Muon performance studies in ATLAS towards a search for the Standard Model Higgs boson
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Chapter 7

Search for $H \rightarrow ZZ^{(*)} \rightarrow \mu^- \mu^+ \mu^- \mu^+$ in 1 fb$^{-1}$ of 7 TeV $pp$ collisions

7.1 Introduction

In Chapters 4 and 5 we have discussed the performance of the Muon Spectrometer in cosmic-data taking as well as in collision data taking. Di-muon final states were used to evaluate the efficiency and muon momentum resolution of the muon reconstruction algorithms. In this chapter we use muons for a physics analysis: the search for Standard Model Higgs bosons decaying into a four muon final state via two intermediate $Z$ bosons.

In Section 7.2 the data-set used for the analysis is described. Section 7.3 covers the applied event selections and shows the observed candidates in simulation and in data after these selections. The significance of the observed signal candidates in data is evaluated in Section 7.4.

7.2 Data-set

Before mentioning the actual data-set used for this analysis we need to define the signal we are searching for. Afterwards, the relevant backgrounds to this particular signal are introduced. The event selections in Section 7.3 aim at reducing these backgrounds while keeping as much signal as possible.

Signal

In this analysis the signal is defined as a Standard Model Higgs boson decaying into four muons via two intermediate $Z$ bosons. Section 2.5 discussed the Higgs production and its decay at the LHC. The dominant production mechanism at the LHC is via gluon-gluon fusion. The branching ratio $H \rightarrow ZZ$ depends on the mass of the Higgs boson (cf. Figure 2.10(b)). Given its mass, a precise prediction can be made of the number of Higgs bosons that we expect to observe in ATLAS. However, the mass of the Higgs boson is an unknown parameter in the Standard Model. Therefore a search is presented for Higgs masses in the range of 115 to 500 GeV.
Search for $H \rightarrow ZZ^{(*)} \rightarrow \mu^- \mu^+ \mu^- \mu^+$ in 1 fb$^{-1}$ of 7 TeV pp collisions

**Backgrounds**

The Standard Model has several processes other than $H \rightarrow ZZ^{(*)} \rightarrow \mu^- \mu^+ \mu^- \mu^+$ which can result in a final state with four muons. We will refer to these processes as Standard Model background. The major component of the background consists of a continuum from irreducible $ZZ$ events. Other important backgrounds are from $Zb\bar{b}$ and $t\bar{t}$ events. In $Zb\bar{b}$ events the semi-leptonic decay of the $b$ quarks can result in two (extra) muons. In $t\bar{t}$ events the decay of the top quark almost always produces a $W$ boson and a $b$ quark. If both $W$ bosons decay to a muon and a neutrino and the $b$ quarks decay semi-leptonically this also results in a four muon final state.

**Data-set**

We have searched for the presence of a Standard Model Higgs signal in the 2011 LHC data-set recorded up till June 26th. Events are triggered at the Event Filter stage by a muon of $p_T > 18$ GeV. The recorded integrated luminosity for this choice of trigger is $1.05 \pm 0.04$ fb$^{-1}$. The uncertainty on the luminosity is $3.7\%$ [65].

A full overview of the simulated data-sets used in this analysis can be found in Appendix B. These include Higgs samples from gluon-gluon fusion in a mass range of 110 to 600 GeV as well as samples for the relevant backgrounds. The $ZZ$ sample from PYTHIA has been reweighted according to MCFM 6.0 [66, 67]. All samples are produced centrally and are greatly reduced in size, i.e. *skimmed*, by selecting events with four leptons [68]. The leptons can be either electrons or muons with some minor quality selections applied. Combined or segment-tagged muons are selected with a $p_T > 7$ GeV. Standalone muons are only added in the forward region, i.e. $|\eta| > 2.5$.

### 7.3 Event selection

The event selections aim at reducing the Standard Model background while keeping as many signal candidates as possible. We apply the selections on simulation and look at the resulting distributions of the four muon invariant mass, $M_{4\mu}$. Table 7.1 gives the numbers after several selection steps, which we discuss below, for simulation and data.

Our signal is a Standard Model Higgs boson decaying to a four muon final state via two intermediate $Z$ bosons. Some obvious preselections can be applied. A primary vertex with at least three associated tracks is required. At least four MUID muons should be present, each with a transverse distance$^1$ to the primary vertex $|d_0| < 1$ mm. Muons from heavy quark decays are expected to originate from displaced secondary vertices, where the leptons from $Z$ boson decays originate from the primary vertex. One of the muons in the event must have triggered the event. The trigger used is EF\_mu18\_MuGirl, which is the lowest $p_T$ unprescaled single muon trigger. The same Inner Detector track quality cuts as discussed in Section 5.2.1 are applied.

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$^1$The transverse distance is defined as the distance in the transverse plane, i.e. $|d_0| \equiv \sqrt{x_0^2 + y_0^2}$. 

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By selecting opposite sign muon pairs and calculating the di-muon invariant mass one obtains multiple $Z$ candidates. From these we select a primary $Z$ candidate and a secondary $Z$ candidate. The primary $Z$ candidate has a di-muon invariant mass closest to the world average value of the $Z$ mass, i.e. 91.1876 GeV, with a maximum allowed deviation of 15 GeV from this value. The secondary $Z$ candidate (or off-shell $Z^*$) is the candidate that has the second closest mass while using two other muons. The selections discussed up to this point are referred to as preselections in Table 7.1. Figure 7.1 shows the masses of the primary and secondary $Z$ candidates in simulation after preselections. In the $ZZ$ sample the generated mass of the secondary $Z$ is always greater than 12 GeV.

**Figure 7.1:** The mass of the primary $Z$ candidate ($M_{12}$) versus the mass of the secondary $Z$ candidate ($M_{34}$) after the preselections. Simulations of the $ZZ$ background, a 150 GeV Higgs, a 200 GeV Higgs and a 300 GeV Higgs are shown.
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Our signal contains at least one on-shell $Z$ boson, i.e. the primary $Z$ candidate. Therefore we ask for at least two high-$p_T$ muons ($p_T > 20$ GeV) in an event. The four muons from the two $Z$ candidates are required to be separated in $\eta$ and $\phi$ by demanding $\Delta R > 0.10$ for all muon combinations. Table 7.1 shows that this selection substantially reduces the background from heavy quark decays.

The background from heavy quark decays is further reduced by requiring that the muons are isolated from other tracks in the Inner Detector and from energy deposits in the calorimeter. For sufficient track isolation the muons should have $ptcone20 < 0.15 \cdot p_T$, where $ptcone20$ is the summed $p_T$ of tracks within a cone of $\Delta R < 0.20$ around the muon. Again the muon itself is excluded from the sum. Calorimetric isolation uses a similar variable $etcone20$: the summed energy deposits in a cone of $\Delta R < 0.20$ around the muon. Again the muon itself is excluded from the sum. The selection on the calorimetric isolation is $etcone20 < 0.20 \cdot p_T$. To correct for pile-up the value of $etcone20$ is lowered by 33.5 MeV for each additional primary vertex observed in the event [69]. Table 7.1 shows that these isolation criteria have a large impact on the backgrounds from heavy quark decays.

<table>
<thead>
<tr>
<th>Sample</th>
<th>H150</th>
<th>H200</th>
<th>H300</th>
<th>ZZ</th>
<th>$tt$</th>
<th>$Zb\bar{b}$</th>
<th>$Z$</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total entries</td>
<td>5721</td>
<td>5539</td>
<td>5545</td>
<td>14969</td>
<td>5 $\cdot$ 10$^{5}$</td>
<td>66 $\cdot$ 10$^{6}$</td>
<td>5 $\cdot$ 10$^{5}$</td>
<td>-</td>
</tr>
<tr>
<td>Events after:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>preselections</td>
<td>2957</td>
<td>3734</td>
<td>3882</td>
<td>11025</td>
<td>307</td>
<td>4 $\cdot$ 10$^{6}$</td>
<td>9</td>
<td>169</td>
</tr>
<tr>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(100%)</td>
<td></td>
</tr>
<tr>
<td>$\geq$ 2 high-$p_T$ $\mu$'s</td>
<td>2898</td>
<td>3721</td>
<td>3873</td>
<td>10953</td>
<td>271</td>
<td>3.6 $\cdot$ 10$^{6}$</td>
<td>8</td>
<td>130</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>2874</td>
<td>3693</td>
<td>3869</td>
<td>10910</td>
<td>153</td>
<td>2.8 $\cdot$ 10$^{6}$</td>
<td>3</td>
<td>31</td>
</tr>
<tr>
<td>track isolation</td>
<td>2684</td>
<td>3442</td>
<td>3703</td>
<td>10458</td>
<td>1</td>
<td>234923</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>calor isolation</td>
<td>2650</td>
<td>3381</td>
<td>3622</td>
<td>10247</td>
<td>1</td>
<td>181683</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>$</td>
<td>d_0</td>
<td>/\sigma(d_0)&lt;3.5$</td>
<td>2619</td>
<td>3342</td>
<td>3599</td>
<td>10161</td>
<td>1</td>
<td>66532</td>
</tr>
<tr>
<td>all tight muons</td>
<td>2539</td>
<td>3245</td>
<td>3472</td>
<td>9892</td>
<td>1</td>
<td>64017</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>(85.9%)</td>
<td>(86.9%)</td>
<td>(89.4%)</td>
<td>(89.7%)</td>
<td>(3.3%)</td>
<td>(1.6%)</td>
<td>(0%)</td>
<td>(5.9%)</td>
<td></td>
</tr>
<tr>
<td>Higgs reco. eff</td>
<td>44.4%</td>
<td>58.6%</td>
<td>61.8%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Events in 1 fb$^{-1}$</td>
<td>0.52</td>
<td>1.04</td>
<td>0.62</td>
<td>5.46</td>
<td>0.02</td>
<td>0.04</td>
<td>0.0</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 7.1: Number of events passing the subsequent selections.

If all selection criteria are fulfilled the four muon invariant mass, $M_{4\mu}$, is computed. The primary $Z$ candidate is constrained to the world average $Z$ mass in this computation. This effectively results in a scaling of the measured muon momentum parameters. If $M_{4\mu}$ is smaller than 190 GeV an additional selection is applied on the impact parameter significance of the two softest muons in the event: $|d_0|/\sigma(d_0) < 3.5$. This substantially reduces the $Zb\bar{b}$ background with only a small effect on the signal (cf. Table 7.1).
The event selections reduce $Z\bar{b}b$ and $t\bar{t}$ down to a rate well below the $ZZ$ background. The $ZZ$ background is irreducible and results in a non-negligible background over the full mass range in this study. Further reduction can possibly be accomplished by exploiting possible differences between $ZZ$ and Higgs samples, e.g. using the mass of the secondary $Z$ candidate or the $p_T$ of the $4\mu$ combination. We have not looked into this possibility but acknowledge the fact that this can improve the strength of this analysis in the future. Figure 7.2 shows the total Standard Model background after all event selections with results for Higgs masses of 150, 200 and 300 GeV added to this.

![Figure 7.2: Four muon invariant mass after event selections for simulation of Standard Model background plus several Higgs samples. All samples are normalized to $1 \text{ fb}^{-1}$.](image)

**Higgs reconstruction efficiency**

For the various Higgs masses the efficiency of the event selection is evaluated. Figure 7.3 shows the Higgs reconstruction efficiency as a function of the simulated Higgs mass. The Higgs reconstruction efficiency is defined as the efficiency for a Higgs decay with a four muon final state to pass all analysis selections, i.e. including preselections.

At low Higgs masses ($\leq 200$ GeV) a lower efficiency is observed: muons in this region will be relatively soft because of the low mass of the secondary $Z$. Soft muons will less often pass our kinematic cuts and isolation requirements. The isolation requirements are nevertheless needed, especially in this region, to reduce backgrounds from $Z\bar{b}b$ and $t\bar{t}$. At high Higgs masses the efficiency reaches a plateau around 70% mainly as a result of the acceptance of the Muon Spectrometer. For $|\eta| < 2.5$ this is about 90%.
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Figure 7.3: Higgs reconstruction efficiency as a function of the simulated Higgs mass.

Data

There are ten events observed in data that pass all event selections. Figure 7.4 shows an event display of one of the observed candidates. Table 7.2 gives the run number, event number and invariant mass of the observed $4\mu$ candidates. It also gives the masses of the primary and secondary $Z$ candidates as $M_{12}$ and $M_{34}$, respectively.$^2$

<table>
<thead>
<tr>
<th>Run</th>
<th>Event</th>
<th>4$\mu$ mass [GeV]</th>
<th>$M_{12}$ [GeV]</th>
<th>$M_{34}$[GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>180124</td>
<td>3972690</td>
<td>138.6</td>
<td>92.3</td>
<td>9.4</td>
</tr>
<tr>
<td>182486</td>
<td>33852512</td>
<td>196.9</td>
<td>99.3</td>
<td>73.1</td>
</tr>
<tr>
<td>182766</td>
<td>5404925</td>
<td>240.7</td>
<td>89.8</td>
<td>83.8</td>
</tr>
<tr>
<td>183003</td>
<td>121009952</td>
<td>620.7</td>
<td>83.5</td>
<td>99.7</td>
</tr>
<tr>
<td>183003</td>
<td>44433120</td>
<td>210.0</td>
<td>92.9</td>
<td>94.3</td>
</tr>
<tr>
<td>183081</td>
<td>101085720</td>
<td>144.2</td>
<td>91.6</td>
<td>47.4</td>
</tr>
<tr>
<td>183272</td>
<td>44764944</td>
<td>101.8</td>
<td>80.3</td>
<td>4.2</td>
</tr>
<tr>
<td>183391</td>
<td>19834576</td>
<td>208.8</td>
<td>90.7</td>
<td>94.7</td>
</tr>
<tr>
<td>183426</td>
<td>47756740</td>
<td>449.1</td>
<td>91.4</td>
<td>89.5</td>
</tr>
<tr>
<td>183580</td>
<td>5574469</td>
<td>200.8</td>
<td>92.1</td>
<td>88.9</td>
</tr>
</tbody>
</table>

Table 7.2: Events in data passing all event selections.

$^2$No cut on the lower value of $M_{34}$ is applied in this analysis. In the simulation of the $ZZ$ background such a cut was applied at 12 GeV. However, the effect of this cut on data is expected to be small as most of the four muon events with $M_{34} < 12$ GeV will not pass the muon $p_T$ requirements. Only a small fraction of events will survive all event selections, creating no artifical peaks in the $4\mu$ mass distribution.
7.3 Event selection

Figure 7.4: Atlantis event display of one $H \rightarrow ZZ \rightarrow 4\mu$ candidate in data.

Figure 7.5 shows the $4\mu$ invariant mass distribution for events passing all selections in data and simulation. We expect a total of 5.52 events from Standard Model background processes. How to interpret the observed excess of candidates is discussed next.

Figure 7.5: Four muon invariant mass for selected events in data and simulation.
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7.4 Discovery/exclusion of a Higgs signal

Our event selections result in 10 observed candidates in data, where 5.52 events are expected from Standard Model (SM) background processes. Is this excess of candidates sufficient to claim a *discovery* of the SM Higgs boson? And if not, can we *exclude* a SM Higgs boson? We will answer these questions for a Higgs mass range of 115 to 500 GeV. First, some concepts need to be introduced.

**Test statistic and likelihood functions**

The observed excess can either be the result of a SM Higgs boson or of an upward fluctuation of SM background events. These two hypotheses form the basis for the study to quantify our results. The first step is to define a *test statistic*, i.e. a variable that distinguishes between the two hypotheses. Our test statistic uses *likelihood functions*, $L$, to answer the following question:

> How much more likely is it that the observed data is the result of a Higgs boson decay on top of Standard Model background processes than from Standard Model background processes alone?

To answer this question two templates are built of the four muon invariant mass distributions: one for the summed background and one for the Higgs signal (cf. Figure 7.2). All templates are normalized to an integrated luminosity of 1 fb$^{-1}$. The templates are used to construct the likelihood functions $L_b$ and $L_{s+b}$ for the background-only and signal-plus-background hypothesis, respectively. We take the construction of $L_b$ as an example:

For each mass bin $i$ of the background template we compute the Poisson probability $P(N_{obs}^i|f_b^i)$, where $N_{obs}^i$ is the number of observed events in data and $f_b^i$ is the background template value for bin $i$. All bins $i$ in a mass range of 115 to 500 GeV are taken into account. The likelihood function is defined as $L_b = \prod_i P(N_{obs}^i|f_b^i)$ and similarly $L_{s+b} = \prod_i P(N_{obs}^i|f_s^i + f_b^i)$.

The background normalization is the dominant systematic in our study. To account for this uncertainty we fit the normalization to the data when building our likelihood functions. This effectively changes our likelihood functions to *profile likelihood functions*: $L_b \rightarrow L_b(\mu_s = 0, \hat{\theta}_b)$, where $\mu_s$ is the (fixed) scaling of the signal template and $\hat{\theta}_b$ is the scaling of the background template that maximizes the likelihood function.

The ratio of the computed likelihoods is used to construct our eventual *test statistic*:

$$X = -2 \ln(Q) = -2 \ln \left( \frac{L_{s+b}(\mu_s = 1, \hat{\theta}_{b+s})}{L_b(\mu_s = 0, \hat{\theta}_b)} \right). \quad (7.1)$$

---

3We do so by choosing the background scaling that maximizes the likelihood function. This method, and its effect on our analysis, is discussed in more detail in Appendix C.
By taking the logarithm of the likelihoods we obtain a sum instead of products in the definition of $\mathcal{L}$. The factor $-2$ is a convention to make the search for the most likely value a search for a minimum value instead of a maximum value. As a result of this definition we observe the following qualitative feature: a higher value for the test statistic indicates a more background-like signal.

**Toy Monte Carlo**

To quantify the significance of the observed value of the test statistic we need to compare this value with distributions from many simulated experiments, obtained with so-called toy Monte Carlo (MC) techniques. A toy mass distribution is built up from our templates as follows: each mass bin is filled by a random number generator from a Poisson distribution, taking the expected number of events from the background (+signal) template in that mass bin as the Poisson mean value for the background-only (signal-plus-background) hypothesis. A test statistic is computed for the toy mass distribution. Each toy MC experiment gives a value for the test statistic. From 100,000 toy MC experiments we obtain two test statistic distributions: one for the background only hypothesis and one for the hypothesis with a Higgs signal added to the background.

**Confidence levels**

Figure 7.6 shows example test statistic distributions for two hypotheses. The signal-plus-background hypothesis is indicated with the dotted line. The background-only hypothesis is shown as a solid line. Two confidence levels (CL) are indicated for a given observed test statistic value, $X_{\text{obs}}$:

- $1 - \text{CL}_b$ indicates the fraction of experiments in the background-only test statistic distribution that have an equal or lower test statistic value than $X_{\text{obs}}$, i.e. that are equally signal like or more signal like than $X_{\text{obs}}$;

- $\text{CL}_{s+b}$ indicates the fraction of experiments in the signal-plus-background test statistic distribution that have an equal or higher test statistic value than $X_{\text{obs}}$, i.e. that are equally background like or more background like than $X_{\text{obs}}$.

By combining these two confidence levels we obtain $\text{CL}_s$, what some people refer to as “an approximate confidence in the signal-only hypothesis” \[72\]. $\text{CL}_s$ is defined as $\text{CL}_{s+b}/\text{CL}_b$ \[4\] and was introduced during Higgs searches at LEP. By normalizing $\text{CL}_{s+b}$ to $\text{CL}_b$ one prevents wrongly claiming an exclusion when the analysis is in fact not sensitive to differences between the two hypotheses.\[5\] But when can a discovery or exclusion actually be claimed?

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\[4\] $\text{CL}_s$ is set to 0 if $\text{CL}_b = 0$.

\[5\] One example of this is when the two test statistic distributions are very similar.
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Figure 7.6: Example test statistic distributions for the background-only (right) and signal-plus-background (left) hypotheses. For a given observed test statistic, $X_{\text{obs}}$, confidence levels $1 - \text{CL}_b$ and $\text{CL}_{s+b}$ are colored and labeled accordingly.

Claiming a discovery or excluding a signal

By convention, a discovery can be claimed if it is improbable that the observed test statistic value is the result of the background-only hypothesis. In this case a value of $1 - \text{CL}_b \leq 5.7 \cdot 10^{-7}$, i.e. a 5$\sigma$ deviation for a Gaussian distribution, is considered as improbable. If no discovery can be claimed the next step is to study whether a signal can be excluded. A signal is excluded if it is improbable that the observed test statistic value is the result of the signal-plus-background hypothesis. For an exclusion a value of $\text{CL}_s \leq 0.05$, i.e. a 2$\sigma$ deviation for a Gaussian distribution, is considered as improbable.

7.4.1 Results

We apply the procedure described above to our data, assuming a Higgs with a mass of 200 GeV. Figure 7.7 shows the toy MC distributions. The shapes of the two distributions are not Gaussian-like because we are dealing with a low number of expected events. The background-only hypothesis is displayed with a solid line. The bands corresponding to $\pm 1\sigma$ and $\pm 2\sigma$ for this hypothesis are colored green and yellow, respectively. The figure indicates the test statistic value obtained in data, i.e. $-1.81$. The corresponding values for $1 - \text{CL}_b$ and $\text{CL}_s$ are 0.26 and 0.78, respectively. From these obtained confidence levels it can be concluded that neither a discovery nor an exclusion can be claimed.

To see if we actually expect to be able to claim a discovery or an exclusion we look at the median values of the two test statistic distributions. For the median of the signal-plus-background hypothesis $1 - \text{CL}_b$ is computed to be 0.187. This indicates that no discovery is expected. The median of the background-only hypothesis $\text{CL}_s$ is computed to be 0.418. This indicates that no exclusion is expected either.

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6 The bands are defined such that 84.1% (97.9%) is within $\pm 1\sigma$ ($\pm 2\sigma$) of the median value.
7.4 Discovery/exclusion of a Higgs signal

Table 7.3 summarizes the results for a Higgs with a 200 GeV mass. The same studies have been performed over the mass range of 115 to 500 GeV with similar results.

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>s+b</th>
<th>b-only</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 - \text{CL}_b$</td>
<td>0.26</td>
<td>0.187</td>
<td>0.500</td>
</tr>
<tr>
<td>$\text{CL}_s$</td>
<td>0.78</td>
<td>0.615</td>
<td>0.418</td>
</tr>
</tbody>
</table>

**Table 7.3:** Confidence levels obtained for a 200 GeV Higgs signal.

**Scaling cross-section and luminosity for a 200 GeV Higgs**

We have found that for the mass range of 115 to 500 GeV no discovery or exclusion can be claimed with the current integrated luminosity and assuming the Standard Model cross section for the Higgs signal. However, it is possible to study at what point an exclusion (a discovery) is expected by scanning the signal cross section (integrated luminosity). Figure 7.8 shows results of such scans for a Higgs mass of 200 GeV.

Figure 7.8(a) shows the CL$_s$ curves for data, for the median value of the background-only hypothesis and for the median value of the signal-plus-background hypothesis. The background curve drops below 0.05 at 3.5, i.e. we expect to exclude a signal at $\sigma = 3.5 \cdot \sigma_{SM}$. The data showed an excess in this mass region (cf. Figure 7.5) and drops below 0.05 at a higher value of $\sigma/\sigma_{SM}$, i.e. data excludes a signal at $\sigma = 6.4 \cdot \sigma_{SM}$.
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**Figure 7.8:** For a Higgs mass of 200 GeV a scan is performed over (a) signal cross section and (b) integrated luminosity. In both figures a line is drawn to indicate at what point an exclusion/a discovery is expected.

A scan over the integrated luminosity is computationally much more expensive than our cross section scan. Figure 7.8(b) shows five obtained points. The results are fitted with an exponential curve which is extrapolated to higher values of integrated luminosity. A discovery is expected at 32.5 fb$^{-1}$.

**Scaling cross-section for a Higgs in the mass range of 115 to 500 GeV**

Exclusion analyses were performed in the Higgs mass range of 115 to 500 GeV. At each Higgs mass the expected and observed cross section scaling where an exclusion can be claimed was determined. In Figure 7.8(a) we showed where for a 200 GeV Higgs the *median* value of the background-only test statistic distribution dropped below 0.05. Likewise, the $\pm 1\sigma$ and $\pm 2\sigma$ bands of the background-only distribution were evaluated. Figure 7.7 shows the $\pm 1\sigma$ and $\pm 2\sigma$ bands as colored bands. These colored bands are translated into the final plot of our results in Figure 7.9. This shows, as a function of the Higgs mass, the cross section scaling where an exclusion can be claimed. The expected values are shown as the dashed line and colored bands for the median values and the $\pm 1\sigma$ and $\pm 2\sigma$ bands, respectively. The observed values are indicated with the solid line.

In the region of 160 to 190 GeV a large bump is observed. This is due to the large decrease of branching ratio for our decay channel in this mass region. Figure 2.10(b) shows that the $H \rightarrow WW$ decay channel is by far the dominant decay channel in this mass region. A decrease in $H \rightarrow ZZ$ branching ratio is also behind the increase visible at masses below 150 GeV. The increase at higher mass can not be explained by a decrease in branching ratio. In fact, this increase reflects the decreasing Higgs production cross section at higher masses (cf. Figure 2.10(a)).

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*One has to run at least $10^7$ toy MC experiments to find a value of $5.7 \cdot 10^{-7}$ for $1 - \text{CL}_b$.\footnote{One has to run at least $10^7$ toy MC experiments to find a value of $5.7 \cdot 10^{-7}$ for $1 - \text{CL}_b$.}
7.5 Conclusions

Our analysis shows to have the largest sensitivity for a Higgs signal with a mass around 200 GeV. It is also in this region that we observe an excess of events above $2\sigma$ from expectation. With updates of the analysis this excess needs to be studied further.

![Figure 7.9: The expected and observed exclusion limits on the Higgs cross section as a function of the mass of the Higgs boson.](image)

7.5 Conclusions

A search for the Standard Model (SM) Higgs boson was performed with 1 fb$^{-1}$ of 7 TeV proton-proton collisions. The four muon final state was selected from data and simulation samples. Ten candidates were observed in data. The compatibility of the observed candidates with the background-only and signal-plus-background hypotheses was evaluated using toy Monte Carlo techniques. No discovery or exclusion of a SM Higgs in the mass range of 115 to 500 GeV can be claimed with the current integrated luminosity. This is in accordance with expectation. With increasing luminosity a discovery in this decay channel alone can be expected at 32.5 fb$^{-1}$.

With the current integrated luminosity a 200 GeV Higgs is observed (expected) to be excluded at about 6.4 (3.5) times the SM cross section. Figure 7.9 shows the results of our exclusion analysis in a mass range of 115 to 500 GeV. Expectation and observation are in reasonable agreement and the features of this result are understood qualitatively.
Search for $H \rightarrow ZZ^*(\ast) \rightarrow \mu^-\mu^+\mu^-\mu^+$ in 1 fb$^{-1}$ of 7 TeV $pp$ collisions

While our exclusion results with a four muon final state do not reach the Standard Model cross section, the $H \rightarrow ZZ^* \rightarrow 4\ell$ results including electrons (i.e. $4\mu$, $4e$ and $2e2\mu$ final states) do approach this already with an integrated luminosity of 1 fb$^{-1}$ \cite{73}. In addition to this, several limits on a Standard Model with a fourth generation of heavy fermions can be set with the $4\ell$ decay channels \cite{74}. In a Standard Model with a fourth generation the productions cross sections increase by a factor of about 4 to 9 for the high and low Higgs mass regions, respectively. This results in an increased sensitivity and therefore more stringent exclusion limits.

Outlook

Our $H \rightarrow ZZ^* \rightarrow 4\mu$ analysis can benefit from further developments. For example, increased sensitivity is (obviously) expected when the integrated luminosity of the data sample increases. In addition, the analysis could possibly benefit from further optimizations of the event selections. Because of the increasing understanding of the Muon Spectrometer muons could be added to the analysis which at this moment are not yet considered, such as standalone muons and calorimeter tagged muons. Also, the profile likelihood functions used in this analysis can be expanded to incorporate more information. This should provide better separation of the signal from the background. With an updated analysis the search for a Standard Model Higgs boson in a four muon final state can continue to be an exciting physics analysis. It will be very interesting, to say the least, to see the development of this analysis in the near future.