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Full report on the thesis submitted by Lucas Henry McConnell

Suppression of the Fake Lepton Background in Same-Sign W-boson Scattering with the ATLAS Experiment

for the degree of **Master of Science (Physics)**

This thesis presents the research that Lucas McConnell has performed since the beginning of 2015 as a student in the ATLAS group at UCT. ATLAS is a particle physics experiment based at the European Organisation for Nuclear Research (CERN) in Geneva (Switzerland). The ATLAS experiment is one of the two multi-purpose experiments at the Large Hadron Collider (LHC), the world's largest particle collider. The LHC provides particle collisions at much higher energy than all previous (and other existing) colliders. It therefore allows us to study the interactions of fundamental particles in a new energy regime that was previously not accessible experimentally. The ATLAS and CMS experiments, which are used to study the particle collisions produced by the LHC, are therefore the tools at allow us to answer a number of today's pressing questions in fundamental physics.

The physics programme of the ATLAS experiment is rich: it includes, among many other topics, detailed studies of the properties of the newly discovered Higgs boson, as well as searches for physics beyond the standard model of particle physics. The subject of study chosen by Lucas, namely the scattering of same-sign W bosons, is at the heart of the ATLAS physics programme. Indeed, this very process has been used to guide the design (e.g. the choice of the collision energy) of the LHC collider. Theories without the newly discovered Higgs boson predict the cross section (probability) of this process to become infinitely large at large collision energy. This prediction is of course unphysical, and this scattering process needs to be studied experimentally to test the theoretical prediction of the regularisation of the cross section via the exchange of a Higgs boson.

The studies presented in this thesis have been performed at an exciting time. The ATLAS experiment has just recently been able to observe W boson scattering for the first time. As much more data are being accumulated, the detailed study of this process can now start.

Chapter 1 of the thesis is devoted to an overview of the theoretical context of Lucas' experimental studies. It starts with a brief overview of the standard model of particle physics and some of its foundations (like e.g. electroweak symmetry breaking). The second part of the chapter takes the reader right to the theoretical aspects of the subject of this thesis, i.e. W boson scattering. This provides a pertinent and accessible discussion of all of the theoretical foundations that are needed to understand the main part of the thesis.

Chapter 2 briefly presents the LHC. The key motivations are clearly explained. The choice to keep this chapter brief is good, since the technical details can be found in the references (and in many other theses).

The ATLAS detector is presented in chapter 3. The description is accurate, but the editorial choices about which aspects to present and how to put them into the bigger picture of the study of W boson scattering are not quite as well done as the choices that have been made in chapter 2.

The first step of all analyses of data from the ATLAS experiment is the reconstruction and identification of "physics objects", i.e. the identification of the experimental signatures left by different types of particles in the ATLAS detector, as well as the precise measurement of the kinematical properties of these particles. The corresponding methods and algorithms, common to most analyses of ATLAS data, are discussed in chapter 4. As the experimental signature of W boson scattering typically involves a large number of different kinds of final state particles (e.g. decay products of the W bosons) that are experimentally difficult to identify, these algorithms are an important basis for the analysis. The choice to present these algorithms in a relatively long chapter is therefore well motivated, and the key aspects are clearly explained. This is particularly true for the description of the two methods that are at the heart of Lucas' studies that will be presented in the following sections, namely the identification of b-jets and isolated leptons.

Chapter 6 provides a good overview of the analysis that is currently used by the ATLAS physicists to study W boson scattering. This baseline analysis procedure has been designed by a large team of physicists, and Lucas has made the choice to present it in a clear, straight-to-the-point manner that is well appreciated. Lucas' contributions to the improvement of the analysis are the topic of the next chapter.

The core of Lucas' contributions to the study of W boson scattering using data from the ATLAS experiment are described in chapter 7. The scattering of W bosons is a rare process. The experimental signature of this process is mimicked by other, unrelated processes that occur at a much larger rate. The design of methods to suppress these so-called background processes (i.e. to distinguish their experimental signature from the signature of W boson scattering events) is therefore a key aspect of the data analysis. Lucas has studied new methods to suppress two of the largest backgrounds and has quantified their performance. The first background is due to particle collisions in which a pair of top quarks is produced. While the signature of the decay of top pairs is similar to the signature of W scattering, it does have the particularity that top quark decays produce jets from heavy b quarks. These b quark jets can be identified using the ATLAS detector. Since no b quark jets are expected in W scattering events, the experimental identification of b quarks allows Lucas to remove a part of the top quark background events from the data sample that is used in the study of W boson scattering. The ATLAS experiment uses different techniques to identify jets from b quarks. Lucas has compared the performances of these different techniques for the purpose of

reducing the background in the dataset that is used to study W boson scattering. He has identified the most pertinent algorithm for this purpose, and he has quantified the level of improvement in the study of W boson scattering that is expected from the use of the most pertinent algorithm.
The second background arises from events in which jets are incorrectly identified as leptons (the latter are an important aspect of the signature of W boson scattering). The idea of Lucas' study is similar to the idea of the study of the top backgrounds described above: ATLAS uses different techniques to improve the identification of true isolated leptons from fake leptons, and Lucas has compared the performance of these algorithms for the purpose of background suppression in the study of W boson scattering.

The thesis is concluded in chapter 8. The goal of Lucas' studies as well as the results that have been obtained are clearly summarised. A paragraph with perspectives for future work by the ATLAS collaboration would have been useful.

The nature, objectives and scientific principles underlying Lucas' research are clearly explained in this thesis. Lucas shows that he masters the relevant experimental techniques and analytical methods that are used. Lucas has obtained new results and clearly explains theses results. The thesis is well written and a pleasure to read. The expectations of a Masters thesis are clearly fulfilled and I wholeheartedly recommend that the degree be awarded to Lucas. The standard is clearly at least "Good", and if the material presented in chapter 7 had been slightly more extensive then I would have recommended the award of a distinction.

Report on MSc thesis *Suppression of the Fake Lepton Background in the Same-Sign W-boson Scattering with the ATLAS Experiment* by Lucas Henry McConnell

The thesis is an analysis of potential improvements to the search for same sign W-boson production in proton-proton collisions at the Large Hadron Collider at CERN, using data collected by the ATLAS experiment. The work does include an original contribution compared to previous studies of this channel.

The thesis is very well written. There is a clear and complete introduction to the background to the work, including the theoretical underpinnings of the Standard Model of Particle physics and triple gauge couplings, the ATLAS experiment and the reconstruction and simulation of *physics objects* from the ATLAS data. The analysis sections shows an understanding of data analysis and approaches to cut optimisation; the observation that a cut on the invariant mass of lepton pairs around the Z-boson mass is interesting. I would prefer if the conclusion had taken a slightly more holistic view of the whole work, and I have recommended a small addition to the Conclusion chapter (see below).

Below, I have listed a small number of changes I would like the author to make before the dissertation is passed. These are editorial changes only, and do not require any further analysis work.

Requested Changes

- Please state the amount of integrated luminosity used in this analysis, how many fb^{-1}? Ok, you don't use any collected data, but you do normalise the MC to a given integrated luminosity.
- In Section 4.4, point 2 "find minimum distance", do you the minimum between all the d_{ij} and d_{iB}? Please clarify exactly what distance you mean!
- Tables 7.1-7.3, please clarify where the numbers come from! Maybe you ran the code yourself - using the cuts introduced in Chapter 6 - to get these numbers of events and the errors are just statistical. In that case, then please state that the errors are statistical (the reader would assume you calculated the numbers yourself). If you got the numbers of events from another piece of work, then please reference that or a similar public document.
- In section 7.3.2, **topoetcone30** is measured in units of GeV; but in the discussion in this section it becomes dimensionless: x=1.0 is mentioned as an example cut, and figures 34 and 36 have no dimensions on the x-axis. This should be clarified. (Also in Appendix C.)
- In section 7.3.2, the definition of **fractional topoetcone30** and **fractional ptvarcone30** should be stated (*i.e.* fraction with respect to what?)
- For the conclusion in Chapter 8, I'd suggest a slightly more holistic wording, summarising the whole thesis and not just your original work from Chapter 7. The text that is there is fine, but I would suggest to add a few sentences at the beginning summarising why same sign W-boson scattering is important, and that your work was trying to improve the sensitivity to this.

Minor Typos (to be corrected)

- Table 1.1 "(same opposite)" should be "(same sign)".
- Section 4.4 "jet be defining"

- Section 4.2 "algorrithm"
- Section 4.7.2 "0,4" should be "0.4"
- Section 6.2.1, the high-level trigger is configured on electrons that have $p_T \geq 24$ GeV and not $p_T \leq 24$ GeV as stated.