) cross section measurement are applied:

- at least 4 jets with \(p_T > 20\) GeV and \(|\eta| < 2.5\)
- at least 3 jets with \(p_T > 40\) GeV and \(|\eta| < 2.5\)

The jets are reconstructed with the cone algorithm using fast detector response simulation (ATLFAST). The single isolated lepton and the missing transverse energy requirements are dropped in order to keep a reasonable amount of events left over after event selection. This omission should not bias the results, because the selection criteria are almost completely uncorrelated\(^5\). Besides, for this study only \(W^\pm \rightarrow \mu^\pm \nu_\mu\) events are considered. Because the results in this section are obtained for \(pp\) collisions at a centre-of-mass energy \(\sqrt{s}\) of 10 TeV instead of 14 TeV, the numbers are not directly comparable to those in Chapter 5.

In Table 7.4 the expected event selection efficiencies for the individual (\(\epsilon_{4j20}\) and \(\epsilon_{3j40}\)) and combined jet requirements (\(\epsilon_{\text{sel}}\)) are given. The most right column shows the event selection efficiency when also including the \(M_W\)-constraint (\(\epsilon_{\Delta M_W}\)), an event is then required to contain at least one di-jet combination with invariant mass within 10 GeV of the \(W\) boson mass. The table shows the predictions without and with simulation of multiple interactions.

The efficiencies are all below 0.3% and thus most of the \(W + \text{jets}\) events are rejected by the \(t\bar{t}\) selection criteria. However, predicted efficiencies differ up to a factor five between the three event generators. ALPGEN predicts significantly higher selection efficiencies, both with and without multiple interactions. The multiple interactions simulated with JIMMY for ALPGEN, have the largest impact on the selection efficiencies. For PYTHIA the inclusion of multiple interactions does not considerably change results. ARIADNE’s estimates are fairly compatible with each other. However, the fact that the

\(^5\)Differences in predicted \(p_T\) spectra for the \(W\) boson, observed in Figure 7.4, imply also differences the \(p_T\) spectra of its decay products, the muon and muon neutrino (and thus \(E_T\)) in this case. These differences appear for the leptons however above 30 GeV, well above the minimum required lepton \(p_T\) and \(E_T\).
7.7. Background from $W +$ jets in $t\bar{t}$ event selection

<table>
<thead>
<tr>
<th>Generator</th>
<th>$\epsilon_{4j20}$</th>
<th>$\epsilon_{3j40}$</th>
<th>$\epsilon_{\text{sel}}$</th>
<th>$\epsilon_{\Delta M_W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia w/o M.I.</td>
<td>$0.070 \pm 0.006$</td>
<td>$0.065 \pm 0.006$</td>
<td>$0.029 \pm 0.004$</td>
<td>$0.012 \pm 0.003$</td>
</tr>
<tr>
<td>Pythia w/ M.I.</td>
<td>$0.084 \pm 0.006$</td>
<td>$0.068 \pm 0.006$</td>
<td>$0.025 \pm 0.004$</td>
<td>$0.012 \pm 0.003$</td>
</tr>
<tr>
<td>Ariadne w/o M.I.</td>
<td>$0.092 \pm 0.003$</td>
<td>$0.088 \pm 0.003$</td>
<td>$0.040 \pm 0.002$</td>
<td>$0.011 \pm 0.001$</td>
</tr>
<tr>
<td>Ariadne w/ M.I.</td>
<td>$0.085 \pm 0.003$</td>
<td>$0.089 \pm 0.003$</td>
<td>$0.033 \pm 0.002$</td>
<td>$0.011 \pm 0.001$</td>
</tr>
<tr>
<td>Ariadne 3p w/o M.I.</td>
<td>$0.095 \pm 0.002$</td>
<td>$0.105 \pm 0.002$</td>
<td>$0.040 \pm 0.002$</td>
<td>$0.013 \pm 0.001$</td>
</tr>
<tr>
<td>Ariadne 3p w/ M.I.</td>
<td>$0.085 \pm 0.006$</td>
<td>$0.091 \pm 0.006$</td>
<td>$0.028 \pm 0.006$</td>
<td>$0.009 \pm 0.001$</td>
</tr>
<tr>
<td>Ariadne 4p w/o M.I.</td>
<td>$0.095 \pm 0.002$</td>
<td>$0.105 \pm 0.002$</td>
<td>$0.040 \pm 0.002$</td>
<td>$0.013 \pm 0.001$</td>
</tr>
<tr>
<td>Ariadne 4p w/ M.I.</td>
<td>$0.095 \pm 0.002$</td>
<td>$0.105 \pm 0.002$</td>
<td>$0.040 \pm 0.002$</td>
<td>$0.013 \pm 0.001$</td>
</tr>
<tr>
<td>Alpgen 3p w/o M.I.</td>
<td>$0.173 \pm 0.001$</td>
<td>$0.189 \pm 0.001$</td>
<td>$0.083 \pm 0.001$</td>
<td>$0.026 \pm 0.001$</td>
</tr>
<tr>
<td>Alpgen 3p w/ M.I.</td>
<td>$0.239 \pm 0.004$</td>
<td>$0.217 \pm 0.003$</td>
<td>$0.101 \pm 0.002$</td>
<td>$0.033 \pm 0.001$</td>
</tr>
<tr>
<td>Alpgen 5p w/o M.I.</td>
<td>$0.283 \pm 0.001$</td>
<td>$0.237 \pm 0.001$</td>
<td>$0.119 \pm 0.001$</td>
<td>$0.040 \pm 0.001$</td>
</tr>
<tr>
<td>Alpgen 5p w/ M.I.</td>
<td>$0.283 \pm 0.001$</td>
<td>$0.237 \pm 0.001$</td>
<td>$0.119 \pm 0.001$</td>
<td>$0.040 \pm 0.001$</td>
</tr>
</tbody>
</table>

Table 7.4: Predicted selection efficiencies (in %) for $W^\pm \rightarrow \mu^\pm \nu_\mu$ events without (top) and with (bottom) taking into account multiple interactions.

The efficiencies seem to decrease, instead of increase, when taking into account multiple interactions, is curious and requires further investigation. In any case, the inclusion of matrix elements for multiple final state partons enhances the efficiencies for both Ariadne and Alpgen, as expected.

In Figure 7.13 the invariant mass distribution, $M_{jjj}$, is shown of the three-jet combination with the highest vector-summed transverse momentum for $W +$ jets events that passed the selection criteria. This distribution is used in the $t\bar{t}$ cross section measurement to extract the $t\bar{t}$ signal. As described in more detail in Section 5.5 of Chapter 5, the hadronic top quark mass is fit by a Gaussian, while a Chebyshev polynomial is fit to the background, including the $W +$ jets contribution. Due to the limited amount of events in the simulated samples available after event selection, the distributions are shown only for Ariadne and Alpgen with matrix element matching for up to three and four final state partons respectively. The predictions are shown with and without including multiple interactions. For the latter case, there is also the large `Alpgen 012345p’ sample available. The distributions are displayed on a logarithmic scale and normalised to unity in order to compare the shapes. There are no significant deviations observable between the distributions.

Finally, Figure 7.14 shows the same distributions as in Figure 7.13, though on a linear scale and normalised according to the predicted cross sections (Table 7.1) and selection efficiencies (Table 7.4). The distributions demonstrate that Alpgen predicts significantly more $W^\pm \rightarrow \mu^\pm \nu_\mu$ events passing the event selection. Without taking into account the multiple interactions, the ratio between Alpgen and Ariadne is roughly a factor two over the full $M_{jjj}$ range shown. With multiple interactions taken into account,
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Figure 7.13: Comparison between Alpgen and Ariadne of the predicted invariant three-jet mass distribution $M_{jjj}$ for $W^\pm \rightarrow \mu^\pm \nu_\mu$ events after $t\bar{t}$ event selection (a) without and (b) with multiple interactions included. Normalised to unity.

Note that the ‘Cut & Count’ method (Section 5.7) relies on the predicted amount of background for the cross section measurement: the number of background events is subtracted from the number of observed events. Hence, the factor $\sim 4$ difference between the predictions indicates a large uncertainty on this measurement coming from the $W^+ +$ jets background normalisation.
7.8 Conclusions & Discussion

Predictions for $W$ + jets and $Z$ + jets production in $pp$ collisions at centre-of-mass energy of 10 TeV in ATLAS have been compared between the event generators PYTHIA, ALPGEN, and ARIADNE. The most remarkable feature of ARIADNE’s dipole cascade is that it predicts larger cross sections for higher jet multiplicities and significantly larger jet activity in the forward regions ($|\eta| > 2.5$). Simulation of multiple interactions and comparison between PYTHIA’s ‘old’ and ‘new’ model, and JIMMY’s model indicates that a substantial contribution from the underlying event to the jet spectra can be expected, especially from JIMMY. Jets originating from the underlying event reach transverse momenta up to 40 GeV.

In addition, Monte Carlo predictions for the ratio of $W^{\pm}$ and $Z$ boson events have been compared for $W^{\pm}$ and $Z$ bosons decaying into muons. This ratio can be used to estimate the amount $W$ + jets events directly from data using $Z$ + jets events. It has been shown that for higher jet multiplicities, ARIADNE predicts a larger ratio than PYTHIA and ALPGEN, while the total inclusive ratios are equal with a value of $\sim$11. When considering jets with a minimum transverse momentum of 20 GeV and a pseudorapidity within 2.5 the uncertainties in this ratio due to the underlying event reduce.

In the perspective of a $t\bar{t}$ cross section measurement, ALPGEN predicts the largest amount of background from $W$ + jets events. The difference with other generators is enhanced when including the underlying event simulation from JIMMY. These differences are larger than the differences due to a variation in the number of final state partons used in the matrix element calculation by the event generator. The predicted shapes of the invariant three-jet mass distributions, eventually used for top quark signal extraction, are in agreement with each other. This is reassuring, despite the factor four difference in predicted amount of background, because the largest uncertainty for the top cross section measurement in Chapter 5 is not the normalisation but the shape of the invariant three-jet mass distribution. For the ‘Cut & Count’ method, however, this is a significant uncertainty.