Search For Displaced Leptons in $\sqrt{s} = 13.6$ TeV $pp$ Collisions with the ATLAS Detector

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Abstract

This report presents the search for charged leptons with large impact parameters using $\sqrt{s} = 13.6$ TeV $pp$ collision data from the ATLAS detector at the LHC. It is a search for new physics, specifically, for displaced decay products indicative of the kinds of long-lived particle signatures expected from gauge-mediated symmetry breaking (GMSB) R-parity conserving supersymmetry (SUSY). The Run 3 displaced leptons search, with a focus on the electron case, aims to exploit the large radius track (LRT) electron definition for improved signal sensitivity. This is in hopes of finding evidence for SUSY. Residing in the exploratory phase, this analysis ranges from Monte-Carlo signal studies to reproduced Run 2 cutflows. The LRT electron object proves to have increased signal acceptance compared to standard electrons, lending support to the LRT-optimized Run 3 analysis.
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1 Introduction

1.1 The Standard Model

Our current understanding of the most fundamental constituents of this universe is summarized by the Standard Model of particle physics. Particle physics, a field that seeks to understand the elementary structure of nature, relies on the Standard Model to provide an accurate description of the particles and forces that compose all physical phenomena.

The Standard Model is a mathematical paradigm of a quantum field theory that describes all known elementary particles as well as three out of the four fundamental forces. The particles described by the Standard Model are divided into two categories: fermions and bosons. As shown in Figure 1, which illustrates the current Standard Model, fermions include three generations of spin 1/2 leptons or quarks. The first generation, consisting of the electron, electron neutrino, up-quark and down-quark, are characterized by their rudimentary nature; they also make up all visible matter in the universe. The only difference between particles of a specific generation is the mass, each generation of particle being heavier than its predecessor. For example, the muon has mass \( m_\mu \approx 106 \text{GeV}/c^2 \) compared to the much smaller electron mass \( m_e \approx 0.000511 \text{GeV}/c^2 \). In addition, second and third generation particles are unstable, decaying quickly into their first generation counterparts. Physicists must utilize high-energy collider experiments to study these short-lived particles. The Dirac equation of relativistic quantum mechanics defines the motion of fermions, with the important consequence that each of these twelve particles has a corresponding antiparticle with equal mass and opposite
charge. Essentially, however, the entirety of the matter in the universe is composed by fermions. The forces exhibited by this matter are due to particles called bosons. [15]

Bosons are spin 1 force-carrying particles. The three fundamental forces, each described by a specific quantum field theory, are also each mediated by a particular "gauge boson." Gauge bosons are the mediators of gauge theories that describe the interactions of elementary particles. The exchange of virtual particles within this mediation depicts the transfer of momentum that later manifests itself as a force. The gauge boson for quantum electrodynamics (QED), or the mediator for the electromagnetic force, is the photon. Electromagnetism is what defines the interactions between charged particles. For quantum chromodynamics (QCD), which corresponds to the strong force, the force-carrying particle is the gluon. The strong nuclear force describes how quarks join together to form hadrons, such as protons and neutrons, which bind together to form nuclei by the same strong interaction. Quarks are distinguished from leptons in this way and in addition to their "color" — to create hadrons, quarks must combine to form a colorless whole. Both the photon and the gluon are massless. However, the W boson, which mediates the weak force, has a very large mass, with \( m \approx 80.4 \text{GeV}/c^2 \) in contrast to the much lighter proton mass of \( m \approx 0.938 \text{GeV}/c^2 \). The Z boson, another mediator of the weak force, is also very massive, yet it is electrically neutral. The weak force is responsible for the radioactive beta decay of atoms as well as nuclear fusion. The fourth force, left out of the Standard Model, is gravity. Even weaker than the weak force, gravity is a purely attractive force that binds the structures of the universe together. The theory of gravitation, however, is inconsistent with quantum mechanics and therefore with the Standard Model of particle physics. [15]

While gauge bosons are "vector bosons" with spin 1, the Higgs boson is a spin 0 "scalar boson." In fact, the Higgs is the only known scalar particle to exist within the Standard Model. While the gauge bosons bring the electromagnetic, strong, and weak force into being, the Higgs is responsible for all particles' acquisition of mass. When the Higgs boson interacts with initially massless particles, the excitation of the Higgs field provides them with mass. This process, called the Higgs mechanism, explains the masses of the W and Z bosons and therefore is the breaking of electroweak symmetry. [10]

The Standard Model is a feat of theoretical and experimental physics. It is a well-tested theory that encapsulates our best understanding of the fundamental particles that compose this universe. However, the Standard Model is not complete. It leaves open several inconsistencies, including — yet not at all limited to — the exclusion of gravity, numerous parameters that are only available experimentally, the existence of dark matter, the question of grand unification, and the "fine tuning" or "hierarchy problem" whereby extensive quantum corrections are applied to explain the Higgs mass. [4]

### 1.2 Supersymmetry

Supersymmetry aims to fill some of the gaps left open by the Standard Model. As an extension of the Standard Model, it predicts that every particle has a corresponding supersymmetric partner differing in spin by 1/2. For example, this means that every fermion has a boson "superpartner" and vice versa. Supersymmetry therefore provides an elegant connection between matter and forces. The supersymmetric lepton is designated a "slepton" — for the electron, a "selectron," for the muon, "muons," for the tau, "stau" and so on. The superpartner of a particle is denoted by the "tilde" symbol, such that the selectron, for example, is written as \( \tilde{e} \). [1] [11] The numerous particles of a supersymmetric SM are illustrated in Figure 3.
The principle of supersymmetry is well-motivated due to its ability to resolve inconsistencies. For instance, the existence of the Higgs boson explains why particles have mass. However, if the Higgs interacted with only SM particles, it would be very heavy. The Higgs mass is incredibly light though, measured by the LHC to be only 125 GeV. It is the sum of the "bare mass" — the mass as the energy of a particle collision approaches infinity — and "quantum corrections," which are contributions from all other SM particles. The mass due to quantum corrections is $-10^8$ GeV, meaning that to get the much smaller Higgs mass — seven orders of magnitude to be exact — the bare mass must be almost the opposite. This coincidence is unsettling. If supersymmetry is correct, however, the superpartners predicted by the model would cancel out the mass contributed to the Higgs by their SM equivalents; the quantum corrections would cancel between fermionic and bosonic interactions. This kind of "fine-tuning" — when parameters are purposefully manipulated — is a fundamental issue in particle physics. Crucially, an enormous amount of fine-tuning must be used in order to obtain the hierarchy between the electroweak and Planck scales. However, using the supersymmetric model, in which quantum corrections cancel, the hierarchy is achieved naturally — therefore solving the "hierarchy problem."

A supersymmetric version of the Standard Model would also support the idea of grand unification — that is, the unification of gauge symmetry groups at high energies, such as those found in the early universe. Grand unification implies that the weak, strong, and electromagnetic forces unify into one single force at this ultra high energy, which is approximately $10^{16}$ GeV. Figure 3 shows the energy at which a Grand Unified Theory (GUT) would exist to merge the electroweak and strong forces. The elegance of supersymmetry does not end at grand unification, but further extends to the realm of dark matter. In many supersymmetric models, the lightest supersymmetric particle (LSP) is a stable weakly interacting particle, which could potentially be a WIMP (Weakly Interacting Massive Particle) dark matter candidate.

In order for supersymmetry to be a viable extension of the Standard Model, it must be a broken symmetry. If supersymmetry was perfectly symmetric, the sparticle superpartners would have the same mass as their SM counterparts, the only difference being their spin. However, experiments throughout the last decade have ruled out this possibility. If supersymmetry was unbroken, it would have been discovered already.
Figure 3: A graphical depiction of the "grand unification" of gauge symmetry coupling constants at high energy (a) without supersymmetry and (b) with a supersymmetric extension of the Standard Model. [15]

1.3 Instrumentation For New Physics

1.3.1 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) is the world’s most powerful particle accelerator, located at CERN (European Council for Nuclear Research) in Geneva, Switzerland. To deconstruct its name, "large" refers to its massive 27 kilometer circumference, "hadron" signifies the kinds of particles the collider accelerates (typically protons and ions), and "collider" denotes the smashing together of such high energy particles. The LHC first started up in 2010 at 7.0 TeV. It was most recently upgraded to energies of 13.6 TeV part of a new phase of experimentation, called Run 3, on July 5, 2022. The primary aim of the LHC is to answer the many remaining questions physicists have about the Standard Model. The collider, illustrated in Figure 4, was built to find new physics that would help complete our fundamental understanding of particles and their interactions. [3]

The LHC accelerates particle beams to near (99.999999%) the speed of light in ultrahigh vacuum, steered around the accelerator ring by superconducting electromagnets kept at -271.3°C, which requires approximately 96 tonnes of superfluid helium. It collides these beams at four different points along the accelerator, as can be seen in Figure 4. Seven detectors are positioned near these crossing points. These include the ATLAS experiment and the Compact Muon Solenoid (CMS), which are both general purpose particle detectors. The more specialized detectors include ALICE and the LHCb in addition to the smallest four, which are TOTEM, MoEDAL, LHCf, and FASER. [3]

Figure 4: The path of accelerated particles in the LHC. [3]
1.3.2 The ATLAS Detector

From Einstein’s famous equation, \( E = mc^2 \), one can conclude that energy and mass are fundamental manifestations of each other. So, when the LHC collides particles at energies of several trillion electronvolts, the collision debris take the form of newly produced particles, which are then detected by ATLAS. The ATLAS Detector, or A Toroidal LHC ApparatuS, is the largest of the detectors at the LHC and the largest volume collider-detector ever built. The layers of the detector form a series of concentric cylinders around the interaction point, where the proton-proton collision happens. Up to 1.7 billion collisions take place every second in the ATLAS detector. Approximately one in a million detection events is marked of potential interest by the "trigger," an event selection system. Filtering through a data volume of more than 60 million megabytes per second, the ATLAS trigger system enables the search for new BSM particles. [2]

![Figure 5: The ATLAS Detector and its four main components: the Inner Detector (ID), the Calorimeter, the Muon Spectrometer, and the Magnet System.](image)

In order to detect new physics beyond the Standard Model, ATLAS must be able to identify particles and reconstruct their tracks. The detector itself, displayed in Figure 5 consists of four main systems. [2]

1. The Inner Detector (ID) resides closest to the interaction point. Surrounded by a magnetic field parallel to the beam axis, the ID is composed of three main parts: the Pixel Detector, the Semi Conductor Tracker (SCT), and the Transition Radiation Tracker (TRT). These systems are able to measure the charge, momentum and track of electrically-charged decay products from proton-proton collisions.

2. Positioned outside the solenoidal magnetic field surrounding the Inner Detector are the calorimeters. The ATLAS detector include two major calorimeters: the Liquid Argon (LAr) Calorimeter and the Tile Hadronic Calorimeter. The LAr Calorimeter absorbs decay products, producing particle "showers" that ionize the liquid Argon, producing an electric current. This process allows the calorimeter to measure the energy deposited by particles ejected from collisions. The LAr Calorimeter records the energy of electrons, photons, and hadrons, while the Tile
Calorimeter measures only hadrons. Since hadrons do not deposit the entirety of their energy in the initial LAr Calorimeter system, they hit the Tile Calorimeter, which is able to measure hadron energies from photon showers.

3. The Muon Spectrometer works to measure the momentum of muons, which typically pass through the Inner Detector and calorimeters undetected. It is the outermost and largest layer of the ATLAS detector.

4. ATLAS utilizes two superconducting magnet systems to bend the trajectories of charged particles for measurement: the solenoidal and toroidal magnets. The Central Solenoid Magnet surrounds the Inner Detector, providing a 2 Tesla magnetic field in a thickness of only 4.5 cm. The outer toroidal magnetic force required to measure the momentum of muons is provided by a very large Barrel Toroid surrounding the center of the detector and two smaller End-Cap Toroids near the ends of the beam pipe.

2 The Search For Displaced Leptons

2.1 Motivation

Many BSM theories include particles that, if they were to be detected at the LHC, would produce displaced decay products. One particular theoretical model that would give rise to displaced signatures is gauge-mediated symmetry breaking (GMSB) R-parity conserving SUSY. In GMSB SUSY models, the undetectable gravitino is the lightest supersymmetric particle (LSP). Due to small gravitational coupling to the LSP, the Next to Lightest Supersymmetric Particle (NLSP) becomes "long-lived." Particles with long lifetimes are a facet of the SM and beyond, however, BSM particles with lifetimes long relative to those of the SM are called Long Lived Particles (LLP). LLP’s have lifetimes ranging from approximately 0.01 to 100 ns. Importantly, these LLP’s can decay far from the primary vertex of proton-proton collision. In other words, they may produce displaced decay products that do not trace back to the interaction point. [5] [9] [8]

Figure 6: GMSB SUSY-motivated decay topology of the displaced leptons search. The Feynman diagram illustrates the decay of pair-produced sleptons ($\tilde{\ell}$) from proton-proton collision into a lepton ($\ell$) and a gravitino ($\tilde{G}$). [8]
Well-motivated versions of the GMSB SUSY model define the slepton as the NLSP. This would result in a long-lived slepton. Figure 6 shows the pair-production of said long-lived sleptons as they are emitted from proton-proton collision. This pair-production, which conserves R-parity, subsequently produces decay products in the form of a lepton ($\ell$) and a gravitino ($\tilde{G}$). Again, R-parity is conserved in the $\tilde{\ell} \rightarrow \ell \tilde{G}$ decay. The production of a gravitino, which does not decay, also provides an attractive dark matter candidate — it only interacts gravitationally, which is what makes it the LSP under GMSB SUSY, and it is undetectable.

Crucial to this analysis, long-lived slepton decay produces displaced leptons. These leptons do not originate from the primary interaction point, but rather from a displaced decay vertex. They are additionally displaced by a lack in momentum associated with the gravitino. Momentum is conserved in proton-proton collision, so since the gravitino is undetectable, there is an apparent "missing" momentum. The leptons' displacement from the primary vertex of collision and also angularly due to the gravitino can be observed in Figure 6. In this particular study, the displaced lepton that is considered is the electron with two unknown parameters: mass [GeV] and lifetime [ns]. If the displaced lepton is discovered, it would lend support to SUSY.

### 2.2 Monte-Carlo Simulation

Monte-Carlo (MC) simulation is an essential tool in order to study the complexity of high energy particle collisions. In the displaced leptons analysis, MC utilizes repeated random sampling event generation while implementing the GMSB SUSY model. Through MC simulation, "truth" level information is gained, which enables observation of the fundamental signal. Analysis of truth variables therefore allows for the elimination of background and preservation of the signal.

Figure 7 shows the distributions for several truth variables plotted from 100 GeV, 1 ns MC simulation. The plots are divided by leading and subleading selectrons — that is, the selectrons with the highest and second highest transverse momentum in the event. Spatial coordinates $\phi$ and $\eta$ signify the angle of a particle relative to the beam axis. Specifically, $\eta$ represents the pseudorapidity, defined by the equation $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$. A particularly insightful plot is that for the decay vertex radius, which is defined as the distance from the primary vertex of collision that a selectron decays into a lepton and gravitino. From Figure 7 it is shown that the decay vertex radius is significant, with the value not falling off until around 7000 mm. Here is evidence that the selectron is decays far from the interaction point. The plot for transverse momentum ($p_T$) is also of particular significance, as it demonstrates the low $p_T$ that the majority of selectron events exhibit.
Figure 7: Truth level variables for leading and subleading (100 GeV, 1 ns) selectron decay events: $\eta$, $\phi$, decay vertex radius [mm], distance from primary to decay vertex [mm], and transverse momentum [GeV], in addition to associated ratio plots.
2.3 Added Motivation: LRT Electrons

Additional motivation for the Run 3 displaced leptons analysis comes from Large Radius Track Electrons (LRT). These are electrons that do not trace back to the interaction point, meaning they are more likely to be displaced.

2.3.1 Large Radius Tracking (LRT)

Large Radius Tracking (LRT), crucial to LLP searches, is an extra inner detector (ID) tracking pass that runs after standard tracking. To reconstruct particles in the detector, the ATLAS reconstruction software creates charged track objects from hits. These hits and tracks are shown in Figure 8. Standard track reconstruction considers particles that originate directly from the interaction point of proton-proton collision, or that decay after only a few millimeters. The reconstruction for signatures that do not point back to the interaction point is lacking in efficiency. LRT, however, involves running a tracking algorithm on unassociated hits that may be displaced from the primary vertex. That is, it runs on hits not already reconstructed to form standard tracks. The LRT algorithm relaxes tracking cuts by loosening the requirements on \( d_0 \), \( z_0 \), and the number of hits, displayed in Figure 8. It allows for consideration and tracking of displaced objects in the detector. \[6\] \[8\]

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Large radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum ( d_0 ) (mm)</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>Maximum ( z_0 ) (mm)</td>
<td>250</td>
<td>1500</td>
</tr>
<tr>
<td>Maximum ( \eta )</td>
<td>2.7</td>
<td>5</td>
</tr>
<tr>
<td>Maximum shared silicon modules</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Minimum unshared silicon hits</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Minimum silicon hits</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Seed extension</td>
<td>Combinatorial</td>
<td>Sequential</td>
</tr>
</tbody>
</table>

**Figure 8:** The table to the left displays the most significant selections that differ for the standard versus large radius tracking algorithms.\[8\] On the right is a visual illustration of standard ID tracking compared to large radius tracking run on leftover hits. Standard hits and tracks are colored in blue, with the hits represented by circles and the tracks as traced lines. Large radius tracking is colored in red. The purple line from the interaction point to a large radius track is equivalent to \( d_0 \), the transverse impact parameter. \[14\]

2.3.2 Run 3 Trigger

In order to optimize the LRT electron object, the new displaced leptons search will implement an upgraded Run 3 trigger. The Run 2 displaced leptons analysis utilized a photon trigger, since, like displaced electrons, photons leave little to zero tracks in the ID. In other words, photons only have a calorimeter signature. A photon could therefore "look" like a displaced electron. Run 3 replaces the photon trigger with a trigger designed to specifically pick up SUSY signatures, such as the displaced
electron. The new trigger, optimized for LRT electrons, allows for a lowering of the $p_T$ requirement, opening a new phase space where many selectron events exist (see $p_T$ plot from Figure 7). The Run 3 trigger will allow for better exploitation of the LRT electron object by running the LRT algorithm on a specific set of events that pass the LRT trigger. [6]

2.3.3 LRT Electron Comparison Plots

The histograms in Figure 9 demonstrate the difference between $d_0$, the transverse impact parameter — that is, the distance of closest approach of the particle’s track to the interaction point in the x-y plane — and the number of pixel hits (NPixHits) for LRT and standard electrons. The plots show distributions from 100 GeV, 1 ns MC simulation — the signal region — in addition to 2018 output data. The $d_0$ plot in Figure 9 illustrates the large transverse impact parameter associated with LRT electrons. The distributions for LRT electrons in signal and data are at significantly larger $d_0$ than for prompt, or standard, electrons. A similar result can be deduced from the NPixHits plot, in which LRT electrons tend to have a lower number of pixel hits. Since pixels reside in the innermost detector layers, which are shown in Figure 8, it is expected that LRT electrons record fewer hits because of their large distance from the interaction point. The low number of pixel hits is therefore directly related to the transverse impact parameter, $d_0$, with a high $d_0$ value corresponding to a low NPixHits count.

![Figure 9](image9.png)

**Figure 9:** Shape comparisons of $d_0$ and the number of pixel hits for 100 GeV MC simulation and 2018 data, separated into LRT and standard electrons.

![Figure 10](image10.png)

**Figure 10:** Shape comparisons of calorimeter variables f1 and f3 for 100 GeV MC simulation and 2018 data, separated into LRT and standard electrons.
Additional shape comparisons for 100 GeV MC and 2018 data are shown in Figure 10. F1 is the energy that the electron deposits in the first layer of the calorimeter, while f3 is the energy deposited in the third layer. Though there is not such a significant difference in the distributions for LRT and prompt electrons, calorimeter variables like f1 and f3 can become a useful tool in order to further optimize the LRT electron definition.

2.4 Run 2 Cutflow

The previous displaced leptons analysis, "Search for Displaced Leptons in $\sqrt{s} = 13$ TeV $pp$ Collisions with the ATLAS Detector," was conducted during Run 2 of the LHC and published by the Physical Review Letters in 2021. The key result of the Run 2 analysis in Figure 11 illustrates the parameters of particles that can be excluded from the Run 3 displaced leptons search. 

In order to exceed the Run 2 analysis, Run 3 differs in several crucial ways that will optimize the LRT electron object for better signal acceptance. The Run 3 search for displaced leptons will utilize better tools for the exploitation of LRT electrons, one of which being the Run 3 trigger. As elaborated on previously, the new analysis uses a trigger specific to LRT events, rather than a standard photon trigger. In addition to the trigger, Run 3 implements the use of calorimeter timing information. The Run 2 analysis did not consider the time that the signal arrived in the calorimeter, which is valuable information in order to eliminate background from signal. Finally, the larger amount of data gained at higher energy from Run 3 will extend the capabilities of the search for displaced leptons.

However, before optimizing the LRT electron object, the cutflow for Run 2 must be reproduced. A cutflow involves making a series of successive cuts on variables associated with the signal region, such as the $p_T$ or $d_0$ seen before. The number of events remaining after each cut is recorded in the cutflow. In these analyses, the cuts are optimized to find displaced leptons. Not only will reproducing the Run 2 cutflow re-establish the metric, but it is important to confirm its utility for the future Run 3 analysis. The cutflows for data and signal in the Run 2 analysis are shown in Figure 12.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure11.png}
\caption{Expected (dashed lines) and observed (solid lines) exclusion contours for NSLP production — stau, smuon, and selectron — as a function of slepton mass and lifetime at 95% confidence level (CL). The selectron ($\tilde{e}$) case is displayed in blue.} \cite{9}
\end{figure}
V.1 Signal cutflow

Cutflow is produced for signal in the 3 SRs: SR-ee in Table 53, SR-μμ in Table 54, and SR-eeμ in Table 55.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Lepton (mass [GeV], lifetime [ns])</th>
<th>Lepton (mass [GeV], lifetime [ns])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(100, 0.1)</td>
<td>(300, 0.1)</td>
</tr>
<tr>
<td>Pass trigger and at least 2 baseline leptons</td>
<td>797.600 ± 61.973</td>
<td>250.145 ± 5.273</td>
</tr>
<tr>
<td>2 leading leptons are electrons</td>
<td>499.539 ± 48.710</td>
<td>145.338 ± 4.023</td>
</tr>
<tr>
<td>ξr &gt; 65 GeV</td>
<td>453.081 ± 45.360</td>
<td>133.565 ± 3.879</td>
</tr>
<tr>
<td></td>
<td>162.566 ± 27.586</td>
<td>126.673 ± 3.748</td>
</tr>
<tr>
<td>both electrons pass isolation</td>
<td>158.394 ± 27.271</td>
<td>125.886 ± 3.736</td>
</tr>
<tr>
<td>Δr-r/ξr ≥ -0.5</td>
<td>108.451 ± 22.454</td>
<td>63.961 ± 2.674</td>
</tr>
<tr>
<td></td>
<td>92.236 ± 20.877</td>
<td>57.063 ± 2.536</td>
</tr>
<tr>
<td></td>
<td>84.191 ± 20.077</td>
<td>52.876 ± 2.430</td>
</tr>
</tbody>
</table>

Table 53: Cutflow for SR-ee for 5 representative signal points.

V.2 Data cutflow

Cutflow is produced for data in regions with exactly 1 lepton to ensure we don’t unblind the SRs: 1-electron region in Table 56, and 1-μ region (with cosmics required to reduce signal contamination) in Table 57.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass trigger and exactly 1 baseline lepton</td>
<td>404448.000 ± 2011.091</td>
</tr>
<tr>
<td>Require 1 electron</td>
<td>386300.000 ± 1965.452</td>
</tr>
<tr>
<td>ξr &gt; 65 GeV</td>
<td>382912.000 ± 1956.816</td>
</tr>
<tr>
<td></td>
<td>336676.000 ± 1834.875</td>
</tr>
<tr>
<td>pass isolation</td>
<td>311048.000 ± 1763.656</td>
</tr>
<tr>
<td>Δr-r/ξr ≥ -0.5</td>
<td>44457.000 ± 210.848</td>
</tr>
<tr>
<td></td>
<td>16926.000 ± 130.100</td>
</tr>
<tr>
<td></td>
<td>11659.000 ± 107.977</td>
</tr>
</tbody>
</table>

Table 56: Cutflow for data in 1-electron region.

Figure 12: From the Run 2 analysis internal note: signal cutflow for the unblinded 2 electron signal region (SR) and data cutflow for regions containing 1 electron in order to ensure unblinded SRs.

2.4.1 Timing Calibration and Cuts

This analysis uses a series of cuts inspired by those applied by the Run 2 analysis in Figure 12 and defined here.

- Pass trigger and exactly 1 baseline electron
  - Trigger topology is shown in Figure 13 and the requirements for baseline electron selection are shown in Figure 14.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>if ≥ e, pT &gt; 160 GeV</td>
<td>HLT_g146_loose</td>
</tr>
<tr>
<td>else if ≥ 2e, pT &gt; 60 GeV</td>
<td>HLT_2g50_loose</td>
</tr>
<tr>
<td>else if ≥ 1μ, pT &gt; 60 GeV,</td>
<td>HLT_mus60_geta0.5_msonly</td>
</tr>
</tbody>
</table>

Figure 13: Topology for triggers used in the cutflow, with HLT_g146_loose and HLT_2g50_loose used to cut on electron specific events.
Figure 14: Required cuts for baseline electron selection.

- $p_T > 65\text{GeV}$
  - Transverse momentum, the momentum in the x-y plane, must be greater than 65 GeV.
- $d_0 > 3\text{mm}$
  - The transverse impact parameter, the distance of closest approach of a particle’s track to the interaction point in the x-y plane, must be greater than 3 mm.
- Pass isolation
  - Isolation uses track and calorimeter based cuts, which determine the cone of activity around a lepton in order to identify signal leptons.
- $\Delta p_T/p_T \geq -0.5$
  - The difference between the electron $p_T$ and the electron track $p_T$ as a function of the electron $p_T$: $(p_T^{\text{track}} - p_T^e)/p_T^e$
- $\chi^2/ndf < 2$
  - The chi squared of the electron’s ID track divided by the number of degrees of freedom must be less than 2. This cut measures the accuracy of the track to ensure a good fit.
- Nmiss $\leq 1$
  - The number of missing tracking layers after the electron’s first track hit must be less than or equal to 1, helping to maintain a good-fitting track.

Figure 15 shows the timing calibration distributions for LRT electrons after each successive cut. 2018 output data, displayed in blue, represents the Standard Model background. The signal is plotted in red with 100 GeV MC simulation. The shift in the timing calibration illustrates the delay in the time that it takes for the signal to reach the calorimeter, compared to the distribution for prompt electrons, which would be centered at zero. As more events are eliminated with the cuts, the statistics to be plotted become diminished. For higher statistics, the timing calibration plots would be smoother, with less error. In addition, the electron decay used for signal has a 1 ns lifetime, which from Figure 11 has already been excluded from the displaced leptons search. With a longer lifetime, the signal region would likely be shifted more drastically. Overall, however, these plots for timing calibration are useful because they demonstrate the signal to be extracted with the cuts.
Figure 15: Timing calibration ($t_{\text{cal}}$) for LRT electrons, using both (100 Gev, 1 ns) signal (red) and 2018 output data (blue). Distributions are plotted after each consecutive cut.
The variable plots in Figure 16 show the distributions of the variables before they are used for cuts. From the $p_T$ plot, the two electron triggers HLT_g140_loose and HLT_2g50_loose from Figure 13 can be seen. The first peak in the distribution represents the events lost by the two electron HLT_2g50_loose trigger. The second peak is due to the one electron event HLT_g140_loose trigger. Once again, the plot for $d_0$ conveys higher values for LRT electrons than for prompt electrons, for which most events reside at low transverse impact parameter. The $\Delta p_T/p_T$ plot shows a large number of LRT electron events at low $\Delta p_T/p_T$, corresponding to a low $p_T^{\text{track}}$ contribution. Since the electron that is reconstructed comes from both the track and calorimeter cluster, a low transverse momentum contribution from the track means that the electron is more likely to be a "fake." The cut on $\Delta p_T/p_T \geq -0.5$ will reduce the number of fake electrons kept, while making sure that the track and cluster contributions for all events are well-matched. The distributions for chi squared/ndf and Nmiss help ensure the accuracy of the reconstructed electron track.

Figure 16: Distributions of cutflow variables before they are cut, with the exception of chi squared/ndf, which is plotted one cut earlier to maintain sufficient statistics. The plots display LRT electron events in red and prompt electron events in blue taken from 2018 output data.
2.4.2 Signal Cutflow

The tables in Figures 17, 18, and 19 all display cutflows for signal. These include the event yield and cut efficiency for each consecutive cut — that is, the number of events remaining after a cut divided by the total number of electron events after the initial "pass trigger and 2 baseline electrons" cut. The signal cutflow requires 2 baseline electrons rather than 1 because it is an unblinded analysis. Figure 17 shows the reproduced cutflow for 100 GeV MC simulation. The cut efficiency for LRT electrons is much higher, at 57.42%, than that for prompt electrons, which is only 2.78%. This is to be expected, as LRT electrons are more likely to be displaced leptons, the object that these cuts are optimized to find. The total signal efficiency of 60.19% is high, meaning that the cuts are effective in keeping signal. This high efficiency is due almost entirely to LRT electrons. The same cutflow for 700 GeV MC simulation is shown in Figure 17. Again, with high signal efficiency, mainly from LRT electrons, one can conclude that the LRT electron object greatly increases signal acceptance. For comparison, the signal cutflow from the Run 2 analysis is shown in Figure 19. Though a 300 GeV mass point was used — since neither 100 GeV, 1 ns nor 700 GeV, 1 ns simulations were available in the Run 2 analysis — signal acceptance is still similarly high.

![Figure 17](image1.png)

Reproduced signal cutflow using (100 GeV, 1 ns) MC simulation, divided by prompt, LRT, and total electron yields in addition to cut efficiencies.

![Figure 18](image2.png)

Reproduced signal cutflow using (700 GeV, 1 ns) MC simulation, divided by prompt, LRT, and total electron yields in addition to cut efficiencies.

---

(100 GeV, 1 ns) MC Signal

<table>
<thead>
<tr>
<th>Cut</th>
<th>Prompt Electron</th>
<th>LRT Electron</th>
<th>All Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield</td>
<td>Efficiency (%)</td>
<td>Yield</td>
</tr>
<tr>
<td>pass trigger and exactly 2 baseline electrons</td>
<td>9</td>
<td>8.33</td>
<td>99</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>9</td>
<td>8.33</td>
<td>93</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>7</td>
<td>6.48</td>
<td>91</td>
</tr>
<tr>
<td>pass isolation</td>
<td>5</td>
<td>4.63</td>
<td>91</td>
</tr>
<tr>
<td>Δpt/pt ≥ -0.5</td>
<td>3</td>
<td>2.78</td>
<td>64</td>
</tr>
<tr>
<td>chi2&lt; 2</td>
<td>3</td>
<td>2.78</td>
<td>62</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>3</td>
<td>2.78</td>
<td>62</td>
</tr>
</tbody>
</table>

Figure 17: Reproduced signal cutflow using (100 GeV, 1 ns) MC simulation, divided by prompt, LRT, and total electron yields in addition to cut efficiencies.

(700 GeV, 1 ns) MC Signal

<table>
<thead>
<tr>
<th>Cut</th>
<th>Prompt Electron</th>
<th>LRT Electron</th>
<th>All Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield</td>
<td>Efficiency (%)</td>
<td>Yield</td>
</tr>
<tr>
<td>pass trigger and exactly 2 baseline electrons</td>
<td>2</td>
<td>1.72</td>
<td>114</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>2</td>
<td>1.72</td>
<td>112</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>2</td>
<td>1.72</td>
<td>111</td>
</tr>
<tr>
<td>pass isolation</td>
<td>2</td>
<td>1.72</td>
<td>111</td>
</tr>
<tr>
<td>Δpt/pt ≥ -0.5</td>
<td>2</td>
<td>1.72</td>
<td>71</td>
</tr>
<tr>
<td>chi2&lt; 2</td>
<td>1</td>
<td>0.86</td>
<td>70</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>1</td>
<td>0.86</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 18: Reproduced signal cutflow using (700 GeV, 1 ns) MC simulation, divided by prompt, LRT, and total electron yields in addition to cut efficiencies.
Figure 19: Run 2 analysis signal cutflow using (300 GeV, 1 ns) MC simulation, divided by prompt, LRT, and total electron yields in addition to cut efficiencies.

2.4.3 Data Cutflow

The reproduced cutflow for data is displayed in Figure 20, with the original Run 2 cutflow that it was based upon shown in Figure 21. Notably, the first cut is for exactly 1 baseline electron, rather than the pair predicted by GMSB R-parity conserving SUSY, as a mechanism to blind the data. From these tables, there are two key takeaways. Firstly, the cut efficiencies for the Run 2 analysis and the new analysis are very similar. The final efficiencies are 0.30% and 0.33%, respectively. Therefore, the table in Figure 20 represents a successful reproduction of the Run 2 cutflow. Secondly, with such low final efficiencies, the cutflows are good at rejecting background — approximately 99.7%.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Yield</th>
<th>% Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>pass trigger and exactly 2 baseline electrons</td>
<td>145.338</td>
<td></td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>135.566</td>
<td>93.28</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>126.673</td>
<td>87.16</td>
</tr>
<tr>
<td>pass isolation</td>
<td>125.886</td>
<td>86.62</td>
</tr>
<tr>
<td>Δp/pt &gt;= -0.5</td>
<td>63.960</td>
<td>44.01</td>
</tr>
<tr>
<td>chi2 &lt; 2</td>
<td>57.063</td>
<td>39.20</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>52.976</td>
<td>36.38</td>
</tr>
</tbody>
</table>

Figure 20: Reproduced data cutflow using 2018 output data as background, with calculated cut efficiencies.
2.4.4 Final Cutflow

Figure 22 shows the aggregate of the signal and data cutflows for the Run 2 and new analyses. Overall, the cutflows present high signal efficiency and good background rejection. Crucially, with high cut efficiency, LRT electrons will increase the sensitivity of the new Run 3 analysis.

3 Conclusions and Next Steps

This study represents the exploratory phase of the Run 3 displaced leptons analysis. It began with the generation of Monte-Carlo simulation plots to understand fundamental signal behavior. The addition of LRT electrons and comparison between simulation and data allowed for further understanding of the signal region. Finally and most significantly, the Run 2 cutflow was able to be successfully reproduced. The cutflow demonstrates the improved signal acceptance from the LRT electron object in addition to good background elimination. The Run 3 analysis therefore seeks to further optimize the LRT electron definition. The new trigger efficiency study will work on lowering the $P_T$ requirement, which would open a new phase space to explore for LRT electrons. The addition of calorimeter timing information, unavailable in the previous analysis, will increase sensitivity and background rejection. Looking at calorimeter variables, such as $f_1$ and $f_3$, provides...
additional methodology to optimize the LRT electron object. Fundamentally, the new displaced leptons search will continue to invest in improving the algorithm and analysis to work with larger volumes of data, for applications to Run 3 and beyond.

4 Acknowledgements

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References


