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Muons in early ATLAS data: from first collisions to W+ W- production
Ottersbach, J.P.

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Physics analyses using muons require a detailed understanding of the performances of the muon identification algorithms. After having discussed the performance of one muon tagging algorithm, MuTagIMO in the last chapter, we will now determine the efficiencies of all ATLAS muon identification algorithms. These efficiencies are key ingredients in any cross section measurement of particles decaying into muons, as for example the $W^+W^-$ cross section measurement that will be discussed in Chapter 6.

We chose the Tag-and-Probe method applied on the decay of $J/\psi$ particles to measure these efficiencies. We show that this method provides an unbiased efficiency measurement of the MS identification, based on data itself. The efficiency includes these of the ID. However, the efficiencies of the trigger system will not be measured.

Since the experiments are dealing with complex event topologies in proton-proton collisions at energies never studied before, the accuracy of corresponding Monte Carlo simulations has to be verified and validated. We measure efficiencies on data and Monte Carlo simulations independently. The results are then compared and studied as a function of the transverse muon momentum for different detector regions.

This chapter is organized as follows. After choosing a dataset, the Tag-and-Probe method is explained in Section 5.2. Handling the background is the subject of 5.3. The detailed efficiency measurements on data are performed in 5.4, followed by an evaluation of the systematic uncertainties. In 5.6 efficiencies on simulated events are determined and compared to the corresponding efficiencies on data. Section 5.7 compares our results with the findings of previous studies within ATLAS. Finally, we conclude this chapter in 5.8.

### 5.1 Selected Dataset

We use the major part of the data recorded between the 23rd of April and the 18th of October 2010 by ATLAS, corresponding to an integrated luminosity of $\mathcal{L} = 18.13$ pb$^{-1}$. We select events where at least 90% of the detector was operational and the magnets were at nominal current. In addition, at least two reconstructed muons of any type are
required. To measure the muon identification efficiencies on simulated events, we use Pythia Monte Carlo samples of $J/\psi$ particles decaying into muons \(^1\).

### 5.2 Tag-and-Probe

The Tag-and-Probe method utilizes the fact that two simultaneous muons are produced in the decay of a $J/\psi$ particle or $Z$-boson. Hence, two real muons are present in these events, allowing to measure muon identification efficiencies on data. While these studies can be performed on the $Z$-boson resonance profiting from very little backgrounds, we choose to use the low $p_T$ muons from $J/\psi$ decays. This allows us to measure the efficiency turn-on curve as well as the plateau region of the algorithms. While the turn-on curve refers to the characteristic threshold at low muon momenta where the individual algorithms become operational, the plateau region refers to the efficiency at higher transverse muon momenta where the efficiency is constant. An additional benefit of using the $J/\psi$ instead of the $Z$-boson resonance is the large production cross section of the $J/\psi$ particles, which is about two orders of magnitude larger than the $Z$-boson cross section. This provides the necessary statistics to probe muons in the $p_T$ range from 2 to 20 GeV.

#### 5.2.1 The Method

One of the muons from the $J/\psi$ decay, the so called tag, needs to pass tight quality cuts to reject backgrounds and is in addition required to have triggered the event. The latter requirement prevents trigger biases. The tag muons should not be confused with the segment tagged or calorimeter tagged muons, see 3.6.

The other muon is called probe, since it is used to “probe” the algorithm under investigation. The probe muon needs to be identified by an algorithm independent of the algorithm whose efficiency is to be determined. This is of utmost importance since the measured efficiencies will otherwise be biased. Figure 5.1 illustrates the method, showing both real muons (dashed black lines) from the $J/\psi$ decay traversing the detector. The reconstructed tag muon also fired the muon trigger (for details on the muon triggering, see 2.3.4 and 3.2). The probe is shown as a calorimeter tagged muon, or calo muon which is independent of the MS measurements used by the algorithm-to-probe to identify the same real muon. Probes identified by the algorithm under investigation are labeled matched. If the algorithm fails to reconstruct the probe muon, it is labeled missed. The invariant mass distribution of missed and matched muons is shown in Figure 5.2(b) for muons identified by Muid Combined (and MuTagIMO). For a detailed description of the algorithms, the reader is referred to 3.6.

The efficiency is then given by

\[
\epsilon := \frac{\text{matched}}{\text{matched} + \text{missed}}.
\]  

\(^1\)The simulated dataset are available for ATLAS collaboration members, see Appendix E.2. For details on the ATLAS event simulation, see 3.3.
This efficiency is measured for different $p_T$ and $\eta$ regions to get a detailed understanding of the algorithm efficiencies and detector performance.

Figure 5.1: The Tag-and-Probe method is illustrated showing a $J/\psi$ decaying into two opposite sign muons (black, dashed) in a simplified cross section of the ATLAS barrel. In the displayed example, the $\mu^+$ is identified as the tag muon, while the probe muon is shown as the calorimeter tagged muon originating from the traversing $\mu^-$. The muon reconstructed by the algorithm whose efficiency is to be determined is shown in light grey.

The correct choice and usage of the probe is essential for an unbiased efficiency measurement. Most commonly, all ID tracks are used as probes\(^2\) since the ID measurements are independent of the MS measurements. However, in proton-proton collisions there are many tracks, originating mainly from QCD processes\(^3\). Hence, an efficiency measurement based on ID tracks faces a large background, which results in relatively large systematical errors. To reduce these errors, we use calo muons, see 3.6.5. Since the calorimeter provides again MS independent measurements, this additional requirement on the probe does not affect or bias the measured efficiencies, but reduces the background significantly and hence leads to a preciser measurement. Figure 5.2 shows the invariant $\mu^+\mu^-$ mass spectrum of the tag and probe pair (without the cut on the invariant mass). A subset of the selected dataset, corresponding to 3 pb\(^{-1}\) of integrated luminosity is used for this comparison. In Figure 5.2(a)\(^{[44]}\) ID tracks are used as probes while Figure 5.2(b) shows

\(^2\)The probe muon is hence not required to be identified as a muon by a muon algorithm in this case.

\(^3\)The average number of ID tracks per event in the selected data sample is $\approx 12$\(^{[43]}\).
the same spectrum using calo muons as probes. The visible peak at the $J/\psi$ mass in the unmatched/missed probe distributions show the inefficiencies of the algorithms. These inefficiencies become significantly smaller if the muon segment tagger muons are added to the combined muons, as is visible in the plots. Comparing Figures 5.2(a) and 5.2(b) the large number of unmatched probes in Figure 5.2(a), corresponding to the large background introduced with the ID track probes becomes apparent.

![Graphs showing muon identification efficiencies](image)

(a) ID track probes  
(b) calo muon probes

**Figure 5.2:** The invariant $\mu^+\mu^-$ mass spectrum of the tag and probe pair is shown for probes that were matched and for those that were missed/unmatched by the respective algorithm(s). Here, these algorithms are the combined muon algorithm (CB) with and without adding segment tagged (ST) muons.

The requirements on the probe muon are independent of the muon identification in order to not bias the efficiencies in any way. The momentum cut on the probe muon rejects calo muons, whose momentum is too low to reach the muon spectrometer. The additional requirements on tag and probe tracks further reduce muon pairs in the selection that do not come from a $J/\psi$ decay. The charges, invariant mass and the common vertex are calculated from Inner Detector measurements.

The requirements on the tag and probe muons are as follows:

1. **tag muon** requirements
   - identified as combined muon (see 3.6.2)
   - $p_T > 4$ GeV
• fired muon trigger and hence caused the event to be recorded (for detailed trigger requirements see Appendix B)
• ID track quality cuts (for details see Appendix C)

2. probe muon requirements

• identified as calo muon (see 3.6.5)
• \( p > 3 \) GeV
• same ID track quality cuts as on the tag muon

3. additional requirements on the tag and probe pair

• opposite charge : \( \mu^+ \mu^- \)
• invariant mass at \( J/\psi \) resonance : \( m_{\mu^+\mu^-} \in [2.65; 3.55] \) GeV
• coming from a common vertex, i.e. a common vertex can be successfully fitted to the two ID tracks of the muons : \( \chi^2_{\text{vertex fit}} < 6 \)

5.2.2 The Selected Tag

Out of all muons identified by the Muid muon algorithms in the selected dataset, 20.9% fulfilling the requirements on a tag muon. Figure 5.3 shows some key distribution of selected tag muons. Their spatial distribution is shown in Figure 5.3(b) while the projection in \( \phi \) and \( \eta \) are shown in 5.3(a) and (d). The corresponding \( p_T \)-spectrum is shown in Figure 5.3(c). The peaks at 6 GeV, 10 GeV and 13 GeV results from events where the threshold of the lowest unprescaled trigger was set to the corresponding values, see Appendix B for details.

5.2.3 The Selected Probe

As mentioned in 5.2.1 we use calo muons as probes. Besides being independent of the MS system and providing a significantly cleaner \( J/\psi \) signal compared to ID probes, there are additional characteristics that are important. One essential feature of the probe is its global distribution. Since the muon identification efficiencies depend strongly on the geometrical detector regions that are traversed by the muons, all parts of the detector need to be covered in order to not introduce biases to the overall efficiencies. Figure 5.4(b) shows an \( \eta - \phi \) map of the selected calo muon probes, while Figure 5.4(a) and (d) show the respective projections. As the plots shows, the full detector is covered.

Another desired characteristic of the probe is a high efficiency. This leads to large statistics and hence smaller statistical uncertainties on the measured efficiencies. The integrated efficiency of the calorimeter taggers is measured to be \( 76.7 \pm 0.2 \% \) for muons with \( p_T \geq 2 \) GeV and reaches \( 85.4 \pm 0.2 \% \) for muons with \( p_T \geq 4 \) GeV. To measure this efficiency, the Tag-and-Probe technique is used with combined muons as probes to test the independent calo muon algorithm. The efficiency as a function of \( p_T \) and \( \eta \) is shown in Figure 5.5.
Figure 5.3: (a) shows an $\eta - \phi$ map and (b) the $p_T$-spectrum of tag muons in events that pass the Tag-and-Probe selection.

The missing efficiency at $\eta = 0$ is due to the MS acceptance hole (see 2.3.4), where no combined muons to probe the calorimeter tagger can be reconstructed.

The calorimeter tagger requires an ID track with a transverse momentum of $p_T \geq 2$ GeV.

The entire $p_T$-spectrum of the selected probe muons, i.e. the probes found in events where also a corresponding tag muon was found and the additional requirements of the tag and probe pair are fulfilled is shown in Figure 5.4(c).

We conclude, that the calo muons are suitable probes for the subsequent measurements.

### 5.3 Background

Although the calo muons provide a clean signal selection, a small background contamination is still present, as visible in the sidebands in Figure 5.2(b). We use a sideband subtraction method to measure the background in the mass window region. The background contamination under the $J/\psi$ signal is estimated from two equally sized intervals.
above and below the $J/\psi$ resonance in the invariant $\mu^+\mu^-$ mass spectrum. We use the intervals $[2.65, 2.95]$ GeV and $[3.25, 3.55]$ GeV as our sidebands, while the signal region is defined as $[2.95, 3.25]$ GeV. The sidebands are then subtracted from the signal region to obtain an estimate of the $J/\psi$ signal. The efficiency given in equation 5.1 is hence modified to

$$\epsilon := \frac{\text{matched} - (\Delta_{\text{matched}}/2)}{\text{matched} - (\Delta_{\text{matched}}/2) + \text{missed} - (\Delta_{\text{missed}}/2)} .$$

(5.2)

$\Delta_{\text{missed}}$ refers to the probes in the sidebands that were missed and $\Delta_{\text{matched}}$ correspondingly to the once that were matched. The factor $1/2$ results from the size of the sidebands compared to the signal region.
5.4 Measured Efficiencies

The efficiencies are measured as a function of the transverse muon momentum for four eta bins, corresponding to four different detector regions. They are grouped into efficiencies of the combined algorithms, the segment taggers and the combination of the two. The displayed errors are statistical. A detailed list of systematic errors can be found in Table 5.1.

5.4.1 Combined Muons

As described in 3.6.2 and 3.6.4 the Muid algorithm family consists of two independent combined muon identification algorithms, Muid Combined and MuGirl refitted. Both perform very well, showing a steep turn-on curve at low transverse momenta and a high efficient, flat plateau for \( p_T > 6 \) GeV, see Figures 5.6. Combining the two algorithms leads to an outstanding efficient muon reconstruction, showing very steep turn-on curves as well as a flat plateau at efficiencies close to one for all detector regions. This combination is hence used by various physics analyses throughout ATLAS.

The combined algorithm of the Staco collection shows particularly in the detector barrel a significantly flatter turn-on curve than the Muid combined algorithms (see Figure 5.6(a)), reaching the plateau region only at \( p_T > 12 \). This efficiency loss at low transverse momentum can be partially recuperated using MuTag, the segment tagger of the Staco collection, as will be shown in 5.4.3.

5.4.2 Segment Tagged Muons

Figure 5.7 shows the efficiencies of the 2 independent Muid segment taggers, MuTagIMO and MuGirl. MuTag is not independent and only adds muons that were missed by Staco
5.4 Measured Efficiencies

Figure 5.6: The efficiency of the ATLAS combined muon algorithms are shown for four detector regions.

Combined, see 3.6.3\(^4\). Therefore, a direct comparison with the Muid segment taggers does not make sense and we do not include the MuTag efficiency in Figure 5.7.

Both, MuTagIMO and MuGirl show the high efficiencies expected from segment tagger algorithms. The major difference between the two is the turn-on curve, clearly visible for $|\eta| \leq 2$, see Figures 5.7(a), 5.7(b), 5.7(c). While the steep turn-on curve of MuGirl starts at an efficiency $\approx 10\%$ for a transverse muon momentum of 2 GeV in the barrel region, MuTagIMO already reaches almost 60\%. Throughout all detector regions, MuTagIMO reaches its plateau sooner than MuGirl, at approximately 5 GeV, and is on average about 4\% points more efficient in the plateau.

\(^4\)The MuTag efficiencies hence drop with $p_T$ to values close to 0 once Staco Combined reaches its plateau. It is meant to be used in combination with Staco, see 5.4.3.
Figure 5.7: The efficiency of the ATLAS segment tagged muon algorithms of the Muid family are shown for four detector regions.

5.4.3 Segment Tagged or Combined Muons

The combination of combined algorithm and segment taggers yields the most efficient muon identification. Since MuGirl refitted takes MuGirl muons as an input, the combination of these two algorithms is omitted and only the combination of MuTagIMO and Muid Combined as well as MuGirl and Muid Combined are shown for the Muid collection. Performances, particularly for MuTagIMO in combination with Muid Combined are excellent and in all detector regions higher or equal to the two other algorithm combination shown in Figure 5.8. Though MuTag can recuperate a large part of the Staco Combined efficiency losses at low $p_T$, seen in 5.4.1, it does not reach the performance of the high efficient MuTagIMO - Muid Combined combination. Since MuTag does not tag ID tracks with $|\eta| > 2$ the Staco or MuTag efficiency drops significantly for low momenta in Figure 5.8(d). The late turn-on of MuGirl in the detector barrel, seen in 5.4.2 propagates into its combination with Muid Combined, compare Figures 5.7(a) and 5.8(a). The plateau efficiencies reach a similar level for all algorithm combinations. The largest


5.5 Systematic Uncertainties

Figure 5.8: The efficiency of the combination of segment tagged and combined muon algorithms are shown for four detector regions.

discrepancy is observed comparing the MuTagIMO - Muid Combined combinations to the Staco combination, with the Muid combination being on average approximately 2% points more efficient in the plateau region, see Table 5.1.

5.5 Systematic Uncertainties

The systematic uncertainties on the performed efficiency measurements are studied for the following sources:

1. **trigger**: The tag muon is required to be matched to the corresponding L2 muon triggers for the first data periods up to period F. For the later periods, statistics of muons firing the next higher threshold triggers is sufficient and we require the tag muon to be matched to EF_\text{mu13} for data periods F2 to G4 and EF_\text{mu15} for G5, G6 and H, which makes the bulk of the data sample. Details on the data periods
Muon Identification Efficiencies

and corresponding triggers are given in Appendix B.

2. **calorimeter identification**: Two independent calorimeter taggers are available, as discussed in 3.6.5. For our efficiency measurement we do not distinguish between calo muons reconstructed by one or the other. We evaluate the systematics introduced by the calorimeter taggers by choosing only muons reconstructed by one of them, the CaloLikelihood tagger. Systematics are calculated for 4 independent detector regions individually, corresponding to the $\eta$ binning used for the efficiency plots shown in 5.4. The quoted systematics are the weighted average of the systematics uncertainties in these detector regions. The weight is given by the number of tag and probe pairs in the corresponding detector region.

3. **sideband subtraction**: The size of the sidebands as well as the signal region are increased from 0.3 GeV to 0.4 GeV, subtracting events in the intervals [2.5; 2.9[, [3.3; 3.7] GeV from the signal region [2.9, 3.3] GeV.

4. **background shape**: To evaluate possible systematic uncertainties introduced by the chosen background subtraction method, we simultaneously fit the distributions of missed and matched probe muons as a function of the invariant dimuon mass in the region $m_{\mu^+\mu^-} \in [2.3, 6]$ GeV. The fit model describing the $J/\psi$ signal in the matched probes distribution is a double-sided exponential that is convoluted with a gaussian. The signal in the missed probe distribution, which corresponds to the inefficiency of the algorithm under investigation is modeled using a Breit-Wigner function convoluted with a gaussian. The backgrounds are modeled by the added background functions.

$$f_{\text{matched}}(m) = \epsilon N \left( \left[ H(\mu) e^{-\gamma m} + (1 - H(\mu)) e^{\gamma m} \right] * e^{-\frac{1}{2} \left( \frac{m - \mu_{\text{matched}}}{\sigma_{\text{matched}}} \right)^2} \right) + b_{\text{matched}}(m)$$

$$f_{\text{missed}}(m) = (1 - \epsilon) N \left( \frac{1}{(m - \mu)^2 + \frac{1}{4} \sigma_{\text{missed}}^2} * e^{-\frac{1}{2} (\frac{m - \mu}{\delta})^2} \right) + b_{\text{missed}}(m) \quad (5.3)$$

$N$ denotes the number of muon pairs in the signal peak, $\mu$ the mean and the $\sigma_x$ are the widths of the signal distributions. $\gamma$ and $\delta$ are additional free parameter. $H$ depicts the Heaviside function. The $b_x(m)$ are the background functions. The efficiency $\epsilon$ obtained from the fit is compared to the one measured using the sideband subtraction method. All parameters in the functions are left free for the fit.

Choosing a linear background $b_x(m) = \alpha_x m + \beta_x$ confirms the results found by the sideband subtraction method precisely. This is expected since the sideband subtraction method assumes a linear background shape. The systematic uncertainties are obtained using an exponential background $b_x(m) = \alpha_x e^{\beta_x m}$. Since statistics, particularly for higher $p_T$ bins in the missed probe muons distribution is too low to obtain stable fit results, we fit the distributions for the integrated statistics $p_T > 2$ GeV and $-2.5 < \eta < 2.5$ and assume this uncertainty to be a constant, i.e. independent of $p_T$ and $\eta$.

5. **kinematic selection**: The $p_T$ requirement on the tag muon is increased to 4.5 GeV.
6. purity of selection: An additional requirement on the tag muon is introduced, to further purify the selection. We require the scattering significance of the tag muon to be smaller than 0.2 [45]. This quantity is only available for the muon algorithms of the Muid family.

Table 5.1 lists the 6 individual contributions to the overall systematic uncertainties, which is the squared sum of these contributions, of the measured efficiencies for muons above certain $p_T$ values. The contribution from the background shape is obtained from the fit of the full statistics and is listed as a constant for each $p_T$ value. The large systematic uncertainties on the calorimeter identification for the Staco Combined algorithm are due to the strong $\eta$ dependence of its efficiency. Although, differences of the underlying $\eta$ distributions of the two independent calorimeter taggers are taken into account for the different detector regions, some differences within the detector regions remain. This holds particularly for the detector barrel, where the Staco Combined efficiencies drop significantly for $|\eta| < 0.8$, see Figure 5.9. This strong dependence on $\eta$ leads to the large observed systematic uncertainty.

![Figure 5.9](image)

**Figure 5.9:** Staco and Muid Combined efficiencies as a function of pseudorapidity are compared for muons with at least four GeV transverse momentum.
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<th>systematic error</th>
<th>trigger</th>
<th>calo id</th>
<th>sidebands</th>
<th>background shape</th>
<th>kinematic selection</th>
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<td>-0.95</td>
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<td></td>
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<td>0.34</td>
<td>0.39</td>
<td>0.84</td>
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<td>0.63</td>
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<td></td>
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<td>98.67</td>
<td>0.34</td>
<td>0.40</td>
<td>0.77</td>
<td>0.18</td>
<td>0.62</td>
<td>-0.28</td>
<td>0.27</td>
<td>0.08</td>
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<td>MuGirl</td>
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<td>0.68</td>
<td>0.68</td>
<td>2.02</td>
<td>-0.15</td>
<td>1.71</td>
<td>-0.73</td>
<td>-0.56</td>
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<td>93.60</td>
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<td>0.38</td>
<td>1.84</td>
<td>-0.31</td>
<td>1.38</td>
<td>-1.02</td>
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<td></td>
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<td>95.04</td>
<td>0.57</td>
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<td>1.46</td>
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<td>-0.56</td>
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<td></td>
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<td>0.72</td>
<td>1.26</td>
<td>-0.18</td>
<td>1.07</td>
<td>-0.29</td>
<td>-0.56</td>
<td>0.09</td>
</tr>
<tr>
<td>MuTagIMO + Muid Combined</td>
<td>$p_T &gt; 2$</td>
<td>91.71</td>
<td>0.52</td>
<td>0.53</td>
<td>0.98</td>
<td>0.08</td>
<td>0.47</td>
<td>-0.68</td>
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<tr>
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<td>0.14</td>
<td>0.16</td>
<td>1.07</td>
<td>-0.06</td>
<td>0.40</td>
<td>-0.95</td>
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<td>0.04</td>
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<tr>
<td></td>
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<td>0.34</td>
<td>0.39</td>
<td>0.84</td>
<td>0.09</td>
<td>0.63</td>
<td>-0.45</td>
<td>0.27</td>
<td>0.06</td>
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<tr>
<td></td>
<td>$p_T &gt; 12$</td>
<td>98.67</td>
<td>0.34</td>
<td>0.40</td>
<td>0.77</td>
<td>0.18</td>
<td>0.62</td>
<td>-0.28</td>
<td>0.27</td>
<td>0.08</td>
</tr>
<tr>
<td>MuGirl + Muid Combined</td>
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<td>0.66</td>
<td>0.66</td>
<td>1.22</td>
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<td>0.23</td>
<td>0.25</td>
<td>1.22</td>
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<td>-1.02</td>
<td>0.37</td>
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<td>97.74</td>
<td>0.43</td>
<td>0.49</td>
<td>0.74</td>
<td>0.03</td>
<td>0.55</td>
<td>-0.29</td>
<td>0.37</td>
<td>0.06</td>
</tr>
<tr>
<td>MuTag + Staco Combined</td>
<td>$p_T &gt; 2$</td>
<td>85.69</td>
<td>0.68</td>
<td>0.69</td>
<td>1.86</td>
<td>0.19</td>
<td>1.50</td>
<td>-0.60</td>
<td>0.82</td>
<td>-0.36</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 4$</td>
<td>95.33</td>
<td>0.36</td>
<td>0.37</td>
<td>1.21</td>
<td>0.00</td>
<td>0.49</td>
<td>-0.72</td>
<td>0.82</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 8$</td>
<td>97.51</td>
<td>0.45</td>
<td>0.50</td>
<td>1.25</td>
<td>-0.20</td>
<td>0.84</td>
<td>-0.36</td>
<td>0.82</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 12$</td>
<td>97.16</td>
<td>0.52</td>
<td>0.59</td>
<td>0.99</td>
<td>-0.15</td>
<td>0.45</td>
<td>-0.28</td>
<td>0.82</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 5.1: Efficiencies of all muon algorithms available for the ATLAS detector, as well as sensible combinations of algorithms are listed with statistical and systematic uncertainties. The efficiencies are integrated over $\eta$ and displayed for different transverse momenta. The total systematic error is the squared sum of the individual contributions. All values are in %.
5.6 Monte Carlo - Data Comparisons

The efficiencies shown in the previous section are now compared to the corresponding efficiencies from simulation. The scaling factor is defined as

$$\text{scaling factor} := \frac{\epsilon_{\text{data}}}{\epsilon_{\text{simulation}}}.$$  \hspace{1cm} (5.4)

The asymmetric statistical errors of the efficiencies are propagated individually for the upper and lower errors. No systematic errors are shown in the plots. The average scaling factor per eta region is shown on the corresponding plot and is obtained by fitting a constant over the full $p_T$-range.

While the plateau regions of the algorithms are expected to show a good agreement between data and Monte Carlo, a similar level of agreement will be very challenging to achieve for the turn-on curves. Already small differences in the material description can shift the thresholds and since the algorithm turn-on curves are very steep, this results in significant disagreements.

Figures 5.10 and 5.11 show the scaling factors (sf) as a function of transverse momentum for the individual muon algorithms and their combinations listed in Table 5.1, for the four previously defined detector regions.

5.6.1 Combined Muons

Data and simulation agree well for combined muons, as shown in the top four rows of Figures 5.10 and 5.11. Some fluctuating discrepancies are observed in the threshold curves and partially do not lie within the plotting range. However, as will be shown in 5.6.3, adding more statistics to the low momentum bins decreases the observed discrepancies, which indicates that they are mainly of statistical nature.

The plateau regions are in good agreement for all Muid algorithms while Staco combined shows some small deviations of several percent in the transition and forward region.

5.6.2 Segment Tagged Muons

Both Muid segment taggers show a good agreement between data and simulation as the central rows in Figures 5.10 and 5.11 show. Even the threshold curve of MuTagIMO shows an excellent agreement, while for the MuGirl one only minor deviations are observed. The efficiencies in the plateau regions are also well described. The scaling factors for MuGirl in the transition and endcap region suggest that the Monte Carlo plateau efficiencies in this region are systematically overestimated by a few percent. However, on average, data and simulation efficiencies of MuGirl agree within two percent. The MuTagIMO efficiencies in data and simulation even agree on a per-mill level.

As in 5.4.2 we omit MuTag at this point and show instead the agreement of the combination of MuTag and Staco Combined in the subsequent subsection.

\footnote{See Appendix D for the values and errors of these scaling factors.}
Figure 5.10: The ratios of efficiencies on data and simulation are shown for the barrel and transition region for all ATLAS muon identification algorithms and various of its combinations.
**Figure 5.11:** The ratios of efficiencies on data and simulation are shown for the endcap and forward detector region for all ATLAS muon identification algorithms and various of its combinations.
5.6.3 Segment Tagged or Combined Muons

Combining segment tagger and combined algorithms leads in addition to highest efficiencies also to the best agreement of data and simulation, as the lower rows of plots in Figure 5.10 and 5.11 show. A particularly excellent agreement of data and Monte Carlo simulation on a per-mill-level for all detector regions is achieved when combining MuTag IMO and Muid Combined. Also the combination of MuGirl and Muid Combined reaches on average a per-mill level agreement. The MuTag - Staco Combined combination suffers particularly in the forward region, since MuTag is not operating at $|\eta| > 2$. But also in the remaining detector regions, the data - MC agreement in the threshold curves is not excellent and deviations of several 10% are observed for the lower $p_T$ bins. However, on average also the algorithm combination of the Staco family shows a good agreement between data and simulated efficiencies, reaching a one percent level.

5.7 Comparison to High Momentum Muons

As mentioned in the introduction 5.2 the Tag-and-Probe efficiency measurement can also be performed using muons from $Z$-boson decays. These muons carry significantly larger momenta, due to the approximately 30 times larger mass of the $Z$-boson compared to the $J/\psi$. The very clean two muon final state with hardly any backgrounds left at the given invariant mass scale allows for a precise measurement of the plateau region of the muon reconstruction algorithms. Once reached, the efficiency plateaus are expected to be invariant of the transverse muon momentum. Hence, one would expect to find the same plateau efficiencies using the $J/\psi$ or the $Z$-boson resonance. Table 5.2 compares the results of this chapter with a measurement performed in the Muon Combined Performance group of ATLAS using a Tag-and-Probe technique on the $Z$-boson resonance [46]. Although the efficiencies of the individual algorithms agree all within the errors, a 1.2% discrepancy for the combined algorithms can be noted. This discrepancy can be understood considering the respective physical event topologies. Since these high momentum muons are the remnants of highly boosted $J/\psi$'s the opening angle between the decay products is very small and hence identifying both muons individually is more difficult, the efficiency decreases. These efficiency losses however can be recuperated using the segment taggers which do not require independent tracks in the MS. Consequently, the efficiencies of the combination of segment tagger and combined algorithm measured on $J/\psi$ and $Z$-boson sample agree better. The errors on the efficiencies measured on the $Z$-boson sample are statistical.

To compare the scaling factors we fit a horizontal line through the two $p_T$-bins $[12; 15]$ and $[15, 20]$ GeV of the scaling factor integrated over all $\eta$. This yields numbers corresponding to the scale factors quoted in [46]. However, highly boosted $J/\psi$'s producing muons with $p_T > 12$ GeV are very rare in simulation. The uncertainty on the scaling factors from $J/\psi$'s is hence large. Table 5.3 lists the scaling factors obtained from the $J/\psi$ and $Z$-boson measurements. The errors on the scaling factors of the $Z$-boson sample are again of statistical nature. For the scaling factors from $J/\psi$, the statistical errors are given by the fit, taking statistical uncertainties of the fitted points into account. Scaling factors
for the Muid algorithm agree well within the errors while some deviation of the order of one percent is seen for the Staco algorithms.

<table>
<thead>
<tr>
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<th>$J/\psi$ (for muon $p_T &gt; 12$ GeV)</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muid Combined</td>
<td>94.6 $^{+0.6}_{-0.7}$ (stat.) $\pm$ 1.1 (sys.)</td>
<td>95.8 $\pm$ 0.1</td>
</tr>
<tr>
<td>Staco Combined</td>
<td>91.6 $^{+0.8}_{-0.9}$ (stat.) $\pm$ 1.7 (sys.)</td>
<td>92.8 $\pm$ 0.2</td>
</tr>
<tr>
<td>MuTagIMO + MuidCombined</td>
<td>98.7 $^{+0.3}_{-0.4}$ (stat.) $\pm$ 0.8 (sys.)</td>
<td>98.0 $\pm$ 0.1</td>
</tr>
<tr>
<td>MuTag + Staco Combined</td>
<td>97.2 $^{+0.5}_{-0.6}$ (stat.) $\pm$ 1.0 (sys.)</td>
<td>97.0 $\pm$ 0.1</td>
</tr>
</tbody>
</table>

**Table 5.2:**Muon reconstruction efficiencies from Tag-and-Probe measurements on $J/\psi$’s and $Z$’s are shown for selected combined and combined + segment tagged algorithms. All values are given in %. The errors on the efficiencies obtained from the $Z$ sample are purely statistical.

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$ (for muon $p_T &gt; 12$ GeV)</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muid Combined</td>
<td>0.999 $\pm$ 0.005</td>
<td>0.995 $\pm$ 0.002</td>
</tr>
<tr>
<td>Staco Combined</td>
<td>0.969 $\pm$ 0.008</td>
<td>0.989 $\pm$ 0.003</td>
</tr>
<tr>
<td>MuTagIMO + MuidCombined</td>
<td>1.001 $\pm$ 0.003</td>
<td>1.001 $\pm$ 0.002</td>
</tr>
<tr>
<td>MuTag + Staco Combined</td>
<td>0.985 $\pm$ 0.004</td>
<td>1.003 $\pm$ 0.002</td>
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**Table 5.3:**The ratio of data and Monte Carlo efficiencies from Tag-and-Probe measurements on $J/\psi$’s and $Z$’s is shown for selected combined and combined + segment tagged algorithms.

### 5.8 Conclusion

The first 18.1 pb$^{-1}$ of data reprocessed in November 2010 with Athena release 16 show already a very high performant muon reconstruction and identification chain, considering the early stage of the experiment. We measured turn-on curves and the efficiency plateaus of all available ATLAS muon algorithms, as well as various of their combinations. Efficiencies from data were compared to the ones from corresponding Monte Carlo simulations. While the efficiency plateaus agree well, partially even up to a per-mill-level, deviation up to many 10% were found in the turn-on curves at low muon momenta. The results were subsequently compared to an independent Tag-and-Probe measurement using the $Z$-boson resonance, revealing a particularly good agreement for the combination of combined algorithms and segment taggers.

Our studies confirm the expectations that the segment taggers are the most efficient
Muon Identification Efficiencies

Muon identification algorithms are essential to identify low momentum muons. We can also conclude that the algorithms of the Muid family are in general higher efficient than the corresponding algorithms of the Staco family.