Muons in early ATLAS data: from first collisions to W+ W- production
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Citation for published version (APA):

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After having laid out the hardware and performance of the ATLAS detector in the previous chapter, the software used to reconstruct physics objects in the recorded data and simulated events will be discussed in this chapter. The main focus here lies on the reconstruction and identification of muons in ATLAS, which will be discussed in 3.6. Before that, the software framework, the trigger, the reconstruction of jets and missing transverse energy as well as Monte Carlo simulations will be described. For tracks reconstructed in the Inner Detector, we refer to [63].

### 3.1 Athena Software Suite

Athena is the modular software framework of ATLAS [28]. All processing levels of ATLAS data, from high-level trigger (see 3.2) to reconstruction and analysis take place in this framework. Also the simulation and processing of generated events is performed within Athena. After a digitization step, the generated and simulated events follow the same reconstruction chain as is used for data events. Athena provides the common functionality and communication between the embedded individual algorithms and components and thus insures the necessary coherence of the software infrastructure. Its development and maintenance are a continuous effort leading to one major software release and various amounts of sub-releases of the software per year. A release is a snapshot of Athena and all its algorithms at a given time, creating a baseline for performance and physics studies. Throughout this thesis, Athena is used in releases 15 which was used to initially process the data recorded in 2010 and release 16 which was used to reprocess the 2010 data and initially process data recorded in 2011 in the months up to August. The algorithm discussed in Chapter 4 deals with both releases and its developments in the transition from Athena release 15 to release 16. Since release 16 has substantial improvements, particularly in terms of performance, as in improved alignments, calibrations and general performance boosts, we choose to use this release for the performance and analysis Chapters 5 and 6.
3.2 Trigger

An average ATLAS raw data event is of size 1.5 Mbyte. Scaling up to the LHC design collision rate of 40 MHz leads to a total data stream of about 60 Tbyte per second which can not be stored and analyzed by computing systems available at present nor in the near future. A selection of interesting events has to be made in real time that can be stored and made available for analysis. The rate of events that can be written to the ATLAS disks was on average 305 Hz in 2011 [84]. Reducing the event rate by five orders of magnitude without losing interesting events is a huge challenge which is taken up by the ATLAS trigger system. It is a 3 level trigger system, with each trigger level refining the decisions made by the previous level. The three trigger levels are in the order of their implementation:

1. L1: The Level 1 trigger is a hardware trigger using custom-made electronics. It uses a limited amount of the available detector information to make a decision within 2.5 µs. The rate is reduced from 40 MHz down to 75 kHz. It searches for high $p_T$ leptons, hadronically decaying $\tau$'s, photons as well as jets. Event variables like total transverse energy and large missing energy are constructed. The L1 trigger rates in June 2010 are shown in Figure 3.1 for the unprescaled EM triggers with $E_T$ threshold 2, 3 and 5 GeV, the unprescaled muon triggers with (6 GeV) and without $p_T$ threshold, as well as for the unprescaled jet and $\tau$ triggers with an $E_T$ threshold of 5 GeV. The minimum bias trigger had to be downscaled by a factor 20 [74]. The muon trigger chambers, RPC’s and TGC’s (see 2.3.4) provide the information for the L1 decision on muons, while calorimeter selections are based on reduced granularity information from all calorimeters. Regions-of-Interest (RoI’s), i.e. detector regions where the L1 has identified a trigger object are created and passed on to the L2.

2. L2: The Level 2 trigger is seeded by the RoI’s of the L1. All available detector data is used within the RoI’s to refine the L1 selection. The L2 reduces the 75 kHz L1 event rate to 3.5 kHz with an average event processing time of 40 ms.

3. EF: The Event Filter trigger is the last element of the ATLAS trigger chain. The EF selections are based on offline analysis procedures reducing the total event rate to a maximum of 200 Hz, which is then stored on disk. It takes of the order of four seconds to process an event by the EF.

L2 and EF are also commonly referred to as the high level trigger (HLT). Unlike the L1 trigger, the HLT is implemented using commercially available computers and networking hardware. It uses the full granularity of all ATLAS calorimeters as well as the full precision of MS and ID measurements. The event rates of the individual triggers are a function of the instantaneous luminosity the LHC provides and the respective threshold of the triggers. Hence, the trigger transverse momentum and energy thresholds have to be increased for higher instantaneous luminosities.
3.3 Monte Carlo Simulations

Simulating events are a necessity of any particle physics experiment throughout all its stages. During development and construction of the experiments simulated samples are needed to evaluate the requirements on the hardware and are essential to validate the reconstruction software. At a later stage, during data taking, simulated events are crucial to compare the recorded data to expectations. This section briefly summarizes the individual steps in the generation of simulated samples for ATLAS, i.e. event generation, simulation, digitization and reconstruction. Figure 3.2 visualizes this production chain.

Figure 3.1: This ATLAS plot shows the unprescaled L1 trigger rates in June 2010 as a function of instantaneous luminosity. The plot is taken from [74].

Figure 3.2: A schematic view on the production chain of simulated samples for ATLAS. Monte Carlo generated samples and data are processed by the same reconstruction.
3.3.1 Event Generation

The effective scattering in high energy proton-proton collisions takes place between the constituents of the protons. These quarks and gluons are referred to as partons and carry fractions of the corresponding proton momenta. The probability of finding a parton with a certain momentum fraction is described by the Parton Distribution Functions (PDF’s). In the hard scattering process the initial partons interact and perform the physics processes under study, as for example the production of $W$-bosons, Higgs particles or the production of $W^+W^-$-boson pairs. Besides these hard scattering processes (HS) the so called underlying event (UE), describing interactions of remaining partons, contributes to the observed event. The parton-parton scattering cross-sections can be calculated using pertubative techniques. Monte Carlo (MC) event generators like Herwig [30, 31], Pythia [32] or Sherpa [33] use random numbers to generate these processes as well as the subsequent decay of the created particles. All particles carrying color charge can radiate off gluons. This process is called final state radiation (FSR). Likewise, partons may also radiate off gluons before the hard scattering, which is referred to as initial state radiation (ISR). The radiated off gluons will in turn radiate off more gluons or decay into quark-antiquark pairs. This process, referred to as parton showering, continues up to a certain energy scale, where the color connected partons are grouped into mesons and baryons. This stage in the event generation is hence called hadronization. As an example, Figure 3.3 visualizes a Higgs event associated with a $t\bar{t}$ quark pair generated by Sherpa.

Finally, the generated events with all its particles are stored as Monte Carlo truth and stay accessible also after the event passed the simulation, digitization and reconstruction steps. Monte Carlo truth information is essential to study and understand various physics processes and detector effects.

3.3.2 Detector Simulation

A complex and detailed description of the ATLAS detector is needed to accurately model the propagation of the generated final state particles through the detector. Interactions with the different detector materials are computed by the ATLAS simulation software G4ATLAS [34], which is based on a detailed model of the entire detector with all its subsystems. The algorithm is a customization for ATLAS of the widely-used Geant4 simulation software suite [35]. G4ATLAS propagates all generated final state particles in small steps to the modeled detector surfaces, evaluating and simulating the possible interactions with the local materials step by step. Also the decays of long-living particles such as e.g. $K$ or $\phi$ mesons are included in the simulation. Consequently, all energy deposits of the traversing particles are stored for each of the approximately 25 million volumes in G4ATLAS.

3.3.3 Digitization

The input of the digitization is the list of energy deposits as obtained from the detector simulation. To allow for detailed comparisons of recorded data and Monte Carlo samples,
these energy deposits need to be converted into detector measurements, i.e. electronic signals of deposited charges and electrical currents. This is done by the digitization step, so the output can be treated like raw data, see Figure 3.2.

3.3.4 Reconstruction

After the digitization step, the Monte Carlo events are processed by the same reconstruction algorithms that are used for data. This coherent processing of data and simulated events is essential to study detector effects as well as physics processes. All physics objects are obtained during this stage, such as tracks, jets but also event variables like the missing transverse energy. Detector calibration and alignment are additional important ingredients for the reconstruction algorithms improving the resulting physics observables. At high luminosity there is a non-negligible probability for multiple protons to interact in a single bunch crossing and hence additional particles are created. These events are referred to as pile-up events. This effect is taken into account for increasing luminosity by adding additional minimum bias events to the Monte Carlo samples during the reconstruction.

A more detailed description of the reconstructed physics objects used in this thesis is
given subsequently. We hereby focus on the muon reconstruction and identification as the title of this thesis suggests.

### 3.4 Jets

Jets are features of the hadronic final-states of an event. They are the remnants of a high energetic parton that showered off partons and produced thus a collimated stream of particles. Since jets carry an integer electric charge and zero net color charge, no fully unambiguous mapping to partons in the event is possible. However, they can be a powerful measure of the QCD processes in the hard scattering of the event. After the hadronization, described in 3.3.1, hadrons and long living mesons created in QCD interactions traverse the Inner Detector before they get absorbed in the ATLAS calorimeters, creating energy deposits in cone shaped collections of clusters. Jets are designed to cluster and add up these energy deposits such that their properties like energy, momentum, etc. reflect as closely as possible the properties of the partons in the hard scattering in the center of the collisions. This way, properties of quarks, gluons but also hadronically decaying particles like $W$- and $Z$-bosons can be determined, although they are generally not physical observables.

Unlike electron or muon reconstruction, that aim to find the track and/or energy deposits of the corresponding particle traversing the detector, jet algorithms do not find pre-existing jets, but define them. Therefore, there are various different concepts of how to define a jet. An overview of the discussed jet algorithms for ATLAS is given in [54]. The default jet algorithm chosen for the collaboration is also used to define jets in Chapter 6. It is referred to as the Anti-$k_T$ jet algorithm [29]. The characteristic feature of this algorithm is that in the vicinity $\Delta R < R$ of a hard, thus high transverse momentum calorimeter object all objects with low transverse momentum are merged with the hard object in the order of their closeness in $\Delta R$. $R$ is a parameter of the algorithm which sets the resolution of the algorithm. Figure 3.4 displays an impressive two jet event in ATLAS, recorded in the last days of the 2010 proton-proton run [75]. The transverse momentum of the highest energetic jet amounts to $p_T = 1.3$ TeV. The total energy deposited in the transverse plane is $E_T = 2.2$ TeV.

### 3.5 Missing Transverse Energy

The missing transverse energy, $E_T^{\text{miss}}$ is the vectorial sum of the energies measured by ATLAS in the transverse plane. Since the exact momentum along the beam-pipe of the constituents of the colliding hadrons in hadron colliders is not known but follows the parton distribution functions, the experiments can only use momentum and energy conservation in the transverse plane. An unbalance of energy in the transverse plane signals particles that escape the detector undetected, such as the weak interacting neutrinos. Due to large underlying event effects and possible pile-up events the uncertainty on $E_T^{\text{miss}}$ is large. Besides the energy deposits in the ATLAS calorimeters, also the muon momentum
3.5 Missing Transverse Energy

Figure 3.4: An event display of a two-jet event recorded by ATLAS in 2010.

measurement in the transverse plane is accounted for in the calculation of the $E_T^{\text{miss}}$.

3.5.1 Implementation

The missing transverse energy is composed of several contributions $^1$. The energy deposits in electromagnetic and hadronic calorimeters are accounted for by summing over the calibrated topological clusters referred to as MET_LocHadTopo in the ATLAS community. The topological clustering covers the pseudorapidity range $|\eta| < 4.5$, leaving out the region $4.5 < |\eta| < 5$ as in this regions there are problems with the energy calibration in the FCAL. The clusters are seeded by calorimeter cell deposits above four standard deviations of the cell noise level. Neighboring cells with energy deposits exceeding two standard deviations are added to the cluster. Afterwards, all the neighboring cell deposits are added as well. The clusters are calibrated to correct for dead material in the detector as well as for out-of-cluster deposits, which correspond to energy deposits in calorimeter cells outside of the reconstructed clusters, i.e. in the tails of hadronic or electromagnetic showers which are rejected by noise cuts.

Muons usually traverse the detector without being absorbed in the calorimeters. The momentum they carry needs to be added to the $E_T^{\text{miss}}$ calculation. A muon term based on ID and MS track measurements of the reconstructed muons in each event is hence added to correct for the muon contributions. The individual $x$ and $y$ contributions are added to the total missing transverse energy, i.e.

$$E_T^{\text{miss}} = \sqrt{(E_{x}^{\text{miss}})^2 + (E_{y}^{\text{miss}})^2}. \quad (3.1)$$

$^1$We follow the recommendations of the ATLAS Jet-$E_T^{\text{miss}}$ group [82].
To reduce the sensitivity to mis-measured muons, we define a quantity called relative missing transverse energy which is defined as:

\[
E_{\text{miss}, \text{rel}} = \begin{cases} 
E_{\text{miss}} \sin(\Delta \phi) & \text{if } \Delta \phi \leq \pi/2 \\
E_{\text{miss}} & \text{if } \Delta \phi > \pi/2 
\end{cases}
\]  

(3.2)

where \(\Delta \phi\) denotes the angle between \(E_{\text{miss}}\) and the closest muon in the transverse plane.

### 3.6 Muon Reconstruction and Identification

As discussed in the previous chapter an efficient muon reconstruction with a precise momentum measurement is essential to explore the physics potential at the LHC with ATLAS. The two tracking devices ID and MS as well as the thick calorimeter, shielding the MS provide the necessary means on the hardware side. Muons are particles that leave measurable signals in several detector subsystems of ATLAS. This is utilized by various algorithms reconstructing and identifying muons. Two comprehensive, independent software packages to reconstruct muon trajectories have been developed, which are also commonly referred to as the two muon algorithm families. They are called Muid [55] and Staco [38, 39] and comprise each a full muon reconstruction and identification chain of algorithms. While Staco is based on muon reconstruction code written in Fortran, called MuonBoy [37], Muid was specifically designed for Athena. Its core reconstruction algorithm, Moore [36] is written in C++ and takes full advantage of the modular Athena framework.

Both algorithm chains follow the same approach to reconstruct and identify muons:

1. A global search for patterns in the MDT hit distribution is performed.
2. The found patterns in the MS are fitted by straight lines to obtain segments.
3. Segments are combined to track candidates that are extrapolated to the interaction point. These MS tracks are called standalone muons.
4. ID tracks and MS tracks are combined to combined muons.
5. ID tracks are also combined with single, or multiple MS segments, without requiring a full MS track. These muons are called segment tagged muons.

An illustration of these steps is presented in Figure 3.5. We follow the given order in this chapter and discuss the individual implementations for the Muid family, for each step. Finally, in 3.6.5 we introduce an independent method to reconstruct muons, using calorimeter energy depositions, the calorimeter tagged muons.

The summary in 3.6.6 gives a compact overview of all available muon identification algorithms, including an attempt to visualize the different muon types.
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Figure 3.5: A schematic view on the standard muon reconstruction and identification in ATLAS, as performed by Muid and Staco.

3.6.1 Standalone Muons

Standalone muons are tracks reconstructed and identified by Moore for the Muid family and by Muonboy for the Staco family. They are purely based on the MS measurements. In the following, we discuss the making of standalone muons by the Moore algorithm. A more detailed description of Moore can be found in [59]. References [39] and [37] explain the corresponding standalone muon reconstruction with the Muonboy package for the Staco family.

Pattern Recognition

The search for patterns in the full MS volume is done using Hough transforms. This method to identify patterns and trajectories in a sample of point measurements was developed by Paul Hough in 1962 to analyze bubble chamber pictures at CERN. Mathematically, it is a transformation $f_H$ transforming elements of $\mathbb{R}^n$ into the Hough space $H$.

$$f_H : \mathbb{R}^n \rightarrow H$$

To illustrate the general concept we choose $n = 2$. Any line can be parametrized in this 2-dimensional $x$-$y$-space as

$$x \sin \phi - y \cos \phi = R_0$$

with $R_0$ being the distance between the origin of the cartesian $x$-$y$-coordinate system and the closest point of the line. The angle $\phi$ is defined by $R_0$ and the positive $x$-axis. However, for each point $(x, y)$ Equation 3.4 describes also a curve in the polar $R_0$-$\phi$-space. This space denotes the Hough space in our example. Drawing the Hough curves of different points on the line in the cartesian system unveils an intersection of all curves in one point of the Hough space. Figure 3.6 illustrates the concept for two independent lines and three random points in the $x$-$y$-space. All points in Figure 3.6(a) are transformed into their curves in the Hough space in (b). The two points in Figure 3.6(b) where all black and all grey curves meet indicate that they originate from the same lines in the $x$-$y$-space.
The three random points in Figure 3.6(a) that do not belong to a common line appear as dashed lines without a common intersection in the Hough space after their transformations. In summary, transforming points \((x_i, y_i)\) in the Hough space and searching for curve intersections will identify points that belong to the same lines in the \(x-y\)-space.

![Figure 3.6](image)

**Figure 3.6**: Two sets of points belonging to two lines are shown in grey and black in the cartesian coordinate system in (a). Their transformation in the Hough space are shown in (b). The open circles represent random points that are transformed into dashed lines in the Hough space.

In practice, more complex, non linear Hough transformations are used to identify not only lines but all sorts of trajectories. The Hough space is binned into a Hough histogram, so the intersection points do not have to be computed individually but only the maxima in the Hough histogram need to be found. This method is considerably faster particularly for a large number of point measurements like in most ATLAS events. The Hough histogram for our example is shown in Figure 3.7. The chosen binning of the histogram is crucial since it is directly related to the patterns. A too small bin size will smear out clear peaks while a too large bin size will degrade the resolution, thus close patterns might not be distinguishable.

Hough transforms are in addition very convenient to use because the processing time of these transformations scales linearly with the number of point measurements \(k\) as opposed to most combinatorial approaches that scale with \(k^3\).

The Hough transforms use measurements of all ATLAS MS subsystems (MDT, CSC, RPC, TGC) to identify patterns in the MS hit collection. The search is performed in two orthogonal planes, the \(x-y\)-plane (\(\phi\) patterns) and the \(R-z\)-plane (\(\eta\) patterns) in which
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Figure 3.7: The binned Hough space is shown. The maxima in the histogram correspond to the searched patterns.

the toroidal field bends the muon trajectories. A straight line $R$-$\phi$ transformation is used to find $\phi$ patterns, while a more complex track model is needed for the curved tracks in the $R$-$z$-plane, see Figure 3.8. From the interaction point to the MS entrance, a straight line parametrizes the trajectories in the $R$-$z$-plane while in the toroidal field, a parabolic parametrization is used. Since the outer endcaps of the MS do not lie within the nominal toroidal field, a straight line transformation is used for this region and completes the transformation used to identify $\eta$ patterns. More details on Hough transforms and the pattern recognition used to reconstruct muons in ATLAS can be found in [60].

Segment Making

Two segment making algorithms were developed, one for the MDT’s one for the CSC’s.

- **MDT segments:** The MDT hits from patterns found by the Hough transformations seed the MDT segment making. In each muon station with hits from a pattern the 4 possible tangents to the drift-radii of the two outer hits are constructed, see Figure 3.9 for an illustration. If at least one of these tangent lines is within 0.2 rad of the estimated pattern direction and at least three hits are found within 1.5 mm of that tangent, a straight line is fitted to all drift radii matching the latter requirement. If the $\chi^2$ value divided by the number of degrees of freedom ($\chi^2$/ndof) of the fit is larger than 10, the MDT hit with the largest contribution to the $\chi^2$ is dropped and the fit is performed again. This step is repeated until the $\chi^2$/ndof is smaller than 10. If the number of fitted hits drops below three, no segment is made. Finally the
fit parameters and their covariance are stored as a MDT segment. RPC or TGC trigger hits associated to the pattern are now associated to the segment.

The resulting MDT segment collection still contains possible ambiguities, that are segments sharing hits. These are solved by the following priority list:

1. largest number of hits on tracks
2. smallest sum of $N_\delta + N_{\text{out-of-time}} + N_{\text{holes}}$
3. largest number of trigger hits
4. smallest $\chi^2/\text{ndof}$

To understand the second item decision, one needs to distinguish between different types of MDT hits. The four distinctive hit types are illustrated in Figure 3.10. For a hit-on-track, the track is a tangent on the drift circle, while for an out-of-time hit, it is a secant. A too small drift circle is often caused by free electrons, created in an ionizing interaction of the muon with the MDT tube walls, that move towards the central wire. These so called $\delta$-electrons create an own drift radius, closer to the center of the tubes. $N_\delta$ stands hence for the number of hits that are associated to $\delta$-electrons. Consequently, $N_{\text{out-of-time}}$ is the number of out-of-time hits and $N_{\text{holes}}$ the number of holes, see Figure 3.10.
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Figure 3.9: A schematic view on two MDT multilayers is shown. The tangent lines to the seeding drift circles (black) are drawn as dashed lines, while the one with the most associated hits in drawn as a solid line.

![Diagram showing Muon Reconstruction](image)

Figure 3.10: The four distinctive MDT hit types are shown. A missing hit is also referred to as a hole.

![Diagram showing MDT Hit Types](image)

- **CSC segments**: Fitting the charge depositions on the $\phi$ and $\eta$ strips of the CSC’s create clusters which are fitted to straight lines to make segments. These $\phi$- and $\eta$-segments are then combined to the final CSC segments with a 3-dimensional position and direction.

**Track Finding**

In order to find the combination of segments that originates from the same muon, the MDT and CSC segment collections are combined and a segment matching is performed. A segment is labeled *compatible* with another if both were found in the same pattern and the two segments are successfully matched in position and direction. Sets of compatible segments are created, the track candidates. Tracks are built segment by segment outside-in from a track candidate. Thus, track fits are seeded by the track candidate segment(s) in the outermost station, normally the outer station. These segment(s) are fitted to the
segment(s) in the next station layer closer to the interaction point, normally the middle station. The resulting 2-segment tracks of successful fits are then fitted to the innermost station layer segment(s). This method allows for the creation of multiple tracks from a single segment seed. If tracks share more than half of their segments, they are merged. The resulting collection of tracks per pattern is first ranked according to their total number of associated hits and the smallest $\chi^2/\text{ndof}$ before their ambiguities are solved. If tracks share the same hits, these hits are assigned only to the higher ranked track. After the ambiguities are solved, the remaining tracks are refitted utilizing a detailed material and geometry description of the associated detector volume. All tracks that cannot be successfully refitted are dropped. The resulting collection of tracks are the Moore tracks.

Subsequently, these tracks are extrapolated inwards to the beam pipe, taking material interactions and energy loss, particularly in the calorimeters into account. At the closest point to the IP, the so-called perigee, the track parameters are determined and stored as standalone muons of the Muid collection.

### 3.6.2 Combined Muons

Prompt muons traverse the Inner Detector before they are measured in the muon system. It is hence reasonable to attempt to identify the ID track, that originates from the muon whose standalone track has already been reconstructed. Muid and Staco both calculate the $\chi^2_{\text{match}}$ of pairs of standalone and ID tracks to find possible matches.

$$\chi^2_{\text{match}} = (t_{\text{MS}} - t_{\text{ID}})^T (\text{cov}_{\text{MS}} + \text{cov}_{\text{ID}})^{-1} (t_{\text{MS}} - t_{\text{ID}})$$  \hspace{1cm} (3.5)

where $t$ symbolizes the track parameters and cov the corresponding covariance matrix [40]. If an ID track passes the $\chi^2_{\text{match}}$ requirement, it is extrapolated to the MS and position and direction of the extrapolated track are compared to the corresponding MS track, the Moore or Muonboy track. If these matching requirements are also fulfilled, the combined track parameters of the Staco Combined muon are obtained from a statistical combination of ID and MS track, which is defined as:

$$t_{\text{Staco}} = \left(\text{cov}_{\text{ID}}^{-1} + \text{cov}_{\text{MS}}^{-1}\right)^{-1} \left(\text{cov}_{\text{ID}}^{-1} t_{\text{ID}} + \text{cov}_{\text{MS}}^{-1} t_{\text{MS}}\right)$$ \hspace{1cm} (3.6)

Muid Combined follows a different approach and obtains its combined track parameters by fitting the ID and MS measurements of the two tracks.

### 3.6.3 Segment Tagged Muons

As discussed in 2.3.4, the Muon Spectrometer has some acceptance holes at $\eta = 0$ and in the ATLAS feet region. But the standalone muon reconstruction is also more challenging in the overlap region between barrel and endcaps at $|\eta| \approx 1.2$, where less measurements are available due to missing third MDT stations. In addition, low momentum muons can produce hits and segments in the MS that are not found by the standalone algorithm, due to the large curvature of these muons.

In order to recuperate these efficiency losses, ID tracks are extrapolated to the muon
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system and matched to segments. The track parameters of the segment tagged muons are taken from the ID track that was successfully matched to one or multiple MS segments. MuTagIMO is the segment tagger of the Muid family and extrapolates ID tracks to all three muon stations, hence, the 'T'ner, 'M'iddle and 'O'uter stations. At every station, a matching to segments in the vicinity of the extrapolated track is made. A detailed description of the algorithm and its performance is given in Chapter 4.

MuTag is the corresponding segment tagger of the Staco family and uses hence Muonboy segments for the matching. Unlike MuTagIMO, it is not an independent identification algorithm, but it only uses ID tracks and MS segments, that are not already part of a Staco Combined muon. Another important difference to MuTagIMO is that it extrapolates in general only to the inner station. For $|\eta| < 1.4$ also the middle stations are included and at $\eta \approx 0$ the outer station are added to reduce the inefficiencies resulting from the $\eta = 0$ acceptance hole. The current configuration of MuTag is specified at [78].

3.6.4 MuGirl Muons

The MuGirl algorithm follows the approach of the segment taggers by extrapolating ID tracks to the MS inner, middle and outer stations [79]. However, instead of matching the extrapolated tracks to either Moore or Muonboy segments in the MS, a local pattern recognition in the vicinity of the extrapolated tracks is performed to create the MuGirl segments. This is done station by station from the inner to the outer. The created segments in each station are used to refine the extrapolated track parameters for the next station. An artificial neural network decides if an extrapolated ID track with its set of MuGirl segments is rejected, or tagged, therewith identified as a MuGirl muon. After an ID track is successfully tagged, a refit of associated ID and MS measurements is performed by MuGirl and a muon with the combined track parameters is created, if the fit is successful. These muons are commonly labeled refitted MuGirl muons. The MuGirl and MuGirl refitted muons are added to the Muid family.

3.6.5 Calorimeter Tagged Muons

The calorimeter taggers are the only muon identification algorithms that are completely independent of the Muon Spectrometer. This interesting feature will be exploited in Chapter 5. Being independent of the MS also allows one to reconstruct muons in the regions where the MS coverage is limited, like at $\eta = 0$. Another use case of calorimeter tagged muons is to enhance the purity of combined or segment tagged muons to be confirmed by the calorimeter taggers. However, the comparatively low efficient calorimeter taggers will decrease the efficiency of such a selection significantly as will be shown in Chapter 5.

Calorimeter tagged muons, also abbreviated to calo muons are stored in an independent collection called CaloTrkMuId [80]. Two algorithms are used to identify calo muons, CaloMuonTag [61] and CaloLikelihood ratio. Both algorithm are seeded with Inner Detector tracks, that are extrapolated to and through the calorimeters. The energy deposits in the electromagnetic and hadronic calorimeters are collected along the extrapolated track. Muons with sufficient momentum to traverse the calorimeter are expected to leave
small, continuous energy deposits with a total of approximately 3 GeV. This makes it distinguishable from an electron whose energy will be deposited mostly entirely in the EM calorimeter layers. Low energetic hadrons will deposit most of their energy in the first layer of the hadronic calorimeters, while high energetic hadrons will deposit large amounts of energy in the central hadronic calorimeter layer. These characteristics are used by CaloMuonTag to veto energy deposits from electrons and hadrons.

The large number of ID tracks in collision events requires a preselection. The extrapolated ID tracks are preselected by requiring a transverse momentum of at least 2 GeV, at least 2 Pixel and 6 SCT hits on the track and an isolation of \( \log_{10}(\frac{p_T^{iso}}{p_T}) < 0.7 \), where \( p_T \) denotes the transverse momentum of the selected track and \( p_T^{iso} \) is the sum of the transverse momenta of all ID tracks in a cone with an angle of 0.45 rad around the selected track. The same cone is used to tighten the isolation by requiring the sum of the energy deposits in the cone along the extrapolated track to be smaller than 15 GeV for \( |\eta| < 1.5 \), 8 GeV for 1.5 < \( |\eta| \) < 1.8 and 12 GeV for \( |\eta| > 1.8 \). These isolation requirement on energy deposits and ID tracks are needed to reject hadrons mimicking muon signals in the calorimeter by showing a very broad showering profile with small energy deposits in the individual calorimeter cells.

Instead of relying on a cut-based selection, the CaloLikelihood ratio algorithm calculates the probability of a muon to induce the measured energy deposits along the extrapolated ID track. The likelihood ratio \( L \) is computed with

\[
L(m_1, m_2, \ldots, m_N) = \frac{\prod_{i=1}^{N} P_{i}^{\mu}(m_i)}{\prod_{i=1}^{N} P_{i}^{\mu}(m_i) + \prod_{i=1}^{N} P_{i}^{bkg}(m_i)}
\]

where \( N \) denotes the number of calorimeter cell measurements associated to the extrapolated ID track and \( m_i \) indicates the measurement in calorimeter cell \( i \). \( P_{i}^{\mu}(m_i) \) is hence the probability of a muon to create the measured energy deposit and \( P_{i}^{bkg}(m_i) \) corresponds to the probability of non-muons to create the same energy deposit. The probabilities are a function of \( \eta \) and \( p_T \) and cached by the algorithm. With \( L \in [0, 1] \), where 0 indicates that the found energy deposits along the extrapolated ID track are very unlikely to originated from a muon, while 1 indicates the opposite. The CaloLikelihood ratio algorithm requires \( L > 0.5 \) to identify a calo muon and store the ID track parameters.

### 3.6.6 Summary

Various techniques are used in ATLAS to reconstruct and identify muons. Calorimeter tagged muons cover the entire range up to \( |\eta| = 2.5 \) while combined muon algorithm provide a highly efficient muon identification with the best momentum resolution, taking full advantage of both ATLAS tracking detectors. Their inefficiencies, particularly at low muon momenta can be recuperated using segment tagged muons. A conceptual overview of the available muon types and the sub-detector systems used for their reconstruction and identification is shown in Figure 3.11. In addition to these different reconstruction and identification techniques, facilitated by the ATLAS design, two different algorithm families have been developed. Table 3.1 lists the available muon algorithms sorted by their belonging families and types.
Figure 3.11: In a simplified cross section of the ATLAS barrel the characteristics of the different types of muons and their signals in the detector are depicted.

Table 3.1: A schematic overview of the different types of muons and their implementations is given. The taggers of the Muid and Staco families use MS segments, while the calorimeter taggers use the calorimeter cell energy depositions.