The top and beyond: missing energy and little Higgs in ATLAS
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Missing Transverse Energy
in $t\bar{t}$ Events

When reconstructing the missing transverse energy of an event, $\vec{E}_T$, a good understanding of all reconstructed final state objects is required, as follows from its definition in (4.9). In many new physics channels, like SUSY decays or heavy resonances like $W'$, the events are busy, i.e. a large number of final state objects is produced. This large number as well as the diversity of final state objects may complicate the $\vec{E}_T$ reconstruction. Semileptonic $t\bar{t}$ decays render a diverse and busy final state as well. Therefore, they provide an excellent environment to study and understand the reconstruction of $\vec{E}_T$ in topologies similar to those of several possible new physics scenarios.

In this chapter, the nomenclature is such that the phrase ‘semileptonic $t\bar{t}$ events’ refers to $t\bar{t}$ events that are identified as semileptonic based on Monte Carlo information and decay via either the electron channel or the muon channel. As discussed in Chapter 5, the tau decay channel is not considered. Events that pass the selection criteria described in Section 5.2 are referred to as selected events.

Section 6.1 discusses the $\vec{E}_T$ reconstruction in semileptonic $t\bar{t}$ events. In Section 6.2 a method is introduced to assess the performance of the $\vec{E}_T$ reconstruction in selected events by means of the transverse mass distribution of the $W$ boson. The results are shown and discussed in Section 6.3.

6.1 Missing Transverse Energy

In semileptonic $t\bar{t}$ events, the assumption $p_T^{\nu} \approx \vec{E}_T$ is usually made, for example when reconstructing the mass of the top quark. However, additional neutrinos are generally present in the event as a result of decaying $b$-quarks, $B^-$, $D^-$, $K$-mesons and pions. In fact, the average number of additional neutrinos is six per semileptonic $t\bar{t}$ event. Generally their transverse momenta are small compared to that of the neutrino from the $W$ boson. Nevertheless, even with a hypothetically perfect detector, the association of $\vec{E}_T$ to $p_T^{\nu}$ is merely an approximation. The quantity that is to be compared to the reconstructed $\vec{E}_T$ is the actual expected missing transverse energy, $\vec{E}_T^{\text{True}}$. It is obtained by summing up the
energies of all stable particles that are expected not to leave any trace in the detector, i.e.

\[ \mathbf{E}_T^{\text{True}} = (E_{x}^{\text{True}}, E_{y}^{\text{True}}) \]

\[ \mathbf{E}_{x,y}^{\text{True}} = \sum_{\text{noninteracting particles}} E_{x,y} \]

The sum runs over all neutrinos that are generated by Monte Carlo in case of $t\bar{t}$ events, whereas in case of SUSY events, the lightest supersymmetric particle is regarded as noninteracting as well. The level of agreement between $\mathbf{p}_T^{\nu}$ and $\mathbf{E}_T^{\text{True}}$ in simulated semileptonic $t\bar{t}$ events is shown in Figure 6.1. Figure 6.1(a) displays the scalar difference $\mathbf{E}_T^{\text{True}} - p_T^{\nu}$, which reflects a good agreement between the quantities in the majority of the events, although long tails are present up to 20 GeV. The comparison of the azimuthal angles is shown in Figure 6.1(b). The difference is generally small and most events in the tails correspond to low values of $p_T^{\nu}$, i.e. to events in which the azimuthal angle is not well defined. This is illustrated by the distribution for events with $p_T^{\nu} > 40$ GeV in the same figure, for which the tails have largely disappeared.

![Figure 6.1](image_url)

(a) The difference between the magnitudes $\mathbf{E}_T^{\text{True}}$ and $p_T^{\nu}$.

(b) The difference between the azimuthal angles $\varphi(\mathbf{E}_T^{\text{True}})$ and $\varphi(p_T^{\nu})$.

Figure 6.1: Comparison between $\mathbf{E}_T^{\text{True}}$ and the $p_T$ of the neutrino in semileptonic $t\bar{t}$ events. The distributions are displayed on a logarithmic scale and normalized to unity.

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1 The notation is such that for instance the scalar quantity $|\mathbf{E}_T^{\text{True}}| = \sqrt{(E_x^{\text{True}})^2 + (E_y^{\text{True}})^2}$ is denoted $\mathbf{E}_T^{\text{True}}$. 

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Reconstruction and Performance of $\not{E_T}$

The sum of transverse momenta of noninteracting particles, $\not{E_T}^{\text{True}}$, is by definition balanced out by the sum of transverse momenta of all interacting particles. The latter are reconstructed and form the input to the missing transverse energy reconstruction. As described in Section 4.6, the $\not{E_T}$ is composed of contributions of all reconstructed objects as well as energy deposits in calorimeter cells outside of reconstructed objects and a correction for inactive material. As a consequence, the quality of the reconstruction is sensitive not only to the detector resolution and coverage, but also to the parametrization of inactive material, the calibration of reconstructed objects and the presence of dead or noisy channels. The impact of noise in the calorimeters is suppressed by making use of cells associated to TopoClusters (cf. Section 4.2).

To illustrate the share of each type of contribution to $\not{E_T}$ in semileptonic $t\bar{t}$ events, the total energy deposit in the calorimeter, $\sum E_T$, is decomposed in Figure 6.2(a). It shows the composition of $\sum E_T$, as defined in (4.14), for events in which the top quark decays through the electron channel. The main contribution of $\sim 70\%$ is coming from jets (RefJet) and as expected, the reconstructed electrons contribute as well (RefEle). It turns out that the contribution from calorimeter cells not assigned to any reconstructed object, $E_T^{\text{CellOut}}$, is more prominent than that of electrons. Figure 6.2(b) shows the distribution of the three largest components together with the total $\sum E_T$. In conclusion, the calibration of calorimeter cells, in particular those that belong to jets, is highly important for a correct determination of the missing transverse energy in semileptonic $t\bar{t}$ events.

![Figure 6.2: Contributions to $\sum E_T$ of TopoCells assigned to each type of object in simulated semileptonic $t\bar{t}$ events that decay through the electron channel.](image-url)
Figure 6.3(a) shows the distribution of reconstructed $E_T$ in simulated semileptonic $t\bar{t}$ events. Recall that the event selection described in Section 5.2 includes the requirement $E_T > 20$ GeV, which rejects only a small fraction of signal events. In the following, the performance of the reconstruction of $E_T$ is investigated in events that pass all selection criteria described in Section 5.2.

![Graph](a) The distribution of reconstructed $E_T$.

![Graph](b) The normalized distributions of $E_T^{\text{Fake}}$ for the electron and muon channel respectively.

Figure 6.3: Missing transverse energy in simulated semileptonic $t\bar{t}$ events.

The fake missing transverse energy, $E_T^{\text{Fake}}$, is defined as the scalar difference between the reconstructed and expected $E_T$, i.e.

$$E_T^{\text{Fake}} = E_T - E_T^{\text{True}}. \quad (6.2)$$

Figure 6.3(b) shows the distribution of $E_T^{\text{Fake}}$ for selected $t\bar{t}$ events in the electron and muon channel separately. The resolution corresponding to the width of a Gaussian fit is 11.37 GeV for the electron channel and 11.97 GeV for the muon channel, yet small non-Gaussian tails are present. Nonzero values of $E_T^{\text{Fake}}$ generally enhance background contributions in searches for new physics. In fact, such an enhancement came to light in Chapter 5 concerning the multi-jet contribution to the semileptonic $t\bar{t}$ event selection.

The $E_T$ resolution, i.e. the Gaussian width of the $E_T^{\text{Fake}}$ distribution, depends on $\sum E_T$ and practically behaves stochastically for selected $t\bar{t}$ events as can be seen in Figure 6.4(a). The curve is the result of the best fit of the function $a \sqrt{\sum E_T}$, which corresponds to $a = 0.48$. The angular resolution for selected events is depicted in Figure 6.4(b). It displays the width of a Gaussian fit to the distribution of $\varphi(E_T) - \varphi(E_T^{\text{True}})$, which improves with increasing values of $E_T$.

Another figure of merit for the performance of $E_T$ reconstruction is the relative bias, which is given by $E_T^{\text{Fake}} / E_T^{\text{True}}$. The mean value of its distribution for selected $t\bar{t}$ events is
6.1 Missing Transverse Energy

![Graph of $E_T$ resolution versus $\Sigma E_T$.](image1)

(a) $E_T$ resolution versus $\Sigma E_T$.

![Graph of $\varphi(E_T)$ resolution versus $E_T$.](image2)

(b) Resolution of $\varphi(E_T)$ versus $E_T$.

Figure 6.4: Resolution of $E_T$ in selected $t\bar{t}$ events.

shown in Figure 6.5 as a function of $E_T^{\text{True}}$. For values $E_T^{\text{True}} > 50$ GeV, the bias is smaller than 2%.

![Graph of $\frac{E_T^{\text{True}} - E_T}{E_T^{\text{True}}}$ versus $E_T^{\text{True}}$](image3)

Figure 6.5: The relative bias in selected semileptonic $t\bar{t}$ events. The error bars indicate the statistical error on the mean of the distribution in each bin of $E_T^{\text{True}}$.

The azimuthal angle of $\varphi(E_T)$ is expected to be a flat distribution based on the symmetry of the detector. However, Figure 6.6 displays a small asymmetry in the $\varphi(E_T)$ distribution. This is mainly caused by the position of the primary vertex in the version of the detector simulation that was used. It is displaced by $(x_0, y_0, z_0) = (1.50, 2.50, -8.65)$ mm from the center of the ATLAS detector. A similar effect is observed in collision data in Chapter 8.

In general, the reconstructed $\varphi(E_T)$ is very sensitive to any unexpected irregularities the detector. The squares in Figure 6.6 show the distribution in a $t\bar{t}$ sample in which a quadrant of the HEC on side C was not powered in the detector simulation. As expected, the impact is substantial in the interval $[-\pi/2, 0]$. This illustrates that $\varphi(E_T)$ is a powerful
6.2 Transverse $W$ Boson Mass

In order to estimate the performance of $\not{E}_T$ reconstruction in data, the distribution of the transverse $W$ boson mass is studied. The mass and width of the $W$ boson are measured by previous accelerator experiments with great precision. The combination of the LEP and Tevatron results gives \[ m_W = 80.398 \pm 0.025 \text{ GeV} \]
\[ \Gamma_W = 2.141 \pm 0.041 \text{ GeV}. \] (6.3)

Under the assumption that the $W$ boson mass and the kinematics of its decay products are well modelled by Monte Carlo, the accuracy of the simulated detector response can be investigated by means of a comparison with data. Obviously, the outcome of such a study is not to be used as input for a $W$ boson mass measurement.

6.2.1 Sensitivity to $\not{E}_T$ Reconstruction Performance

The missing transverse energy in semileptonic $t\bar{t}$ events is mainly caused by the undetected neutrino from the leptonically decaying $W$ boson. The combination of the transverse momentum of the neutrino and that of the corresponding charged lepton $l$, results in the transverse mass of the $W$ boson:
\[
(m_{W,\text{true}}^T)^2 = (P_{T,\text{true}}^l + P_{T,\text{true}}^\nu)^2 = 2P_{T,\text{true}}^l P_{T,\text{true}}^\nu \left[ 1 - \cos (\Delta \varphi(l_{\text{true}}, \nu)) \right],
\] (6.4)

under the assumption that the mass of the charged lepton is negligible. The angle $\Delta \varphi(l_{\text{true}}, \nu)$ is the opening angle in the transverse plane between the charged lepton and

![Figure 6.6: The distributions of the reconstructed $\varphi(\not{E}_T)$ and the $\varphi(\not{E}_T^{\text{true}})$ in selected $t\bar{t}$ events.](image)
6.2 Transverse $W$ Boson Mass

![Graph](image)

(a) The distributions of the reconstructed (full) and true (dashed) transverse $W$ boson mass.  
(b) The dependence of the mean and peak of the $m_W^T$ distribution on the amount of $E_T^{\text{Fake}}$.

Figure 6.7: The transverse $W$ boson mass in simulated semileptonic $t\bar{t}$ events.

The neutrino. The reconstructed $E_T$ approximates $p_T^\nu$ and the transverse $W$ boson mass is reconstructed as

$$ (m_W^T)^2 = 2p_T^\nu E_T [1 - \cos (\Delta \varphi (l, E_T))] \quad (6.5) $$

This expression is clearly sensitive to the quality of the reconstruction of missing transverse energy, both in magnitude and direction. Figure 6.7(a) shows the distributions of $m_{W,\text{true}}^T$ and $m_W^T$ in simulated semileptonic events. The characteristic shape of the transverse projection is the Jacobian peak. The sharp edge around 80 GeV in the $m_{W,\text{true}}^T$ distribution is determined by the value of the $W$ boson mass as given in (6.3). A small tail is observed above $m_W$ which is caused by the corresponding nonzero intrinsic width of the $W$ boson mass. The resolution on the reconstructed transverse momentum of the charged lepton is better than 2% for electrons and better than 4% for muons (cf. Chapter 4), which is why the width of the Jacobian peak in the reconstructed $m_W^T$ distribution in Figure 6.7(a) is dominated by the resolution on the missing transverse energy.

The position of the Jacobian peak as well as the width of the distribution are sensitive to the amount of $E_T^{\text{Fake}}$ in the event. Figure 6.7(b) shows how the position of the maximum as well as the mean value of the entire distribution shift with varying amounts of $E_T^{\text{Fake}}$.

Several scenarios of badly reconstructed $E_T$ are imaginable and their impact on the $m_W^T$ distribution is illustrated here by means of some examples.

In the first example, we assume that the calibration of TopoClusters inside jets is affected by systematic effects and the contribution of $E_T^{\text{RefJets}}$ is under- or overestimated by 20%. Such a large effect is expected to be unlikely, but serves the purpose of illustrating the
impact on the reconstructed $m_T^W$. The contribution of $E_T^{\text{CellOut}}$ is subject to the same calibration as $E_T^{\text{RefJets}}$ and thus adjusted as well. The resulting $m_T^W$ distributions are tilted with respect to the nominal distribution, which is illustrated for selected events in Figure 6.8(a). An overestimation of the contribution from jets and TopoCells outside of final state objects results in a worse $E_T$ resolution, which in turn renders a broader $m_T^W$ distribution. In addition, the magnitude $E_T$ is scaled and an increased number of events passes the event selection.

The second example concerns the scenario in which the contribution from electrons is subject to a systematic effect. Apart from the impact on $E_{x,y}^{\text{RefEle}}$, the transverse momentum of the electron in (6.5) is adjusted accordingly as well. The impact on the $m_T^W$ distribution is a shift. This is illustrated in Figure 6.8(b) which shows the $m_T^W$ distributions when $E_T^{\text{RefEle}}$ is under- or overestimated by 5%. In this scenario, the $E_T$ is scaled with respect to the nominal distribution, yet the resolution is hardly affected.

![Figure 6.8: The impact of badly reconstructed $E_T$ on the $m_T^W$ distribution in events that pass the electron channel selection in 200 pb$^{-1}$.](image)

In conclusion, systematic variations of the $E_T$ reconstruction result in deformations of the $m_T^W$ distribution; either in a shift of the distribution or a broadening of the peak. This effect is utilized in order to assess the quality of the $E_T$ reconstruction in data in the following section. The final aim is to recognize and quantify a total systematic deviation of the $E_T$ reconstruction from the simulation. The difference in impact on the distribution between the examples mentioned above may in fact hint to the source of the deviation and inspire further investigations.

### 6.2.2 Fit Method

In order to exploit the sensitivity of the transverse $W$ boson mass to the $E_T$ reconstruction performance, the distribution as reconstructed from data is compared to a number of Monte
Carlo generated templates in each of which a scenario of wrongly reconstructed $\not{E}_T$ is assumed. Rather than investigating each of the many possible sources of a deviation of the $\not{E}_T$ reconstruction in data from simulation, the possible deviation is more generally decomposed into a scale $\alpha$ and an additional resolution $r$. In each template, the $x$- and $y$- components of $\not{E}_T$ are scaled with a parameter $\alpha$ and convoluted with a normalized two-dimensional Gaussian distribution of width $r$. A template with $r = 0$ and $\alpha = 1$ thus corresponds to the nominal $\not{E}_T$ resolution according to the simulation as addressed in Figure 6.4(a). For every set of $\alpha \in [0.70, 1.30]$ and $r \in [0, 30]$, the transverse $W$ mass distribution from Monte Carlo, $m_T^{W,MC}(\alpha, r)$, is compared to the distribution obtained from the data. In the interval $m_T^W \in [50, 120]$ GeV, the $\chi^2$ is calculated by comparing the two distributions in each bin $i$,

$$\chi^2 = \sum_i \left( \frac{m_{T,i}^W - m_{T,i}^{W,MC}}{\sigma_i^2} \right)^2,$$

where $\sigma_i^2$ is the sum of the squared statistical uncertainties on the two histograms in the $i$th bin. The normalization is determined by requiring the number of Monte Carlo events in the region $m_T^{W,MC} \in [50, 120]$ GeV to be equal to the number of data events, i.e. no assumption is made concerning the absolute production cross section. For each value of $\alpha$ and $r$ for which a template exists, the $\chi^2$ is calculated. The two-dimensional $\chi^2$ distribution is subsequently fitted with a parabola in order to retrieve the position of its minimum, $(\alpha, r)^{\text{fit}}$. The statistical uncertainty is determined from the contour line that describes where the $\chi^2$ is increased with 2.30 with respect to its minimum. The values $(\alpha, r)^{\text{fit}}$ corresponding to the minimum $\chi^2$ reveal if the reconstructed $\not{E}_T$ is underestimated or overestimated by some scale $\alpha$ and/or displaying a higher resolution than expected from simulation.

In practice, the sample of events that is acquired by applying the event selection of Section 5.2 contains contributions from $W + \text{jets}$, single top, multi-jet and dileptonic $t\bar{t}$ events in addition to the semileptonic $t\bar{t}$ events. Fortunately, the dominant background contribution from $W + \text{jets}$ events in fact contains an actual $W$ boson and the $m_T^W$ distribution is still a good reflection of the performance of the $\not{E}_T$ reconstruction in events that resemble the semileptonic $t\bar{t}$ topology. Although from a physics point of view, these events are a background to $t\bar{t}$ events, in the reconstruction performance study at hand, they are regarded as signal. This statement is motivated in Section 6.2.3. Multi-jet events, however, are expected to distort the distribution as neither the reconstructed electron nor muon nor the reconstructed $\not{E}_T$ are caused by a leptonically decaying $W$ boson. The distributions of the reconstructed transverse $W$ boson mass in simulated events that pass the selection criteria are shown in Figure 6.9(a) for the electron channel and in Figure 6.9(b) for the muon channel. Table 6.1 shows the expected composition of selected events in the interval $m_T^W \in [50, 120]$ GeV for 200 pb$^{-1}$.

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2 In case of one fit parameter, $\Delta \chi^2 = 1$ corresponds to a coverage probability of 68 %, i.e. the standard error. Here the number of fit parameters is two and $\Delta \chi^2 = 2.3$ gives the standard error.
The selected $W + \text{jets}$ events can be regarded as signal in the context of this performance study, which enhances the number of events that is available in 200 pb$^{-1}$ of accumulated data and statistical fluctuations are reduced. Because an actual $W$ boson is reconstructed, the shape of the $m_W^T$ distribution for $W + \text{jets}$ events that pass the selection criteria is similar to that for $t\bar{t}$ events. The agreement is explicitly investigated by constructing a scenario in which the contribution from $W + \text{jets}$ events in the sample of simulated events is multiplied by a factor of two. The templates that are compared to this “diluted” distribution contain all samples except for the multi-jet events and they contain the nominal share of $W + \text{jets}$ events. Figure 6.10 shows the result of the fit for the muon channel in a scenario in
6.2 Transverse $W$ Boson Mass

Figure 6.10: Template fit in the muon channel in a scenario with a double contribution from $W + \text{jets}$ events.

which the contribution from $W + \text{jets}$ events is multiplied by a factor of two. The outcome of the fit is $(\alpha, r)^{\text{fit}} = (0.99^{+0.016}_{-0.013}, 0.8^{+2.68}_{-0.78} \text{ GeV})$, i.e. the shape of the diluted distribution is in good agreement with the nominal template distribution. Hence, the fit method is independent of the ratio of the $W + \text{jets}$ cross section to the $t \bar{t}$ cross section.

6.2.4 Multi-jet Events

Estimation of the Contribution

As shown in Table 6.1, the restriction to perform the template fit only in the interval $m_T^W \in [50, 120] \text{ GeV}$ strongly reduces the influence of multi-jet events. However, due to the uncertainty on the production cross section (cf. Section 3.3.1), the prediction on the multi-jet contribution from Monte Carlo is not reliable. The aim is to extract this contribution from the data instead. To this end, the $m_T^W$ distribution of multi-jet events is disentangled from the other contributions by means of the template fit.

Figure 6.9 showed that multi-jet events are characterized by small values of the reconstructed $m_T^W$. This observation is further clarified below. As a consequence, the impact of multi-jet events on the template fit is expected to be minor given that the fit is performed in the interval $m_T^W \in [50, 120] \text{ GeV}$. However, the difference between the complete data distribution and the best template is expected to be due to multi-jet events, which are not contained in the template. Therefore, the multi-jet contribution is estimated by subtracting the template for $(\alpha, r)^{\text{fit}}$ from the data distribution.

The procedure is tested here by means of an input distribution which contains events from all Monte Carlo samples, but in which the actual number of events is limited to 200 pb$^{-1}$. First, the $m_T^W$ distribution for events in the muon channel is regarded. The outcome of the template fit is $(\alpha, r)^{\text{fit}} = (0.99^{+0.014}_{-0.011}, 1.6^{+3.22}_{-1.58} \text{ GeV})$, i.e. the scale of $E_T$ is compatible with the nominal value $\alpha = 1.0$ and the additional resolution $r$ is small with respect to the nominal resolution of approximately 12 GeV. Figure 6.11(a) shows the template corresponding to these values and the resulting estimation of the multi-jet contribution. The estimation agrees very well with the multi-jet contribution according to
Monte Carlo. To illustrate the robustness of the method, the same procedure is applied to a scenario in which the multi-jet contribution is multiplied by a factor of two. The result is shown in Figure 6.11(b).

Figure 6.11: The outcome of the multi-jet estimation based on the template fit in the muon channel. The number of input events corresponds to 200 pb$^{-1}$ integrated luminosity.

Secondly, the multi-jet contribution in the electron channel is investigated. Figure 6.12 shows the estimation of the multi-jet contribution in the electron channel as extracted from the template fit. The best template corresponds to $(\alpha, r)^\text{fit} = (0.99^{+0.020}_{-0.021}, 1.1^{+3.50}_{-1.10} \text{GeV})$ and also in the electron channel, the obtained multi-jet estimation is in good agreement with the distribution according to Monte Carlo.

Figure 6.12: Estimation of the multi-jet contribution to the $m_T^W$ distribution by means of a template fit in the electron channel.
6.2 Transverse $W$ Boson Mass

Figure 6.13: Comparison between the $m_T^W$ distributions for different jet selection criteria in simulated multi-jet events. The number of events corresponds to the number of selected events in 200 pb$^{-1}$ integrated luminosity.

Multi-jet Characteristics

The shape of multi-jet contribution in Figure 6.9 clearly differs from the contributions from other types of events. Moreover, the contribution in the electron channel differs from that in the muon channel. Further investigation is limited by the number of events in the Monte Carlo samples, due to which the multi-jet events in Figure 6.9 obtained large weight factors to correspond to 200 pb$^{-1}$. Although the error bars are scaled accordingly, the size of the samples is not sufficient to mimic the expected statistical fluctuations in 200 pb$^{-1}$. In order to overcome this obstacle, an ad hoc procedure is introduced to obtain a larger sample of multi-jet events. For the purpose of this study, a larger sample is obtained by loosening the selection criteria.

The jets requirement described in Section 5.2.4 is modified as follows: merely one reconstructed jet with $p_T > 40$ GeV is required in the muon channel and the jets requirement is completely disregarded in the electron channel. The $m_T^W$ distributions with the new criteria are then scaled to agree with the number of events that are expected pass the complete event selection in 200 pb$^{-1}$ as given in Table 6.1. The kinematics of the additional events that are accepted in this scheme could differ from the original events, but recall that all multi-jet events in the electron channel pass the top jet filter described in Section 3.3. In fact, Figure 6.13 shows that the obtained distributions are in reasonable agreement with the original description with the full event selection applied. The increased number of events allows for a more detailed investigation of the shape of the $m_T^W$ distribution in multi-jet events. Note that this ad hoc scenario serves the purpose of this illustration only and would not be necessary when studying collision data.

It has been shown that in the majority of the multi-jet events, the reconstructed $m_T^W$
is considerably smaller than $m_W$ and the events do not enter the range in which the fit is performed. The explanation follows from the definition of $m_W^T$ in (6.5). Generally, in multi-jet events that pass the lepton requirement, a jet is falsely reconstructed as an isolated charged lepton. As a consequence of the incorrect assignment, nonzero $E_T$ is introduced, which is likely to point in the direction of the missed jet. This $E_T$ may also be caused by actual neutrinos that originate from semileptonically decaying $b$-jets. Figure 6.14 shows that indeed the opening angle in the transverse plane generally adopts smaller values in multi-jet events than in $t\bar{t}$ events. The peak around zero is particularly narrow for multi-jet events in the muon channel, where the reconstructed muon most often originates from a semileptonically decaying $B$ hadron and is thus accompanied by a neutrino.

However, in part of the multi-jet events the opening angle $|\Delta \varphi (l, E_T)|$ adopts larger values. Either the reconstructed $\varphi (E_T)$ suffers from an inferior resolution or the presence of two semileptonically decaying $b$-jets complicates the interpretation of $\varphi (E_T)$. In such events, in which $\cos (\Delta \varphi (l, E_T)) \approx -1$, the expression in (6.5) becomes more sensitive to the reconstructed values of $E_T$ and $p_T$. Both are steeply falling distributions with a lower threshold at 20 GeV, which is determined by the selection criteria (cf. Figure 5.4). In these type of events, the reconstructed $m_W^T$ is likely to adopt values around 40 GeV, which is indeed observed in Figure 6.13.

![Figure 6.14](image)

(a) The electron channel.

(b) The muon channel.

Figure 6.14: Comparison between the $\Delta \varphi (l, E_T)$ distribution in selected multi-jet events and in selected $t\bar{t}$ events. The distributions are normalized to unity.

Multi-jet events in which the opening angle $\Delta \varphi (l, E_T)$ is small are already suppressed by the restriction $m_W^T > 50$ GeV. In order to further suppress the multi-jet contribution, an additional requirement is imposed when performing the template fit method. Instead of the opening angle with respect to the lepton, the azimuthal angle of $E_T$ is now compared to that of the closest reconstructed jet:

- The opening angle in the transverse plane between the reconstructed $E_T$ and the
closest reconstructed jet is to satisfy $|\Delta \varphi(E_T, \text{jet})| > 0.3$.

The motivation for this requirement is illustrated by Figure 6.15, which displays the normalized distributions for multi-jet events and $t\bar{t}$ events that are selected in the muon channel and satisfy $m_{T}^{W} > 50$ GeV. When the $E_T$ in an event points in the same direction as a reconstructed jet, large $E_T^{\text{Fake}}$ is likely to be present due to a mis-reconstruction of the jet.

![Figure 6.15: The angle $|\Delta \varphi(E_T, \text{jet})|$ between the reconstructed $E_T$ and the closest reconstructed jet in the transverse plane. The distributions are shown for $t\bar{t}$ and multi-jet events that are selected in the muon channel and satisfy $m_{T}^{W} > 50$ GeV.](image)

6.2.5 $b$-Tagging

In the future, as soon as the efficiency of the $b$-tagging algorithm is reasonably well understood, the event selection can be extended to include the requirement that two $b$-tagged jets are reconstructed. Such an additional requirement will greatly improve the purity of the sample of selected events. However, the number of available events in 200 pb$^{-1}$ decreases since all contributions are affected. In particular the contribution from $W + \text{jets}$ events will be severely diminished. The cumulative distributions for the muon channel are shown in Figure 6.16, where jets are $b$-tagged if their combined weight is larger than 5.0 (cf. Figure 4.5). Depending on the progress of $b$-tagging validation, the performance of the $E_T$ reconstruction may be investigated in such a sample as well by means of the $m_{T}^{W}$ template fit.

6.3 Results of the Template Fit

The proposed method to investigate the performance of the $E_T$ reconstruction is now tested in a wide range of scenarios. The templates include all event samples except for multi-jet events. The input scenarios contain all Monte Carlo samples, yet the number of events in each of the input distributions is restricted as to correspond to 200 pb$^{-1}$. The input distributions are obtained by scaling the components of the reconstructed $E_T$ in these events with $\alpha$ and convoluting them with a Gaussian of width $r$ GeV. For events that pass
the selection criteria after this modification, the transverse $W$ boson mass is reconstructed and fitted to the templates.

To illustrate the procedure, the $m_W^T$ distributions corresponding to the input, the nominal template and the best fit are shown in Figure 6.17(a) for one specific scenario. The input distribution corresponds to events in which $\not{E}_T$ is subject to $\alpha = 0.8$ and $r = 8$ GeV and the events pass the electron channel selection criteria. The template that renders the

![Graph showing the cumulative distributions of $m_W^T$ for selected events in the muon channel with the additional requirement that two $b$-tagged jets are reconstructed.](image)

Figure 6.16: The cumulative distributions of $m_W^T$ for selected events in the muon channel with the additional requirement that two $b$-tagged jets are reconstructed.

![Graph showing the $m_W^T$ distribution in selected events in which $\not{E}_T$ is modified (markers), the distribution corresponding to the best template (line) and the original distribution (dashed line).](image)

(a) The $m_W^T$ distribution in selected events in which $\not{E}_T$ is modified (markers), the distribution corresponding to the best template (line) and the original distribution (dashed line).

![Graph showing the contours corresponding to deviations of $1\sigma, 2\sigma$ and $3\sigma$ around the point that provides the minimal $\chi^2$.](image)

(b) The contours corresponding to deviations of $1\sigma, 2\sigma$ and $3\sigma$ around the point that provides the minimal $\chi^2$.

Figure 6.17: The result of an example where the template fit is performed on simulated events in which $(\alpha, r)$ is set to $(0.8, 8$ GeV). The distributions correspond to selected events in the electron channel in $200 \text{ pb}^{-1}$.  

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minimal $\chi^2$ in this example corresponds to $(\alpha, r)^{\text{fit}} = (0.78^{+0.027}_{-0.018}, 8.7^{+1.72}_{-1.09}$ GeV), which agrees well with the input values. The contours that correspond to standard deviations of 1$\sigma$, 2$\sigma$ and 3$\sigma$ around the minimum are indicated in Figure 6.17(b). A correlation is observed between the scale $\alpha$ and the width $r$, indicating that their contributions to the shape of $m_W^T$ can not be disentangled entirely.

The results of the template fit for all investigated scenarios are graphically displayed in Figure 6.18. The input values cover all combinations of $\alpha \in \{0.8, 0.9, 1.0, 1.1, 1.2\}$ and $r \in \{0, 4, 8, 12\}$ GeV. Figures 6.18(a) and 6.18(c) contain the respective values of $\alpha^{\text{fit}}$ and $r^{\text{fit}}$ in the electron channel, while Figures 6.18(b) and 6.18(d) display the results in the muon channel. The results are in good agreement with the input values for most of the scenarios. The electron channel seems slightly more challenging than the muon channel, which is likely to be caused by the difference in contributions from multi-jet events. It turns out that an addition of more than 8 GeV to the original resolution is too severe to be retrieved exactly. The value of $r^{\text{fit}}$ is generally overestimated whereas the value of $\alpha^{\text{fit}}$ is underestimated in these cases. This bias is caused by the fact that the fit model does not include the multi-jet contribution and by the correlation between the fit parameters. A large disagreement with the nominal values is nevertheless observed, indicating that the reconstruction algorithm and the detector performance need to be investigated. An additional resolution on $E_T$ of the order of the nominal resolution is however quite unlikely.

As described in Section 6.2.1 there are many possible reasons for the reconstructed $E_T$ to deviate from the expectation from Monte Carlo. Not all scenarios are quantitatively described by the above parametrization, although discrepancies do indicate that further investigation is required. If the nominal values are not retrieved, each of the contributions in (4.9) is to be investigated in more detail. For example, in case a discrepancy is observed in the muon channel whereas the electron channel results are in agreement with the nominal values, it makes sense to adjust the fit model as to retrieve a scale in the contribution of $E_{\text{MuonBoy}}$. A scenario, for instance, in which the calorimeter response is locally distorted results in nonzero values of $r^{\text{fit}}$ and is subsequently best identified by regarding the distribution of $\varphi(E_T)$.

Conclusion

The template fit method using $m_W^T$ provides a way to test and understand the performance in events with large final state activity and in the electron and muon channel separately. Its results clearly indicate the compatibility of the $E_T$ reconstruction in the data with the expectation from Monte Carlo. The method is stable under variations of the cross sections of $W + \text{jets}$ as well as multi-jet events. As a bonus, the poorly understood contribution from multi-jet events may be extracted from data.

The proposed method is performed on a small sample of 2010 data in Chapter 8.
Missing Transverse Energy in $t\bar{t}$ Events

Figure 6.18: The results of the $m_T^W$ template fit in all scenarios constructed with simulated events.

(a) The values of $\alpha^\text{fit}$ for all scenarios in the electron channel.

(b) The values of $\alpha^\text{fit}$ for all scenarios in the muon channel.

(c) The values of $r^\text{fit}$ for all scenarios in the electron channel.

(d) The values of $r^\text{fit}$ for all scenarios in the muon channel.