Radiating top quarks
Gosselink, M.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Production of $W +$ jets, $t\bar{t}$, and $t\bar{t}H$

The production of $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ in hadronic collisions have similar event topologies due to the appearance of a $W^{\pm}$ boson and jets in the decay chain of a top quark. $W +$ jets production has the largest cross section of the three processes and is the main background to $t\bar{t}$ signals, while $t\bar{t}$ production, in turn, is the dominant background for $t\bar{t}H$ searches. To gain more insight in the production of $W +$ jets, $t\bar{t}$, and $t\bar{t}H$, the momentum fractions, $x_1$ and $x_2$, of the two partons interacting in the hard scattering of the proton-proton collision have been studied for the three processes. The goal of this study is to investigate whether the reconstruction of these momentum fractions can be used as a tool to discriminate between $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ production.

4.1 Momentum fractions

Momentum fractions were already introduced in Chapter 1, Eq.(1.1). They relate the amount of energy in the hard scattering $\sqrt{s}$ to the total centre-of-mass energy $\sqrt{s}$ in the $pp$ collision:

$$\hat{s} = x_1 x_2 s \quad \text{with} \quad x_1 x_2 = \frac{M^2_{\text{inv}}}{s}$$

where $M_{\text{inv}}$ is the total invariant mass of the particles produced in the hard scattering. Hence for each final state a unique minimum amount of energy is required, otherwise the production is kinematically not allowed. For example, to create two top quarks of 175 GeV, a minimum invariant mass of 350 GeV is needed. With $\sqrt{s} = 14$ TeV at the LHC, this implies that $x_1 x_2 \geq 6.25 \times 10^{-4}$ for $t\bar{t}$ production (assuming a pure $2 \to 2$ hard process).

The characteristic momentum fraction distributions for $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ production are studied throughout this chapter at leading order with the PYTHIA v6.415 Monte Carlo generator using the CTEQ6.1L PDF. The cross sections, calculated with PYTHIA, are given in Table 4.1. The $W +$ jets cross section is approximated by the $W^{\pm} + g/q$ hard process\(^1\). The values of the momentum fractions $x_1$ and $x_2$ used in the

---

\(^1\)This corresponds to PYTHIA’s process switch `MSEL=14`: the tree-level matrix element is used, which should give a better description of the high-$p_T$ region than the lowest order matrix element for $W^{\pm}$ boson production.
PDF evaluation are considered as the reference values.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{LO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + q/g$</td>
<td>344 nb</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>498 pb</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>521 fb</td>
</tr>
</tbody>
</table>

Table 4.1: Cross sections calculated at leading order with Pythia.

The typical momentum fraction distributions of the three processes are shown in Figure 4.1. Both the $x_1$, $x_2$, and $x_1x_2$-distributions show that there is a clear separation in the regions populated by the different type of events. Note however that the histograms are normalised to unity and that the overlap of the distributions is thus larger than the figures suggest. The distributions show that indeed the boundaries are given by the minimum required $x_1x_2 \geq M_{\text{inv}}/\sqrt{s}$, corresponding to -4.5 for $W +$ jets, -3.2 for $t\bar{t}$, and -2.9 for $t\bar{t}H$ events on the logarithmic scale. The upper limit is given by $x_1x_2 = 1$. The $x_1, x_2$-distribution is symmetrical as expected from $pp$ collisions.

Figure 4.1: Distributions of (a) the momentum fractions $x_1$ and $x_2$ separately and (b) the combined momentum fraction $x_1x_2$ for the $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ production processes. The distributions are normalised to unity.

Figure 4.1(b) shows that the tails of the distributions are larger at higher $x_1x_2$ values than at lower values. This is due to the fact that only on the right side of the peak phase space is available for increased momentum of the outgoing particles and production of additional (hard) partons. The left side is limited by the threshold for particle production at rest.
4.2 Reconstruction of $x_1$ and $x_2$

In order to measure $x_1$ and $x_2$, the original particles produced in the hard interaction need to be reconstructed. In theory, this can be done by adding up all four momenta of the particles’ decay products. Experimentally this can only be done by using reconstructed jets, leptons, and missing transverse energy $\not{E}_T$. Before doing so, an intermediate step is made. There is namely one particular problem that arises when large $\not{E}_T$ is involved caused by a neutrino (from $W \rightarrow ℓν$ decay): the longitudinal component of the neutrino momentum can not be reconstructed unambiguously. Whether this imposes a problem on the reconstruction of $x_1$ and $x_2$ will be studied first.

4.2.1 Neutrino momentum

In Figure 4.2 again the momentum fraction distributions of $W + \text{jets}$, $\bar{t}t$, and $tH$ events are compared with each other. This time, $x_1$ and $x_2$ are reconstructed by adding up all the four-vectors of the decay products in the Monte Carlo truth information, and using Eq.(1.1). The $W^\pm$ boson in $W + \text{jets}$ is forced to decay leptonically, while in $\bar{t}t$ and $ttH$ one of the $W^\pm$ bosons decays leptonically and the other hadronically. In the case of $W + \text{jets}$, reconstruction is done with the lepton, neutrino, and accompanying parton which recoiled against the $W^\pm$ boson (and eventually forms a jet). The $\bar{t}t$ pair is reconstructed from the $b, \bar{b}, q, q', ℓ, \text{ and } ν$. The $ttH$ system is reconstructed like $\bar{t}t$ plus two $b$-quarks from the Higgs decay. To mimic the loss of information on the longitudinal component of the neutrino momentum, $p_ν^z$ is set equal to zero and the energy is corrected accordingly.

As can be seen by comparing Figure 4.2 with Figure 4.1, for $W + \text{jets}$ events the impact of the missing neutrino $p_ν$ is large. Small values of $x_1$ and $x_2$ are not reconstructed properly resulting in a curved $x_1, x_2$-distribution. The combined $x_1, x_2$-distribution shows a smearing with respect to the originally generated distribution. Although also for $\bar{t}t$ and $ttH$ events a smearing of the original distributions is visible, the distributions seem to suffer less from the absence of $p_ν(ν)$ than in the $W + \text{jets}$ case. Between the distributions of the three processes there is still a clear separation visible.

Two effects are playing a rôle in the fact that the reconstruction of $W + \text{jets}$ events suffers more from lacking the information on the neutrino $p_ν$ than $\bar{t}t$ and $ttH$. First of all, in the $\bar{t}t$ and $ttH$ case the total momentum of the system is carried by 6 and 8 particles respectively. The effect of missing longitudinal neutrino momentum is therefore less than for the $W + \text{jets}$ case, where the total system’s momentum is divided over only 4 particles. Secondly, neutrinos in $W + \text{jets}$ events cover a larger pseudo-rapidity range. This can be seen in Figure 4.3 where the pseudo-rapidity $η$ of neutrinos from $W$ decay in the three processes is compared.

4.2.2 Jets and acceptance

The next two steps towards a more realistic reconstruction of the hard scattering are (i) using jets instead of decay particles from the Monte Carlo truth information, and (ii)
Chapter 4. Production of $W +$ jets, $t\bar{t}$, and $t\bar{t}H$

Figure 4.2: Reconstructed distributions of (a) the momentum fractions $x_1$ and $x_2$ separately and (b) the combined momentum fraction $x_1x_2$ for the (semi-)leptonically decaying $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ processes. The longitudinal component of the neutrino momentum was set to zero in the reconstruction. The distributions are normalised to unity.

Figure 4.3: Pseudo-rapidity distributions of neutrinos from $W$-decay in $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ events. The distributions are normalised to unity.

including detector acceptance. The jets are ATLAS cone 0.4 truth jets. The lepton and missing energy (neutrino momentum without longitudinal component) are still taken from the Monte Carlo truth list. The detector acceptance limits the range of measurable transverse momentum and rapidity of a lepton, jet, and $E_T$. To estimate this effect on the reconstruction of $x_1$ and $x_2$ some basic acceptance cuts are applied to the physics
objects used in the reconstruction. These cuts are summarised in Table 4.2. Figure 4.4 shows the $x_1x_2$-distributions for the three processes when performing the reconstruction with jets with and without including the acceptance cuts.

| $|\eta|_{\text{max}}$ | $p_{T,\text{min}}$ |
|----------------------|---------------------|
| $e, \mu, \tau$       | 2.5 20 GeV          |
| jet                  | 2.5 20 GeV          |
| $E_T$                | $-$ 20 GeV          |

Table 4.2: Cuts applied to objects to mimic detector acceptance effects.

![Figure 4.4](a) and (b)

Figure 4.4: Reconstructed distributions of the combined momentum fractions $x_1x_2$ using jets (a) without detector acceptance cuts and (b) with detector acceptance cuts for the (semi)leptonically decaying $W +$ jets, $t\bar{t}$, and $t\bar{t}H$ processes. The distributions are normalised to unity.

When comparing Figure 4.4(a) with Figure 4.2 the diffusive effect of the reconstruction with jets on the distributions becomes clear. The $x_1x_2$-distributions is flatter and more smeared. Although the loss in accuracy due to the usage of jets is experimentally unavoidable, the exact amount will depend on the choice of jet algorithm and its parameters. This is outside the scope of this study.

Another typical feature visible in the figure is that the reconstructed distribution is shifted towards a larger $x_1x_2$ value. This is caused by the fact that the jets originate not only from the hard interaction, but also from initial state radiation and multiple interactions.

Figure 4.4(a) also demonstrates that the overlap of the distributions increased significantly. This means that distinguishing between the processes becomes more difficult
when reconstructing the particles created in the hard scattering using jets. Note again that the histograms are normalised to unity. Using absolute normalisation (Table 4.1), the $W + \text{jets}$ distribution is almost three orders of magnitude larger than the $t\bar{t}$ distribution. This is demonstrated in Figure 4.5.

Comparing Figure 4.4(a) with Figure 4.4(b) shows that only part of the $x_1$ and $x_2$ phase space is reconstructed. The shapes of the peaks in the distributions of all three processes are sharper and narrower. Although at first maybe counter-intuitive, this suggests that the acceptance cuts improve the reconstruction. The most probable reason for this is that the softer jets (mainly from radiation and multiple interactions) are discarded. Therefore a ‘cleaner’ event is reconstructed. The peaks of the reconstructed distributions are very similar to the originally generated ones in Figure 4.1. The broader tails indicate the degradation in the resolution due to the usage of jets.

### 4.2.3 Jet multiplicity

In the previous paragraph it was shown that – when looking at the normalised distributions – a clear separation between $W^\pm$ boson and top quark events is possible using $x_1$ and $x_2$. This changes drastically when increasing the minimum required jet multiplicity in events from zero up to four to select more top-like events, as shown in Figure 4.6. The histogram points out that $W^\pm$ boson events with increasing jet multiplicity populate the same region as top events. Events with at least four jets peak around a value $10\log(x_1 x_2) \approx -3$, close to the value where $t\bar{t}$ events would peak. Thus requiring a minimum jet multiplicity gives indeed a bias to more top-like events. Since typical top event selection criteria include jet multiplicity to discriminate between processes, this indicates that not much can be gained by using an additional cuts on $x_1$ and $x_2$.

![Figure 4.5: Same as Figure 4.4(b), now on a logarithmic scale and with the normalisations according to the cross sections of Table 4.1 (in pb).](image)

![Figure 4.6: Reconstructed $x_1, x_2$-distribution of 50,000 $W + \text{jets}$ events with different jet multiplicity requirements: from $\geq 0$ up to $\geq 4$ jets.](image)
4.2.4 Hadronic $W^\pm$ boson events

In the case of hadronically decaying $W^\pm$ bosons, reconstruction of $x_1$ and $x_2$ does not suffer from the missing longitudinal neutrino momentum. In principle, $x_1$ and $x_2$ could be completely reconstructed using jets. In figure 4.7 both $x_1$, $x_2$- and $x_1x_2$-distributions are reconstructed for fully hadronic $W + \text{jets}$, $t\bar{t}$, and $t\bar{t}H$ events. For the jets, a minimum transverse momentum of $p_T > 20$ GeV and maximum pseudo-rapidity of $|\eta| < 2.5$ was required.

![Reconstructed distributions of (a) the momentum fractions $x_1$ and $x_2$ separately and (b) the combined momentum fraction $x_1x_2$ for the fully hadronic $W + \text{jets}$, $t\bar{t}$, and $t\bar{t}H$ processes. Basis acceptance cuts are applied. The distributions are normalised to unity.](image)

Figure 4.7: Reconstructed distributions of (a) the momentum fractions $x_1$ and $x_2$ separately and (b) the combined momentum fraction $x_1x_2$ for the fully hadronic $W + \text{jets}$, $t\bar{t}$, and $t\bar{t}H$ processes. Basis acceptance cuts are applied. The distributions are normalised to unity.

First of all, the distributions are better reconstructed and more separated than in the case of leptonic $W^\pm$ boson decay. In the $x_1$, $x_2$-distributions there is no deformation present on the edges of the distributions like in the leptonic case. The reconstructed distribution of $W + \text{jets}$ events shows a double peak: the principal at the expected production threshold ($10 \log(x_1x_2) \approx -4.5$) and second broader peak around $-7$. The latter is an effect of the limited detector acceptance: these events only contain a single jet that passed the selection criteria, hence the $x_1$ and $x_2$ that are reconstructed correspond to the invariant mass of a jet (typically $1 - 10$ GeV) and not to the mass of the $W^\pm$ boson.

In Figure 4.8(a), $x_1x_2$ is reconstructed as function of the jet multiplicity for hadronic $W + \text{jets}$ events. In this case, the required minimum jet multiplicity ranges from two to six jets. Again, like for leptonic decaying $W^\pm$ bosons, the higher the jet multiplicity, the higher the reconstructed value of $x_1x_2$. Fully hadronic decaying $t\bar{t}$ events produce typically six or more jets. Unfortunately, the $x_1x_2$-distribution for $W + \text{jets}$ with at least six jets peaks at the same value where the $t\bar{t}$ distribution is expected to peak ($-3.2$).

A close up of the peak region is shown in Figure 4.8(b). Only $W$, $t\bar{t}$ and $t\bar{t}H$ events with at least six jets are shown. Although the distributions peak at slightly different
values with respect to each other, a separation for event selection seems not achievable.

4.3 Conclusions

It has been shown that in principle reconstruction of the momentum fractions \( x_1 \) and \( x_2 \) of the incoming partons can be used for event selection. However, one should expect the accuracy to which \( x_1 \) and \( x_2 \) can be reconstructed to be limited due the detector acceptance and offline reconstruction (e.g., jets). In the case of leptonic \( W^\pm \) boson decay, the reconstruction is strongly affected by the lack of information on the longitudinal component of \( E_T \). Other, not detector related factors, such as initial state radiation, underlying events, and pile up\(^2\), cause further degradation of the separating power of a cut on \( x_1x_2 \). The complexity of \( x_1 \) and \( x_2 \) reconstruction with respect to detector response and the presence of other adequate selection criteria, like jet multiplicity, make a ‘\( x_1x_2 \)-cut’ less favourable. For this reason, theoretical uncertainties from parton density functions and higher order QCD corrections have not been further investigated.

\(^2\) not studied in this chapter