Search for lepton number violating supersymmetry with the ATLAS experiment at the LHC

Dominik Krauss

Max Planck Institute for Physics

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Content

- Standard Model and its limitations
- Introduction to Supersymmetry and R-Parity
- Short recap of the ATLAS experiment
- Search for final states with four leptons
- Search for displaced vertices with two leptons
- Summary
The Standard Model (SM)

Describes the electromagnetic, weak and strong interactions

Interactions mediated by gauge bosons

Matter made of fermions (leptons and quarks)

Mass generation of particles explained by Higgs mechanism
(Some) Limitations of the Standard Model

- Dark matter
- Grand unification
- Neutrino masses
- Hierarchy problem

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Higgs boson only fundamental scalar (spin 0) particle in SM

Every scalar particle receives corrections to its mass:

\[ f H \]

Example: Fermion loop

Corrections \( \Delta m_H \propto \) energy scale up to which SM is valid

If no new physics up to \( M_{\text{Planck}} \approx 10^{19} \) GeV (when gravity becomes strong)

\( \rightarrow m_H \approx 10^{19} \) GeV

Measured \( m_H = 125 \) GeV
Mighty supersymmetry

First discussed in 1971

Symmetry between fermions and bosons

Able to solve some of the open questions

Minimal supersymmetric extension of SM (MSSM) adds over 100 new parameters

Gigantic parameter space to be probed in LHC searches
- SUSY operator: $\hat{Q} |\text{fermion}\rangle = |\text{boson}\rangle$ and vice versa
- Lagrangian of SUSY theory invariant under SUSY transformations
- Introduces partners to all SM particles
- Spins of partners differ by 1/2
- Other quantum numbers are the same
- Superpartner masses have to be different (otherwise already observed)
  $\Rightarrow$ SUSY is broken
Four additional Higgs bosons

Superpartners of electroweak gauge bosons and higgs bosons mix to neutralinos $\tilde{\chi}^0$ and charginos $\tilde{\chi}^\pm$

Sfermions are scalar particles
Solution to the Hierarchy Problem

\[ \Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda^2 + \ldots \]

\[ \Delta m_H^2 = +\frac{\lambda_S}{16\pi^2} \Lambda^2 + \ldots \]

- SUSY introduces scalar bosons to every SM fermion
  → Corrections cancel exactly in unbroken supersymmetry
  → Higgs boson remains light

- MSSM: Soft SUSY breaking
  → Only \( \ln \Lambda \) dependence
• SUSY allows unification of the three SM interactions around an energy of $10^{16}$ GeV

• Many candidates for a grand unified theory like string theory include SUSY
MSSM Lagrangian allows lepton and baryon number violating terms

Violation of both quantum numbers allows fast proton decay:

\[ p \left\{ \begin{array}{c} d \\
\bar{u} \\
u \\
u \\
u \\
\end{array} \right. \\
\left\{ \begin{array}{c} \lambda''_{112} \\
\lambda'_{112} \\
\bar{u} \\
u \\
u \\
\end{array} \right\} e^+ \pi^0 \]

Multiplicative quantum number R-parity:

\[ R_p = (-1)^{3(B-L)+2s} : R_p(\text{SUSY}) = -1 \text{ and } R_p(\text{SM}) = 1 \]

Consequences of R-parity conservation:

- Lepton and baryon number conserved \(\rightarrow\) no proton decay
- SUSY particles produced in pairs
- Lightest supersymmetric particle (LSP) stable \(\rightarrow\) dark matter candidate if neutral
R-parity violation

- Only lepton or baryon number is violated $\rightarrow$ no proton decay
- Introduce symmetry allowing only one violation (several possibilities)
- Differences to R-parity conservation:
  - Single production of SUSY particles possible (but usually not considered)
  - LSP decays to SM particles (no dark matter candidate anymore):

$$\tilde{\nu}^* \mu / \tilde{\nu}^* \ne$$
$$\tilde{\chi}^0_1$$
$$\tilde{\nu}_\mu / \tilde{\nu}_e$$

- Neutrinos can mix with Neutralinos and gain masses
- R-parity violation not ruled out by experimental observations
  $\rightarrow$ Important to search for it!
The dashed tracks are invisible to the detector.
Example SUSY model with lepton number violation:

Experimental signature determined by lifetime \( \tau \) of \( \tilde{\chi}_1^0 \):

- \( \tau < 1 \) ps: Four leptons in primary proton-proton collision
- \( 1 \) ps \(< \tau < 1 \) ns: Displaced vertices with two leptons
- \( \tau > 100 \) ns: No leptons inside detector, instead missing energy

In the following: First two cases considered
Search for final states with four leptons

- Search for events with at least four charged leptons
- Only electrons and muons, taus considered in future

Signal model considered for preliminary run 2 results
Two signal regions:

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$N(e, \mu)$</th>
<th>$Z$ boson</th>
<th>$m_{\text{eff}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRA</td>
<td>$\geq 4$</td>
<td>veto</td>
<td>$&gt; 600$</td>
</tr>
<tr>
<td>SRB</td>
<td>$\geq 4$</td>
<td>veto</td>
<td>$&gt; 900$</td>
</tr>
</tbody>
</table>

$Z$ boson veto: $|m(\ell^+ \ell^-) - m(Z)| < 10$ GeV

Low mass veto: $m(\ell^+ \ell^-) < 4$ GeV and $|m(\ell^+ \ell^-) - m(\Upsilon)| < 1$ GeV

$m_{\text{eff}} = \sum_{\text{signal leptons}} p_T + \sum_{\text{jets with } p_T > 40 \text{ GeV}} p_T + E_T^{\text{miss}}$

- Very good discriminator between background and signal
- Much larger for signal due to high masses of SUSY particles
Background processes

Irreducible background: SM processes with four leptons in the final state

- $ZZ$, $t\bar{t}Z$, $VVZ$, Higgs and many others
- Many processes include $Z$ boson decays $\rightarrow Z$ veto important to lower background

Reducible background: At least one of the four leptons is fake

- Origin of fake leptons: Semileptonic $b$ and $c$ hadron decays, misidentification of jets or photon conversions
- Dominated by $t\bar{t}$
<table>
<thead>
<tr>
<th>Signal region</th>
<th>SRA</th>
<th>SRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irreducible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>0.6 ± 0.4</td>
<td>0.20 ± 0.19</td>
</tr>
<tr>
<td>t\bar{t}Z</td>
<td>1.43 ± 0.23</td>
<td>0.47 ± 0.09</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.4 ± 0.4</td>
<td>0.11 ± 0.11</td>
</tr>
<tr>
<td>VVZ</td>
<td>0.31 ± 0.06</td>
<td>0.123 ± 0.027</td>
</tr>
<tr>
<td>Others</td>
<td>0.32 ± 0.04</td>
<td>0.181 ± 0.022</td>
</tr>
<tr>
<td>1-fake \ell reducible</td>
<td>0.168 ± 0.018</td>
<td>0.069 ± 0.014</td>
</tr>
<tr>
<td>2-fake \ell reducible</td>
<td>0.48 ± 0.24</td>
<td>0.11 ± 0.05</td>
</tr>
<tr>
<td>Σ SM</td>
<td>3.6 ± 0.6</td>
<td>1.26 ± 0.26</td>
</tr>
</tbody>
</table>

- t\bar{t}Z dominant background
- Very low total background
Preliminary run 2 results

- Two events observed in SRA and zero events in SRB
- Very good agreement with prediction
- $\tilde{\chi}_1^\pm$ excluded up to 1.1 TeV
Search for displaced vertices with two leptons

- Search for long-lived neutral particles decaying to at least two leptons
- Sensitive to lifetimes of order ps to ns
- Only electrons and muons
Displaced vertex with at least two leptons

- \( r_{DV} < 300 \text{ mm} \) and \(|z_{DV}| < 300 \text{ mm}\)

- Displacement: 4 mm in transverse (xy) plane to all PVs

- Material veto using 3D detector map

- \( m_{DV} > 10 \text{ GeV} \)

- Oppositely charged leptons
Selection efficiency

- Selection efficiency for two choices of sparticle masses:

\[ \tau_c \]

\[ \tau_c \]

\[ 1 \quad 10^2 \quad 10^3 \quad 10^4 \]

- Vertex-level efficiency

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.1</th>
<th>0.12</th>
<th>0.14</th>
<th>0.16</th>
<th>0.18</th>
<th>0.2</th>
<th>0.22</th>
<th>0.24</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m(\tilde{q}) = 700 \text{ GeV}, m(\tilde{\chi}_1^0) = 50 \text{ GeV} )</td>
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</table>

\[ \tilde{q} \to q[\tilde{\chi}_1^0 \to \mu \mu \nu] \]

- Reconstruction of displaced vertices challenging \( \rightarrow \) Low efficiencies

- Light long-lived particles especially challenging
Random crossing of unrelated leptons forming a vertex

Estimation done using data:
- Select random combinations of leptons from different events and perform vertexing
  → Gives probability $p$ that a random crossing forms a vertex
- Count number of lepton pairs $N_{\ell\ell}$ in data
- Estimate $= N_{\ell\ell} \cdot p$

Validation using vertices with two non-leptonic tracks:
Plots show results and limits for $\mu\mu$ vertices

No ee, $e\mu$ or $\mu\mu$ vertex observed (background expectation $\approx 10^{-3}$ vertices)
• SUSY addresses many important open questions in particle physics
• Two types of SUSY (R-parity conserved or not)
• Important to search for both cases
• SUSY not found yet at the LHC
• Plenty of room for SUSY to hide