Searches for direct production of weakly interacting SUSY states at the LHC — Gauginos, Higgsinos, Sleptons

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On behalf of ATLAS and CMS
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**Supersymmetry**

- Each boson from the SM gets a fermionic partner
- Each fermion from the SM gets a bosonic partner

**MSSM:**
- 2 Higgs doublets required (2HDM)
  - One gives mass to up-type quarks
  - Other to bottom-type quarks and charged leptons
• Symmetry between bosons and fermions

• Appealing theory addition to the SM. eg. Stabilizes Higgs mass of 125 GeV

• Gluinos and squarks (strong SUSY partners) probed to multi-TeV scale at the LHC.

• SUSY partners of the electroweak sector are produced at a much lower rate: $X_{sec}$ is 3 to 5 orders of magnitude lower

• less probed
What are gauginos, Higgsinos and SLeptons?

- SUSY partners of the SM electroweak sector
  - $U(1) \rightarrow \text{Bino}$, $SU(2) \rightarrow \text{Winos}$
  - Higgs $\rightarrow$ Higgsinos
  - Leptons $\rightarrow$ sleptons

SUSY gauge eigenstates

graphic credit: M. Swiatlowski
Charginos and neutralinos

- SUSY partners of the SM electroweak sector
  - $U(1) \rightarrow \text{Bino}$, $SU(2) \rightarrow \text{Winos}$
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  - Leptons $\rightarrow$ sleptons

SUSY gauge eigenstates

mix to form:

SUSY mass eigenstates

graphic credit: M. Swiatlowski
Gauginos and higgsinos can be light

- Possible SUSY model as of today:
  - heavy squarks and gluinos
  - Gauginos and higgsinos are light
- Important to search for electroweak SUSY partners at the LHC!

SUSY gauge eigenstates

mix to form:

SUSY mass eigenstates

graphic credit: M. Swiatlowski
Typical mass spectrums of chargino-neutralinos

- Depending on the mass scales of Bino/Winos/Higgsinos, lightest chargino/neutralinos form different mass spectrums.

- Two main mass spectrums explored at the LHC:
  - Wino-like, Higgsino-like
  - Wino-like spectrum has larger cross section

- Cross-sections for 500 GeV sparticles @ 13 TeV
  - 45 fb*
  - 11 fb*

*Cross-sections for 500 GeV sparticles @ 13 TeV (χ₀₂, χ⁻₁ only)
Large number of signal topologies

- Can decay via light sleptons
- Large number of signal topologies to study!!

Decays, with Sleptons

Higgsino-like

Wino-like

45 fb*

11 fb*

*Cross-sections for 500 GeV sparticles @ 13 TeV

(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1$ only)
### Signatures explored at the LHC

<table>
<thead>
<tr>
<th>Signature</th>
<th>Searches from ATLAS and CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 lepton (e/μ)</td>
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</tr>
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<td>&gt;=4 leptons</td>
<td>ATLAS-SUSY-2016-21, (including τ)</td>
</tr>
<tr>
<td>taus</td>
<td>CMS-SUS-17-002, CMS-SUS-17-003</td>
</tr>
<tr>
<td>3,4 b Jets (H(bb),Z(bb))</td>
<td>ATLAS-CONF-2017-081, CMS-SUS-16-044</td>
</tr>
<tr>
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</tr>
<tr>
<td>Combination</td>
<td>CMS-SUS-17-004</td>
</tr>
</tbody>
</table>

- Impressive search program
- Impossible to cover them all today!
- Will highlight a few
- Hopefully I can still tell you a relatively complete story

- Using 36 fb-1 pp data collected at the LHC @ 13 TeV, organized by signatures.
GMSB model, mass degenerate charginos and neutralinos. All of these neutralinos are assumed to be higgsino-like states. The second neutralino can decay to either of the Z or H bosons.

Signal models and Monte Carlo simulation

In GMSB model, mass degenerate charginos and neutralinos. All of these neutralinos are assumed to be higgsino-like states. The second neutralino can decay to either of the Z or H bosons.

A special case: Gauge mediated SUSY breaking

- GMSB Higgsinos: enhanced production with higgsino cross-section
- Combination to cover full model space
- New, 79.8 fb⁻¹: Exotic Higgs decay via neutralinos/gravitino

Slepton status

- Direct Slepton
- RPV smuon. New!
Search Highlights - WH(Lνbb) + MET

- Wino-like mass spectrum: larger cross section
- Dedicated search for WH topology.
- 1 lepton (e/μ) + bb: Clean final state, large BF of H→bb
- Two b's form Higgs mass peak, main background 2L TTbar directly controlled in the sideband.
- Previous analyses reach chargino mass of \(~\)200 GeV.
- Probes chargino mass up to 550 GeV.
M.LIU

Also studied WZ final state in several analyses, using 2L/3L leptons events.

New analysis by ATLAS using recursive jigsaw technique.

Parallel talk: Electroweak production SUSY searches in ATLAS. Shion Chen.
\[ \tilde{\chi}^0_2 \tilde{\chi}^\mp_1 \rightarrow W(\rightarrow l^+l^-/q\bar{q}) \tilde{\chi}^0_1 Z(\rightarrow ll) \tilde{\chi}^0_1 \]

**ATLAS Preliminary**

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

New!

- ~3 sigma excess seen, several search regions combined
- Not present in conventional search targeting the same signal model.
- Parallel talk: Electroweak production SUSY searches in ATLAS. Shion Chen

\[ m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0} \]
Search Highlights – compressed Higgsino

- Higgsino-like spectrum:
  - Lower cross section
  - Challenging signatures:
    - $\Delta m \sim \text{tens of GeV}$: Soft decay products
    - $\Delta m \sim \text{hundreds of MeV}$: Long-lived signatures. (not covered in this talk)

$\Delta m \sim \text{hundreds of MeV}$ to tens of GeV

Higgsino-like

$\tilde\chi^0_2 \rightarrow \tilde\chi^0_1 \rightarrow \tilde\chi^\pm_1$
Search Highlights — compressed Higgsino with soft leptons

- Dedicated searches with similar search strategy:
  ATLAS: SUSY-2016-25 CMS: SUS-16-048,

- Soft leptons pt: 4-5 GeV, hard to trigger

- ISR jet to get the system boosted —> large missing transverse energy to be triggered:
  - MET > 200 GeV. (ATLAS pure MET trigger)
  - MET>125 GeV (CMS MET+ soft lepton trigger)
soft leptons – interpretations

**ATLAS**

√s = 13 TeV, 36.1 fb⁻¹

ee/μμ, mℓℓ shape fit

All limits at 95% CL

\( pp \rightarrow \tilde{\chi}_2^0 \pm ^\dagger, \tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow W^* \tilde{\chi}_1^0 \)

\( m(\tilde{\chi}_1^\pm) = [m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2 \)

Comparable exclusion by CMS
see backup
Figure 7: The observed 95% CL exclusion contours (black curve) assuming the NLO cross sections, with the variations corresponding to the uncertainty in the cross sections for the higgsino pMSSM, which has been introduced in the text. The dashed (red) curves present the band covering 68% of the limits in the absence of signal. The model considers all possible production processes.

Bino mass: $1/2 \times$ Wino mass

Higgsino mass

CMS

33.2-35.9 fb$^{-1}$ (13 TeV)

95% CL upper limit on cross section [pb]
Search Highlights - GMSB Higgsino

- Special case: GMSB Higgsino:
  - Gravitino is the LSP
  - Enhanced production of $\tilde{\chi}_1^0 \tilde{\chi}_1^0 + X_{\text{soft}}$
    - Picks up all contributions from $\tilde{\chi}_2^0 \tilde{\chi}_1^+$ etc....
  - Collectively referred to as higgsinos.
Search Highlights - GMSB Higgsino

- Dedicated searches using events with >= 3 b jets
- ATLAS-CONF-2017-081 CMS:SUS-16-044
- Large branching fraction of H->bb
Higgsino mass > 300 GeV

- Missing transverse energy trigger: MET > 200 GeV

Higgsino mass < 300 GeV:

- B-jet based trigger

Excluding higgsino masses: [130,230], [290, 880] GeV, assuming 100% BF to Higgs.
• Sensitivity weakened as higgsino-→Z+Gravitino branching ratio gets larger: BR(Z→bb) ~15%.

• Need to be combined with other analyses to cover full model space.
• Combined sensitivity: no strong dependence on the BR of Higgsino → H+Gravitino.
Search Highlights — exotic Higgs decay via SUSY particles New!

- Use 79.8fb-1 data. (2016+2017)
- Zh production
  - Z->ll, Higgs decays via neutralinos/gravitinos, which decays to γ + LSP.
  - γ(γ)+2l + MET final state
Search Highlights — exotic Higgs decay via SUSY particles

- Limit on Higgs BF to $\gamma(\gamma) + \text{MET}$:

- 5-18% depending on NLSP and LSP masses
Search highlights — Outline

- Wino-like spectrum
  - WH and WZ: New!
- Compressed Higgsinos spectrum

A special case: Gauge mediated SUSY breaking

- GMSB Higgsinos: enhanced
- Combination is necessary
- New, 79.8 fb⁻¹: Exotic Higgs decay via neutralinos/gravitino

Slepton status

- Direct Slepton
- RPV smuon. New!
Sleptons: direction production has low cross section

First/second generation slepton decays don’t suffer from branching ratio (eg. ee/mm +MET). see CMS result in backup.
Direct stau production

- Staus are challenging and are interesting NLSP for DM co-annihilation
- Searched for stau production in all-hadronic and leptonic channels
- Need a little bit more data!

CMS Preliminary
35.9 fb$^{-1}$ (13 TeV)

**SUS-17-002**

$m_{\tilde{\tau}} = 1$ GeV

95% CL limit on $\sigma / \sigma_{\text{theory}}$

At least one $\tau$ decays leptonically

Upper limit on $\sigma / \sigma_{\text{theory}}$

**SUS-17-003**

$m_{\tilde{\tau}} = 1$ GeV

Both $\tau$ decays hadronically

Left-handed scenario
Search for RPV smuons

up/down quarks produced in abundance

- R parity violated models: allow lepton/baryon number violation

- $\lambda'_{211}$: 2nd generation slepton coupling to 1st generation quarks.

- Same-sign $\mu\mu + \text{jets}$, no MET $\rightarrow$ can fully reconstruct slepton/electroweakino masses

![Diagram of slepton decay](image)
Upper limit on cross section placed and translated to upper limit set on $\lambda^{'211}$ coupling strength

Map simplified model to full model points in Constrained MSSM (cMSSM) with $\lambda^{'211}$ as additional coupling

The most stringent limits on this particular model of RPV SUSY.
Summary and... stay tuned!


- Extensive electroweak SUSY search program performed by ATLAS and CMS
  - No new physics observed, large regions of phase space probed.
  - Large parameter space to be probed, many searches can benefit from larger dataset, e.g. Stau search.
  - ~120 fb⁻¹ of data expected for LHC Run 2 data-taking, > 40 fb⁻¹ collected in 2017.
  - 3000 fb⁻¹ expected from High-luminosity LHC


- Large parameter space to be probed, many searches can benefit from larger dataset. e.g. Stau search.
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<table>
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<tr>
<th>Session time</th>
<th>Talk</th>
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<tbody>
<tr>
<td>Tuesday 5/6 11:30 am - 1:00 pm</td>
<td>RPV SUSY searches in ATLAS and CMS. Kin Ho Lo</td>
</tr>
<tr>
<td>Wednesday 6/6 11:30 am - 1:00 pm</td>
<td>Electroweak production SUSY searches in CMS. Carlos Francisco Erice Cid</td>
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<td>Thursday 7/6 11:30 am - 1:00 pm</td>
<td>Compressed SUSY searches in ATLAS. Joana Machado Miguens</td>
</tr>
<tr>
<td>Thursday 7/6 11:30 am - 1:00 pm</td>
<td>Compressed SUSY searches in CMS. Constantin Heidegger</td>
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Examples of models explored at the LHC

- \( \tilde{\chi}_1 \) production
- \( \tilde{\chi}_1 \) and \( \tilde{\chi}_2 \) production
- Decays to \( W, Z \) or \( H \)
- Dark matter candidates

- Higgsino-like states
- Bino-like states

- Event reconstruction and selection
- Background estimation

- ATLAS detector description

- \( \mu^+ \mu^- \) signal regions
## Signatures explored at the LHC

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<td></td>
<td></td>
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<td>SUS-16-048</td>
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<tr>
<td>Same-sign lepton pair/ 3 leptons (e/μ)</td>
<td>SUSY-2016-24</td>
<td>SUS-16-039 (including (\tau))</td>
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<td></td>
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- 36 fb⁻¹ pp data collected at the LHC @ 13 TeV.
Combination to cover full phase space

- SUS-16-039: Multilepton: Same-sign 2L+ 3L
- SUS-16-034: OS 2L + MET + jets
- SUS-16-048: Soft-2lepton

Figure 8: The 95% CL upper limits on the production cross sections in the plane of $m_1$ for the models of SUS-17-004: Soft-2lepton

Figure 9: The analysis with the best expected exclusion limit at each point in the plane of $m_1$ and $m_2$ for the models of SUS-16-034: OS 2L + MET + jets

Combination to cover full phase space

CMS

$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$
$\tilde{\chi}_1^0 \rightarrow W^{\pm} \tilde{\chi}_1$
$\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1$

$MSLiu$
**Searches with soft leptons targeting compressed spectra**

<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>
<tr>
<td>$E_T^{\text{miss}}/H_T^{\text{lep}}$</td>
<td>Electroweakino SRs</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$, $m_{\ell\ell}$, $E_T^{\text{miss}}/H_T^{\text{lep}}$</td>
<td>$&lt;2$</td>
</tr>
<tr>
<td>$&lt;70$ GeV</td>
<td></td>
</tr>
<tr>
<td>&gt; max (5, 15 − $2 m_{\ell\ell}$/1 GeV)</td>
<td>Slepton SRs</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>&gt; max (3, 15 − 2($m_{T2}^{100}$/GeV − 100))</td>
</tr>
</tbody>
</table>

- **Soft leptons**
- **Reject photon conversions**
- **Reject Low mass resonants**
- **ISR boost to get MET**
- **Reject top**
- **Reject $Z(\tau\tau)$**
Searches with soft leptons targeting compressed spectra

<table>
<thead>
<tr>
<th>Region</th>
<th>Leptons</th>
<th>$E^\text{miss}_T/H^\text{lep}_T$</th>
<th>Additional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-top</td>
<td>$e^+e^-, \mu^+\mu^-, \mu^0\mu^0, \mu^0e^\mp$</td>
<td>$&gt;5$</td>
<td>$\geq 1$ b-tagged jet(s)</td>
</tr>
<tr>
<td>CR-tau</td>
<td>$e^+e^-, \mu^+\mu^-, \mu^0\mu^0, \mu^0e^\mp$</td>
<td>$\in [4, 8]$</td>
<td>$m_{\tau\tau} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>VR-VV</td>
<td>$e^+e^-, \mu^+\mu^-, \mu^0\mu^0, \mu^0e^\mp$</td>
<td>$&lt;3$</td>
<td>$\Delta R_{ll} &lt; 2, m_{Tll} &lt; 70$ GeV</td>
</tr>
<tr>
<td>VR-SS</td>
<td>$e^+e^-, \mu^+\mu^-, \mu^0\mu^0, \mu^0e^\mp$</td>
<td>$&gt;5$</td>
<td>$\geq 1$ b-tagged jet(s)</td>
</tr>
<tr>
<td>VRDF-$m_{\ell\ell}$</td>
<td>$e^+\mu^-, \mu^+\mu^- &gt; \text{max}(5, 15 - 2m_{\ell\ell})$</td>
<td>$&gt; \text{max}(5, 15 - 2m_{\ell\ell})$</td>
<td>$\Delta R_{ll} &lt; 2, m_{Tll} &lt; 70$ GeV</td>
</tr>
<tr>
<td>VRDF-$m_{T2}^{100}$</td>
<td>$e^+\mu^-, \mu^+\mu^- &gt; \text{max}(5, 15 - 2m_{T2}^{100})$</td>
<td>$&gt; \text{max}(5, 15 - 2m_{T2}^{100})$</td>
<td>$\Delta R_{ll} &lt; 2, m_{Tll} &lt; 70$ GeV</td>
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- Top background estimated from a b-tagged region.
- Tau background estimated on Z peak.
- Diboson backgrounds validated in data
- Fake lepton estimated with fake rate method, validated with a Same-sign dilepton region
- Mll and MT2 shape modeling validated using e/m events
The results of the search are interpreted using the model described in Section 1, and upper limits on the slepton pair production cross section are provided in Figure 3 for three scenarios, assuming the existence of both mass degenerate left- and right-handed sleptons, only left-handed sleptons and only right-handed sleptons. The cross section for the right handed sleptons is about a third of that of the left-handed sleptons and thus the origin of the different limits.

**Figure 3:** Cross section upper limit and exclusion contours at 95% CL for the direct slepton production as a function of the $e^e$ and $e^\mu$ masses, assuming the production of both left- and right-handed sleptons of two flavors (top), or production of only left- (bottom left) or right-handed (bottom right) sleptons of two flavors. The region under the thick red dotted (black solid) line is excluded by the expected (observed) limit. The thin red dotted curves indicate the regions containing 95% of the distribution of limits expected under the background-only hypothesis. The thin solid black curves show the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

**SUSY-2016-24**

**SUSY-17-009**
In RPV models, lepton number violation, $X_1^0$ decays to $ll\nu$

- Wino-like $\tilde{X}^{\pm}$ and $\tilde{X}^0$ masses up to 1.46 TeV, 1.06 TeV are excluded,
In RPV models, lepton number violation, \( \chi_1^0 \) decays to \( ll\nu \), low MET compared to RPC signatures.

Analysis selects 4 leptons: \( e/\mu/\tau \), allowing up to 2 hadronically decaying \( \tau \).

Events categorized with whether a dilepton pair is consistent with \( Z \) boson, MET and \( M_{\text{eff}} \).

Wino-like \( \chi^{-1}/\chi^{02} \) and \( l^+l^-/\nu^- \) masses up to 1.46 TeV, 1.06 TeV are excluded.