Searches for charginos and neutralinos in final states with many leptons using the ATLAS detector

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on behalf of the ATLAS collaboration
# Overview of SUSY electroweak searches in ATLAS

<table>
<thead>
<tr>
<th>Topic</th>
<th>Reference</th>
</tr>
</thead>
</table>

**New!**: in this talk
2- or 3-lepton (e, μ) final states
Motivation and strategy

Search for the production of pair-produced electroweakinos, decaying via W and Z bosons to produce final states with 2 or 3 light charged leptons (e, μ):

A recursive jigsaw reconstruction (RJR) is employed to extract a basis of complementary variables that are used to optimize the search.
Recursive jigsaw in a nutshell

A method for decomposing measured properties event-by-event to provide a basis of kinematic variables.

→ Achieved by approximating the rest frames of intermediate particle states in each event.

→ A natural basis of kinematic observables calculated by recursively evaluating the momentum and energy of different objects in these reference frames.

Reconstructed objects: leptons, jets, $E_T^{\text{miss}}$ as input

Set of kinematic observables discriminating $S$ from $B$
Signal regions (SR) in both the 2l and 3l channel are designed to be sensitive to High, Intermediate and Low mass splittings.

Dedicated regions with an ISR-system of jets provide an orthogonal region to the low mass to enhance the reach.

Validation and control regions close to the SR demonstrate a good data/MC agreement → gives confidence in background estimation methods.

$m_{\text{eff}}$-like RJR observable in a VV CR.
Results

- Main background contribution is from $VV$ (3L), $VV$ + $Z$+jets (2L).
- Expected and observed yields are compatible in most regions.
- Mild excesses are seen in 4 SRs all targeting the low mass splitting.

Local significance:

- $2L$: 1.4$\sigma$
- $3L$: 2.0$\sigma$, 2.1$\sigma$, 3.0$\sigma$
Statistical interpretation - upper limits

2L/3L search with RJR

2L/3L alternative search
Multi-lepton (e, μ, τ) final states
RPV scenarios (L-violated term)

LSP is a bino-like neutralino:

- $\tilde{\chi}^0_1$ decays via RPV interaction $\tilde{\chi}^0_1 \rightarrow \ell^+_k \ell^+_i / \nu^+_j / \nu^+_i$
- mediated by L-number-violating term

$$W_{LLE} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k$$

9 Yukawa $\lambda$ couplings

<table>
<thead>
<tr>
<th>Two scenarios with $\lambda^{12k}$ and $\lambda^{i33}$ coupling</th>
<th>$k/i = 1$</th>
<th>$k/i = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LL\bar{E}12k$ ($k \in 1, 2$)</td>
<td>$\lambda^{12k}$</td>
<td>$e_\mu e_\mu e_\mu$</td>
</tr>
<tr>
<td>$LL\bar{E}i33$ ($i \in 1, 2$)</td>
<td>$\lambda^{i33}$</td>
<td>$e_T \nu / \tau_T \nu_\tau$</td>
</tr>
</tbody>
</table>

Gluino-pair decay

Wino-like chargino & neutralino decay

lepton SU(2) doublets

lepton SU(2) singlet
RPC scenarios

Mass-degenerate higgsino triplet motivated by naturalness.

General Gauge Mediated (GGM) SUSY models predict the gravitino is nearly massless → possibility to study light higgsinos!

Higgsinos $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \tilde{\chi}_2^0$ can decay to gravitinos giving rise to final states with many leptons.
## Signal Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>$N(e, \mu)$</th>
<th>$N(\tau_{\text{had-vis}})$</th>
<th>$p_T (\tau_{\text{had-vis}})$</th>
<th>Z boson</th>
<th>Selection</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR0A</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &gt; 600$ GeV</td>
<td>General</td>
</tr>
<tr>
<td>SR0B</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &gt; 1100$ GeV</td>
<td>RPV $LLE12k$</td>
</tr>
<tr>
<td>SR0C</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>require 1st &amp; 2nd SFOS</td>
<td>$E^\text{miss}_T &gt; 50$ GeV</td>
<td>higgsino GGM</td>
</tr>
<tr>
<td>SR0D</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>require 1st &amp; 2nd SFOS</td>
<td>$E^\text{miss}_T &gt; 100$ GeV</td>
<td>higgsino GGM</td>
</tr>
<tr>
<td>SR1</td>
<td>$= 3$</td>
<td>$\geq 1$</td>
<td>$&gt; 30$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &gt; 700$ GeV</td>
<td>RPV $LLEi33$</td>
</tr>
<tr>
<td>SR2</td>
<td>$= 2$</td>
<td>$\geq 2$</td>
<td>$&gt; 30$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &gt; 650$ GeV</td>
<td>RPV $LLEi33$</td>
</tr>
</tbody>
</table>

\[
m_{\text{eff}} = \sum_{\ell=e, \mu, \tau} p_T(\ell) + \sum_{p_T(j) > 40 \text{ GeV}} p_T(j) + E^\text{miss}_T
\]

Classification according to number of signal light charged leptons (L) or taus (T).

**Z requirement:** any combination $1^{\text{st}}$ SFOS $81.2 < m_{LL} < 101.2$ GeV, $2^{\text{nd}}$ SFOS $61.2 < m_{LL} < 101.2$ GeV

**Z veto:** any combination SFOS $81.2 < m_{LL} < 101.2$ GeV
Background estimation

Irreducible background

- Processes with four or more leptons in the final state
- e.g. ZZ, ttZ, VVZ (V = Z, W), ttWW, 4t, Higgs
- Estimated from Monte Carlo simulation

Reducible background

- Processes with at least one fake lepton
- e.g. tt, Z + jets
- Estimated with a data-driven “fake-factor” method
### Background modeling validation

The general modeling of the irreducible and reducible backgrounds is tested in VRs:

<table>
<thead>
<tr>
<th>Validation Region</th>
<th>$N(e,\mu)$</th>
<th>$N(\tau_{\text{had-vis}})$</th>
<th>$p_T(\tau_{\text{had-vis}})$</th>
<th>Z boson</th>
<th>Selection</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR0</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &lt; 600$ GeV</td>
<td>$t\bar{t}$, $Z+$jets, $ZZ$</td>
</tr>
<tr>
<td>VR0Z</td>
<td>$\geq 4$</td>
<td>$= 0$</td>
<td>$&gt; 20$ GeV</td>
<td>require 1st &amp; veto 2nd</td>
<td>–</td>
<td>ZZ</td>
</tr>
<tr>
<td>VR1</td>
<td>$= 3$</td>
<td>$\geq 1$</td>
<td>$&gt; 30$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &lt; 700$ GeV</td>
<td>$t\bar{t}$, $Z+$jets</td>
</tr>
<tr>
<td>VR2</td>
<td>$= 2$</td>
<td>$\geq 2$</td>
<td>$&gt; 30$ GeV</td>
<td>veto</td>
<td>$m_{\text{eff}} &lt; 650$ GeV</td>
<td>$t\bar{t}$, $Z+$jets</td>
</tr>
</tbody>
</table>

*Inclusive $p_T(e,\mu)$ distribution in VR0*
Signal region distributions

2.3σ excess in SR0D

RPV models

GGM models
Exclusion limit contours - RPV

Low $m_{\text{NLSP}}$: sensitivity loss due to collimated di-taus

**RPV Wino W/Z NLSP**

**RPV Gluino NLSP**
Exclusion limit contours - Higgsino

$\tilde{\chi}_1^\pm$ masses $< 103$ GeV excluded by LEP.
Synopsis

Numerous efforts in ATLAS searching for SUSY in the electroweak sector.

Selected results for searches focusing on final states with many leptons were presented.

No hints for supersymmetry seen so far, few mild excesses observed though

- RPV: $m_{\text{NLSP}} \lesssim 1.5 \text{ TeV}$ (wino), $1.05 \text{ TeV}$ (slepton), $2.3 \text{ TeV}$ (gluino)
- GGM RPC: $m_{\text{NLSP}} \lesssim 300 \text{ GeV} \ @ \ BR(\tilde{\chi}_1^0 \to Z) = 100\%$ (higgsino)

Aim to exploit the entire LHC dataset $\sim 140 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$ for more exploration and to shed light on the excesses observed.
“Search for chargino-neutralino production using recursive jigsaw reconstruction in final states with two or three charged leptons in proton-proton collisions at 13 TeV with the ATLAS detector.”

arXiv:1806.02293

“Search for supersymmetry in events with four or more leptons in $\sqrt{s}=13$ TeV pp collisions with ATLAS”

arXiv:1804.03602

“Search for higgsino pair production in the hh topology in final states with ≥3b-jets using the ATLAS detector in $\sqrt{s}=13$TeV pp collisions”

arXiv:1806.04030
Auxiliary Material
In the Minimal Supersymmetric Standard Model (MSSM), baryon number (B) and lepton number (L) are no longer conserved by all of the renormalizable couplings in the theory.

B and L conservation have been tested very precisely (proton lifetime) → MSSM couplings need to be very small in order not to be in conflict with experimental data.

R-parity symmetry introduced to act on the MSSM fields that forbids these couplings

\[ R = (-1)^{3(B-L)+2S} \]  \( (S= \text{spin}) \)

**Standard Model particles:** R-parity = +1

**Supersymmetric particles:** R-parity = −1 (sparticles in pairs)

**RPC models:** Lightest Supersymmetric Particle (LSP) stable, neutral, weakly interacting, feels gravity, massive (0.1-1 TeV) → DM candidate (WIMP)

**RPV models:** motivated by fact that proton decay involves violating both L and B number simultaneously, conserving either B or L in the Lagrangian → LSP allowed to decay

**Canonical signature of SUSY events:** cascade decays, large particle multiplicity, substantial missing (transverse) momentum (RPC)
RPV electroweak or strong models

Simplified models

(a) Wino W/Z NLSP

(b) Wino W/h NLSP

(c) $\tilde{\ell}_L/\tilde{\nu}$ NLSP

(d) $\tilde{g}$ NLSP
Exclusion limit contours - RPV

Low $m_{\text{NLSP}}$: sensitivity loss due to collimated di-taus

(a) RPV wino $W/Z$ NLSP

(b) RPV wino $W/h$ NLSP
Exclusion limit contours - RPV

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

4 lepton

- **Observed** (\( \pm 1 \sigma_{\text{exp}} \))
- **Expected** (\( \pm 1 \sigma_{\text{exp}} \))

\( \lambda_{132} = 0 \)
\( \lambda_{123} = 0 \)

(c) RPV \( \tilde{\ell}_{L}/\tilde{\nu} \) NLSP

(d) RPV \( \tilde{g} \) NLSP
4L Retrospect

- **SUSY-2013-13**
  - 8 TeV, 20.3/fb
  - Wino masses excluded up to 750 GeV

- **SUSY-2016-21**
  - ICHEP 2018
  - 13 TeV, 36.1/fb
  - Wino masses excluded up to 1.4 TeV

- **ATLAS-CONF-2016-075**
  - ICHEP 2016
  - 13 TeV, 13.3/fb
  - Wino masses excluded up to 1.1 TeV
Object selection

<table>
<thead>
<tr>
<th>p_T</th>
<th>Electron</th>
<th>Muon</th>
<th>Tau</th>
<th>Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 7 GeV</td>
<td>&gt; 5 GeV</td>
<td>&gt; 20 GeV</td>
<td>&gt; 20 GeV</td>
</tr>
<tr>
<td></td>
<td>&lt; 2.47</td>
<td>&lt; 2.7</td>
<td>&lt; 2.47</td>
<td>&lt; 2.8</td>
</tr>
</tbody>
</table>

→ Electrons, muons: isolated, medium ID

→ Hadronic taus: 1/3-prong, medium BDT ID

→ Single- and di-lepton triggers employed

→ Mixed-flavor triggers as well, highly efficient for signal events (99% for μ, 96% for e).

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Offline p_T threshold [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Single isolated e</td>
<td>25</td>
</tr>
<tr>
<td>Single non-isolated e</td>
<td>61</td>
</tr>
<tr>
<td>Single isolated μ</td>
<td>21</td>
</tr>
<tr>
<td>Single non-isolated μ</td>
<td>41</td>
</tr>
<tr>
<td>Double e</td>
<td>13, 13</td>
</tr>
<tr>
<td>Double μ (symmetric)</td>
<td>–</td>
</tr>
<tr>
<td>(asymmetric)</td>
<td>19, 9</td>
</tr>
<tr>
<td>Combined eμ</td>
<td>8(e), 25(μ)</td>
</tr>
</tbody>
</table>
Main discriminant variables

\[ E_\text{miss}^{T} \]

\[ m_{\text{eff}} = \sum_{\ell = e, \mu, \tau} p_T(\ell) + \sum_{p_T(j) > 40 \text{ GeV}} p_T(j) + E_\text{miss}^{T} \]

Thresholds are chosen to be optimal for the RPV/RPC scenarios with different NLSPs considered in the analysis.
Background modeling validation

<table>
<thead>
<tr>
<th>Sample</th>
<th>VR0</th>
<th>VR0Z</th>
<th>VR1</th>
<th>VR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>132</td>
<td>365</td>
<td>116</td>
<td>32</td>
</tr>
<tr>
<td>SM Total</td>
<td>123 ± 11</td>
<td>334 ± 52</td>
<td>91 ± 19</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>ZZ</td>
<td>65 ± 7</td>
<td>234 ± 23</td>
<td>8.8 ± 1.0</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td>t\bar{t}Z</td>
<td>3.9 ± 0.6</td>
<td>10.5 ± 1.5</td>
<td>1.76 ± 0.25</td>
<td>0.60 ± 0.10</td>
</tr>
<tr>
<td>Higgs</td>
<td>5 ± 4</td>
<td>43 ± 37</td>
<td>3.2 ± 2.9</td>
<td>1.3 ± 1.2</td>
</tr>
<tr>
<td>VVV</td>
<td>2.9 ± 0.6</td>
<td>16.1 ± 3.4</td>
<td>1.23 ± 0.27</td>
<td>0.29 ± 0.07</td>
</tr>
<tr>
<td>Reducible</td>
<td>46 ± 7</td>
<td>28 ± 26</td>
<td>76 ± 19</td>
<td>22 ± 6</td>
</tr>
<tr>
<td>Other</td>
<td>0.40 ± 0.07</td>
<td>2.7 ± 0.5</td>
<td>0.34 ± 0.06</td>
<td>0.16 ± 0.04</td>
</tr>
</tbody>
</table>

Other = tWZ, tWtW, 4t

→ No significant excesses above the SM expectations are observed in any VR.
Background modeling validation

Downward trend due to leading electron
(SR0A/B require high $m_{eff}$)

Insignificant (~1.5σ)
Background modeling validation

(c) $p_T (e, \mu)$ in VR0Z

(d) $E_T^{miss}$ in VR0Z
Background modeling validation

(a) $p_T (e, \mu)$ in VR1

(b) $p_T (\tau_{\text{had-\text{vis}}})$ in VR1
Background modeling validation

(c) $p_T (e, \mu)$ in VR2

(d) $p_T (\tau_{had-vis})$ in VR2
Background modeling validation

VR0Z
$E_T^{\text{miss}}$

VR0
$p_T(e, \mu)$

VR1
$p_T(\tau)$

VR2
$p_T(e, \mu)$
Systematic uncertainties

Theoretical uncertainties:
→ $\mu_R$, $\mu_F$, PDF
→ Cross section
- 12% ttZ
- 6% ZZ
- 20% VVV
- 20% VH/VBF Higgs
- 100% ttH, ggH
(acceptance)

$E_T^{miss}$ selection affected by jet systematics, otherwise theory (ZZ) or fake background uncertainties dominated.
Expected and observed yields

Consistent with the SM expectations within a local significance of at most 2.3σ.
Fake factor method

3 signal + 1 loose (≠signal) leptons
→Estimates 1-fake + 2*2-fake background

\[ N_{SR}^{red} = \left[ N_{CR1}^{data} - N_{irr}^{CR1} \right] \times F_{w,1} - \left[ N_{CR2}^{data} - N_{irr}^{CR2} \right] \times F_{w,1} \times F_{w,2} \]

Apply a fake factor to extrapolate to the SR:

Could find this from MC or data...

...but the fake factor depends on lepton kinematics, lepton type, fake source, physics process…

Fake factors applied to CRs in data

2 signal + 2 loose (≠signal) leptons
→Estimates 2-fake background

Subtraction of second term removes double counting of 2-fakes

3-, 4-fake components are negligible (systematic unc)

\[ F = \frac{N_{signal}}{N_{loose}} \]

\( p_T, \quad e, \quad \mu, \quad \tau, \quad \eta, \quad \text{prongs} \)

HF, LF, CO, \( t\bar{t}, \) Z+jets...
Solution: Find an overall FF for each CR to account for mix of fake leptons

From MC: Ratio signal/loose in MC events
- \( N_{\text{lep}} \geq 1 \) lepton
- [pT, eta, e/mu, HF/CO/LF]
- (Z+jets stats poor, only ttbar fake factors used)

\[
F_w = \sum_{i,j} \left( R_{ij} \times s_i \times F_{ij} \right)
\]

From data: Correct HF and CO MC fake factors to data
- Independent of physics process.
- HR or CO fake-rich CRs
- [pT, eta, e/mu, HF/CO,LF]

From MC: Fraction of fake lepton type & source in SR
- [pT, e/mu, HF/CO/LF]
- CR2 similar and used for better stats
Systematics

CP-recommendations ....

... + those from fake background

- Fake factors (stat unc in MC samples)
- Scale factors (stat un in MC samples & data in CRs)
- Fake fractions (stat unc in MC samples)

These largely cancel between the two terms in the method

- Stat. unc. from data in CR1 and CR2 -- dominates
- Neglected terms (small absolute values added from upper estimations of 3 and 4-fakes)
Limits

\[ \langle \epsilon \sigma \rangle^{95 \text{ CL}}_{\text{obs}} \text{ fb} \]

95% CL upper limit on signal \( \sigma \times \epsilon \)

\[ S^{95 \text{ CL}}_{\text{obs}} \]

observed upper limit at 95% CL

\[ S^{95 \text{ CL}}_{\text{exp}} \]

expected upper limit at 95% CL

\[ \text{CL}_b \]

= \( P_B(-\ln Q > -\ln Q_{\text{obs}}) \) value for B-only hypothesis

\[ p_{s=0} \]

one-sided \( p_0 \) value using pseudo-experiments

\[ Z \]

local significance \( Z \) (number of equivalent Gaussian std deviations)

- Exclusion limits: observed and expected 95% CL limits are calculated by performing pseudo-experiments for each SUSY model point
- Profile likelihood ratio used as a test statistic to exclude the S+B hypothesis: signal model excluded at 95% CL if the CL\( _s \) (S+B hypothesis) < 0.05
GGM Higgsino exclusion contours

(e) RPC GGM higgsino
Higgsino multi-b

$E_T^{\text{miss}}$ and $m_{\text{eff}}$ distributions in the low-mass SR.
Combined fit results for high-mass and low-mass analyses. The transition between the two analyses occurs at \( m_{\text{higgsino}} = 300 \text{ GeV} \).

In the range \( 200 \text{ GeV} < m_{\text{higgsino}} < 300 \text{ GeV} \), the observed limit is 1–2 \( \sigma \) weaker than expected due to the data exceeding the background in several bins with \( E_T^{\text{miss}} > 100 \text{ GeV} \) in the low-mass analysis.
ATLAS SUSY Searches* - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell \ell, \ell \ell \rightarrow q\bar{q} \tau \bar{\tau} ) Jets</th>
<th>( \mathcal{F}_{\ell}^{\text{max}} )</th>
<th>( \mathcal{F}_{\ell}^{\text{max}} )</th>
<th>Mass limit</th>
<th>( \sqrt{s} = 7, 8, 13 ) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{t}_L, \tilde{t}_R \rightarrow q\bar{q} \tau \bar{\tau} ) ( \rightarrow q\bar{q} \tau \bar{\tau} )</td>
<td>( 3 ) jets</td>
<td>Yes</td>
<td>56.1</td>
<td>0.43</td>
<td>1.35</td>
</tr>
<tr>
<td>( \tilde{b}_L, \tilde{b}_R \rightarrow q\bar{q} \tau \bar{\tau} ) ( \rightarrow q\bar{q} \tau \bar{\tau} )</td>
<td>( 3 ) jets</td>
<td>Yes</td>
<td>56.1</td>
<td>0.43</td>
<td>1.35</td>
</tr>
<tr>
<td>( \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 \rightarrow q\bar{q} \tau \bar{\tau} ) ( \rightarrow q\bar{q} \tau \bar{\tau} )</td>
<td>( 3 ) jets</td>
<td>Yes</td>
<td>56.1</td>
<td>0.43</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Reference

<table>
<thead>
<tr>
<th>( \sqrt{s} = 7, 8, 13 ) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1712.02332</td>
</tr>
<tr>
<td>1712.02332</td>
</tr>
<tr>
<td>1706.03731</td>
</tr>
<tr>
<td>1706.03731</td>
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</tbody>
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ATLAS Preliminary

\( \sqrt{s} = 7, 8, 13 \) TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.