CHAPTER 1

INTRODUCTION

Particle physics seeks to understand the fundamental structure of the universe by defining the minimal set of particles and interactions required to describe all physical phenomena. The Standard Model (SM) is the best attempt at such a description. The SM has undergone decades of rigorous testing and can explain almost all phenomena we see in experiments. Yet it is known that the SM is missing explanations for crucial physical phenomena like quantum description of gravity or a dark matter candidate. As a result, many Beyond the Standard Model (BSM) theories have been developed and tested, hoping to extend and complete the picture the SM gives. So far, no evidence for any of these theories has been seen.

The Large Hadron Collider (LHC) at European Center for Nuclear Research (CERN), a 27 km particle collider outside of Geneva, Switzerland, is the largest particle physics experiment in the world, and provides an extremely effective environment to test the SM and a wide variety of BSM theories. This thesis uses data from the A Toroidal LHC Apparatus (ATLAS) experiment, one of the four largest experiments along the LHC ring.

Beams of protons circulate and collide in the LHC, and if two protons collide with sufficiently high energy, massive particles can be created; $\sqrt{s} = 8$ TeV collisions enabled the 2012 discovery of the Higgs boson with mass of 125 GeV. The LHC provides 60 million collisions per second, enabling physicists to search for new and rare physical phenomena. Unfortunately, after 8 years of data taking no evidence of BSM physics has been found. Data taking is scheduled to resume in 2022 with only a moderate increase in collision energy and about a factor 2 more data.

This is a call to expand the suite of BSM searches by re-examining the assumptions made in searches that have been performed so far. What could we have missed in our search for new physics at the TeV scale? The LHC detectors are designed to look the decays of short-lived, heavy particles with the assumption that the decay products will be *prompt* and trace back to the collision point. This misses a large range of intermediate lifetimes of possible

BSM particles that decay inside of the detector material. These signatures are challenging, but not impossible, to identify with ATLAS as they result in *displaced* SM particles that do not point back to the collision point. Many SM particles are long lived, like muons or neutrons, and many BSM theories predict particles with lifetimes that result in displaced decays. This thesis presents a search for one such signature.

This thesis presents a search for two displaced SM leptons, either electrons or muons, that are not connected by a displaced vertex. Due to the displacement and lack of vertex, a BSM particle decaying to this signature would be vetoed by all other analyses at the LHC, even those targetting LLPs. This search has unique sensitivity to a specific Gauge Mediated Supersymmetry Breaking (GMSB) Supersymmetry (SUSY) model where the Lightest Supersymmetric Particle (LSP) is the superpartner to the graviton, the gravitino, and the Next Lightest Supersymmetric Particle (NLSP) is a slepton ($\tilde{\ell}$), the superpartner to a lepton. The $\tilde{\ell}$ is long lived because it must decay to the gravitino through the very weak gravitational coupling. The last time this model was explored was in the OPAL experiment at Large Electron-Positron Collider (LEP) [1], where masses up to about 90 GeV were probed for the full range of lifetimes, immediately decaying to detector stable and all possible signatures in between. This search probes almost an order of magnitude of mass phase space in a limited lifetime phase space, and in a significantly more challenging environment than LEP.

Since this is the first search for displaced leptons at the LHC particle selection algorithms and robust data-driven background estimates needed to be developed. This search for displaced leptons uses 136fb^{-1} of data collected by ATLAS during Run 2 of the LHC. Major backgrounds come from fakes of the reconstruction algorithms and muons from cosmic rays. Less than 1 background events are predicted and zero events are seen, and so limits on the mass and lifetime of $\tilde{\ell}$.

This thesis is organized into three main sections: first the search is motivated theoretically, then the experimental setup is described, and finally the search strategy and its results are presented.

Chapter 2 provides theoretical motivation for searches for SUSY and in particular long lived and GMSB SUSY.

Chapter 3 describes the LHC and its design and operation.

Chapter 4 describes the ATLAS subdetectors and how they are used to measure particles.

Chapter 5 details particle reconstruction algorithms and the modifications made for this analysis.

Chapter 6 describes the ATLAS data and Monte Carlo simulation (MC) simulation of the signal model.

Chapter 7 provides context for LLP decays and searches.

Chapter 8 describes the analysis strategy, lepton selection requirements and final event selection criteria.

Chapter 9 details the backgrounds to this signature and the algorithms for estimating them.

Chapter 10 describes the uncertainties applied to signal MC in order to use the data to make a statement about the SUSY model.

Chapter 11 presents the unblinded results as well as a description of the statistical interpretation.

Chapter 12 provides reflections on the analysis as well as possible improvements for future ATLAS analyses for displaced leptons.