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

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2022 REU Program at Columbia University - Nevis Labs
Outline

1. **Introduction**
   a. The Standard Model and Beyond
   b. Instrumentation for New Physics
      i. The LHC
      ii. The ATLAS Detector

2. **Search for Displaced Leptons**
   a. Motivation
   b. Monte-Carlo Simulation
   c. Added Motivation: LRT Electrons
   d. Run 2 Cutflow

3. **Conclusions and Next Steps**
The Standard Model of Particle Physics

- The Standard Model (SM) is a well-tested theory that encapsulates our best understanding of the fundamental constituents of this universe
  - Mathematical paradigm of a quantum field theory (QFT) that describes the particles and forces that constitute all physical phenomena

### Standard Model of Elementary Particles

**Fermions** - spin ½ particles that compose all matter
- **Leptons**
  - 3 generations of charged leptons (electron, muon, tau) and their electrically neutral neutrino counterparts
- **Quarks**
  - 3 “colors” (red, green, blue)
  - Building blocks for hadrons (e.g. protons, neutrons), which are “colorless” combinations of quarks

**Bosons** - spin 1 force-carrying particles
- **Gauge bosons**
  - Gluon - mediator for the strong nuclear force of quantum chromodynamics (QCD)
  - Photon - mediator for the electromagnetic force of quantum electrodynamics (QED)
  - W and Z bosons - mediators for the weak force
- **Higgs boson** - responsible for the interaction that gives a particle its mass
The Standard Model of Particle Physics

The Standard Model is an incomplete model of nature...

- Only 3 out of the 4 fundamental forces are included in the SM
  - Gravity, the weakest of the forces, is inconsistent with quantum mechanics and therefore missing from the SM
- Numerous parameters are only available experimentally
- Does not explain the existence of dark matter, which makes up ~85% of matter in the universe
- There is still the question of “grand unification” of the electroweak and strong forces
- The “hierarchy problem” or “fine-tuning” problem whereby extensive quantum corrections are applied to explain the Higgs mass
Beyond the Standard Model: **Supersymmetry**

- Supersymmetry (SUSY) aims to fill some of the gaps left open by the Standard Model.
- An extension of the SM:
  - Every particle has a supersymmetric partner differing in spin by $\frac{1}{2}$
  - e.g. every fermion has a boson “superpartner” and vice versa, a spin $\frac{1}{2}$ lepton has a paired “slepton” with integer spin 0.
- Well-motivated due to its ability to resolve inconsistencies of the SM.
- If SUSY exists, it must be a broken symmetry:
  - sparticles would not have the same mass as their partner particles.
  - If the sparticles did have the same mass (and so the only difference being spin), we would have found them already.
Arguably our best tool to search for new physics Beyond the Standard Model (BSM)...

The Large Hadron Collider (LHC)

- The LHC is the world’s most powerful particle accelerator, located at CERN (European Council for Nuclear Research) in Geneva, Switzerland
  - First started up in 2010 at 7.0 TeV (Run 1)
  - Upgraded to energies of 13.6 TeV (Run 3) on July 5, 2022
- “Large” = 27 km circumference
- “Hadron” = the kinds of particles the LHC accelerates, typically protons and ions
- “Collider” = two beams travelling in opposite directions, which collide at 4 points along the accelerator
- 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 (a.k.a. almost absolute zero)
The ATLAS Detector

- A Toroidal LHC ApparatuS (ATLAS) ... if you were wondering how they got the cool name
- The largest volume collider-detector ever built
- The layers of the detector consist of concentric cylinders around the interaction point
- Four major systems:
  - **Inner Detector** - measures direction, momentum, and charge of electrically charged decay products of pp collision
  - **Calorimeter** - measures the energy a particle loses as it moves through the detector
  - **Muon Spectrometer** - undetected by the inner detector and calorimeter, muons are identified and their momenta measured
  - **Magnet System** - superconducting magnets bend the trajectories of charged particles
- The ATLAS Collaboration has ~3000 authors from 181 institutions in 42 different countries
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   c. Added Motivation: LRT Electrons
   d. Run 2 Cutflow

3. Conclusions and Next Steps
The Search for Displaced Leptons: Motivation

- Many BSM theories include particles that, if produced at the LHC, can give rise to signals with displaced objects in the detector
- Under SUSY, pair-produced sleptons will each decay into a lepton and an undetectable gravitino (see Fig 1)
- Long-lived particles (LLP) (0.01 - 100 ns) beyond the Standard Model (BSM) produce displaced decay products
- Working with Gauge Mediated Symmetry Breaking (GMSB) R-parity conserving SUSY model
  - The nearly massless and also “invisible” gravitino is the lightest SUSY particle (LSP)
  - The next-to-lightest SUSY particle (NSLP) can become long-lived due to small gravitational coupling to the LSP
  - Well-motivated versions of this GMSB SUSY model have a slepton as an LLP

Figure 1: Illustration of the simplified model decay topology considered in this search. In this GMSB-inspired configuration sleptons, being selectrons (\(\tilde{e}\)), smuons (\(\tilde{\mu}\)) or staus (\(\tilde{\tau}\)), are pair produced and subsequently undergo direct decays to a lepton and a gravitino LSP.
The Search for Displaced Leptons: Motivation

- Usually, the search is for leptons that originate from the primary vertex
  - Instead, we are looking for leptons with “displaced decay vertices that do not trace back to the interaction point” (Run 2 Analysis) — **displaced leptons**
    - Why don’t they trace back?
      - The leptons are products of displaced long-lived slepton decay
      - Momentum is conserved in pp collision + gravitino is undetectable → “missing” momentum
- If displaced leptons are discovered, it would lend support to SUSY
- Focusing on the selectron case, with the displaced lepton being an electron with 2 unknown parameters: mass [GeV] and lifetime [ns]
Monte-Carlo Simulation

- Using Monte-Carlo simulated proton-proton collision events, analyze selectron decay variables
  - Monte-Carlo = repeated random sampling event generation, which implements GMSB SUSY model
- “Truth” level information gained through simulation lets us observe how the fundamental signal behaves
  - i.e. variables that can allow us to reject background while keeping the signal
- For 100 GeV selectron and assumed lifetime of 1 ns:
Added Motivation: Large Radius Track (LRT) Electrons

- ATLAS reconstruction software creates charged track objects from hits
- Large Radius Tracking (LRT) is an additional Inner Detector (ID) tracking pass that is run after standard tracking
  - Run on leftover hits with relaxed tracking cuts
  - Crucial to Long-Lived Particle (LLP) searches
    ○ (Joint Search Workshop: LRT Development (J.C. Burzynski))
- **Large Radius Track (LRT) electrons**
  - Do not trace back to the primary vertex
  - Important because they could be a displaced lepton
- New Run 3 triggers for displaced leptons
  - Versus Run 2 photon trigger
  - New triggers allow us to lower the transverse momentum (pt) requirement
    - So, new phase space to explore at lower pt, where many selectrons exist (see pt plot from previous slide)
    - Will allow us to better exploit the LRT electron object
      - ...by running the LRT algorithm on a specific set of events that pass the LRT trigger (Run 3 trigger)
LRT Electron Comparison Plots for MC Simulation and Data

- **Cuts** (*including same sign blinding*):
  - Electron pt > 20 GeV and electron energy > 5 GeV and leading electron charge = subleading electron charge
    - Same sign blinding
  - LRT electron pt > 20 GeV and LRT electron energy > 5 GeV and leading LRT electron charge = subleading LRT electron charge

- 100 GeV Monte-Carlo simulation
  - i.e. MC simulation for 100 GeV selectron with lifetime 1 ns
- 2018 output data

**Plotting variables from…**

- 100 GeV Monte-Carlo simulation
  - i.e. MC simulation for 100 GeV selectron with lifetime 1 ns
- 2018 output data

**d0 for 2018 Data and 100 GeV MC**

**NPixHits for 2018 Data and 100 GeV MC**

**NPixHits = the number of pixel hits** (*pixels reside in innermost detector layers*)

- Expect less from LRT electrons bc larger d0
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>404485.000 $\pm$ 2011.991</td>
</tr>
<tr>
<td>Require 1 electron</td>
<td>386300.000 $\pm$ 1965.452</td>
</tr>
<tr>
<td>$p_T &gt; 65$ GeV</td>
<td>382912.000 $\pm$ 1956.816</td>
</tr>
<tr>
<td>$</td>
<td>d_{0}</td>
</tr>
<tr>
<td>pass isolation</td>
<td>311048.000 $\pm$ 1763.656</td>
</tr>
<tr>
<td>$\Delta p_T/p_T &gt; -0.5$</td>
<td>44457.000 $\pm$ 210.848</td>
</tr>
<tr>
<td>$\sum E_T &lt; 2$</td>
<td>16926.000 $\pm$ 130.100</td>
</tr>
<tr>
<td>$N_{\text{miss}} \leq 1$</td>
<td>11659.000 $\pm$ 107.977</td>
</tr>
</tbody>
</table>

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

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-μμ in Table 55.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Slepton (mass [GeV], lifetime [ns])</th>
<th>Staus (mass [GeV], lifetime [ns])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass trigger and at least 2 baseline leptons</td>
<td>(100, 0.01)</td>
<td>(200, 0.1)</td>
</tr>
<tr>
<td>2 leading leptons are electrons</td>
<td>797.600 $\pm$ 61.973</td>
<td>250.145 $\pm$ 5.273</td>
</tr>
<tr>
<td>$p_T &gt; 65$ GeV</td>
<td>499.539 $\pm$ 48.710</td>
<td>145.338 $\pm$ 4.023</td>
</tr>
<tr>
<td>$</td>
<td>d_{0}</td>
<td>&gt; 3$ mm</td>
</tr>
<tr>
<td>both electrons pass isolation</td>
<td>162.546 $\pm$ 27.586</td>
<td>126.673 $\pm$ 3.748</td>
</tr>
<tr>
<td>$\Delta p_T/p_T &gt; -0.5$</td>
<td>158.394 $\pm$ 27.271</td>
<td>125.886 $\pm$ 3.736</td>
</tr>
<tr>
<td>$\sum E_T &lt; 2$</td>
<td>108.451 $\pm$ 22.454</td>
<td>63.960 $\pm$ 2.674</td>
</tr>
<tr>
<td>$N_{\text{miss}} \leq 1$</td>
<td>92.236 $\pm$ 20.837</td>
<td>57.063 $\pm$ 2.536</td>
</tr>
<tr>
<td>$\Delta R_{1,2} &gt; 0.2$</td>
<td>84.191 $\pm$ 20.077</td>
<td>52.876 $\pm$ 2.430</td>
</tr>
</tbody>
</table>

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

- The previous search for displaced leptons
  - PRL “Search for Displaced Leptons in $\sqrt{s}=13$ TeV pp Collisions with the ATLAS Detector” (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.051802)
- What’s new for the Run 3 analysis?
  - Better tools that will optimize the LRT Electron object for better signal acceptance
    - Run 3 trigger
    - Calorimeter timing information
  - More data gained from Run 3 (soon!)
- Idea for now: using the same cuts and variables from the Run 2 analysis, reproduce the cutflow for data and signal
Timing Calibration and Cuts

- Pass trigger and exactly 1 baseline electron
  - Triggers are used to select events in data containing electrons
- Pt > 65 GeV
  - Transverse momentum, i.e. momentum in the x-y plane

- Peaks in pt plot come from requiring the event to pass our two triggers (HLT_g140_loose and HLT_2g50_loose)
- Shift in timing cal plot shows delay
  - Not shifted much as we would like, would need longer lifetime (currently 1 ns)
Timing Calibration and Cuts

- **$d_0 > 3$ mm**
  - Transverse impact parameter, i.e., the distance of closest approach of the particle's track to the interaction point in the x-y plane
- **Pass isolation**
  - Isolation uses track and calorimeter based cuts, which determine the cone of activity around a lepton, 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 fraction of the electron $p_T$
  - Electron that is reconstructed comes from track and calorimeter cluster → want these to be well matched
    - High $\Delta p_T/p_T$ → high $p_T$ track contribution
    - Low $\Delta p_T/p_T$ → low $p_T$ track contribution, electron more likely to be a “fake”

\[ \frac{(p_T^{\text{track}} - p_T^e)}{p_T^e} \]

**$d_0$ before $d_0 > 3$ mm cut**

**$\Delta p_T/p_T$ before $\Delta p_T/p_T \geq -0.5$ cut**
Timing Calibration and Cuts

- chiSq/ndf<2
  - The chi squared of the electrons ID track divided by # of degrees of freedom
  - Measures the accuracy of the track

- Nmiss <= 1
  - The number of missing tracking layers after the electron track’s first hit

Chi Squared/ndf before ChiSq/ndf<2 cut

Nmiss before Nmiss<2 cut
### 100 GeV Signal Cutflow

<table>
<thead>
<tr>
<th>Cut</th>
<th>Prompt Electron</th>
<th>LRT Electron</th>
<th>All Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Efficency (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</td>
<td>9</td>
<td>99</td>
<td>108</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>9</td>
<td>93</td>
<td>102</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>7</td>
<td>91</td>
<td>98</td>
</tr>
<tr>
<td>pass isolation</td>
<td>5</td>
<td>91</td>
<td>96</td>
</tr>
<tr>
<td>Δpt/pt &gt;= -0.5</td>
<td>3</td>
<td>64</td>
<td>67</td>
</tr>
<tr>
<td>chiSq &lt; 2</td>
<td>3</td>
<td>62</td>
<td>65</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>3</td>
<td>62</td>
<td>65</td>
</tr>
</tbody>
</table>

Run 2 Analysis for 300 GeV and 1 ns

<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>135.565</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>Δpt/pt &gt;= -0.5</td>
<td>63.960</td>
<td>44.44</td>
</tr>
<tr>
<td>chiSq &lt; 2</td>
<td>57.063</td>
<td>39.26</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>52.876</td>
<td>36.38</td>
</tr>
</tbody>
</table>

- Much higher cut efficiency for LRT electrons than for prompt electrons
- Total signal efficiency is high, i.e. keeping a lot of signal
  - Almost entirely from LRT electrons
700 GeV Signal Cutflow

<table>
<thead>
<tr>
<th>Cut</th>
<th>Prompt Electron</th>
<th>LRT Electron</th>
<th>All Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>Efficiency (%)</td>
<td>Yield</td>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</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 &gt;= -0.5</td>
<td>2</td>
<td>1.72</td>
<td>71</td>
</tr>
<tr>
<td>chiSq &lt; 2</td>
<td>1</td>
<td>0.86</td>
<td>70</td>
</tr>
<tr>
<td>Νmiss &lt;= 1</td>
<td>1</td>
<td>0.86</td>
<td>70</td>
</tr>
</tbody>
</table>

(Similar to 100 GeV signal)

- Much higher cut efficiency for LRT electrons than for prompt electrons
- Total signal efficiency is high, i.e. keeping a lot of signal
  - Almost entirely from LRT electrons
## Data Cutflow

<table>
<thead>
<tr>
<th>2018 Data</th>
<th>Run 2 Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut</td>
<td>Total Yield</td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</td>
<td>6356</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>5617</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>5087</td>
</tr>
<tr>
<td>pass isolation</td>
<td>4900</td>
</tr>
<tr>
<td>Δpt/pt &gt;= -0.5</td>
<td>48</td>
</tr>
<tr>
<td>chiSq &lt; 2</td>
<td>22</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Yield</td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</td>
<td>3863003</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>3829127</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>3366766</td>
</tr>
<tr>
<td>pass isolation</td>
<td>3110484</td>
</tr>
<tr>
<td>Δpt/pt &gt;= -0.5</td>
<td>44457</td>
</tr>
<tr>
<td>chiSq &lt; 2</td>
<td>16926</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>11659</td>
</tr>
</tbody>
</table>

- Very similar efficiencies for new data analysis and Run 2 data cutflow
  - Successful reproduction of Run 2 analysis
- Efficiency 0.33% → rejecting 99.67%
  - The analysis is good at rejecting background!
### Final Cutflow

<table>
<thead>
<tr>
<th>Cut</th>
<th>(100 GeV, 1 ns) Signal</th>
<th>(700 GeV, 1 ns) Signal</th>
<th>2018 Data [background]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Yield</td>
<td>Total Efficiency (%)</td>
<td>Total Yield</td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</td>
<td>108</td>
<td>116</td>
<td>6356</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>102</td>
<td>94.44</td>
<td>114</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>98</td>
<td>90.74</td>
<td>113</td>
</tr>
<tr>
<td>pass isolation</td>
<td>96</td>
<td>88.89</td>
<td>113</td>
</tr>
<tr>
<td>Δpt/pt &gt;= -0.5</td>
<td>67</td>
<td>62.04</td>
<td>73</td>
</tr>
<tr>
<td>χ² &lt; 2</td>
<td>65</td>
<td>60.19</td>
<td>71</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>65</td>
<td>60.19</td>
<td>71</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut</th>
<th>(300 GeV, 1 ns) Signal</th>
<th>2018 Data [background]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Yield</td>
<td>Total Efficiency (%)</td>
</tr>
<tr>
<td>pass trigger and exactly 1 baseline electron</td>
<td>145.338</td>
<td>3863003.00</td>
</tr>
<tr>
<td>pt &gt; 65 GeV</td>
<td>135.565</td>
<td>3829127.00</td>
</tr>
<tr>
<td>d0 &gt; 3 mm</td>
<td>126.673</td>
<td>3366766.00</td>
</tr>
<tr>
<td>pass isolation</td>
<td>125.886</td>
<td>3110484.00</td>
</tr>
<tr>
<td>Δpt/pt &gt;= -0.5</td>
<td>63.960</td>
<td>44457.00</td>
</tr>
<tr>
<td>χ² &lt; 2</td>
<td>57.063</td>
<td>16926.00</td>
</tr>
<tr>
<td>Nmiss &lt;= 1</td>
<td>52.876</td>
<td>11659.00</td>
</tr>
</tbody>
</table>

### In conclusion…

- High signal efficiency, good background rejection
- With high cut efficiency, LRT electrons will increase sensitivity of new analysis
  - Why?
    - Will be better able to pick out LRT objects with Run 3 trigger
    - Reach lower pt thresholds on our triggers with LRT → explore new phase space
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Conclusions and Next Steps

✓ Generated Monte-Carlo Simulation plots to understand fundamental signal behavior
✓ Added LRT electrons and generated comparison plots with Monte-Carlo and Run 2 data
✓ Successfully reproduced the Run 2 cutflow:
  o Demonstrated behavior of variables being cut
  o Observed better signal acceptance with the LRT electron object
  o Good background rejection with the data cutflow

This study represents the “exploratory phase” of the Run 3 displaced leptons analysis… there is still much to be done!

● Further optimize the LRT electron definition by:
  o Addition of the Run 3 trigger
    ■ work on lowering the cut on transverse momentum (pt) with trigger efficiency study to explore new phase space for LRT electrons
  o Planning to add calorimeter timing info to Run 2 result for increased sensitivity and background rejection
    ■ i.e. Run 2 did not consider the time the signal arrived in the calorimeter
  o looking at calorimeter variables (such as f1 and f3, see backup)

● Continue to invest in improving the algorithm and analysis to work with much more data
  o Apply to Run 3 — and beyond!

★ LRT electrons will increase signal sensitivity of the Run 3 analysis!


Acknowledgements

- The research group:
  - The ATLAS Collaboration and the Columbia ATLAS group
  - My fellow REUs who I’m glad I have gotten to know over the past 10 weeks
  - Everyone at Nevis who made this REU possible, with special thanks to John, Georgia, and Amy
  - The National Science Foundation (NSF) for funding this research under Grant No. PHY/1950431

Faculty Mentor: John Parsons

Postdoctoral Researcher: Julia Gonski

Graduate Students: Andrew Smith and Eleanor Woodward

Thank you!
Questions?
LRT Electron Comparison Plots for MC Simulation and Data

- $f_1 =$ the energy deposited by the electron at the first layer of the calorimeter
- $f_3 =$ the energy deposited by the electron at the third layer of the calorimeter

"f1 for 2018 Data and 100 GeV MC"

"f3 for 2018 Data and 100 GeV MC"