SUSY searches - electroweak production

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On behalf of the ATLAS and CMS collaborations
LPNHE/CNRS
Why SUSY? Why electroweak SUSY?

- SUSY: a framework, many realizations – not magic

- Why SUSY?
  - Provide a dark matter candidate
  - Unify the fundamental forces at high energies
  - Solves the fine-tuning problem of the Higgs mass

- So far all the inclusive/wide reach searches performed have found no SUSY
  - No more big jumps in luminosity/energy in the near future

Why SUSY? Why electroweak SUSY?

- Do not panic: we can push the field still!

- New/advanced performance tools

- Look for lower cross-section processes: electroweak SUSY
  - Latest strong SUSY limits ~TeV scale, thus making electroweak production promising and important probe to search for SUSY at the LHC

Electroweak Sector:

\[ \tilde{B} \text{ (bino), } \tilde{\nu} \text{ (wino), } \tilde{H} \text{ (higgsino)} \]

\[ \tilde{\chi}_i^{\pm} \text{ w/ } i \in [1,2] \text{ (charginos) } \]

\[ \tilde{\chi}_i^0 \text{ w/ } i \in [1,4] \text{ (neutralinos) } \]
Huge effort from both collaborations to looks at the Run-2 data for EWK SUSY

- Reaching sensitivity to the TeV scale

- EWK SUSY gives a high number of potential signatures: essentially anything from SM + missing transverse energy

- Impossible to cover all the available results
  - I will try to give an overview of what is available: classical signatures and compressed scenarios but focus only on new results wrt SUSY2017

- More details in the parallel sessions, in particular on Tuesday afternoon
A "typical" EWK SUSY search
A “typical” EWK SUSY search

- Usually searches are optimized either for:
  - Discovery: inclusive cut & count signal regions (SRs)
  - Exclusion: more complex, involving shape-fits, MVAs, etc

- Typical handles on new physics
  
  Object counting
  (soft) leptons, (b-) jets, MET...

  Kinematic variables
  \(H_T, m_{\text{eff}}, m_T, m_{T^2} \ldots\)

  Composite objects/event shapes
  razor variables, JSS, recursive jigsaw reconstruction

- Background estimation approach:
  
  - For each important process define a representative control region (CR)
  
  - Fit the background to data simultaneously in all CRs to get the scale factors (SF)
  
  - Validate these SFs in the validation regions (VR) then use them in the SRs

*Check Jesse Liu's talk*
A word regarding results and interpretations:

- Signal models are important to interpret our results
  - Can explain a discrepancy in an existing analysis

- Currently almost exclusively Simplified Models are used:
  - Limited number of free parameters
  - Relatively easy to present results (2-D scans in particle masses)
  - Typically assuming 100% branching ratios for the considered decay chains
  - But
    - Unrealistic situation: “Do not confuse limits in simplified models with real limits on SUSY masses” [Sven Heinemeyer, LHCP2018]
Classical SUSY EWK signals

Neutralino and chargino production

- Stable lightest $\tilde{\chi}_1^0$
- Decaying lightest $\tilde{\chi}_1^0$

- Cleanest signatures: leptons & MET (similar to SM EWK)
- Main irreducible background: dibosons
- Jet vetos common to reduce ttbar backgrounds

Reminder 1: neutralinos and charginos are mixings of the Higgsinos and the electroweak boson’s partners

Reminder 2: Stable lightest supersymmetric particle (LSP) $\tilde{\chi}_1^0 \rightarrow$ Dark matter candidate

Long lived particles searches will be covered by Laura Jeanty
Classical SUSY EWK signals

Summary sleptons searches:

Direct slepton pair production

<table>
<thead>
<tr>
<th>Topology</th>
<th>Final state</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct light slepton</strong></td>
<td>2L0J + MET</td>
<td><strong>1803.02762 (~500 GeV in slepton mass)</strong></td>
<td>1806.05264 (~290/400 GeV in left/right handed slepton mass)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 soft leptons + MET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct stau</td>
<td>2 taus + MET</td>
<td>Phys. Rev. D 93, 052002 (2016)</td>
<td><strong>1807.02048</strong> Upper limit 0.66 pb on σxBR</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^- \tilde{\chi}_1^+ \bar{\chi}_1^0$ via light slepton</td>
<td>2L0J/3L+MET</td>
<td><strong>1803.02762 (~750 GeV limit in $m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$)</strong></td>
<td><strong>1807.07799 (2L)</strong> JHEP 03 (2018) 166 (3L+2LSS) ~800 GeV for $\tilde{\chi}_1^\pm$ and 320 GeV for $\tilde{\chi}_2^0$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^- \tilde{\chi}_1^+ \bar{\chi}_2^0$ via stau</td>
<td>2 taus + MET</td>
<td>Eur. Phys. J. C 78 (2018) 154 (~1.1 TeV limit in $m(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0)$), had. taus</td>
<td><strong>1807.02048</strong> Up to 560 GeV depending on config.</td>
</tr>
</tbody>
</table>

Slepton-mediated chargino/neutralino decay

Motivated by bino co-annihilation, g-2 oriented scenario etc.
Selected dileptons: opposite charge, same flavour

Veto in hadronic jets and $m_{T2}$ selection:
- Upper bound on mass of pair-produced particles each decaying to l+LSP
- $m_{T2} > 90$ GeV suppresses WW

Search binned in MET (m_{ll} and m_{T2}) for CMS (ATLAS)
Main backgrounds: ttbar, WW
No excess found

CMS: 1806.05264
ATLAS: 1803.02762

*Check Daniel Antrim and Alexis Kalogeropoulos’ talks
Exactly two muons with same charge and invariant mass > 15 GeV
At least two jets are required and the signal region is divided into bins in the M_{slepton}-m_{\chi} plane
- Events from signal processes would lead to a broad peak around the slepton mass in the M_{slepton} plane
- Main backgrounds: non prompt muons mainly from ttbar and dibosons
- No excess found
## Classical SUSY EWK signals

### Summary gaugino searches: stable lightest $\tilde{\chi}_1^0$

<table>
<thead>
<tr>
<th>Topology</th>
<th>Final state</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via $WW$</td>
<td>2L0J + MET</td>
<td>ATLAS-CONF-2018-042</td>
<td>1807.07799</td>
</tr>
<tr>
<td></td>
<td>2L/3L + MET</td>
<td>1803.02762</td>
<td>JHEP 03 (2018) 166</td>
</tr>
<tr>
<td></td>
<td>2L/3L + MET RJR</td>
<td>1806.02293</td>
<td>JHEP 03 (2018) 076</td>
</tr>
<tr>
<td></td>
<td>3L+HT</td>
<td></td>
<td>JHEP 03 (2018) 160 (specific treatment of the &quot;WZ corridor&quot;)</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $Wh$</td>
<td>Wh</td>
<td>Eur. Phys. J. C (2015) 75:208 (Run1)</td>
<td>JHEP 11 (2017) 029</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $Zh$</td>
<td>Zh</td>
<td>Eur. Phys. J. C (2015) 75:208 (Run1)</td>
<td>JHEP 03 (2018) 076</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0 \tilde{\chi}_3^0$ via $ZZ$</td>
<td>4L</td>
<td>Phys. Rev. D. 90, 052001 (2014) (Run1)</td>
<td>JHEP 03 (2018) 076</td>
</tr>
<tr>
<td>Combination</td>
<td></td>
<td></td>
<td>JHEP 03 (2018) 160</td>
</tr>
</tbody>
</table>

*Check Basil Schneider and Matthew Klein' talks*
Chargino/neutralino production: 2L/3L + MET RJR

- Use recursive jigsaw reconstruction techniques (RJR)
  - Algorithm recursively reconstructing the decay chain of pair produced heavy particles
- Event selection: 8 regions targeting different $\Delta M$
  - [2L, 3L]x[ISR, low, intermediate, high]
- 3.0 $\sigma$ excess in 3 lepton ISR selection (compressed scenarios)
  - Shape not consistent with any benchmark signals or backgrounds
  - Not present in the conventional 2L/3L analysis using the same data

Example of RJR "tree" for compressed scenario and 2L
Chargino production: 2L0J + MET

- Leptonic decay of the W considered: two isolated leptons (e, μ) with opposite charge, $m_{\ell\ell} > 25$ (20) GeV and MET > 110 (140) GeV for ATLAS (CMS).
- $m_{T2}$ binned regions for model-dependent exclusions and inclusive SRs for model independent results.

- Main background is SM WW and top production.
- No deviation from SM: stronger limits wrt Run 1 limit.
• Limits on slepton-mediated charginos & neutralinos reaching beyond 1 TeV — large BR to multileptons

*Mass limits at 95% CL obtained in the context of simplified models
Statistical combination of all CMS analyses targeting direct decays of neutralino/chargino pairs to SM bosons. 6 main publications of CMS

- Setting even higher limits in the electroweak SUSY energy scale

**Diagram:**

- Particles and processes involved in the production and decay of neutralino/chargino pairs.

**Graphs:**

- CMS: pp → \( \tilde{\chi}_1^0 \tilde{\chi}_2^0 \), 35.9 fb\(^{-1}\) (13 TeV).
  - Data points and expected signal strengths for various processes.
  - Channels studied: \( \geq 3\ell \) (WH), 2\(\ell\) on-Z (WZ), 2\(\ell\) soft (WZ), \(H\) → γγ (WH), 3\(\ell\) (WZ).

**References:**

- CMS: JHEP 03 (2018) 160
Classical SUSY EWK signals

- Lightest neutralino decays in a class of scenarios:
  - Decay into SM particles (RPV)
  - Decay into gravitino LSP (GMSB), etc...

- Decay one step further
  - More additional associated objects
  - Better experimental sensitivity in general

### Summary gaugino searches: decaying lightest $\tilde{\chi}_1^0$

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<thead>
<tr>
<th>Topology</th>
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<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RPV decay of $\tilde{\chi}_1^0$</strong></td>
<td>$\tilde{\chi}_1^0 \rightarrow Z/h \ G$</td>
<td>1804.03602 (4L)</td>
<td>SUS-13-010 (Run 1, 4L)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \rightarrow \gamma/G$</td>
<td></td>
<td>JHEP 03 (2018) 166 (leptons)</td>
<td>JHEP 03 (2018) 076 (leptons)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JHEP 03 (2018) 160</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \rightarrow \gamma + \text{MET}$</td>
<td>$\gamma + \text{MET}$</td>
<td>Phys. Rev. D 97, 092006 (2018)</td>
<td>Phys. Lett. B 780 (2018) 118</td>
</tr>
<tr>
<td>$Z + \gamma + \text{MET}$</td>
<td>ATLAS-CONF-2018-019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + \gamma + \text{MET}$</td>
<td></td>
<td>SUS-17-012</td>
<td></td>
</tr>
</tbody>
</table>
- RPV wino decay, gauginos decaying via ZZ
  - High lepton multiplicity in final state

- >=4 leptons, 0 - 2 hadronically decaying taus
- 6 different SRs to gain sensitivity to different models

- Cutting on \( m_{\text{eff}} \) or MET and veto or requirements on Z boson
- Main backgrounds: ZZ, ttZ and fakes

- No significant excess seen
  - Mild excess observed (2.3 \( \sigma \)) in 0 tau, on-shell Z
Searches with photons: $\gamma$+MET

- **Diphoton signature with MET**

- **Selection:**
  - CMS requires 1 photon, ATLAS requires 2 photons
  - Jet agnostic
  - MET > 150, 250 GeV (ATLAS), >300 GeV (CMS)
  - High energy scale (event-wide $p_T$ sum)

- **Main backgrounds:** diphotons and fakes

- **No significant excess. Exclude up to 1.2 TeV chargino/neutralino**
First 80/fb SUSY result from ATLAS, Zh with \( h \rightarrow {\text{neutralino}} \)

**Selection:**
- \( Z \rightarrow ll, \text{MET}>95 \text{ GeV and } \geq 1 \text{ photon} \)
- Jet veto and cuts on angular/Z-h \( p_T \)-balance

**Main backgrounds:** >95% from jet/electron faking photons, data-driven estimation

No significant excess observed. 10-60% improvement wrt Run-1 limits on Higgs BR

*Check Johannes Schulz’s talk*
In “natural” SUSY models, Higgsinos should be light
If the lightest $\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1$ are dominated by the Higgsino, expect $O(0.1 - 10 \text{ GeV})$ mass splittings and very difficult signatures!

**Challenges: Higgsinos and compressed scenarios**

- **Scenario 1:** GMSB higgsino NLSP
  - $W^*/Z^*$ → undetected fermions
  - $\Delta m \sim$ few GeV

- **Scenario 2:** higgsino LSP
  - Compressed higgsinos and sleptons
  - $W^*/Z^*$ → leptons
  - $\Delta m \sim$ few GeV

- **Scenario 3:** ultra-compressed higgsino LSP
  - $W^*/Z^*$ → undetected fermions
  - $\Delta m \sim$ 300 MeV

**ATLAS:** 1806.04030
**CMS:** PRD 97 (2018) 032007
**Decays via on-shell $h/Z$**

Already presented last December: big impact from JSS techniques!

**ATLAS:** Phys. Rev. D 97, 052010 (2018)
**Also presented last December**

Emphasize the importance of looking at the corners! Which usually means thinking outside the box also for performance as was the case of soft leptons!

**ATLAS:** JHEP 06 (2018) 022
**CMS:** 1804.07321 (just accepted by JHEP!)

Heavy degenerate EW gauginos → disappearing tracks. Another example of thinking outside the box.
Combined Higgsino limits

Part of the statistical combination effort from CMS mentioned before

*Check Rakhi Mahbubani's talk
A brief overview presented of the new high quality results made public by both collaboration.

- More details in the parallel sessions!

All results available at CMS and ATLAS SUSY public website.

EWK SUSY becoming more and more interesting with increasing stats accumulated.

Standard signatures well covered. Now we need to think outside the box:
- Corners and signatures not explored?
- Improvements in our reconstruction process needed? Push the boundaries of new physics searches using new techniques rather than $\sqrt{N}$ and $\sqrt{s}$!

Stay tuned!
Chargino/neutralino production: 2L/3L + MET RJR

Figure 1: Diagrams for the physics scenarios studied in this paper: (a) $\tilde{\chi}_1^+\tilde{\chi}_1^0$ with decays via leptonically decaying $W$ and $Z$ bosons, (b) $\tilde{\chi}_1^+\tilde{\chi}_2^0$ with decays to two-lepton plus two-jet plus $E_T^{miss}$ final states through a hadronically decaying $W$ boson and a leptonically decaying $Z$ boson, (c) $\tilde{\chi}_1^+\tilde{\chi}_2^0$ production in association with an initial state radiation jet (labeled "$j$" in the figure) with decays via leptonically decaying $W$ and $Z$ bosons and (d) $\tilde{\chi}_1^+\tilde{\chi}_2^0$ production in association with an initial state radiation jet with decays to two-lepton plus two-jet plus $E_T^{miss}$ final states through a hadronically decaying $W$ boson and a leptonically decaying $Z$ boson.

Figure 2: (a) The "standard" decay tree applied to pair-produced sparticles ("parent" objects), $P$ decaying to visible states "V" and invisible states "I". (b) Decay trees for the $2\ell + 2\text{jet}$ final state and (c) $3\ell$ final state. (d) The "compressed" decay tree. A signal sparticle system $S$ decaying to a set of visible momenta V and invisible momentum I recoils from a jet-radiation system ISR.
Searches with photons: W+γ+MET

*Check Johannes Schulz’s talk*
Overview of SUSY results: electroweak production

36 fb$^{-1}$ (13 TeV)

$\mathbf{pp} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow \ell \ell \ell \rightarrow \ell \nu \ell \ell \ell \ell$

- $3\ell$: arXiv:1709.05406
- $3\ell + 2\ell$ same-sign: arXiv:1709.05406
- $3\ell + 2\ell$ same-sign: arXiv:1709.05406
- $3\ell + 2\ell$ same-sign: arXiv:1709.05406
- $3\ell + 2\ell$ same-sign: arXiv:1709.05406
- $3\ell + 2\ell$ same-sign: arXiv:1709.05406

$\mathbf{pp} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow \tau \nu \ell \ell \rightarrow \tau \nu \ell \ell \ell \ell$

- $3\ell$/$\tau$: arXiv:1709.05406
- $3\ell$/$\tau$: arXiv:1709.05406
- $3\ell$/$\tau$: arXiv:1709.05406
- $3\ell$/$\tau$: arXiv:1709.05406
- $3\ell$/$\tau$: arXiv:1709.05406

$\mathbf{pp} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow WZ\tilde{\chi}_1^0$

- $3\ell$ opposite-sign: arXiv:1709.08908
- $3\ell$ opposite-sign: arXiv:1709.08908
- $3\ell$ opposite-sign: arXiv:1709.08908
- $3\ell$ opposite-sign: arXiv:1709.08908
- $3\ell$ opposite-sign: arXiv:1709.08908

$\mathbf{pp} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow WZ/\tilde{\chi}_1^0$

- $2\ell$ opposite-sign: arXiv:1801.03957
- $2\ell$ opposite-sign: arXiv:1801.03957
- $2\ell$ opposite-sign: arXiv:1801.03957
- $2\ell$ opposite-sign: arXiv:1801.03957
- $2\ell$ opposite-sign: arXiv:1801.03957

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
Jetless off-Z double lepton

Events with a pair of opposite charge same flavor (OCSF) leptons.

Stransverse mass variable:

$$M_{T2}(\ell\ell) = \min_{p_T^{\text{miss1}}+p_T^{\text{miss2}}=p_T^{\text{miss}}} \left( \max \left[ M_T(p_T^{\text{lep1}}, p_T^{\text{miss1}}), M_T(p_T^{\text{lep2}}, p_T^{\text{miss2}}) \right] \right)$$

<table>
<thead>
<tr>
<th>Reduce tt, QCD</th>
<th>Reduce resonances</th>
<th>Reduce WW, tt</th>
<th>Sensitive to multiple $m_{\text{LSP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{jets}}$</td>
<td>$m_{\ell\ell}$ [GeV]</td>
<td>$M_{T2}(\ell\ell)$ [GeV]</td>
<td>$p_T^{\text{miss}}$ [GeV]</td>
</tr>
<tr>
<td>0 (&gt; 25 GeV)</td>
<td>&gt; 20 and not in [76, 106]</td>
<td>&gt; 90</td>
<td>100–150, 150–225, 225–300, &gt;300</td>
</tr>
</tbody>
</table>

Dominated by multiple effects that alter the shape of $p_T^{\text{miss}}$

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>1-15</td>
</tr>
<tr>
<td>Fast simulation $p_T^{\text{miss}}$ modeling</td>
<td>0-20</td>
</tr>
<tr>
<td>Unclustered energy shifted $p_T^{\text{miss}}$</td>
<td>0-8</td>
</tr>
<tr>
<td>Muon energy scale shifted $p_T^{\text{miss}}$</td>
<td>0-20</td>
</tr>
<tr>
<td>Electron energy scale shifted $p_T^{\text{miss}}$</td>
<td>0-4</td>
</tr>
</tbody>
</table>

Carlos Erice Cid, LHCP2018
Jet inclusive off-Z double lepton

→ Selecting events with an OC lepton pair. Veto third lepton.

→ Minimal requirements to reject resonances.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$\geq 20$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
</tr>
</tbody>
</table>

→ Search strategy based on multiple bins on $N_{\text{Jets}} - N_{\text{b-Tag}}$ classified by lepton composition.

→ Exploit shape differences in the $M_{T2}(\ell\ell)$ variable (multiple bins).

$M_{T2}$ modelling for the backgrounds is crucial
Also different effects in the resolution of $p_T^{\text{miss}}$

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Change in yields</th>
<th>Change in $M_{T2}(\ell\ell)$ shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>1-6%</td>
<td>3-15%</td>
</tr>
<tr>
<td>Unclustered energy</td>
<td>1-2%</td>
<td>2-16%</td>
</tr>
<tr>
<td>$M_{T2}(\ell\ell)$ shape (Top)</td>
<td>-</td>
<td>4-18%</td>
</tr>
<tr>
<td>$M_{T2}(\ell\ell)$ shape (WW)</td>
<td>-</td>
<td>1-15%</td>
</tr>
<tr>
<td>$M_{T2}(\ell\ell)$ shape (Drell-Yan)</td>
<td>-</td>
<td>1-13%</td>
</tr>
</tbody>
</table>
Double lepton final state interpretations

→ Common points: light sleptons models.
→ Additional interpretation on terms of chargino pair production.

Carlos Erice Cid, LHCP2018
Semileptonic LLP decays

- Search for long-lived particles through a displaced vertex with several tracks including a high $p_T$ muon.
- Forward coverage ($2<\eta<5$) and low trigger $p_T$ threshold gives sensitivity to small LLP masses.
- Cover LLP lifetimes from 5 ps up to 100 ps and masses in the range 20–80 GeV.

- Also neutralino production in RPV models with mass in 23–98 GeV range.