Chapter 1

INTRODUCTION

For centuries philosophers and scientists, among them physicists, have pursued the idea that there is a simplicity underneath the apparent complexity of natural phenomena. This quest for simplicity, which to many is also a quest for beauty, have led physicists to contemplate the universe at ever smaller and ever larger scales. As they progress, physicists have become more and more convinced that their quest is fruitful, that a satisfactory picture of the physical world is attainable, even though major paradigm shifts have occurred many times over.

In the search for a theoretical understanding of physical phenomena at ever smaller scales, particle physicists have been guided by the idea that matters are made up from a small number of elementary particles, that these particles interact through certain fundamental forces, and that a knowledge of the elementary particles and their fundamental interactions is equivalent to a full understanding of the physical world.

This simple yet profound idea, that all one needs to know is a knowledge of the elementary particles and their fundamental interactions, has been implemented quantitatively. In the second half of the 20th century, particle physicists have been able to construct a theoretical framework, called the Standard Model, in which the elementary particles and their interactions are identified and classified, and on the basis of which many calculations have been carried out with outstanding precision. In this respect, a famous example is the calculation of the magnetic moment of the electron, where the agreement between theoretical calculation and experimental measurement has reached the level of ten decimal figures [26], among the most precise in physics.

According to the Standard Model, there is a small number of elementary particles that are classified into bosons and fermions. Fermions, which are the constituents of matter, carry spin 1/2 and, depending on their properties, interact with each other by one or more fundamental forces by exchanging bosons. The bosons, which have integer spins, are thus the force carriers, and some of them may carry charges themselves, which make some of them capable of interacting with each other. Particle physicists have, to a great extent, succeeded in proposing and clarifying, both qualitatively and quantitatively, these elementary interactions. More remarkably, they have found in the process that the unifying principle of the Standard Model is the principle of symmetry. The entire theoretical framework of the Standard Model is constrained by spacetime symmetry, the Poincaré group, and local gauge symmetries, the groups $U(1)$, $SU(2)$, and $SU(3)$, underlie its different components.

To particle physicists, the Standard Model, even though a fantastic achievement of 20th-century physics and ranks among the greatest intellectual achievements of all time, is not absolutely satisfactory. First of all, presently we know that there are four fundamental forces that exist in nature. The electromagnetic force takes place between particles that carry electric charges. Subatomic forces, including the weak and the strong forces, take place between particles that carry the weak and the strong charges, respectively. The electromagnetic and the weak forces have been unified into a single force called the electroweak force, and together with the strong force, make up the three fundamental forces in the Standard Model. Gravity, a fundamental force that takes place between any two particles that carry masses, is however not part of the Standard Model. In this sense, the Standard Model is not seen as a complete physical theory of nature.

There are other problems with the Standard Model as well. Neutrino masses, the hierarchy problem, the nature of dark matter, the unification of the electromagnetic, weak, and strong forces, are problems believed to lie beyond the scope of the Standard Model.

Among the many ideas that have been proposed, supersymmetry is perhaps the one that stands out and one that is most actively pursued. It is a theoretically consistent framework that started with the question whether or not it would be possible to extend spacetime symmetry. Indeed, gauge symmetries are not related to spacetime symmetry, in the sense the commutators between the generators of the gauge groups and those of the Poincaré groups all vanish. Spacetime symmetry may be extended, provided, along with adding new generators to the spacetime generators, we consider their anti-commutators. Supersymmetry unifies bosons and fermions, thereby in a sense further simplifying of our picture of the physical world. It, however, adds some complexity into our physical picture of nature with a considerable increase of the number of elementary particles and their interactions. At the same time, supersymmetry provides solutions to a number of open questions that have been raised, such as the hierarchy problem, dark matter, and the unification of the three fundamental forces of the Standard Model.

For any physical theory, the ultimate test is experiments. Since its operation in 2009, the Large Hadron Collider based at CERN, or the LHC as it is often called, has given physicists opportunities to verify if supersymmetry is indeed a symmetry of nature. A great number of physicists is participating in this process, which is still going on. This they do by analyzing the data that have been collected and are being collected at the LHC, searching for signs that supersymmetry exists.

The LHC centre-of-mass energy makes it possible to probe a number of physics models that extend the Standard Model. Many of these models predict unstable hypothetical particles that decay into Standard Model particles such as top quarks and weak bosons which, being unstable themselves, decay either leptonically or hadronically. Leptonic processes, expected in a fraction of the total number of interactions, produce electrons and muons. Thus electrons and muons are important physics objects in the search for new physics, all the more because leptonic processes are often not plagued with hadronic backgrounds which are so numerous in high-energy interactions. On the other hand, pure Standard Model processes, in particular the strong and weak interactions, also take place abundantly at the LHC, and many of these interactions produce again particles such as the top quarks and the weak bosons. Again, leptonic processes are to be expected in a fraction of the total number of interactions, and thus electrons and muons are important physics objects that need to be accurately reconstructed and calibrated , in order that Standard Model background can be accounted for as reliably as possible.

This thesis is one among many works that have been carried out by experimental physicists at CERN as the search for supersymmetry continues. The common theme is electrons, specifically improving the selection of signal electrons in SUSY searches[1]. The contexts of the work are as follow.

- In some SUSY searches, the final state consists of a pair of same-sign leptons, where the leptons are electrons and muons. In general, SUSY cross sections are much smaller than the Standard Model background cross section and, as we continue to push to unexplored phase space, we often have to deal with situations that involve a very small signal on top of a very large background. Correct determination of the charges of the leptons is very important, as charge mis-identification rates occur on the order of O(1%), while Standard Model processes that provide opposite-sign dileptons (dominantly $Z \rightarrow e^+e^-$ bosons) occur approximately 10^3 times more commonly than genuine Standard Model sources of same-sign leptons (dominantly WZ production), and as a result, opposite-sign sources of dileptons can constitute a large background in these searches. At ATLAS, electron charge is determined in the Inner Detector which is embedded in a solenoidal magnetic field. This determination is not always correct, however, due to the apparent straightness of a track or bremsstrahlung, and as a result the sign of the charge might be mis-measured, or mis-identified. In this thesis, the estimation of the rate of charge mis-identification by a likelihood function is described in chapter 5.

- Many SUSY searches target strongly-interacting processes, as these have relatively high cross sections. Processes that involve pair productions of gluinos, which are hypothetical partners of the Standard Model gluons, is an example. These super-particles are also highly motivated as they are expected by naturalness to have a mass around the TeV scale [90]. This thesis describes, in chapter 6, the search in which the final state consists of large missing transverse momentum due to the neutralino, as well as multiple jets, where at least three of the jets must be b-jets. The focus is on the leptonic channel[2] where electrons and muons are involved, and we describe in some detail a new scheme of overlap removal between jets and muons that was introduced into the analysis, to maximize signal acceptance in the presence of dileptonically-decaying boosted top quarks.

  In the same chapter we also discuss the optimization of some important discriminating variables, the result of which was used in the design of the signal regions of the analysis.

[1] The works are applicable to other beyond-the-Standard-Model searches.

[2] The hadronic channel which requires zero lepton is also part of the analysis; however, the chapter only focuses on the leptonic channel as it is directly related the work done in this thesis.

- Starting from Run 2, the LHC centre-of-mass was upgraded to 13 TeV. In a number of SUSY searches that involve leptons in the final state, more electrons were found to be within $\Delta R = 0.4$ of jets. The SUSY search that involves pair productions of gluinos discussed above is an example, in which considerable signal acceptance was gained when electrons within $\Delta R = 0.4$ were selected. At ATLAS, only standard electrons are calibrated, and it is important to make sure that this calibration, in particular for the identification efficiencies, remains valid for electrons found within $\Delta R = 0.4$ of jets. This thesis develops a method for measuring the identification efficiencies for electrons found inside jets and performs the initial measurement. The measurement uses a dilepton $(e\mu)$ $t\bar{t}$ sample enriched in boosted top quarks. The top quark decays almost all of the time into a W and b-quark, and the electrons in the sample are located inside the b-quarks. The work is described in chapter 7.

  Prior to the work initiated in this thesis, no attempt had been made to measure the identification efficiencies for these electrons.

The remaining chapters are organized as follow. Chapter 2 discusses briefly the symmetry principles that underlie the Standard Model, as well as its particle contents and forces. In the same chapter we give also a general discussion of the shortcomings of the Standard Model as well as a discussion of the basic ideas of supersymmetry. Chaper 3 describes the LHC, including a discussion of the LHC accelerator and the ATLAS detector. All the works in this thesis are associated with the ATLAS experiment. Chapter 4, on the other hand, gives an introduction of electron reconstruction and identification at ATLAS.