Muon signatures in ATLAS: A search for new physics in $\mu^+\mu^-$ events

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Chapter 6

Prompt same-sign muon pairs

A wide range of proposed extensions to the Standard Model, including supersymmetry, predict enhanced rates for collision events at the LHC containing two prompt leptons with equal electric charge. As the SM cross-section for such signatures in relatively small, prompt same-sign (SS) dilepton cross-section measurements can be used to search for new physics beyond the SM.

In this chapter we use the template fitting method of Chapter 5 and the knowledge of muons from pion and kaon decays of Chapter 4 to determine the cross-section for inclusive prompt SS dimuon events in ATLAS and compare the result with SM predictions. As the main SM contribution to the prompt SS dimuon cross-section comes from $WZ$ and $ZZ$ diboson production where both bosons decay to muons, we also consider the subset of prompt SS dimuon events with a third opposite-sign muon, to determine the $Z+$prompt muon cross-section.

Using these prompt SS dimuon and $Z+$prompt muon cross-sections, it is possible to exclude some phase-space of the proposed new physics models. As an example, in Section 6.5, we determine limits in the mSUGRA\textsuperscript{1} phase-space.

6.1 Introduction

In the SM, prompt high momentum muons are almost exclusively produced in the decay of gauge bosons, specifically: $Z$- and $W$-bosons as well as offshell photons ($\gamma^*$), where a $Z$ or $\gamma^*$ decays to $\mu^+\mu^-$ and $W^{\pm}$ to $\mu^\pm\nu_\mu$ or $\mu^\pm\overline{\nu}_\mu$ depending on the charge of the $W$-boson. Top-quarks can also lead to prompt muons due to their decay to a $W$-boson and a $b$-quark with a branching ratio of close to 100%. The muon is then produced in the subsequent decay of the $W$-boson. As none of these SM particles result in the production of two SS prompt muons, events which contain at least two muons of equal charge can only be created in events with at least two gauge bosons.

The main SM contribution to the SS prompt muon cross-section comes from $(Z/\gamma^*)W^\pm$ and $(Z/\gamma^*)(Z/\gamma^*)$ diboson production. The cross-section for these two processes is taken from simulation and, for $\gamma^*$ masses above 20 GeV, is approximately 17.5 and 5.7 pb

\textsuperscript{1}mSUGRA is introduced in Section 1.2.5
respectively. With a branching ratio of $Z/\gamma^* \rightarrow \mu^+\mu^-$ of 3.366% and of muonic decays of W-bosons of 10.56%, this leads to SS prompt muon pair cross-section contributions of 62.1 and 6.5 fb respectively. Apart from these two main channels there is also a small contribution from $W^\pm W^\pm$ which can be produced together with two (anti-)quarks in events where the two (anti-)quarks scatter through the exchange of a gluon in a t-channel diagram and both (anti-)quarks radiate a W-boson. The last SM contribution comes from the associative production of gauge bosons with a $t\bar{t}$ pair. All other SM sources of SS prompt muon pairs are negligible.

SS dimuon signatures in new physics models

Several new physics models can also give rise to final states with prompt SS muon pairs. One of these models is supersymmetry which is described in Chapter 1. Other models include: universal extra dimensions [42], left-right symmetric models [43–46], Higgs triplet models [47–49], little Higgs models [50], fourth-family quarks [51] and flavour changing neutral current [52–57]. The production process and the rate by which these models create prompt SS dimuons depends on the new physics model and typically on the phase-space point within the model. In some cases the SS muon pair is produced in the decay of a single double charged particle such as a doubly charged Higgs-boson, but in other models, such as for R-parity conserving SUSY, the two muons are produced in two somewhat independent decay chains. As discussed in Section 1.3, in most of the SUSY phase-space a significant contribution to the prompt SS muon cross-section comes from diboson events, similar as in the SM, except that the bosons are produced in the decay of SUSY particles.

Analysis method

Although we use SUSY to motivate our search for prompt SS muon pairs in ATLAS and we compare our results with expectations from mSUGRA, our primary goal is to test the SM with the least possible bias from theoretical expectations. We therefore measure the inclusive cross-section for prompt SS dimuons in a fiducial volume chosen to minimise the restrictions on the muons while ensuring a proper event reconstruction in ATLAS. As discussed in Chapter 2, this means that both muons must be within the MS volume ($|\eta| < 2.5$) and at least one of the muons must fall within the trigger range $|\eta| < 2.4$. We further require that both muons have $p_T > 25$ GeV. This is both to limit the background of non-prompt muons and to ensure a well understood trigger rate. Apart from these basic restriction on $p_T$ and $\eta$ of the muons no other requirement is put on either the kinematics of the muon pair or the rest of the event.

The main challenge of measuring such an inclusive prompt SS muon pair cross-section lies in understanding the background from muon pairs where one or both muons are non-prompt. We estimate this background using the template fitting method described in Chapter 5 which allows us to separate prompt muons from muons produced in the decay of B- and D-mesons as well as $\tau$s without making any assumptions on the kinematics of these background events. By considering high momentum muons ($p_T > 25$ GeV) we automatically reject almost all muons produced in the decay of prompt pions and kaons. Any
possible remaining contribution from this category of muons is estimated by considering the $\Delta p_T$ value (see Equation 3.1) of the muons, as motivated in Chapter 4.

Another possible background to prompt SS muon pairs comes from prompt opposite-sign muon pairs where the charge of one of the muon was misidentified. We limit this contribution by requiring that the independent charge measurements of the ID and MS tracks obtain the same charge. The remaining contribution is estimated from simulation and tested using muons from Z-boson decays and is shown to be negligible [58].

**Previous analyses in ATLAS**

The analysis presented in this chapter provides an alternative to previously performed prompt SS dimuon searches in ATLAS [58] which only considered isolated muons. Apart from this isolation criteria on the muons the main difference between the methods lies in the estimation of the non-prompt background. In Ref. [58] this contribution is estimated by extrapolating from the number of events in control regions, while we fit this contribution directly in the signal region, thereby removing any dependence on the kinematics of these background events. In Section 6.6 we compare the sensitivity of the two methods.

### 6.2 Data set and muon selection

The cross-section measurements presented in this chapter are performed on the data collected in Period D to K of 2011. This is the same data set as used in Chapter 5, except that we require the data to pass some additional basic data-quality cuts\(^2\), resulting in an integrated luminosity of \(2.28 \pm 0.08\) fb\(^{-1}\) [59].

#### 6.2.1 Trigger

The events are selected using Event Filter level triggers designed to select single high momentum muons. Specifically we require the events to be selected by either a combined muon EF trigger for muons with \(p_T > 18\) GeV (\(EF\_mu18\_MG\)) or a MS only EF trigger for muons with \(p_T > 40\) GeV and \(|\eta| < 1.05\) (\(EF\_mu40\_MSonly\_barrel\))^3. The use of this second trigger is to compensate for a small decline in the \(EF\_mu18\_MG\) trigger efficiency for muons in the barrel regions with a momentum of more than 200 GeV. Although this trigger was added for completeness it does not significantly affect the results presented in the chapter, as such very high momentum muons are very rare. In data-taking Periods J and K of 2011 the \(EF\_mu18\_MG\) was prescaled. Therefore in these periods the \(EF\_mu18\_MG\_medium\) trigger was used instead, which has slightly higher quality cuts on the muon tracks.

The trigger efficiency with respect to the offline reconstruction for the combination of the \(EF\_mu18\_MG\) and \(EF\_mu40\_MSonly\_barrel\) triggers is shown in Figure 6.1. In the

\(^2\)These additional requirements are implemented in the form of a *Good Run List* which rejects events obtained when one or more of the subdetector was not working optimally. The main cause in the luminosity drop introduced by this *Good Run List* is due to some problems in the liquid argon calorimeters.

\(^3\)The ATLAS muon triggers are described in Section 2.4.2.
barrel region $|\eta| < 1.05$ (left plot) the efficiency is given as a function of $\eta$ and $\phi$ and holds for muons with $p_T > 20$ GeV, corresponding with the momentum plateau region. The low efficiency bins at negative $\phi$ are due to the feet regions of the MS. In the end-cap regions, $1.05 < |\eta| < 2.4$, (right plot) the trigger efficiency does not significantly depend on either $\eta$ or $\phi$ and is therefore given as a function of $p_T$. The trigger does not extend beyond $|\eta| = 2.4$.

6.2.2 Muon Selection

To ensure a high quality on the selected muon tracks, as well as to use the same muon selection as used to obtain the muon trigger efficiencies the following requirements were added to the basic muon selection of Section 2.3.1:

- $p_T > 15$ GeV
- $z_0 < 10$ mm (to limit the number of tracks from pile-up collisions)
- The charge of the ID and MS track must be the same (to ensure an accurate charge measurement).
- At least 1 B-layer hit, if a B-layer hit is expected.
- At least 2 pixel hits, where dead pixels along the track are considered as hits.
- At least 6 SCT hits, where dead strips along the track are considered as hits.
- The number of holes (missing hits) in the pixel and SCT track is smaller than 3.
6.2. Data set and muon selection

- If $|\eta| < 1.9$, at least 6 TRT hits and/or outliers hits, where the number of TRT outliers hits is less the 90% of the total.

- If $|\eta| > 1.9$, the number of TRT outliers hits should be less the 90% of the total TRT hits if the track has at least 6 TRT hits and/or outliers hits.

This corresponds to the minimum muon requirements used in this chapter. In most cases we use a stronger $p_T$ requirement ($p_T > 25$ GeV) to limit the non-prompt background as well as to be in the plateau region of the selected triggers. The minimum $p_T$ requirement of each selected muon is always indicated in the text.

Muon reconstruction efficiency

The reconstruction efficiency for muons passing this selection is shown in Figure 2.10 where the reconstruction efficiency is given by the fraction of true muons above a given momentum threshold which are properly reconstructed. As we want to relate reconstructed muons with their reconstructed properties to the original true muons, we use a slightly modified definition of the reconstruction efficiency given by the number of reconstructed muons with a reconstructed $p_T > 15$ or 25 GeV in a certain detector region over the number of true muons with a true $p_T > 15$ or 25 GeV in the same detector region. This definition of the reconstruction efficiency depends slightly on the muon reconstruction resolutions and kinematic distributions of the muons. Specifically it includes some threshold effects such as reconstructed muons with a higher (lower) momentum than the true momentum, leading to a higher (lower) efficiency. In case of a flat momentum distribution these two contributions would cancel, but depending on the steepness of the $p_T$ distribution at the $p_T$ threshold this effect could result in "efficiencies" larger than one.

The reconstruction efficiency for muons with $p_T > 15$ GeV is given in Figure 6.2 as a function of $\eta$. The efficiency is obtained from a high statistics sample of simulated $Z \rightarrow \mu^+\mu^-$ events and is corrected for differences in efficiency and momentum resolution between data and simulation. To quantify the dependence of the muon reconstruction efficiency on the kinematic distribution of the muons the results are compared with the efficiency obtained from simulated $ZZ$ and $ZW$ events. The values obtained by the three samples agree within statistics, showing no significant dependence on possible threshold effects.

From Figure 6.2 it is clear that the muon reconstruction efficiency depends on $\eta$, with a much lower efficiency in at $\eta \sim 0$ due to a gap in the MS as was discussed in Section 2.3.1. The efficiency in the MS barrel to end-cap transition regions (around $|\eta| = 1.2$) is also somewhat lower than in the rest of the MS region. Apart from this dependence on $\eta$ the muon reconstruction efficiency also depends on $\phi$, specifically on whether the track was reconstructed in a small or large MS segment or in the overlap regions between segments. Furthermore the reconstruction efficiency is lower in the MS feet regions. For each of these different $\phi$ regions the differences in efficiency between data and simulation was obtained separately and incorporated in the distributions of Figure 6.2. In this chapter we do not use the $\phi$ dependence of the efficiency explicitly since events in ATLAS are essentially $\phi$
Figure 6.2: The reconstruction efficiency for muons passing the selection of Section 6.2.2, given by the fraction of reconstructed muons with $p_T > 15$ GeV over true prompt muons with $p_T > 15$ GeV, as a function of $\eta$, obtained simulated $Z$, $ZZ$ and $ZW$ samples. The efficiencies are corrected for differences between data and simulation.

symmetric and therefore the $\phi$ distribution of muons in all simulated samples and in data should be the same.

As shown in Figure 2.10, for muon with $p_T > 15$ GeV, the reconstruction efficiency is independent of the muon transverse momentum. We therefore only need to take the $\eta$ dependence of the muon reconstruction efficiency into account.

6.2.3 Monte Carlo samples

To compare the measured cross-sections in this chapter with theoretical expectations we rely on simulated events to obtain the total and fiducial theoretical cross-sections from SM and SUSY processes. These simulated samples are all listed in Appendix A, while the generating procedure is described in Section 2.5.

Standard model processes

The production of $(Z/\gamma^*) (Z/\gamma^*)$ and $(Z/\gamma^*) W^\pm$ events is generated at NLO with a total cross-section of 5.7 and 17.5 pb respectively. The uncertainty on this cross-section, taken from Ref. [58], is 12%: 10% due to higher order corrections and 7% from the PDFs.

For $W^\pm W^\pm$ production we use a sample generated at LO. It has a cross-section of 221 fb with an estimated K-factor of 1.0 $\pm$ 0.5. Unfortunately the only available sample contains a filter requiring two jets of at least 20 GeV. Without this added requirement the cross-section for $W^\pm W^\pm$ production is 287 fb. As we do not include any jet requirements in our analysis, we reweight the available sample to this total cross-section. This is based on the assumption that the jet-filter does not affect the kinematics on the muons, which
Unfortunately is not true. However the uncertainty due to this assumption should fall well within the 50% uncertainty from the K-factor.

The last category of SM events which contribute to the prompt SS dimuon cross-section are $t\bar{t}W^\pm$ and $t\bar{t}Z$ production. These samples are also generated at LO, with an estimated cross-section of 208 and 177 fb respectively. The estimated K-factor for these samples is $1.30 \pm 0.65$.

These different contributions to the prompt SS dimuon cross-section are discussed further in Section 6.3.6 and listed in Table 6.2.

**SUSY processes**

To estimate the SUSY prompt SS dimuon cross-section for the mSUGRA plane defined by $A_0 = 0$ GeV, $\tan(\beta) = 10$ and $\mu > 0$ we use the 350 samples of the mSUGRA grid defined in Appendix A. These samples are generated at LO and corrected to the NLO cross-section calculated by PROSPINO [60, 61], a program specialized in the calculation of SUSY cross-sections. These corrections are done separately for all SUSY points and each production process and are therefore typically different for, for example, $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{q}$ production. The cross-section estimation for gluino and squark production is further improved to the next-to-leading-log order, which incorporates some additional NNLO effects, using NLL-FAST [62–66]. The uncertainty on the cross-section is obtained by varying the PDF between CTEQ [25] and MSTW [27] and varying the uncertainties on both these PDF due to the uncertainty on $\alpha_s$ and on the scale-factor used to separate perturbative and non-perturbative processes.

As an indication for the cross-section and the relative uncertainties, Figure 6.3 shows the estimated mSUGRA fiducial cross-section for prompt SS muon pairs with $p_T(\mu) > 25$ GeV in the ATLAS detector acceptance and the relative uncertainty on this cross-section for each point on the mSUGRA grid.

![Figure 6.3: The estimated mSUGRA fiducial cross-section for prompt SS muon pairs with $p_T(\mu) > 25$ GeV in the ATLAS detector acceptance in fb (left) and the relative uncertainty on this cross-section (right) for each point on the mSUGRA grid discussed in Section 6.2.3. This grid is defined in the mSUGRA plane with $A_0 = 0$ GeV, $\tan(\beta) = 10$ and $\mu > 0$.](image-url)
6.3 Prompt SS muon pair cross-section

The main goal of this analysis is to determine the fiducial cross-section for inclusive, prompt, SS, high momentum ($p_T > 25$ GeV) muon pairs in the ATLAS detector acceptance (one muon with $|\eta| < 2.4$ due to the trigger acceptance and the other muon with $|\eta| < 2.5$). We do this by selecting SS muon pairs passing these requirements and fitting the prompt fraction for each muon. The number of events where both muons are prompt can then be estimated from these fitted fractions. As we are interested in the inclusive fiducial cross-section, we do not put any further requirements on the selected events. Specifically this means that besides the selected muon pair the event can contain additional leptons and/or jets.

The most straightforward way to estimate the probability that both muons in a selected muon pair are prompt is to multiply the prompt probability of the first muon with that of the second. This is the approach used in Chapter 4 to estimated the pion and kaon contamination to dimuon pairs. It is based on the assumption that the prompt fraction of both muons are uncorrelated. In Chapter 4 this assumption, which we tested on simulated events, was possible because, except for the very low invariant mass region, the production of $\pi/K$ and non-$\pi/K$ muons is independent. Unfortunately this is not true for prompt and non-prompt muons as, for example, $t\bar{t}$ events can lead to signatures with one prompt muon and one non-prompt muon with equal charge. In these types of events the probability for the second muon to be prompt is dependent on whether the first muon was prompt or not. Therefore if, for example, we measure a prompt fraction of 20% for both muons, the fraction of events where both muons were prompt could be 4%, if the prompt fractions are uncorrelated, but could also be 0%, if all prompt muons are produced in combination with a non-prompt muon. This dependence on the correlation between the prompt fraction of the muons is taken as a systematic uncertainty. To limit the relative size of this uncertainty, we use a tight selection on one of the selected muons such that its prompt fraction is close to one.

This tight selection on one of the selected muons is achieved using both an isolation cut and a cut of the $d_0$-significance on the most isolated muon. To quantify the effect of these added selection criteria and therefore to be able to estimate the cross-section without isolation or impact parameter restrictions, we correct the obtained cross-section using the efficiency of the $d_0$-significance cut. As discussed further in Section 6.3.2 this efficiency is obtained from the prompt muon templates. The effect of the isolation cut is quantified by estimating separately the fiducial cross-section for events with at least one muon isolated, and events with both muons isolated. The isolation independent cross-section is then estimated using these two values.

6.3.1 Event selection

We apply the following event selection:

- The event contains at least one $\mu^+\mu^-$ pair.
- The most isolated muon is denoted as $\mu_1$ and the other as $\mu_2$, where the isolation
is given by $p_T$-cone40/$p_T$.\(^4\)

- $p_T > 25$ GeV, for both muons.
- At least one muon is isolated: $p_T$-cone40/$p_T < 0.08$, for $\mu_1$.
- If the event contains more than one $\mu^\pm \mu^\pm$ pair passing these selections, the pair with the most isolated second muon, $\mu_2$, is selected.
- One of the selected muons is matched to a trigger object ($\Delta R < 0.15$) and has $|\eta| < 2.4$.
- The most isolated muon is produced close to the interaction point: $-2 < d_0\text{-sig} < 1$, for $\mu_1$.

As mentioned previously, the isolation and impact parameter requirements on the most isolated muon are necessary to ensure a high prompt fraction for this muon. To estimate the efficiency of the isolation cut, we also consider the subset of events where the second muon, $\mu_2$, is isolated ($p_T$-cone40/$p_T < 0.08$).

The cut-flow for this selection is given in Table 6.1. In total there are 1118 events that pass our event selection, of which 94 have both muons isolated. The invariant mass distribution for all SS muon pairs with $p_T > 25$ GeV is shown in Figure 6.4 together with the distribution for events with one or both muons isolated.

<table>
<thead>
<tr>
<th>Cut</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one $\mu^\pm \mu^\pm$ pair</td>
<td>77126</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV for both muons</td>
<td>8809</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$\mu_1$ is isolated</td>
<td>1657</td>
</tr>
<tr>
<td>muon matched to a trigger object</td>
<td>1649</td>
</tr>
<tr>
<td>$-2 &lt; d_0\text{-sig}(\mu_1) &lt; 1$</td>
<td>1118</td>
</tr>
<tr>
<td>$\mu_2$ is isolated</td>
<td>94</td>
</tr>
</tbody>
</table>

Table 6.1: The cut-flow for the event selection of Section 6.3.1 on the data set described in Section 6.2.

## 6.3.2 Cross-section measurement

To estimate the fiducial cross-section for inclusive prompt, SS, high momentum ($p_T > 25$ GeV) muon pairs in the ATLAS detector acceptance, we first determine the cross-sections for events where at least one of the muons is isolated and for events where both muons are isolated. The cross-sections for these two subset of events are then used to calculate the cross-section independent of isolation criteria.

\(^4\) $p_T$-cone40 is defined as the sum of the $p_T$ of all tracks in a cone with angle 0.4 around the muon.
Figure 6.4: The invariant mass distribution of high momentum ($p_T(\mu) > 25$ GeV) $\mu^+\mu^-$ pairs in the data sample of Section 6.2 (black lime) as well the distribution for the subset of muon pairs with one (red line) or both (blue line) muons isolated ($p_T$-cone40/$p_T < 0.08$).

The number of signal events in the selected data sample where at least one of the selected muons is isolated is obtained by calculating, for each event separate, the probability that both muons are prompt. This probability is corrected for the trigger and muon reconstruction efficiency as well as for the applied $d_0$-significance cut on $\mu_1$. This leads to the following expression for the cross-section:

$$\sigma_{SS: \mu_1=\text{isolated}}^\text{fid} = \frac{1}{\mathcal{L}} \sum_{\text{events}} \frac{\mathcal{P}_{\mu_1}(\mu_1) \cdot \mathcal{P}_{\mu_2}(\mu_2)}{\epsilon_{\text{trigger}}(\mu_1, \mu_2) \cdot \epsilon_{\text{reco}}(\mu_1) \cdot \epsilon_{\text{reco}}(\mu_2) \cdot \epsilon_{d_0\text{-sig}}}, \quad (6.1)$$

where $\mathcal{L}$ denotes the integrated luminosity, $\epsilon_{\text{trigger}}$ and $\epsilon_{\text{reco}}$ the trigger and muon reconstruction efficiencies, $\epsilon_{d_0\text{-sig}}$ the efficiency of the $d_0$-significance cut on $\mu_1$ and $\mathcal{P}_{\mu_1}$ and $\mathcal{P}_{\mu_2}$ give the probability that $\mu_1$ and $\mu_2$ are prompt.

In Equation 6.1 we assume that the probability that both muons are prompt is equal to $\mathcal{P}_{\mu_1}(\mu_1) \cdot \mathcal{P}_{\mu_2}(\mu_2)$. As mentioned before this is based on the assumption that $\mathcal{P}_{\mu_1}(\mu_1)$ and $\mathcal{P}_{\mu_2}(\mu_2)$ are uncorrelated. We quantify the uncertainty due to this assumption on the measured cross-section by considering the case where the prompt fraction of $\mu_1$ and $\mu_2$ are fully anti-correlated. In this case the $\mathcal{P}_{\mu_1}(\mu_1) \cdot \mathcal{P}_{\mu_2}(\mu_2)$ term in Equation 6.1 should be replaced by $\mathcal{P}_{\mu_1}(\mu_1) + \mathcal{P}_{\mu_2}(\mu_2) - 1$ in events with $\mathcal{P}_{\mu_1}(\mu_1) + \mathcal{P}_{\mu_2}(\mu_2) > 1$ and by zero otherwise. This corresponds to the minimum number of prompt muon pairs possible given $\mathcal{P}_{\mu_1}(\mu_1)$ and $\mathcal{P}_{\mu_2}(\mu_2)$.

$\mathcal{P}_{\mu_1}$ and $\mathcal{P}_{\mu_2}$:

The probability that $\mu_1$ is prompt, $\mathcal{P}_{\mu_1}$, is determined by fitting the $d_0$-significance distribution for $\mu_1$ (without the $d_0$-significance cut) using the template fitting method of
Chapter 5. The result of the fit is shown in the left plot of Figure 6.5. The prompt probability of each individual muon is obtained from the fitted fraction of the prompt PDF over the total distribution at the $d_0$-significance value corresponding to that of the muon. The statistical uncertainty on this value is obtained using a profile likelihood on the signal fraction of the fit. The systematic uncertainty calculation is described in Chapter 5. The right plot of Figure 6.5 gives $P_{\mu_1}$ as a function of the $d_0$-significance.

The probability that $\mu_2$ is prompt, $P_{\mu_2}$, is determined in a similar way by fitting the $d_0$-significance distribution for $\mu_2$. This is done separately for three bins depending on the $p_T$ of the closest jet to the muon track, where this $p_T$ is taken to be zero in events without any jets. The result of these fits are shown in Figure 6.6. The majority of prompt muons have a closest jet $p_T$ of less than 20 GeV. For these muons the value for $P_{\mu_2}$ is plotted as a function of the $d_0$-significance in the top right plot of figure Figure 6.6. We did not bin the fits for $\mu_1$ in a similar way as the isolation criteria on this muon remove most of the correlation between the impact parameter distribution of the muon and the properties of the nearest jet.

The template fitting method of Chapter 5 is able to separate the prompt muon contribution from muons from B-meson, D-meson and $\tau$ decays. Unfortunately it is not able to differentiate between prompt muons and prompt pions and kaons. As this contribution to high momentum muons is expected to be very small, we do not consider prompt pions and kaons in the determination of $P_{\mu_1}$ and $P_{\mu_2}$. The systematic uncertainty due to this omission is quantified by calculating the cross-section after rejecting muons with $\Delta p_T > 0.5$. The use of the $\Delta p_T$ value is motivated in Chapter 4. For all cross-sections measured in this chapter, the uncertainty from prompt pions and kaons turns out to be negligible.

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5 This binning in $p_T$(jet) is motivated in Chapter 5

6 See Equation 3.1.
Figure 6.6: Top left and bottom: The $d_0$-significance distribution for $\mu_2$ in the event selection of Section 6.3.1 fitted using the template fitting method of Chapter 5 for different bins in closest jet $p_T$. Top right: $P(\mu_2)$ as a function of the $d_0$-significance of $\mu_2$ for muons whose closest jet has $p_T < 20$ GeV. The red lines denote the statistical uncertainty while the blue line gives the systematic uncertainty obtained from using templates constructed from simulated $t\bar{t}$ events.

$\mathcal{L}$, $\varepsilon_{\text{reco}}$, $\varepsilon_{\text{trigger}}$ and $\varepsilon_{d_0\text{-sig}}$:

As mentioned in Section 6.2 the integrated luminosity of the selected data sample is 2.28 fb$^{-1}$ with an uncertainty of 3.7% [59].

The muon reconstruction efficiency for each muon is taken from Figure 6.2 and depends on $\eta$. The trigger efficiency of the event depends on $p_T$, $\eta$ and $\phi$ of both muons, as well as on the data period. The efficiency to trigger at least one muon is:

$$\varepsilon_{\text{trigger}}(\mu_1, \mu_2) = 1 - (1 - \varepsilon_{\text{trigger}}(\mu_1))(1 - \varepsilon_{\text{trigger}}(\mu_2)),$$

where the efficiency per muon is discussed in Section 6.2.1. As we require the trigger object to be matched with a muon with $|\eta| < 2.4$ the trigger efficiency for muon with $|\eta| > 2.4$ is automatically zero. The binning used for the muon trigger and reconstruction efficiency is the same binning as shown in Figure 6.1 and 6.2. For all cross-section measurements performed in this chapter the uncertainty from the trigger and reconstruction efficiency turns out to be negligible.
6.3.3 Result for events with at least one muon isolated

Using Equation 6.1 we can extract the fiducial cross-section for prompt, SS, high momentum \( (p_T > 25 \text{ GeV}) \) muon pairs in the ATLAS detector acceptance (one muon with \( |\eta| < 2.4 \) and the other muon with \( |\eta| < 2.5 \)) with at least one of the muons isolated:

\[
\sigma_{\text{SS; } \mu_1=\text{isolated}}^{\text{fid}} = 48^{+23}_{-10}(\text{stat})^{+33}_{-17}(\text{syst}) \text{ fb}.
\]

The statistical uncertainty contains both the Poisson uncertainty on the number of events, calculated by adding the contribution of each event in quadrature, and the uncertainty on the fit results due to statistical fluctuations in the signal shape. As discussed in Section 6.3.2 this second uncertainty, which dominated the total statistical uncertainty, is obtained from a profile likelihood on the prompt fraction in the fits for \( \mathcal{P}_{\mu_1}(\mu_1) \) and \( \mathcal{P}_{\mu_2}(\mu_2) \). The upper limit on the systematic uncertainty is dominated by the choice in the templates used in the \( d_0 \)-significance fits. As discussed in Chapter 5 this uncertainty is estimated by using templates constructed from simulated \( t\bar{t} \) events. The lower limit on the systematic uncertainty is dominated by the uncertainty in the correlation between \( \mathcal{P}_{\mu_1}(\mu_1) \) and \( \mathcal{P}_{\mu_2}(\mu_2) \). All other uncertainties are negligible.

6.3.4 Result for events with both muons isolated

We determine the cross-section for events in which both muons are isolated using the same approach as for events with at least one muon isolated. The corresponding fits on the \( d_0 \)-significance distributions of \( \mu_1 \) and \( \mu_2 \) are shown in Figure 6.7.

Figure 6.7: The \( d_0 \)-significance distribution for \( \mu_1 \) (left) and \( \mu_2 \) (right) in the event selection of Section 6.3.1 with both muons isolated. The left plot does not include the \( d_0 \)-significance cut on \( \mu_1 \). Both distributions are fitted using the template fitting method of Chapter 5.
The estimated fiducial cross-section for the subset of events in which both muons are isolated is:

\[ \sigma_{\text{SS; } \mu_1, \mu_2 = \text{isolated}}^{\text{fid}} = 32^{+7}_{-9}\text{(stat)}^{+7}_{-2}\text{(syst)} \text{ fb}. \]

The statistical uncertainty is still dominated by the uncertainties on \( \mathcal{P}_{\mu_1} \) and \( \mathcal{P}_{\mu_2} \) returned by the fits. The upper limit on the systematic uncertainty is caused by the effect of changing the templates used in the \( d_0 \)-significance fits to templates constructed from simulated \( \bar{t}t \) events. The lower value on the systematic uncertainty is a combination on the uncertainty to how we combine \( \mathcal{P}_{\mu_1} \) and \( \mathcal{P}_{\mu_2} \) (1.4 fb), the systematic uncertainty on the \( d_0 \)-significance fits (1.2 fb) and the uncertainty on the integrated luminosity (1.1 fb).

The relative uncertainties for this cross-section measurement are significantly smaller than the uncertainties on \( \sigma_{\text{SS; } \mu_1 = \text{isolated}}^{\text{fid}} \) despite a difference in statistics of about an order of magnitude. For the statistical uncertainty, this is because the uncertainty is not dominated by the Poisson term but by the effect of the statistical uncertainty of the \( d_0 \)-significance distribution shapes on the fitted prompt fractions. This uncertainty is dominated by statistical uncertainties in the tails of the distributions and is therefore relatively larger for more non-prompt dominated muon samples. As the prompt fraction for \( \mu_2 \) and to a lesser degree for \( \mu_1 \), is significantly higher with the additional isolation requirement on the second muon, this leads to corresponding smaller uncertainties.

The more prompt dominated muon selections are also the reason for the smaller systematic uncertainties, as the shape of the prompt template is more stable and better understood than the different non-prompt template shapes which depend on the properties of the nearby jets and on the uncertainty on \( d_0 \) (see Chapter 5). Therefore the systematic uncertainty on the fits due to our choice in templates is smaller with a relative smaller non-prompt contribution. Also the uncertainty due to combining \( \mathcal{P}_{\mu_1}(\mu_1) \) and \( \mathcal{P}_{\mu_2}(\mu_2) \) into the probability of two prompt muons, is much smaller for \( \sigma_{\text{SS; } \mu_1, \mu_2 = \text{isolated}}^{\text{fid}} \) than for \( \sigma_{\text{SS; } \mu_1 = \text{isolated}}^{\text{fid}} \) due to the prompt fraction of almost 100% on \( \mu_1 \) shown in Figure 6.7.

### 6.3.5 The SS prompt dimuon cross-section

Using the cross-sections obtained for events with at least one and with both muons isolated, we estimated the isolation independent fiducial cross-section for prompt SS dimuons in ATLAS.

Assuming that for signal events the probability that one of the muons is isolated is independent of whether the other muon is also isolated the following equations hold:

\[
\sigma_{\text{SS; } \mu_1, \mu_2 = \text{isolated}}^{\text{fid}} = \epsilon_{\text{isolation}}^2 \sigma_{\text{SS}}^{\text{fid}} \\
\sigma_{\text{SS; } \mu_1 = \text{isolated}}^{\text{fid}} = (2\epsilon_{\text{isolation}}^2 - \epsilon_{\text{isolation}}^2) \sigma_{\text{SS}}^{\text{fid}}.
\]

Therefore:

\[
\sigma_{\text{SS}}^{\text{fid}} = \frac{(\sigma_{\text{SS; } \mu_1, \mu_2 = \text{isolated}}^{\text{fid}} + \sigma_{\text{SS; } \mu_1 = \text{isolated}}^{\text{fid}})^2}{4\sigma_{\text{SS; } \mu_1, \mu_2 = \text{isolated}}^{\text{fid}}}
\]

(6.2)
Using Equation 6.2 we estimate the fiducial cross-section for inclusive prompt, SS, high momentum ($p_T > 25$ GeV) muon pairs in the ATLAS detector acceptance to be:

$$\sigma_{SS}^{\text{fid}} = 50^{+24}_{-11} \text{(stat)}^{+43}_{-20} \text{(syst)} \text{ fb.}$$

The statistical uncertainty is obtained by using the same relative uncertainty as on $\sigma_{SS;\mu_1=\text{isolated}}^{\text{fid}}$. This is motivated by the observation that the statistical uncertainties of $\sigma_{SS;\mu_1=\text{isolated}}^{\text{fid}}$ and $\sigma_{SS;\mu_1,\mu_2=\text{isolated}}^{\text{fid}}$ are highly correlated. Since the relative uncertainty on $\sigma_{SS;\mu_1=\text{isolated}}^{\text{fid}}$ is much larger it dominates the uncertainty on $\sigma_{SS}^{\text{fid}}$. The upper value of the systematic uncertainty is obtained from evaluating Equation 6.2 with the results using templates from simulated $t\bar{t}$ events. The lower value of the systematic uncertainty corresponds to the lower systematic limit for $\sigma_{SS;\mu_1,\mu_2=\text{isolated}}^{\text{fid}}$ as it is impossible for the total fiducial cross-section to be smaller than $\sigma_{SS;\mu_1,\mu_2=\text{isolated}}^{\text{fid}}$.

### 6.3.6 Comparison with SM predictions

Using the MC samples and cross-sections given in Section 6.2.3 we estimate the theoretical, SM, fiducial cross-section for prompt SS dimuons at the LHC to be:

$$\sigma_{SS;\text{SM}}^{\text{fid}} = 39.3 \pm 4.5 \text{ fb.}$$

The contributions from the individual SM processes are listed in Table 6.2. In calculating the uncertainty on the total fiducial cross-section we assume the uncertainty on the cross-section of the $ZW^{\pm}$ and $ZZ$ samples to be fully correlated. The same holds for the uncertainty on the K-factor of the $t\bar{t}W$ and $t\bar{t}Z$ cross-sections. All other uncertainties are assumed to be uncorrelated.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{SS;\text{SM}}^{\text{fid}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZW^{\pm}$</td>
<td>29.3 ± 3.5</td>
</tr>
<tr>
<td>ZZ</td>
<td>4.9 ± 0.6</td>
</tr>
<tr>
<td>$W^{\pm}W^{\pm}$</td>
<td>2.0 ± 1.0</td>
</tr>
<tr>
<td>$t\bar{t}W$</td>
<td>2.0 ± 1.0</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>Total</td>
<td>39.3 ± 4.5</td>
</tr>
</tbody>
</table>

Table 6.2: The theoretical prediction from the SM for $\sigma_{SS;\text{SM}}^{\text{fid}}$ for different processes.

Combining this theoretical SM cross-section with our measured cross-section we conclude that the non-SM contribution to the fiducial prompt SS dimuon cross-section is:

$$\sigma_{SS;\text{non-SM}}^{\text{fid}} = 10^{+49}_{-24} \text{ fb},$$

showing no indication of physics beyond the SM. The uncertainty on $\sigma_{SS;\text{non-SM}}^{\text{fid}}$ is obtained from combining the theoretical uncertainty with the statistical and systematic uncertainty on the measured cross-section in quadrature.
6.3.7 95% CL upper limit

The values for the cross-sections shown so far are quoted with our best estimate for a 1σ uncertainty, approximately corresponding to a 68% confidence level (CL). When interpreting these results for the exclusion of new physics models, the 95% CL upper limit is more commonly used. As some of the systematic uncertainties are highly non-Gaussian we cannot simply multiply the quoted uncertainties by a factor of 1.664 to obtain this upper limit. Instead we recalculate all separate uncertainties for this 95% CL limit before combining them. This includes using a wider range for the width of the Gaussian used to convolute the templates for the $d_0$-significance fits (see Section 5.6.1).

The uncertainty due to the possible correlations between the prompt probability of both muons, and the uncertainty in the choice of templates ($t\bar{t}$ versus non-$t\bar{t}$) is not increased compared to the 68% CL values. The reason for this is that these uncertainties are already estimated by looking at the full range of possibilities. In the case of the correlation between the prompt probability of the two muons we consider the case of fully anti-correlated probabilities to calculate the uncertainty. As it is impossible for these muons to be more than 100% anti-correlated, increasing this uncertainty is unrealistic. Similarly, the uncertainty due to the choice in templates reflects the uncertainty in the type of background events. The normal templates represent the simplest event topologies while the $t\bar{t}$ templates correspond to the most complex SM events, involving a wide range of different particles. Therefore, varying between the two sets of templates already incorporates all possible SM backgrounds.

As we have no easy way to estimate the background composition of our data selection we cannot build a likelihood function for the uncertainty from our choice in templates. Using the most conservative approach we therefore estimate the 95% CL upper limit to the fiducial cross-section of prompt SS dimuons in ATLAS, by calculating this cross-section and the upper limit using only templates from $t\bar{t}$. The best estimate for this cross-section is 93 fb with a 95% CL upper limit of 130 fb. This difference is dominated by the statistical uncertainties on the fits. Using the SM cross-section discussed in Section 6.3.6, this leads to a 95% CL upper limit to the non-SM contribution to $\sigma_{SS}^{bd}$ of 91 fb. In Section 6.5 we use this value to determine exclusion limits in the mSUGRA phase-space.

6.4 The Z+prompt muon cross-section

The largest SM contribution to the prompt SS dimuon cross-section comes from $ZW$ and $ZZ$ production. We therefore also determine the cross-section for the subset of prompt SS dimuon events with a third opposite-sign muon ($p_T > 15$ GeV, $|\eta| < 2.5$), such that one $\mu^+\mu^-$ is produced in the decay of a $Z$-boson with invariant mass between 81.2 and 101.2 GeV. We determine this $Z$+prompt muon cross-section by selecting a high purity sample of $Z$-boson candidates and determining the prompt fraction for the third muon using the template fitting method of Chapter 5.
6.4. The Z+prompt muon cross-section

6.4.1 Event selection

We apply the following Z-boson selection:

- The event contains at least one $\mu^+\mu^-$ pair with invariant mass between 81.2 and 101.2 GeV.

- $p_{T\text{cone}}/p_T(\mu) < 0.08$, for both muons in the $\mu^+\mu^-$ pair.

- $d_0\text{-sig} < 5$, for both muons in the $\mu^+\mu^-$ pair.

- If the events contains more than one $\mu^+\mu^-$ pair, the pair with invariant mass closest to 91.2 GeV is chosen.

Furthermore the events must pass these additional selections:

- The event contains at least one additional muon ($p_T > 15$ GeV), denoted as $\mu_3$.

- $p_T > 25$ GeV, for both muons in the $\mu^\pm\mu^\pm$ pair.

- $|\eta| < 2.4$, for one of the muons in the $\mu^\pm\mu^\pm$ pair.

- If the events contains more than one possible candidate for $\mu_3$, the most isolated muon is chosen.

- One of the three selected muons is matched to a trigger object ($\Delta R < 0.15$) and has $p_T > 20$ GeV and $|\eta| < 2.4$.

Applying this event selection on the data sample introduced in Section 6.2 results in 136 selected events. The cut-flow for is shown in Table 6.3.

<table>
<thead>
<tr>
<th>Cut</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least one $\mu^\pm\mu^\pm$ pair</td>
<td>77126</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV, for both muons in $\mu^\pm\mu^\pm$</td>
<td>8809</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Additional opposite-sign muon</td>
<td>614</td>
</tr>
<tr>
<td>$81.2$ GeV $&lt; m_{\mu^+\mu^-} &lt; 101.2$ GeV</td>
<td>213</td>
</tr>
<tr>
<td>One of the muon is matched to a trigger object</td>
<td>213</td>
</tr>
<tr>
<td>$p_{Tcone40}/p_T(\mu) &lt; 0.08$, for both muons in $\mu^+\mu^-$</td>
<td>136</td>
</tr>
<tr>
<td>$</td>
<td>d_0\text{-sig}</td>
</tr>
</tbody>
</table>

Table 6.3: The cut-flow for the event selection of Section 6.4.1 on the data set described in Section 6.2.
6.4.2 Cross-section measurement

The fiducial cross-section for the associated $Z \to \mu^+\mu^-$ plus additional prompt muon production is calculated by combining the purity of the $Z$-boson selection with the prompt fraction of $\mu_3$ and correcting the event weight with the trigger and reconstruction efficiency as well as with the selection efficiency on the $Z$-boson. This leads to the following formula:

$$\sigma_{Z+\mu}^{\text{fid}} = \frac{1}{L} \sum_{\text{events}} \mathcal{P}_Z \mathcal{P}_{\mu_3}(\mu_3) \epsilon_{\text{iso}} \epsilon_{\text{trigger}}(\mu^+_Z, \mu^-_Z, \mu_3) \epsilon_{\text{reco}}(\mu^+_Z) \epsilon_{\text{reco}}(\mu^-_Z) \epsilon_{mz}(\mu^+_Z, \mu^-_Z),$$

(6.3)

where $\mathcal{P}_Z$ denotes the purity of the $Z$-selection, $\epsilon_{\text{iso}}$ the efficiency of the isolation and impact parameter cut on the muons from the $Z$-boson candidate and $\epsilon_{mz}$ the efficiency of the invariant mass cut.

The value for the luminosity as well as for the trigger and reconstruction efficiency are already discussed in Section 6.3.2. The only difference is that the trigger efficiency now includes the probability that the third muon is triggered, provided that $p_T > 20$ GeV and $|\eta| < 2.4$.

$\mathcal{P}_Z$ and $\epsilon_{\text{iso}}$:

We estimate the purity of the $Z$-boson selection, $\mathcal{P}_Z$, and the efficiency of the combined isolation and impact parameter cuts, $\epsilon_{\text{iso}}$, from the invariant mass distribution of the $Z$-boson candidates (without the invariant mass cut). Figure 6.8 shows this distribution for $Z$-boson candidates without (left plot) and with (right plot) the muon isolation and $d_0$-significance requirements. We estimate the number of signal events in the considered invariant mass range by fitting these distributions using an exponential function to describe the background and Breit-Wigner convoluted with a Gaussian for the signal. The Breit-Wigner peak value and width are fixed to the $Z$-boson mass (91.2 GeV) and width (2.5 GeV) while the mean of the Gaussian is set to zero. The resulting fits are included in Figure 6.8. The purity of the selected $Z$-boson candidates corresponds to the number of signal events in the mass range over the total number of events: $\mathcal{P}_Z = 0.897 \pm 0.022 \pm 0.023$, where the first uncertainty denotes the statistical uncertainty from the fit while the second uncertainty denotes the systematic uncertainty due to our choice in fitting function. This systematic uncertainty was obtained from fitting the distributions using only a simple Gaussian distribution with a mean value of 91.2 GeV for the signal. The fitted efficiency for the applied isolation and $d_0$-significance cuts, is equal to the ratio between the number of signal events, in mass range between 81.2 and 101.2 GeV, between the two plots in Figure 6.8: $\epsilon_{\text{iso}} = 0.840 \pm 0.047 \pm 0.002$.

In Equation 6.3 we are interested in the ratio $\frac{\mathcal{P}_Z}{\epsilon_{\text{iso}}}$. In this case the number of signal events after the isolation and impact parameter cuts is no longer relevant. $\frac{\mathcal{P}_Z}{\epsilon_{\text{iso}}}$ equals the total number of events in the applied $Z$-boson selection (both signal and background) over the number of signal events in the invariant mass range between 81.2 and 101.2 GeV before the isolation and $d_0$-significance requirements. Using this ratio we estimate $\frac{\mathcal{P}_Z}{\epsilon_{\text{iso}}}$ to be $1.07 \pm 0.05 \pm 0.03$. 
6.4. The Z+prompt muon cross-section

Figure 6.8: The invariant mass distribution for the Z-boson candidates in the selection of Section 6.4.1 without (left plot) and with (right plot) the muon isolation and impact parameter requirement. The distributions are fitted using an exponential function for the background and a Breit-Wigner convoluted with a Gaussian for the signal.

\( \mathcal{P}_{\mu_3} \):

The prompt probability of the third muon, \( \mathcal{P}_{\mu_3} \), is determined by fitting the \( d_0 \)-significance distribution of \( \mu_3 \). The result of this fit is shown in Figure 6.9 as well as the \( \mathcal{P}_{\mu_3} \) distribution as a function of the \( d_0 \)-significance. Similar as in Section 6.3.2 the possible contamination from prompt pions and kaons is estimated by considering the effect of rejecting muons with \( \frac{\Delta p_T}{p_T} > 0.5 \) on the obtained cross-section and turns out to be negligible.

Figure 6.9: Left: The \( d_0 \)-significance distribution for \( \mu_3 \) in the event selection of Section 6.4.1, fitted using the template fitting method of Chapter 5. Right: \( \mathcal{P}_{\mu_3} \) as a function of the \( d_0 \)-significance of \( \mu_3 \). The red lines denote the statistical uncertainty while the blue line gives the systematic uncertainty obtained from fitting the distribution using templates constructed from simulated \( t \bar{t} \) events.
\[ \epsilon_{mZ}(\mu^+_Z, \mu^-_Z) : \]
\[ \epsilon_{mZ}(\mu^+_Z, \mu^-_Z) \] represents the difference in the efficiency of the invariant mass cut between the true and reconstructed invariant mass of the Z-boson. It is defined as the fraction of reconstructed Z-bosons with a reconstructed invariant mass between 81.2 and 101.2 GeV over those with a true Z-mass, obtained from combining the true muon momenta, in this mass range. The value for \( \epsilon_{mZ}(\mu^+_Z, \mu^-_Z) \) is obtained from simulated \( Z \to \mu^+ \mu^- \) events in which the momentum resolution of the muons was corrected for differences between data and simulation. It is approximately 0.99 with a slight dependence on the momentum resolution of the two muons in the Z-boson selection. As the momentum resolution of muons depends on the detector region, \( \epsilon_{mZ}(\mu^+_Z, \mu^-_Z) \) was calculated separately for muons in the MS barrel region (|\( \eta \)| < 1.05), the transition region (1.05 < |\( \eta \)| < 1.7), the MDT end-cap region (1.7 < |\( \eta \)| < 2.0) and the CSC end-cap region (2.0 < |\( \eta \)| < 2.5). The obtained values were confirmed using simulated \( ZZ \) and \( ZW \) events.

Since both \( \epsilon_{mZ}(\mu^+_Z, \mu^-_Z) \) and the muon reconstruction efficiency depend on the muon momentum resolution their uncertainties are correlated. Furthermore while evaluating the uncertainty on \( \sigma_{Z+\mu}^{acc} \) due to the different efficiencies it is, in principle, important to remember that the efficiency uncertainties for muons in the same \( p_T, \eta \) and \( \phi \) bin are fully correlated, although both uncertainties turn out to be negligible.

The Z-boson+prompt muon cross-section

Using Equation 6.3 we measure an fiducial associated cross-section for \( Z \to \mu^+ \mu^- \) with an additional prompt muon within the ATLAS detector acceptance of:

\[ \sigma_{Z+\mu}^{fid} = 29.0^{+5.0}_{-9.6} \text{(stat)}^{+4.6}_{-1.3} \text{(syst)} \text{ fb}. \]

The statistical uncertainty is dominated by the uncertainty in the \( d_0 \)-significance fit for \( \mu_1 \) (\( +3.7 \) fb) and to a lesser extend on the Poisson uncertainty (\( \pm 3.1 \) fb) and the statistical uncertainty on \( \epsilon_{Z+\mu}^{acc} \) (\( \pm 1.5 \) fb). The relevant contributions to the systematic uncertainty are from the systematic uncertainty of \( \mathcal{P}_{\mu_1} \) (\( +4.4 \) fb), the luminosity (\( \pm 1.0 \) fb) and the systematic uncertainty on \( \epsilon_{Z+\mu}^{acc} \) (\( \pm 0.8 \) fb)

6.4.3 Comparison with SM predictions.

As mentioned previously, the only SM contributions to the Z-boson plus prompt muon cross-section come from \( ZZ \), \( ZW \) and \( t\bar{t}Z \) production. The theoretical prediction from the SM for the cross-section of this subset of prompt SS dimuon events is:

\[ \sigma_{Z+\mu,SM}^{ fid} = 29.2 \pm 3.4 \text{ fb}. \]

The contribution of the individual processes are listed in Table 6.4.
6.5. Exclusion limits on the mSUGRA phase-space

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma_{Z+\mu,SM}^{\text{fid}} ) (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ZW^\pm )</td>
<td>( 23.6 \pm 2.8 )</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>( 4.6 \pm 0.6 )</td>
</tr>
<tr>
<td>( t\bar{t}Z )</td>
<td>( 0.9 \pm 0.4 )</td>
</tr>
<tr>
<td>Total</td>
<td>( 29.2 \pm 3.4 )</td>
</tr>
</tbody>
</table>

Table 6.4: The theoretical prediction from the SM for \( \sigma_{Z+\mu,SM}^{\text{fid}} \) for different processes.

contribution to this cross-section is estimated to be:

\[
\sigma_{Z+\mu,\text{non-SM}}^{\text{fid}} = -0.2^{+7.6}_{-10.6} \text{ fb}.
\]

6.5 Exclusion limits on the mSUGRA phase-space

It is possible to use the measured cross-section quoted in this chapter to reject some new physics models. As an example we use the 95% CL upper limit for the non-SM fiducial cross-section of SS prompt muon pairs given in Section 6.3.7 to calculate limits in the mSUGRA phase-space\(^7\) plane defined by \( A_0 = 0 \) GeV, \( \tan(\beta) = 10 \) and \( \mu > 0 \).

The expected SUSY cross-section for this signature is obtained using the simulated mSUGRA sample described in Section 6.2.3. Due to the relatively small branching ratio of SUSY events producing two prompt SS muons and the limited amount of events generated (between 25000 and 10000 per SUSY point), only 0 to about 100 events pass our selection per SUSY point. The leads to non-negligible statistical uncertainties on the expected fiducial cross-sections. To reduce these uncertainties we also consider prompt electron production, thereby increasing the available Monte Carlo statistics by a factor of four. This addition is justified because in mSUGRA the decay steps producing the two SS leptons are independent and muon and electron production is nearly identical (since smuons and selectrons have the same mass).

The resulting limit on the mSUGRA phase-space plane defined by \( A_0 = 0 \) GeV, \( \tan(\beta) = 10 \) and \( \mu > 0 \) as a function of \( m_0 \) and \( m_{1/2} \) is given in Figure 6.10. The region of \( m_{1/2} < 60 \) GeV is excluded independent of \( m_0 \). For low values of \( m_0 \) the lower limit on \( m_{1/2} \) to about 150 GeV at \( m_0 = 100 \) GeV.

6.6 Conclusion and discussion

Using the template fitting method of Chapter 5 we were able to determine the fiducial cross-section for inclusive prompt, SS, high momentum \( (p_T > 25 \) GeV) muon pairs in the ATLAS detector acceptance (one muon with \( |\eta| < 2.4 \) due to the trigger acceptance and the other muon with \( |\eta| < 2.5 \)). The measured cross-section of \( \sigma_{SS}^{\text{fid}} = 50^{+24}_{-11}(\text{stat})^{+43}_{-20}(\text{syst}) \) fb

\(^7\)The mSUGRA phase-space is discussed in Chapter 1.
Figure 6.10: The 95% and 84% CL exclusion limit in the mSUGRA plane defined by $A_0 = 0$ GeV, $\tan(\beta) = 10$ and $\mu > 0$, as a function $m_0$ and $m_{1/2}$ obtained using the measured fiducial SS prompt dimuon cross-section measured in this chapter.

was obtained without making any assumptions on the kinematics of either signal or background events and is independent of simulated cross-sections. This value is consistent with the expected SM cross-section obtained from simulations: $\sigma_{SS:SM}^{\text{fid}} = 39.3 \pm 4.5$ fb.

As a wide range of new physics models, including supersymmetry, predict enhanced rates for prompt SS dimuon production at the LHC, we can use the 95% CL upper limit to the non-SM contribution of this cross-section to exclude part of the models. This limit is estimated to be 91 fb. As an example we calculated the 95% CL exclusion limit for one plane in the mSUGRA phase-space (see Figure 6.10).

### 6.6.1 Comparisons with other ATLAS results

The analysis used to obtain the cross-sections and exclusion limits presented in this chapter was developed to be as data-driven and model independent as possible. Although this specific analysis has not previously been performed, other methods have been used in ATLAS to calculate similar quantities. In this section we compare our analysis with other ATLAS results.

**The prompt SS dimuon cross-section measurement**

This specific cross-section for inclusive prompt SS dimuons in the ATLAS detector acceptance has not been measured previously. The most general similar analysis previously performed in ATLAS is the measurement of the cross-section for prompt SS dimuons
for isolated muons with $p_T > 20$ GeV [58]. Apart from the isolation criteria the main difference between that analysis and the one presented in this thesis is that the former estimates the non-prompt background by extrapolating the number of events from control regions to the signal regions, while we fit the prompt content directly in the signal region. The 95% confidence level upper limit quoted in Ref. [58] for the non-SM contribution to the fiducial cross-section is 58 fb for $m_{\mu^+\mu^-} > 15$ GeV. From Figure 6.4 we can see that this invariant mass cut should have no significant effect on the cross-section. This limit is more stringent than our upper limit of 91 fb. This is primarily because the amount of background and therefore the uncertainty on this background is much smaller for isolated muons than for all muons. This upper limit of 58 fb can therefore be more closely compared to the uncertainty on the cross-section for two isolated muons obtained in this analysis, $\sigma_{\text{SS}}^{\text{fid}} \mu_1, \mu_2 = \text{isolated} = 32^{+7}_{-9}\text{(stat)}^{+7}_{-2}\text{(syst)}$ fb, which also shows significantly smaller uncertainties than $\sigma_{\text{SS}}^{\text{fid}}$. We use the same isolation criteria on these muons as in Ref. [58].

Despite the smaller uncertainties on the cross-section for isolated muons we chose to present our results independent of muon isolation, as the isolation of prompt muons depends heavily on the event topology, specifically on the number and distributions of jets in the event. These jet distributions, obtained from simulation, not only depend on the type of interaction (the hard scatter) but also on the amount and type of pile-up events, on the amount and hardness of parton radiation (parton showering) and on the underlying event. As discussed in Section 2.5 these last processes are non-perturbative and therefore can introduce a large uncertainty on the simulated distributions. However, it should be noted that despite these theoretical uncertainties, prompt SS dimuon cross-sections for isolated muons currently lead to more stringent limits on new physics models. For this reason we chose to only compute the limits for the mSUGRA phase-space shown in Figure 6.10. With increased luminosity this isolation independent measurement should become more competitive, as more statistics would reduce both the statistical and systematic uncertainty on the $d_0$-significance fits performed in this analysis. This reduction in the systematic uncertainty with increased statistics is because we would be able to bin the data in more narrow bins in closest jet $p_T$ and $\sigma_{d_0}$ (discussed in Chapter 5), thereby limiting the difference in results due to the choice in templates, which is currently the main systematic uncertainty.

The exclusion limits on the mSUGRA phase-space

Apart from the isolated SS dimuon cross-section measurement of Ref. [58] there are also a wide range of analyses in ATLAS aimed at testing more specific new physics models. Most relevant for this discussion are the analyses based on high momentum jets and large missing transverse energy that currently provides the best limits on the mSUGRA phase-space [15]. These limits, shown in Figure 1.9, are a lot stronger than the limits provided by our prompt SS dimuon cross-section. The reason for this, discussed in more detail in Chapter 1, is that the mSUGRA mass spectrum always results in signatures with high energetic jet and large missing transverse energy, which might not hold for the entire SUSY phase-space. On the other hand the branching ratio for the production of SS dimuons is probably more representative for SUSY in general.
Although more model specific analyses can produce stronger limits for specific new physics models, they might not be able to cover the full phase-space of new physics possibilities, which is why we chose to leave our analyses as model independent as possible.

The $Z+$-prompt muon cross-section measurement

Apart from the fiducial inclusive prompt SS dimuon cross-section discussed above we also measured the cross-section for prompt SS dimuon events which are part of the $Z+$-prompt muon cross-section. The measured fiducial cross-section for this process is 
\[ \sigma_{Z+\mu}^{\text{fid}} = 29.0^{+5.0}_{-9.0} \text{(stat)}^{+4.6}_{-1.3} \text{(syst)} \text{ fb} \]
which is in agreement with the expected SM cross-section of 
\[ \sigma_{Z+\mu,\text{SM}}^{\text{fid}} = 29.2 \pm 3.4 \text{ fb}. \]

We performed this measurement mainly as a cross-check for our SS prompt dimuon cross-section measurement as most of the SM contribution to $\sigma_{SS}^{\text{fid}}$ comes from $ZZ$ and $ZW^\pm$ pair production. However this cross-section by itself could be used to exclude new physics models, as some of these models, including supersymmetry, also increase the $Z+$-prompt muon production cross-section.

It is important to note that the measurement performed in the chapter is not the most accurate method to determine either the $ZW$ or $ZZ$ cross-section in ATLAS. Analyses which use the existence of a fourth muon in $ZZ$ events [67] or missing $E_T$ in $ZW$ events [68] are able to further reduce the systematic uncertainties while those using both decay channels to muons and electrons increase the available statistics by a factor close to four. However, as we are using this $Z$-boson plus prompt muon cross-section measurement to search for new physics, we choose to leave this analysis fully independent of the production mechanism of the third prompt muon.

6.6.2 Possible improvements

The fiducial prompt SS dimuon cross-section measurement described in this chapter uses a template method to separate the prompt muon signal from the non-prompt background. The main drawback of such template fitting methods is that they need a minimum number of events to provide reliable fit results. The main advantage is that the method is fully model independent, allowing the same analysis to be used in different signal regions. With more statistics it would therefore be possible to measure the inclusive prompt SS dimuon cross-section using this method as a function of the invariant mass of the muon pair, or separately for different event topologies, such as depending on the missing transverse energy of the event. This last suggestion would for example significantly increase the sensitivity of this method for models, such as mSUGRA, which also predict large missing transverse energy. With the integrated luminosity of data available for this thesis, the amount of selected SS muon pairs was unfortunately insufficient to perform such more specific analyses.