Muon signatures in ATLAS: A search for new physics in ±± events
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Citation for published version (APA):

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Chapter 3

Muon momentum scale and resolution from single muons

Measuring the muon momentum scale and resolution in collision data is an important step in the understanding and validation of the ATLAS detector and muon reconstruction performance. In this chapter we present an analysis to measure the muon momentum scale and resolution in ATLAS from an inclusive single muon sample by performing template fits on the relative momentum difference between the Inner Detector (ID) and Muon Spectrometer (MS) momentum measurement of combined muon tracks\(^1\) [34, 35]. This method, described in Section 3.2, was used during the first few months of \(\sqrt{s} = 7\) TeV collisions at the LHC and provided the first reliable results on the muon momentum scale and resolution in ATLAS from collision data.

We present the muon momentum scale and resolution in ATLAS as function of \(p_T\) and \(\eta\) of the combined muons, as obtained with 1.2 \(\text{pb}^{-1}\) of collision data. The precise data set and event selection used are described in Section 3.4, while the results are shown and discussed in Section 3.5. This chapter also includes a validation of the method on simulated events and a comparison of the results with other methods.

3.1 Introduction

The expected muon momentum scale and resolution in ATLAS can be determined from the design of the detector and the resolution of the individual hits. The actual scale and resolution may differ from this expectation due to effects such as misalignment or uncertainties in the material distribution or magnetic field description of the detector. To minimise these effects the MS is equipped with an optical alignment system, discussed in Section 2.2.4. Despite this tool, residual misalignment can result in significant differences in muon momentum scale and resolution between data and simulation.

Before the start up of the LHC, muons from cosmic rays were used to further align the detector. Momentum resolution studies performed with these muons during the first half of 2010 show good agreement between data and simulation [36], indicating an alignment

\(^1\)The definition of combined tracks is given in Section 2.3.1.
not far from design accuracy. However, due to the angular distribution of muons from cosmic rays, only part of the detector could be aligned this way and some remaining differences in scale and resolution between data and simulation were expected in early collision data, especially in the MS end-cap regions.

It is therefore necessary to measure the muon momentum scale and resolution in a data driven fashion directly on collision data. This provides a useful tool for the understanding and commissioning of the ATLAS detector as well as for validating the Monte Carlo simulation. Knowing the scale and resolution in data is also important for most physics analyses involving muons, as they affect both the efficiency of muon selection cuts and distribution shapes.

The standard method to determine the muon momentum scale and resolution in collision data is to study the Z-boson resonance. The scale and resolution are then obtained from the offset of the peak value and the width of this resonance, leading to results such as the ones shown in Section 2.3.1. Unfortunately, during the first months of data taking the available data did not contain sufficient Z-bosons for detailed resolution analyses.

We therefore developed a method to estimate the muon momentum scale and resolution from low momentum single muons by comparing their ID and MS momentum measurements. Due to the high cross-section for such muons, mostly from the decay of heavy flavour quarks, this method was able to obtain the first estimate for the muon momentum scale and resolution in collision data as a function of both $p_T$ and $\eta$ of the combined muon track with only 17 nb$^{-1}$ of integrated luminosity [34]. This provided the necessary information for the first W- and Z-boson measurements [37] as well as illustrated the state of the ATLAS alignment.

The results shown in this chapter describe the muon reconstruction performance as it was in September of 2010, obtained with approximately 1.2 pb$^{-1}$ of data. This data set, with several million muons passing our basic selection, was chosen because it contains sufficient muons to not be limited by the available luminosity but instead by the number of available simulated events used to describe background distributions.

It is important to note that because this single muon method is based on comparing the momentum measurements of the ID and MS, it provides an estimate for the combined momentum resolution of the two subdetectors (ID $\oplus$ MS) and is not able to decouple the individual resolutions. This combined resolution is not the same as the resolution of combined muons which is always better than that of either stand-alone tracks. However the combined resolution does provide an upper limit for the resolution of combined muons.

### 3.2 Analysis method

Muons with sufficient energy to pass though the calorimeters ($p_T > 3$ GeV) are usually measured by two independent subdetectors, the Inner Detector (ID) and the Muon Spectrometer (MS). Such combined muons can be used to estimate the muon momentum scale and resolution by studying their momentum imbalance, the relative momentum difference between the ID and MS stand-alone measurements. We do this by performing template fits on the momentum imbalance distribution of combined muon tracks in ATLAS.
3.2. Analysis method

3.2.1 The momentum imbalance of combined muon tracks

We defined the momentum imbalance, \( \Delta p/p \), of combined muon tracks as:

\[
\Delta p/p = \frac{p_{ID} - p_{MS}}{p_{ID}},
\]

where \( p_{ID} \) is the muon momentum as measured by the ID, while \( p_{MS} \) is the momentum of a track reconstructed in the MS back-extrapolated to the primary vertex. \( p_{MS} \) includes a correction for the expected muon energy loss through the ATLAS calorimeters.

For muons produced before the first ID layer, such as muons produced in the direct decay of W- and Z-bosons or heavy flavour quarks, the width of the \( \Delta p/p \) distribution provides a measure for the combined momentum resolution of both subdetectors (ID ⊕ MS). The \( \Delta p/p \) value corresponding to the peak of the distribution gives the momentum scale of the ID with respect to the MS.

For muons produced within or behind the ID volume, in the decay of long-lived particles such as pions and kaons, a combined muon is formed by combining a muon track in the MS with and ID track which, either partially or totally, comes from the meson before decaying. As part of the meson energy is transferred to the created neutrino, this introduces a large and positive momentum imbalance due to the energy difference between the meson and the muon.

For simplicity we refer to muons produced in the decay of all pions and kaons as background muons. All other muons are considered part of the signal. Figure 3.1 shows the \( \Delta p/p \) distribution of signal and background muons obtained from a simulated di-jet sample\(^2\), illustrating the differences in distribution shape between these muon types.

Figure 3.1: The \( \Delta p/p \) distribution for muons in the JF17 sample (see Appendix A), separated by muon origin.

\(^2\)The JF17 simulated sample, defined in Appendix A.
The $\Delta p / p$ distribution of muons produced before the ID volume.

For muons produced before the first layer of the ID, signal muons, the shape of the $\Delta p / p$ distribution is a convolution of a Gaussian, due to the instrumental resolutions of both subdetectors, with a Landau distribution, accounting for large energy loss fluctuations in the calorimeters with respect to the average. Given these considerations we use the following convolution function to fit the $\Delta p / p$ distribution:

$$ f(\Delta p / p; \mu_G, \sigma_G, \sigma_L) = \int d\mu_L[G(\Delta p / p; \mu_G, \sigma_G) \times L(\Delta p / p; \mu_L, \sigma_L)] $$

where $\mu_G$ and $\sigma_G$ are the mean value and the standard deviation of the Gaussian ($G$), while $\mu_L$ is the most probable value of the Landau distribution ($L$) and $\sigma_L$ is its width.$^{3}$

The muon momentum scale and resolution are obtained by fitting the $\Delta p / p$ distribution of signal muons with this function. The momentum scale corresponds with the $\Delta p / p$ value of the maximum of the fitted signal distribution while the resolution is given by the width of the signal distribution, defined as $\sigma_G + \sigma_L$.

The $\Delta p / p$ distribution of muons from pion and kaon decays

An inclusive sample of relatively low momentum muons, such as the one used in this analysis, contains a significant contribution from pion and kaon decays. This background produces a large tail on the positive side of the $\Delta p / p$ distribution, which is almost impossible to remove. Therefore, instead of trying to reduce this background, we fit its contribution to the $\Delta p / p$ distribution using templates to describe the background shape.

The exact shape of the $\Delta p / p$ distribution of pion and kaon decays depends strongly on the decay distance. We consider three types of decays:

- Early decays: A few percent of the pions and kaons decay before the first pixel layer. Such early decays in flight result in a $\Delta p / p$ distribution which is identical to that of signal muons.

- Late decays: Some pions and kaons, especially with high momentum, reach the calorimeters and lose much of their energy before decaying. The resulting track in the MS is therefore typically of low momentum. As the $\Delta p / p$ definition uses the MS momentum measurement extrapolated to the primary vertex, this momentum is extrapolated to slightly above the expected energy loss in the calorimeters ($\sim 3$ GeV). The shape of the $\Delta p / p$ distribution for late decays in flight is therefore a peak close to $\Delta p / p = 1 - 3 \text{GeV}_{\text{PID}}$.

- Intermediate decays: Most pions and kaons decay within the ID volume. Their $\Delta p / p$ distribution depends on the flight direction, decay distance and decay-angle but also on the detector and reconstruction performance in combining partial meson/muon

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$^{3}$The width of the Landau distribution is defined by the width parameter of the RooFit::RooLandau functions from the RooFit analysis package [38].
tracks. This results in a broad distribution with $\Delta p/p$ values between that of early and late decays.

The relative contributions of these three types of decays depends on the momentum and angular distribution of the mesons and is different for pions and kaons, although the majority always consists of intermediate decays.

As the shape of the $\Delta p/p$ distribution of pion and kaon decays depends on many variables and is not easily described by a simple analytical expression, we use templates constructed from simulated data to describe this shape.

**Extracting the background templates**

To build the background templates used to fit the $\Delta p/p$ distribution in data, we select simulated muons from pion or kaon decays using hit based truth matching. The selected reconstructed combined muons should have ID tracks that are either matched to a truth pion or kaon or to a muon produced in the decay of a pion or kaon. The templates of the $\Delta p/p$ distribution are then built using the RooFit::RooKeysPdf class from the RooFit analysis package [38].

As the $\Delta p/p$ distribution of background muons depends on some of the properties of the reconstructed muons, it is important that the templates are created from simulated events with the same properties as those in the studied data. As we perform the analysis on an inclusive sample of low momentum muons, the templates should be extracted from simulated Minimum Bias events. Unfortunately the available sample has limited statistics and very few muons with $p_T > 10$ GeV. We therefore use the much larger di-jet sample called JF17\(^4\).

Apart from increased statistics the two samples differ somewhat in the kinematic range of the muons, specifically in the $p_T$ and isolation distribution. This is shown in the left plots of Figure 3.2 which show the normalized $p_T$ and $E_T$-cone20 (isolation variable)\(^5\) distributions of combined muons in the Minimum Bias and JF17 simulated sample. To ensure that despite these differences the template shapes remain unaffected by the choice in simulated sample, we studied the effect of $p_T$ and $E_T$-cone20 of the muons on the shape of the $\Delta p/p$ distribution. The top right plot of Figure 3.2 shows the $\Delta p/p$ distribution of background muons for different $p_T$ ranges, while the bottom right plot shows the same for different $E_T$-cone20 ranges. From these plots we can conclude that the $\Delta p/p$ distribution of background muons does not significantly depend on the muon isolation. However, as expected from the description of the $\Delta p/p$ distribution of pion and kaon decays, the templates do depend on the $p_T$ of the muons. We therefore construct the background templates from the JF17 sample, with the selected muons reweighted to the Minimum Bias $p_T$ spectrum.

To ensure that the templates correctly describe the background $\Delta p/p$ distribution of a given data sample any selection criteria used on the data should in principle also be applied on the simulated samples before building the templates. However, variables that do not influence the physical process of pion and kaon decays and do not affect the muon

\(^4\)Both simulated samples are listed in Appendix A.

\(^5\) $E_T$-cone20 is defined as the energy deposited in a cone of size $\Delta R = 0.2$ around the muon track.
reconstruction in simulation have no effect on the background shape. We therefore do not need to take these variables into account when creating the templates. As the number of available simulated muons often a limiting factor for studying the muon momentum scale and resolution in great detail using this method, this is a definite advantage. For example, the template shapes are independent of the sign of $\eta$, the charge and the isolation of the muon.

### 3.2.2 Fitting the momentum scale and resolution

We fit the $\Delta p_p$ distribution on data to a PDF which is the sum of the signal Landau-Gauss convolution and the obtained background template, leaving the signal to background fraction as a free parameter. In total the fit has 4 free parameters: $\mu_G$, $\sigma_G$ and $\sigma_L$ from Equation 3.2 and the signal to background ratio\(^6\). The best fit parameters are returned

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\(^6\)The signal to background ratio is used in Chapter 4 to estimate the pion and kaon fraction of muon samples.
by a likelihood fit to the unbinned $\Delta \frac{p}{p}$ distribution. As an example Figure 3.3 shows the $\Delta \frac{p}{p}$ distribution of muons in data with $|\eta| < 1.05$ for two different $p_T$ ranges: $6 \text{ GeV} < p_T < 8 \text{ GeV}$ and $8 \text{ GeV} < p_T < 10 \text{ GeV}$. The best-fit to these distributions and the corresponding fitted signal and background components are included.

Figure 3.3: The $\Delta \frac{p}{p}$ distribution of muons in data ($\int L \cdot dt \approx 1.2 \text{ pb}^{-1}$) with $|\eta| < 1.05$ and $6 \text{ GeV} < p_T < 8 \text{ GeV}$ (left) or $8 \text{ GeV} < p_T < 10 \text{ GeV}$ (right). The best-fit function for these distribution (full-line), the signal (dashed-line) and background (dotted-line) components are also displayed.

The momentum scale is obtained by taking the position of the maximum of the signal distribution returned by the fit. The resolution is given by the width of the signal distribution, for which we quote the linear sum $\sigma_G + \sigma_L$, as this is the definition used in earlier resolution analyses based on cosmic muons in ATLAS [36]. Although the fit is not always able to reliably separate the Landau and Gaussian part of the signal distribution, as this depends heavily on the exact shape of background distribution, the fitted combined width of the signal peak is stable.

Shift of the background templates

The simple fitting procedure described so far assumes that the background distribution in data is the same as in simulation. Unfortunately this is only an approximation as both the muon momentum scale and resolution affect the background distribution shape and, as discussed previously, the scale and resolution might not be the same in data and simulation. We therefore need to modify the templates to properly describe the background $\Delta \frac{p}{p}$ distribution in data.

A difference in momentum resolution can be simulated by convoluting of the background distribution with a Gaussian, with the width of the Gaussian depending on the difference in resolution between data and simulation. As the resolution in data is one of the parameter we want to fit, this width should be a free parameter. Unfortunately such a convolution leads to unstable fit results. We therefore do not include a convolution of the background templates in the fitting procedure. This simplification does not significantly affect the fitted scale and resolution as those values are determined from the shape...
of the peak of the $\Delta p_p$ distribution, which does not strongly depend to the exact background shape. This was confirmed by refitting the $\Delta p_p$ distribution in data using templates convoluted with a Gaussian of fixed width.

Differences in momentum scale between data and simulation lead to shifts of the background template along the $\Delta p_p$ axis. The fitting procedure used in this analysis can be very sensitive to such shifts, as the right-hand side of the $\Delta p_p$ distribution determines the fitted normalization of the background template. A shift of the templates of a few percent can, for example, lead to fits with a fitted background distribution close to zero. In such fits the background tail is fitted by the Landau, resulting in an artificially large estimated scale and resolution. We therefore include this scale dependence of the background distribution by shifting the background templates by the same amount as the signal, $\mu_G$. This is based on the assumption that any detector effects present in data which are not correctly simulated in the Monte Carlo samples can affect the reconstruction performance of either subdetectors as well as the matching between the two stand-alone tracks, but should not affect the physical processes involved. Therefore any shift of the $\Delta p_p$ distribution in data compared to simulation should be independent of the muon origin, which means that the shift of the background distribution should be equal to the difference in scale between data and simulation.

By shifting the background template by the value $\mu_G$ we also assume that in the simulation, $\mu_G = 0$, which is valid if the signal distribution in simulation peaks at zero ($(\Delta p_p)_{\text{max}} = 0$) and that $\mu_G = (\Delta p_p)_{\text{max}}$. Unfortunately both of these assumptions are only approximately correct. The maximum of the distribution for simulated signal events can be off by up to $1-2\%$. This effect is enhanced further when looking at low $p_T$ Muid muons where the reconstruction algorithm underestimates the energy loss in the calorimeter by $\sim 200$ MeV. The assumption $\mu_G = (\Delta p_p)_{\text{max}}$ is only valid in the limit where $\sigma_G \gg \sigma_L$ and only a pure Gaussian form remains. Otherwise $(\Delta p_p)_{\text{max}} > \mu_G$. In the fits considered $(\Delta p_p)_{\text{max}} - \mu_G$ is typically of the same order $0-2\%$. We shift the background by the value $\mu_G$, despite these limitations, because there are insufficient simulated muons to precisely determine the maximum of the signal distribution on Monte Carlo without using a fit, and there is no simple analytical formula to calculate $\mu_G - (\Delta p_p)_{\text{max}}$. The effect of this choice is taken into account when calculating the systematic uncertainty. How this is done is described in more detail in Section 3.2.3.

### 3.2.3 Uncertainties on the estimated scale and resolution

In Section 3.2.2 we described how to obtain the best estimate for the muon momentum scale and resolution from inclusive single muon samples. In this section we describe the determination of the uncertainty on this estimate.

**Statistical uncertainty**

As mentioned in Section 3.2.2 we take the peak value of the signal distribution as the momentum scale and the total width ($\sigma_G + \sigma_L$) as the resolution. The statistical uncertainty
is calculated using a 2-D profile likelihood with $\mu_G$ and the combined width $(\sigma_G + \sigma_L)$ as the parameters of interest. As it is not possible to describe the scale value, $(\Delta p/p)_{\text{max}}$, as a simple analytical function of $\mu_G$, $\sigma_G$ and $\sigma_L$ it is difficult to perform a profile likelihood fit on this value. We therefore take the uncertainty on $\mu_G$ as the uncertainty on the scale. In cases where the profile likelihood calculation failed to obtain a upper or lower boundary, symmetric errors are assumed.

### Systematic uncertainty

There are three systematic uncertainties that can affect the results and need to be quantified:

- The uncertainty on the background template shapes due to the limited number of muons in the Monte Carlo samples,
- The uncertainty on the shift of the background template,
- The uncertainty due to possible differences in the pion to kaon ratio between collision data and simulated events.

### Statistical uncertainty on the background template shapes

The fitting procedure of Section 3.2.2 does not take the statistical uncertainty on the background template shapes into account. As there is a factor approximately 150 more muons in the collision data considered in this chapter than in the simulated JF17 sample, this uncertainty is not negligible. To take this uncertainty on the template shape into account we generate a number of toy-Monte-Carlo-templates, which are then used to fit the data. This is done separately for each of the considered kinematic regions.

The toy-MC-templates are created from toy-MC-data sets, which is turn are generated from the original background template. Each toy-MC-data set contains the same amount of muons as the original simulated sample and is therefore statistically equivalent to this original sample. As an example Figure 3.4 shows 300 such toy-MC-templates overlaid with the original background distribution of the JF17 sample for muons with $|\eta| < 1.05$ and $6 \text{ GeV} < p_T < 8 \text{ GeV}$. It also shows the the fits obtained on collision data using these toy-MC-templates, and the resulting measured momentum scales and resolutions.

As can be seen from Figure 3.4 both the scale and resolution distributions are approximately Gaussian. We therefore take the mean value of these distributions as the most probable values for the scale and resolution, and the RMS as the systematic uncertainty due to the template shape. As computation time is a limiting factor when doing unbinned fits on a large amount of data, we perform only 8 fits (7 toy-MC-templates) per kinematic region.

### Uncertainty on the shift of the background templates

We shift the background template by an amount equal to $\mu_G$. The reason for this, including its limitations, is discussed in Section 3.2.2. The main problem is that we should shift the background by the value $(\Delta p/p)_{\text{max}}$ instead of $\mu_G$. To quantify the effect of this approximation on the fitted momentum scale and resolution we consider the difference
Figure 3.4: Top left: The $\Delta p/p$ distribution of background muons, with $|\eta| < 1.05$ and 6 GeV $< p_T < 8$ GeV, in the simulated JF17 sample (red dots) together with 300 toy-MC-templates (black lines). Top right: The $\Delta p/p$ distribution for muons in collision data ($\int L \cdot dt \approx 62$ nb$^{-1}$) passing these same requirements (dots) with the best-fit functions for this distribution using the toy-MC-templates (full-line) and the corresponding signal (dashed-line) and the background (dotted-line) components. Bottom: The muon momentum scale (left) and resolution (resolution) obtained by the 300 fits shown in the top right plot. The red line shows the best Gaussian fit through the distribution.

between ($\Delta p/p$)$_{\text{max}}$ and $\mu_G$. We then refit the $\Delta p/p$ distribution shifting the background by a new value $\mu'_G - \mu_G + (\Delta p/p)_{\text{max}}$ instead of $\mu'_G$, where $\mu'_G$ denotes the mean of the fitted signal Gaussian in the refit. The resulting difference in scale and resolution is considered a systematic uncertainty.

In order not to be influenced by the uncertainty from the template shape, this procedure should be repeated for all toy-MC-templates. Unfortunately this is not practical due to the large computing time involved. We therefore perform this second fit on the original template and take the difference between this fit, and the mean of the toy-MC-fits as the uncertainty. If this uncertainty is significantly larger ($>30\%$) than the uncertainty due to simulated statistics, we perform four additional fits with toy-MC-templates. This is to limit the effect of a fit possibly converging to a local minima giving an unrealistically large
3.2. Analysis method

systematic uncertainty. The uncertainty is then given by the difference between the mean of these five measurements and the mean from the original fits.

Uncertainty on the background content

The background in this analysis consists of muons from pion and kaon decays. Table 3.1 lists the relative signal, pion and kaon contributions in the Minimum Bias and JF17 simulated samples. The relative pion to kaon ratio of both simulated samples differs by approximately 30%.

<table>
<thead>
<tr>
<th>Muon Type</th>
<th>Minimum Bias MC</th>
<th>JF17 MC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># muons</td>
<td>percentage</td>
</tr>
<tr>
<td>total</td>
<td>1423</td>
<td>100%</td>
</tr>
<tr>
<td>signal</td>
<td>725</td>
<td>51%</td>
</tr>
<tr>
<td>pion decays</td>
<td>370</td>
<td>26%</td>
</tr>
<tr>
<td>kaon decays</td>
<td>328</td>
<td>23%</td>
</tr>
</tbody>
</table>

Table 3.1: Different contributions to the muon content of the simulated Minimum Bias and JF17 sample. The muon selection criteria are given in Section 3.4.1. The signal contribution of both samples is dominated by muons from heavy flavour quark decays.

This uncertainty in the exact background composition affects the template shapes, as muons from pion and kaon decays have slightly different $\Delta p_t$ distributions (see Figure 3.1). To quantify the effect of this uncertainty on the fit results we built two new templates, one where the pion contribution is doubled and one where the kaon contribution is doubled. The difference in scale and resolution obtained when using these templates compared to the best value for the scale and resolution using the toy-MC-templates, is taken as the uncertainty due to the background content. As was the case for the systematic uncertainty due to the relative background shift, we redo these fits four times, using toy-MC-templates, if the uncertainty coming from the background content is at least 30% larger than the uncertainty due to the limited simulated statistics.

Combining the separate uncertainties

For the muon momentum scale and resolution obtained in the collision data we quote the statistical and systematic uncertainty separately. Due to the large difference in muon sample size between the available collision data and the simulated samples used to build the templates, the systematic uncertainty is typically dominated by the uncertainty on the background template shape due to limited simulated statistics. This uncertainty does not only affect the determination of the best fit value, but also the calculation of the other systematic uncertainties, as we are unable to perform sufficient toy-MC-fits to decouple these effects. Because the statistical uncertainty on the background shape is present in all the calculated systematic uncertainties, these uncertainties are highly correlated. We therefore take the maximum of the three uncertainties as the systematic error.

When measuring the muon momentum scale and resolution on the simulated JF17 sample, the background content and the statistical fluctuations in the templates are the
same as in the fitted pseudo-data. Therefore no systematic uncertainty due to the background content or the statistical error on the templates needs to be taken into account. In this case we show the combined statistical and systematic uncertainty, by adding the statistical uncertainty and the uncertainty due to the relative background shift in quadrature.

3.3 Validation on simulated Minimum Bias events

To show that our fit is able to correctly separate the signal and background contributions to the $\Delta p$ distribution and correctly models the signal shape, we have tested our method on the simulated Minimum Bias sample listed in Appendix A. We fit this sample as if it were data and compare the signal and background components of the fit directly with the true signal and background components of the sample. Figure 3.5 shows the result for four different $p_T$ bins. Both the signal and background distributions are correctly fitted within available statistical uncertainties. Unfortunately this simulated sample does not contain enough muons to test this method separately for different $\eta$ regions.

![Figure 3.5: Best fit obtained on a simulated Minimum Bias sample, for Muid muons in different $p_T$ ranges. The signal (black dots) and background (white dots) data points are shown separately. Overlain is the signal (full line) and background (dotted line) part of the best fit to the total signal + background distribution.](image-url)
3.4 Data set and event selection

In this chapter, we analysed a data set corresponding to an integrated luminosity of approximately $1.2 \text{ pb}^{-1}$ of collision data at $\sqrt{s} = 7 \text{ TeV}$. This data set was obtained with stable LHC beams between the 30th of March and the 15th of August 2010, with events passing detector data quality checks and selected on-line by any of the ATLAS muon triggers. The events are reconstructed using the best detector description and reconstruction software available at the time, known as the May 2010 reprocessing.

Collision events are selected if coming from a paired LHC proton bunch. Furthermore each event must contain a minimum of three inner detector tracks associated with a reconstructed primary vertex. These selections are aimed at rejecting muons from cosmic rays.

As mentioned in the previous section, two Monte Carlo samples are used to construct the templates: a Minimum Bias and a di-jet (JF17) sample. Both samples are described in more detail in Appendix A. The JF17 sample is also used to obtain the expected muon momentum scale and resolution from simulation.

3.4.1 Muon Selection

To ensure well reconstructed muon tracks we add the following requirements to the basic muon selection of Section 2.3.1:

- $p_T > 5 \text{ GeV}$
- At least 1 hit in the pixel detector
- At least 5 hits in the SCT detector

Using this selection the data set used in this chapter contains in total $5.27 \times 10^6$ combined muons. The JF17 and Minimum Bias samples contain $3.4 \times 10^4$ and $1.4 \times 10^3$ combined muons respectively.

3.5 Results

We present our estimate for the muon momentum scale and resolution as a function of $p_T$ and $\eta$ of the combined muon tracks. These results, obtained from the data set introduced in the Section 3.4, report the state of the muon reconstruction performance as it was in September of 2010. A comparison with the results obtained on the simulated JF17 sample is also included.

To interpret these results, it is important to note that the muon momentum scale and resolution shown in this section are obtained from comparing the ID and MS standalone momentum measurements and therefore indicate the relative ID to MS momentum scale and the combined (ID $\oplus$ MS) momentum resolution, which is always larger than

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7All fits used to obtain the results presented in the section are included in an ATLAS communication note [35].
the momentum resolution of combined muons. Furthermore, since we are looking at the momentum difference between the MS and ID stand-alone measurements, this analysis is not able to decouple the momentum resolution of the two subdetectors. To interpret the results in terms of the individual detector performances we often include an indication for the relative contribution of the two detectors in the text. At the times this analysis was performed, between June and September of 2010, this information was deduced from simulated events. By the end of 2010 this information was confirmed by Z-boson studies such as the results shown in Section 2.3.1.

3.5.1 Momentum scale and resolution as a function of $p_T$

The $p_T$ dependence of the relative uncertainty on the measured muon momentum, the muon momentum resolution, is of the form:

$$\frac{\sigma_{p_T}}{p_T} = \frac{P_0}{p_T} \oplus P_1 \oplus P_2 \times p_T,$$

(3.3)

where the $P_0$ quantifies the momentum resolution due to the energy loss in material, $P_1$ quantifies the resolution due to multiple scattering and $P_2$ is the result of the intrinsic resolution of the individual hits, which starts to dominate the momentum resolution for tracks with $p_T > 100$ GeV.

For muons in the range $5$ GeV $\leq p_T \leq 20$ GeV, the ID momentum resolution is dominated by multiple scattering and is therefore approximately constant as a function of momentum. The size of this resolution depends on $\eta$ and is approximately 2% at small $|\eta|$ where considerable alignment efforts with cosmic muons where possible, and $\sim 4 \sim 5\%$ in the end-caps. The MS stand-alone muon momentum resolution in the barrel region ($|\eta| < 1.05$) is mostly determined by energy loss fluctuations up to a momentum of 10 GeV, leading to a decrease in measured momentum resolution with increasing momentum. Above 10 GeV multiple scattering becomes dominant, reaching a plateau in the resolution at about 5%. In the end-cap regions of the MS ($|\eta| > 1.05$) a minimum $p_T$ requirement of 5 GeV ensures that the momentum of the muons is high enough for the multiple scattering terms to dominate the entire $5 \sim 20$ GeV region, resulting in a flat resolution distribution. The size of the momentum resolution in this region is similar to that in the barrel region: $\sim 5\%$.

The muon momentum scale should be zero independent of momentum. However for muons reconstructed by the Muid algorithm, the energy loss in the calorimeters was underestimated by about 200 MeV leading to a none-zero scale in both data and simulation. The relative effect of this underestimation, and therefore the momentum scale, decreases with increasing momentum. This effect was fixed in the November 2010 reprocessing.

The results on the relative momentum scale and resolution are displayed in Figure 3.6 as a function of $p_T$, for the barrel ($|\eta| < 1.05$) and end-cap ($|\eta| > 1.05$) regions separately. The statistical uncertainties fall within the size of the marker. The systematic uncertainties are given by the light blue rectangles. In the text we always quote the combined statistical and systematic uncertainties. For comparison, we also display the momentum scale and
Figure 3.6: The momentum scale (left) and resolution (right) for muons in the barrel (|\(|\eta| < 1.05\) (top) and end-cap (|\(|\eta| > 1.05\) (bottom) regions as a function of \(p_T\), for collision data (black dot) and the simulated JF17 sample (red cross). For data the statistical and systematic uncertainties are displayed separately by black lines and light blue rectangles respectively, with the statistical uncertainty falling within the size of the marker. For simulation the red crosses indicate the total uncertainty.
resolution values obtained from the simulated JF17 sample. In this case the red crosses give the combined statistical and systematic uncertainty.

In the barrel region, a good agreement between data and simulation is found. The estimated momentum resolution is between $(5.8 \pm 0.1)\%$ for muons with $p_T$ between 5 and 6 GeV and $(4.7 \pm 0.1)\%$ for muons with $p_T$ between 10 and 20 GeV. The corresponding resolutions in simulation are $(5.4 \pm 0.3)\%$ and $(3.9 \pm 0.1)\%$. This small difference in resolution is primarily due to some missing material in the simulation. Also the scale shows good agreement between data and simulation with a measured scale between the $(2.9 \pm 0.5)\%$ and $(1.0 \pm 0.2)\%$ depending on $p_T$.

The estimated momentum resolution in the end-caps is constant between the momentum range of 5 to 20 GeV, with a value between $(8.7 \pm 0.3)\%$ (5 GeV $< p_T < 6$ GeV) and $(8.2 \pm 0.3)\%$ (8 GeV $< p_T < 10$ GeV). The difference in resolution between data and simulation is much larger $\sim 2-3\%$ than in the barrel. This is not unexpected as, due to geometrical acceptance, the end-caps could not be aligned as precisely using cosmic muons. In more recent data reprocessing the difference between data and simulation is smaller, as can be seen in the plots of Section 2.3.1.

### 3.5.2 Momentum scale and resolution as a function of $\eta$

As discussed in Chapter 2, different technologies are used in the MS to measure muon tracks depending on the spatial direction of the tracks, with MDT chambers covering most of the detector, while CSCs are used in the more forward regions, $|\eta| > 2.0$. For this reason, as well as the geometrical detector layout, the expected nominal muon momentum resolution depends on the detector region. As most of these dependences are independent of $\phi$, we study the muon momentum scale and resolution in different $\eta$-bins. The results for muons with 5 GeV $< p_T < 20$ GeV are listed in Table 3.2 and shown in Figure 3.7.

<table>
<thead>
<tr>
<th>$\eta$-range</th>
<th>Scale (%)</th>
<th>Resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data</td>
<td>Simulation</td>
</tr>
<tr>
<td>$-2.5 &lt; \eta &lt; -2.0$</td>
<td>1.3$\pm$0.1</td>
<td>0.7$\pm$0.5</td>
</tr>
<tr>
<td>$-2.0 &lt; \eta &lt; -1.4$</td>
<td>2.1$\pm$0.6</td>
<td>$-0.4$</td>
</tr>
<tr>
<td>$-1.4 &lt; \eta &lt; -1.05$</td>
<td>5.4$\pm$0.7</td>
<td>1.2$\pm$0.4</td>
</tr>
<tr>
<td>$-1.05 &lt; \eta &lt; -0.5$</td>
<td>2.5$\pm$0.4</td>
<td>1.5$\pm$0.2</td>
</tr>
<tr>
<td>$-0.5 &lt; \eta &lt; 0$</td>
<td>2.1$\pm$0.3</td>
<td>0.9$\pm$0.2</td>
</tr>
<tr>
<td>$0 &lt; \eta &lt; 0.5$</td>
<td>2.2$\pm$0.3</td>
<td>1.0$\pm$0.2</td>
</tr>
<tr>
<td>$0.5 &lt; \eta &lt; 1.05$</td>
<td>2.7$\pm$0.4</td>
<td>1.3$\pm$0.2</td>
</tr>
<tr>
<td>$1.05 &lt; \eta &lt; 1.4$</td>
<td>3.2$\pm$0.6</td>
<td>0.7$\pm$0.2</td>
</tr>
<tr>
<td>$1.4 &lt; \eta &lt; 2.0$</td>
<td>$-0.2$</td>
<td>0.5$\pm$0.4</td>
</tr>
<tr>
<td>$2.0 &lt; \eta &lt; 2.5$</td>
<td>1.6$\pm$0.2</td>
<td>0.6$\pm$0.4</td>
</tr>
</tbody>
</table>

Table 3.2: The estimated momentum scale and resolution on data and the simulated JF17 sample for different $\eta$-regions. The quoted uncertainty contains both statistical and systematic effects.
3.5. Results

Figure 3.7: The momentum scale (left) and resolution (right) as a function of $\eta$, for muons in data (black) and in the simulated JF17 sample (red). For data the statistical and systematic uncertainty are displayed separately by black lines and light blue rectangles respectively, with the statistical uncertainty falling within the size of the marker. For simulation the red cross indicates the total uncertainty.

The barrel region: $|\eta| < 1.05$

All tracks in the barrel region of the MS should pass through three layers of MDT chambers, with the exception of tracks passing through the gap at $\eta \approx 0$. As discussed in Section 3.5.1, the agreement between data and simulation in this region is relatively good, due to alignment efforts performed with muons from cosmic rays. The momentum resolution and scale in the central part of the detector is somewhat better than in the more forward regions of the barrel. This is due to the shorter path through the calorimeters, and therefore smaller energy loss, at small $|\eta|$.

The transition regions: $1.05 \leq |\eta| < 1.4$

The transition regions contain tracks outside the MS barrel region that do not reach the outer MS end-cap ring. These tracks are measured by the inner and middle end-cap rings. In the design of the MS a third measurement should be made in the EE ring (see Figure 2.7), however most EE chambers are not yet installed in ATLAS. Therefore most tracks in the transition regions are reconstructed from only two position measurements, leading to a less precise momentum determination. As the transition regions fall outside the geometrical acceptance of most muons from cosmic rays, and the optical alignment system of the MS does not provide barrel to end-cap alignment, these regions can only be
aligned using collision muons. Therefore, at the time of this study, the difference between data and simulation in both momentum resolution and scale is large and asymmetric in $\eta$. This asymmetry in $\eta$ was not unexpected as the level of random misalignment need not be the same in both regions, however this analysis was one of the first that clearly showed and quantified this effect, giving valuable feed-back for the MS alignment effort. In newer data reprocessing this asymmetry is no longer present. This can be seen in the plots of Section 2.3.1.

The MDT end-cap regions: $1.4 \leq |\eta| < 2.0$
Muons passing through these regions of the MS end-caps are measured by three layers of MDT chambers. The nominal momentum resolution should therefore be similar to that in the barrel region. The large difference between data and simulation in these region is primarily due to misalignment in the ID end-caps, as most of the MS misalignment was removed using the optical alignment system.

The CSC end-cap regions: $2.0 \leq |\eta| < 2.5$
In these regions the momentum measurement in the MS depends on the CSC measurement which is expected to be less precise than that of the MDTs, leading to a slightly worse nominal resolution. The level of misalignment in these regions is similar to that in the $1.4 \leq |\eta| < 2.0$ regions.

3.6 Comparison with other methods

We have cross-checked the results shown in this chapter two other methods used in ATLAS at the time this analysis was performed: the single-sided Gauss method and an analysis performed on muons from cosmic rays.

3.6.1 Comparison with the single-sided Gauss method

The single-sided Gauss method is a simplified version of the template fitting method which does not separate signal and background. The $\frac{\Delta p}{p}$ distribution is fitted with a single Gaussian function. The momentum scale is then defined as the central value of the Gaussian, and the resolution is its half-width. As the background from pions and kaons is prominent at positive values of $\frac{\Delta p}{p}$, the fit is performed on an asymmetric range which varies with the $p_T$ and $\eta$ bins, chosen in order to minimize the background contamination and to ensure a reasonable fit result in terms of $\chi^2/n.d.f$. As an example the top left plot of Figure 3.8 shows this fit for muons with $|\eta| \leq 1.05$ and $8 \text{ GeV} \leq p_T \leq 10 \text{ GeV}$.

As the single-sided Gauss method does not take the background contribution into account, it introduces considerable biases. Most notably, because the background contribution is asymmetric around $\frac{\Delta p}{p} = 0$, the scale is shifted towards positive values. As this shift depends strongly on the chosen fit range, the scale obtained using the single-sided Gauss fit is unreliable.
The obtained resolution is also biased as the fit consists only of a single Gaussian, without a Landau component. This leads to an underestimation of the resolution by about 0.5% to 1%. At higher momenta, where the Landau component becomes less important, this effect is reduced. Despite this clear bias we consider a comparison in the obtained resolution between the two methods meaningful to show that both methods find the same trend for the $p_T$- and $\eta$-dependence of the resolution. The comparison between the single-sided Gauss method and our template based method is shown as a function of $p_T$ and $\eta$ in Figure 3.8 showing similar distributions for both methods.

Although the single-sided Gauss method provides less reliable results than the template fitting method, it was heavily used in ATLAS to provide quick first estimates on the resolution. Not only is this method very easy and intuitive to run, it does not rely on Monte Carlo samples and therefore does not suffer from their limited statistics. This is why the single-sided Gauss method in Figure 3.8 could be run on narrower bin sizes and on higher momentum muons than the template fitting method.
3.6.2 Comparison with data from cosmic rays

Cosmic showers produced in the earth’s atmosphere are a source of high-energetic muons. Some of these muons reach the ATLAS detector and can be measured by the MS and, if the muon passes through the center of the detector, by the ID. Such cosmic muons pass through the entire detector and produce two separate tracks through the MS, one in the upper and one in the lower hemisphere of the detector. By comparing these two tracks it is possible to estimate the muon momentum resolution in the MS [36].

In Figure 3.9 we compare our results with the best fit to the relative $p_T$ resolution of the MS obtained using cosmic rays [36]. The comparison is unfortunately only possible for muons with $|\eta| < 1.05$, given the reduced geometrical acceptance of the MS end-caps for muons from cosmic rays.

![Figure 3.9: The momentum resolution for the MS obtained from cosmic ray muons [36] (red dots) and the the momentum resolution (ID $\oplus$ MS) from collision data using our template method (blue triangles).](image)

Although this comparison is useful as a validation of our method, some differences exist between the two methods which account for the slight difference in results.

- Some improvement on the alignment of the detector was made between the publication of the results from cosmic rays and the results of the template fitting method shown in this chapter.

- The kinematic range of cosmic muons is different than that in collision data. This is especially true for the $\phi$ distribution since most cosmic muons traverse the detector from top to bottom. Furthermore all collision tracks radiate from the interaction point, which is not true for cosmic muons.

- The results from cosmic ray muons represent the MS stand-alone resolution, while our results estimate the combined resolution (ID $\oplus$ MS). This difference is less than
1% since the MS resolution dominates for low momentum muons in the barrel region (see Section 3.5.1).

- The cosmic analysis applies slightly different selections on the muons (see Ref. [36]).

3.7 Conclusions

We studied the muon momentum scale and resolution in ATLAS using a template method based on fitting the measured relative momentum difference of combined muon tracks in the Inner Detector with respect to the Muon Spectrometer. As this method runs on inclusive samples of low momentum muons, which have a relatively high cross-section, we were able to provide the first reliable data driven results on the muon momentum scale and resolution in the ATLAS collision data [34,35]. These results, discussed in Section 3.5, were used to study the muon reconstruction performance during the first few months of collisions at $\sqrt{s}=7$ TeV.

By estimating the scale and resolution as a function of $\eta$ (and $\phi$) of the muon tracks we were able to identify detector regions with relative better or poorer muon reconstruction performance. In general a good agreement between data and simulation was found in both momentum scale and resolution for muons in the MS barrel regions, indicating a good understanding of the central region of the detector. Despite the calibration and alignment performed on the barrel using muons from cosmic rays, such good agreement in early collision data was not guaranteed. Due to the spatial distribution of cosmic ray muons, which pass through the detector from top to bottom, they could only be used to align some of the $\phi$ sectors around $\phi = \pm \frac{1}{2} \pi$. The alignment of the rest of the detector relied on the relative alignment of the MS optical alignment system. Therefore achieving, in such early collision data, a difference of at most 1% in both muon momentum scale and resolution between data and simulation, is an impressive result, especially as this difference does not depend significantly on $\phi$. The estimated resolution of $(4.7 \pm 0.1)\%$ for collision muons with $p_T > 10$ GeV is compatible with the resolution measured with cosmic ray muons. The remaining difference between data and simulation is dominated by a slight underestimation of the material distribution in the simulation which is corrected in more recent Monte Carlo samples.

In the end-cap regions we found a larger difference in resolution between data and simulation ($\sim 2 - 3\%$). This is primarily due to misalignment effects, as these regions could not be fully aligned with muons from cosmic rays, although some material was also missing in the simulation. The largest degradation in resolution and scale is in the transition regions ($1.0 \leq |\eta| < 1.4$) as the MS barrel to end-cap alignment is not included in the MS optical alignment system. Most of the discrepancy between data and simulation of the more forward end-cap regions is due to misalignment in the ID, where no hardware oriented alignment exists. From Table 3.2 we can see an asymmetry in the end-cap alignment with a poorer muon reconstruction performance for negative $\eta$. By estimating the muon momentum scale and resolution in these regions as a function $\phi$ we could conclude that this misalignment does not depend on the MS sector.
These results on the state of the muon reconstruction performance could not be used as direct input for the ATLAS alignment, however they did provide useful feedback for the alignment of the MS, and to a lesser degree of the ID, by helping guide the efforts to regions with poorer alignment.

Apart from helping evaluate the muon reconstruction performance, the estimated scale and resolution were also used in physics analyses. Specifically they were used to interpret the results of the first W- and Z-bosons measurements [37] as both the scale and resolution affect the shape of these resonances. Furthermore, by repeating our analysis with different muon selection criteria, such as hit requirements, we were able to quantify the effect of these criteria on the momentum resolution and therefore the width of the resonances. The muon momentum scale and resolution obtained by these first W- and Z-bosons studies are compatible with our results.