Muon signatures in ATLAS: A search for new physics in ±± events
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Introduction

To understand the universe around us, it is important to know the characteristics of all the fundamental building blocks of matter as well as their interactions. Our current knowledge of these elementary particles is contained within the Standard Model [1–3].

The Standard Model of particle physics was first established in the 1960’s. In the last 50 years it has been thoroughly tested using a wide range of experimental data. This includes the discovery of predicted particles, such as the W- and Z-boson and the top quark, but also the measurement of interaction rates between the elementary particles. At present, the only particle of the Standard Model which has not been experimentally verified is the Higgs-boson, although current results at the LHC show indications of a Higgs-boson-like particle with a mass of approximately 125 GeV [4–6].

Although the Standard Model is able to correctly describe and predict all currently measured particle interactions and properties there is some indirect evidence for physics beyond the Standard Model. The most famous evidence is provided by astronomical observations that indicate that only 17% of the mass of the universe consists of known visible matter [7]. The remaining 83% are referred to as dark matter. As none of the Standard Model particles can account for all this dark matter, the vast majority of the mass of the universe should consist of new non-Standard Model particles.

One way to obtain direct evidence of such new elementary particles is to try to create them in controlled high energy particle collisions using a particle accelerator. A wide range of such accelerators has been built, varying greatly in the maximum possible collision energy, the collision rate and the types of particles colliding. As so far no evidence for physics beyond the Standard Model has been found at any of these accelerators, strong limits can be set on the properties of possible new particles. However, as the collisions must create sufficient energy to produce such new particles, the detection and exclusion range of accelerators is always limited to particles with a mass smaller than the collision energy. For direct searches of new particles, it is therefore important to study collisions with as high energy as possible.

At present the most powerful accelerator in the world is the Large Hadron Collider (LHC) which has collided protons with a center of mass energy of 7 TeV. This is more than 3.5 times the maximum energy of any other accelerator. In this thesis we study such collisions at the LHC, detected using the ATLAS detector, to search for evidence of new heavy particles.

The expected signature for physics beyond the Standard Model in ATLAS depends strongly on the properties of these new particles. Many theoretical extensions of the Standard Model have been proposed predicting a wide range of such new particles, most
of which are expected to decay before reaching the detector. These particles can therefore only be discovered through their decay products. In this thesis we focus exclusively on one possible decay product, the muon, which is experimentally relatively easy to identify.

Multiple processes can lead to the production of muons at the LHC. As our main goal is to search for new physics particles, which typically decay before propagating a significant distance, we are searching for muons produced at the interaction point, called prompt muons. While many particles can decay to muons, only a few Standard Model particles can result in the creation of prompt muons: top quarks, W-bosons, Z-bosons and off-shell photons\(^1\). Pairs of prompt muons are even more rare and can only be produced in the decay of Z-bosons and off-shell photons, or in collision events containing at least two different decay chains, such as \(W^+W^-\) production. As most such production processes create a particle anti-particle pair, with one resulting in the production of a muon and the other with an anti-muon, and since both the Z-boson and photon are electrically neutral, the vast majority of prompt muon pairs produced in ATLAS consists of muons with opposite electric charge.

Prompt muon pairs with equal electric charge, same-sign muons, are, according to the Standard Model, almost exclusively produced in \(ZZ\) and \(ZW\) events, both with a relatively small cross-section. On the other hand, a wide range of physics theories beyond the Standard Model predict additional signatures of prompt same-sign muon pairs in ATLAS which, in some cases, have a production rate similar or even larger than predicted by the Standard Model. The main goal of this thesis is to determine the cross-section for prompt same-sign muon pairs in ATLAS and compare it with the Standard Model expectation, in the hope of finding evidence for physics beyond the Standard Model.

Outline

In Chapter 1 we describe the Standard Model of particle physics as well as a possible extension in the form of supersymmetry and use it to motivate our search for prompt same-sign muon pairs. This search is performed using data provided by the LHC and collected by the ATLAS detector, both of which are discussed in Chapter 2 including a description of the ATLAS trigger, reconstruction and simulation software used in the rest of the thesis. Together, Chapter 1 and 2 should provide all relevant background information necessary to understand the analyses presented in this thesis.

In Chapter 3 we study the muon reconstruction performance of ATLAS, specifically the muon momentum scale and resolution during the first few months of data-taking. One of the particularities of the analysis in Chapter 3 is that we need to separate the contribution from muons from pion and kaon decays to that of other muons. This is done using a template fitting method. In Chapter 4 we use a slightly modified version of this method to study the contribution of muons from pion and kaon decays to the invariant mass distribution of muon pairs in ATLAS.

As we are interested in prompt muon pairs, we furthermore need to be able to separate prompt muons from muons produced in the decay of \(b\)- and \(c\)-quarks and taus. This is

\(^1\)The Higgs-boson would also be capable of producing prompt muons. However, even if the Higgs-boson exists, the corresponding cross-section is too small to affect the results in this thesis.
achieved using a different template fitting method, exploiting the difference in impact parameter distributions between the considered muon types. This method is described and validated in Chapter 5.

In Chapter 6 we use the methods developed in the earlier chapters to determine the inclusive prompt same-sign muon cross-section in ATLAS, which we compare with the Standard Model predictions. The results of this analysis are also interpreted in terms of exclusion limits for a simplified supersymmetric model.