Radiating top quarks
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Detection of top quarks in ATLAS

The ATLAS detector (A Toroidal LHC ApparatuS) has been designed [148] and built [149] to exploit the rich physics potential provided by the LHC. This potential ranges from more precise measurements of the Standard Model parameters to the search for new physics phenomena. The detection of top quark events will play a prominent rôle, not only in understanding physics, but also in understanding the detector; the complex event topology requires the full detector capabilities. In this chapter first an overview of the ATLAS detector and its expected performance will be given. In the second part of the chapter, jet reconstruction, a key element in the detection of top quark events, is treated.

Figure 3.1: Cut-away view of the ATLAS detector.
Chapter 3. Detection of top quarks in ATLAS

3.1 The ATLAS detector

The ATLAS detector, shown in Figure 3.1, has a length of 44 meters, a diameter of 25 meters and an overall weight of approximately 7,000 tonnes. It is located 92 meters under the ground at Point 1 of the LHC ring. The detector acquired its name ‘A Large Toroidal LHC ApparatuS’ due to the magnet system. It consists of four large superconducting magnets: a solenoid, a barrel toroid and two end-cap toroids. The major detector components are the inner detector, the calorimeters, and the muon spectrometer. The installation of the detector parts started in 2003 and was fully completed in 2008.

The main design criteria of the ATLAS detector were:

- Efficient tracking at high luminosity for high-$p_T$ lepton momentum measurements, electron and photon identification, $\tau$-lepton and heavy-flavour identification;
- Good electromagnetic calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and missing transverse energy measurements;
- High-precision muon momentum measurements with the capability to guarantee accurate measurements at the highest luminosity using the muon spectrometer alone;
- Efficient triggering with low $p_T$-thresholds on electrons, photons, muons, and $\tau$-leptons, thereby providing high data-taking efficiencies for most physics processes of interest at the LHC;
- Large acceptance in pseudorapidity with almost full azimuthal coverage for all of the major detector systems;

These general requirements cover the needs for top quark physics. The reconstruction of top quark events typically involves isolated leptons, ($b$ quark) jets, and missing transverse energy due to neutrinos escaping undetected. The performance goals set for each subsystem to obtain accurate measurements of these objects are given Table 3.1.

3.1.1 Inner detector

The inner detector records tracks of charged particles with a transverse momentum above a threshold of approximately 0.1 GeV and within a pseudo-rapidity range of $|\eta| < 2.5$. The charge and transverse momentum of a particle can be determined from the bending of its track in the 2 Tesla axial magnetic field provided by the solenoid surrounding the inner detector. With the vertexing layer (the tracking layer closest to the interaction point) the inner detector can be used to measure the position of the primary vertex and identify secondary vertices with high accuracy. The latter is needed for tagging jets originating from $b$ and $c$ quarks and $\tau$ leptons. For top quark physics, ‘$b$-tagging’ of jets is a powerful tool to suppress background since top quarks nearly always decay to $b$ quarks. Finally, the inner detector is also capable of separating electrons from pions up to $|\eta| = 2.0$. 
3.1. The ATLAS detector

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>$\sigma_{p_T}/p_T = 0.05% \times p_T \oplus 1%$</td>
<td>$\pm2.5$</td>
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<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 10% / \sqrt{E} \oplus 0.7%$</td>
<td>$\pm3.2$</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td>$\sigma_E/E = 50% / \sqrt{E} \oplus 3%$</td>
<td>$\pm3.2$</td>
</tr>
<tr>
<td>barrel and end-cap</td>
<td>$\sigma_E/E = 100% / \sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
</tr>
<tr>
<td>forward</td>
<td>$\sigma_{p_T}/p_T = 10%$ at $p_T = 1$ TeV</td>
<td>$\pm2.7$</td>
</tr>
</tbody>
</table>

Table 3.1: General performance goals of the ATLAS detector [149]. Note that, for high-$p_T$ muons, the muon-spectrometer performance is independent of the inner-detector system. The units for $E$ and $p_T$ are in GeV.

Layout

The layout of the inner detector is illustrated in Figure 3.2. The precision tracking detectors using pixels and silicon micro-strips (SCT) cover the region $|\eta| < 2.5$. In the barrel region, they are arranged on concentric cylinders around the beam axis while in the end-cap regions they are located on disks perpendicular to the beam axis. All pixel layers are segmented in $R - \phi$ and $z$ with typically three pixel layers crossed by each track. For the SCT, eight strip layers are crossed by each track, resulting in four space points.

![Cut-away view of the ATLAS inner detector.](image)

Figure 3.2: Cut-away view of the ATLAS inner detector.

The transition radiation tracker (TRT) measures tracks up to $|\eta| = 2.0$. In addition, the TRT enhances the electron identification capabilities by the detection of transition-
radiation photons in the xenon-based gas mixture of the drift (straw) tubes. The intrinsic accuracy on the measured drift radii is $\sim 130 \mu m$ per straw. In the barrel region, the straws are parallel to the beam axis with their wires divided into two halves at $\eta = 0$ to reduce the occupancy per readout channel. In the end-cap region, the straws are arranged radially in wheels. The straw hits at the outer radius contribute significantly to the momentum measurement, since the measured track length is extended considerably.

**Tracking performance**

A measure of the tracking performance is the resolution of track parameters. Two important track parameters, especially for $b$-tagging, are the transverse and longitudinal impact parameters, $d_0$ and $z_0$ respectively. The two impact parameters are the minimum transverse and longitudinal distance of an extrapolated track to the primary vertex. Therefore, they allow to discriminate against primary and secondary tracks.

In Figure 3.3 the expected resolutions of the two impact parameters are shown as function of the track $p_T$ for different pseudo-rapidity ranges. The resolutions are estimated by matching reconstructed tracks with Monte Carlo tracks in simulated $t\bar{t}$ events for two $b$-tagging algorithms. At low transverse momentum the resolution is dominated by multiple scattering, whereas at high transverse momentum the resolution is limited by the intrinsic accuracy of the inner detector. For larger pseudo-rapidities, the amount of inner detector material traversed by a charged particle increases, resulting in a degraded resolution. For a central track with $p_T = 5$ GeV, which is typical for $b$-tagging, the transverse impact parameter resolution is about 35 $\mu m$.

![Figure 3.3](image)

*Figure 3.3: Expected track impact parameter resolution versus track $p_T$, for several bins in the track pseudo-rapidity. First plot is for transverse impact parameter $d_0$, second for longitudinal impact parameter $z_0$.***

**Vertexing performance**

Identification of $b$ quark jets relies on the properties of the production and weak decay of $B$ hadrons. The most important one is the relatively large lifetime of about 1.5 ps
3.1. The ATLAS detector

$\langle l \rangle = \beta \gamma c \tau$, therefore leads to a signature with one or more displaced secondary vertices. For example, $B$ hadrons inside a jet with transverse momentum of 50 GeV, travel on average about 3 mm in the transverse plane before decaying.

Figure 3.4 shows the resolution achieved on the inclusively reconstructed $B$ hadron decay vertex with respect to the true $B$ hadron position in simulated $t\bar{t}$ events. A core can be seen, corresponding to the cases where most of the reconstructed tracks really stem from the $B$ hadron vertex, approaching the intrinsic resolution of the vertex reconstruction, while a very large tail to higher flight lengths can be observed, due to tracks coming from the decay of the charmed hadron of the $b \to c$ hadron cascade.

![Diagram](image)

**Figure 3.4:** Residuals of the reconstructed three dimensional (left) and transverse (right) flight length of the inclusive secondary vertex with respect to the true $B$ hadron position for two vertexing algorithms.

3.1.2 Calorimeters

The calorimeters, presented in Figure 3.5, are sampling calorimeters covering the range $|\eta| < 4.9$. The electromagnetic (EM) calorimeter has a fine granularity (depending on $\eta$ but typically $\Delta \eta \times \Delta \phi \approx 0.025 \times 0.025$) in the pseudo-rapidity region matched to the inner detector and is suited for precision measurements of electrons and photons. The hadronic calorimeter has a coarser granularity (typically $\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1$), which is sufficient to satisfy the physics requirements for jet reconstruction and $E_T$ measurements. The total thickness of the electromagnetic calorimeter in the barrel (end-cap) region is more

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$^1$due to the subsequent decay of a charmed hadron
than 22 (24) radiation lengths. The total thickness of the hadronic calorimeter in the barrel region (end-cap) is more than 9.7 (10) interactions lengths. These depths provide a good containment of electromagnetic and hadronic showers and limit punch-through into the muon system.

Figure 3.5: Cut-away view of the ATLAS calorimeter system.

Layout

The EM calorimeter is divided into a barrel part (|\eta| < 1.475) and two end-cap components (1.35 < |\eta| < 3.2). It is a lead–Liquid Argon (LAr) detector with accordion-shaped copper electrodes and lead absorber plates over its full coverage. The accordion geometry provides complete \( \phi \) symmetry without azimuthal cracks. In the region |\eta| < 1.8, a presampler detector is used to correct for energy lost by electrons and photons before reaching the calorimeter.

The hadronic calorimeter consists of a tile calorimeter, two hadronic end-caps calorimeters (HEC), and two forward calorimeters (FCal). The tile calorimeter covers the region |\eta| < 1.0 and its two extended barrels the range 0.8 < |\eta| < 1.7. Steel is used as the absorber and scintillating tiles as the active material. The two HECs extend from |\eta| = 1.5 to 3.2, thereby overlapping slightly with the tile calorimeter and the FCals. In the HECs, copper plates are interleaved with LAr gaps, providing the active media. Finally, the two FCals covers the range 3.1 < |\eta| < 4.9. They both consist of three modules: the first, made of copper, is optimised for electromagnetic measurements, while the other two, made of tungsten, measure predominantly the energy of hadronic interactions. The sensitive medium is LAr. The FCals are very important to guarantee that particles do not escape at very large \( \eta \) thereby significantly degrading the \( E_T \) resolution.
Electromagnetic performance

Expectations for the performance of the electromagnetic calorimeter have been based on detailed simulation studies. One of these studies is on the energy resolution as a function of energy, shown in Figure 3.6, for electrons for three values of $|\eta|$. The results include the expected electronic noise contribution of 190 MeV (240 MeV) for electrons in the barrel (end-cap) region. At larger $\eta$-values, the resolution is degraded with respect to the one at the more central value of $\eta$. Fits to the energy resolution yield stochastic terms of respectively 10.0, 15.1, and 14.5% $\sqrt{\text{GeV}}$. The $\eta$-region between 1.37 and 1.52 is in general not used for precision measurements with electrons because the energy resolution is significantly reduced in this region. It corresponds to the difficult transition region between the barrel and end-cap cryostats.

Figure 3.6: Expected relative energy resolution as a function of energy for electrons at $|\eta| = 0.3$, 1.1, and 2.0. The curves represent fits to the points at the same $|\eta|$ by a function containing a stochastic term, a constant term and a noise term.

Figure 3.7: Overall reconstruction and identification efficiency of various levels of electron cuts: loose, medium, and tight isolation as a function of $E_T$ for single electrons (open symbols) and for isolated electrons in a sample of physics events with a busy environment (full symbols).

Figure 3.7 shows in more detail the overall reconstruction and identification efficiencies for three sets of electron cuts: the $E_T$ dependence of the efficiencies is shown for single electrons of fixed $E_T$ as well as for physics processes containing isolated electrons from cascade decays of supersymmetric particles to illustrate the rather stable behaviour of the cuts when moving from the ideal case of single particles to a busy environment with many additional jets in the event. The somewhat worse efficiency observed in complex events is attributed to the fraction of cases when the electron candidate is close to or even within a high-$p_T$ jet. The overall efficiency of the cuts remains stable for even higher electron energies (the efficiency of the tight isolation cuts is 68% for electrons of $E_T = 500$ GeV).
Hadronic performance

The reconstruction and calibration of jets from calorimeter signals is discussed in detail in Section 3.2. One of the prerequisites for a good jet reconstruction performance is signal linearity. The signal linearity for calorimeter jets is expressed by the ratio of the reconstructed jet energy and the matched Monte Carlo truth jet energy, \( E_{\text{jet}}/E_{\text{truth}} \), in simulated di-jet events. Figure 3.8 shows for two different regions in \(|\eta|\), that the signal linearity for jets, made from calorimeter towers signals within a cone of \( \Delta R = 0.7 \), is reasonable over the whole energy range after global calibration is applied. Figure 3.8 also shows the deviations from signal linearity expected for jets reconstructed at the electromagnetic energy scale, i.e. without any hadronic calibration applied. In this case, the reconstructed jet signals correspond to only \( \sim 65\% \) (at the lowest energies) to \( \sim 80\% \) (at the highest energies) of the true jet energy.

\[
\sigma_E = \sqrt{a^2 E + b^2 E^2 + c^2} \quad (3.1)
\]

For central jets in the region \( 0.2 < |\eta| < 0.4 \), the stochastic term is \( a \approx 60\% \sqrt{\text{GeV}} \), while the high-energy limit of the resolution, expressed by the constant term, is \( c \approx 3\% \) with the current global calibration. One important contribution to the \( \eta \)-dependence of the jet energy resolution is the noise, which varies quite rapidly due to the increasing...

Figure 3.8: Signal linearity for cone tower jets with \( \Delta R = 0.7 \), as expressed by the ratio of reconstructed tower jet energy to the matching truth jet energy \( E_{\text{rec}}/E_{\text{truth}} \), in two different regions of \(|\eta|\) and as a function of \( E_{\text{truth}} \). Jet signals calibrated at the electromagnetic energy scale are compared to the fully calibrated jets.

Figure 3.9: Fractional energy resolution for calibrated cone tower jets reconstructed with \( \Delta R = 0.7 \) and \( \Delta R = 0.4 \) in two different regions of \(|\eta|\) and as a function of \( E_{\text{truth}} \).
readout-cell size and the change in calorimeter technology in the hadronic calorimeters from the low-noise tile calorimeter to the (higher-noise) LAr calorimeter with increasing $\eta$. The noise term $b$ in the energy resolution function is found to increase from 0.5 GeV to 1.5 GeV when going from the barrel to the end-cap $\eta$-region shown in Figure 3.9.

$E_T$ performance

Although missing transverse energy is an important quantity for background suppression, it is also a very sensitive and complex quantity. For a good $E_T$ determination a great understanding of the detector response and reconstructed objects is needed. A measure of the $E_T$ performance is the linearity of response. In Figure 3.10 the expected $E_T$ linearity of response as function of true $E_T$ is shown for a number of simulated processes of interest. The evolution of the linearity of response is illustrated for each of the major steps in the $E_T$ reconstruction: the uncalibrated $E_T$ at the electromagnetic scale, the reconstructed $E_T$ based on globally calibrated cell energies and reconstructed muons, the reconstructed $E_T$ including in addition the cryostat correction and finally the refined $E_T$ calibration. After the last step, the linearity for all processes is within 1%.

Figure 3.10: Linearity of response, defined as $(E_T^{\text{true}} - E_T)/E_T^{\text{true}}$, for reconstructed $E_T$ as a function of the average true $E_T$ for different physics processes: $Z \rightarrow \tau^+\tau^-$ ($20$ GeV), $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ ($35$ GeV), semi-leptonic $t\bar{t}$ ($68$ GeV), $A \rightarrow \tau^+\tau^-$ with $m_A = 800$ GeV ($124$ GeV) and events containing supersymmetric particles at a mass scale of $1$ TeV ($280$ GeV).

The $E_T$ resolution $\sigma$ is shown in Figure 3.11. The simple fit function $\sigma = a \cdot \sqrt{\sum E_T}$ shows that the resolution follows an approximate stochastic behaviour over a wide range of values of the total transverse energy deposited in the calorimeters $\sum E_T$. The fit yields values between 0.53 and 0.57 for the parameter $a$, for various processes with $\sum E_T$.
values between 20 and 2000 GeV. For low values of $\sum E_T$ the contribution from noise is important and for very high values of $\sum E_T$ the constant term in the energy resolution dominates, analog to the $b$ and $c$ terms in Eq. (3.1). In these regions departures from the stochastic behaviour are thus expected and observed.

### 3.1.3 Muon spectrometer

The only charged particles that (are supposed to) pass through the calorimeter are muons. High-$p_T$ muons are often a signature of interesting physics events, such as $W \rightarrow \mu \nu$ decays in $t \bar{t}$ or maybe even $H \rightarrow ZZ^{(*)} \rightarrow 4\mu$. In the muon spectrometer, muons with momenta ranging from approximately 3 GeV (the minimum due to energy loss in the calorimeters) to 3 TeV can be identified and measured in a pseudo-rapidity range up to 2.7 using a toroidal magnetic field. Muon measurements are a combination of accurate measurements in the muon spectrometer and in the inner detector. The inner detector provides the best measurements of tracks at low to intermediate momenta while the muon spectrometer performs better above $\sim 30$ GeV. Note that measurements from the muon spectrometer at low momenta are still required to identify the inner detector tracks as muons.

**Layout**

The conceptual layout of the muon spectrometer is shown in Figure 3.12. Over the range $|\eta| < 1.4$, magnetic bending is provided by the large barrel toroid. For $1.6 < |\eta| < 2.7$, muon tracks are bent by two smaller end-cap magnets inserted into both ends of the barrel toroid. Over $1.4 < |\eta| < 1.6$, usually referred to as the transition region, magnetic deflection is provided by a combination of barrel and end-cap fields.

Figure 3.12: *Cut-away view of the ATLAS muon system.*
Over most of the $\eta$-range, a precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by monitored drift tubes (MDT’s). In the barrel region, tracks are measured in chambers arranged in three cylindrical layers around the beam axis. In the transition and end-cap regions, the chambers are installed in planes perpendicular to the beam, also in three layers. In the innermost plane, at $2 < |\eta| < 2.7$, cathode strip chambers (CSC’s) with higher granularity are used to withstand the demanding rate and background conditions.

The muon trigger system covers the pseudorapidity range $|\eta| < 2.4$. Resistive plate chambers (RPC’s) are used in the barrel ($|\eta| < 1.05$) and thin gap chambers (TGC’s) in the end-cap regions ($1.05 < |\eta| < 2.7$). The trigger chambers for the muon spectrometer serve a threefold purpose: provide bunch-crossing identification, provide well-defined $p_T$ thresholds, and measure the muon coordinate in the direction orthogonal to that determined by the precision-tracking chambers.

### Muon performance

The performance of muon reconstruction depends on both the muon spectrometer and inner detector. This can be seen in, for example, the expected resolution and efficiency which have been determined from simulation. Figure 3.13 shows the stand-alone (muon spectrometer solely) and combined momentum (muon spectrometer and inner detector track) resolutions as function of $p_T$ for $|\eta| < 1.1$. The stand-alone resolution displays its characteristic behaviour with optimal resolution at $\sim 100$ GeV. At lower transverse momenta, the stand-alone resolution is dominated by fluctuations in the energy loss in the calorimeters, whereas at higher transverse momentum, it is dominated by the intrinsic MDT tube accuracy, assumed to be 80 $\mu$m in the case of a calibrated and aligned detector. At low transverse momenta, the combined resolution reflects directly the dominant performance of the inner detector, which is itself limited by multiple scattering for transverse momenta below $\sim 10$ GeV.

In Figure 3.14 the expected single muon reconstruction efficiency is shown as function of $|\eta|$ for muons with $p_T = 100$ GeV. The efficiency is defined as the fraction of simulated muons which are reconstructed within a cone of size $\Delta R = 0.2$ of the initial muon. The results are shown for three tracking reconstruction strategies: stand-alone, combined, and segment tag (inner detector track with a muon spectrometer segment). The efficiency for stand-alone tracks drops to very low values in the region with $\eta \sim 0$ because of the large gap for cabling to the solenoid, calorimeter and inner detector. In this region there are very few muon stations. The stand-alone efficiency also drops substantially close to $\eta = 1.2$, which corresponds to a region in the barrel/end-cap transition region where several stations are missing. The efficiency for combining stand-alone muon tracks with the inner detector is very high in the central region, starts to drop for $|\eta| > 2.0$ and decreases rapidly to 0 for $|\eta| > 2.4$. The segment tags contribute only to a limited extent to the overall efficiency for $1.4 < |\eta| < 2.0$ for muons with high $p_T$. For lower $p_T$ the contribution is however substantial.
3.1.4 Trigger system

With bunch crossings at 40 MHz and approximately 23 collisions per bunch crossing, the event rate is too high to store and analyse all the raw detector data, which is roughly 1.5 MB per event. Therefore ATLAS has a trigger system with three distinct levels to reduce the data rate to $\sim 300$ MB/s: L1, L2, and the event filter (EF). Each trigger level refines the decisions made at the previous level and, where necessary, applies additional selection criteria.

**L1**

The L1 trigger searches for high transverse-momentum muons, electrons, photons, jets, and $\tau$-leptons decaying into hadrons, as well as large missing and total transverse energy. Information from the muon trigger chambers and all calorimeters (with reduced-granularity) are processed by the central trigger processor, which implements a trigger ‘menu’ made up of combinations of trigger selections. In each event, the L1 trigger defines one or more Regions-of-Interest (RoI’s), i.e. the geographical coordinates in $\eta$ and $\phi$, of those regions within the detector where its selection process has identified interesting features. L1 trigger decisions are made in less than 2.5 $\mu$s, reducing the rate to about 75 kHz.

**L2**

The L2 selection is seeded by the RoI information provided by the L1 trigger. L2 selections use, at full granularity and precision, all available detector data within the RoI’s (approximately 2% of the total event data). The L2 menus are designed to reduce the
trigger rate to approximately 3.5 kHz, with an event processing time of about 40 ms, averaged over all events.

**EF**

The final stage of the event selection is carried out by the event filter, which reduces the event rate to roughly 200 Hz. Its selections are implemented using offline analysis procedures within an average event processing time of the order of four seconds.

### 3.2 Jet reconstruction

Jet reconstruction is essential for the detection of top quarks. The precise properties of jets, like shape, size, and contents, depend on the algorithm used for jet finding. Ideally, the reconstructed jets exactly correspond to final state partons of the hard interaction. Although jets are typically boosted in the same direction as the partons they originate from, jets consist of different types of particles which do not necessarily all produce measurable signals in the calorimeters. Several calibration steps are thus needed to properly reconstruct jets from the calorimeter signals.

In ATLAS the jet reconstruction sequence is implemented as shown in Figure 3.15. The implementation allows for the use of a variety of jet clustering algorithms using as input any reconstruction object having a four-momentum representation. In the following sections three aspects of jet reconstruction in ATLAS will be discussed: input to jet reconstruction, jet clustering algorithms, and jet calibration.

#### 3.2.1 Input to jet reconstruction

The typical inputs for jet finding are calorimeter signals for ‘reconstructed’ or ‘calorimeter’ jets, and stable particles from the Monte Carlo generator for ‘truth particle’ jets. For the reconstruction of calorimeter jets, two different types of calorimeter signals can be used: towers and topological clusters. Truth particle jets are only available in simulated data and are very useful for comparison with reconstructed jets to determine the impact of detector acceptance and resolution on jet reconstruction performance. Although less common, it is also possible to use charged inner detector tracks for reconstructed jets and Monte Carlo final state partons for truth particle jets.

**Calorimeter towers**

Towers are formed by collecting calorimeter cells into bins of a regular $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ grid and, depending on their location, summing up their signals or a fraction of their signal, corresponding to the overlap area fraction between the tower bin and the cell in $\Delta \eta$ and $\Delta \phi$. This summing stage is non-discriminatory, meaning all calorimeter cells are used in the towers. Towers with negative signals are dominated by noise, and cannot directly be used in jet finding because they do not have valid physical four-vectors. Instead, they are recombined with nearby positive signal towers in order to
Figure 3.15: Schematic view on the reconstruction sequences for jets from calorimeter towers (left), uncalibrated (center) and calibrated (right) topological calorimeter cell clusters in ATLAS. The reconstruction (software) domains are also indicated.
compensate with positive noise. The resulting towers have a net signal which is positive and can be used by the jet finders. Since the noisy cells still contribute to the jets, this approach can be understood as an overall noise cancellation rather than suppression.

Calorimeter tower signals were until recently the default input for jet finding in ATLAS. For consistency, only tower signals have therefore been used in this thesis for jet reconstruction.

**Topological clusters**

Topological clusters are currently the default input for the reconstruction of transverse missing energy and jets respectively. Topological cell clusters represent an attempt to reconstruct energy depositions in the calorimeter in three directions. Direct nearest, secondary nearest, and further outlying neighbouring cells are collected around seed cells using thresholds of $|E_{\text{cell}}|/\sigma_{\text{cell}} > 4$, $2$, and $0$ respectively for the significant absolute signal above the total noise (electronics plus pile-up). If a resulting cluster contains multiple local signal maxima, it is split into smaller clusters.

Contrary to the signal tower formation, topological cell clustering includes actual noise suppression, meaning that cells with no signal at all are most likely not included in the cluster. This results in substantially less noise and less cells in cluster jets than in tower jets. A comparison of the jet reconstruction performance between the two calorimeter input signals in Section 3.2.4 will show that differences for high-$p_T$ jets are rather small. It is therefore expected that the choice of input signal will not significantly affect the analyses in this thesis.

**Truth particles**

Truth particle jets are formed by applying a jet algorithm to all stable particles (neutral and charged) in the final state within $|\eta| < 5$. A particle is defined stable when it has a lifetime in the laboratory frame of more than $3.3 \times 10^{-12}$ s, or equivalently, a decay length of more than 10 mm. The particles can emerge from the hadronisation of a hard-scattered parton, from initial- and final-state radiation, and from the underlying multiple interactions in the event. The kinematic properties of these particles are taken at their generation vertex, before any interaction with the detector and its magnetic field. Neutrinos and muons generated in the collision are excluded from these truth jets, as they have their own observables, i.e. missing transverse momentum for neutrinos and explicitly reconstructed tracks for muons.

### 3.2.2 Jet clustering algorithms

The actual reconstruction of jets from a collection of input-objects (either calorimeter signals or MC truth particles) is carried out by a jet clustering algorithm. During this research the two default algorithms in ATLAS were a seeded fixed cone algorithm and a successive recombination algorithm. Both algorithms are used in two different configurations, shown in Table 3.2, one producing narrow jets for e.g. $W$-mass spectroscopy in $t\bar{t}$ events or events containing large multiplicities of jets as in supersymmetric models, and
the other producing wider jets for e.g. QCD studies of di-jet and multi-jet final states at luminosities below $10^{33}\text{cm}^{-2}\text{s}^{-1}$.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Main parameter</th>
<th>Application</th>
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<tr>
<td>Seeded fixed cone</td>
<td>$R_{\text{cone}} = 0.4$</td>
<td>$W^\pm \rightarrow jj$ in $t\bar{t}$, SUSY</td>
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<td>(seed $p_T &gt; 1 \text{ GeV}$)</td>
<td>$R_{\text{cone}} = 0.7$</td>
<td>inclusive jet cross-section, $Z' \rightarrow jj$</td>
</tr>
<tr>
<td>$k_T$</td>
<td>$R = 0.4$</td>
<td>$W^\pm \rightarrow jj$ in $t\bar{t}$, SUSY</td>
</tr>
<tr>
<td></td>
<td>$R = 0.6$</td>
<td>inclusive jet cross-section, $Z' \rightarrow jj$</td>
</tr>
</tbody>
</table>

Table 3.2: Default jet finder configurations used in ATLAS.

Seeded fixed cone algorithm

The iterative seeded fixed cone jet finder works as follows. First, all input (calorimeter signals or MC truth particles) is ordered in decreasing order in transverse momentum $p_T$. If the object with the highest $p_T$ is above the seed threshold, all objects within a cone in pseudorapidity $\eta$ and azimuth $\phi$ with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < R_{\text{cone}}$ ($R_{\text{cone}}$ is the fixed cone radius) are combined with the seed. A new direction is calculated from the four-momenta inside the initial cone and a new cone is centered around it. Objects are then (re-)collected in this new cone, and again the direction is updated. This process continues until the direction of the cone does not change anymore after recombination, at which point the cone is considered stable and is called a jet. At this point the next seed is taken from the input list and a new cone jet is formed with the same iterative procedure. This continues until no more seeds are available. The jets found this way can share constituents, and signal objects contributing to the cone at some iteration maybe lost again due to the recalculation of the direction at a later iteration.

Because soft particles might change the jet configuration, this algorithm is not infrared safe. This can be (at least) partly recovered by introducing a split and merge step after the jet formation is done. Jets which share constituents with more than a certain fraction $f_{\text{sm}}$ of the $p_T$ of the less energetic jet are merged, while they are split if the amount of shared $p_T$ is below $f_{\text{sm}}$, with $f_{\text{sm}} = 0.5$ in ATLAS. Other important parameters of the ATLAS cone jet finder are a seed threshold of $p_T > 1 \text{ GeV}$, and a narrow ($R_{\text{cone}} = 0.4$) and a wide cone jet ($R_{\text{cone}} = 0.7$) option.

From a theoretical standpoint this particular cone jet finder is by design only meaningful to leading order for inclusive jet cross-section measurements and final states like $W/Z + 1 \text{ jet}$ (with the $W/Z$ decaying leptonically). It is not meaningful at any order for 3-jet final states, $W/Z + 2 \text{ jets}$, and for the measurement of the dijet invariant mass in 2 jets + $X$ final states.

Although using this algorithm might be problematic for comparison with theoretical predictions, this is not the case for comparison between simulated data and collision data in the same experimental environment. The reason for this is that by using the same jet algorithm for the reconstruction of simulated data and collision data, effects
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from the jet algorithm are included in both cases. Therefore, unless stated otherwise, the fixed cone jet algorithm with $R_{\text{cone}} = 0.4$ is the default jet algorithm used in this thesis, conform the default choice of ATLAS for top quark physics at the time. The cone algorithm is also used for the high-level trigger, because this particular implementation is fast.

$k_T$ algorithm

The $k_T$ algorithm is an implementation of a sequential recombination jet finder in ATLAS. The algorithm analyses for all pairs of input objects $i$ and $j$ (partons, particles, reconstructed detector objects with four-momentum representation) a distance measure, defined as:

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \frac{\Delta R_{ij}^2}{R^2} = \min(p_{T,i}^2, p_{T,j}^2) \frac{\Delta \eta_{ij}^2 + \Delta \phi_{ij}^2}{R^2}$$

(3.2)

where $R$ is a free parameter which controls the size of jets. Besides the $d_{ij}$, also the distance of each object $i$ relative to the beam, given by $d_{iB} = p_{T,i}^2$, is determined. The next step is finding the minimum $d_{\text{min}}$ of all $d_{ij}$ and $d_{iB}$. If $d_{\text{min}} = d_{ij}$, the corresponding objects $i$ and $j$ are combined into a new object $k$ according to their four momenta. Both objects $i$ and $j$ are removed from the list, and the new object $k$ is added to it. If $d_{\text{min}} = d_{iB}$, the object $i$ is considered to be a jet by itself and removed from the list.

This procedure is repeated for the resulting new sets of $d_{ij}$ and $d_{iB}$ until all objects are removed from the list. This means that all original input objects end up to be either part of a jet or to be jets by themselves.

The idea behind this algorithm is that the distance measure in Eq.(3.2) corresponds to the squared inverse of the splitting probability for one parton $k$ to go into two, $i$ and $j$, in the limit where either $i$ or $j$ is soft and they are collinear to each other [150]. Because of this close relation to the structure of QCD divergences, this algorithm is also used to determine the various emission scales when merging the parton showering with matrix elements as described in Section 2.2.3.

Contrary to the cone algorithm described earlier, there are no constituents shared between jets. Furthermore, the procedure is infrared and collinear safe because it does not use seeds. On the other hand, disadvantages of this algorithm are that it is computationally slower and that the shape of jets is irregular. As a result of the latter, corrections for detector effects are more complicated than for the cone algorithm. In ATLAS, the default configurations are $R = 0.4$, for narrow, and $R = 0.6$, for wide jets.

Alternative jet finders

In 2009, the SISCone [151] and anti-$k_T$ [152] algorithms have been introduced in ATLAS as alternative cone and sequential recombination algorithm respectively. In contrast with the ATLAS seeded fixed cone jet finder, SISCone (Seedless Infra-red Safe Cone) is a collinear and infrared safe algorithm. This is achieved by starting with all stable cones rather than with seeds to find hard stable cones. This final set of hard stable cones is then unaffected by the presence of soft particles. A downside over this jet finder however is that it is rather slow [153].
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The anti-$k_T$ algorithm clusters objects according to Eq.(3.2) with $p_T^{-2}$ instead of $p_T^2$, which means that it clusters the other way round compared to the $k_T$ algorithm: softer objects will be merged with harder objects in order of their closeness in $\Delta R$ and the circular jet boundary is unaffected by soft radiation.

Although at the time of writing an extensive performance study was still ongoing [154], preliminary results [155, 156] indicate that, compared to other jet finders, the anti-$k_T$ algorithm has an outstanding performance in events with busy multijet topologies and will most likely be the future default jet algorithm. In Section 3.2.4 differences in the performance of the jet algorithms mentioned above will be demonstrated.

3.2.3 Jet calibration

The ultimate goal, reconstruction of jets at the parton level, requires that all jet energy is identified and that any possible difference between observed energy and true energy as a consequence of the detector acceptance, jet algorithm, and physical processes, is accounted for.

As shown in the left plot of Figure 3.16, according to simulation, the fraction of the total jet energy carried by the different particle types in a jet is basically independent of energy\(^2\). About 25% of the energy is carried by photons (mainly from $\pi^0$ decays) and therefore, 25% of the energy deposits in the calorimeters comes directly from pure electromagnetic showers. The right plot shows the average fractional energy observed in the different calorimeter samplings with respect to the true jet energy in the central calorimeter regions ($|\eta| < 0.7$). The observed energy corresponds to the electromagnetic component hadronic shower and without additional calibration it is therefore at the so-called ‘electromagnetic scale’. Most of the energy (about 2/3\(^{rd}\) of the observed ‘jet EM energy’) is measured by the electromagnetic calorimeter.

Figure 3.16: Left: fractional energy carried by different particle types as function of jet energy. Right: fraction of true energy observed in the different calorimeter samplings for a jet in the central ($|\eta| < 0.7$) calorimeter region as function of its true energy.

\(^2\)This is a result of the fact that fragmentation functions are independent of jet energy.
3.2. Jet reconstruction

The total observed jet energy differs significantly from the true jet energy. The large discrepancy is due to the following detector effects:

- the response to hadrons is lower than to electrons and photons, and is non-linear with hadron energy;
- the presence of dead material and cracks in the calorimeters;
- tracks bending in and out the jet cone due to the solenoidal magnetic field;
- neutrinos from the decay of particles inside a jet can not be detected at all.

There are two strategies in ATLAS to correct for these detector effects. The first method is ‘H1 calibration’, and second method ‘local calibration’. H1 calibration is applied after the jet finding stage (sequence I and II in Figure 3.15), while local calibration is applied before the jet finding stage (sequence III). Because the latter method is relatively new and not yet performing as well as the former, it is currently not extensively used in ATLAS. Therefore, only H1 calibrated jets are used in this thesis.

H1 calibration

The longstanding calibration scheme for calorimeter jets in ATLAS is based on cell signal weighting. It can be applied to both tower and cluster jets. The basic idea behind this approach is that low signal densities in calorimeter cells indicate a hadronic signal and thus need a signal weight for compensation of the order of the electron/pion signal ratio $e/\pi$, while high signal densities are more likely generated by purely electromagnetic showers and therefore do not need additional signal weighting.

Each cell $i$ in the jet is weighted by a function depending on the cell location $X_i$ and the cell signal density $\rho_i = E_i/V_i$, with $E_i$ being the electromagnetic energy signal of the cell, and $V_i$ being the volume of the cell. The weighting factor $w \approx 1.0$ for high density signals and rising up to $w \approx 1.5$, the typical $e/\pi$ for the ATLAS calorimeters, with decreasing cell signal densities. The weighting functions are universal in that they do not depend on any jet feature or variable. The calibrated jet four-momentum $(E_{\text{jet}}, \vec{p}_{\text{jet}})$ is then recalculated from the weighted cell signals, which are treated as massless four-momenta $(E_i, \vec{p}_i)$ with fixed directions:

$$\begin{align*}
(E_{\text{jet}}, \vec{p}_{\text{jet}}) &= \sum_{i=1}^{N_{\text{cells}}} w_i(\rho_i, X_i) \left( E_i, \vec{p}_i \right) \\
\end{align*}$$

The signal weighting functions have been determined by comparing reconstructed calorimeter tower jet energies with matching Monte Carlo truth particle jet energies in fully simulated QCD dijet events, using seeded fixed cone jets ($R_{\text{cone}} = 0.7$).

Residual non-linearities (as function of $p_T$) and non-uniformities (as function of $\eta$) are corrected by an additional calibration function parametrised in both variables. These corrections have also been calculated for other standard jet finding configurations and calorimeter signals. The calibration has been determined using the ideal, non-distorted detector geometries. After these energy scale corrections, jets are calibrated to the particle level.
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In-situ calibration

Further refinement of the jet energy scale to the parton level can not be achieved in a generic way. This step has to be performed in the context of a specific physics process or analysis, because physics effects such as such as clustering, fragmentation, initial and final state radiation, underlying event and pile-up (multiple proton-proton interactions) need to be taken into account. Typical processes for this in-situ calibration are di-jet, $\gamma + \text{jet}$, $Z + \text{jet}$, and $W \rightarrow jj$ decays in $t\bar{t}$ events. This topic is however beyond the scope of this thesis.

3.2.4 Jet reconstruction performance

The jet reconstruction performance depends on all the three aspects of jet reconstruction discussed above: signal inputs, clustering algorithms, and calibrations. In this section two of dependencies are highlighted. First, it will be shown how the choice of calorimeter signal as input to jets affects the performance. Then, it will be demonstrated how the choice of jet algorithm affects the performance.

Towers versus clusters

The efficiencies and purities are shown for cone tower and cone cluster jets in VBF produced $H \rightarrow \tau^+\tau^-$ as function of $p_T$ and y in Figures 3.17 and 3.18. For this process the Higgs mass is assumed to be 120 GeV and the $\tau$ only decays leptonically. The jets were reconstructed with $R = 0.7$ and were matched for the efficiency and purity determination with the truth particles using a matching radius $\Delta R_m = 0.5$. These results show that for $p_T > 40$ GeV, the performance of the tower and cluster jets are very similar. For lower values of $p_T$, however, the cluster jets are found with both higher efficiency and purity than tower jets.

![Figure 3.17](image)

**Figure 3.17:** Efficiency (left) and purity (right) of jet reconstruction in VBF-produced Higgs-boson events as a function of $p_T$ of the truth particle jet for cone tower and cone cluster jets with $\Delta R = 0.7$.

For jets reconstructed with $p_T > 10$ GeV, the fake rates in the central region are quite high, ranging from 30% for cluster jets to 45% for tower jets as can be seen in
3.2. Jet reconstruction

Figure 3.18. In the forward regions, the jet-tagging efficiencies are close to 90% for cluster jets while they are only around 50% for tower jets with, however, significantly higher fake rates of \( \sim 10\% \) for the cluster jets. These results are clearly also quite sensitive to pile-up, so it is important to stress here that the numbers above apply only for initial data-taking at luminosities between \( 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \) and \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \).

\[
\text{Efficiency (left) and purity (right) of jet reconstruction in VBF-produced Higgs-boson events as a function of the rapidity of the truth particle jet for } p_T^{\text{jet}} > 10 \text{ GeV and } p_T^{\text{jet}} > 20 \text{ GeV and for cone tower and cone cluster jets with } \Delta R = 0.7.
\]

ATLAS cone and \(k_T\) versus SISCone and anti-\(k_T\) algorithms

The performance of the two (former) default ATLAS algorithms, fixed-cone jet finder and \(k_T\), have been compared with the new algorithms, SISCone and anti-\(k_T\), in the busy event topology of the supersymmetric benchmark process called “SU4”. The signatures of this process are very similar to that of \(t\bar{t}\) production [157]. The jet reconstruction efficiency and purity as a function of jet \(p_T\) for all four algorithms is shown in Figure 3.19. The efficiency and purity are determined by matching reconstructed jets with truth jets that are within a distance \(R = 0.2\).

Both higher efficiencies and purities are obtained for the sequential recombination algorithms and especially for the anti-\(k_T\) algorithm. The same conclusion is also obtained using towers as inputs to the jet algorithms and also using wider jets. Although not shown here, also studies on the influence of pile-up on the jet performance indicate that the anti-\(k_T\) algorithm is the most stable performing algorithm.

For the results in this thesis, quantitatively significant changes are expected when switching to another jet algorithm because of the substantial differences in reconstruction efficiency and purity. However, qualitatively, these changes will be of minor importance as they do not directly affect the systematic uncertainties, such as the modelling of the underlying physics.
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Figure 3.19: Jet efficiency (left) and jet purity (right) as a function of the true jet $p_T$ using topological clusters jet as input for different jet algorithms with $R = 0.4$ and for $|\eta| < 2.5$ and $p_T > 20$ GeV in events where supersymmetric particles are produced according to the SU4 model.

3.3 The typical $t\bar{t}$ event

Figure 3.20 shows an event display of a simulated semi-leptonic $t\bar{t}$ event in the ATLAS detector. The $t\bar{t}$ pair is produced in a proton-proton collision at a centre-of-mass energy of 10 TeV. The anti-top quark decays leptonically via a $W^-$ boson into a muon and a neutrino, the top quark decays hadronically via a $W^+$ boson into jets, resulting in the characteristic signatures: a single isolated lepton, a large amount of missing transverse energy, and multiple high-$p_T$ jets of which two identified as coming from $b$ quarks.
3.3. The typical $t\bar{t}$ event

Figure 3.20: Event display of a simulated semi-leptonic $t\bar{t}$ event in the ATLAS detector. The event display shows (a) a fish-eye projection along the beam axis, (b) a side projection of the $\rho - \phi$ plane (with $\rho = \sqrt{x^2 + y^2}$), and (c) a lego plot of reconstructed objects in the $\eta - \phi$ plane. The fish-eye projection and the side projection show the reconstructed inner detector tracks, energy depositions in the calorimeter cells, and the muon track including the hits in the MDT stations. The magenta dashed line indicates the $\phi$-direction of the missing transverse energy. In the lego plot the amount of energy deposited in the $\eta - \phi$ plane is shown. The gray circles around the energy depositions indicated in yellow represent the five reconstructed jets with $p_T$ above 20 GeV. The additional blue circles around two gray circles mean that those jets are identified as jets coming from $b$ quarks. The highest tower in red represents the 27 GeV muon. The magenta dashed line is the projection of the missing transverse energy in $\eta - \phi$ plane. The amount of missing transverse energy is 59 GeV.