Compressed SUSY searches in ATLAS
LHCP 2018 - Bologna

Joana Machado Miguéns
University of Pennsylvania

on behalf of the ATLAS Collaboration

June 7th 2018
Why compressed

just a few examples...

naturalness in MSSM (tree level)

\[- \frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2\]

\(\mu\) controls Higgsino masses

two-loop correction to \(m_H\) from gluinos

one-loop correction to \(m_H\) from stops

natural SUSY should be light
decoupled SUSY can be heavy

Natural SUSY mass spectrum

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natural SUSY mass spectrum


\[ \tilde{B}, \tilde{W} \]

\[ \tilde{g} \]

\[ \tilde{t}_L, \tilde{t}_R \]

\[ \tilde{b}_L \]

\[ \tilde{b}_R \]

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decoupled SUSY can be heavy

higgsino LSPs motivated by naturalness & naturally compressed
Why compressed

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\[ \text{ATLAS} \]

Samples from the initial likelihood scan
Excl. by Run-1 2\ell + 3\ell + 4\ell
EWK model

natural SUSY
should be light

decoupled SUSY
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Why compressed

just a few examples...

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two-loop correction to $m_H$ from gluinos

one-loop correction to $m_H$ from stops

$\mu$ controls Higgsino masses

natural SUSY mass spectrum


\[
\tilde{B} \quad \tilde{W} \\
\tilde{L}_i, \tilde{e}_i \\
\tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \\
\tilde{b}_R
\]

decoupled SUSY

yellow means not excluded

clear gap in sensitivity for

compressed SUSY models

higgsino LSPs motivated by

naturalness & naturally compressed

arXiv:1608.00872 [hep-ex]

ATLAS

Samples from the initial likelihood scan

Excl. by Run-1 $2\ell + 3\ell + 4\ell$

EWKH model

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Why compressed

and from S. Heinemeyer talk yesterday

Where we will find SUSY

If SUSY exists: it should explain \((g - 2)\mu\)!

\[ \Rightarrow \text{there should be (relatively) light EW SUSY particles!} \]

1.) pMSSM11 fit to all existing data

\[ \Rightarrow \text{predictions of fit to all data: light EW particles} \]

\[ \Rightarrow \text{mass hierarchy: } M_1 \sim M_2 < \mu \]

\[ \Rightarrow \text{problem for the LHC: compressed spectra} \]

2.) “natural SUSY” with low fine-tuning

\[ \Rightarrow \text{prediction: light EW particles (possible)} \]

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Why compressed
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Compressed searches

Will focus on searches for **EWK production** of SUSY particles

*check out J. Long, Y. Nakahama and B. Petersen's talks for strong production*
Compressed searches

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2 soft leptons ($e^+e^-/\mu^+\mu^-$)

compressed EWKinos

\[
p \rightarrow \tilde{\chi}_1^\pm W^* \tilde{\chi}_2^0 Z^* \rightarrow j q \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow j q \tilde{\chi}_1^0 \tilde{\chi}_1^0
\]

compressed sleptons

\[
p \rightarrow \tilde{\ell} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{\ell} \tilde{\chi}_1^0 \tilde{\chi}_1^0
\]
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2 soft leptons (e⁺e⁻/μ⁺μ⁻)

- Compressed EWKinos
- Compressed sleptons
- Disappearing track

Long-lived EWKinos

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exploit distinct features from decay products
Compressed searches

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**2 soft leptons** $(e^+e^-/\mu^+\mu^-)$

**compressed EWKinos**

- $W^* \rightarrow p \tilde{\chi}_1^0 \tilde{\chi}_2^- Z^* \rightarrow j q \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm$ small $\Delta m$

**compressed sleptons**

- $p \tilde{\ell} \tilde{\ell}$ soft lepton mass edges and **disappearing tracks**

**disappearing track**

**long-lived EWKinos**

- $p \tilde{\chi}_1^0 j \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ small $\Delta m$
- disappearing $\pi^\pm$

*exploit distinct features from decay products*

soft lepton mass edges and **disappearing tracks**
Compressed searches

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**2 soft leptons** ($e^+e^-/\mu^+\mu^-$)

**disappearing track**

**compressed EWKinos**

**compressed sleptons**

**long-lived EWKinos**

exploit **distinct features from decay products**

soft lepton mass edges and **disappearing tracks**

ISR jet selection enhances MET from soft LSPs
ATLAS: A Toroidal LHC ApparatuS

major upgrades for Run 2 detectors (e.g. IBL), trigger, DAQ, reconstruction

excellent performance under challenging LHC conditions
peak lumi $2.14 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
over 64 interactions per crossing

analyses use 36 fb$^{-1}$ of 13 TeV pp LHC data collected by ATLAS

2015 + 2016
2 soft leptons ($e^+e^-/\mu^+\mu^-$)


compressed EWKinos

compressed sleptons
Soft leptons

small $\Delta m$ means very soft decay products ($p_T \sim \Delta m/2$)

ATLAS is pushing lepton reconstruction to very low $p_T$

analysis uses 4 GeV muons and 4.5 GeV electrons!
fake lepton bkg dominant at low $p_T$ & estimated entirely from data using "Fake Factor" method

$Z \rightarrow \tau\tau$ & top quark bkg normalized to data in dedicated control regions

data used as much as possible to estimate backgrounds
Distinct signatures

**kinematic endpoint at**

\[ m_{\ell\ell} = \Delta m \]

from

\[ N2 \rightarrow N1 \] decay

**kinematic endpoint at**

\[ m_{T2} = 100 + \Delta m \]

from

slepton \( \rightarrow \) N1 decay
Distinct signatures

kinematic endpoint at
\[ m_{\ell\ell} = \Delta m \] from
N2 \rightarrow N1 decay

shape fits in \( m_{\ell\ell} \) and \( m_{T2} \) used to improve sensitivity
Results

No significant excess seen over the background prediction.
Interpretation

**Higgsino LSP**
- Motivated by naturalness
- \( m(\tilde{\chi}^0_2) \approx 145 \text{ GeV} \)
- \( \Delta m \) as low as 3 GeV

**Wino NLSP/bino LSP**
- Motivated by DM relic abundance
- \( m(\tilde{\chi}^0_2) = m(\tilde{\chi}^1_1) \) [GeV]
- \( m(\tilde{\chi}^0_2) = m(\tilde{\chi}^0_1) \) [GeV]
- Expected limit \( \pm 1\text{σ}_{\text{exp}} \)
- Observed limit \( \pm 1\text{σ}_{\text{theory}} \)
- LEP \( \tilde{\chi}^0_1 \) excluded
- ATLAS 8 TeV \( \tilde{\chi}^0_2 \) excluded
- \( \Delta m \) as low as 2.5 GeV

**Slepton NLSP/Bino LSP**
- Motivated by muon g-2 tension
- \( m(\tilde{\chi}_L,R) \) [GeV]
- \( m(\tilde{\ell}_{L,R}) \) [GeV]
- Expected limit \( \pm 1\text{σ}_{\text{exp}} \)
- Observed limit \( \pm 1\text{σ}_{\text{theory}} \)
- LEP \( \tilde{\chi}^0_1 \) excluded
- ATLAS 8 TeV \( \tilde{\chi}^0_2 \) excluded
- \( \Delta m \) as low as 1 GeV

**First direct limits on Higgsino since LEP! (also from CMS)**

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disappearing track


ATL-PHYS-PUB-2017-019

long-lived EWKinos
Long-lived EWKinos

ultra compressed EWKinos can be long-lived
e.g. $c\tau \sim 1.5 \text{ cm} \ (0.05 \text{ ns})$ for Higgsinos with $\Delta m \sim 300 \text{ MeV}$

look for "tracklets" in ATLAS pixel layers
veto hits in the silicon strips - track disappears once C1 decays

new IBL in Run 2 allows for shorter tracks
increased sensitivity to shorter lifetimes compared to Run 1
Tracklet backgrounds

Hadron undergoes hard scattering or lepton emits a photon - pixel and SCT hits not associated to the same track

Nearby particles generate random combinations of hits

*bkgs reduced with isolation & track quality requirements estimated from data templates constrained at low MET*
no excess seen over the background prediction

pure higgsino LSPs with $\Delta m \sim 275$ MeV excluded up to 152 GeV

pure wino LSPs with $\Delta m \sim 160$ MeV excluded up to 460 GeV
Summary and Conclusions
Summary of EWK searches

**ATLAS limits on compressed SUSY particles filling in the sensitivity gaps and extending to regions not probed since LEP!**

*no signs of SUSY yet but ATLAS continues to take data so stay tuned*

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Back-up
Supersymmetry (SUSY)

- Fundamental symmetry between fermions and bosons that presents solutions to some problems of the SM:
  - SUSY particles provide opposite-sign loop corrections to the Higgs mass, canceling out quadratic divergencies
  - If R-parity = (-1)\(^3(B-L)+2s\) conserved, Lightest SUSY particle (LSP) is stable and natural Dark Matter candidate
  - Achieve unification of gauge couplings at \(M_{\text{GUT}} \approx 10^{16}\) GeV
How to search for SUSY

- Make **assumptions** on mass spectra and use **simplified models** to define signatures and guide searches
  - *R-parity conservation* - **RPC**: pair-produced SUSY particles decaying to LSP
  - *R-parity violation* - **RPV**: LSP decays to SM particles

- **Signal regions** built with high S/B using discriminating variables

- **Backgrounds:**
  - Irreducible predicted from MC or normalized in **control regions**
  - Reducible estimated from data-driven methods
  - Checked in **validation regions**

If coloured sparticles (including 3rd gen.) have very large masses, direct EWK-inino production becomes dominant.

Leptonic decays of charginos, neutralinos, sleptons are a main feature of EWK SUSY searches.

Distinctiveness of multileptonic signatures counterbalance low cross sections x BR.

Available Run-2 data already sufficient to probe significant portions of the parameter space.
**Dark matter interpretation of ATLAS Run 1 searches**

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**ATLAS Simulation**
Samples from the initial likelihood scan
EWKh model

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**ATLAS**
Samples from the initial likelihood scan
Excl. by Run-1 2\(\ell\) + 3\(\ell\) + 4\(\ell\)
EWKh model

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## 2 soft leptons MC samples

<table>
<thead>
<tr>
<th>Process</th>
<th>Matrix element</th>
<th>Parton shower</th>
<th>PDF set</th>
<th>Cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z^{(<em>)}/\gamma^</em> + \text{jets}$</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>NNPDF 3.0 NNLO [86]</td>
<td>NNLO [87]</td>
</tr>
<tr>
<td>Diboson</td>
<td>SHERPA 2.1.1 / 2.2.1</td>
<td>SHERPA 2.2.1</td>
<td>NNPDF 3.0 NNLO</td>
<td>Generator NLO</td>
</tr>
<tr>
<td>Triboson</td>
<td>SHERPA 2.2.1</td>
<td></td>
<td>NNPDF 3.0 NNLO</td>
<td>Generator LO, NLO</td>
</tr>
</tbody>
</table>

- Signal samples generated at LO using MG5_aMC@NLO with up to two extra partons and showered with Pythia8
- Resummino at NLL+NLO used to compute the cross-sections
- Madspin used for the decays of the EWK samples
- Lepton BRs computed using SUSY-HIT
2 soft leptons EWKino $m_{ll}$

$\sqrt{s} = 13$ TeV

$m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (100, 80)$ GeV

Wino cross-sections = 4 x Higgsino cross-sections
### 2 soft leptons event selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>Common requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>$= 2$</td>
</tr>
<tr>
<td>Lepton charge and flavor</td>
<td>$e^+e^-$ or $\mu^+\mu^-$</td>
</tr>
<tr>
<td>Leading lepton $p_T^{\ell_1}$</td>
<td>$&gt; 5$ (5) GeV for electron (muon)</td>
</tr>
<tr>
<td>Subleading lepton $p_T^{\ell_2}$</td>
<td>$&gt; 4.5$ (4) GeV for electron (muon)</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>$&gt; 0.05$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$&gt; 200$ GeV</td>
</tr>
<tr>
<td>Number of jets</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>Leading jet $p_T$</td>
<td>$&gt; 100$ GeV</td>
</tr>
<tr>
<td>$\Delta \phi(j_1, p_T^{\text{miss}})$</td>
<td>$&gt; 2.0$</td>
</tr>
<tr>
<td>$\min(\Delta \phi(\text{any jet}, p_T^{\text{miss}}))$</td>
<td>$&gt; 0.4$</td>
</tr>
<tr>
<td>Number of $b$-tagged jets</td>
<td>$= 0$</td>
</tr>
<tr>
<td>$m_{\tau\tau}$</td>
<td>$&lt; 0$ or $&gt; 160$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electroweakino SRs</th>
<th>Slepton SRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>$&lt; 2$</td>
<td>—</td>
</tr>
<tr>
<td>$m_{\ell_1}$</td>
<td>$&lt; 70$ GeV</td>
<td>—</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/H_{T^\text{lep}}$</td>
<td>$&gt; \max \left( 5, 15 - 2 \frac{m_{\ell\ell}}{1 \text{ GeV}} \right)$</td>
<td>$&gt; \max \left( 3, 15 - 2 \left( \frac{m_{100}}{1 \text{ GeV}} - 100 \right) \right)$</td>
</tr>
<tr>
<td>Binned in $m_{\ell\ell}$</td>
<td>$m_T^{\ell_2}$</td>
<td>$m_T^{100}$</td>
</tr>
</tbody>
</table>

$$m_{T^2}^{m_{\chi}} \left( p_T^{\ell_1}, p_T^{\ell_2}, p_T^{\text{miss}} \right) = \min_{q_T} \left( \max \left[ m_T \left( p_T^{\ell_1}, q_T, m_{\chi} \right), m_T \left( p_T^{\ell_2}, p_T^{\text{miss}} - q_T, m_{\chi} \right) \right] \right)$$
2 soft leptons event selection

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Compressed SUSY searches in ATLAS  
LHCP 2018 - Bologna
2 soft leptons event selection
**2 soft leptons MET/HT^{lep}**

**ATLAS**

Higgsino, m(χ_2^0) = 100 GeV

- Total Background
- Δm(χ_2^-0, χ_1^0) = 3 GeV
- Δm(χ_2^-0, χ_1^0) = 10 GeV
- Δm(χ_2^-0, χ_1^0) = 20 GeV

**ATLAS**

Slepton, m(χ_2^0) = 100 GeV

- Total Background
- Δm(̄τ, χ_2^-0) = 3 GeV
- Δm(̄τ, χ_2^-0) = 10 GeV
- Δm(̄τ, χ_2^-0) = 20 GeV

**ATLAS**

Data / SM

Events / 2.5

ATLAS

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

SR/\(m_{ll}\)

Data

\(t\bar{t}\), single top

Total SM

Fake/nonprompt

Others

\(\tilde{\tau}: m(\tilde{\ell}) = (105, 100)\) GeV

\(\tilde{\tau}: m(\tilde{\ell}) = (110, 100)\) GeV

**ATLAS**

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

SR/\(m_{T2}^{100}\)

Data

\(t\bar{t}\), single top

Total SM

Fake/nonprompt

Others

\(\tilde{\tau}: m(\tilde{\ell}) = (105, 100)\) GeV

\(\tilde{\tau}: m(\tilde{\ell}) = (110, 100)\) GeV
2 soft leptons CRs and VRs

<table>
<thead>
<tr>
<th>Region</th>
<th>Leptons</th>
<th>$E_T^{\text{miss}}/H_T^{\text{lep}}$</th>
<th>Additional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-top</td>
<td>$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$&gt; 5$</td>
<td>$\geq 1$ $b$-tagged jet(s)</td>
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<tr>
<td>CR-tau</td>
<td>$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$\in [4, 8]$</td>
<td>$m_{\tau\tau} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>VR-VV</td>
<td>$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$&lt; 3$</td>
<td>$\Delta R_{\ell\ell} &lt; 2, m_{T_1} &lt; 70$ GeV</td>
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<tr>
<td>VR-SS</td>
<td>$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$&gt; 5$</td>
<td>$\Delta R_{\ell\ell} &lt; 2, m_{T_1} &lt; 70$ GeV</td>
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<tr>
<td>VRDF-$m_{\ell\ell}$</td>
<td>$e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$&gt; \max\left(5, 15 - 2 \frac{m_{\ell\ell}}{1 \text{ GeV}}\right)$</td>
<td>$\Delta R_{\ell\ell} &lt; 2, m_{T_1} &lt; 70$ GeV</td>
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<tr>
<td>VRDF-$m_{T_2}^{100}$</td>
<td>$e^{\pm}\mu^{\mp}, \mu^{\pm}e^{\mp}$</td>
<td>$&gt; \max\left(3, 15 - 2 \left(\frac{m_{T_2}^{100}}{1 \text{ GeV}} - 100\right)\right)$</td>
<td>$\Delta R_{\ell\ell} &lt; 2, m_{T_1} &lt; 70$ GeV</td>
</tr>
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</table>

$m_{\tau\tau} = \text{sign} \left( m_{\tau\tau}^2 \right) \sqrt{|m_{\tau\tau}^2|}$

$m_{\tau\tau}^2 \equiv 2 p_{\ell_1} \cdot p_{\ell_2} (1 + \xi_1)(1 + \xi_2)$

$\xi_i$ obtained by solving $p_T^{\text{miss}} = \xi_1 p_T^{\ell_1} + \xi_2 p_T^{\ell_2}$

$m_{\tau\tau}$ negative when one of the leptons points in the opposite direction of $p_T^{\text{miss}}$
2 soft leptons uncertainties

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

<table>
<thead>
<tr>
<th>Relative uncertainty</th>
<th>Fake factor</th>
<th>Statistical</th>
<th>Experimental</th>
<th>Background modeling</th>
<th>Normalization</th>
<th>Total</th>
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<tr>
<td>[130,\infty]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2 soft leptons VRs

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Total SM
- Fake/nonprompt
- $Z(\to \tau\tau)$+jets
- Others
- Data
- $t\bar{t}$, single top
- Diboson

**VRDF-m$_{ll}$ [GeV]**

- VR-VV
- VR-SS ee+/ue
- VR-SS u+u+e/e+u

**VRDF-m$_{T2}$ [GeV]**

- $1$, $3$, $5$, $10$, $20$, $30$, $40$, $60$
- $100$, $102$, $105$, $110$, $120$, $130$, $\infty$

**Events**

$(n_{obs} - n_{pred}) / \sigma_{tot}$

- $2^\circ$
- $0$
- $-2$

---

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2 soft leptons VR-DF

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2 soft leptons VR-VV

Events / 5 GeV

Data / SM

m_{T2}^{100} [GeV]

ATLAS

νs = 13 TeV, 36.1 fb⁻¹

VR-VV

Data

tf, single top

Total SM

Z(\rightarrow\tau\tau)+jets

Fake/nonprompt

Others

Data / SM

m_{ll} [GeV]

ATLAS

νs = 13 TeV, 36.1 fb⁻¹

VR-VV

Data

tf, single top

Total SM

Z(\rightarrow\tau\tau)+jets

Fake/nonprompt

Others

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2 soft leptons VR-SS

![Graphs showing data and SM comparisons for different mass distributions.](image-url)
2 soft leptons CRs

### Data / SM

- **ATLAS**
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - CR-top

<table>
<thead>
<tr>
<th>Events / 5 GeV</th>
<th>$m_{T^2}$ [GeV]</th>
<th>$m_{ll}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^3$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^2$</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10$^1$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>10$^0$</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>10$^{-1}$</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>10$^{-2}$</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

### Number of b-tagged jets

<table>
<thead>
<tr>
<th>Data / SM</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>10$^3$</td>
<td>10$^2$</td>
<td>10$^1$</td>
<td>10$^0$</td>
<td>10$^{-1}$</td>
<td>10$^{-2}$</td>
<td>10$^{-3}$</td>
<td>10$^{-4}$</td>
</tr>
</tbody>
</table>

### ATLAS

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- CR-tau

<table>
<thead>
<tr>
<th>Events / 5 GeV</th>
<th>$m_{ll}$ [GeV]</th>
<th>$m_{T^2}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^3$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^2$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^1$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^0$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^{-1}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10$^{-2}$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

---

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2 soft leptons NUHM2 limits

\begin{align*}
\text{NUHM2: } m_0 &= 5 \text{ TeV, } A_0 = -1.6 m_0, \tan\beta = 15, \mu = 150 \text{ GeV, } m_A = 1 \text{ TeV} \\
\sqrt{s} &= 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \\
\text{Theoretical uncertainty} \\
\text{Observed limit} \\
\text{Expected limit} \\
\text{Expected } \pm \sigma_{\text{exp}} \\
\text{Expected } \pm 2 \sigma_{\text{exp}} \\
\text{All limits at 95\% CL} \\
ee/\mu\mu, m_{\tilde{\chi}_1^0} \text{ shape fit} \\
\tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W^* \tilde{\chi}_1^0
\end{align*}

\[\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \text{ [GeV]} \]

\[m_{1/2} \text{ [GeV]} \]
disappearing track higgsino lifetimes

c\tau[\text{mm}] \sim 7 \times \left[ \left( \frac{\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)}{340 \text{ MeV}} \right)^3 \sqrt{1 - \frac{m_{\pi}^2}{\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)^2}} \right]^{-1}

Example lifetimes:

\mu = 100 \text{ GeV} \implies \Delta m = 257 \text{ MeV}, \text{ so } c\tau = 19.3 \text{ mm}

\mu = 1 \text{ TeV} \implies \Delta m = 355 \text{ MeV}, \text{ so } c\tau = 6.7 \text{ mm}
disappearing track tracklet reconstruction efficiency

ATLAS Simulation

- Fraction of chargino decays
  - EW prod., $m_{\tilde{\chi}_1} = 400$ GeV, $\tau_{\tilde{\chi}_1} = 0.2$ ns
- Pixel tracklets
- Standard tracks

Decay radius [mm]

Fraction of chargino decays [mm$^{-1}$]

Reconstruction efficiency

Pixel tracklets (EW prod., $m_{\tilde{\chi}_1} = 400$ GeV, $\tau_{\tilde{\chi}_1} = 0.2$ ns)
disappearing track event selection

<table>
<thead>
<tr>
<th>Selection requirement</th>
<th>Electroweak channel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected signal</td>
</tr>
<tr>
<td>Trigger</td>
<td>434 559 704</td>
<td>1276   (0.20)</td>
</tr>
<tr>
<td>Jet cleaning</td>
<td>288 498 579</td>
<td>1181   (0.19)</td>
</tr>
<tr>
<td>Lepton veto</td>
<td>275 243 946</td>
<td>1178   (0.19)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ and jet requirements</td>
<td>2 697 917</td>
<td>579.1  (0.092)</td>
</tr>
<tr>
<td>Isolation and $p_T$ requirement</td>
<td>464 524</td>
<td>104.2  (0.017)</td>
</tr>
<tr>
<td>Geometrical $</td>
<td>\eta</td>
<td>$ acceptance</td>
</tr>
<tr>
<td>Quality requirement</td>
<td>6134</td>
<td>29.6   (0.0047)</td>
</tr>
<tr>
<td>Disappearance condition</td>
<td>154</td>
<td>24.1   (0.0038)</td>
</tr>
</tbody>
</table>

**Isolation and $p_T$ requirements:**
- $\Delta R > 0.4$ between tracklet and any jet with $p_T > 50$ GeV or MS track
- $p_T^{\text{cone40}}/p_T < 0.04$
- Candidate tracklet must be highest $p_T$ track or tracklet in event, and have $p_T > 50$ GeV

**Quality requirement:**
- Hits on all four pixel layers; zero holes
- Zero “low quality” hits
- $|d_0|/\sigma(d_0) < 2$, $|z_0\sin(\theta)| < 0.5$ mm
- Fit $\chi^2$ probability $> 10$

**Disappearance condition:** zero SCT hits associated to tracklet

**Table 1:**

<table>
<thead>
<tr>
<th>Decay radius [mm]</th>
<th>MET and jet requirements:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>MET &gt; 140 GeV</td>
</tr>
<tr>
<td>9</td>
<td>at least one jet with $p_T &gt; 140$ GeV</td>
</tr>
<tr>
<td>295</td>
<td>$\Delta\phi &gt; 1.0$ between MET and up to four leading jets with $p_T &gt; 50$ GeV</td>
</tr>
</tbody>
</table>

**For Wino signal point:**

$(m_{\tilde{\chi}_1^+}, \tau_{\tilde{\chi}_1^+}) = (400$ GeV, 0.2 ns)
disappearing track backgrounds

**Track to Tracklet Smearing Validation**

- Standard tracks
- Pixel tracklets
- Smeared tracks
- $Z \rightarrow \mu\mu$ candidates

**Fake Tracklet Control Region**

- ATLAS
- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- EW production
- Fake control region

**Graphs**

- Log-log plot of tracklets vs. $p_T$ (GeV)
- Ratio of data to fit for tracklet smearing validation
- Comparison of data and fit in the fake tracklet control region
disappearing track fitted regions

\[ \text{Tracklets} \]

\[ \text{ATLAS} \quad \sqrt{s} = 13 \text{TeV}, 36.1 \text{ fb}^{-1} \]

EW production

Low \( E_T^{\text{miss}} \) region

\( (m_{\chi}, \tau_{\chi}) = (400 \text{ GeV}, 0.20 \text{ ns}) \)

Data / BG

Tracklet \( p_T \) [GeV]

\[ \text{Tracklets} \]

\[ \text{ATLAS} \quad \sqrt{s} = 13 \text{TeV}, 36.1 \text{ fb}^{-1} \]

EW production

High \( E_T^{\text{miss}} \) region

\( (m_{\chi}, \tau_{\chi}) = (400 \text{ GeV}, 0.20 \text{ ns}) \)

Data / BG

Tracklet \( p_T \) [GeV]
disappearing track uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electroweak channel [%]</th>
<th>Strong channel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected signal events</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>$\alpha$ in signal $p_T$ resolution function</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$\sigma$ in signal $p_T$ resolution function</td>
<td>5.3</td>
<td>7.2</td>
</tr>
<tr>
<td>$\log r_{ABCD}$</td>
<td>15</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$\alpha$ in background $p_T$ resolution function</td>
<td>5.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$\sigma$ in background $p_T$ resolution function</td>
<td>2.2</td>
<td>5.0</td>
</tr>
<tr>
<td>$p_0$ parameter of the fake-BG $p_T$ function</td>
<td>2.5</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$p_1$ parameter of the fake-BG $p_T$ function</td>
<td>8.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Expected number of muon events</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>
disappearing track pure higgsino limits

\[ \tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_1^0 \] production

ATLAS Preliminary
\[ \sqrt{s}=13\text{TeV}, 36.1 \text{ fb}^{-1} \]

- Observed 95% CL limit (\( \pm 1 \sigma_{\text{theory}} \))
- \( \tilde{\chi}_1^\pm \) excluded
- Expected 95% CL limit (\( \pm 1 \sigma_{\text{exp}} \))
- Theoretical line for pure higgsino
- LEP2 \( \tilde{\chi}_1^\pm \) excluded
disappearing track yields

<table>
<thead>
<tr>
<th>Number of observed events</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of expected events</td>
<td></td>
</tr>
<tr>
<td>Hadron+electron background</td>
<td>6.1 ± 0.6</td>
</tr>
<tr>
<td>Muon background</td>
<td>0.15 ± 0.09</td>
</tr>
<tr>
<td>Fake background</td>
<td>5.5 ± 3.3</td>
</tr>
<tr>
<td>Total background</td>
<td>11.8 ± 3.1</td>
</tr>
</tbody>
</table>

Number of expected signal events
for the higgsino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (160\,\text{GeV}, 0.05\,\text{ns})$

| 10.3 ± 2.1 |

Number of expected signal events
for the wino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm}) = (400\,\text{GeV}, 0.2\,\text{ns})$

| 13.5 ± 2.1 |