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

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Chapter 8

Summary and conclusions

On the 30th of March, in the year 2010, experimental particle physics entered a new era. On that day, the large hadron collider (LHC) started delivering proton-proton collisions, at an unprecedented center of mass energy of 7 TeV, to the four experiments located around the LHC. At this record breaking collision energy the leading theory in particle physics, the Standard Model, can be studied at the TeV scale. Studied, confirmed, extended, or perhaps even falsified! The Standard Model precisely predicts the properties of elementary particles, and their interactions, at energy scales up to the TeV scale. The LHC provides an environment to test these predictions. In addition, a mechanism can be tested that is thought to account for particle masses: the Higgs mechanism. If this Higgs mechanism, proposed in 1964 by Higgs, Brout and Englert, is in fact how nature works then a new particle, the Higgs boson, must exist.

The Higgs boson is an unstable particle that can, in principle, be identified by studying its decay products. Up to the time of writing, it has not been observed at previous experiments nor at the LHC. This is not because people don’t look hard enough, it is because the mass of the Higgs boson falls, unluckily, outside the kinematic range of previous particle accelerators. The value for the mass of the Higgs boson is not predicted by theory. With the mass of the Higgs boson also the expected decay products, or decay channels, vary. If the mass is known then several precise Standard Model predictions can be made about the decay channels. First step is therefore to discover the Higgs. Once discovered, one is able to test the Standard Model predictions. These two things were a great motivation to plan the LHC and its four experiments, some 25 years ago.

How do you detect a particle that was never observed before, with a detector that is unique in its kind, without actually knowing where to look? Two of the four LHC experiments, i.e. ATLAS and CMS, are so-called general purpose detectors, built to detect a wide range of possible physics signals, including Higgs decays. In this thesis we present results for a Higgs search with the Muon Spectrometer of ATLAS. Before such a search can be performed a lot of effort is spent on making sure that the detector performs the way it was expected to perform. The only way to do this is to use physics signals that have well known properties. These processes allow for a calibration of the detector. By studying and understanding these signals one gains confidence to look for new, and maybe also unexpected, signals.
Summary and conclusions

ATLAS has shown excellent performance from the very first proton-proton collision onwards. The Muon Spectrometer (MS) of ATLAS forms no exception to this. This good performance is partly due to an elaborate commissioning effort using cosmic-ray data, before proton-proton collisions were delivered. The performance of the MS in cosmic-ray data is presented in Chapter 4. The relative momentum resolution is parametrized by

\[ \frac{\sigma_{p_T}}{p_T} = P_0 \oplus P_1 \oplus P_2 \cdot p_T, \]

where three contributing terms are identified. The uncertainty on the energy loss corrections is denoted by \( P_0 \), the multiple scattering term by \( P_1 \) and the intrinsic resolution term by \( P_2 \). The values obtained from a fit to cosmic-ray data (simulation) in the barrel region are \( 0.35 \pm 0.02 \) (0.35) GeV, \( 0.038 \pm 0.001 \) (0.035) % and \( 2.0 \pm 0.3 \times 10^{-4} \) (1.2) GeV\(^{-1} \) for \( P_0 \), \( P_1 \) and \( P_2 \), respectively. The multiple scattering term is underestimated due to missing material in the simulated detector description. For muons with a transverse momentum, \( p_T \), below 40 GeV the data show a good agreement with the predictions from simulation. At higher values of \( p_T \) the resolution in data is worse due to additional contributions from calibration, alignment and the description of the magnetic field.

Further performance studies were carried out with proton-proton collision data. Chapter 5 gives the results of our performance studies using \( Z \rightarrow \mu^- \mu^+ \) decays, one of the physics signals with well known properties that we referred to before. The reconstruction efficiency was evaluated using a tag-and-probe method. For combined muons the efficiency in data (simulation) was found to be \( 0.960 \pm 0.003 \) (0.966 \pm 0.002). The category of tight muons has an efficiency of \( 0.977 \pm 0.003 \) (0.977 \pm 0.002). This increase is mostly located in the \( |\eta| \) region above 1.05 and at \( |\eta| \approx 0 \). In these regions the tagger algorithms recover part of the efficiency.

The \( Z \rightarrow \mu^- \mu^+ \) decays were also used to study the muon momentum scale and resolution. A description of the di-muon invariant mass distribution was constructed and fitted to simulation. Subsequently, detector effects were added to the model and fits to distributions from data were performed. Both the momentum scale and the resolution were studied using either combined (CB), standalone (SA) or Inner Detector (ID) track parameters. The momentum scale with ID and CB parameters showed an asymmetry in positive and negative endcaps that is mainly attributed to misalignments in the Inner Detector. The resolution for CB, SA and ID parameters shows higher values in data for the full \( \eta \) range. This is partially due to missing material in the detector description used in simulation. Remaining misalignments and the symmetric magnetic field description also contribute to the observed discrepancies. The measured resolutions for CB parameters in the barrel region are in agreement with our cosmic-ray results.

An observation of di-muon final states in heavy-ion (lead-lead) collisions was presented in Chapter 6 of this thesis. The production cross sections of \( J/\psi \rightarrow \mu^- \mu^+ \) and \( Z \rightarrow \mu^- \mu^+ \) decays were studied as a function of the event multiplicity, or centrality. A decreasing cross section was observed for \( J/\psi \) decays, beyond statistical and systematic uncertainties. This decrease can be explained in terms of \( J/\psi \) suppression by the quark-gluon-plasma. No decrease was observed in the \( Z \) decays, although the limited statistics prevent drawing definite conclusions in this case.
Finally, in Chapter 7 of this thesis, we presented a search for the Standard Model Higgs boson in a final state with four muons. We used 1 fb$^{-1}$ of the 2011 ATLAS data-set for this analysis. Figure 8.1 shows one of the candidates that was observed in data. In total 10 candidates were observed and 5.52 were expected from Standard Model background processes. The significance of this excess was evaluated in the mass range of 115 to 500 GeV. We found that no discovery or exclusion can be claimed. The signal cross section was scaled to determine at what point an exclusion is expected to be claimed. The best sensitivity is at a Higgs mass of 200 GeV where we expect to exclude a signal at 3.5 times the Standard Model cross section. The observed limit for this mass is 6.4 times the Standard Model cross section. The further development of this signal, if more data is analyzed and other Higgs channels are added, will be exciting next steps in a decisive phase of the search for this elusive particle. Will the era of the Higgs hypothesis end soon? Only time (and LHC data) will tell.

![Figure 8.1: One of the possible Higgs candidates with a four muon final state. The four muon invariant mass is 449 GeV. The mass of the primary and secondary Z candidate is 91.4 GeV and 89.5 GeV, respectively.](image-url)