Identification of muons in ATLAS
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Chapter 4
Muon segment tagging

4.1 Introduction

Muon segment tagging is the process of identifying Inner Detector tracks as muons by matching the track withMuon Spectrometer segments. As a complement to the combined and standalone muon reconstruction, the muon tagging procedure improves the total muon reconstruction performance in several ways. First of all, the tagging algorithm recovers muons in the region where the Muon Spectrometer has limited coverage. Secondly, muon tagging is efficient for identifying muons with low transverse momentum. Finally, muon tagging provides a robust alternative to the combined and standalone algorithms since it applies a looser matching technique.

In this Chapter, the principles of muon tagging are explained. Furthermore, the implementation of a specific muon tagging algorithm, MuTagIMO, is explained in detail. The performance of the muon tagging is discussed in Chapter 6 for cosmic ray muon events and in Chapter 7 for simulated physics events.

Section 4.2 explains the principle of muon segment tagging. The subsequent sections 4.3-4.7 discuss the implementation of the muon tagging algorithm. The final section, 4.8, discusses the technical implementation of MuTagIMO in ATHENA.

4.2 Muon segment tagging principle

The procedure of tagging muons using reconstructed segments in the Muon Spectrometer can be divided in several steps:

1. As a starting point, Inner Detector tracks are taken. Track filtering is performed to remove low momentum tracks. Other filter criteria may be applied as well.

2. Not all segments are used in the tagging procedure and a segment filter is applied to the segments. Segments of low quality, for instance with too few hits, are omitted at this stage.

3. The Inner Detector tracks are extrapolated through the calorimeters to the Muon Spectrometer. The common tracking tools are used to perform the extrapolation.
The extrapolation results in a prediction of where the Inner Detector track would end up in the Muon Spectrometer under the hypothesis that the track originates from a muon.

4. The extrapolated track parameters are matched with the parameters of segments in the muon stations. Matching variables are constructed that serve as a measure of the quality of the match. Tracks and associated segments that pass the matching criteria are labeled as muon candidates.

5. After the track-segment matching step, the muon candidates are collected. In an ambiguity solving procedure, multiple associated segments in one muon station are solved by associating the segment with the best match and removing the association of the remaining segments. Multiple tracks sharing the same segment are solved by associating the segment to the track with the best match.

6. From the resulting muon candidates, muons are built.

The MuTagINO tagging algorithm will be explained in more detail in the following sections.

4.3 Track and segment filtering

The Inner Detector tracker reconstructs the order of a hundred tracks per event. It is therefore sensible to filter out tracks which will most probably not be identified as muons. This lowers the fake rate and makes the tagging algorithm faster.

Muons lose more than 3 GeV energy in the calorimeters, as shown in Figure 3.10. For this reason, tracks with momentum lower than 3 GeV are not extrapolated to the muon system. Tracks with low transverse momenta, smaller than 2 GeV, are not extrapolated either.

A fraction of the Inner Detector tracks contain only hits from the TRT sub-detector. These tracks have a high probability to originate from $V_{2}$ particles and bremsstrahlung electrons rather than from muons, as discussed in section 3.2. Therefore these tracks are not used for muon tagging. This is brought about by requiring at least 4 hits from the pixel and SCT detectors on a track.

A dedicated tool is available to perform track selection with: TrackParticleFilterTool. The track selection cuts are summarized in table 4.1.

The Muon Spectrometer segments are filtered to suppress mis-identified tracks. Segments reconstructed in MDT stations are required to have at least two hits per multilayer and at most three holes on a segment. A hole is a hit expected but not found, see the detailed explanation section 3.3.3. Some MDT stations (chamber type BEE) have only one multilayer. To segments from these stations only the hole criterion is applied. Segments reconstructed in CSC chambers are passed without further requirements to the tagging algorithm.

The selection of segments is performed by the SegmentsFilterTool. The setting of the SegmentsFilterTool is summarized in table 4.2.
4.4 Segment preselection

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<td>minimum momentum $p$</td>
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<tr>
<td>minimum transverse momentum $p_T$</td>
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</tr>
<tr>
<td>$\eta_{\text{max}}$</td>
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Table 4.1: The properties of the TrackParticleFilterTool, shown with the default setting for MuTagIMO.

<table>
<thead>
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</tr>
<tr>
<td>min nr hits per multilayer</td>
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</tr>
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<td>all MDT stations</td>
</tr>
<tr>
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<td>disabled</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$</td>
<td>disabled</td>
</tr>
</tbody>
</table>

Table 4.2: The properties of the SegmentsFilterTool, shown with the default setting for MuTagIMO.

4.4 Segment preselection

After the filtering of Inner Detector tracks and spectrometer segments, the tracks are extrapolated to the Muon Spectrometer volume. Extrapolation is a CPU intensive procedure. Extrapolation each track to each segment would potentially cause the tagging algorithm to become slow. A preselection of segments is made by selecting segments in the region of the Muon Spectrometer where the extrapolated track traverses the spectrometer. This way, the number of segments to extrapolate to will be reduced.

The estimation is done by extrapolating the track to a set of abstract surfaces, 3 cylinders and 2 times 4 discs, following the design of the ATLAS spectrometer station layers. The abstract surfaces are defined with such dimensions (see table 4.3) that hermiticity is ensured, the cylinders describing the barrel spectrometer overlap with the discs describing the end caps. A loose, global match is made between the extrapolated track and segments to preselect segments candidates.

Note that the extrapolation of the track is done with the hypothesis that the track is coming from a muon. The extrapolated track is the prediction of where the muon track would traverse the Muon Spectrometer.

The preselection is done in 3 steps. First, a requirement on matching station layer level is done to select the segments reconstructed in the same station layer as the abstract surface. Secondly, a match is performed using the distance of the extrapolated track to the segment.

- **Station layer requirement**: A selection is done on the station in which the segment is reconstructed and the abstract surface to which the track is extrapolated. In this way, no segments in the inner barrel stations will be assigned as a candidate
Muon segment tagging

<table>
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<th>( b ) (mm)</th>
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</tr>
<tr>
<td>BM</td>
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<td>10000</td>
</tr>
<tr>
<td>BO</td>
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<table>
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<th>( R_{\text{min}} ) (mm)</th>
<th>( R_{\text{max}} ) (mm)</th>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>negative for C side</td>
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<td>2200</td>
<td>12000</td>
</tr>
<tr>
<td>EE(A/C)</td>
<td>9700</td>
<td>5000</td>
<td>8500</td>
</tr>
</tbody>
</table>

Table 4.3: Abstract surfaces describing the Muon Spectrometer station layers.

match of a track extrapolated to an outer end-cap disc surface.

- **Global \( \phi \) cut**: The next requirement is on the position in the non-precision plane of the Muon Spectrometer, the global \( xy \)-plane. With this requirement one selects segments in the right sector of the spectrometer. The value of the distance requirement in this coordinate depends on the presence of \( \phi \) measurements on the segment, hits in the \( xy \)-plane. Segments reconstructed by MDT hits alone do not have a measurement of the second coordinate and therefore a looser cut is applied. The resolution of a segment without \( \phi \) hits on the second coordinate is approximately the tube length.

The global angle \( \phi^{\text{exp}} \) in the \( xy \)-plane calculated from the global position is:

\[
\phi^{\text{exp}} = \arccos(y_e, x_e)
\]  

(4.1)

Where \( y_e \) and \( x_e \) are the global coordinates of the measurement. The difference of the positions \( \Delta \phi^{\text{exp}} \) between the extrapolated track and the segment is given by:

\[
\Delta \phi^{\text{exp}} = \phi^{\text{exp}}_{\text{extrap}} - \phi^{\text{exp}}_{\text{seg}}
\]  

(4.2)

Where \( \phi^{\text{exp}}_{\text{extrap}} \) is the position of the extrapolated track, \( \phi^{\text{exp}}_{\text{seg}} \) the position of the segment, see Figure 4.1 a). The criterion of passing the requirement is given by

\[
|\Delta \phi^{\text{exp}}| < \sqrt{\sigma^2 + \sigma^2_{\phi}}
\]

(4.3)

where \( \sigma_{\phi} \) is the extrapolation error in \( \phi \). The value of \( \sigma_{\phi} \), the cut-off distance, can be set in the MuTagMatchingTool and is per default set to 0.5 rad, corresponding to roughly one sector.

The preselection in the precision plane of the Muon Spectrometer is done in the \( Rz \)-plane. For the barrel and end cap regions two variables are defined:
4.4 Segment preselection

Figure 4.1: Graphical representation of the segment preselection variables in the Muon Spectrometer barrel: a) $\Delta \phi$ and b) $\Delta \theta$.

Figure 4.2: Graphical representation of the segment preselection variable in the Muon Spectrometer endcap: $\Delta R$.

- **Global $\theta$ cut:** For segments reconstructed in the Muon Spectrometer barrel, a requirement is set on the precision coordinate of the Muon Spectrometer, $\theta^{\text{pos}}$. The variable $\theta^{\text{pos}}$ is the global angle in the $Rz$-plane calculated from the position of the track and segment:

$$\theta^{\text{pos}} = \text{atan}(R, z_k), \quad R = \sqrt{x_k^2 + y_k^2} \quad (4.4)$$

The difference in position in the global $Rz$-plane in the barrel $\Delta \theta^{\text{pos}}$ is given by:

$$\Delta \theta^{\text{pos}} = \theta^{\text{pos}}_{\text{extr}} - \theta^{\text{pos}}_{\text{seg}} \quad (4.5)$$

Where $\theta^{\text{pos}}_{\text{extr}}$ is the position of the extrapolated track, $\theta^{\text{pos}}_{\text{seg}}$ the position of the
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segment, see Figure 4.1b). The criterion of passing the requirement is given by:

$$|\Delta \theta^{\text{seg}}| < c_6$$

(4.6)

Where $c_6$ is set on a value of 0.1 rad.

- **Global $R$ cut:** For end cap stations in the forward region of the Muon Spectrometer, the precision coordinate in the global $R$-plane is the transverse distance $R$:

$$\Delta R = R_{\text{exTrk}} - R_{\text{seg}}$$

(4.7)

When a segment from an end cap station passes the requirement on $\theta^{\text{seg}}$, a requirement on the ratio $\Delta R/L$ is set, where $L$ stands for the 3 dimensional distance:

$$\frac{|\Delta R|}{L} < c_R$$

(4.8)

Where $c_R$ is the cut-off value set in the MuTagMatchingTool to a default value of $\frac{1}{5}$, such that a $\Delta R$ of 1000 mm for segments at a 3D distance $L = 7500$ mm gets accepted. Figure 4.2 shows $\Delta R$ graphically.

Segments meeting these requirements are preselected.

4.5 Segment matching

After the segment preselection, precise matching is performed between the track and segment candidates. The Inner Detector track is extrapolated to the surface on which the segment is defined. Matching is done in the local coordinate system of the segment station, on both the position and the direction in the precision plane. For low momentum tracks, more stringent requirements are placed.

The extrapolated track parameters are expressed with respect to a plane surface on which the segment is defined, as described in section 3.4.1. Figure 4.3 shows the local coordinate system of a plane surface associated to an MDT segment. The origin of the plane surface is taken as the position of the reconstructed segment. The $x$-axis is in the direction of the wire, making the local position parameter loc$X$ the non-precision coordinate of the segment. In this reference frame, loc$Y$ is the precision coordinate of the segment in this plane (see table 3.1 for the definitions of the local parameters).

The direction in the local coordinate system of the plane surface is given by the parameters $\alpha_{xz}$ and $\alpha_{yz}$. The angle $\alpha_{xz}$ is the angle of the projection of the segment in the local $x$-$z$-plane, angle $\alpha_{yz}$ the angle in the local $y$-$z$-plane. With these definitions, $\alpha_{xz}$ represents the direction in the precision plane and $\alpha_{yz}$ the direction in the non-precision plane.

Muon candidates are tracks that meet the following requirements:

- **Local position pull cut:** the pull is the distance between the extrapolated track and segment position divided by the errors in the precision plane:

$$|P_{\text{loc}Y}| < c_{\text{loc}Y} : \quad P_{\text{loc}Y} = \frac{\Delta_{\text{loc}Y}}{\sqrt{\sigma_{\text{exTrk[loc}Y]}^2 + \sigma_{\text{seg[loc}Y]}^2 + \sigma_{\text{loc}Y}^2}}$$

(4.9)
4.5 Segment matching

![Segment matching diagram](image)

**Figure 4.3:** Local coordinate system of a plane surface.

Where $\Delta_{\text{loc}Y}$ is the difference of the $\text{loc}Y$-position between segment and extrapolated track, $\sigma_{\text{extr}k,\text{loc}Y}$ the error of the $\text{loc}Y$-parameter given by the extrapolation, $\sigma_{\text{seg},\text{loc}Y}$ the error of the $\text{loc}Y$-parameter as given by the segment fit. An extra safety-factor is introduced here, $\sigma_{\text{glob}Y}$, which protect the pull of becoming too large for very high momentum tracks, when the errors on the track may become very small. The value can be set by properties of the MuTagMatchingTool, a default value of 10 mm is applied. The value of $c_{\text{loc}Y}$ is set to 5. Thus matches with a pull of less than 5$\sigma$ are accepted.

- *Local direction pull cut:* where the pull is based on the angular difference divided by the error in the precision plane:

$$|P_{mz}| < c_{\alpha z}, \quad \begin{aligned} P_{mz} &= \frac{\Delta_{\alpha z}}{\sqrt{\sigma_{\text{extr}k,\alpha z}^2 + \sigma_{\text{seg},\alpha z}^2 + \sigma_{\text{mz},\alpha z}^2}} \end{aligned}$$

(4.10)

Where $\Delta_{\alpha z}$ is the difference in the precision angle of the segment and extrapolated track, $\sigma_{\text{extr}k,\alpha z}$ the error of the $\alpha_z$ direction parameter as given by the extrapolation. To obtain the error on $\alpha_z$, a transformation between the global and local coordinates should be made since the extrapolation provides errors with respect to the global coordinate system. This transformation involves a Jacobian which is explained in appendix A. $\sigma_{\text{seg},\alpha z}$ stands for the error of the local direction parameter, provided by the segment fit. As in the position matching, a safety-factor is implemented to prevent very large pulls in the precision direction. The value of the safety-factor is set to 0.5 mrad. The value of $c_{\alpha z}$ is set to 5.

Throughout this chapter, performances are shown for various simulated samples. The performances are shown for *muon candidates*: Inner Detector tracks with one or more Muon Spectrometer segments associated to it. The Inner Detector tracks are truth-matched with simulated particles and classified as either *muon* or *non-muon*. A track is truth-matched to a simulated particle when more than 80% of its hits originate from the
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Figure 4.4: The pull distributions of the two precision matching variables; a) $P_{\text{locY}}$ and b) $P_{\text{yz}}$.

Muon tracks are tracks which are truth-matched to a simulated muon. Non-muon tracks are tracks which are not truth-matched or truth-matched to a particle that is not a muon. Figure 4.4-a) shows the pull distribution of the matching variable $P_{\text{locY}}$ and Figure 4.4-b) shows the distribution of $P_{\text{yz}}$ for a $t\bar{t}$ sample. The gray distributions show the matching variables for muons, the black lines show the distributions for non-muon tracks. The width of the pull distribution is wider for non-muons than for muons. Non-muon track parameters that are extrapolated to the segment surface have a poorer match to the segment parameters than extrapolated muon track parameters. Requiring that the pull of the matching variable is less than 5 selects muons and rejects some non-muons. Additional requirements have to be imposed to reduce the non-muon background which fall within the 5 sigma peak.

The width of the pull distribution of the muon track matches is around 1.1 for both $P_{\text{locY}}$ and $P_{\text{yz}}$. The errors of the matching variables are thus underestimated. The dominant contribution to the errors are from the extrapolation of the Inner Detector track parameters.

Figure 4.5 shows the distribution of transverse momentum of tagged tracks for the $t\bar{t}$-sample, both for muon tracks (gray) and for non-muon tracks (black). Most of the non-muon tracks have low transverse momenta. To reduce the mis-identification rate a more stringent requirement, dependent on the track momentum, is imposed.

- **Transverse momentum dependent pull cut:** To suppress low transverse momentum
4.5 Segment matching

Figure 4.5: The transverse momentum distributions of muon candidates.

non-muon background, a \( p_T \) dependent cut is introduced:

\[
e_{\text{pull}} = \frac{1}{4} \left( \frac{1}{p_T} - 1 \right)^2 + 2 \text{ for } 2 < p_T < 9 \text{ GeV} \quad (4.11)
\]

Where \( p_T \) stands for the transverse momentum of the Inner Detector track in GeV. For very low momentum tracks, a tighter cut on the pull variables is applied. The requirement on the pull starts at a value of 2 for tracks with a \( p_T \) of 2 GeV, the minimum value of the track \( p_T \) used by the track filter. The requirement relaxes to a value of 5, the default value used in the segment matching, for tracks with a \( p_T \) of around 9 GeV. The parabolic shape of \( e_{\text{pull}} \) is an empiric interpolation such that the variable pull requirement works well for both \( t\bar{t} \) events and \( Z^0 \rightarrow \mu^+\mu^- \) events with added cavern background safety factor 5.

The \( p_T \)-dependent cut is applied on the following matching variables:

\[
|p_{\text{muV}}| < e_{\text{pull}} \quad (4.12)
\]

\[
|p_{\text{muX}}| < e_{\text{pull}} \quad (4.13)
\]

\[
|p_{\text{hoX}}| < 2 \cdot e_{\text{pull}} \quad (4.14)
\]

The requirement is looser for the second position coordinate pull, \( p_{\text{hoX}} \), since this coordinate is measured with less precision in the Muon Spectrometer. The \( p_{\text{hoX}} \) matching variable is defined in the same way as \( p_{\text{muV}} \) (Eq. (4.9)).

Eq. (4.11) is shown in Figures 4.6 and 4.7 (black curve) together with the distributions of the \( p_{\text{muV}} \) matching variable for two samples, \( t\bar{t} \) events (Figure 4.6) and \( Z^0 \rightarrow \mu^+\mu^- \) events with cavern background safety factor 5 (Figure 4.7). Plot a) shows muon tracks, plot b) shows non-muon tracks. The figures demonstrate the effectiveness of the requirement. The \( p_T \)-dependent pull cut works well for high-multiplicity samples, such as the \( Z^0 \rightarrow \mu^+\mu^- \) sample with cavern background safety factor 5, as is demonstrated in Figure 4.7.
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**Figure 4.6:** The distribution of $P_{\text{locY}}$ as function of transverse momentum $p_T$ for a $t\bar{t}$ sample, shown together with the added $c_{\text{pull}}$ value (shaded area). The distribution for a) muon tracks, b) non-muon tracks.

**Figure 4.7:** The distribution of $P_{\text{locY}}$ as function of transverse momentum $p_T$ for a $Z^0 \rightarrow \mu^+ \mu^-$ sample with cavern background safety factor 5, shown together with the added $c_{\text{pull}}$ value (shaded area). The distribution for a) muon tracks, b) non-muon tracks.

- **Residual cut:** the segment and extrapolated track should not be displaced too much, even though the pull matching variables are small. A maximum value for the residual in local position $\Delta_{\text{locY}}$ and local direction $\Delta_{\text{locZ}}$ is applied to reject matches with very low momentum tracks.

$$|\Delta_{\text{locY}}| < c_{\Delta_{\text{locY}}}, \quad |\Delta_{\text{locZ}}| < c_{\Delta_{\text{locZ}}}, \quad (4.15)$$

The cut-off values are $c_{\Delta_{\text{locY}}} = 500$ mm and $c_{\Delta_{\text{locZ}}} = 300$ mrad. Figure 4.8 shows the distribution for a) $\Delta_{\text{locY}}$ and b) $\Delta_{\text{locZ}}$ for both muons (gray) and non-muons (black) of a $t\bar{t}$ sample. Non-muon matches have in general, a large residual. Fig-
Figure 4.8: The residuals a) $\Delta_{\text{loc}Y}$ and b) $\Delta_{\text{non}}$ for a $t \bar{t}$ sample. The gray distribution shows values for muons, the black line for non-muons.

Figure 4.9: The residuals a) $\Delta_{\text{loc}Y}$ and b) $\Delta_{\text{non}}$ for muons from a $J/\psi$ sample.

Figure 4.9 shows the residuals for muons from a $J/\psi$ sample. The requirements on the maximum residual reduces the non-muon background in the $t \bar{t}$ sample whilst retaining most of the muons in $J/\psi$ events.

Segments matching with the extrapolated track are associated to that track. Tracks
Muon segment tagging

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<tr>
<td>(c_\theta)</td>
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<td>segment preselection (Rz)-plane barrel</td>
</tr>
<tr>
<td>(c_R)</td>
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<td>segment preselection (Rz)-plane end cap</td>
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<tr>
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<td>position matching in (Rz)-plane</td>
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<tr>
<td>(c_{\phi z})</td>
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</tr>
<tr>
<td>(c_{\Delta x y})</td>
<td>0.5 mrad</td>
<td>safety-factor direction</td>
</tr>
</tbody>
</table>

Table 4.4: The properties of the MuTagMatchingTool, shown with the default setting for MuTagIND.

with associated segments are referred to as muon candidates.

4.5.1 Matching configuration

The extrapolation of tracks and the matching with segments is done with a dedicated tool, the MuTagMatchingTool. The requirements on the various matching parameters, the global matching variables used to preselect segments and the local matching variables used in the segment association, can be set in this tool as well. The safety-factors appearing in the calculations of the pull matching variables in expressions 4.9 and 4.10 can be configured as well. Table 4.4 summarizes the properties and cuts of the MuTagMatchingTool for running on simulated data. For tagging commissioning data such as cosmic, a looser matching is preferable and the MuTagMatchingTool is configured accordingly. Chapter 6 will discuss cosmic muon tagging in detail.

4.6 Ambiguity solving

Muon candidates may contain ambiguities such as multiple segments associated to the same track in the same muon station, or tracks associated to the same segment. The set of muon candidates are cleaned up in three steps: Segment cleaning and track cleaning followed by final track and segment cuts.

4.6.1 Segment cleaning

Multiple segments from the same muon station may be associated to the muon candidate. Only one segment per station is expected. The segment with the smallest distance in the precision plane is associated to the muon candidate; the other segments are dropped.
4.6.2 Track cleaning

Multiple Inner Detector tracks may have the same segment(s) associated. This occurs especially in events with collinear tracks, or events with high Inner Detector activity. In order to decide which track belongs to the segment, a rejection factor \( f_R \) is calculated.

The rejection factor is a measure of how likely the track is coming from a muon, given a set of matching variables. When muon candidates share associated segments, the candidate with the highest rejection factor is most likely to be a muon. The other candidates lose association to the shared segment.

The following variables are used to construct the rejection factor:

- **number of MDT segments**, \( n_{\text{Seg}} \). A muon is more likely to reach multiple MDT chambers than other particles. Favoring tracks traversing a larger part of the Muon Spectrometer suppresses the low momentum background.

- **position residual**, \( \Delta_{\text{locY}} \). The track with the smallest precision position distance is more likely to be the correct track.

- **direction residual**, \( \Delta_{\text{locY}} \). The track with the smallest angular difference is more likely to be the correct track.

For each of the matching variables, a rejection factor is calculated by dividing the distributions of the variable for muon over non-muon tracks. The discriminating variable \( f_R \) is defined as the product of the rejection factors of the three matching variables:

\[
f_R(n_{\text{Seg}}, \text{locY}, \alpha_{y}) = f_{R,n_{\text{Seg}}}(n_{\text{Seg}}) \cdot f_{R,\text{locY}}(\text{locY}) \cdot f_{R,\alpha_y}(\alpha_{y}) \tag{4.16}
\]

with \( f_{R,n_{\text{Seg}}} \) the rejection factor of the number of segments, \( f_{R,\text{locY}} \) and \( f_{R,\alpha_y} \) the rejection factor of the position and direction residual respectively.

In order to treat the large tails in the distribution of the position and direction residuals properly, the residuals are transformed in the following way:

\[
L_{\text{locY}} = \ln \left( 1 + \frac{\Delta_{\text{locY}}}{w_{\text{locY}}} \right), \quad L_{\alpha_y} = \ln \left( 1 + \frac{\Delta_{\alpha_y}}{w_{\alpha_y}} \right) \tag{4.17}
\]

Where \( w_{\text{locY}} \) and \( w_{\alpha_y} \) are constants which one can chose arbitrarily. The values are set to \( w_{\text{locY}} = 20 \text{ mm} \) and \( w_{\alpha_y} = 4 \text{ mrad} \). This operation transforms large values of the residuals in the tails closer to the core of the distribution.

Figure 4.10 shows the distributions of the number of segments, and the residuals for both muon tracks (gray) and non-muon tracks (black) for the \( tt \) sample. Figure 4.11 shows the rejection factors versus the matching variables (black dots) together with a parametrized function (gray line) fitted to the shape of the rejection factor. The rejection factor of the number of segments is fitted by a Fermi function in the range \( 0 < n_{\text{Seg}} < 3 \):

\[
f_{R,n_{\text{Seg}}}(n_{\text{Seg}}) = \frac{\alpha}{1 + \exp(\beta - \frac{n_{\text{Seg}}}{\gamma})} + \delta, \quad \begin{cases} 
\alpha = 3.62 \\
\beta = 20.45 \\
\gamma = 0.13 \\
\delta = 0.10
\end{cases} \tag{4.18}
\]
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Figure 4.10: Distributions of a) the number of MDT segments, b) $L_{locY}$ and c) $L_{locZ}$ for muon candidates sharing association to the same segment. Muon tracks are shown in gray, non-muon tracks in black.

Figure 4.11: Rejection factors as function of a) the number of MDT segments, b) $L_{locY}$ and c) $L_{locZ}$. 
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The rejection factor for the residuals is fitted by the following empirical functions:

\[
R_{\text{res}}(L_{\text{res}}) = \frac{\alpha}{1 + \beta L_{\text{res}} + \gamma L_{\text{res}}^2}
\]

\[
R_{\text{res}}(L_{\text{res}}) = \frac{\alpha}{1 + \beta L_{\text{res}} + \gamma L_{\text{res}}^2}
\]

For each set of muon candidates sharing a associated segment, the rejection factor \(R(n \text{Seg}, \text{locY}, \alpha_{\text{res}})\) is calculated using the parameterized rejection functions. Plot a) in Figure 4.12 shows the rejection factor distribution for both muons (gray) and non-muons (black). The muon candidate with the highest \(R\) factor keeps the association to the segment. The muon candidates with the lower \(R\) value loses the association to the shared segment. The muon candidate is dropped when it has no more associated segments left.

In Eq. (4.16), the total rejection factor \(R(n \text{Seg}, \text{locY}, \alpha_{\text{res}})\) is defined as the product of the rejection factors per variable. If the variables are independent and the rejection functions per variable are properly parametrized, the factorized rejection is the optimal value one can obtain. In other words, the total rejection factor has the highest discriminating power. In that case, the ratio of the distribution of the rejection factor for muons over non-muons will have a value of 1 for a rejection of 1 and will have a linear behavior.

![Figure 4.12: The rejection factor \(R\) of muons (gray) and non-muons (black) is shown in plot a). Plot b) shows the ratio \(R_{\text{res}}(L_{\text{res}})\) versus \(\log(R)\) (black) shown with the function \(e^{\log(\alpha)\cdot \log(R)\cdot \log(\gamma)}\) (gray).](image)
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with respect to $f_R$. This is explained in more detail in Appendix B.

Figure 4.12-b) shows the ratio of the rejection factor of muons over non-muons plotted versus the (logarithm of) the rejection as black dots. The gray line is the function $e^{\beta g(t)}$ and illustrates the behavior of the distribution. The distribution has a value of 1 for a rejection of 1 and follows the exponential, indicating that the variables are independent and the rejection functions are properly parametrized.

4.6.3 Final track and segment cuts

The non-muon background can be further reduced by looking at the full event topology and tightening the requirements on the segment quality and track momentum in complicated events.

Figure 4.13 shows the number of MDT segments used to tag an Inner Detector track as muon, for the $t\bar{t}$ sample. The gray histogram shows the muon tracks (tracks truth matched to simulated muons), the black line the non-muon tracks (tracks truth matched to other simulated particles, or tracks which are not truth matched at all). Most of the non-muon background come from tracks tagged with a single-MDT segment. Figure 4.5 shows the transverse momentum distribution for muon tracks (gray) and non-muon tracks (black line). Most of the non-muon background comes from low momentum tracks.

Reducing the mis-identification rate by just removing low momentum tracks is not an option, since that will reduce tagging efficiency for low momentum muons from $J/\psi$ decays. Simple rejection of tracks tagged with only one MDT segment will reduce the fake rate too at the cost of muon tracks, especially those which will not be identified by combined muon algorithms in regions with limited coverage of muon stations.

More intelligent cuts are needed to reduce the non-muon background without losing

![Figure 4.13: Number of segments associated to the muon candidate. Muons are shown in gray, non-muons in black.](image)

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Muon tracks. Muon track candidates are selected applying the following stringent cuts:

- **At least one MDT segment associated:** Figure 4.13 shows the number of associated MDT segments for a $t\bar{t}$ sample. It is clear that muon candidates without MDT segments associated, i.e. only CSC segments are used to tag the track, are non-muon tracks. Requiring the muon candidate to have at least one MDT segment associated reduces the non-muon background.

Since most of the non-muon background comes from muon candidates with only one MDT segment associated, the following cuts are added to muon candidates with one MDT segment association:

- **Segment holes cut:** In busy events, where the number of segments is high, a stricter cut on the number of holes ($h_{\text{holes}}$) on the reconstructed segments is applied to enforce that high quality segments are used in a tag:

  \[
  h_{\text{holes}} < c_{\text{holes}} : \quad c_{\text{holes}} = \begin{cases} 
  4 & n_{\text{seg}} < 30 \\
  3 & 30 < n_{\text{seg}} < 50 \\
  2 & 50 < n_{\text{seg}} 
  \end{cases} \quad (4.21)
  \]

  Figure 4.14-a) shows the distribution of the number of holes on the MDT segment associated to the muon candidate versus the segment multiplicity of the event, for a $t\bar{t}$ sample. Figure 4.14-b) shows the same for a $Z^0 \rightarrow \mu^+\mu^-$ with added cavern background (safety factor 5) sample. Muon tracks are shown by gray boxes, non-muon tracks by open boxes. The background is lowered by rejecting muon candidates that do not pass the segment holes cut.

- **Track $p_T$ cut:** Since most of the non-muon background comes from low transverse momentum muon candidates, a stricter cut on the track $p_T$ is applied for events with a high number of muon segments:

![Figure 4.14: Number of holes on the associated segment versus the segment multiplicity of the event, for muon candidates with 1 MDT segment associated. a) $t\bar{t}$ sample, b) $Z^0 \rightarrow \mu^+\mu^-$ sample with cavern background safety factor 5.](image_url)
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\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4.15.png}
\caption{Muon candidate transverse momentum versus segment multiplicity for $t\bar{t}$ events. The muon tracks are shown in plot a), non-muon tracks in plot b). The shaded area shows the added $p_T$-cut imposed on single MDT muon candidates.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4.16.png}
\caption{Muon candidate transverse momentum versus segment multiplicity for $Z^0 \rightarrow \mu^+\mu^-$ events with caviar background SF5. The muon tracks are shown in plot a), non-muon tracks in plot b). The shaded area shows the added $p_T$-cut imposed on single MDT muon candidates.}
\end{figure}

\begin{equation}
\left\{ \begin{array}{ll}
\text{if } n_{\text{seg}} < 10 & \\
\frac{2 \text{GeV}}{10 \text{ GeV}} & \\
\frac{10 \text{ GeV}}{100 < n_{\text{seg}}} \end{array} \right.
\end{equation}

Where $n_{\text{seg}}$ is the segment multiplicity of the event and $p_T$ the transverse momentum of the Inner Detector track. The lower limit of 2 GeV tracks coincides with the momentum cut at the track filtering step. The upper limit of 10 GeV is only applied on tracks in very busy events.

Figure 4.15 shows the transverse momentum for muon candidates versus the segment multiplicity of the event for the $t\bar{t}$ sample. Muon tracks are shown in plot...
a), non-muon tracks in plot b). The added transverse momentum cut is shown by the line; track candidates with a transverse momentum under the $p_T$ value are dropped, as is shown by the shaded area. $t\bar{t}$ events are moderately busy and imposing a tighter momentum cut removes only a fraction of the mis-identified particles. Busier events such as $Z^0 \rightarrow \mu^+\mu^-$ with added cavern background (safety factor 5) benefit significantly from the added transverse momentum cut as is shown in Figure 4.16.

Muon candidates passing the final track and segment cuts are passed to the muon builder.

4.7 Muon building

After the ambiguity solving step, the Inner Detector tracks with their associated muon spectrometer segments are identified as muon and a muon object (see section 3.5.3) is made.

The track and its associated segments are grouped as an object called MuTagObject. This object contains the Inner Detector track, the associated segments grouped with the extrapolated track parameters evaluated at the segment surface. The constructed matching variables are stored as well. The MuTagObject is part of the MuTag EDM described in appendix C. The MuTagObject is converted to the ATLAS EDM Analysis::Muon object, as discussed in section 3.5.3, with tools available in the MuTag framework.

First, a track is extracted from the MuTagObject describing the Inner Detector track and its hits. Secondly, a so called Rec::TrackParticle is created from the track by associating a vertex to the track. For this, an extra input collection VxCandidates is needed to provide the vertices. Finally, a muon object is created in the form of an Analysis::Muon and the segments used to tag the track, are added to the muon object. These muon building steps are performed by dedicated converter tools described in appendix C.

4.8 MuTagIMO algorithm structure

This section describes the software package MuonSegmentTaggers, developed to perform muon segment tagging as described in the previous sections. Each step in the tagging procedure described in section 4.2 corresponds to a set of dedicated tools in the MuonSegmentTaggers package. The package itself is an extension to the MuTag framework described in appendix C.

Figure 4.17 shows a schematic overview of the MuonSegmentTaggers packages. The MuTagIMO algorithm collects the tracks and segments according to the tracking EDM classes Rec::TrackParticleCollection and Trk::SegmentCollection. The input class of vertex locations, VxContainer, is required in the final muon building step.
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The MuTagIMO algorithm delegates the full tagging procedure to the MuTagIMOTool. This tool calls the filtering tools TrackParticleFilterTool and SegmentsFilterTool to prepare the input collections. The set of abstract muon station layer surfaces according to table 4.3 is provided by the MSSurfaces class. The extrapolation of tracks and matching with segments is performed by the MuTagMatchingTool that uses the ATLAS extrapolator (see section 3.4.2) configured. The resulting tag candidates are further processed by the MuTagAmbiSolverTool performing the ambiguity solving.

The grouping of the muon candidates tracks with their associated segments into a MuTagObject is done by the DoMuTagObjectTool. From the MuTagObject, a set of converters in the UpdateMuTagContainersTool construct the output collections Trk::TrackCollection, Rec::TrackParticleContainer and Analysis::MuonContainer.

4.9 Summary

In this chapter, the concepts of muon segment tagging is presented. This includes the implementation of muon segment tagging as done by the MuTagIMO algorithm. The filtering of the tracks and segments, the preselection of segments and the matching of the segments to the track is discussed in detail. The ambiguity solving step with several techniques to suppress the non-muon background has been presented, as well as the building of muons from muon candidates. The technical implementation of the MuTagIMO algorithm has been summarized in the last section.